Air/Moisture-Ingress Furnace Development

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AGR TRISO Fuels Program Review
Idaho Falls, ID
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Outline

• Purpose for air/moisture-ingress testing
• Data to be collected
• Test conditions
• Samples to be tested
• Development and current status
Purpose of Safety Testing in Air and Steam

- Safety testing of AGR fuel has only been under helium (FACS/CCCTF)
- Accident scenarios in HTGRs include depressurized conduction cooldown events:
  - Main coolant line break with air-ingress
  - Steam generator tube leak with moisture-ingress
- Fuel oxidation will occur when exposed to air or steam at high temperatures:
  - Compact matrix and particle OPyC layer oxidation
  - SiC generally resistant to but will slowly oxidize as well
- Small amounts of fission products accumulate in compact matrix during irradiation
- Oxidation of matrix and OPyC will mobilize fission products outside of the OPyC
- Exposed kernels (from as-fabricated defects or failures) vulnerable to hydrolysis
- This activity falls under elements 3 and 5 of the Technical Program Plan (TPP-3636)
  - #3 Safety testing
  - (#4 Fuel performance modeling)
  - #5 Fission product transport and source term
Air/Moisture Ingress Furnace Goals

- Test irradiated TRISO fuels in oxidizing environments representative of air and moisture ingress accidents in HTGRs
- Measure fission product releases as a function of time
- Relate fission product releases and release rates to fuel irradiation history, test conditions, and extent of fuel oxidation
- Use collected data for:
  - Fuel qualification and licensing
  - Input to and comparisons with predictive models and simulations
  - Reactor accident source term analysis
## Air/Moisture Ingress System Bounding Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total test pressure (kPa)</td>
<td>~85 (ambient)</td>
</tr>
<tr>
<td>Air Partial Pressures (kPa)</td>
<td>0.1 to 85</td>
</tr>
<tr>
<td>Moisture Partial Pressures (kPa)</td>
<td>0.1 to 85</td>
</tr>
<tr>
<td>Temperature Range (°C)</td>
<td>$T_{\text{min}} \leq 800, T_{\text{max}} \geq 1650$</td>
</tr>
<tr>
<td>Flow velocity at the sample (m/s)</td>
<td>0.1 to 0.2</td>
</tr>
<tr>
<td>Test durations (hr.)</td>
<td>100 +</td>
</tr>
</tbody>
</table>

Data Collection

- Fission product releases as a function of test time
  - Fission product gases:
    - Kr-85 (indicates failure of all three TRISO layers)
    - Xe-133 (could be measured from tests following re-irradiation)
  - Never before done in air/moisture: condensable fission products
    - Ag-110m
    - Cs-134/137 (indicates SiC layer failure)
    - Eu-154/155
    - I-131 (measured from re-irradiated samples)
    - Sr-90

- Extent of sample oxidation as a function of time
Potential Samples

- Irradiated fuel compacts, fuel bodies, pebbles, graphite with fission products
**Experiment Layout**

**Test Gas Supply**
- Bottled air
- Mass flow controller
- Mixer
- Mass flow controller
- Steam Generator
- Mass flow meter
- T-junction

**Bottled helium for mixing with air and for inert heat up**
- Mass flow controller
- Steam bypass during heat up

**Bottled helium for mixing with steam**
- Mass flow controller

**Deaerated Water Supply**
- Mass flow meter
- T-junction

**Air/He bypass during heat up**
- Mass flow controller

**Furnace**
- Test gas pre-heater
- Filter package (heated at 150 °C):
  - Glass wool pre-filter
  - HEPA filter
  - Zeolite filter (optional)
  - Gamma detector
- Red shading denotes trace heaters

**Mass-Spectrometer/CO analyzer**
- Dual stream sampler
- Instrument Exhaust
- Heated capillaries

**Fission gas monitoring system for Kr-85 and Xe-133**
- Charcoal traps
- Gamma detectors

**Exhaust**
- Exhaust to FCF stack

**FCF Operating Corridor**
- FCF Air Cell
- Condenser (~1°C)
- Mass flow meter
- He sweep gas supply

**Red shading**
- Denotes trace heaters
- Thermal gradient tube heating zones and gamma detectors
**Experiment Layout**

- **Bottled air**
- **Mass flow controller**
- **Mixer**
- **Steam Generator**
- **T-junction**
- **Furnace/Test Section**
- **Furnace**
- **Filter package (heated at 150 °C):**
  - Glass wool pre-filter
  - HEPA filter
  - Zeolite filter (optional)
  - Gamma detector
- **Deaerated Water Supply**
- **Mass flow meter**
- **Steam bypass during heat up**
- **Thermal gradient tube heating zones and gamma detectors**
- **Red shading denotes trace heaters**
- **Bottled helium for mixing with air and for inert heat up**
- **Bottled helium for mixing with steam**
- **Mass flow controller**
- **Test gas pre-heater**
- **Mass-Spectrometer/CO analyzer**
- **Instrument Exhaust**
- **Dual stream sampler**
- **Heated capillaries**
- **He sweep gas supply**
- **Fission gas monitoring system for Kr-85 and Xe-133:**
  - Charcoal traps
  - Gamma detectors
- **Exhaust to FCF stack**
- **H₂O Trap (e.g. drierite)**
- **Condenser (~1°C)**
Experiment Layout

- **Bottled air**
- **Mass flow controller**
- **Mixer**
- **Steam Generator**
- **Mass flow controller**
- **Mass flow meter**
- **Furnace**
- **Test gas preheater**
- **T-junction**
- **Red shading denotes trace heaters**
- **Condensable fission product collection**
- **Filter package (heated at 150 °C):**
  - Glass wool pre-filter
  - HEPA filter
  - Zeolite filter (optional)
  - Gamma detector
- **Deaerated Water Supply**
- **Mass-Spectrometer/CO analyzer**
- **Instrument Exhaust**
- **Dual stream sampler**
- **Heated capillaries**
- **He sweep gas supply**
- **Condenser (~1°C)**
- **H₂O Trap (e.g. drierite)**
- **Fission gas monitoring system for Kr-85 and Xe-133:**
  - Charcoal traps
  - Gamma detectors
- **Exhaust to FCF stack**
- **FCF Operating Corridor**
- **FCF Air Cell**

Red shading denotes trace heaters.
**Experiment Layout**

- **Bottled air**
- **Mass flow controller**
- **Mixer**
- **Steam Generator**
- **Mass flow meter**
- **Test gas pre-heater**
- **Filter package (heated at 150 °C):**
  - Glass wool pre-filter
  - HEPA filter
  - Zeolite filter (optional)
  - Gamma detector
- **Red shading denotes trace heaters**
- **Furnace**
- **Dual stream sampler**
- **Heated capillaries**
- **Mass-Spectrometer/CO analyzer**
- **Deaerated Water Supply**
- **Instrument Exhaust**
- **H₂O Trap (e.g. drierite)**
- **Condenser (~1°C)**
- **Noble Gas Fission Product Collection**
- **Exhaust to FCF stack**
- **He sweep gas supply**

- **FCF Operating Corridor**
- **FCF Air Cell**
**Experiment Layout**

- **Bottled air**
- **Steam Generator**
- **Furnace**
- **Test gas pre-heater**
- **Filter package (heated at 150 °C):**
  - Glass wool pre-filter
  - HEPA filter
  - Zeolite filter (optional)
  - Gamma detector

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**Gas analysis**

- **Mass-Spectrometer/CO analyzer**
- **Instrument Exhaust**
- **Dual stream sampler**
- **Heated capillaries**
- **Fission gas monitoring system for Kr-85 and Xe-133:**
  - Charcoal traps
  - Gamma detectors

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- **Deaerated Water Supply**
- **Mixer**
- **Mass flow controller**
- **Mass flow meter**
- **T-junction**

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- **Air/He bypass during heat up**
- **Bottled helium for mixing with air and for inert heat up**
- **Bottled helium for mixing with steam**
- **Steam bypass during heat up**
- **Fission gas monitoring system for Kr-85 and Xe-133:**
- **Charcoal traps**
- **Gamma detectors**

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- **FCF Operating Corridor**
- **FCF Air Cell**
- **Exhaust to FCF stack**
- **Condenser (~1°C)**
- **He sweep gas supply**

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- **Red shading denotes trace heaters**

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- **13**
**Sample Process Flow**

**HFEF (or AL)**
Irradiated Fuel/Graphite Samples

- **Compacts**
- **Fuel Bodies**
- **Graphite with Fission Products**

Loose fuel particles

**FCF**

- Furnace
- Test gas pre-heater
- Detectors

**Thermal gradient tube**

**Stay in FCF**

- Aerosol and charcoal filter

**AL**

- Thermal gradient tube leachate

**HFEF**

- Sample(s) of steam condensate
- Irradiated fuel or graphite
### Simplified Overall Schedule

<table>
<thead>
<tr>
<th>Activity</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
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<tbody>
<tr>
<td>Conceptual Design</td>
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<td></td>
<td></td>
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<tr>
<td>Benchtop testing*</td>
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<tr>
<td>60% design review for in-cell system**</td>
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<tr>
<td>Final design</td>
<td></td>
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<tr>
<td>FCF facility modifications</td>
<td></td>
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<tr>
<td>Equipment procurement and fabrication</td>
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<tr>
<td>Phase 1 and Phase 2 qual in mockup</td>
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<tr>
<td>Install equipment in FCF air cell</td>
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<tr>
<td>Feedthrough(s) installation</td>
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<tr>
<td>Phase 3 qualifications</td>
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<tr>
<td>Approval for hot operations</td>
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</tr>
<tr>
<td>Initiate air/moisture ingress safety test</td>
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</tbody>
</table>

*4 milestone to initiate benchtop development testing by 3/31/17

**L2 milestone to complete 60% design review by 9/15/17
## Elapsed Timeline

<table>
<thead>
<tr>
<th>Date</th>
<th>Events</th>
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</thead>
<tbody>
<tr>
<td>Nov 2015</td>
<td>TCT Meeting and Input</td>
</tr>
<tr>
<td>May 2016</td>
<td>Chose lab for benchtop testing</td>
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<tr>
<td>June 2016</td>
<td>FOR-284 rev. 0</td>
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<tr>
<td>June 2016</td>
<td>TEV-2729 rev. 1</td>
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<tr>
<td>July 2016</td>
<td>Selected FCF air hot-cell window A3</td>
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<tr>
<td>July 2016</td>
<td>Assembled design team</td>
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<tr>
<td>July 2016</td>
<td>Initiated bi-weekly design meetings</td>
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<tr>
<td>Aug 2016</td>
<td>Acquired bench testing furnace</td>
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<tr>
<td>Aug 2016</td>
<td>FOR-284 rev. 1</td>
</tr>
<tr>
<td>Sept 2016</td>
<td>Initiated equipment specifications</td>
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<tr>
<td>Sept 2016</td>
<td>Began soliciting vendor quotes for benchtop equipment</td>
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<tr>
<td>Oct 2016</td>
<td>Initiated material request for gas analysis equipment</td>
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<tr>
<td>Nov 2016</td>
<td>Furnace moved into lab for benchtop testing</td>
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<tr>
<td>Nov 2016</td>
<td>Initiated material request for gas analysis equipment</td>
</tr>
<tr>
<td>Nov 2016</td>
<td>Initiated SDD</td>
</tr>
<tr>
<td>Nov 2016</td>
<td>Outlined conceptual design report</td>
</tr>
<tr>
<td>Nov 2016</td>
<td>Initiated SDD</td>
</tr>
</tbody>
</table>
**Elapsed Timeline (continued)**

- **Jan 2017**
  - In-cell furnace conceptual design review
  - Completed conceptual design document merging F&ORs with necessary specifications

- **Feb 2017**
  - Completed focused review of benchtop development furnace laboratory instruction (LI)

- **Mar 2017**
  - Initiated benchtop testing with zirconia furnace tube

- **Apr 2017**
  - Released LI-805
  - Started benchtop valve board construction

- **May 2017**
  - Received MS/CO analyzer
  - Tested furnace flanges

- **Jun 2017**
  - Installed and trained on MS/CO analyzer
  - Began testing LaBr$_3$

- **Jul 2017**
  - Installed and trained on MS/CO analyzer
  - Began testing LaBr$_3$

- **Remainder of FY17**
  - Complete benchtop system construction
  - Benchtop testing of graphite with air/He and steam/helium mixtures, stable fission product surrogate testing
  - Aug-Sept: in-cell system 60% design review
Current benchtop testing – tube materials/flanges

- Currently testing with Al₂O₃ and ZrO₂
- Ramp rates of 200°C/hr have been used successfully with ZrO₂
- Faster ramp rates may be tested
**Current benchtop testing – gas analysis**

- Mass spectrometer, CO analyzer, multi-stream selector to measure oxidation products from reaction of carbon with H$_2$O/air (CO, CO$_2$, H$_2$, etc.)
Current benchtop testing – furnace temperature profiling

- Profiling for test temperatures 800-1600°C in steam/air
- 6 thermocouples, Type-K for low temperature zones, Type-B for high temperature zones
- SiC sheath
- Profile entire furnace length: one probe inserted from left, one probe inserted from right
Current benchtop testing – thermal gradient tube design to enable post-test leaching

- Multiple tube sleeves inserted inside single piece tube
- Tube end-caps clamp entire assembly together
- Ordered these in ZrO₂ and Al₂O₃
- Test deposition of stable isotopes of: Ag, Cs, Eu, I, Sr

For in-cell use, sleeve sections sized to correspond to LaBr₃ field of view along TGT and known temperature zones
Completed P&ID for Benchtop Development.
Generated Preliminary P&IDs for In-cell System
Preliminary In-Cell P&ID Showing Furnace and Furnace Outlet Gas Flow

NOTES
1. SEE THE FOLLOWING SHEETS:
A. LEGEND, ABREVIATIONS & KEY PLANS SEE SHEET T-2
B. GENERAL PIPING NOTES SEE SHEET P-1
C. COMPONENT LIST AND VALVE LIST SEE SHEET P-3
D. INSTALLATION SEE SHEETS P-8 THRU P-7

2. ALL TUBING IS 1/4" OD UNLESS OTHERWISE NOTED.
In-cell System Status

• Secured use of FCF Window A3
• Conceptual design review completed February 2017 (fulfilled L4 milestone)
• 60% design review to be completed end of August 2017 (L2 milestone)
  – Piping and instrumentation diagrams (P&ID)
    • Out-of-cell equipment: gas supply, gas analysis, fission gas monitoring
    • In-cell equipment: gas supply lines, furnace, filters, TGT, etc.
    • Equipment lists/specs
  – Valve boards/equipment layouts in cell corridor and FCF basement
  – Facility electrical diagrams
  – Instrumentation and control: hardware/software
  – Feedthroughs: number, location, inputs/outputs, shell design
  – Mockup: equipment layout
  – Facility: DSA update, draft Criticality Safety Evaluation
• Taking steps to order manipulators this year
In-cell System: Furnace Loading (video)
In-cell System: Thermal Gradient Tube Gamma Detectors (video)

- Shutter and detector distance control

Tungsten Shielding/Collimation

LaBr₃(Ce) detectors
On-going Work

• In-cell system 60% design review by end of FY2017 (L2 milestone)

• Target for in-cell system final design is March 2018

• Long-lead-time equipment for in-cell system will be purchased at-risk as-appropriate

• Benchtop testing: oxidization of graphite, gas analysis, surrogate fission product transport, etc.

• Benchtop testing will continue beyond in-cell system final design

• Seeking bids from manufacturers for in-cell furnace
Questions and Discussion

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(208) 526-8410
Possible Air-Ingress Accident Conditions
Depressurized Loss of Forced-Convection (DLOFC)

• Safety-Related Design Condition-10 (SRDC-10)¹
  – Cooling is by conduction and radiation to the reactor cavity cooling system (RCCS)
  – Peak fuel temperature: 1620°C
  – Time to reach peak fuel temperature: 80 hours
  – Air-ingress occurs after depressurization

Possible Moisture-Ingress Accident Conditions

- Safety-Related Design Condition-6 (SRDC-6)\(^1\)
  - Depressurized conduction cooldown event
  - Moderate steam generator leak duration: < 30 minutes
  - Peak core temperature: 1540°C
  - Time to reach peak temperature: 100 hrs