Fission Gas Monitoring for the AGR-5/6/7 Experiment

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Presented by R.G. Fronk

Gas-Cooled Reactor
Fuels and Methods Program Review
June 18-19, 2019
Outline

• What is our Mission?
• What is the Fission Product Monitoring System (FPMS)?
• AGR-5/6/7 Data Collection
• Continuing work
• Conclusion
Program Goals and Objectives

• The primary mission for AGR-5/6/7 is to support fuel qualification for the Nuclear Regulatory Commission (NRC): accomplish fuel margin testing (AGR-7), and pilot scale fuel fabrication capabilities.
  - AGR-5/6: Formal fuel qualification irradiations and the
  - AGR-7: Fuel Margin Test.

• The margin test demonstrates that there is a margin between the highest fuel temperature in an operating high temperature gas reactor (HTGR) and the temperature at which fuel particle failure rate becomes unacceptable.

• The purpose of the Fission Product Monitoring system is to provide real time fission gas monitoring in support of fuel performance.

• Real-time monitoring provides time-level reporting of release-to-birth ratios.
Fission Product Monitoring System (FPMS)
Gross Monitoring System

- Monitors gross-rate coming from gas line.
- Provides ‘time-stamp’ for analysis for failure.
Gamma-Ray Spectrometer System

• Bank of high-resolution High-Purity Germanium (HPGe) Detectors

• Provides real-time quantification of released fission gas.

• Data is used to calculated release-to-birth ratio.
Gamma-Ray Spectrometer System (cont.)

Sealed Sample Changer

Inlet line
Outlet line

Sample chamber (lid removed)
Containment “Beaker”
System Calibration

- **Efficiency Calibration** – Aerogel infused with dispersed mixed gamma-ray source.
- **Energy Calibration** – Natural Th disk source.
FPM – Data Reprocessing, Analysis and Auxiliary Programs

• Isotopes selected for analysis based on their short half-lives.
  
  Enables the inventory to reach equilibrium within the fuel.

• Optimal half-lives are on the order of 30 seconds – 10 hours.

<table>
<thead>
<tr>
<th>Isotopes</th>
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<tbody>
<tr>
<td>Kr-85m</td>
</tr>
<tr>
<td>Xe-131m</td>
</tr>
<tr>
<td>Kr-87</td>
</tr>
<tr>
<td>Xe-133</td>
</tr>
<tr>
<td>Kr-88</td>
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<tr>
<td>Xe-137</td>
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<tr>
<td></td>
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<tr>
<td>Xe-138</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Xe-139</td>
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</tbody>
</table>

• E.g., Xe-135 has 9.14-hour half-life, 249-keV gamma-ray
Summary of Gross Gamma Data

AGR-5617 Daily Gross Gamma Counts for All Cycles
The gross gamma detectors were moved to zero position on 04/05/2018

GG Counts: • Average  Maximum  □ Standard Deviation

[Graph showing daily gross gamma counts for capsules 1 to 5 with dates from 10 Feb 2018 to 23 Feb 2019]
Summary of Preliminary Release to Birth Ratios
Preliminary Fuel Evaluation

![Graph showing Kr-85m R/B for U.S. and German fuels]

- **U.S. Fuel**
  - Irradiation temperature (°C): 930 - 1350
  - Burnup (%FIMA): 6.3 - 80
  - Fast fluence ($10^{25}$ n/m²): 2.0 - 10.2

- **German Fuel**
  - Irradiation temperature (°C): 800 - 1320
  - Burnup (%FIMA): 7.5 - 15.6
  - Fast fluence ($10^{25}$ n/m²): 0.1 - 8.5
Accomplishments Since May 2018

• Successfully monitored 4 irradiation cycles
• Finished leadout flow testing and determination of transport volumes.
• Software upgrades are being implemented to transition from older coding languages to current languages.
• From experiment data, thousands of spectroscopy files were analyzed and release to birth ratios were determined.
Path Forward

• Daily monitoring of the experiment.
  ß Gas Flows
  ß Temperature
  ß Gaseous Fission Products
• Determine I-135 per cycle
• Continue to improve software
  ß Integrate Auto energy calibration
• Evaluate AGR-5/6/7 to past TRISO fuel experiments
Conclusion

- The purpose of our support of AGR 5/6/7 is to provide data on fission product migration and retention in the next generation reactor.

- Larger capsule volumes and an increase in the amount of fuel per capsule impact how gaseous fission products FPMS thus impacting the birth-to-release calculations.

- Early R/B indicate that the data may be similar to that of AGR-2.

- As AGR-5/6/7 matures, data and test conditions will be re-evaluated as needed.

- To date, we have never seen a failure of the fuel.
Thank you!

- Dr. Edward L. Reber
- Dr. Ryan Fronk
- Dr. Julie Bowen
- Thomas Nance
- RML
- ATR LOC
Additional Slides
The NEFT has higher fast fluence \((4.4 \times 10^{14} \text{ n/cm}^2/\text{s})\) and thermal \((1.1 \times 10^{14} \text{ n/cm}^2/\text{s})\) neutron flux, which allow irradiations to achieve the burnup and fast neutron fluence requirements in a shorter period of time (i.e., approximately 20 to 24 months versus 30 to 36 months in a Large B position).
AGR-5/6/7 Objectives

• The AGR-5/6/7 experiment is a combination of three tests from the early program plan.

• These tests serve as the formal fuel qualification irradiations (AGR-5/6) and the margin test (AGR-7).

• The purpose of the margin test is to demonstrate that there is a margin between the highest fuel temperature in an operating high temperature gas reactor (HTGR) and the temperature at which fuel particle failure rate becomes unacceptable.

The primary mission for AGR-5/6/7 is to support fuel qualification for the Nuclear Regulatory Commission (NRC), accomplish fuel margin testing (AGR-7), and pilot scale fuel fabrication capabilities.
## AGR-5/6/7 Fuel Parameters

<table>
<thead>
<tr>
<th>Capsule</th>
<th>No. of Particles</th>
<th>Packing Fraction</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>309,060</td>
<td>40%</td>
</tr>
<tr>
<td>2</td>
<td>72,448</td>
<td>25%</td>
</tr>
<tr>
<td>3</td>
<td>54,360</td>
<td>25%</td>
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<tr>
<td>4</td>
<td>52,728</td>
<td>25%</td>
</tr>
<tr>
<td>5</td>
<td>81,432</td>
<td>40%</td>
</tr>
</tbody>
</table>

### AGR Temperature Goals

**AGR-5/6: The time average temperature distribution goals:**
- $\geq 600^\circ C - < 900^\circ C$ for 30% of the fuel
- $\geq 900^\circ C - <1050^\circ C$ for 30% of the fuel
- $\geq 1050^\circ C - <1250^\circ C$ for 30% of the fuel
- $\geq 1250^\circ C - <1400^\circ C$ for 10% of the fuel

**AGR-7 (Capsule 3): The time average, peak temperature:**
- $1350 \pm 50^\circ C - 1500 \pm 50^\circ C$

- TRISO-particle fuel in the form of cylindrical compacts.
- Nominally 25.0mm in length and 12.3 mm in diameter.
- 194 compacts distributed within 5 capsules that contain a U-235 content of 35.7 grams and total uranium content of 230.3 grams.
- The particles are UCO low enriched uranium (LEU) fuel kernels with an enrichment level of 15.5wt%.
- The TRISO over-coating process yields AGR-5/6/7 fuel particles that have 870-μm nominal diameter.
- Number of particles per capsule are obtained by dividing the uranium mass content of a compact by the uranium mass content of a particle.
AGR-5/6/7 Capsule 1

- Bottom capsule in test train
- Contains ten fuel stacks (90 compacts)
- A hollow center to reduce total energy deposition
- 228.6mm long
- No thru-tubes
- Capsule 1 is completely sealed which means there is no cross-talk between capsule 1 and the other capsules

With no thru-tubes there is more room for fuel stacks and, therefore, capsule 1 contains the most fuel (60%) of the AGR-5/6 capsules.
AGR-5/6/7 Capsules 2, 4 and 5

- Four fuel stacks each and like Capsule 1, contains hollow centers
- Capsule 2 contains 32 compacts and is 203.2mm in length
- Capsules 4 and 5 each contain 24 compacts and are 152.4mm in length
AGR-5/6/7 Capsule 3

- Capsule 3 is the AGR-7 margin test
- Three fuel stacks consisting of a total of 24 compacts
- 203.2 mm inches in length

Capsule 3 contains a unique design feature in that the graphite holder has been separated into two pieces, allowing the center mass to run hot while keeping the thru-tubes relatively cool, thereby extending the life of the instrumentation lines contained within the thru-tubes.
AGR-5/6/7 Capsule Cross Section

**Summary**

**Capsule 1**
- Capsule Shell
- Thru Tube
- Gas Gap
- Fuel Stack
- Graphite Holder

**Capsule 2, 4, 5**
- Capsule Shell
- Gas Gap
- Graphite Holder

**Capsule 3**
- Capsule Shell
- Outer Gas Gap
- Outer Graphite Holder
- Inner Graphite Holder
- Inner Gas Gap
- Thru Tube

**Advanced Reactor Technologies (ART)**
AGR-5/6/7 Uniqueness

- AGR-5/6/7 was designed to stay in the reactor for high power runs.
- Contains more thermocouples than any other AGR experiment - 54!

<table>
<thead>
<tr>
<th>Capsule</th>
<th>Number of TC’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

- Self-Powered Neutron Detector (SPND) located in capsules 2, 3, 4 and 5.
- One Micro-Pocket Fission Detector (MPFD) in capsule 5.
- One ultrasonic temperature sensor (capsule 5) and
- Two fiber-optic temperature sensors also located in capsule 5.
AGR-5/6/7 Installation into the ATR
Determination of Transport Volumes – Why?

• To determine fuel performance parameters, fission gas measured at the FPMS must be corrected for decay during the transport time from the constantly – irradiated fuel capsule to the FPMS measurement location.

• Capsule effluent gas flow rates change according to the desired experimental conditions, it is necessary to define a capsule-to-FPMS transport must be determined so corrections associated with the flow dependent transport time (and corresponding decay) can be made.

Larger capsule volumes and an increase in the amount of fuel per capsule impact how gaseous fission products such as longer and shorter lived isotopes of Kr and Xe are transported to the FPMS thus impacting the release activity calculations that are used in conjunction with birth rates as a metric of fuel performance.
Determination of Transport Volumes – How?

- Five capsules are stacked one on top of the other.
- Instrumentation and gas lines from lower capsules pass through capsules above by means of “thru tubes”.
- In the plenum region between capsules there are no thru-tubes therefore required thermocouple and gas lines can be routed into and out of each capsule.
- Leadout tube (not shown) connects capsule train to reactor top head.
- The other end of the leadout bolts to a reactor vessel flange. Thus the leadout acts as a conduit for the various gas lines and leads to enter and exit the ATR reactor vessel.
How? Continued

- Thermal expansion allowances required that while the thru-tubes could be brazed or welded to the upper capsule heads, the lower closure plates had to be a tightly machined slip fit.

- To ensure that capsule cross talk through the leadout volume did not occur, a helium (He) gas supply is provided to the leadout.

- Gas flows provided to the leadout must exit through the small slip-fit leakage path around the capsule thru-tubes, if the leadout flow rate is adjusted so that all capsules receive some inlet flow from the leadout, capsule cross talk can be eliminated.

- Since there is no thru-tube in capsule one, there should be no cross-talk between capsule 1 and the other capsules.
Preliminary AGR-5/6/7
Transport Testing/Line Volum

- Leadout flow set to 10 sccm Helium.
- Measurements were collected at 3 different total flow set points.
- Volumes are from the top of each capsule to their respective FPM.
- Currently the following isotopes are used in the model: Kr-89, Xe-135m, Xe-137, Xe-138 and Ne-23.
- Values needed to compute release activity.

Capsule to FPM Line Volumes
\[ V_t \text{ capsule 1} = 240 \pm 13 \text{ scc} \]
\[ V_t \text{ capsule 2} = 282 \pm 13 \text{ scc} \]
\[ V_t \text{ capsule 3} = 317 \pm 07 \text{ scc} \]
\[ V_t \text{ capsule 4} = 293 \pm 04 \text{ scc} \]
\[ V_t \text{ capsule 5} = 282 \pm 23 \text{ scc} \]
Preliminary R/B – First Four Cycles-Capsule 1 (40%PF)
Preliminary R/B – First Four Cycles - Capsule 2
Preliminary R/B – First Four Cycles - Capsule 3
Preliminary R/B – First Four Cycles - Capsule 4

![Graph showing R/B and NE lobe power with dates and isotopes]
Preliminary R/B – First Four Cycles - Capsule 5 (40% PF)