Thermal Simulator Development: Non-Nuclear Testing of Space Fission Systems

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INTRODUCTION

Non-nuclear testing can be a valuable tool in the development of a space nuclear power system. at the NASA MSFC Early Flight Fission Test Facility (EFF-TF), highly designed electric heaters are used to simulate the heat from nuclear fuel to test space fission power and propulsion systems.

To allow early utilization, nuclear system designs must be relatively simple, easy to fabricate, and easy to test using non-nuclear heaters to closely mimic heat from fission. In this test strategy, highly designed electric heaters are used to simulate the heat from nuclear fuel, allowing one to develop a significant understanding of individual components and integrated system operation without the cost, time and safety concerns associated with nuclear testing.

THERMAL SIMULATOR DESIGN

The thermal simulators (heaters) developed at the EFF-TF have been applied in a variety of reactor concepts. To accurately represent the fuel, the simulators should be capable of matching the overall properties of the nuclear fuel rather than simply matching the fuel temperatures. This includes matching thermal stresses in the pin, pin conductivities, total core power, and core power profile (axial and radial) during both static and dynamic test conditions.

Initial simulator development requirements were driven by past space reactor work and bounding parameters were chosen to be as challenging as possible. Additionally, the simulators must be electrically isolated from the core to prevent shorting and should be physically isolated to prevent test article contamination by the simulators (e.g. due to sublimation, outgassing, etc.).

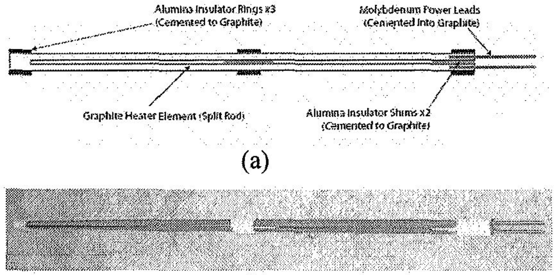
Operational requirements for the thermal simulators incorporate desired lifetime, thermal cycling, and test environment. EFF-TF thermal simulators were required to withstand thousands of hours of operation over hundreds of thermal cycles and to operate in a vacuum (~10^{-3} to 10^{-6} torr) or in a low pressure high-purity gas (e.g. He, CO_2, Ar, etc.) environment. To simplify insertion in each reactor test article and to minimize the impact of the thermal simulators on the ability to achieve a prototypic non-nuclear test article, a single-ended heater design was selected.

THERMAL SIMULATOR TESTING

Thermal simulators have been tested in single element and full core array configurations. [1-3] Some of these tests are summarized below. Power is provided to each test article via an automated 32-zone power and control system. Employing multiple independent power zones allows simulation of the expected radial power profile of the tested reactor design, under nominal or off-nominal conditions.

Graphite Heater Element

Early testing utilized graphite rod heaters that essentially act as a large resistor, with the rod itself split down the middle axially (Fig. 1(a)). Alumina pieces are inserted along the center of the two halves of graphite to prevent contact, which would short the element. Additional alumina insulator rings are used at three points along the length of the graphite to electrically isolate the heater from the test article. A complete graphite heater assembly is shown in Fig. 1(b).



(a)

(b)

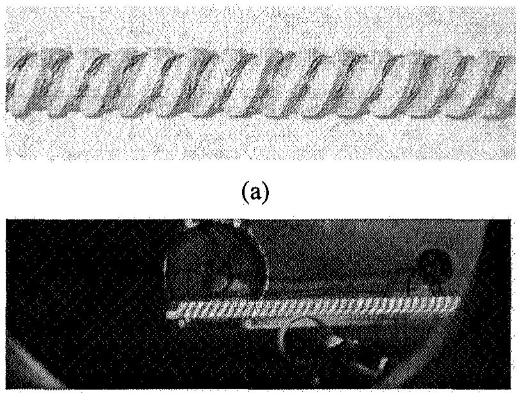
Fig. 1. Graphite Rod Heater Element.

In a graphite element, the axial power profile can be modified by variation of the element diameter along its length, resulting larger power deposition in smaller diameter regions. A majority of the tested elements have a square cut-out region at the axial center, but elements have also been fabricated with the diameter cut to a specific equation to exactly match the axial power profile of the corresponding nuclear fueled system.

Refractory Wire Heater Elements

Refractory metal wire wrapped heater element designs have also been fabricated and tested (Fig. 2) for use with reactor concepts that require refractory materials. This element design also reduces the minimum achievable pin diameter relative to graphite rod; elements having an overall sheathed assembly diameter of 0.65 cm have been fabricated and tested. Several refractory metal wires have been considered, wrapped in either a single pass or double pass fashion around a spiral groove etched along an alumina mandrel.

Initial refractory element tests employed a mandrel having a constant pitch groove (Fig. 2(a)), resulting in constant axial power density. Mandrels with a constantly changing pitch (corresponding to a prescribed equation determined by reactor designers at LANL) have been produced to demonstrate manufacturability of the design, but work to date has focused on using the lower cost, constant pitch mandrels to assess materials performance for long-life thermal simulators. Testing has been conducted for rhenium, tantalum, tungsten, molybdenum, hafnium and niobium.


(a)

(b)

Fig. 2. Refractory Element Testing; (a) Tungsten Wire Braid Wrapped on a 0.410" Alumina Mandrel; (b) Vacuum Chamber Test of a Rhenium Element at 5 kW.

CONCLUSIONS

Testing has demonstrated that graphite rod heater elements are significantly more robust than any of the tested refractory wire elements, allowing instantaneous power changes without affecting the integrity of the heater. However, compatibility of graphite with some proposed core materials led to the investigation of refractory materials for thermal simulators. Advanced graphite elements are currently being investigated for use in lower power, stainless steel reactor cores for surface power applications.

Although none of the tested refractory elements could go from zero to full power (~5 kW) in a single step, power ramping over one hour was successful; additional testing must be performed to determine the maximum power ramp rate that can be applied without element failure. Initial testing of the refractory wire wrapped heater element designs indicated that the performance of single ended, double helix element designs for rhenium, tantalum, and tungsten braid warranted additional testing. Further testing at high power levels suggest that tungsten may be the most desirable material for thermal simulator assembly should the reactor design require refractory metal elements.

REFERENCES

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2. M.K. VANDYKE, "Early Flight Fission Test Facilities (EFF-TF) To Support Near-Term Space Fission Systems," *STAIF-2004*, Albuquerque, NM, American Institute of Physics, Vol. 699, pp. 713-719 (2004).
3. S.M. BRAGG-SITTON, R. DICKENS, et al., *Heater Development, Fabrication and Testing: Analysis of Fabricated Heaters*, NASA MSFC report number ER11-05-WI1-001 (2005).

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Presentation Summary

- Thermal Simulator Requirements for Space Fission Systems
- Initial Simulator Design
- Thermal Simulator Testing
- Application to Space Reactor Systems
  - SAFE-100a Heat Pipe Cooled Reactor
  - Direct Drive Gas Cooled Reactor
  - Liquid Metal Cooled Reactor
- Current Work: High Fidelity, Instrumented Simulator Development
- Conclusions / Future Direction

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

- Use of specialized electric heaters to simulate heat from nuclear fuel
  - Attempt to match overall fuel properties
  - Operation in extreme environments (e.g. vacuum)

Initial Simulator Requirements

- Initial requirements driven by past space reactor work (e.g. SNAP, SP-100)
- Bounding parameters selected to be the most challenging
- Basic requirements:
  - Linear heat rate ~100 W/cm
  - Power density ~100 W/cm^3
  - Average power peaking ~1.33 (cosine distribution)
  - Up to 1400 K at clad / sheath OD
  - Pin diameters ~0.65 – 2.4 cm (0.25″ – 0.95″)
  - Pin power ~0.5 to 6 kW per pin
  - $\leq$ 150 VDC to avoid voltage breakdown in low P environment
  - Fabrication repeatability

Initial Simulator Requirements, cont.

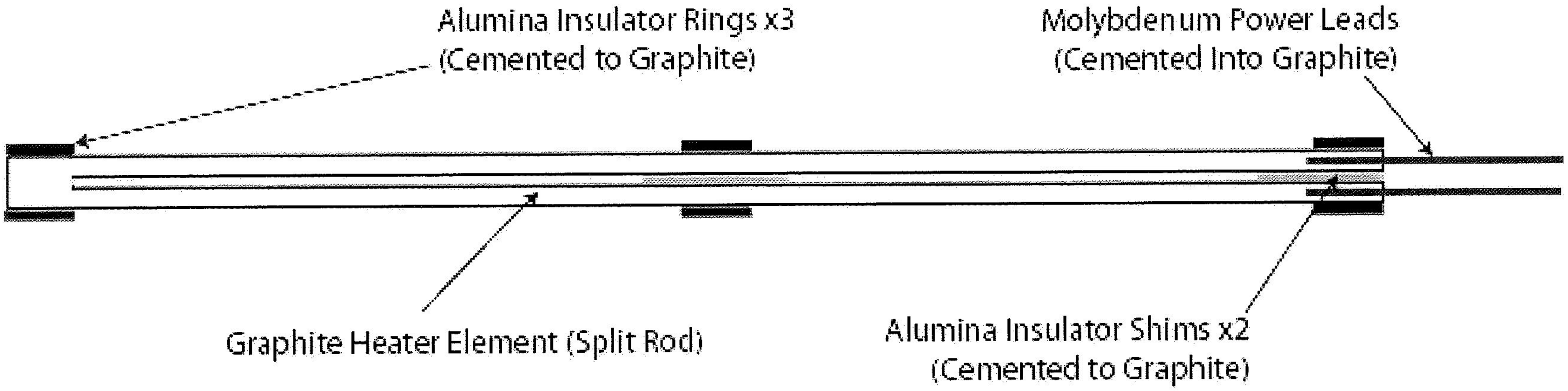
- Operational requirements:
  - Operation in vacuum or low pressure high-purity gas (He, CO_2, Ar, etc) environment
  - Lifetime ~10,000+ hours
  - Thermal cycling ~200+ cycles
  - Electrical isolation from core test article
  - Physical isolation from core test article to prevent contamination
  - Single-ended heater element for maximum prototypic geometry
  - Cross section of electrical connection no greater than simulator diameter
  - Accommodate 200-500 pins per core
  - Full core operation with multiple independent control zones
  - Ability to measure temperature within or near simulator

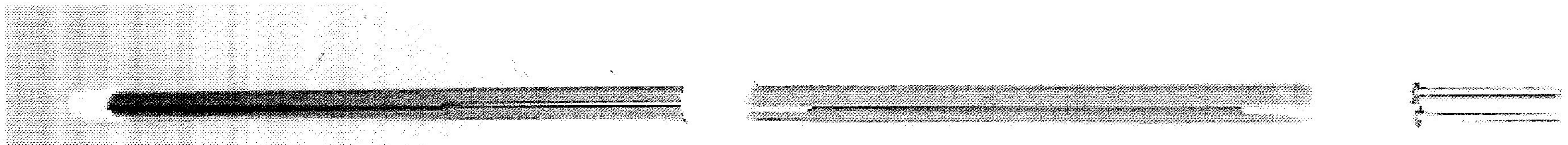
Commercial Availability

- Off-the-shelf heater elements
  - Generally not applicable for vacuum operation at the desired temperature levels
  - Prior to in-house development, several tubular heater elements were tested to failure in vacuum
- Custom designed heater elements for reactor simulators
  - Used in terrestrial reactor applications
  - Very expensive to produce in small numbers

→EFF-TF sought a solution that would cost <$1000 per simulator and could meet the established requirements.

Basic Graphite Heater Element Design





0.375" OD x 21.6"

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

Graphite Heater Element Application

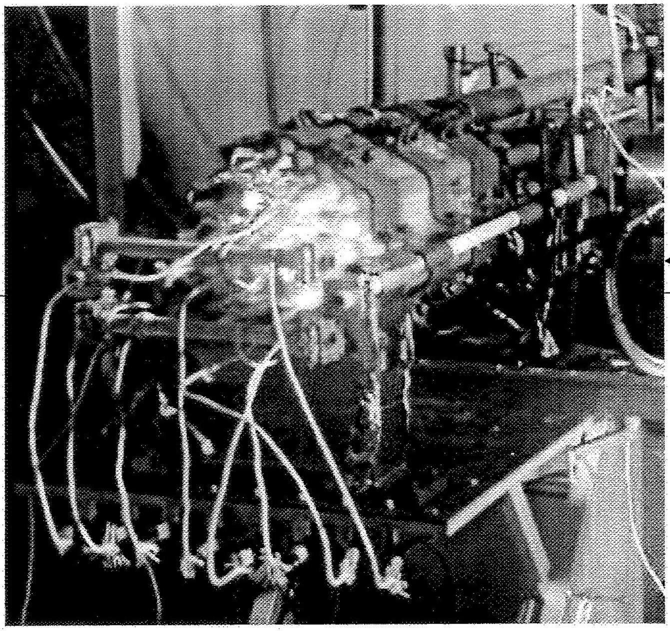
- >350 fabricated and tested to date with no failures
- TC between lead spacers registered 2275 K at 5 kW in vacuum
- Heat pipe cooled reactor concept (0.375″ max OD)
  - SAFE 30
  - SAFE 100 (variable OD element)
  - SAFE 100a (variable OD element)
- Direct gas cooled reactor concept (variable OD element, 0.375″ max)
- Liquid metal (NaK) cooled reactor concept (0.305″ OD)
  - Testing commenced 10/31

- Potential Issues:
  - May present compatibility issues for some core materials
  - Minimum size limited by coupler connection and physical integrity
  - Power shaping from inner diameter (material removed from outer diameter to date)

Electrical Integration

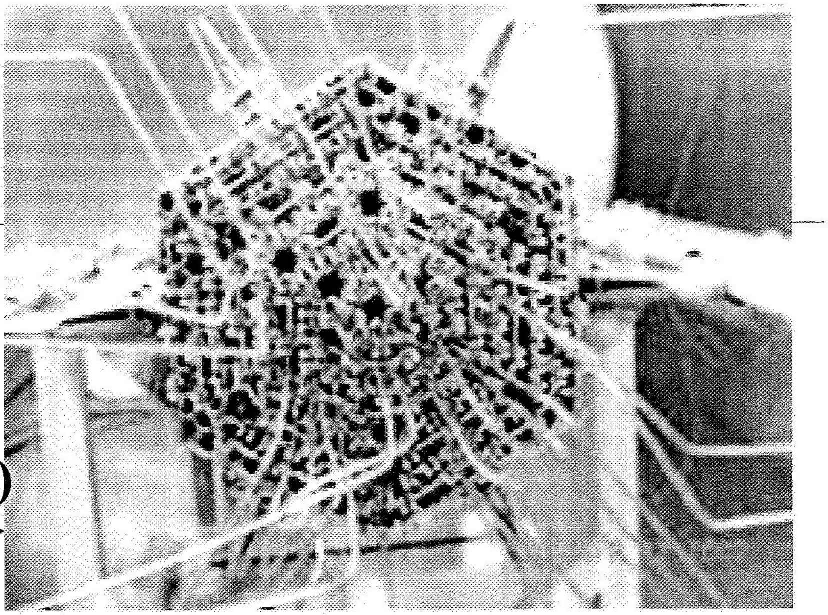
- Must take into account the total number of heater elements in small footprint

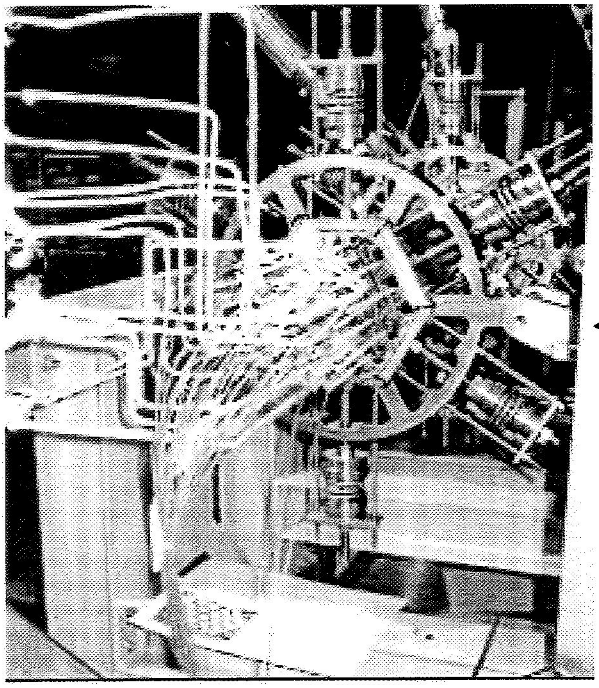
  → Complexity significantly increases as the pin size is reduced and the total number of pins increases
- Depends on reactor type and operating environment
  - Presence of a pressure vessel
  - Simulator impact on flow plenum
  - Presence of an electrically conductive media in flow plenum
  - Requirement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



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

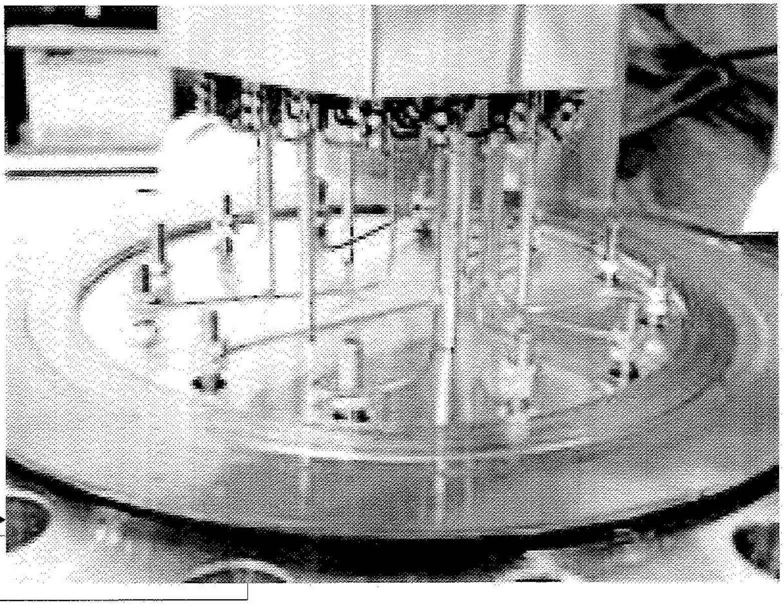
183 Simulators,
SAFE 100
(~ 10.4" by 11.5")





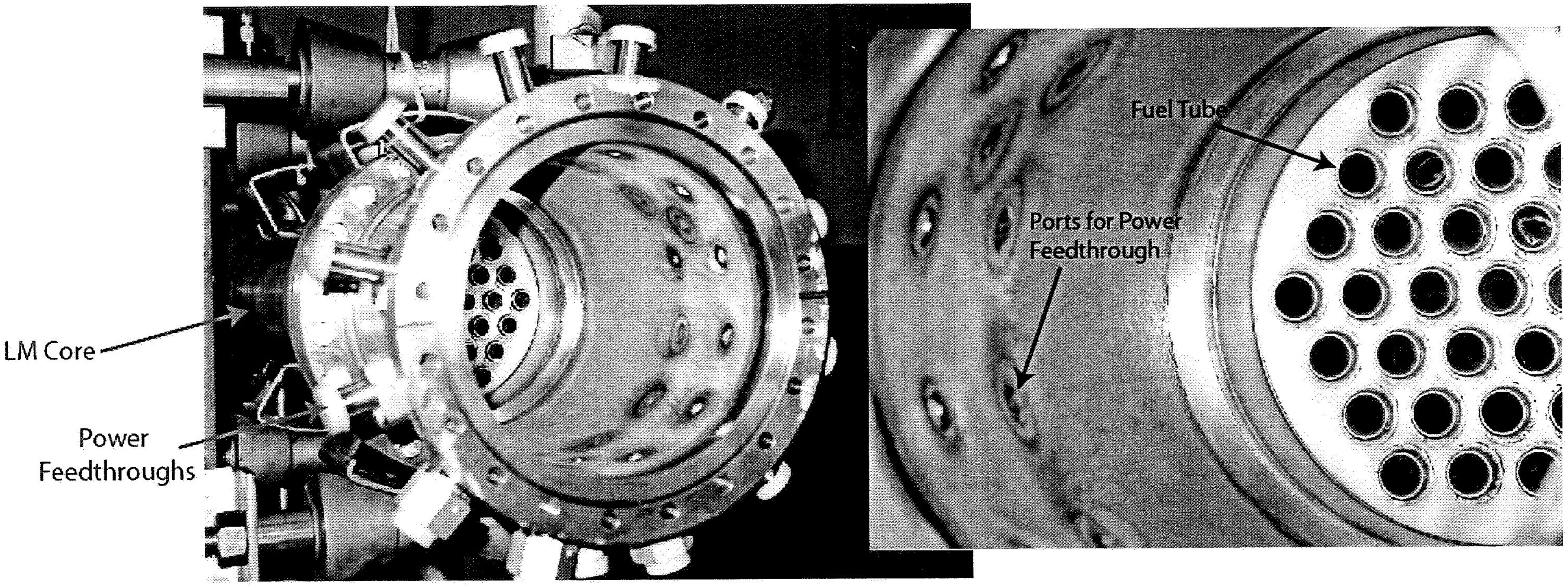
57 Simulators,
SAFE 100a
(~ 7" by 6.5")

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

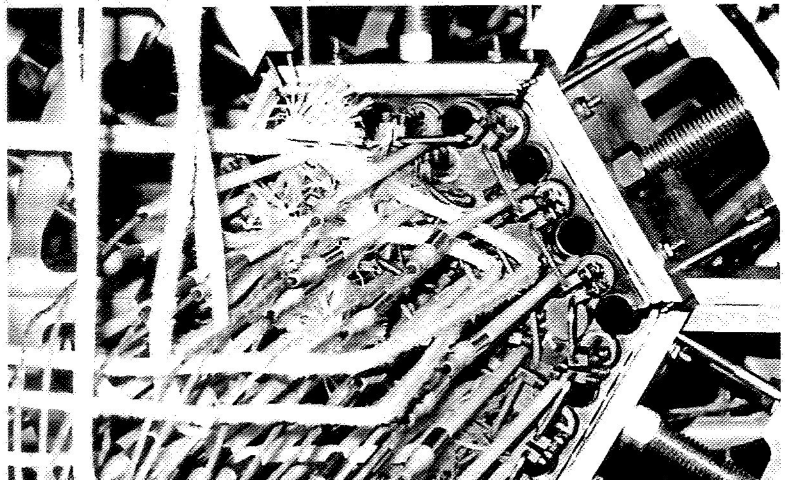


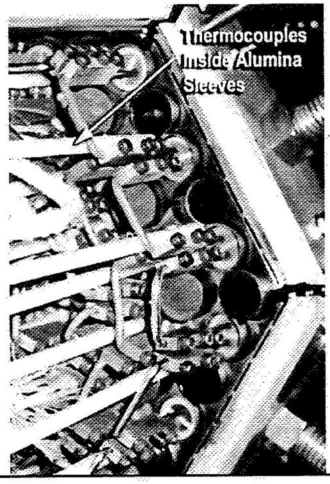
Electrical Integration – Core Face Seal

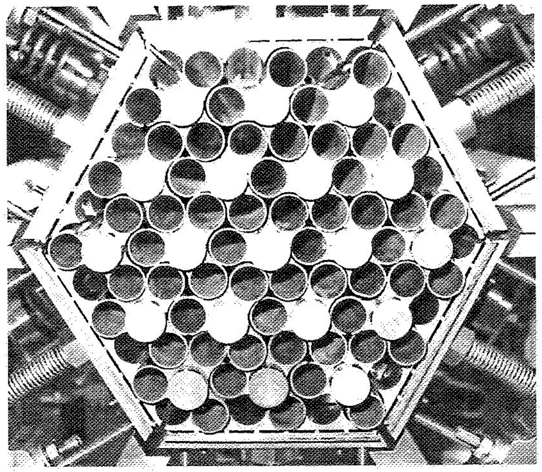
- Prevents contact with conductive media in liquid metal system
- Allows for operation with high purity gas on ID of simulator sheath
- Prevents material incompatibility issues

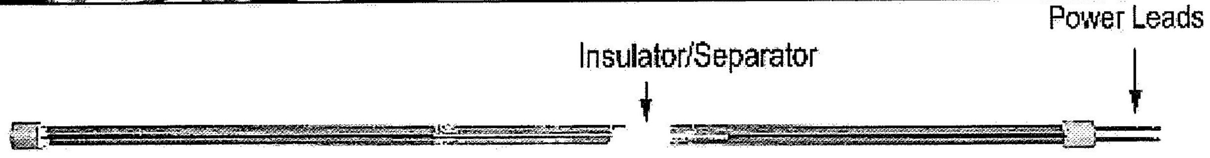


Configuration in SAFE100a Test Article



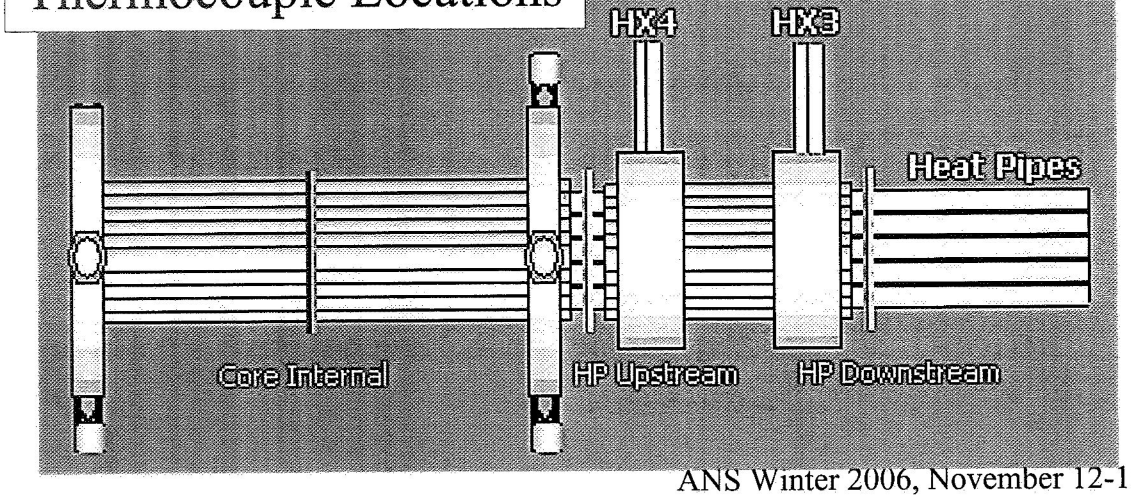






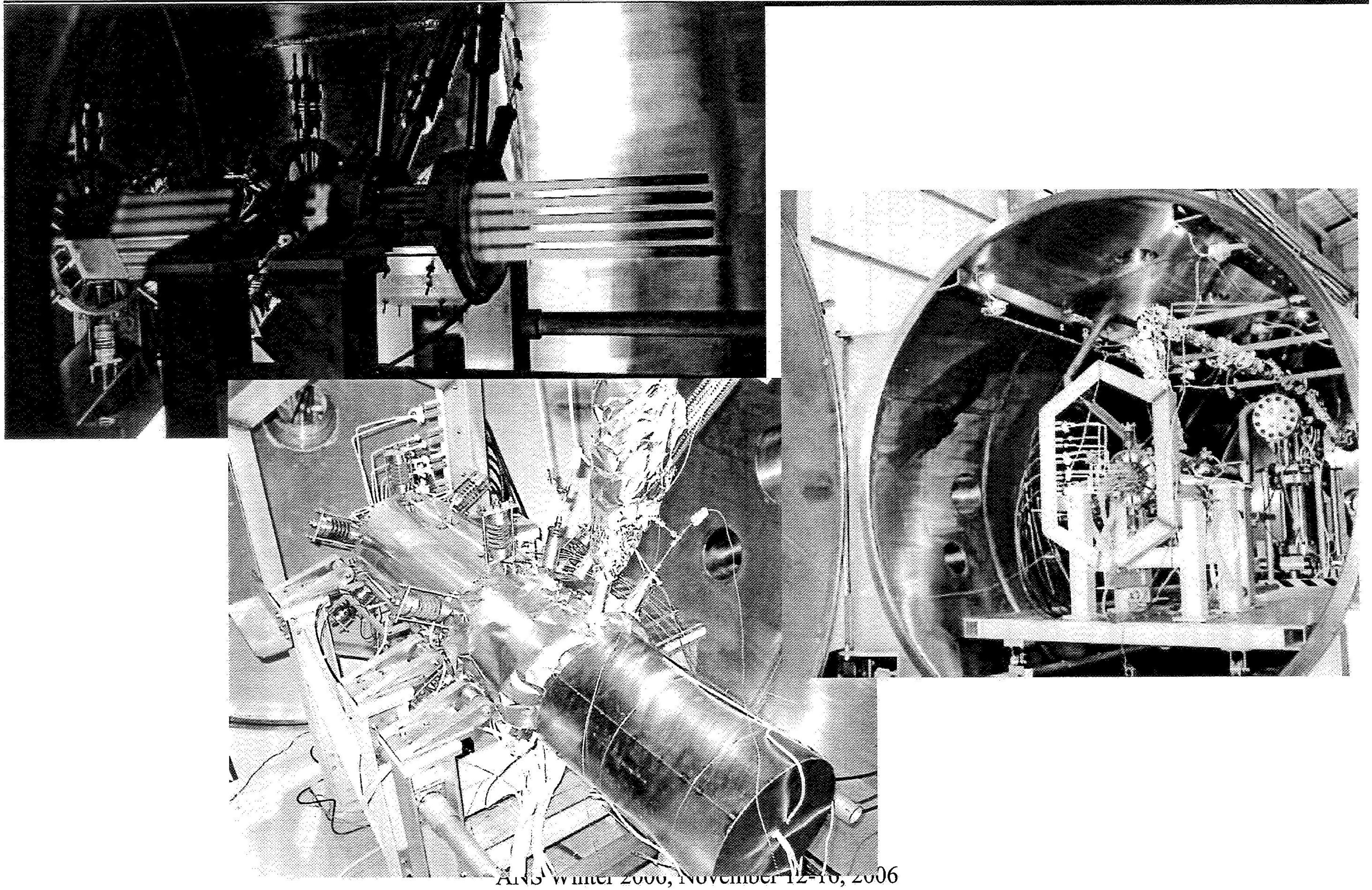
Heater Element Design

Thermocouple Locations

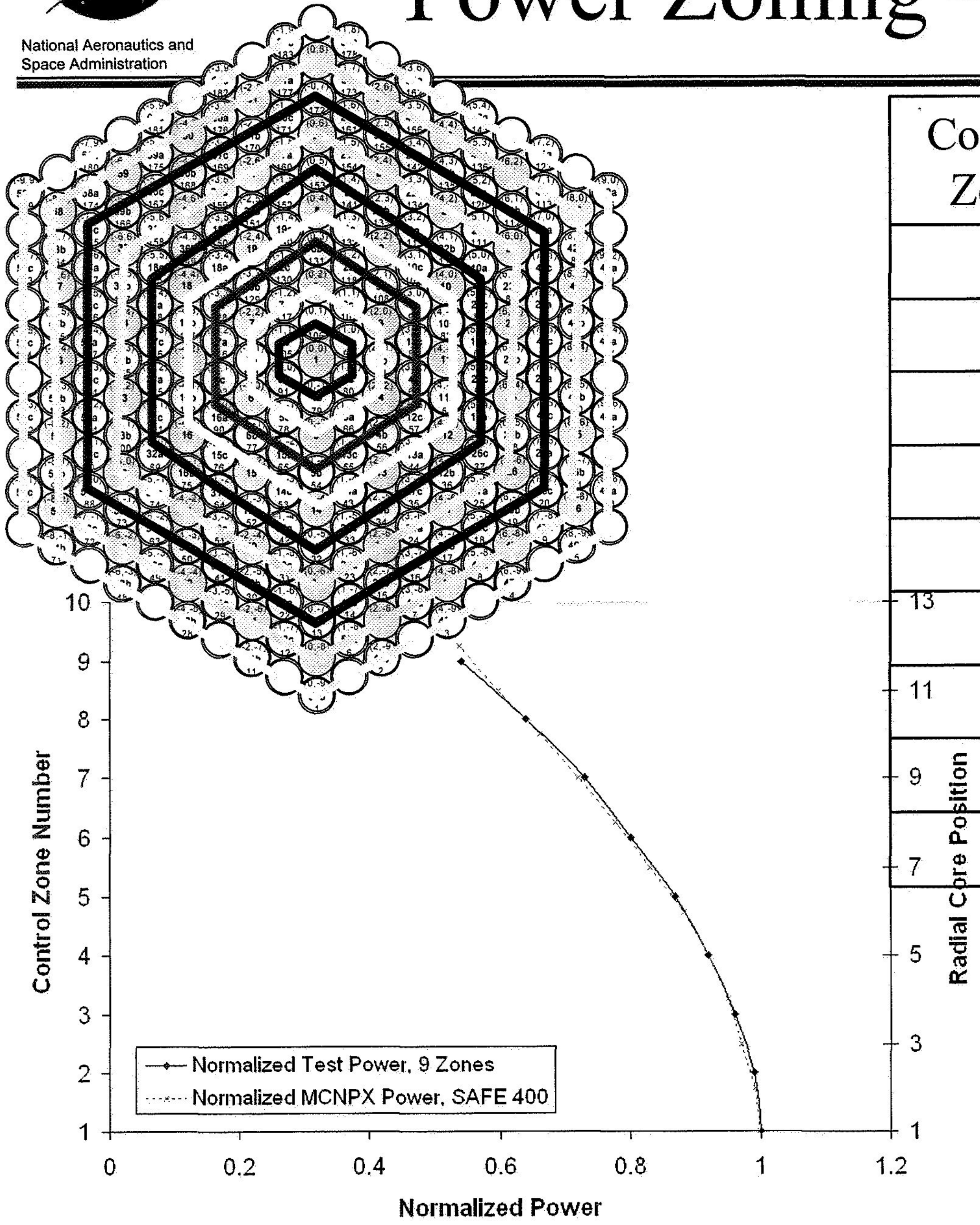


Graphite heaters shaped axially to approximate cosine shaped axial power distribution present in a nuclear core.

Final SAFE-100a Test Configuration

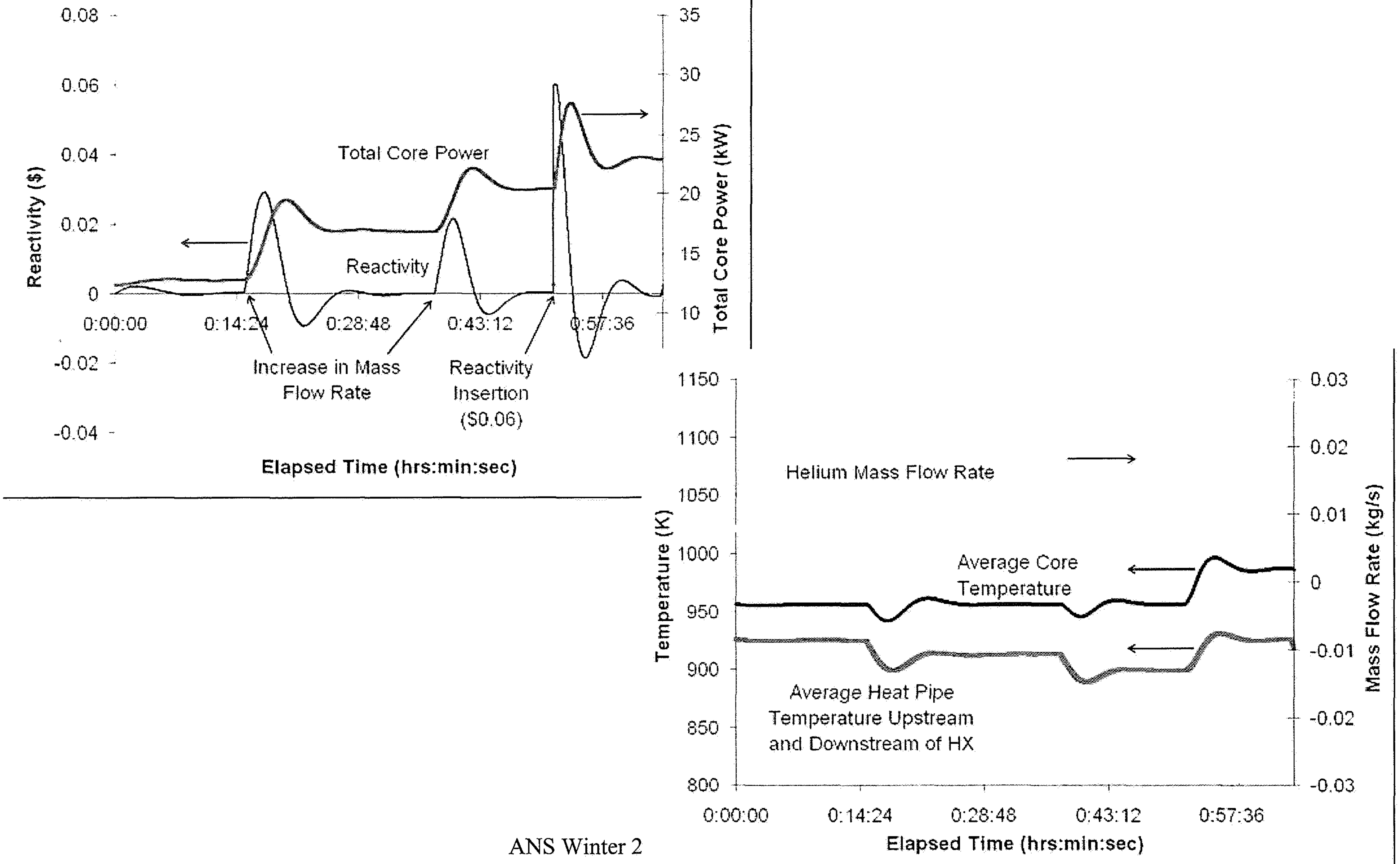


Power Zoning – SAFE 100

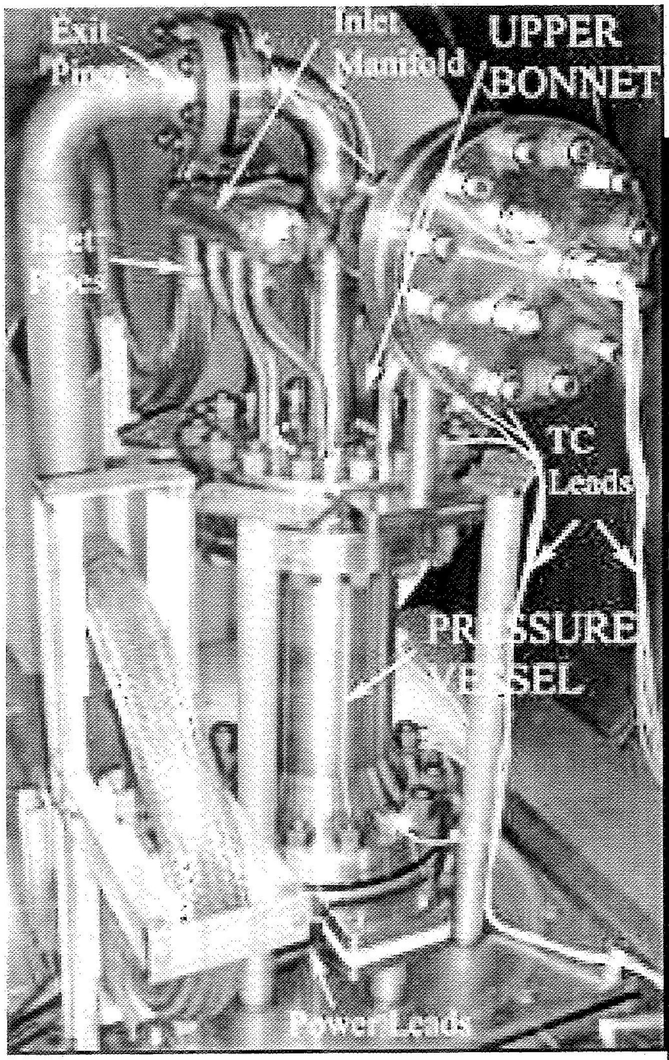


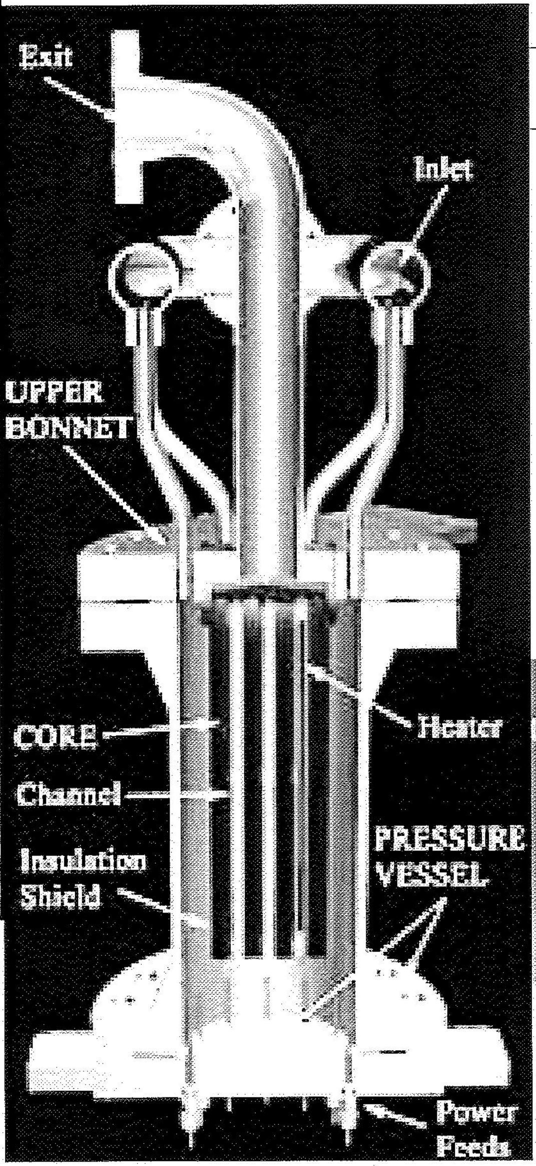
Control Zone	Color	Power Supply	Fraction of Power
1	Navy	F1	0.134
2	Aqua	G1	0.133
3	Brown	G2	0.129
4	Yellow	G3	0.123
5	Purple	G4	0.117
6	Orange	H1	0.107
7	Black	H2	0.098
8	Green	H3	0.086
9	Pink	H4	0.072

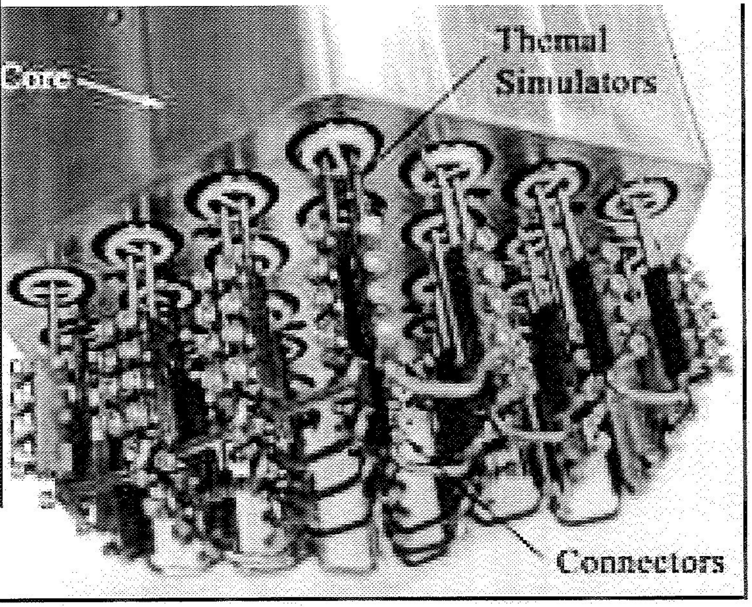
SAFE-100a
System Dynamic Response



Direct Drive Gas Cooled Reactor Test Article Configuration







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Modified Power Interface Concept

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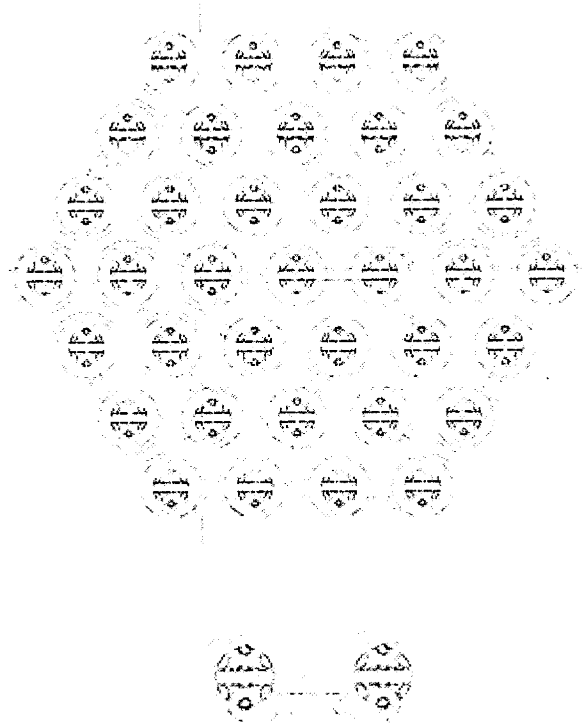
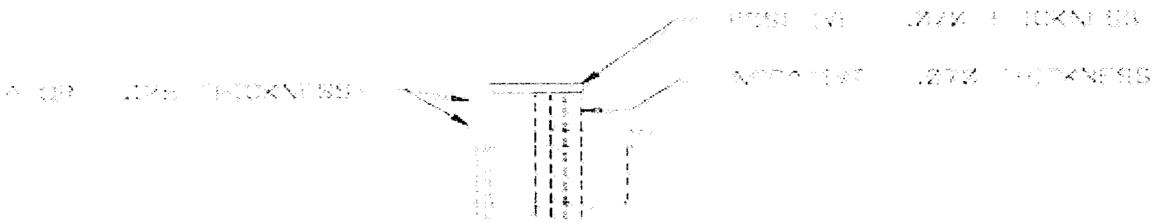
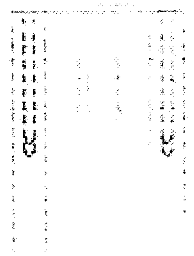
- Circuit board type interface to minimize simulator impact on flow plenum
- Applicable to designs that require a flow plenum but do not utilize electrically conductive coolant (e.g. gas cooled system)
- Baseline design developed for 37 pin DDG concept







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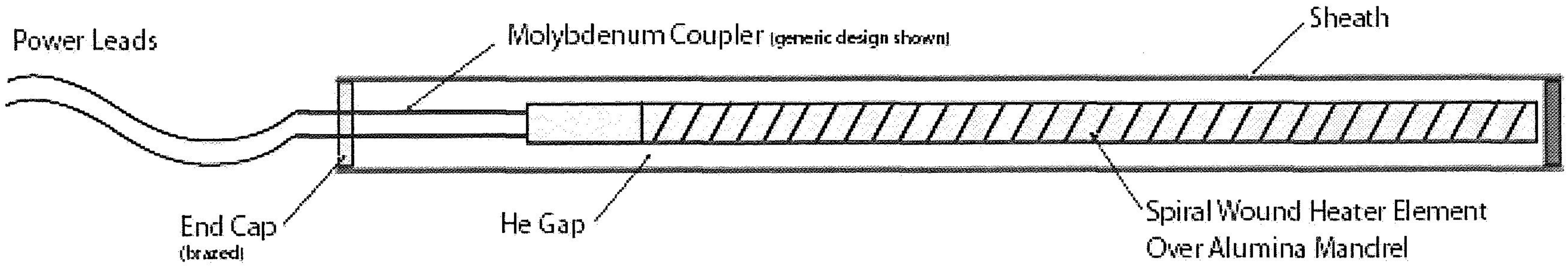
Refractory Wire Wrapped Elements

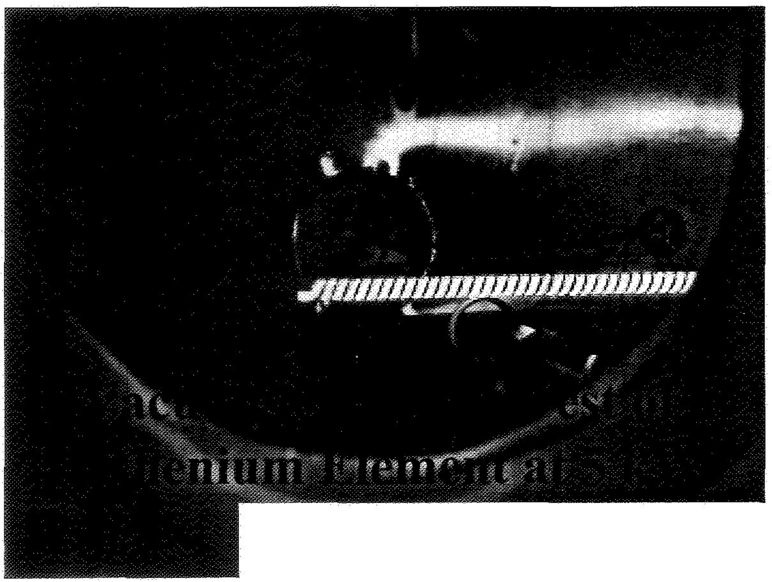
- Use with refractory metal concepts to prevent contamination and compatibility issues
- Achieve smaller diameter pins
  - Minimum fabricated assembly size: 0.65 cm (0.255″) at sheath OD
  - 0.400″ and 0.625″ assemblies tested
- Single wire or wire braid wrapped in single or double pass helical fashion around alumina mandrel (99.8% purity Al_2O_3)
- Variable wire pitch used to accomplish axial power shaping
- Constant coupling to sheath axially results from constant OD
- Tests conducted for:

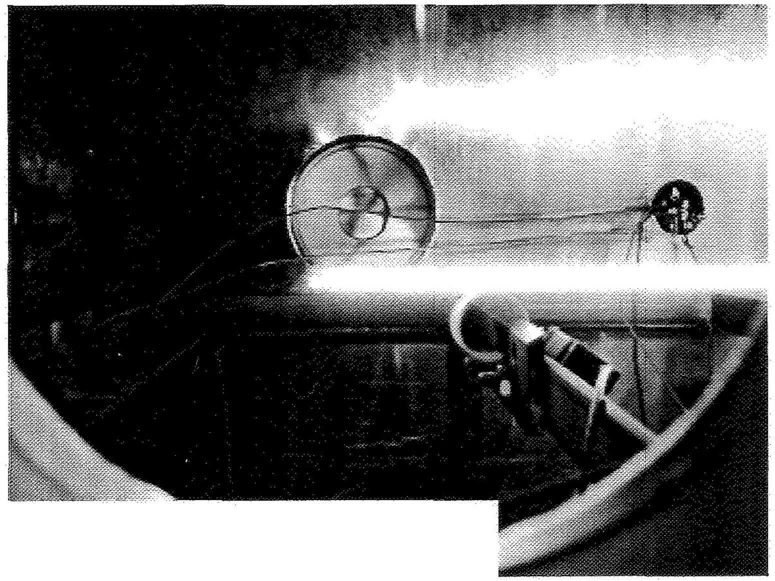
  Rhenium
  Tungsten
  Niobium
  Tantalum
  Hafnium
  Molybdenum

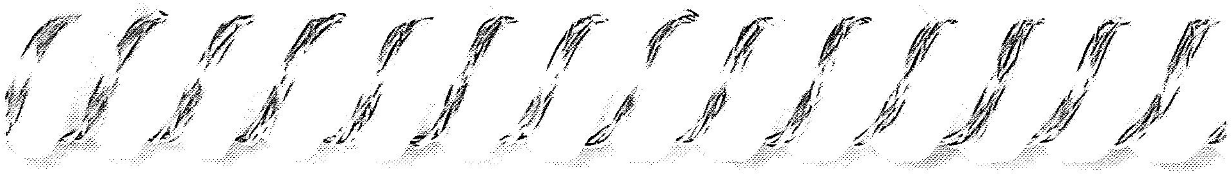
*wire size ranges from 0.010″ to 0.040″ – balance of resistivity, ductility and integrity at temperature

Refractory Wire Wrapped Elements







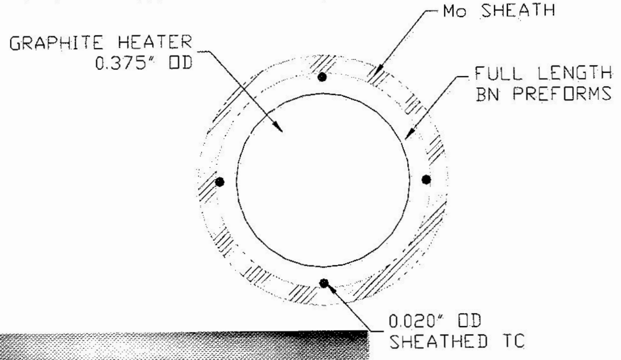


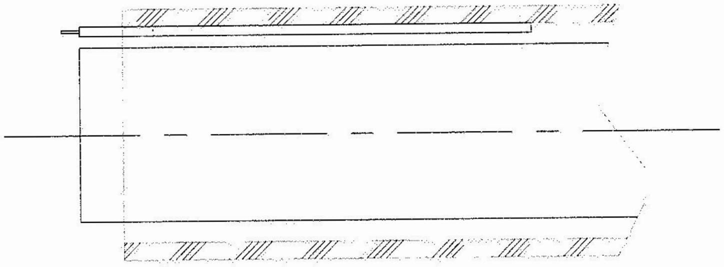
Tungsten Wire Braid Wrapped on a 0.410" Alumina Mandrel

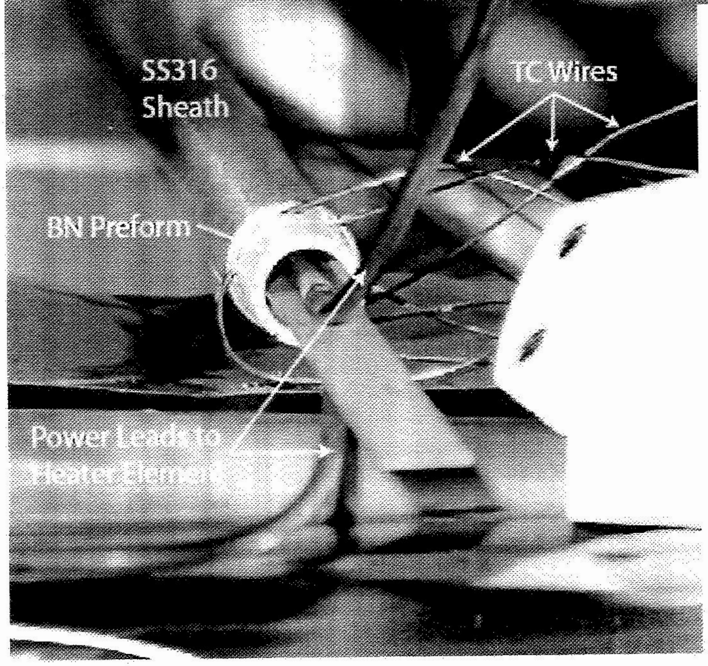
Refractory Elements – Test Results

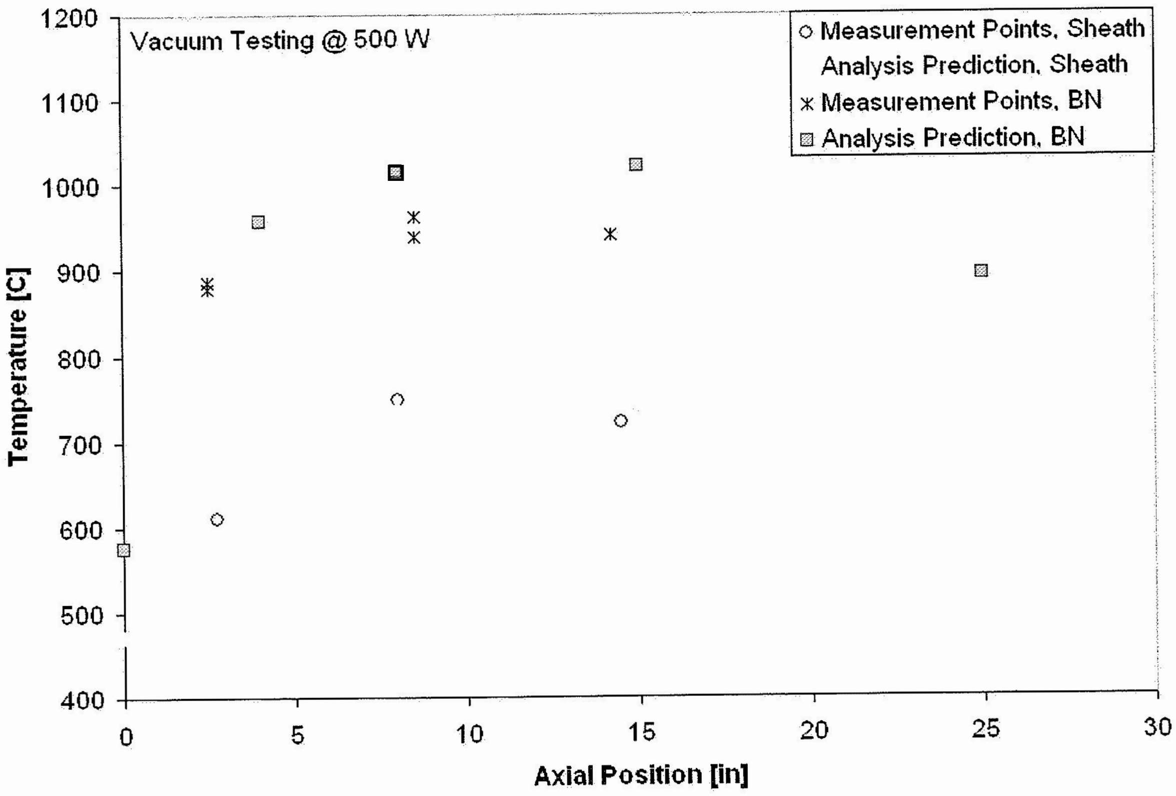
- Minimum requirement: 100 hrs @ 1200 W, with operation at up to 6000 W desired
- Single Pass:
  - Return wire down center of mandrel – inadequate heat removal through Al_2O_3 mandrel
  - Several elements "broke-down" at high power levels, presumably due to over temperature conditions
- Less robust than graphite elements
  - Require power ramping vs. instantaneous application of full power
  - Highly susceptible to material impurities – localized failure points
  - Doping to adjust material resistivity can result in hot spots
  - Variability associated with hand wrapping wire on mandrel
- Tungsten demonstrated to be most desirable for simulator assembly
  - Operated >130 hrs at 5.4 kW (0.015″ wire, 3 wire braid)
  - Relatively low cost
  - Limited material ductility (require use of small diameter wires)

Instrumented Element Design



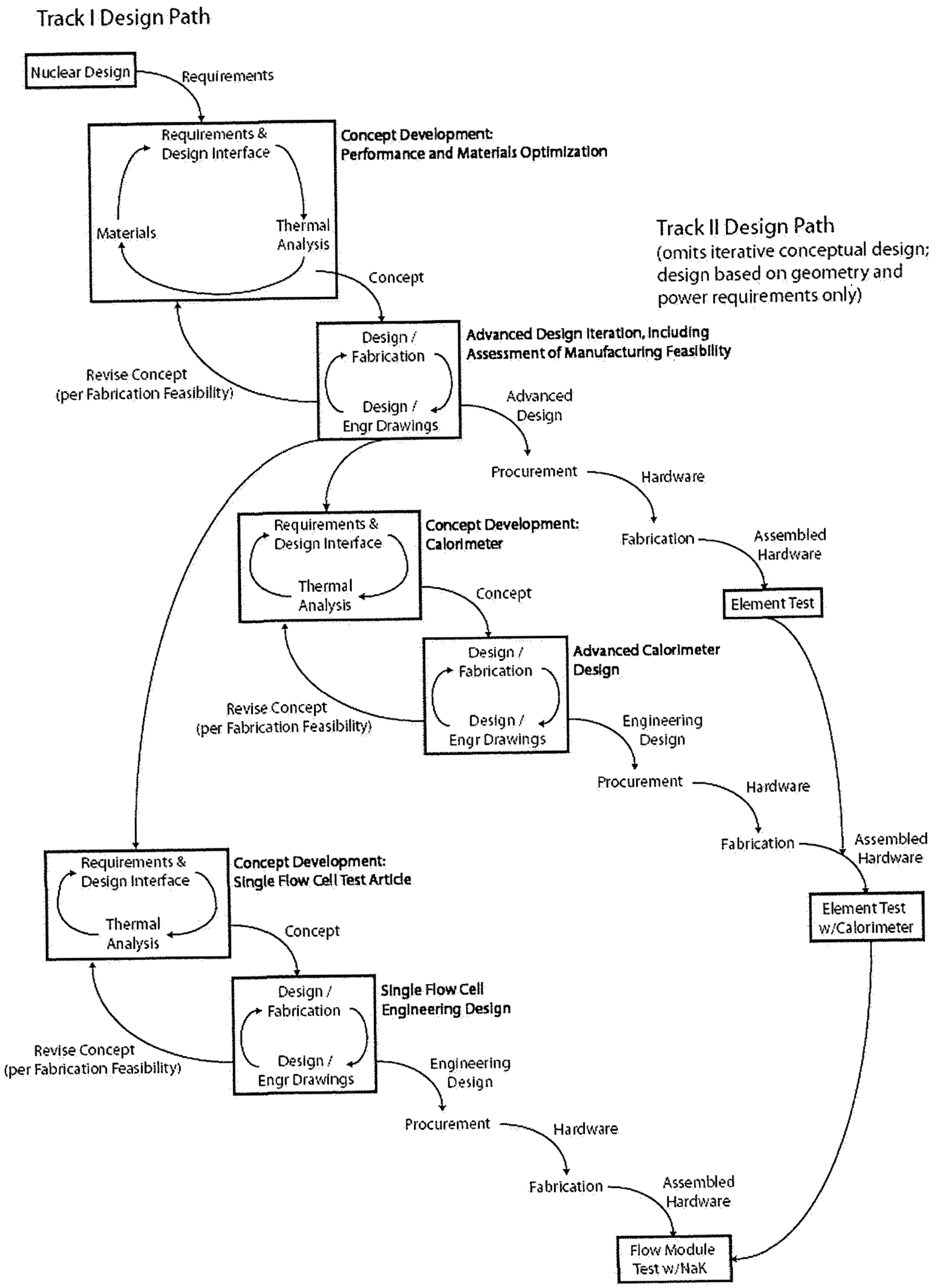






High Fidelity Simulator Design Strategy

- Receive nuclear fuel pin performance characteristics from reactor designers (static 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



Track I Design Path

Nuclear Design

Requirements

Requirements & Design Interface

Thermal Analysis

Materials

Concept Development: Performance and Materials Optimization

Concept

Design / Fabrication

Design / Engr Drawings

Advanced Design Iteration, Including Assessment of Manufacturing Feasibility

Revise Concept (per Fabrication Feasibility)

Advanced Design

Procurement

Hardware

Fabrication

Assembled Hardware

Element Test

Requirements & Design Interface

Thermal Analysis

Concept Development: Calorimeter

Concept

Design / Fabrication

Design / Engr Drawings

Advanced Calorimeter Design

Revise Concept (per Fabrication Feasibility)

Engineering Design

Procurement

Hardware

Fabrication

Assembled Hardware

Element Test w/Calorimeter

Requirements & Design Interface

Thermal Analysis

Concept Development: Single Flow Cell Test Article

Concept

Design / Fabrication

Design / Engr Drawings

Single Flow Cell Engineering Design

Revise Concept (per Fabrication Feasibility)

Engineering Design

Procurement

Hardware

Fabrication

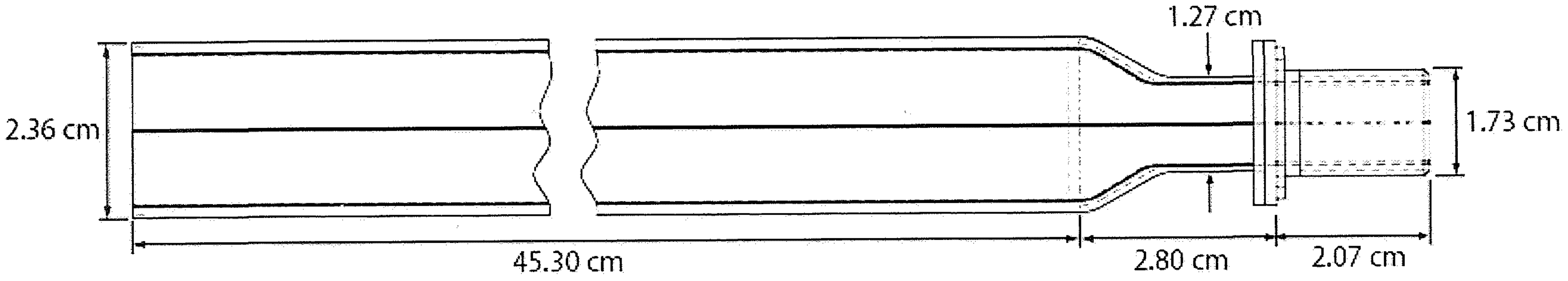
Assembled Hardware

Flow Module Test w/NaK

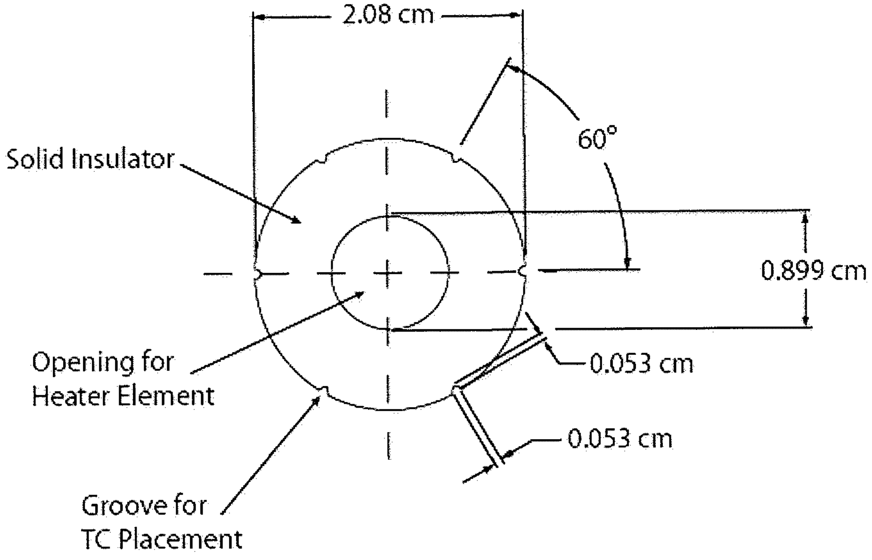
Track II Design Path

(omits iterative conceptual design; design based on geometry and power requirements only)

Current Simulator Design Goals



- Fully instrumented (TCs, with option for fiber optics in future)
- 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 static and transient operation



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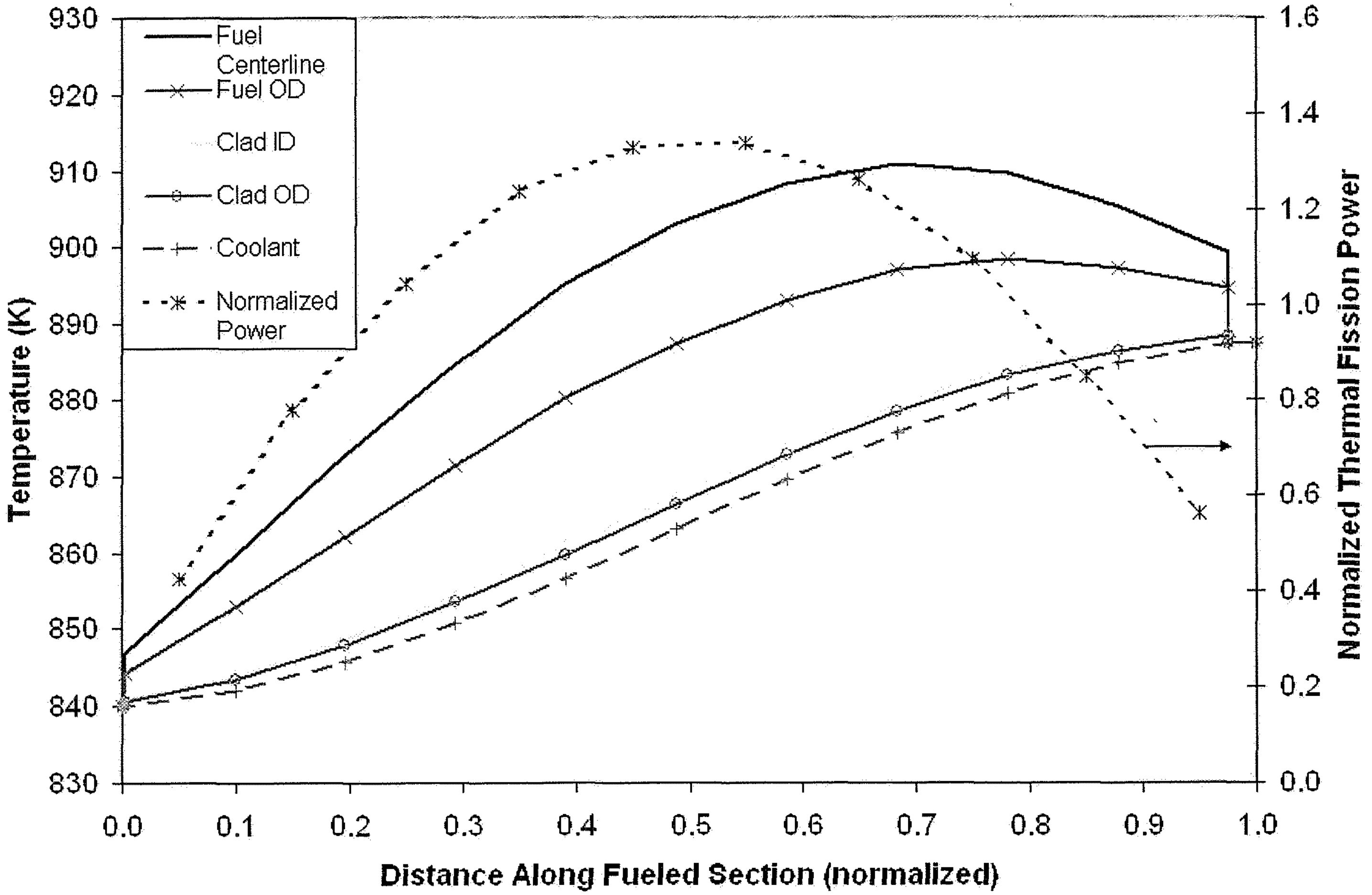
Space Administration

Static Pin Performance Matching



98 kWt, 0.86 kW/pin (nominal)

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