MSFC-297

National Aeronautics and Space Administration

George C. Marshall Space Fight Center

Development of High Fidelity, Fuel-Like Thermal Simulators for Non-Nuclear Testing

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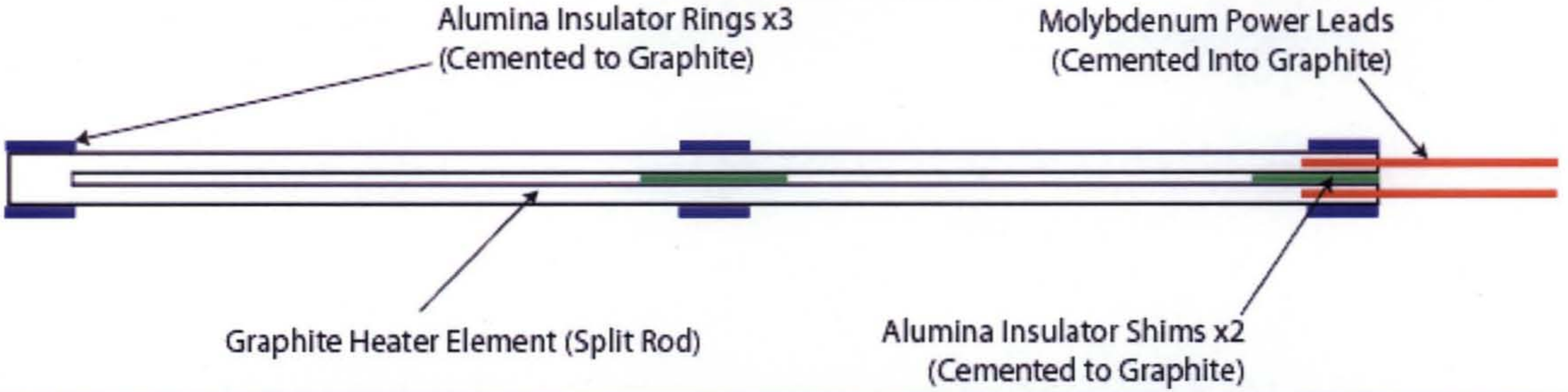
Presentation Summary

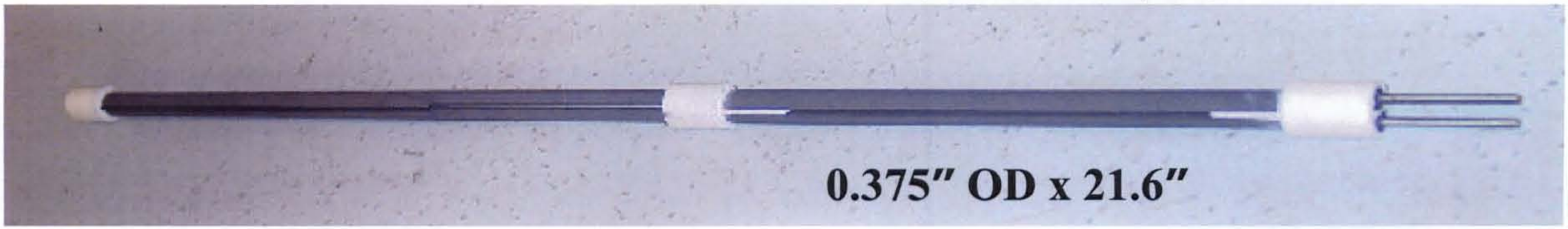
- Instrumented Thermal Simulator Development
  - Design Basis
  - Assembly
  - Test Configurations
- Results
  - Thermal Analysis
  - Experimental Results
- Conclusions
- Future Directions

Testing Strategy

- Non-nuclear tests can enable the development of a space nuclear power system →
  Develop an understanding of individual components and integrated system operation without the cost, time, safety concerns associated with nuclear testing
- Accomplish through use of specialized electric heaters to simulate heat from nuclear fuel
  - Attempt to match overall fuel properties
  - Operation in extreme environments (e.g. vacuum)

Basic Graphite Heater Element Design



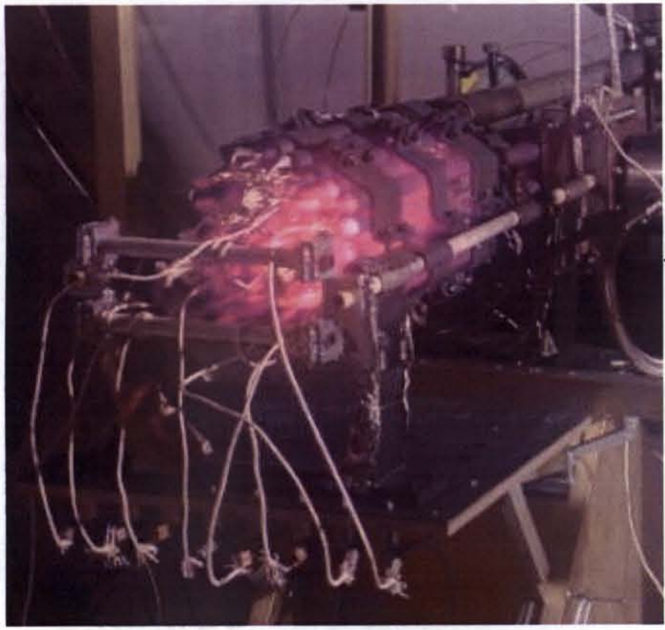


- Low cost (~$200/element)
- Robust "workhorse" heater element
  - Withstand instantaneous power changes
  - Have been operated for 1000s of hours and 100s of thermal cycles
- Can be shaped to provide a prescribed axial power profile

Electrical Integration

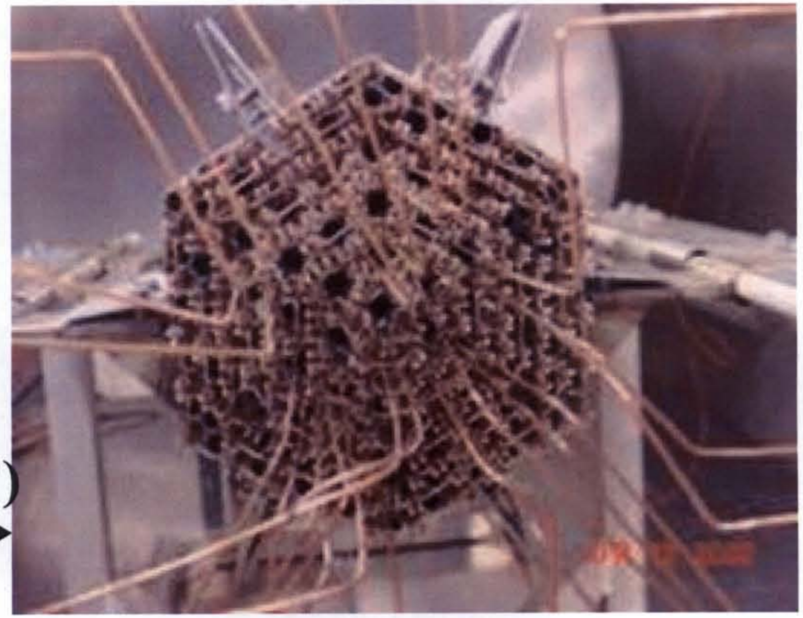
- Must take into account the total number of heater elements in small footprint

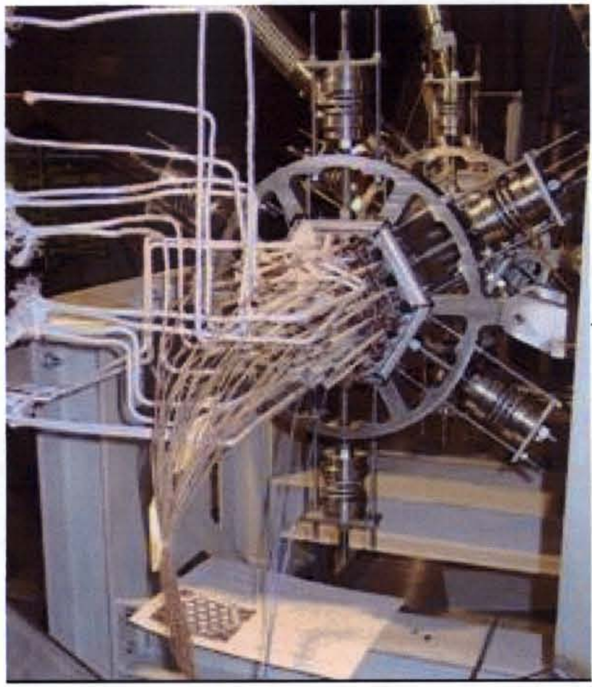
  → Complexity significantly increases as the pin size is reduced and the total number of pins increases
- Depends on reactor type and operating environment
  - Presence of a pressure vessel
  - Simulator impact on coolant flow plenum
  - Presence of an electrically conductive media in flow plenum
  - Requirement of gas inside simulator assembly for improved thermal coupling



48 Simulators, SAFE 30 (~ 9" by 8")

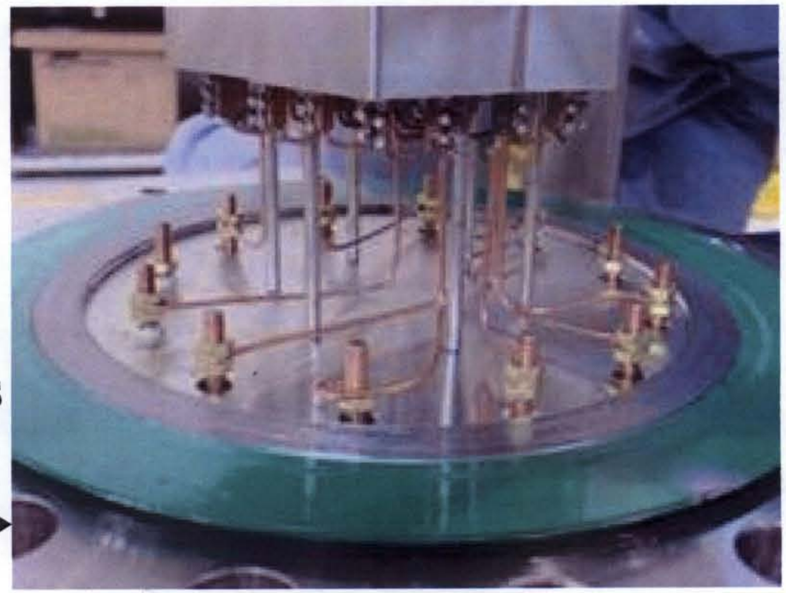
183 Simulators, SAFE 100 (~ 10.4" by 11.5")





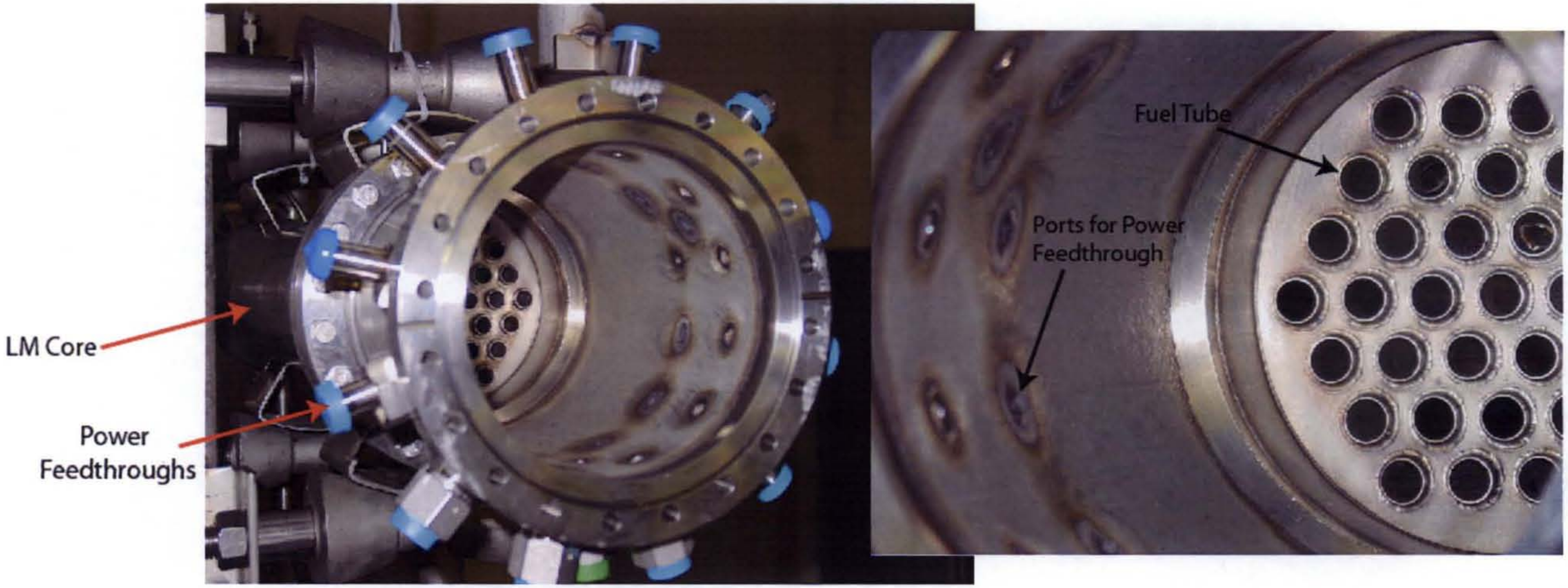
57 Simulators, SAFE 100a (~ 7" by 6.5")

37 Simulators, Direct Drive Gas (~ 6.25" by 7.1")



Electrical Integration – Core Face Seal

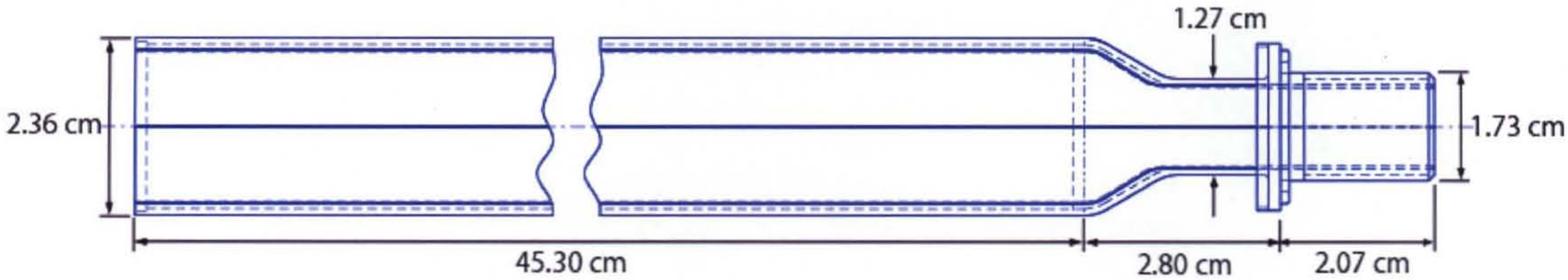
- Prevents contact with conductive media in liquid metal system
- Allows for operation with high purity gas on ID of simulator sheath
- Prevents material incompatibility issues



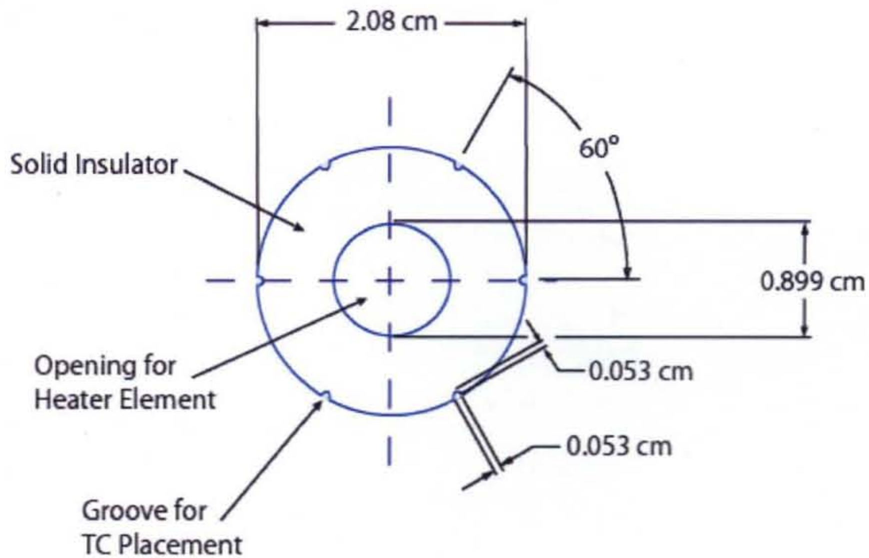
High Fidelity Simulator Design Strategy

- Receive nuclear fuel pin performance characteristics from reactor designers (steady state and dynamic)
- Develop conceptual design to match pin performance under nominal steady state operation and during transient maneuvers
- Develop simulator engineering design
- Develop calorimeter test article design (for test w/active heat removal)
- Build, test, validate – testing of bare element and with active heat removal in a relevant environment
- Iterate design to improve performance; demonstrate repeatability

Current Simulator Design Objectives



- Fully instrumented sheath, ID/OD (TCs, with option for fiber optics on ID)
- Ability to swap out heater element to test variable axial power profiles
- Minimum impact on flow plenum (CFD analysis pending)
- Match fuel pin thermal inertia and clad surface temperature during steady state and transient operation
- Current simulator corresponds to a NaK cooled reactor core design



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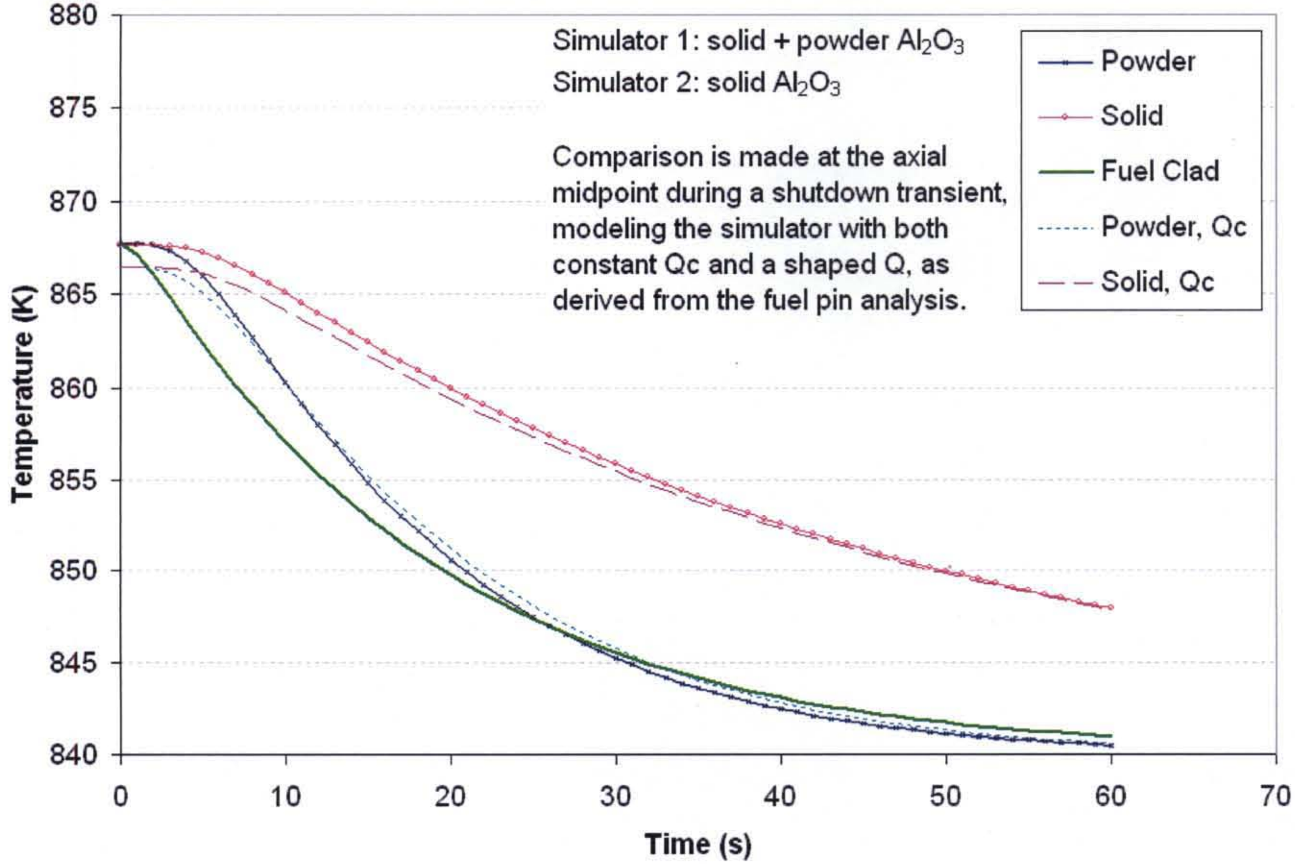
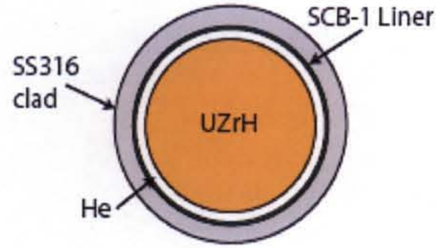
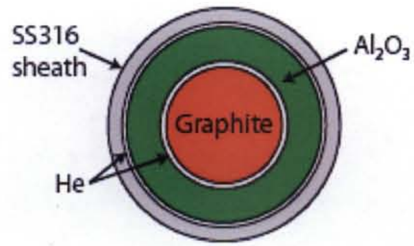
Transient Thermal Analysis: Shutdown

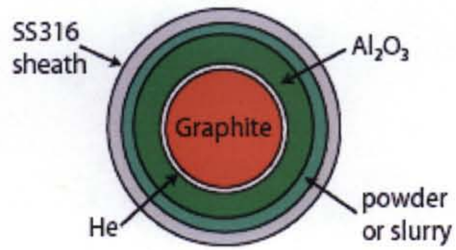




Fuel Element



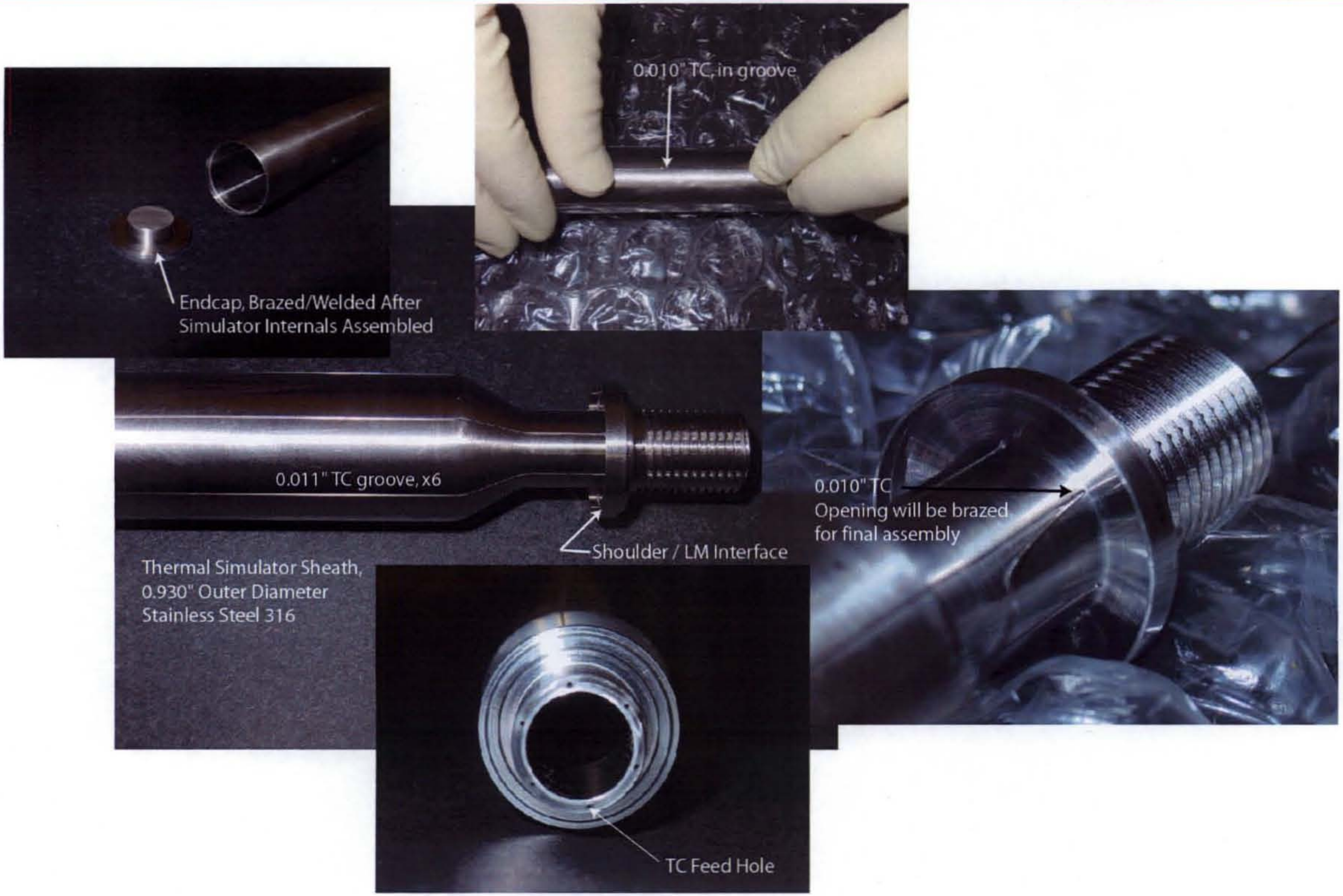
"Solid" Simulator



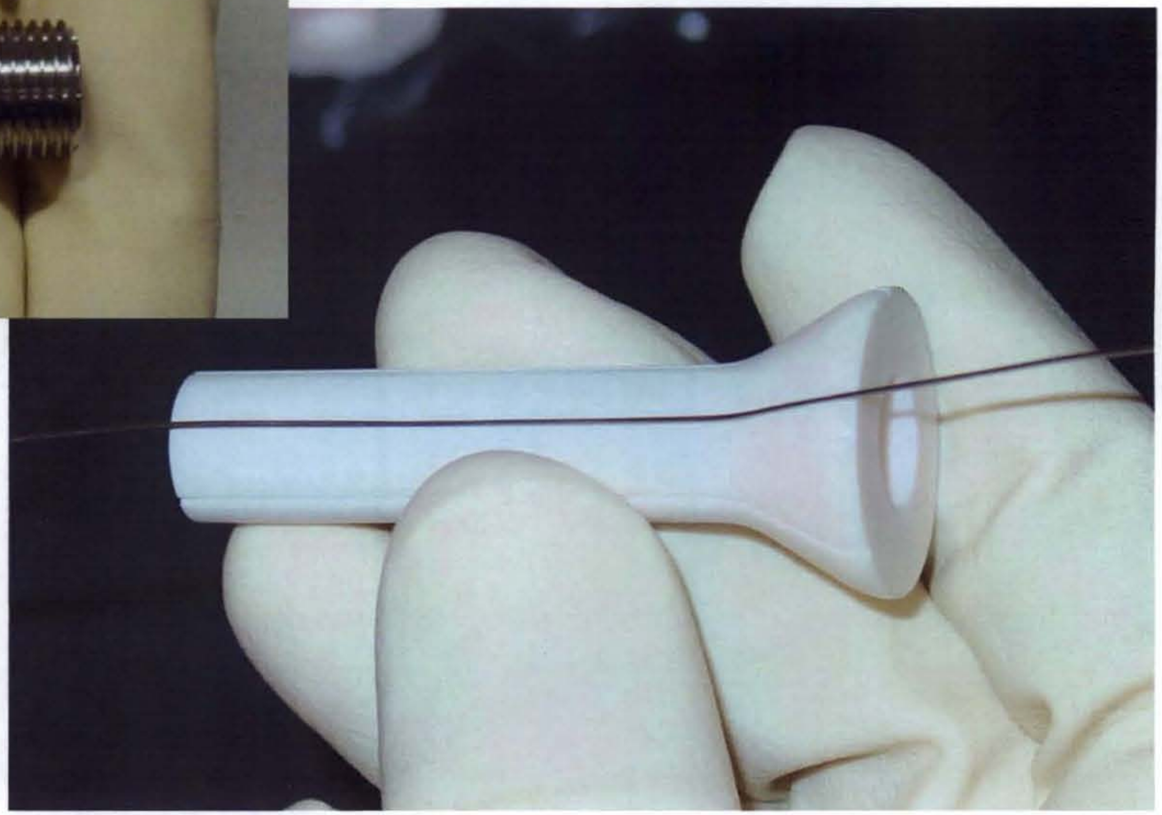
"Powder" Simulator

Shutdown from: 98 kWt, 0.86 kW/pin (nominal)

Instrumented Simulator: Hardware



Instrumented Simulator: Hardware



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Instrumented Simulator: Hardware

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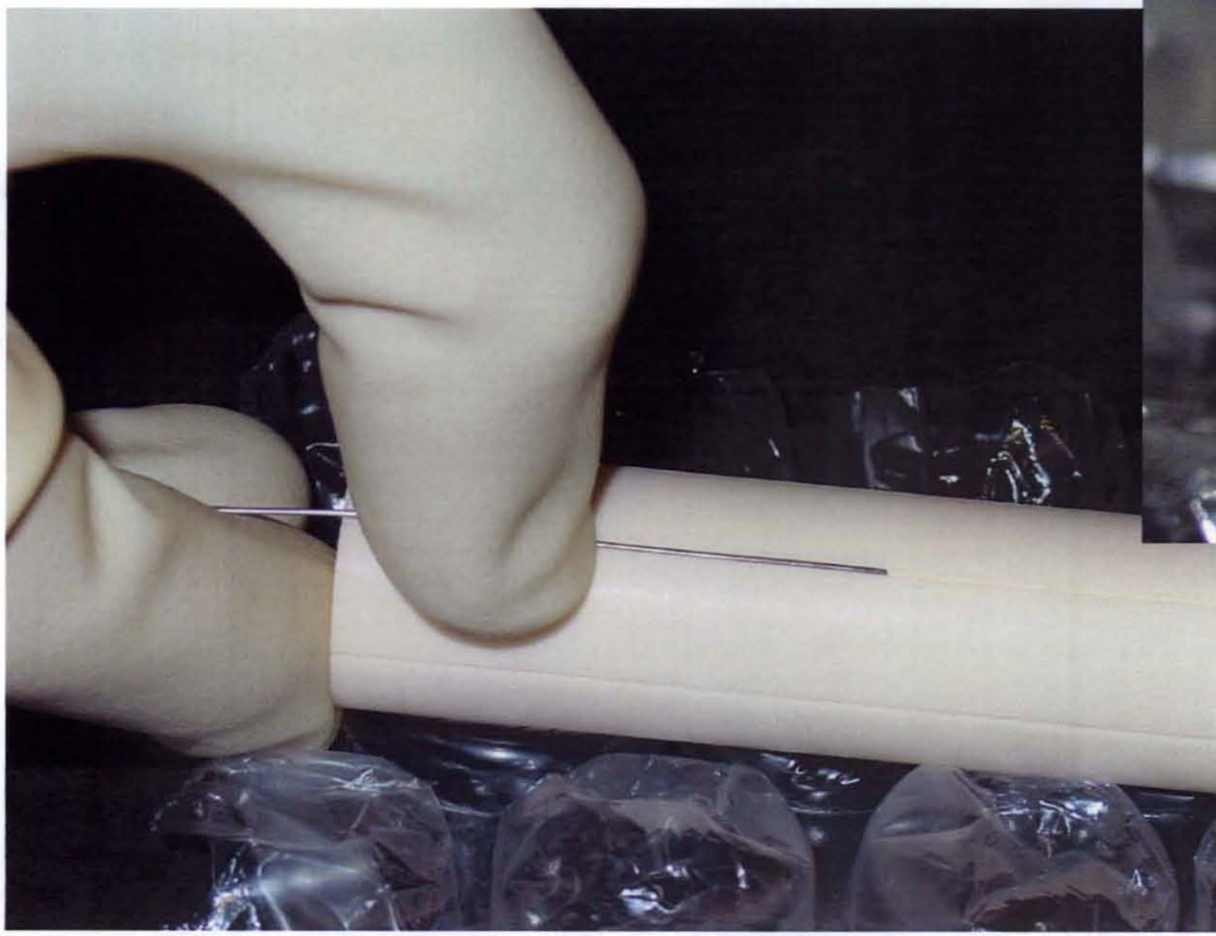

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Instrumented Simulator: Assembly

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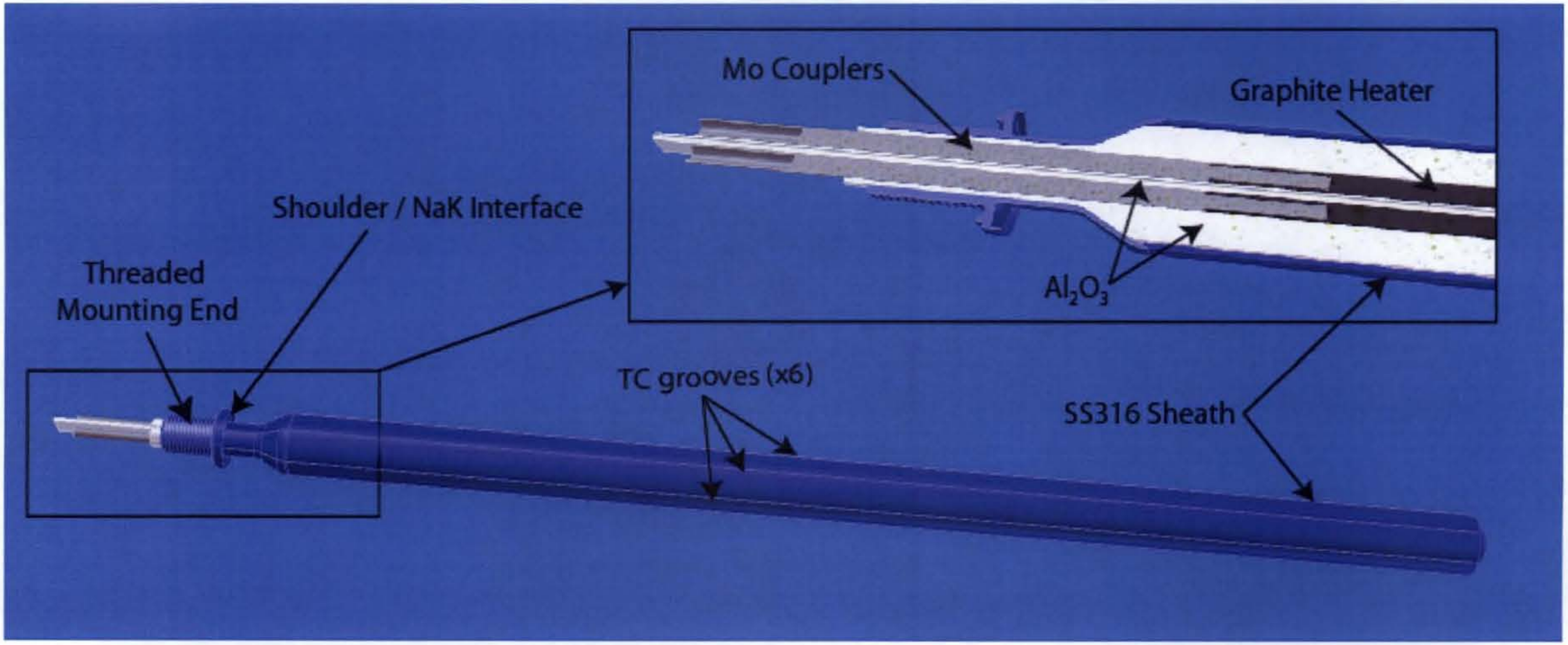
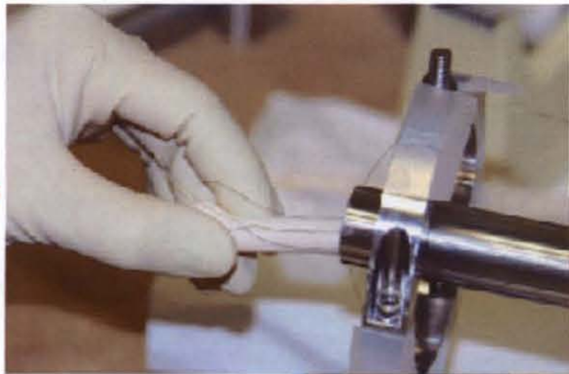
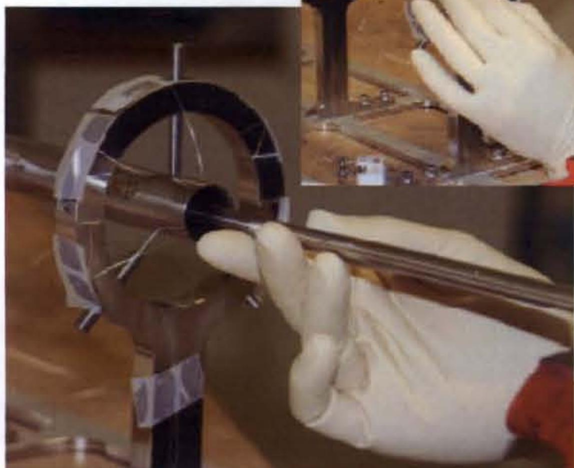
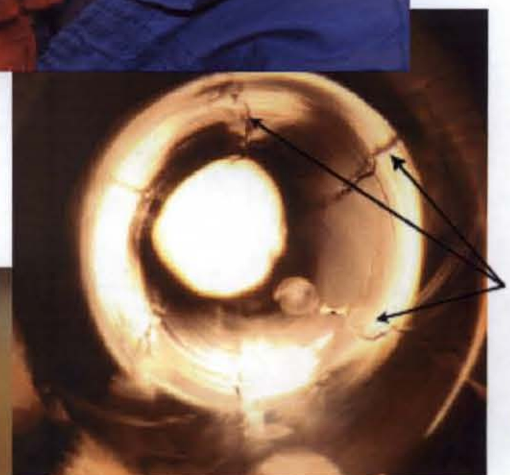




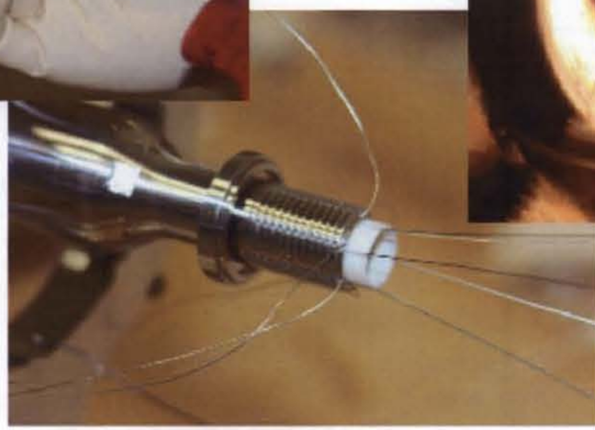
TC installation on bottle shaped insulator

Insertion of insulator into sheath assembly





TCs running along sheath ID with bottle shaped insulator installed (flashlight used to illuminate assembly)



TCs installed on bottle shaped insulator

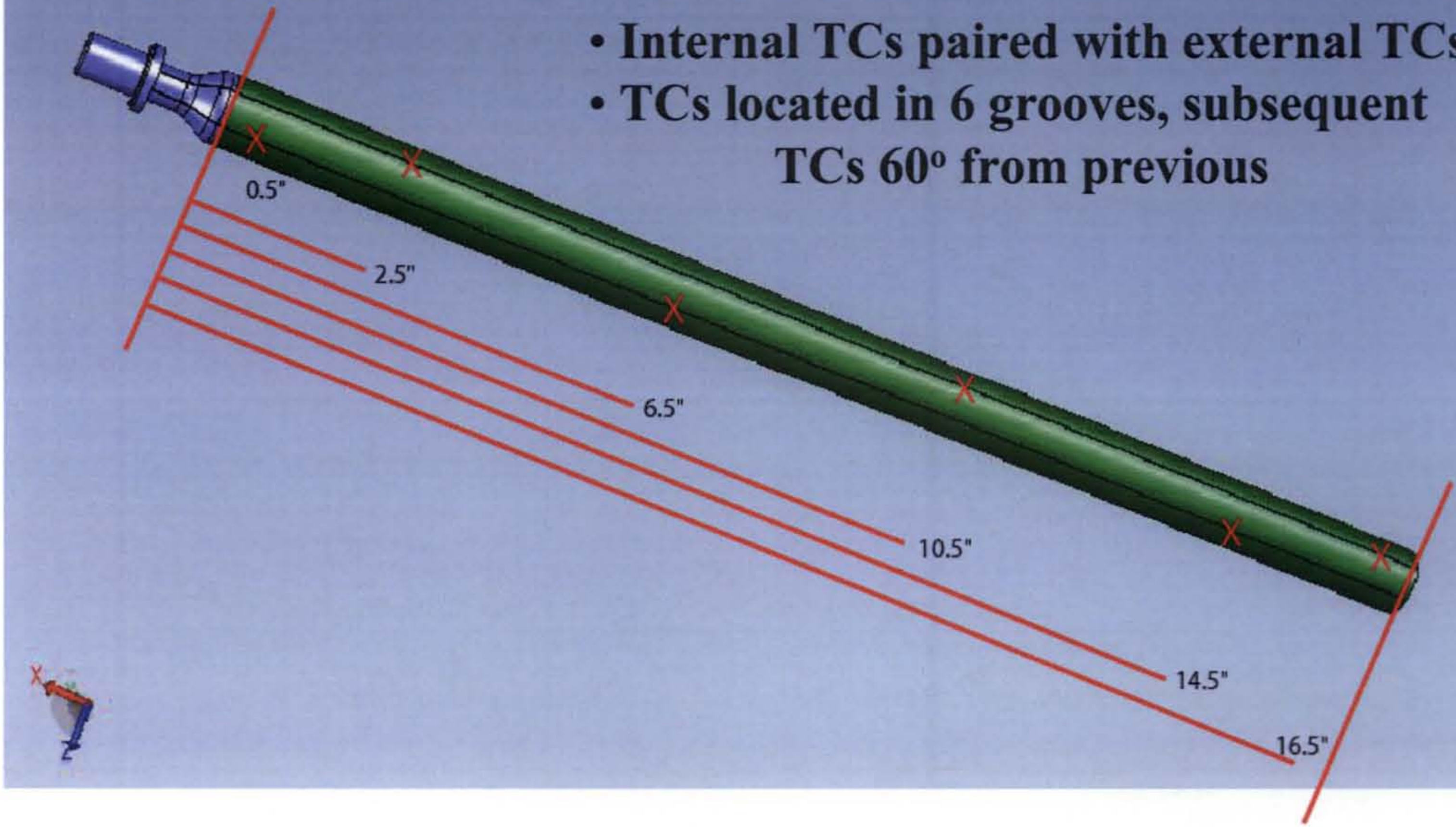
Instrumented Simulator: Test Plan

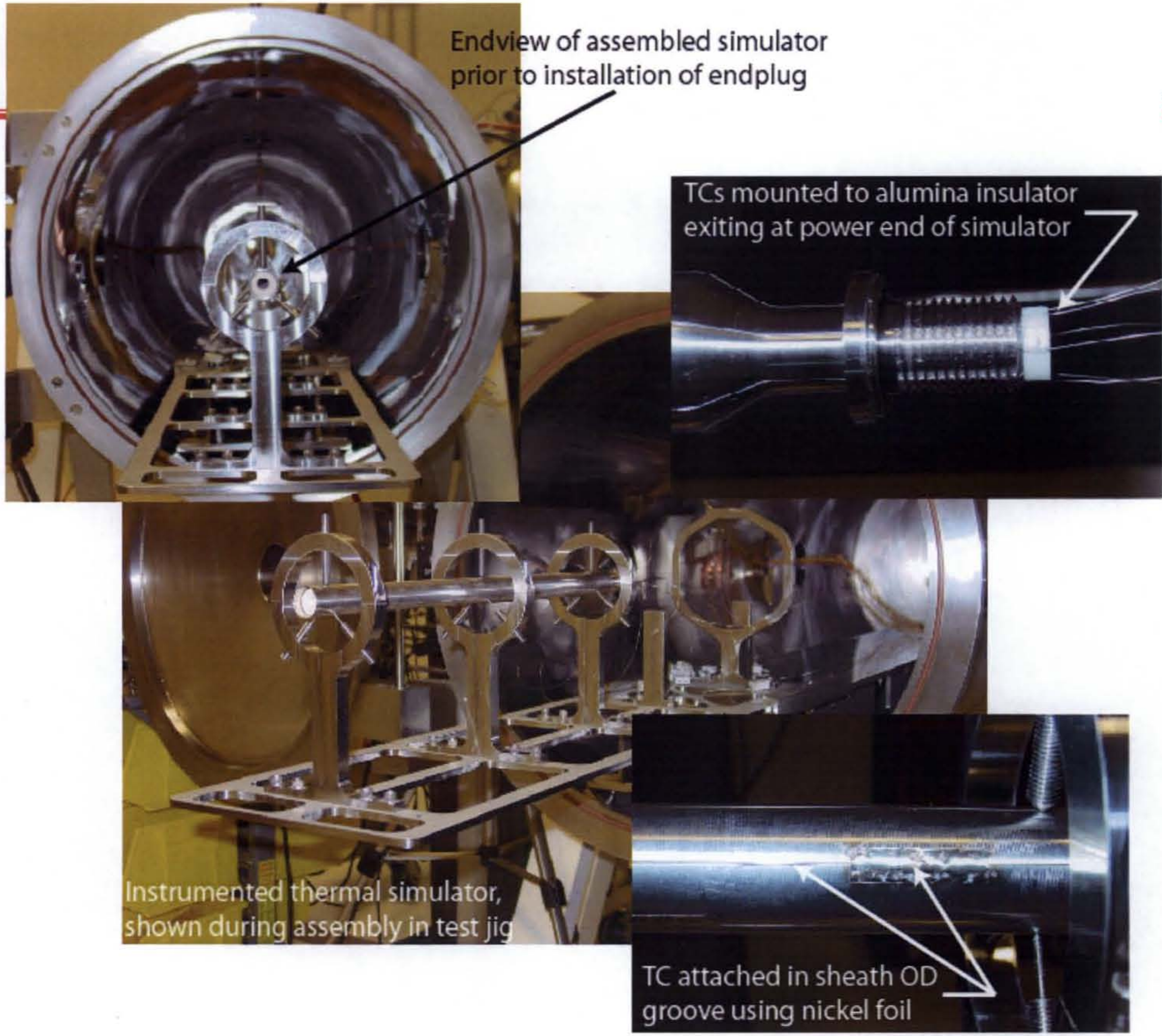
- Bare Element Checkout Testing
  - Verification of basic operation in simplified configuration without added variables
  - Vacuum and inert environment (He or Ar)
- Calorimeter Testing
  - Active heat removal via water cooled "calorimeter" jacket
  - Provides enhanced, tailored, and measured heat extraction at realistic simulator sheath design temperatures
  - Allows measurement of simulator temperature profile and thermal response via TCs and optical techniques without liquid metal concerns
- Single Flow Cell – NaK Heat Removal
  - Representative flow cell from full reactor design
  - Characterization of performance in intended operational environment prior to full core build and test
  - Benchmarking of thermal models used for high fidelity (performance matching) simulator design

Simulator Instrumentation

Axial Thermocouple Positions:

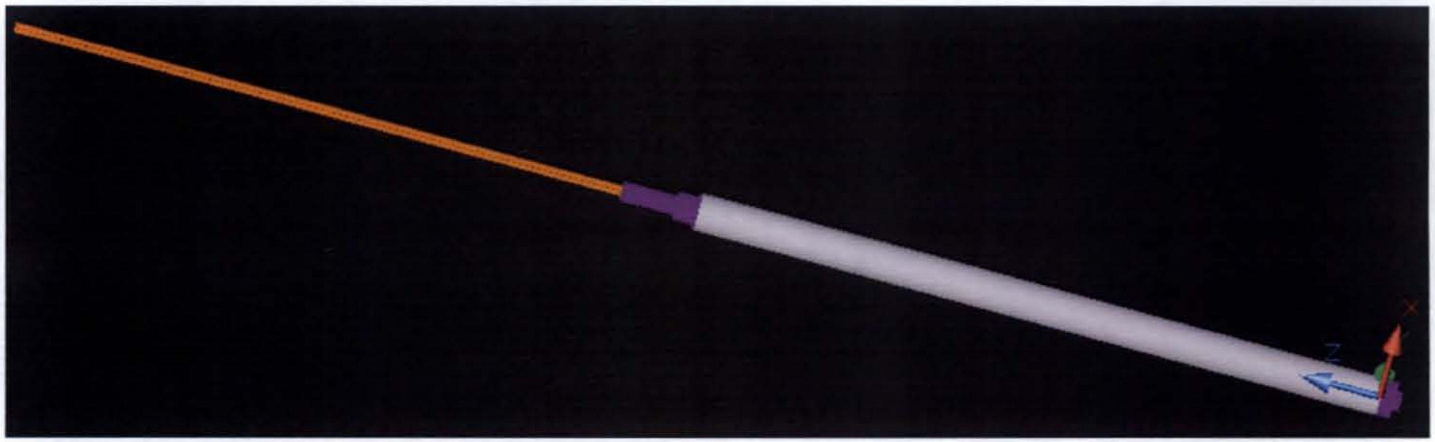
- Internal TCs paired with external TCs
- TCs located in 6 grooves, subsequent TCs 60° from previous




Endview of assembled simulator
prior to installation of endplug
TCs mounted to alumina insulator
exiting at power end of simulator
Instrumented thermal simulator,
shown during assembly in test jig
TC attached in sheath OD
groove using nickel foil

Thermal Analysis

- Model: Thermal Desktop
- Analysis: Sinda / Fluint
- Models conduction, radiation and natural convection
- Incorporates end effects including:
  - Bottle shaped sheath
  - Power leads
  - End cap
  - Axial variation in sheath emissivity



Test and Analysis Results, Bare Element

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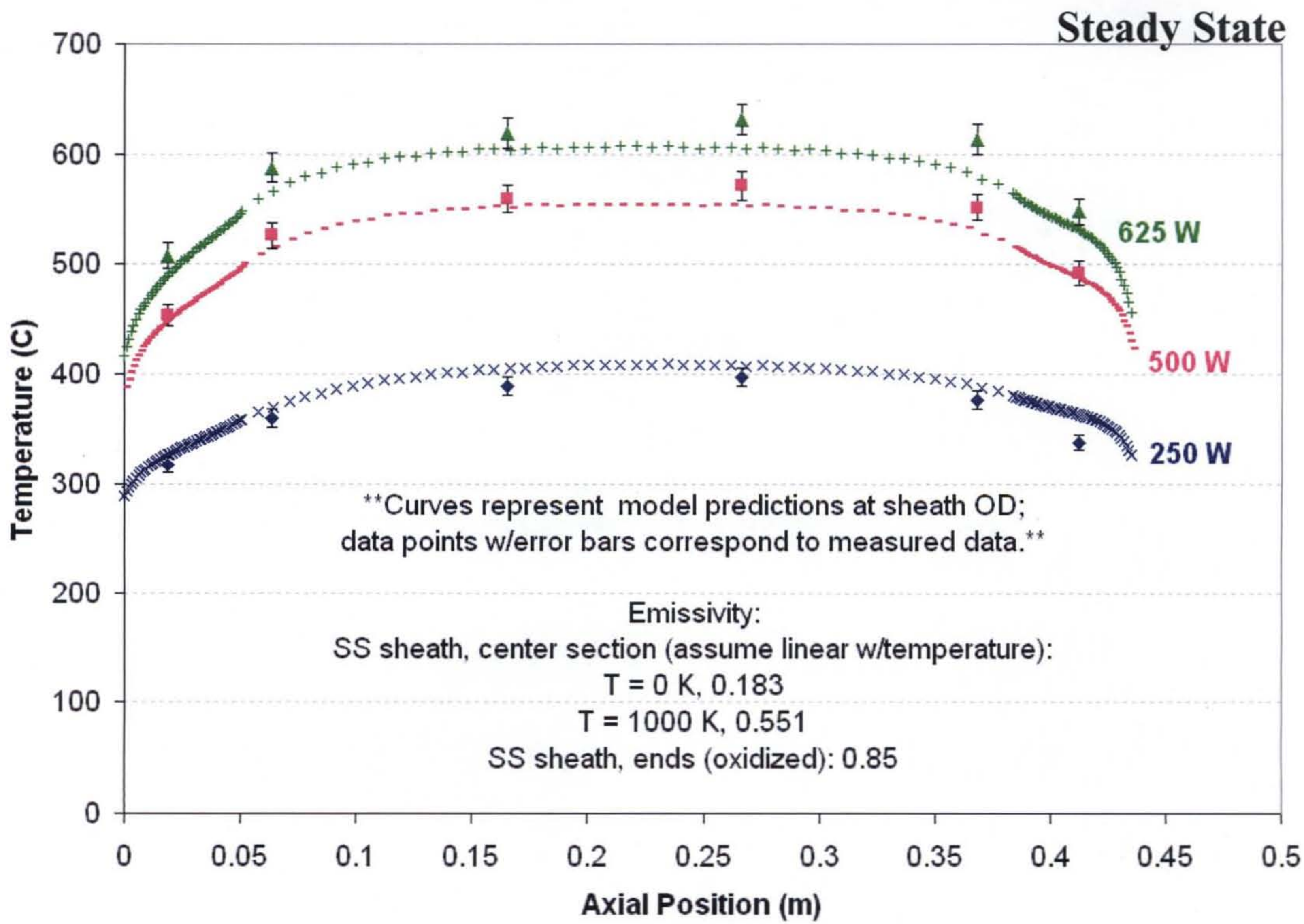
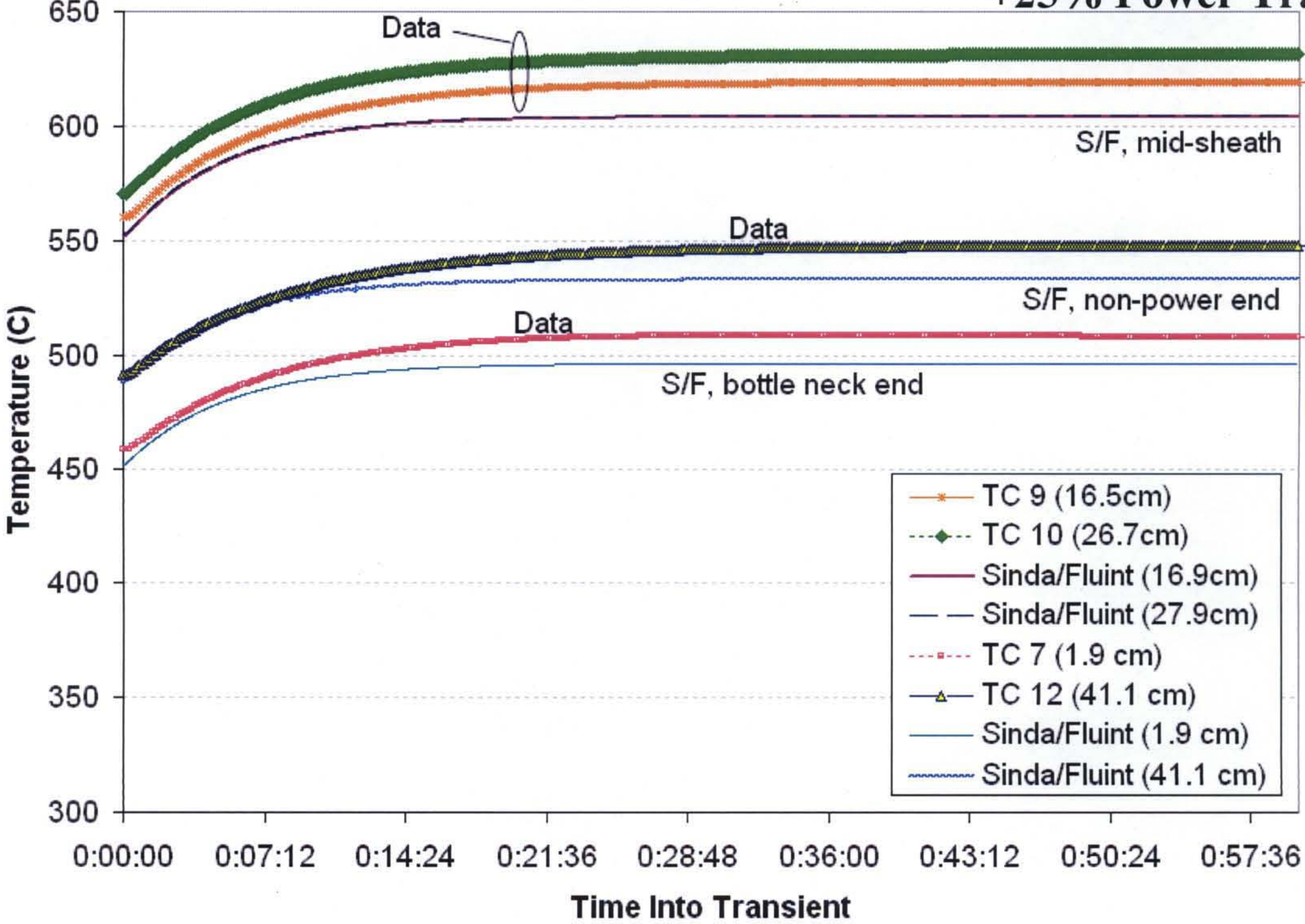


Transient Results, Bare Element

+25% Power Transient



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Transient Results, Bare Element

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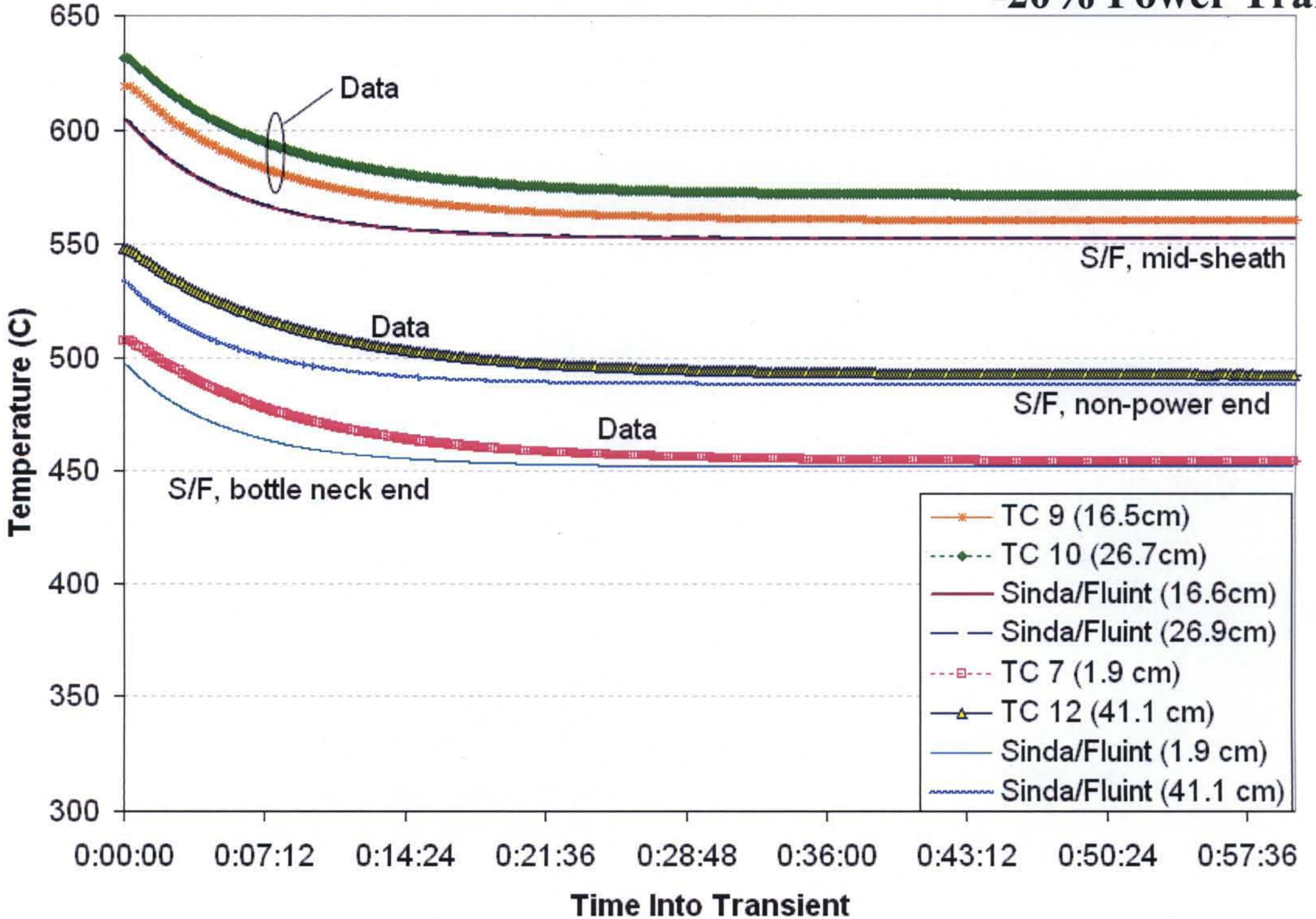
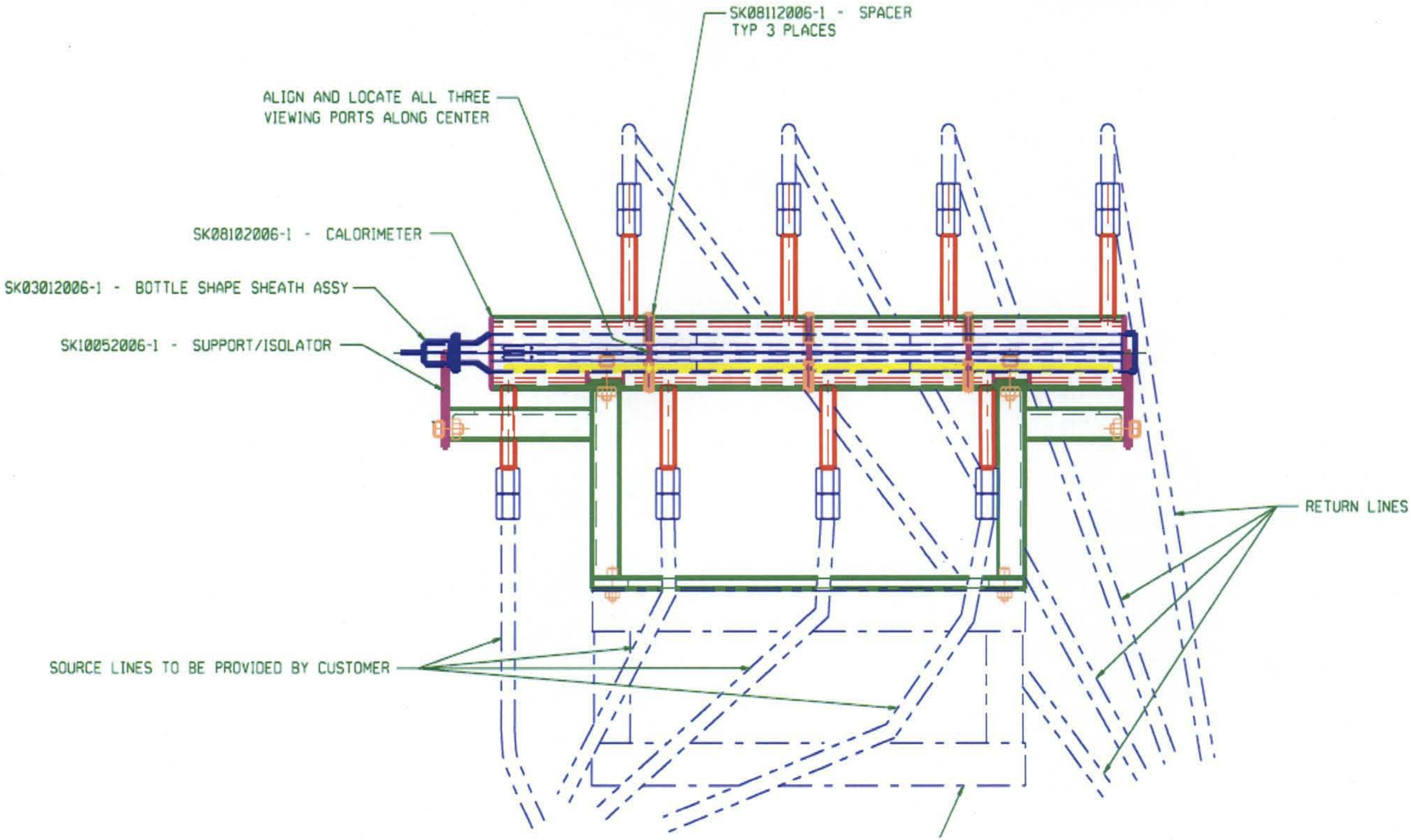
-20% Power Transient



Calorimeter Testing



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Installed Calorimeter Hardware

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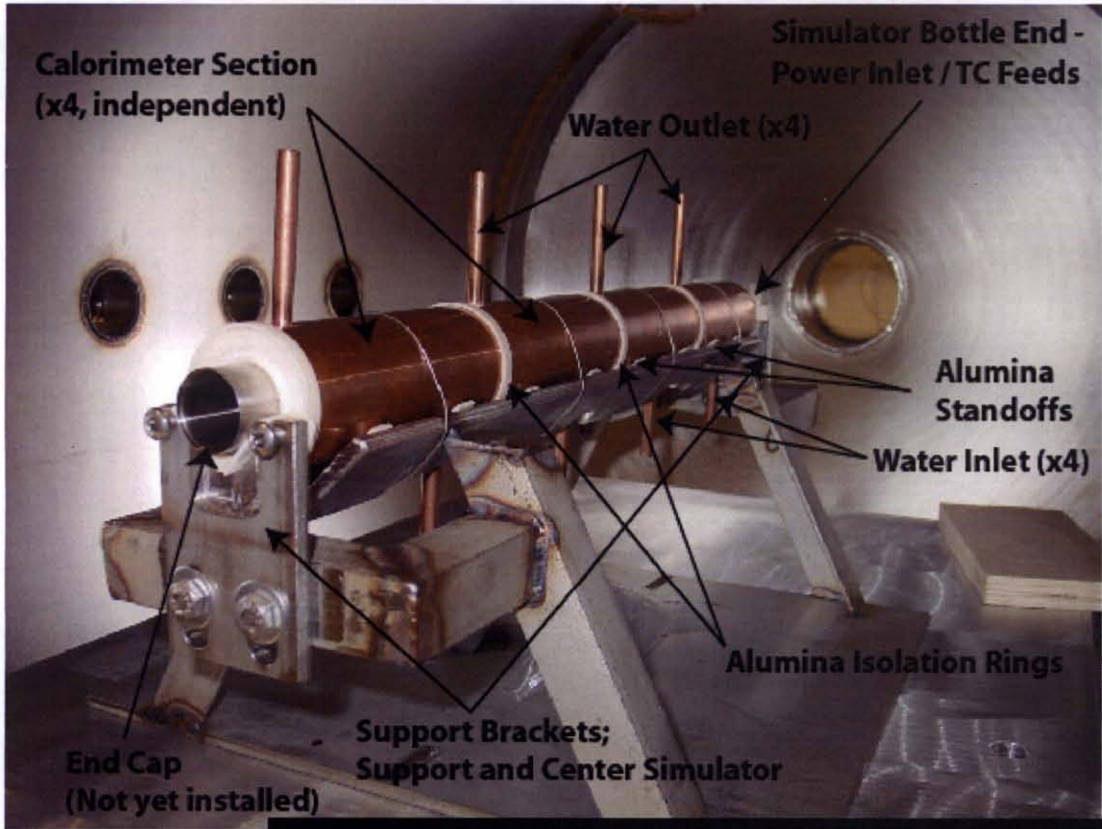
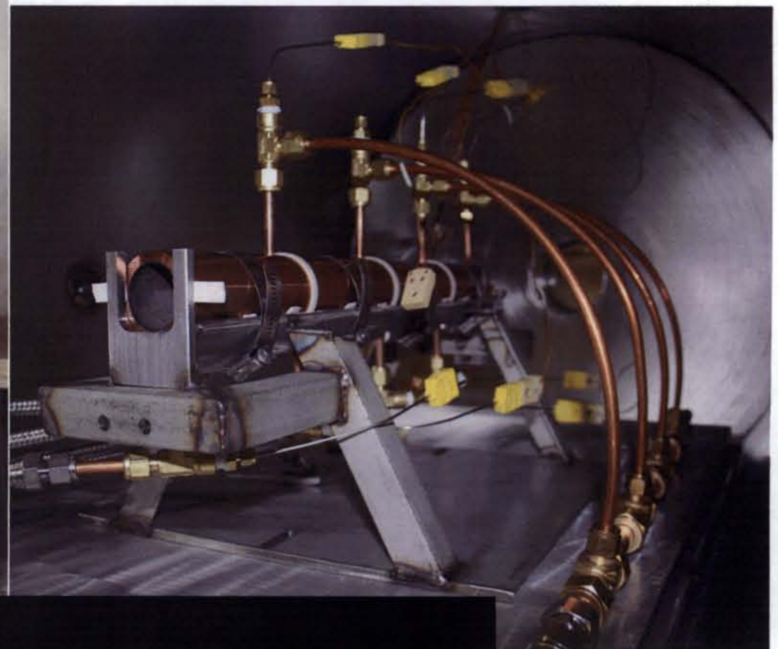
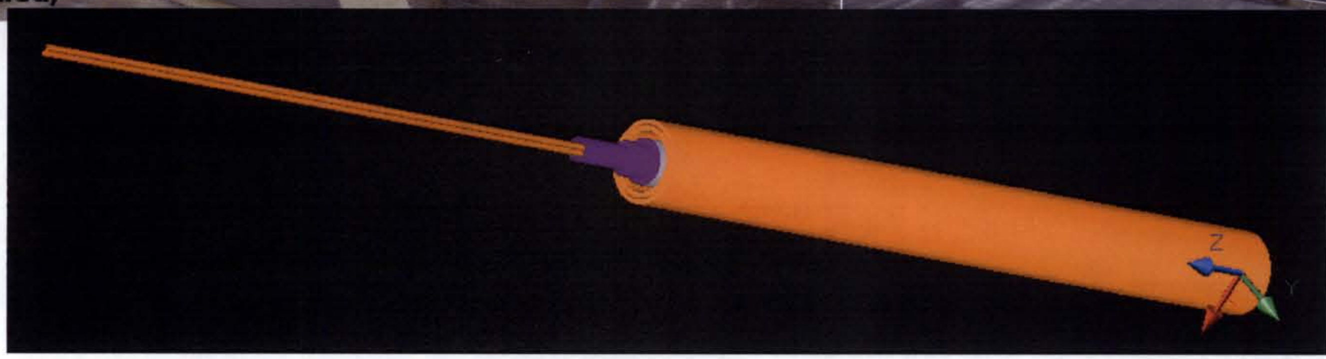
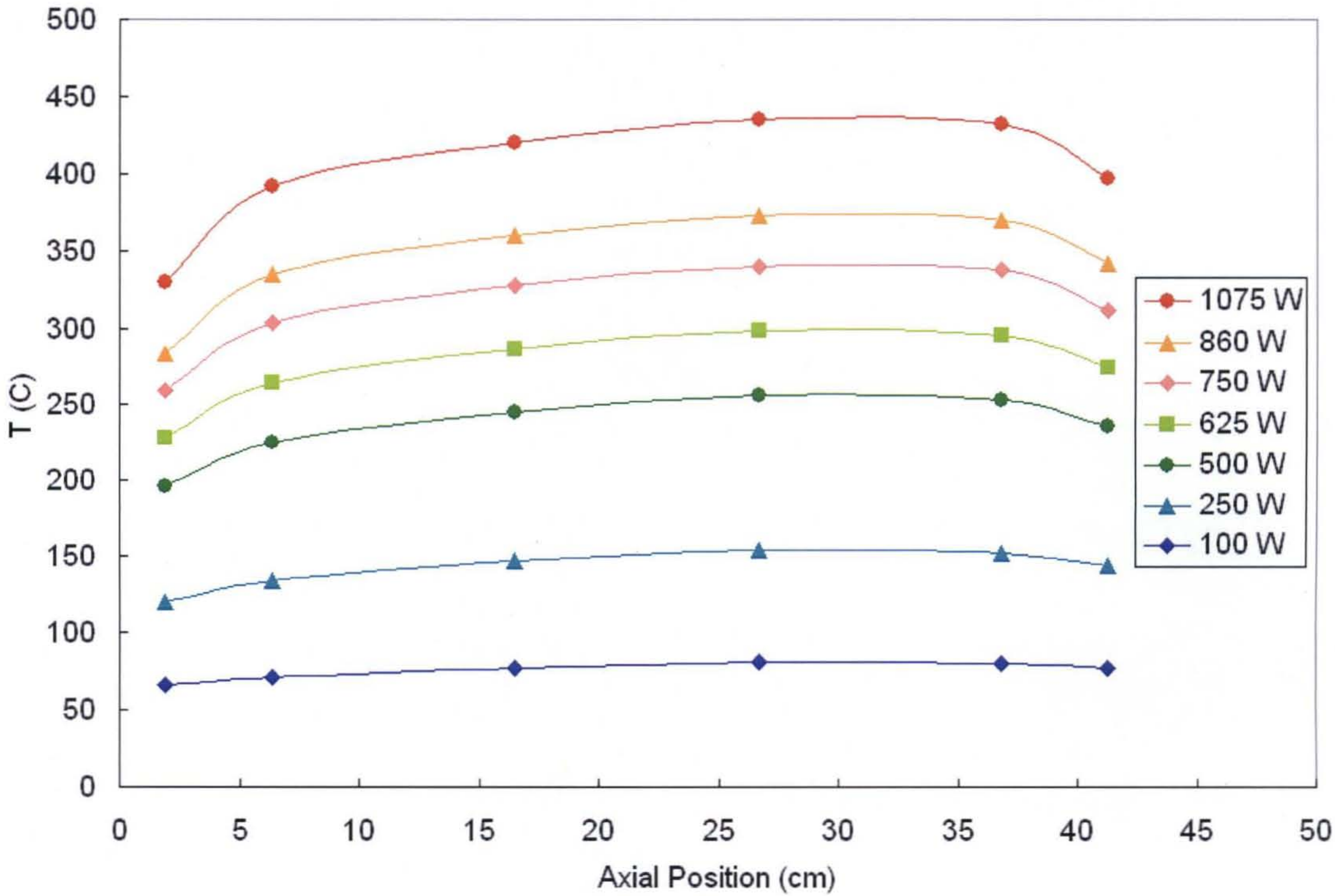


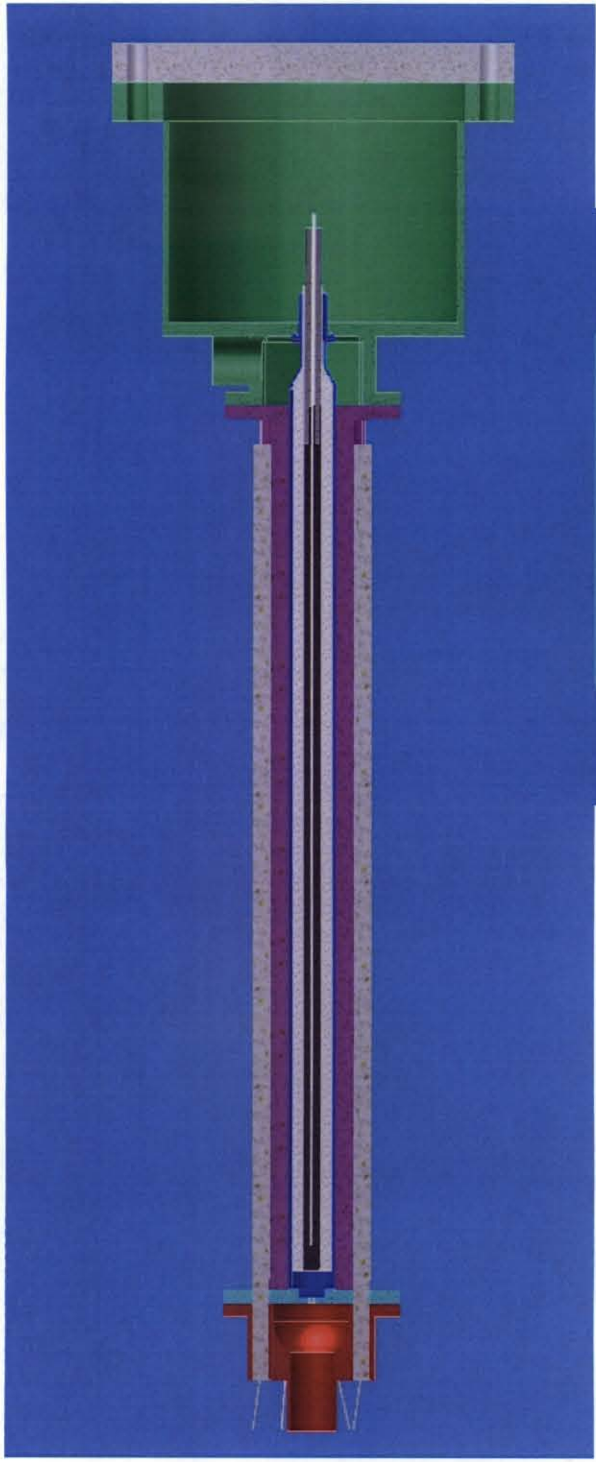


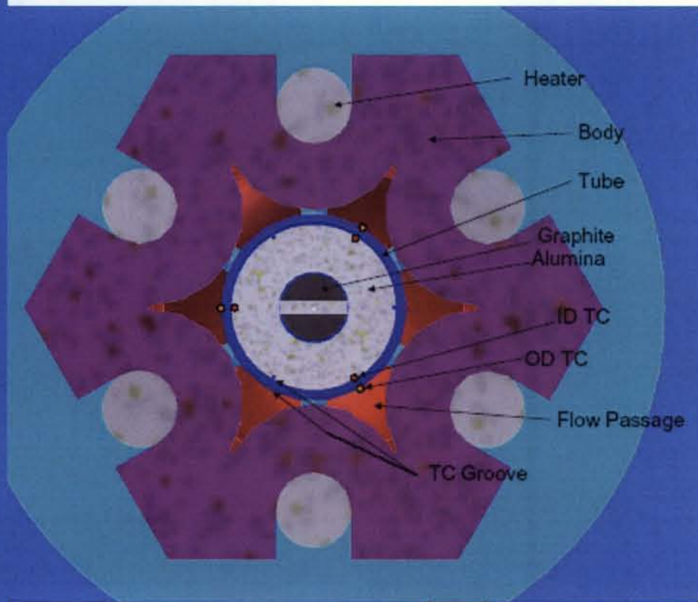


Initial Calorimeter Results

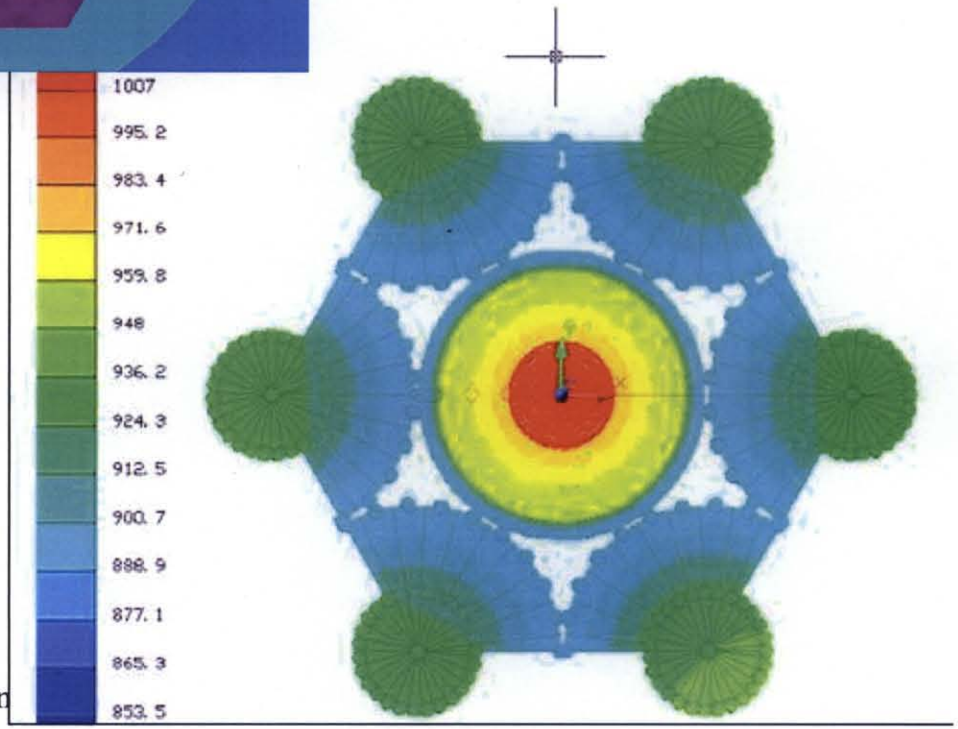


NaK Flow Cell



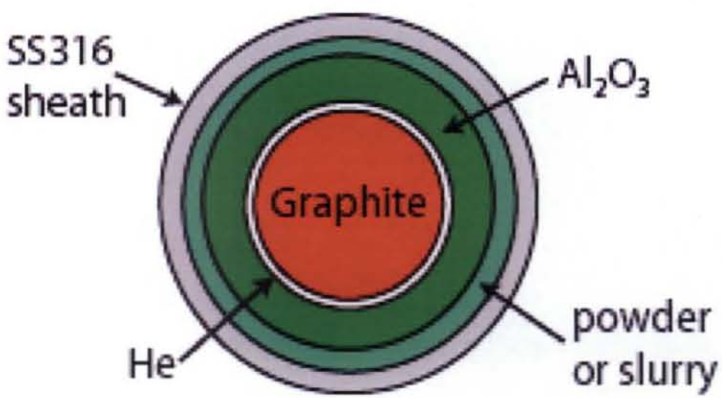


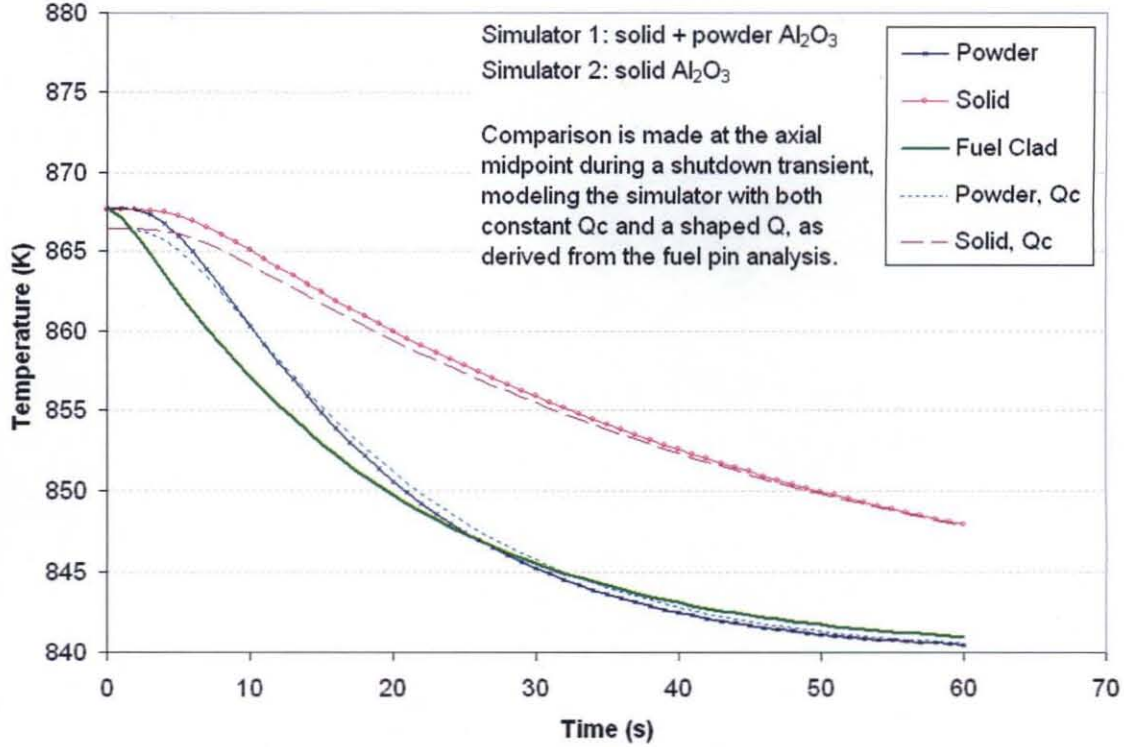
Preliminary flow cell design and analysis results.



Thermal Coupling Material Testing

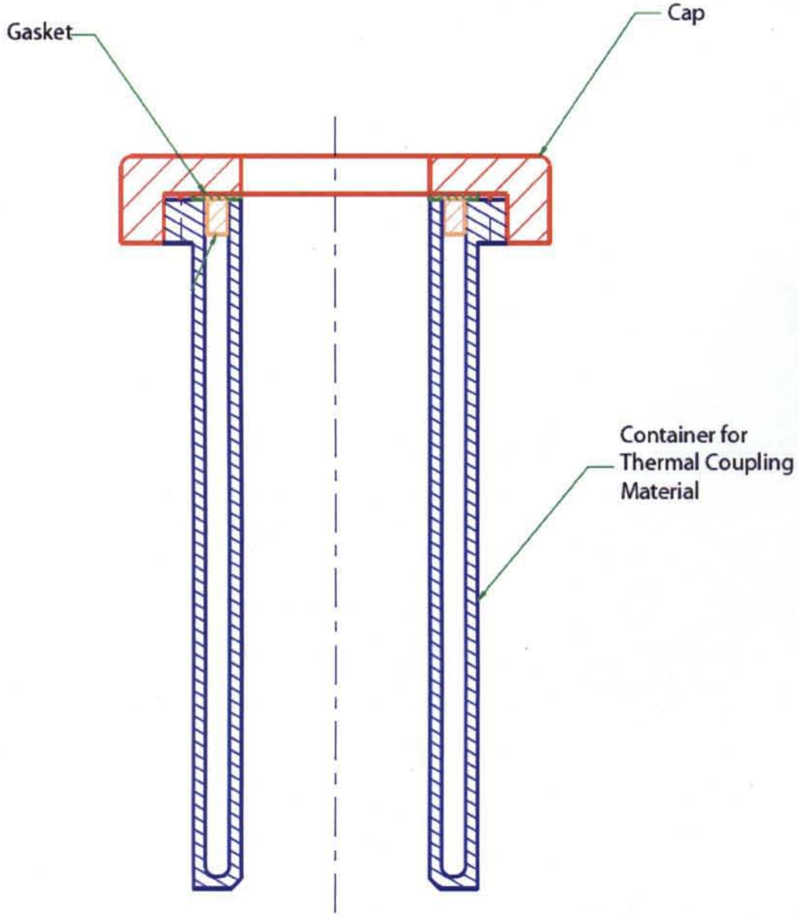
- Materials tested to eliminate second gas gap in simulator design
- Analysis shows that proposed design improves transient performance of simulator
- Properties of powder and slurry materials highly dependent on composition, packing fraction
- Use in simulator design and fabrication requires repeatability of fill technique





Thermal Coupling Material Testing

- Fill gap sized to correspond to simulator design
- TCs installed in grooves on vessel ID and OD
- Use of a short, high resistance heater to indirectly heat the fill material



Initial Results – Vacuum Testing

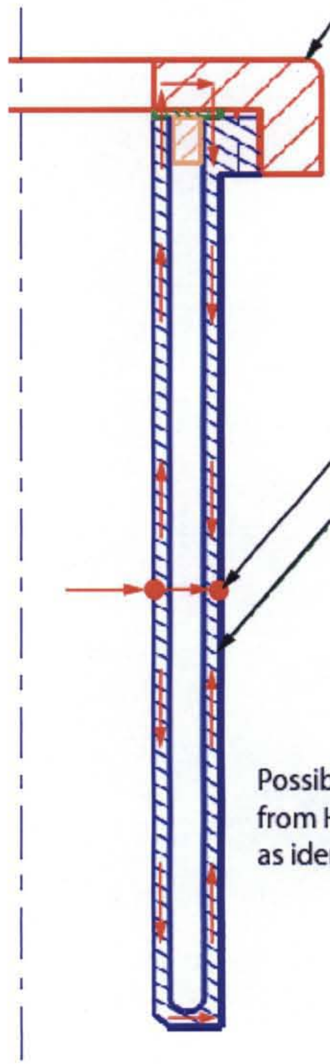
Material	Average Gap Temperature (K)	Packing Fraction	Calculated Conductivity (vacuum)	Fraction of Solid (theor.) Conductivity
Empty Vessel	670 K 795 K	N/A	0.355 ± 0.029 0.347 ± 0.023	N/A
Alumina, 4N, -325 Mesh	684 K	0.28	0.177 ± 0.011	0.025
Aluminum Nitride, 2N, -325 Mesh	663 K	0.41	0.640 ± 0.071	0.013
Aluminum Nitride, 3N5, -200 Mesh	671 K 730 K	0.33	0.209 ± 0.014 0.271 ± 0.017	0.004 0.006
Natural Diamond	610 K 722 K	0.53	0.211 ± 0.014 0.233 ± 0.015	1E-04 1E-04
Carbonaceous Cement, C-34	666 K 798 K 870 K	0.94	0.906 ± 0.131 0.770 ± 0.074 0.798 ± 0.067	0.20 0.18 0.19

Initial Results – Helium Testing

Material	Average Gap Temperature (K)	Packing Fraction	Calculated Conductivity (600 torr He)	Fraction of Theoretical Conductivity
Empty Vessel	435 K 538 K	N/A	0.601 ± 0.050 0.696 ± 0.048	N/A
Alumina, 4N, -325 Mesh	437 K	0.28	1.091 ± 0.110	0.156
Aluminum Nitride, 2N, -325 Mesh	432 K 537 K	0.41	1.138 ± 0.140 1.213 ± 0.208	0.024 0.025
Aluminum Nitride, 3N5, -200 Mesh	426 K 528 K	0.33	0.779 ± 0.074 0.792 ± 0.056	0.016 0.017
Natural Diamond	427 K 530 K	0.53	1.166 ± 0.163 1.144 ± 0.099	5.8E-03 5.7E-03
Carbonaceous Cement, C-34	433 K 535 K 605 K	0.94	1.543 ± 0.242 1.661 ± 0.164 1.852 ± 0.165	0.32 0.36 0.41

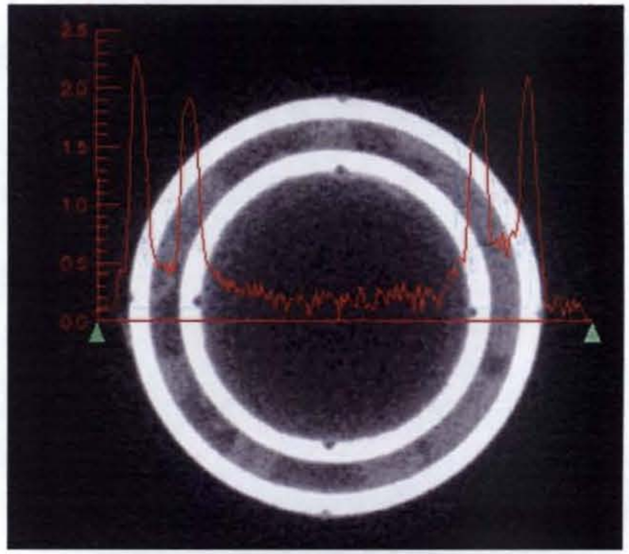
Potential Heat Paths

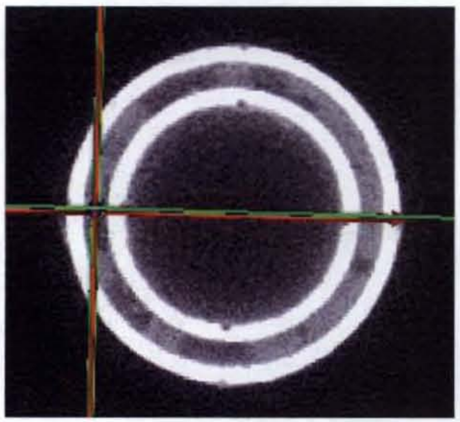
- Conductivity results affected by additional heat transfer along walls and through ends of test vessel
- Potential Solutions:
  - Isolate halves of test vessel with non-conductive end caps
  - Lengthen test vessel such that minimum resistance path is across fill gap

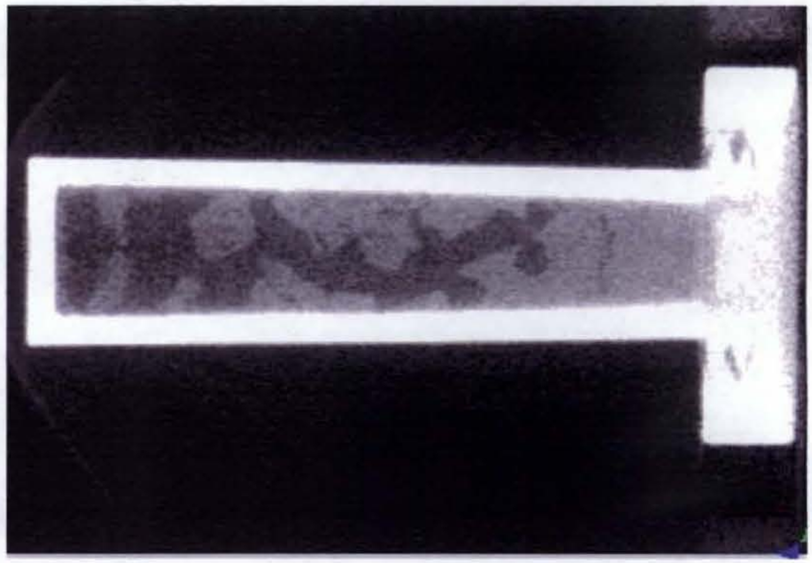


CT Analysis: C-34

- Non-destructive analysis to assess fill density
- High resolution images: 0.1092 mm pixel size
- Results indicate non-uniform C-34 density, possibly resulting from:
  - Heterogeneous composition
  - Air bubbles entrained during mixing process
- Achieved 94% theoretical density – suggests a slurry material provides more reliable fill than powder fill materials







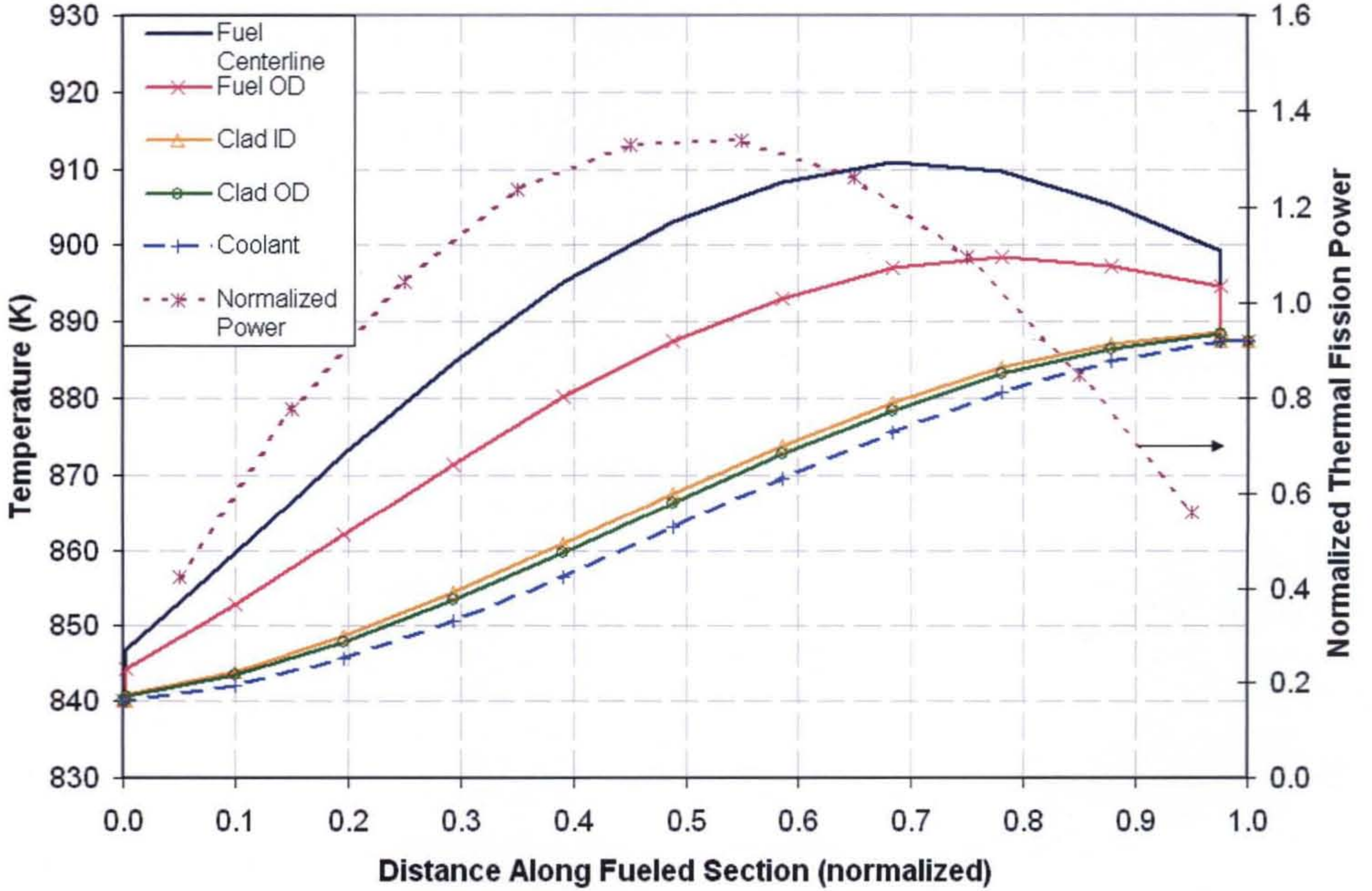
Conclusions / Future Work

- Thermal simulator development is a "work in progress" that is constantly being improved
- Work to-date has provided a database of options (fabricability and performance) that can be called on when a reactor design is finalized
- Current testing is being used to benchmark thermal models
- Final simulator design will be specific to a given reactor core design

Acknowledgements

- The work described within this report was supported by NASA, in whole or part, as part of the program's technology development and evaluation activities. Any opinions expressed are those of the authors and do not necessarily reflect the views of NASA.

Static Pin Performance Matching



98 kWt, 0.86 kW/pin (nominal)

Axial Temperature Distribution