Gas Assay, Sample, & Recharge (GASR) System
Volume Determination

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Acknowledgements

• Dave Sell
  GASR Process Engineer

• Scott White, Dawnette Hunter, Matt Larson
  GASR Operators

• Hot Fuel Examination Facility (HFEF)
The FCRD Advanced Fuel Campaign is tasked with development of near-term Accident Tolerant LWR fuel technology and performing research and development of long-term resource enhancement options.

- Advanced LWR fuels with enhanced performance, safety, and reduced waste generation
- Transmutation fuels with enhanced proliferation resistance and resource utilization

Capabilities Development for Science-Based Approach to Fuel Development
- Advanced characterization and PIE techniques
  - Advanced in-pile instrumentation
  - Separate effects testing
  - Transient testing infrastructure

ADVANCED FUELS CAMPAIGN

NEAMS
Fuel Development R&D Life Cycle

Advanced Fuel Design → Feedstock Preparation & Characterization

Performance Assessment → Postirradiation Examination

Multi-Physics Modeling & Simulation (Moose-Bison-Marmot)

Ceramic & Metallic Fuel and Material Fabrication

U.S. gov’t, commercial, foreign gov’t and other program scope

Fresh Fuel Characterization

Out-of-Pile Testing

Transient Testing Potential

Irradiation Testing

Unique & world-leading irradiation capabilities

Closing the fuel cycle

World-leading PIE capabilities
**Irradiation Testing Goals**

- **Improve fuel**
  - understand fuel behavior
  - test changes to fuel design

- **Conduct scoping tests**
  - identify new fuels (composition, geometry, additives, new cladding, cladding coatings and liners)
  - compare irradiation behavior
  - down-select options

- **Build qualification data**
  - Irradiate fuels in prototypic conditions

- **Perform postirradiation examination (PIE)**
  - collect data on fuel behavior: swelling, growth, fission gas release, creep, fuel cladding chemical/mechanical interaction, microstructure, burnup, …
**Fuel Performance Phenomena**

- Dimensional changes
  - axial growth
  - radial swelling

- Fission gas production and release (pin pressure)

- Fuel restructuring (zone formation)

- Constituent redistribution

- Fuel Cladding Chemical/Mechanical Interaction

- Performance phenomena depend on
  - composition
  - burnup

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Transverse metallographic section from the high temperature region of a U-19Pu-10Zr element at 3 at.% burnup with superimposed microprobe scans, showing zone formation, cracking and Zr-U redistribution.

Fission gas released to plenum above fuel for various metallic fuels as a function of burnup (EBR-II irradiation)

**PIE Activities**

- **Baseline Nondestructive PIE**
  - visual
  - neutron radiography (thermal, epi-thermal)
  - gamma scan (axial isotopic data)
  - metrology (radial swelling)

- **Baseline Destructive PIE**
  - fission gas analysis
  - optical microscopy / metallography
  - microhardness
  - analytical chemistry / burnup analysis

- **Additional PIE**
  - fracture toughness
  - SEM, EBSD, WDS, FIB, TEM, EPMA
  - micro-XRD
  - thermal properties
Gas Assay, Sample, & Recharge System (GASR)

- Connect a pin, element, or container to seal head
- Puncture boundary with laser
- Measure pressure of gas after expansion into GASR system
- Expand into series of volumes to collect gas sample
- Backfill and expand gas to measure element volume
- Gas sample collected and analyzed with gas mass spectrometer (separate facility)
GASR Challenges

- System in use since 1984
- Knowledge of system volumes and uncertainties is necessary to measure and characterize an unknown volume (e.g., experimental fuel pin)
- Recent repairs required a new volume determination
  - replaced: valve, pressure transducer, manifold tubing connection
  - new laser flash lamps installed
- Large system volume compared to experimental fuel pin volume
  - ~200 cm$^3$ system volume
  - ~1-15 cm$^3$ experimental fuel pin volume
Standard Pin Puncture Set-up

Pressure limit at HW PT = 25 psia (1.72 bar, 1293 Torr)

Initial Pressure
- Seal Head
- Valve V-8
- In-Cell Honeywell Pressure Transducer (PI-7)
- Pin

Gas Expansion
- Valve V-12
- Manifold
- Valve V-10
- Sample Line
- Sample Bottle
- Sample Valve V-4/V-5

Aux Volume
- External Gas Supply

Pressure Transducer (PI-2)
Pressure Transducer (PI-1)

In-Cell
Out-of-Cell

Hot cell boundary
Basis for Gas Expansion

• Ideal gas law:

\[ PV = nRT \]

• For constant temperature, adiabatic, sealed system \((n_1=n_2, \ T_1=T_2)\):

\[ P_1V_1 = P_2V_2 \]

\[ P_{initial}V_{initial} = P_{final}V_{final} \]

\[ P_{initial} \sum_{\text{initial}} V_i = P_{final} \sum_{\text{final}} V_i \]
Volume Determination Set-up

Pressure Transducer (PI-1)

Seal Head

Valve V-8

In-Cell Honeywell Pressure Transducer (PI-7)

Pressure Transducer (PI-2)

Valve V-12

Manifold

Valve V-1

Sample Line

Sample Valve V-4/V-5

Temporary Tubing

External Gas Supply

Initial Pressure

Gas Expansion

Pressure limit = 10 psia
(0.689 bar, 517 Torr)

Calibrated Volume

Calibrated Volume

Out-of-Cell Valve

Calibrated Volume

In-Cell

Out-of-Cell
Volume Determination Method: Volume I

Pressure Transducer (PI-1)

Seal Head

Valve V-12

Manifold

Pressure Transducer (PI-2)

Valve V-1

Valve V-10

Sample Line

Sample Valve V-4/V-5

Temporary Tubing

External Gas Supply

Calibrated Volume

Out-of-Cell

In-Cell

Out-of-Cell Honeywell Pressure Transducer

Calibrated Volume Isolation Valve

Hot cell boundary

Valve V-8

In-Cell Honeywell Pressure Transducer (PI-7)

Aux Volume
Volume Determination Method: Volume I

- Calibrated Volume
- Sample Valve V-4/V-5
- Honeywell Pressure Transducer
- Isolation Valve
- Manifold
- Seal Head
- Valves V-8, V-10, V-12
- Pressure Transducer PI-1, PI-2
- In-Cell Honeywell Pressure Transducer PI-7
- Sample Line
- Temporary Tubing
- External Gas Supply
- Hot cell boundary
- Calibrated Volume
Volume Determination Equations (Volume I)

\[ P_{\text{cal}} V_{\text{cal}} = P_{\text{tube}} V_{\text{total}} \]

\[ P_{\text{cal}} V_{\text{cal}} = P_{\text{tube}} (V_{\text{cal}} + V_{\text{tube}}) \]

\[ P_{\text{cal}} V_{\text{cal}} = P_{\text{tube}} V_{\text{cal}} + P_{\text{tube}} V_{\text{tube}} \]

\[ P_{\text{cal}} V_{\text{cal}} - P_{\text{tube}} V_{\text{cal}} = P_{\text{tube}} V_{\text{tube}} \]

\[ (P_{\text{cal}} - P_{\text{tube}}) V_{\text{cal}} = P_{\text{tube}} V_{\text{tube}} \]

\[ V_{\text{tube}} = \frac{P_{\text{cal}} - P_{\text{tube}}}{P_{\text{tube}}} V_{\text{cal}} \]
Volume Determination Method: Volume I

[Diagram showing flow process with various components and connections: pressure transducers, valves, tubing, and seals.]
Volume Determination Method: Volume I
**Volume Determination Method: Volume I**

- **Calibrated Volume**
- **Sample Valve**
- **Valve V-4/V-5 Out-of-Cell Honeywell Pressure Transducer**
- **Isolation Valve**
- **Manifold**
- **Seal Head**
- **Pressure Transducer (PI-1)**
- **Valve V-12**
- **Pressure Transducer (PI-2)**
- **Valve V-10**
- **Sample Line**
- **Volume**
- **Valve V-8**
- **In-Cell Honeywell Pressure Transducer (PI-7)**
- **Aux Volume**
- **External Gas Supply**
- **Valve V-1**
- **Temporary Tubing**
- **Out-of-Cell Valve V-4/V-5**
- **Calibrated Volume**
- **External Gas Supply**
- **Hot cell boundary**
- **In-Cell**
- **Out-of-Cell**
- **Calibrated Volume Isolation Valve**
- **Aux Volume**
- **Valve V-8**
- **In-Cell Honeywell Pressure Transducer (PI-7)**
- **Aux Volume**
- **External Gas Supply**
- **Valve V-1**
- **Temporary Tubing**
- **Out-of-Cell Valve V-4/V-5**
- **Calibrated Volume**
- **External Gas Supply**
- **Hot cell boundary**
Volume Determination Method: Volume I

- **In-Cell**
  - Honeywell Pressure Transducer (PI-1)
  - Pressure Transducer (PI-2)
  - Valve V-10
  - Valve V-12
  - Valve V-8
  - In-Cell Honeywell Pressure Transducer (PI-7)
  - Seal Head

- **Out-of-Cell**
  - Sample Line
  - Sample Valve V-4/V-5
  - Valve V-4
  - Valve V-5
  - Out-of-Cell Honeywell Pressure Transducer
  - Calibrated Volume
  - Temporary Tubing
  - External Gas Supply

- **Aux Volume**

- **External Gas Supply**

- **Hot cell boundary**
Volume Determination Equations (Volume I)

\[ V_{\text{tube}} = \frac{P_{\text{cal}} - P_{\text{tube}}}{P_{\text{tube}}} V_{\text{cal}} \]

\[ V_{\text{SL}} = \frac{P_{\text{cal}} - P_{\text{SL}}}{P_{\text{SL}}} V_{\text{cal}} - V_{\text{tube}} \]

\[ V_{\text{MF}} = \frac{P_{\text{cal}} - P_{\text{MF}}}{P_{\text{MF}}} V_{\text{cal}} - V_{\text{tube}} - V_{\text{SL}} \]

\[ V_{\text{SH}} = \frac{P_{\text{cal}} - P_{\text{SH}}}{P_{\text{SH}}} V_{\text{cal}} - V_{\text{tube}} - V_{\text{SL}} - V_{\text{MF}} \]

\[ V_{\text{PT}} = \frac{P_{\text{cal}} - P_{\text{PT}}}{P_{\text{PT}}} V_{\text{cal}} - V_{\text{tube}} - V_{\text{SL}} - V_{\text{MF}} - V_{\text{SH}} \]

\[ V_{\text{Aux}} = \frac{P_{\text{cal}} - P_{\text{Aux}}}{P_{\text{Aux}}} V_{\text{cal}} - V_{\text{tube}} - V_{\text{SL}} - V_{\text{MF}} - V_{\text{SH}} - V_{\text{PT}} \]
Volume Determination Method: Volume II

Volume Determination Method: Volume II
Volume Determination Method: Volume II

- Pressure Transducer (PI-1)
- Valve V-8
- Seal Head
- In-Cell Honeywell Pressure Transducer (PI-7)
- Manifold
- Valve V-12
- Valve V-1
- Valve V-10
- Sample Valve V-4/V-5
- Temporary Tubing
- External Gas Supply
- Out-of-Cell Volume Isolation Valve
- Calibrated Volume
Volume Determination Method: Volume II

- Seal Head
- Valve V-8
- In-Cell Honeywell Pressure Transducer (PI-7)
- Valve V-12
- Pressure Transducer (PI-1)
- Manifold
- Valve V-1
- Pressure Transducer (PI-2)
- Valve V-10
- Sample Line
- Sample Valve V-4/V-5
- Temporary Tubing
- External Gas Supply
- Hot cell boundary
- Out-of-Cell
- Out-of-Cell Honeywell Pressure Transducer
- Calibrated Volume
- Calibrated Volume Isolation Valve
- Calibrated Volume
Volume Determination Equations (Volume II)

\[ P_{\text{cal}}(V_{\text{cal}} + V_{\text{tube}} + V_{\text{SL}}) = P_{\text{MF}}(V_{\text{cal}} + V_{\text{tube}} + V_{\text{SL}} + V_{\text{MF}}) \]

\[ V_{\text{MF}} = \left( \frac{P_{\text{cal}} - P_{\text{MF}}}{P_{\text{MF}}} \right) (V_{\text{cal}} + V_{\text{tube}} + V_{\text{SL}}) \]

\[ P_{\text{cal}}(V_{\text{cal}} + V_{\text{tube}} + V_{\text{SL}}) = P_{\text{MF}}(V_{\text{cal}} + V_{\text{tube}} + V_{\text{SL}} + V_{\text{MF}}) \]

\[ V_{\text{SH}} = \left( \frac{P_{\text{cal}} - P_{\text{SH}}}{P_{\text{SH}}} \right) (V_{\text{cal}} + V_{\text{tube}} + V_{\text{SL}}) - V_{\text{MF}} \]

\[ P_{\text{cal}}(V_{\text{cal}} + V_{\text{tube}} + V_{\text{SL}}) = P_{\text{PT}}(V_{\text{cal}} + V_{\text{tube}} + V_{\text{SL}} + V_{\text{MF}} + V_{\text{SH}} + V_{\text{PT}}) \]

\[ V_{\text{PT}} = \left( \frac{P_{\text{cal}} - P_{\text{PT}}}{P_{\text{PT}}} \right) (V_{\text{cal}} + V_{\text{tube}} + V_{\text{SL}}) - V_{\text{MF}} - V_{\text{SH}} \]
Volume Determination Method: Volume III

Pressure Transducer (PI-1)

Seal Head
Valve V-8

In-Cell Honeywell Pressure Transducer (PI-7)

Manifold
Valve V-12
Valve V-1

Sample Line
Sample Valve V-4/V-5

Temporary Tubing

External Gas Supply

Calibrated Volume

Out-of-Cell

Pressure Transducer (PI-2)

Valve V-10

Calibrated Volume Isolation Valve

Out-of-Cell Honeywell Pressure Transducer

Calibrated Volume

In-Cell

External Gas Supply

Hot cell boundary
Volume Determination Method: Volume III
Volume Determination Equations (Volume III)

\[
P_{\text{cal}}(V_{\text{cal}} + V_{\text{tube}} + V_{SL} + V_{MF})
= P_{SH}(V_{\text{cal}} + V_{\text{tube}} + V_{SL} + V_{MF} + V_{SH})
\]

\[
V_{SH} = \left(\frac{P_{\text{cal}} - P_{SH}}{P_{SH}}\right)(V_{\text{cal}} + V_{\text{tube}} + V_{SL} + V_{MF})
\]

\[
P_{\text{cal}}(V_{\text{cal}} + V_{\text{tube}} + V_{SL})
= P_{PT}(V_{\text{cal}} + V_{\text{tube}} + V_{SL} + V_{MF} + V_{SH} + V_{PT})
\]

\[
V_{PT} = \left(\frac{P_{\text{cal}} - P_{PT}}{P_{PT}}\right)(V_{\text{cal}} + V_{\text{tube}} + V_{SL} + V_{MF}) - V_{SH}
\]
Uncertainty Analysis

- Start with one known volume (± volume)
  - ± 0.1 cm$^3$

- Measure pressure (± pressure)
  - ± 0.0125 psia = 0.862 mbar = 0.646 Torr

- Calculate uncertainty of each volume component

- Each volume component builds upon uncertainty of previous components
Uncertainty Analysis (Volume I)

\[ \sigma_u^2 = \left( \frac{\partial u}{\partial x} \right)^2 \sigma_x^2 + \left( \frac{\partial u}{\partial y} \right)^2 \sigma_y^2 + \left( \frac{\partial u}{\partial z} \right)^2 \sigma_z^2 + \ldots \]

where \[ u = f(x, y, z, \ldots) \]

\[ \sigma_{V_{\text{tube}}}^2 = \left( \frac{V_{\text{cal}}}{P_{\text{tube}}} \right)^2 \sigma_{P_{\text{cal}}}^2 + \left( \frac{P_{\text{cal}}V_{\text{cal}}}{P_{\text{tube}}^2} \right)^2 \sigma_{P_{\text{tube}}}^2 + \left( \frac{P_{\text{cal}}}{P_{\text{tube}}} - 1 \right)^2 \sigma_{V_{\text{cal}}}^2 \]

\[ \sigma_{V_{\text{SL}}}^2 = \left( \frac{V_{\text{cal}}}{P_{\text{SL}}} \right)^2 \sigma_{P_{\text{cal}}}^2 + \left( \frac{P_{\text{cal}}V_{\text{cal}}}{P_{\text{SL}}^2} \right)^2 \sigma_{P_{\text{SL}}}^2 + \left( \frac{P_{\text{cal}}}{P_{\text{SL}}} - 1 \right)^2 \sigma_{V_{\text{cal}}}^2 + \sigma_{V_{\text{tube}}}^2 \]

\[ \sigma_{V_{\text{MF}}}^2 = \left( \frac{V_{\text{cal}}}{P_{\text{MF}}} \right)^2 \sigma_{P_{\text{cal}}}^2 + \left( \frac{P_{\text{cal}}V_{\text{cal}}}{P_{\text{MF}}^2} \right)^2 \sigma_{P_{\text{MF}}}^2 + \left( \frac{P_{\text{cal}}}{P_{\text{MF}}} - 1 \right)^2 \sigma_{V_{\text{cal}}}^2 + \sigma_{V_{\text{tube}}}^2 + \sigma_{V_{\text{SL}}}^2 \]
Uncertainty Analysis (Volume I)

\[
\sigma_{V_{SH}}^2 = \left( \frac{V_{cal}}{P_{SH}} \right)^2 \sigma_{P_{cal}}^2 + \left( \frac{P_{cal}V_{cal}}{P_{SH}^2} \right)^2 \sigma_{P_{SH}}^2 + \left( \frac{P_{cal}}{P_{SH}} - 1 \right)^2 \sigma_{V_{cal}}^2 + \sigma_{V_{tube}}^2 + \sigma_{V_{SL}}^2 \\
+ \sigma_{V_{MF}}^2
\]

\[
\sigma_{V_{PT}}^2 = \left( \frac{V_{cal}}{P_{PT}} \right)^2 \sigma_{P_{cal}}^2 + \left( \frac{P_{cal}V_{cal}}{P_{PT}^2} \right)^2 \sigma_{P_{PT}}^2 + \left( \frac{P_{cal}}{P_{PT}} - 1 \right)^2 \sigma_{V_{cal}}^2 + \sigma_{V_{tube}}^2 + \sigma_{V_{SL}}^2 \\
+ \sigma_{V_{MF}}^2 + \sigma_{V_{SH}}^2
\]

\[
\sigma_{V_{Aux}}^2 = \left( \frac{V_{cal}}{P_{Aux}} \right)^2 \sigma_{P_{cal}}^2 + \left( \frac{P_{cal}V_{cal}}{P_{Aux}^2} \right)^2 \sigma_{P_{Aux}}^2 + \left( \frac{P_{cal}}{P_{Aux}} - 1 \right)^2 \sigma_{V_{cal}}^2 + \sigma_{V_{tube}}^2 \\
+ \sigma_{V_{SL}}^2 + \sigma_{V_{MF}}^2 + \sigma_{V_{SH}}^2 + \sigma_{V_{PT}}^2
\]
Uncertainty Analysis (Volume II)

\[ \sigma_{V_{MF}}^2 = \left( \frac{V_{cal} + V_{tube} + V_{SL}}{P_{MF}} \right)^2 \sigma_{P_{cal}}^2 + \left( \frac{P_{cal}(V_{cal} + V_{tube} + V_{SL})}{P_{MF}^2} \right)^2 \sigma_{P_{MF}}^2 \]

\[ + \left( \frac{P_{cal}}{P_{MF}} - 1 \right)^2 \left( \sigma_{V_{cal}}^2 + \sigma_{V_{tube}}^2 + \sigma_{V_{SL}}^2 \right) \]

\[ \sigma_{V_{SH}}^2 = \left( \frac{V_{cal} + V_{tube} + V_{SL}}{P_{SH}} \right)^2 \sigma_{P_{cal}}^2 + \left( \frac{P_{cal}(V_{cal} + V_{tube} + V_{SL})}{P_{SH}^2} \right)^2 \sigma_{P_{SH}}^2 \]

\[ + \left( \frac{P_{cal}}{P_{SH}} - 1 \right)^2 \left( \sigma_{V_{cal}}^2 + \sigma_{V_{tube}}^2 + \sigma_{V_{SL}}^2 \right) + \sigma_{V_{MF}}^2 \]

\[ \sigma_{V_{PT}}^2 = \left( \frac{V_{cal} + V_{tube} + V_{SL}}{P_{PT}} \right)^2 \sigma_{P_{cal}}^2 + \left( \frac{P_{cal}(V_{cal} + V_{tube} + V_{SL})}{P_{PT}^2} \right)^2 \sigma_{P_{SH}}^2 \]

\[ + \left( \frac{P_{cal}}{P_{PT}} - 1 \right)^2 \left( \sigma_{V_{cal}}^2 + \sigma_{V_{tube}}^2 + \sigma_{V_{SL}}^2 \right) + \sigma_{V_{MF}}^2 + \sigma_{V_{SH}}^2 \]
Uncertainty Analysis (Volume III)

\[
\sigma_{V_{SH}}^2 = \left( \frac{V_{cal} + V_{tube} + V_{SL} + V_{MF}}{P_{SH}} \right)^2 \sigma_{P_{cal}}^2 \\
+ \left( \frac{P_{cal}(V_{cal} + V_{tube} + V_{SL} + V_{MF})}{P_{SH}^2} \right)^2 \sigma_{P_{SH}}^2 \\
+ \left( \frac{P_{cal}}{P_{SH}} - 1 \right)^2 \left( \sigma_{V_{cal}}^2 + \sigma_{V_{tube}}^2 + \sigma_{V_{SL}}^2 + \sigma_{V_{MF}}^2 \right)
\]

\[
\sigma_{V_{PT}}^2 = \left( \frac{V_{cal} + V_{tube} + V_{SL} + V_{MF}}{P_{PT}} \right)^2 \sigma_{P_{cal}}^2 \\
+ \left( \frac{P_{cal}(V_{cal} + V_{tube} + V_{SL} + V_{MF})}{P_{PT}^2} \right)^2 \sigma_{P_{PT}}^2 \\
+ \left( \frac{P_{cal}}{P_{PT}} - 1 \right)^2 \left( \sigma_{V_{cal}}^2 + \sigma_{V_{tube}}^2 + \sigma_{V_{SL}}^2 + \sigma_{V_{MF}}^2 \right) + \sigma_{V_{SH}}^2
\]
## Volume and Uncertainty Analysis Summary

### Preliminary results

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<tr>
<th>Run</th>
<th>temp tube</th>
<th>SL</th>
<th>MF</th>
<th>SH</th>
<th>PT</th>
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<td>$V_{\text{SL}}$</td>
<td>$\sigma_{V_{\text{SL}}}$</td>
<td>$V_{\text{MF}}$</td>
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<td>120.00</td>
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<td>67.26</td>
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<td>119.85</td>
<td>0.861</td>
<td>67.34</td>
<td>1.486</td>
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</table>
## Volume Method Comparison

<table>
<thead>
<tr>
<th>Run</th>
<th>Manifold</th>
<th>Seal Head</th>
<th>Pressure Transducer</th>
</tr>
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<td>$\sigma_{VMF}$</td>
<td>$V_{SH}$</td>
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<td>Vol I</td>
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<td>20.56</td>
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<td>Vol II</td>
<td>67.11</td>
<td>0.740</td>
<td>20.33</td>
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<tr>
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<td>20.29</td>
<td>0.695</td>
<td>16.39</td>
</tr>
</tbody>
</table>

Preliminary results
Standard Pin Puncture Set-up
Standard Pin Puncture Set-up
Standard Pin Puncture Set-up

- Pin
- Pressure Transducer (PI-1)
- Valve V-12
- Valve V-8
- Seal Head
- Manifold
- Pressure Transducer (PI-2)
- Valve V-10
- Valve V-1
- Aux Volume
- In-Cell Honeywell Pressure Transducer (PI-7)
- Sample Bottle
- Sample Valve V-4/V-5
- Sample Line
- External Gas Supply
- Out-of-Cell
- In-Cell
- Hot cell boundary
Standard Pin Puncture Set-up

- Pin
- Seal Head
- Valve V-8
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Standard Pin Puncture Set-up

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- Sample Bottle
- Aux Volume
- Manifold
- Valve V-10
- Valve V-12
- Valve V-8
- Seal Head
- Pin
Uncertainty Analysis (Pin Volume)

\[ P_{SH}(V_{pin} + V_{SH} + V_{PT}) = P_{MF}(V_{pin} + V_{SH} + V_{PT} + V_{MF}) \]

\[ V_{pin} = \left( \frac{P_{MF}}{P_{SH} - P_{MF}} \right) V_{MF} - (V_{SH} + V_{PT}) \]

\[ \sigma_{V_{pin}}^2 = \left( \frac{P_{SH}V_{MF}}{(P_{SH} - P_{MF})^2} \right)^2 \sigma_{P_{MF}}^2 + \left( \frac{P_{MF}V_{MF}}{(P_{MF} - P_{SH})^2} \right)^2 \sigma_{P_{SH}}^2 \]

\[ + \left( \frac{P_{MF}}{P_{SH} - P_{MF}} \right)^2 \sigma_{V_{MF}}^2 + \sigma_{V_{SH}}^2 + \sigma_{V_{PT}}^2 \]
Summary

• GASR component volumes have been characterized following system repair

• Preliminary uncertainty analysis has been completed
  – Pressure measurement uncertainty is primary contributor to overall uncertainty
  – Uncertainty analysis refinement/verification needed

• Standard pins (known volume and pressure) are being tested in GASR

• Current analysis highlights the challenges of analyzing small fuel pins

• System improvements and upgrades are in design and will focus on:
  – reliable components
  – total system volume
  – reduced pressure measurement uncertainty