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Local Heat Flux Measurements with Single Element Coaxial Injectors

Gregg Jones•, Christopher Protz†, Brad Bullard†,
NASA Marshall Space Flight Center, Huntsville, AL, 35812

James Hulka‡
Jacobs Sverdrup, MSFC Group, Huntsville, AL, 35812

ABSTRACT

To support the mission for the NASA Vision for Space Exploration, the NASA Marshall Space Flight Center conducted a program in 2005 to improve the capability to predict local thermal compatibility and heat transfer in liquid propellant rocket engine combustion devices. The ultimate objective was to predict and hence reduce the local peak heat flux due to injector design, resulting in a significant improvement in overall engine reliability and durability. Such analyses are applicable to combustion devices in booster, upper stage, and in-space engines, as well as for small thrusters with few elements in the injector. In this program, single element and three-element injectors were hot-fire tested with liquid oxygen and ambient temperature gaseous hydrogen propellants at The Pennsylvania State University Cryogenic Combustor Laboratory from May to August 2005. Local heat fluxes were measured in a 1-inch internal diameter heat sink combustion chamber using Medtherm coaxial thermocouples and Gardon heat flux gauges. Injectors were tested with shear coaxial and swirl coaxial elements, including recessed, flush and scarfed oxidizer post configurations, and concentric and non-concentric fuel annuli. This paper includes general descriptions of the experimental hardware, instrumentation, and results of the hot-fire testing for three of the single element injectors – recessed-post shear coaxial with concentric fuel, flush-post swirl coaxial with concentric fuel, and scarfed-post swirl coaxial with concentric fuel. Detailed geometry and test results will be published elsewhere to provide well-defined data sets for injector development and model validatation.

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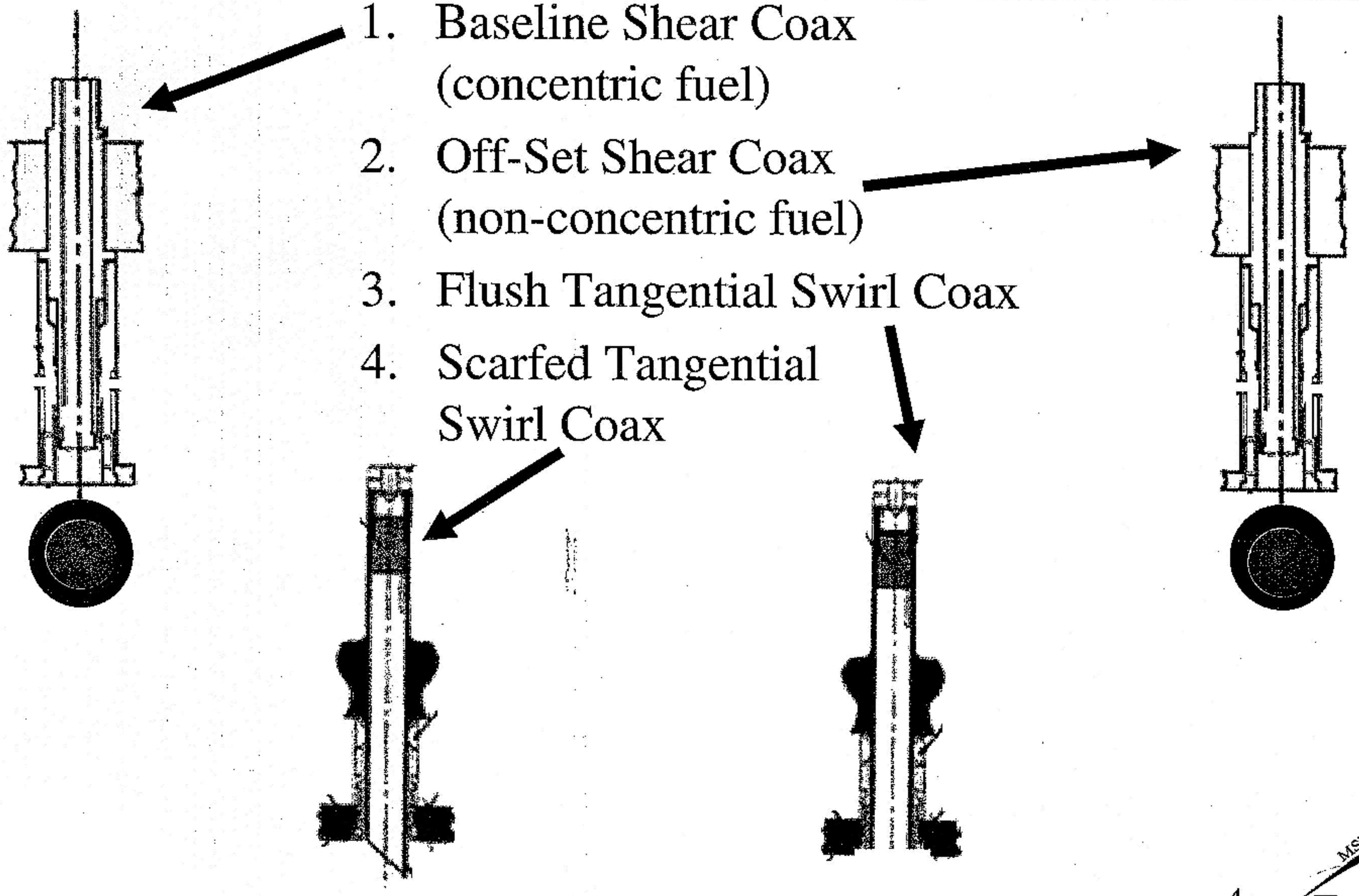
Heat Transfer is Essential to Exploration Mission

- In-space engines *must* be extremely reliable
  - Combustor compatibility and durability are critical factors in engine reliability
    - defined by *local* heat transfer, not bulk heat transfer
  - Current capability to analyze *local* heating effects from injector is insufficient and must be improved
- Some exploration engine cycles also *depend* on heat transfer to be operational
  - Expander and tap-off engine cycles use combustion chamber heat for turbine drive gas energy
- Past heat transfer design methods are not efficient
  - Previous engine development used mostly empirical methods and "test-fail-fix" design philosophy

MSFC Program Objective – Reduce *Local* Peak Heat Flux Due to Injector

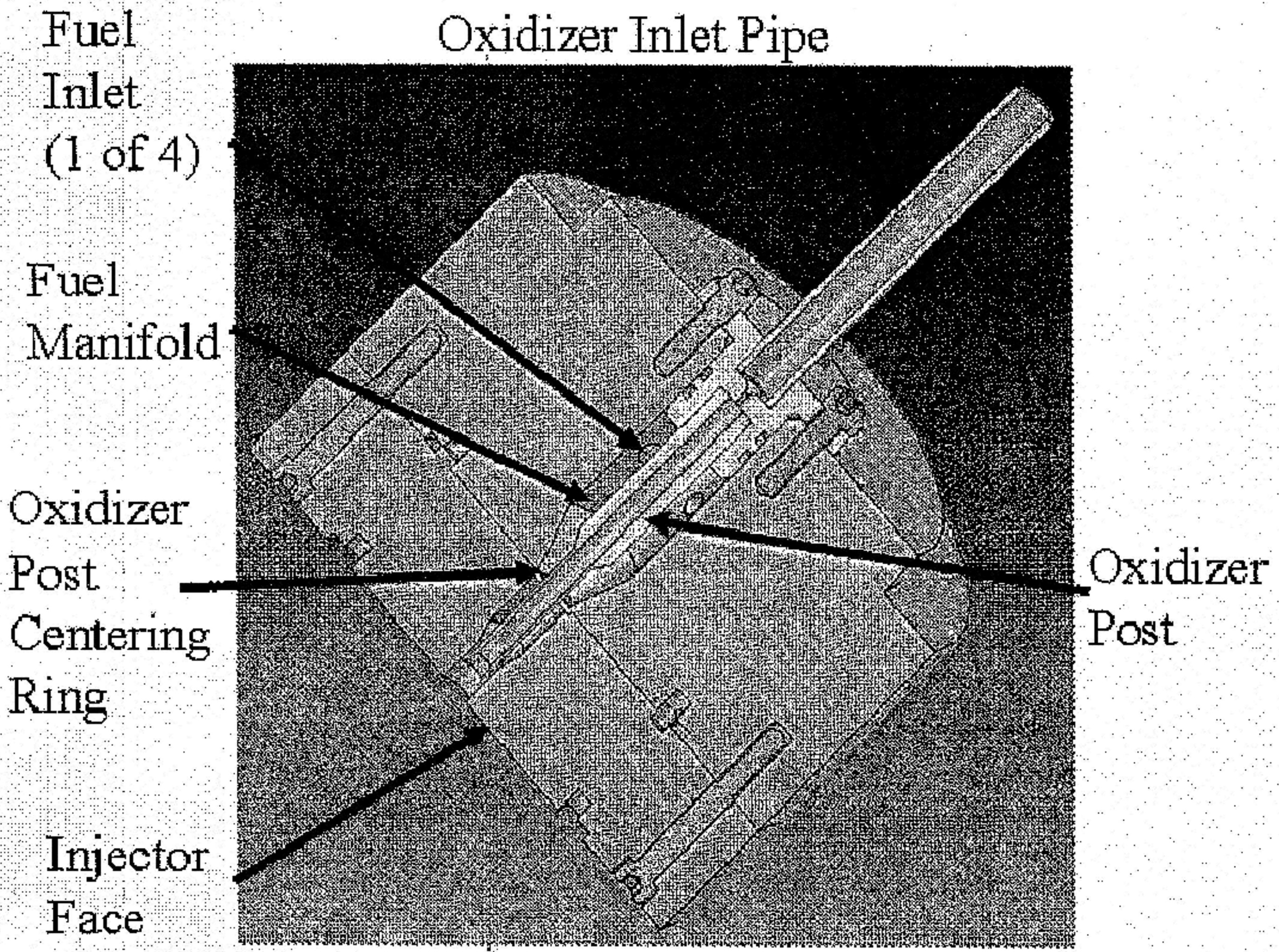
- Improve local heat transfer analysis capability
  - Current capability to analyze local injector heating effects is largely one-dimensional and empirical
  - Improve computational fluid dynamic (CFD) model capability
    - Add features for three-dimensional flows, real fluids, and faster turnaround capability
    - Validate CFD model with highly-resolved small scale experiments
      - Multiple injection element types
      - Single-element and small multi-element
- Develop advanced injector designs to reduce local peak wall heat flux
  - Previous injectors developed by "test-fail-fix" were not optimized
  - Design, fabricate, and test advanced elements in highly-resolved small scale experiments

Conventional Injector Element Types Tested for MSFC Injector Program

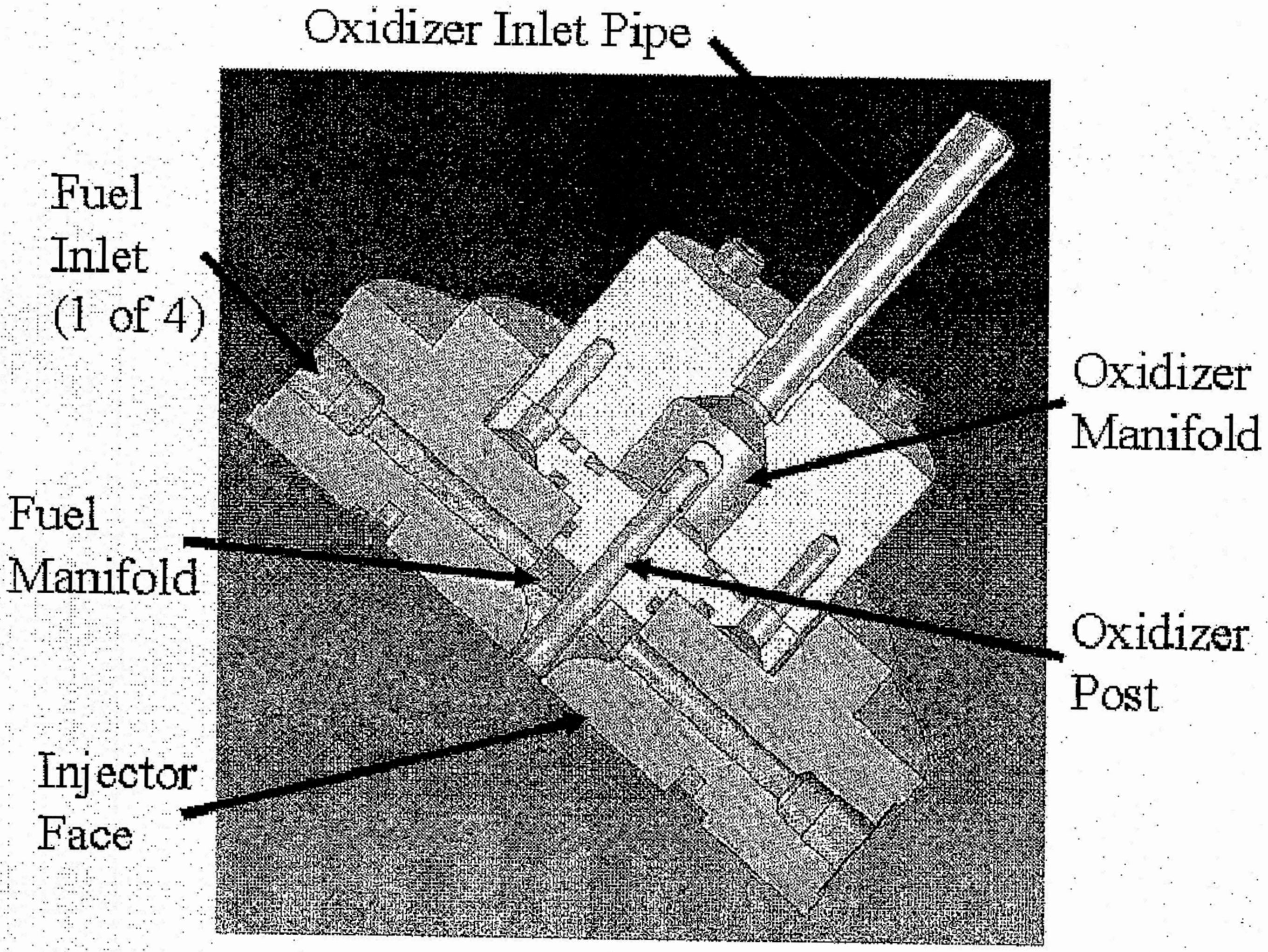


1. Baseline Shear Coax (concentric fuel)
2. Off-Set Shear Coax (non-concentric fuel)
3. Flush Tangential Swirl Coax
4. Scarfed Tangential Swirl Coax

Single Element Shear Coax



Single Element Swirl Coax



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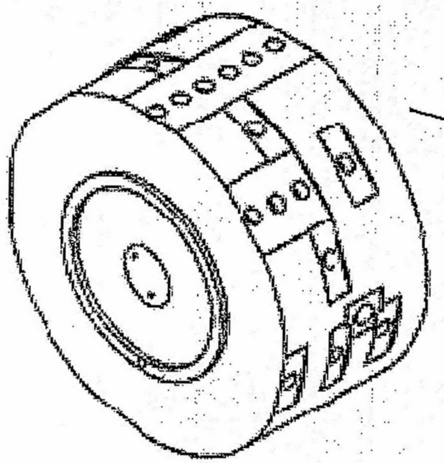
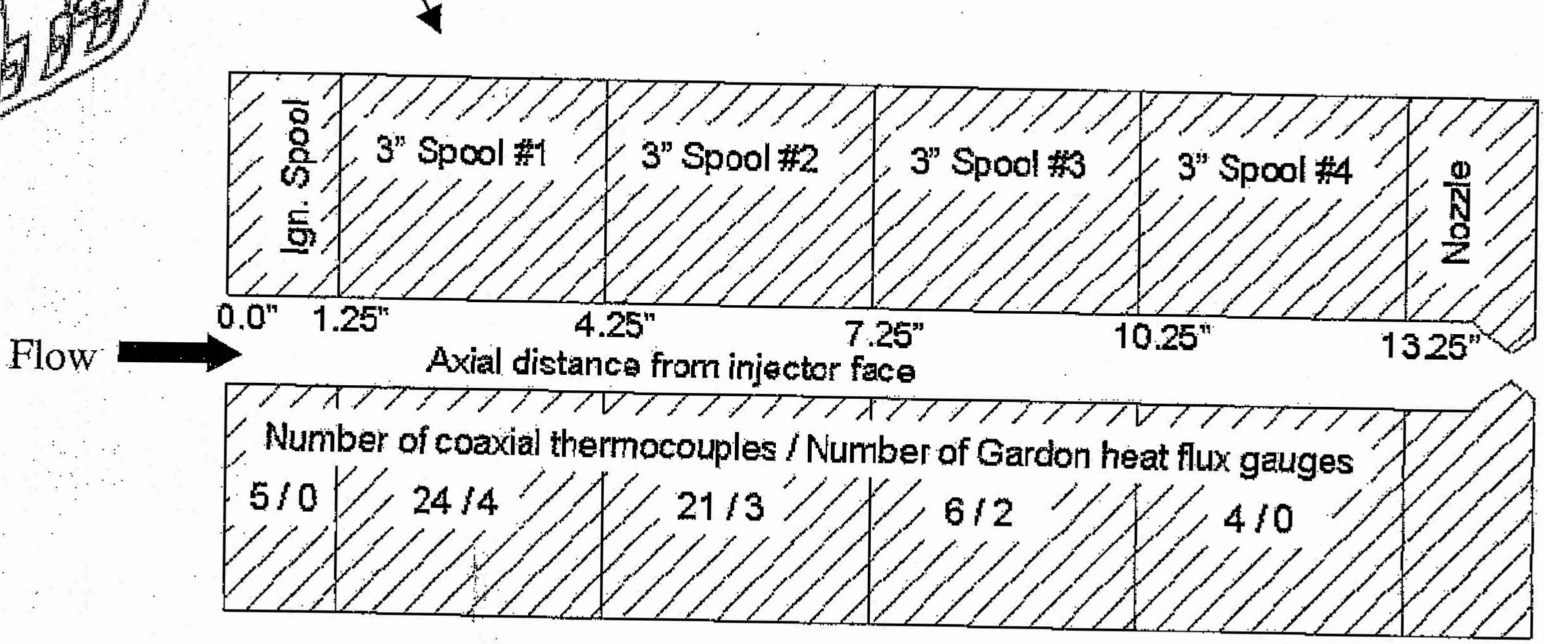
Compatibility/Heat Transfer Combustion Chamber

- Modular chamber with multiple spools
- 1-inch ID, 6-inch OD



Individual Chamber Spool



Layout of Chamber Spools with Instrumentation

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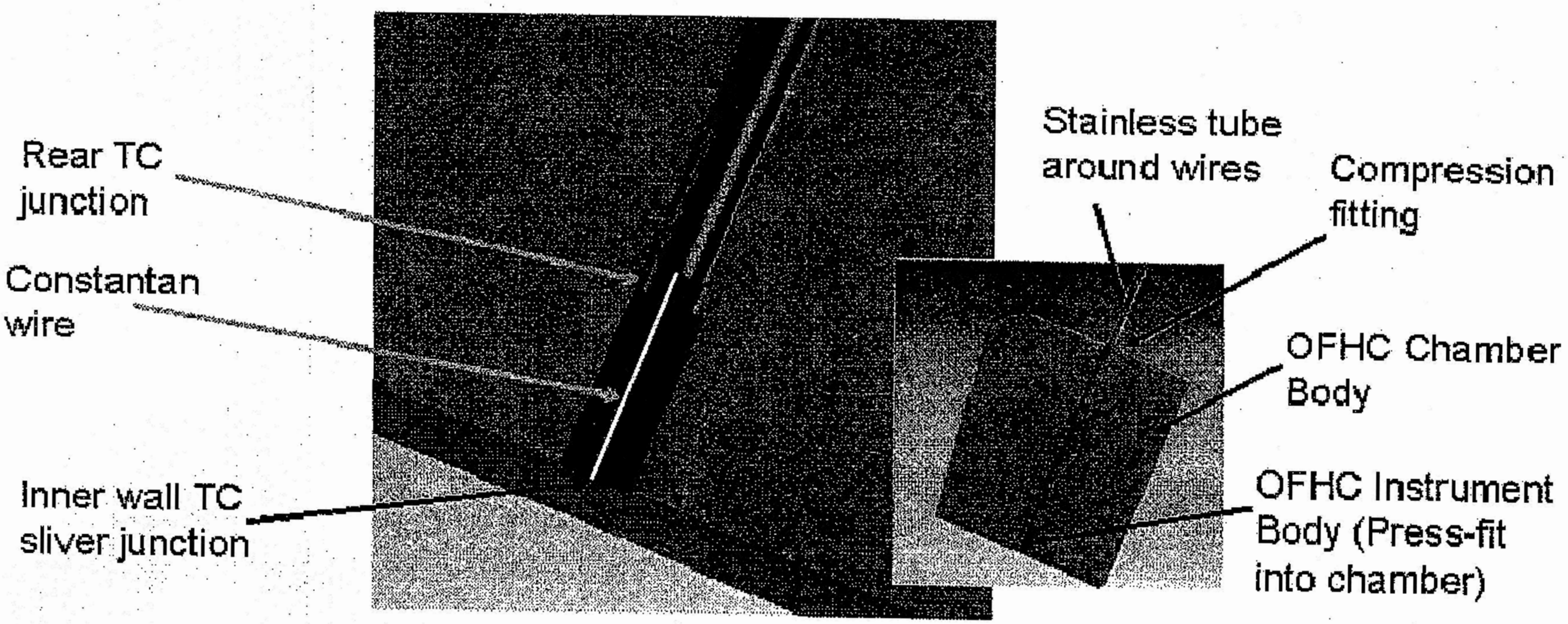
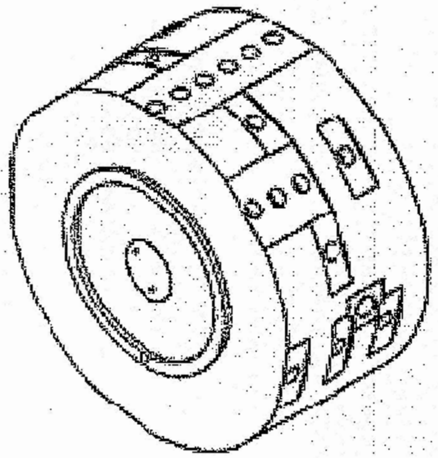
Medtherm Coaxial Thermocouple

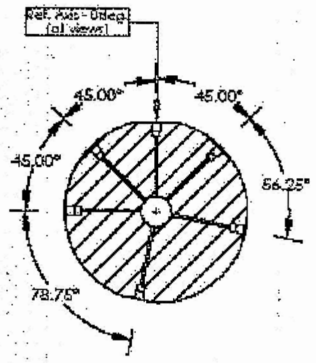


Examples of Coaxial Thermocouple Layouts at Different Axial Locations

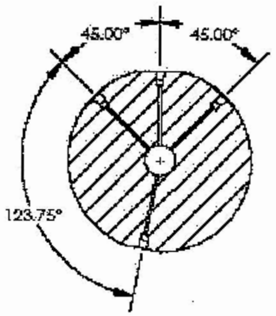
- Up to 10 sections per spool



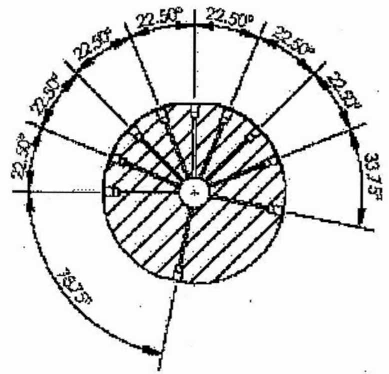
Individual Chamber Spool



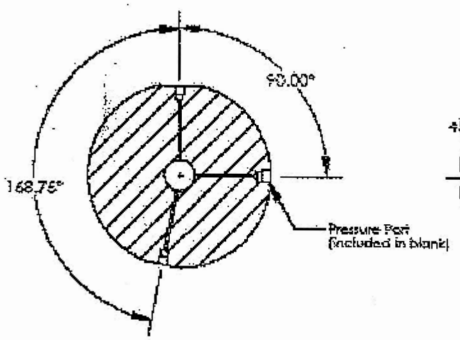
SECTION A-A



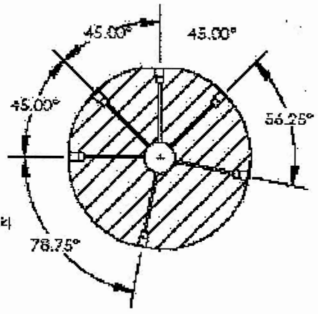
SECTION B-B



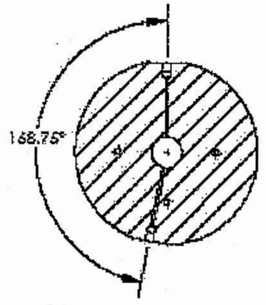
SECTION C-C



SECTION D-D

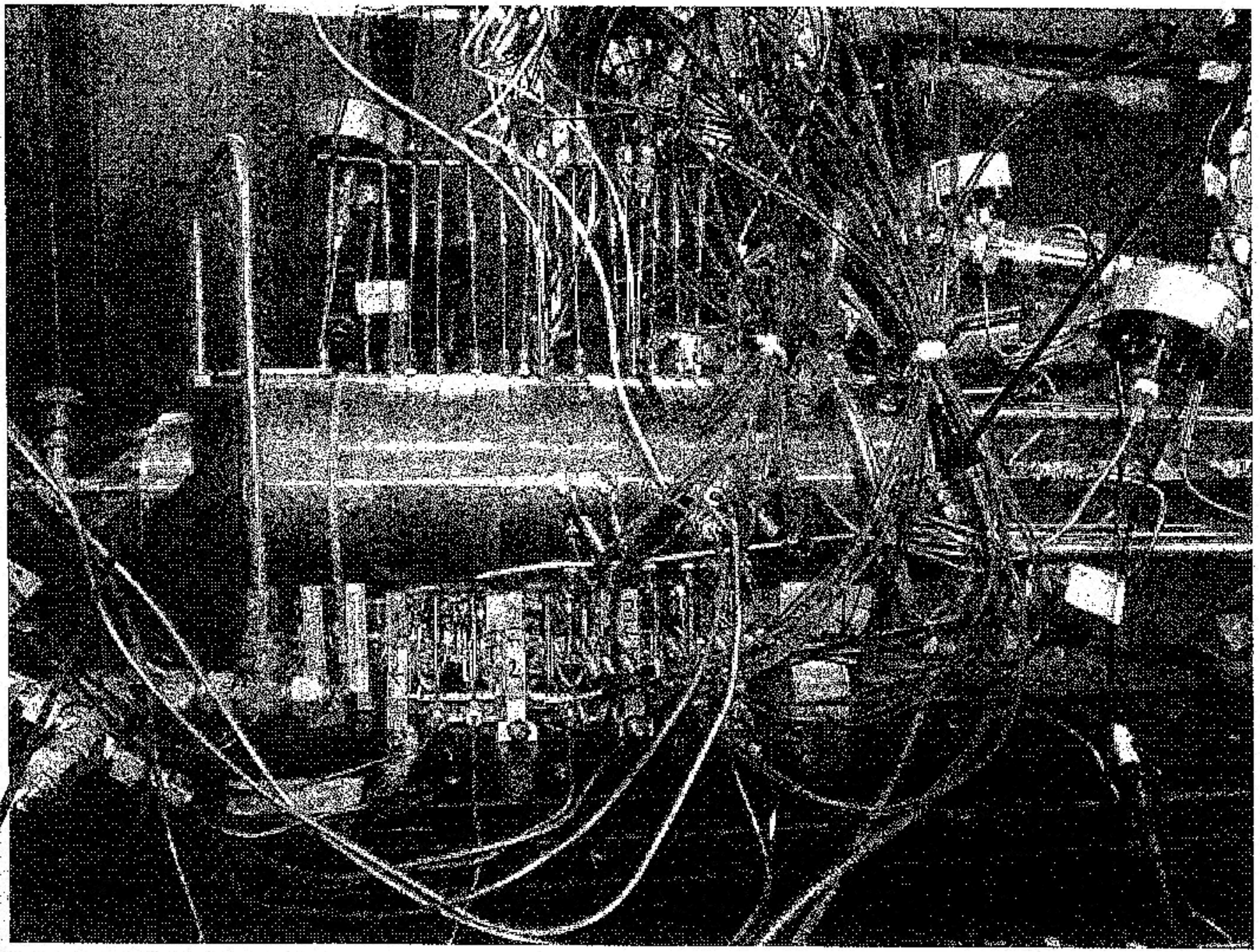


SECTION E-E

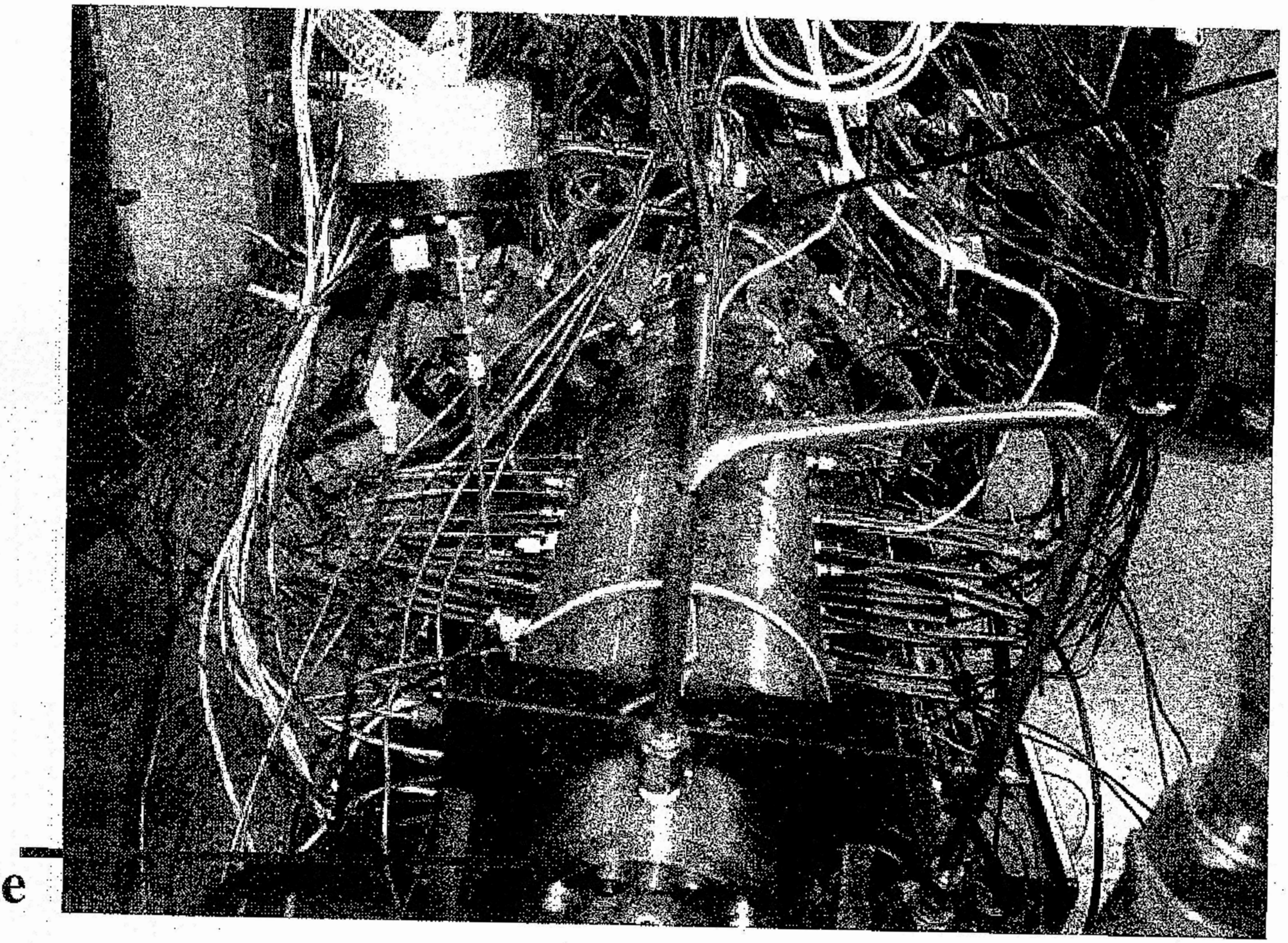


SECTION F-F

Compatibility/Heat Transfer Test Rig at The Pennsylvania State University

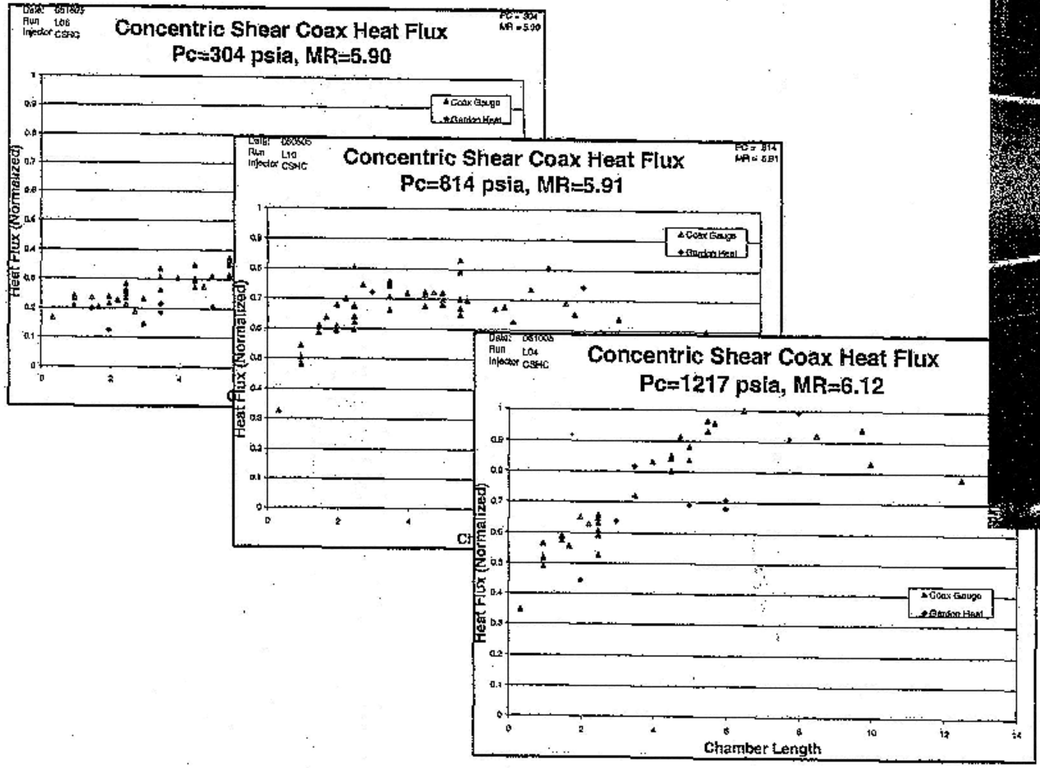


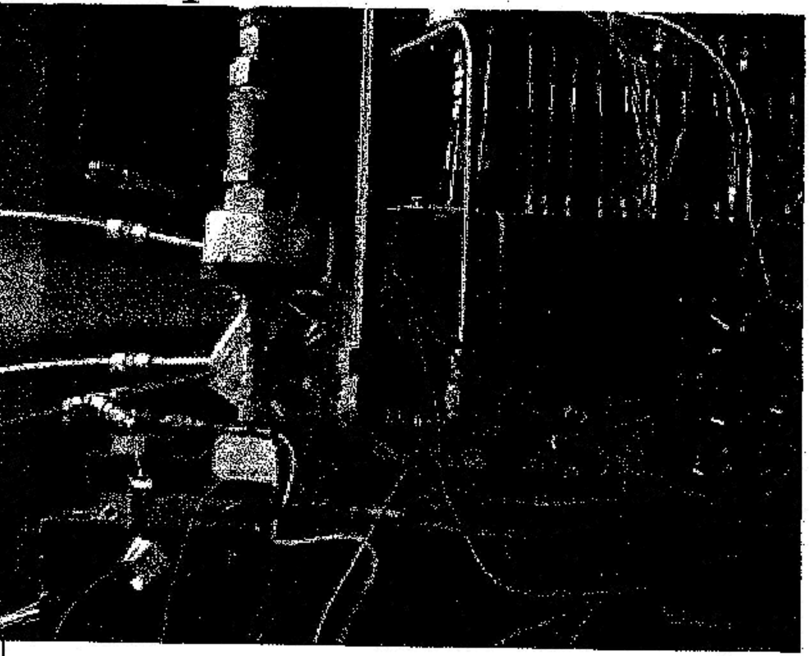
Compatibility/Heat Transfer Test Rig at The Pennsylvania State University



Over 100 Tests Completed at Penn State

- 109 tests completed
- 10 injector configurations tested
- Chamber pressures varied from 300 – 1200 psia
- Mixture ratio varied from 5 to 6.5

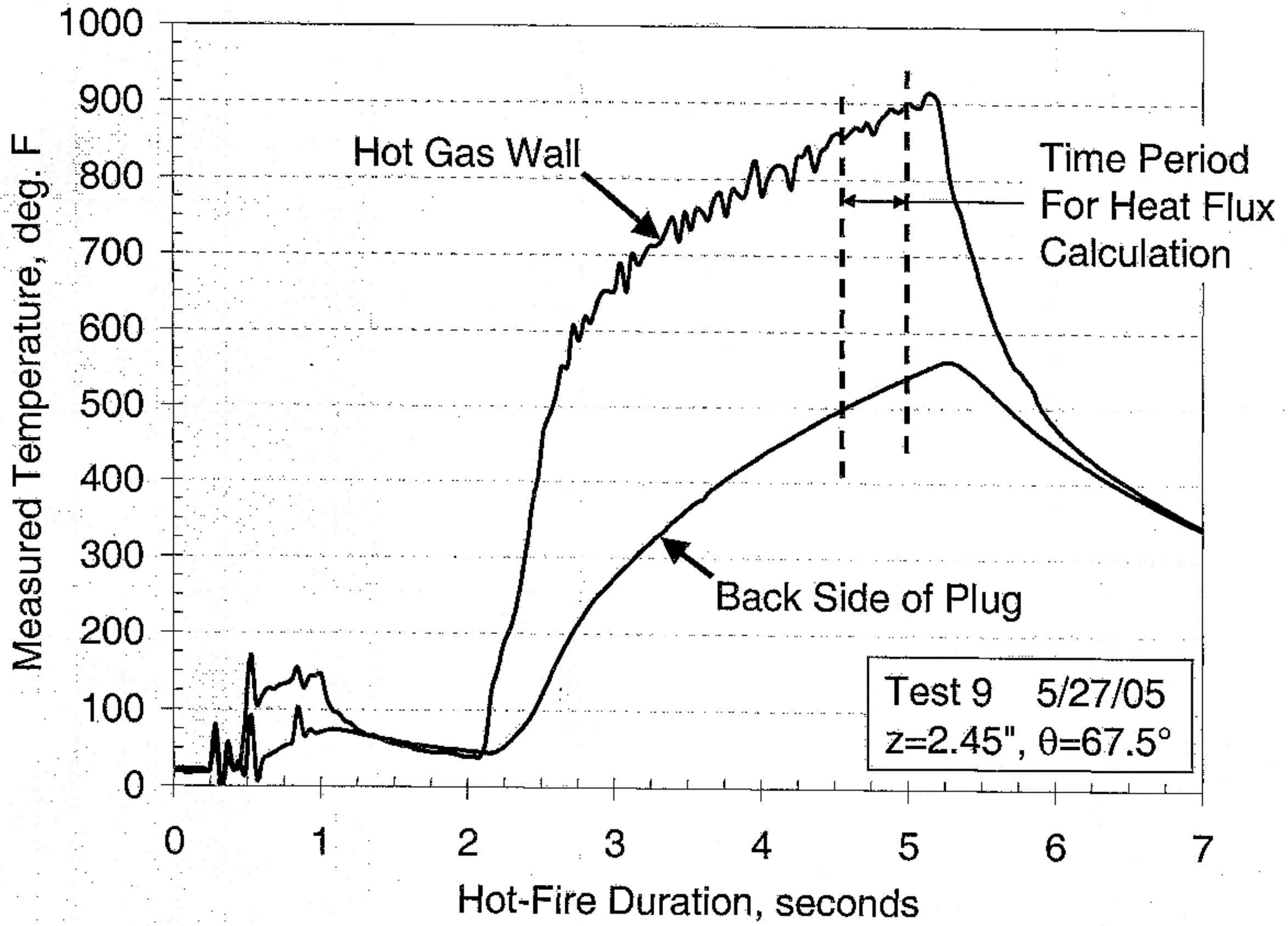




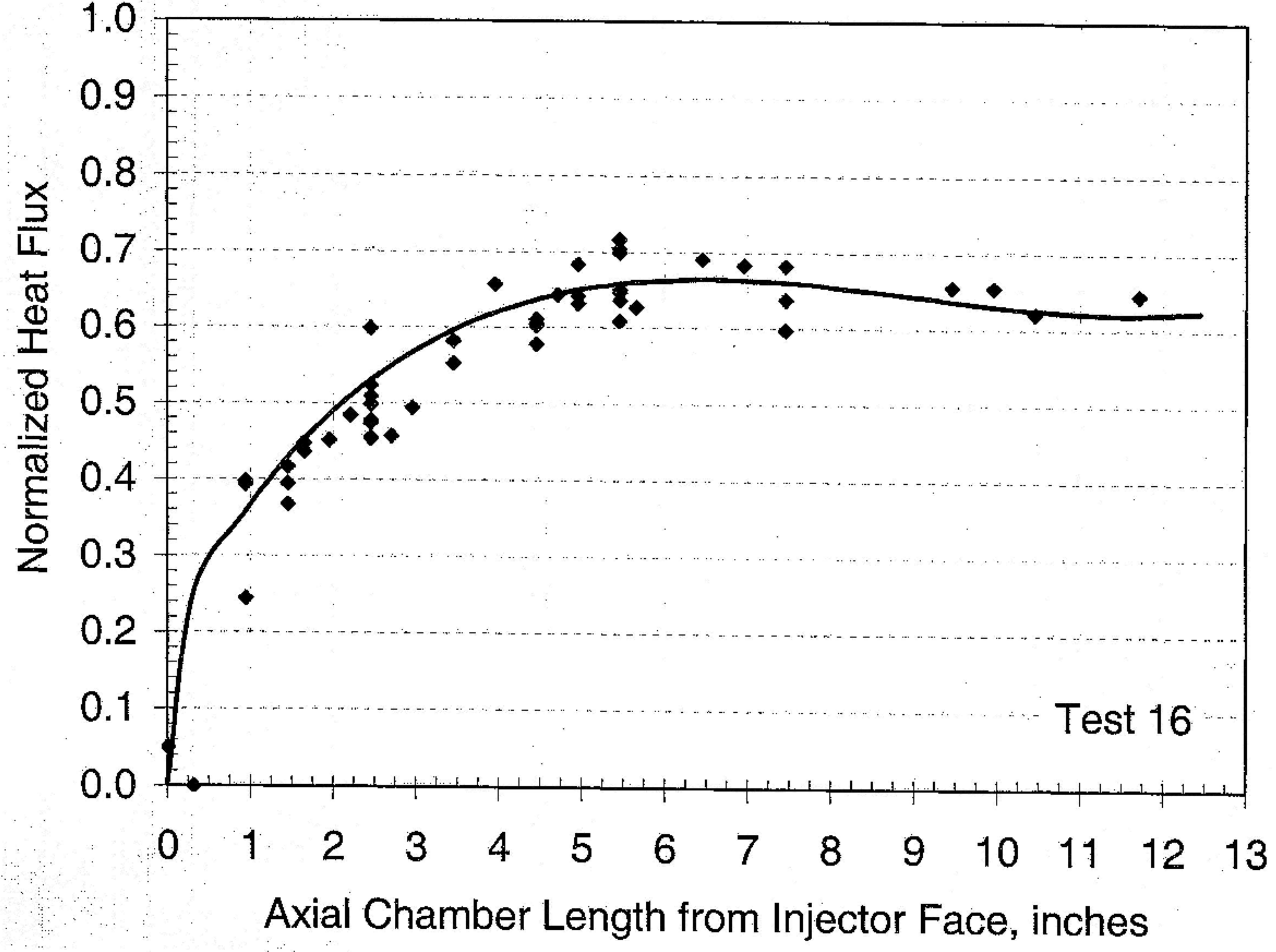
Evaluation of Test Data Validity

- Uncertainty of heat flux from Medtherm coaxial thermocouple
  - Previously evaluated at the PSU CCL for 2003 gas/gas testing
  - Calculated uncertainty ~ 0.6 %
- Accuracy and repeatability
  - Compared normalized heat flux from different gauges in same location after injector was rotated
  - Analysis of many tests from 4 injectors and 3 mixture ratios
  - Includes run-to-run and gauge-to-gauge variability
  - Average deviation calculated ~ 3%
- Effect of contact of press-fit plug with the bulk chamber
  - Effect varies as a function of test duration
  - Raw data examined and averaged summary period selected to exclude effect
- Effect of plug recessing or protruding into chamber
  - Specific locations noted; evaluation in progress with CFD analyses
- Effect of selection of summary period with variable test durations
  - Heat flux naturally biased lower the later the data collected due to wall temp
  - If wall temperature not included, added variability ~ 1%

Heat Flux Calculated From Coax Thermocouples



Measured Heat Flux Data Fit to High-order Polynomial Function



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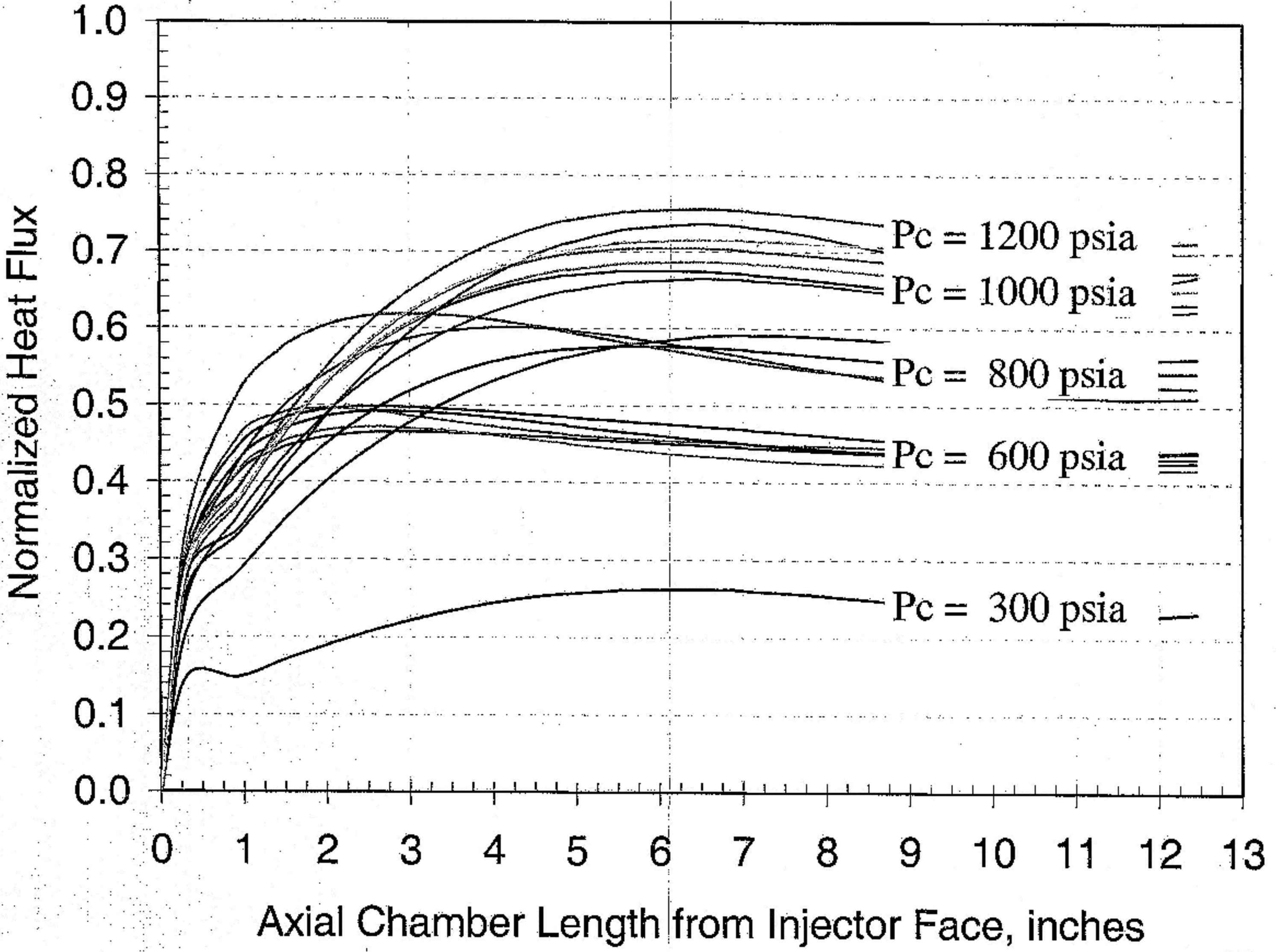
Heat Flux Data for Concentric Shear Coax



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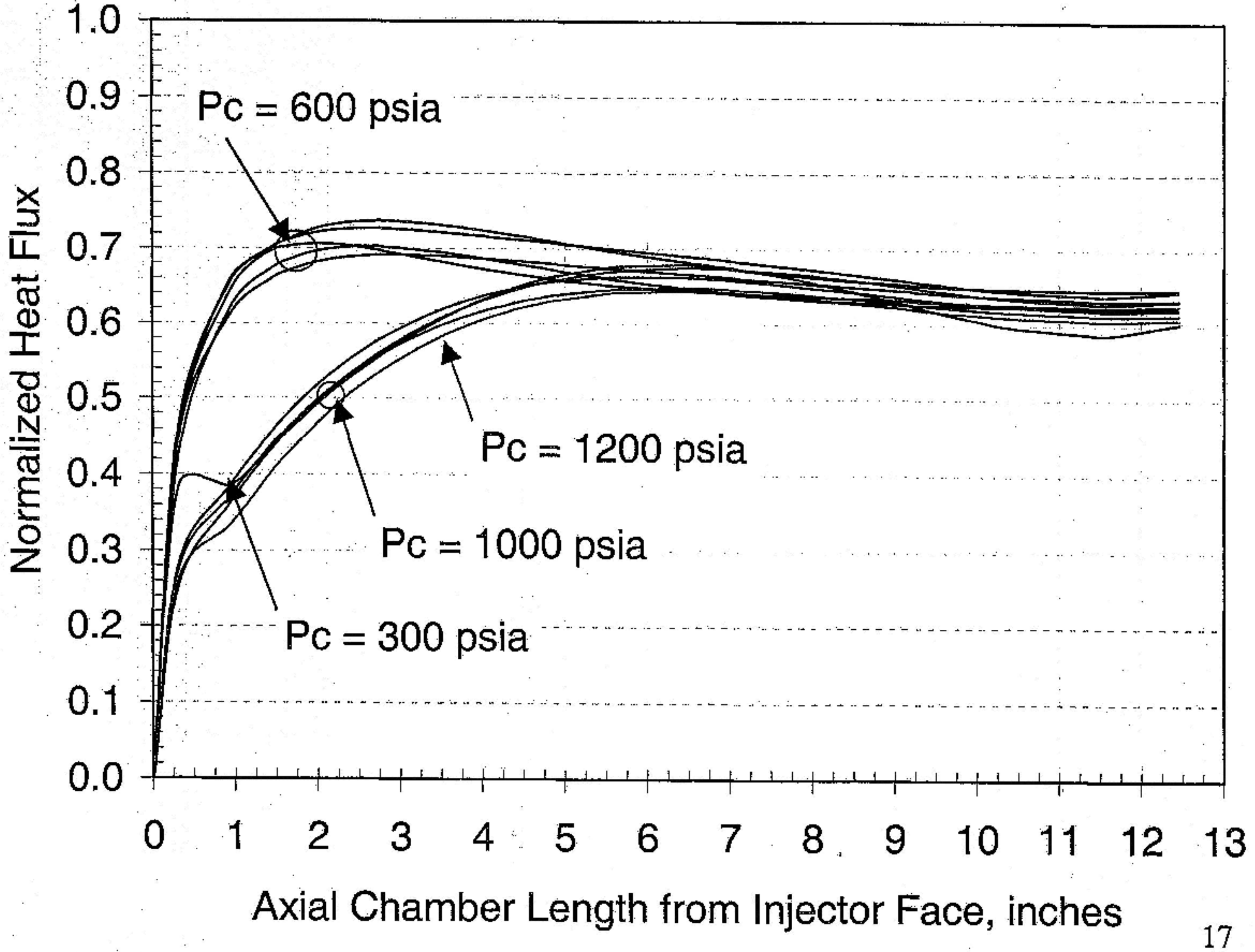
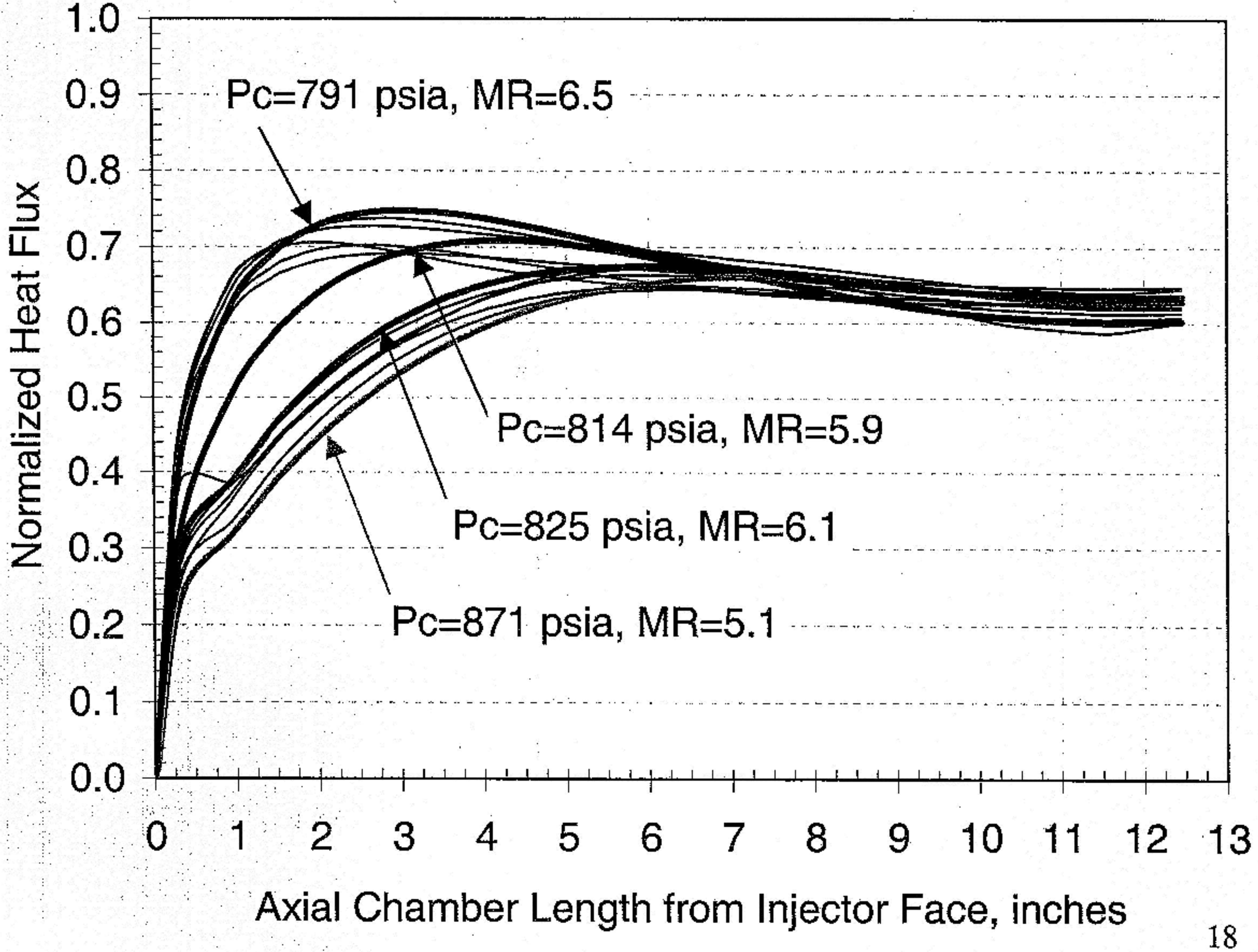
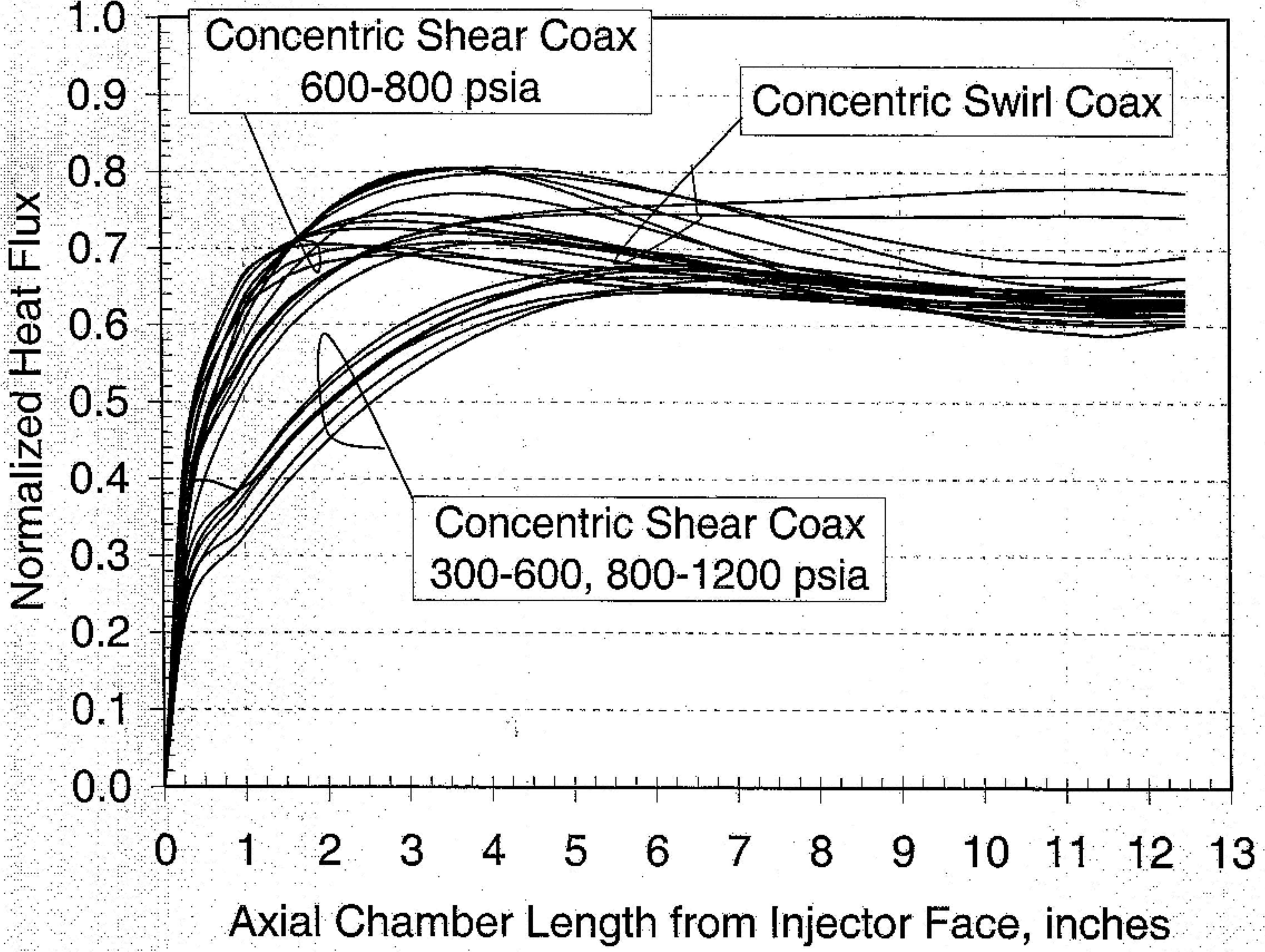
Concentric Shear Coax Heat Flux Collapses to Two Separate Groups with $Pc^{0.8}$



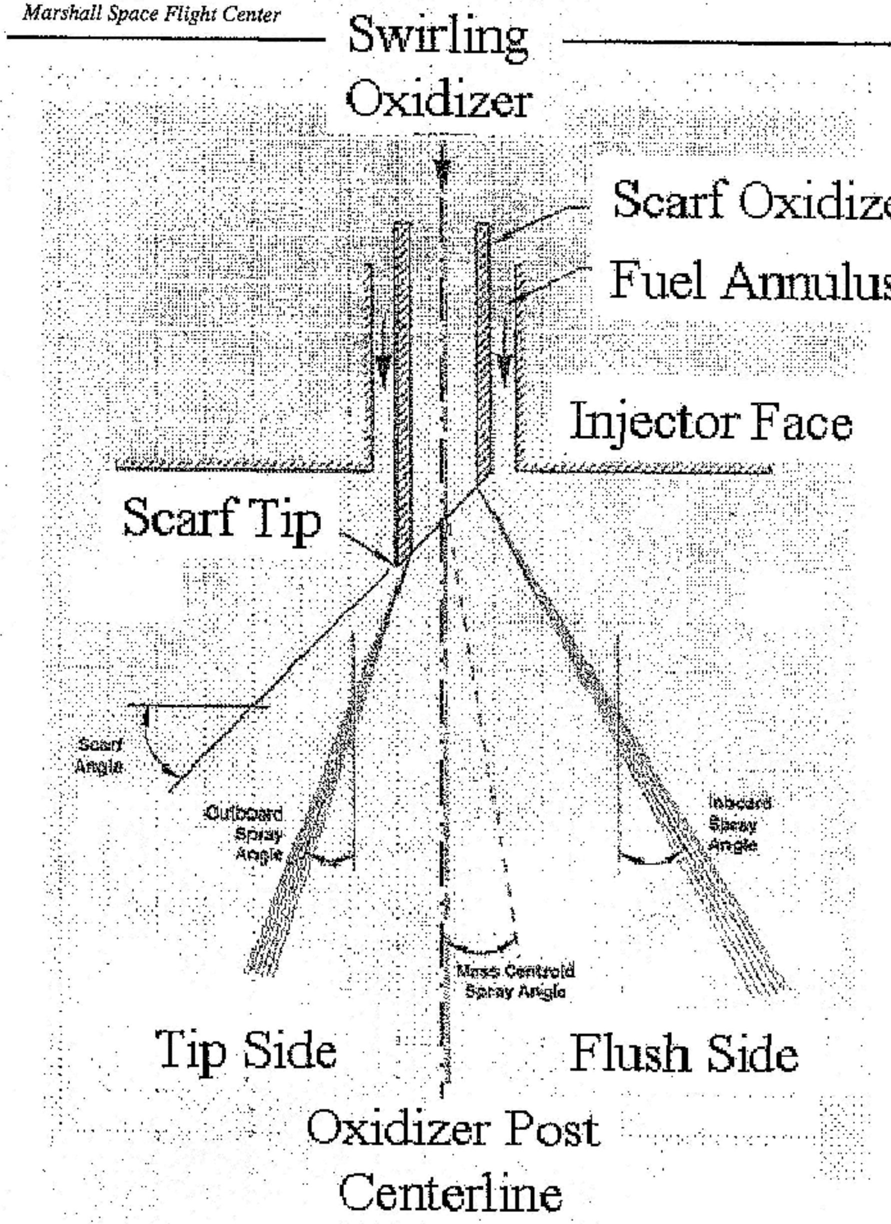
Differences Occur Around Critical Pressure of Oxygen (736 psia)

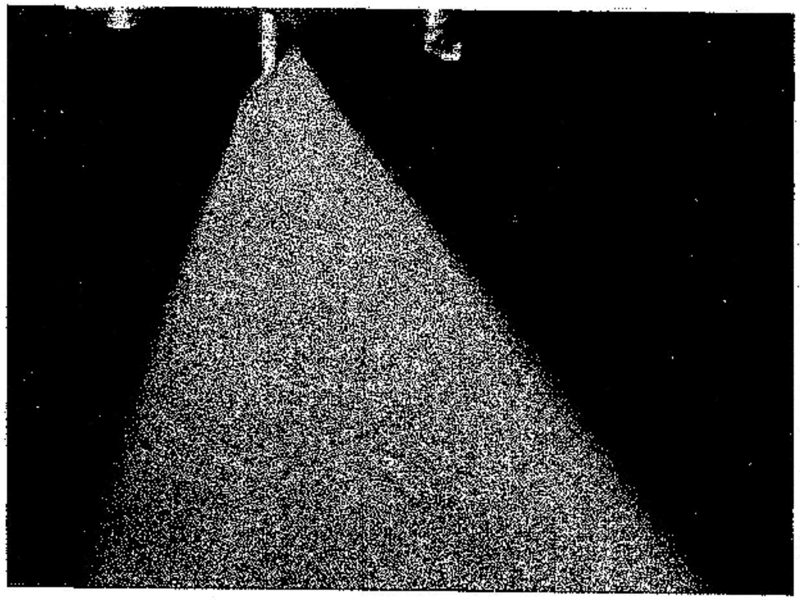


Concentric Swirl Coax Versus Concentric Shear Coax

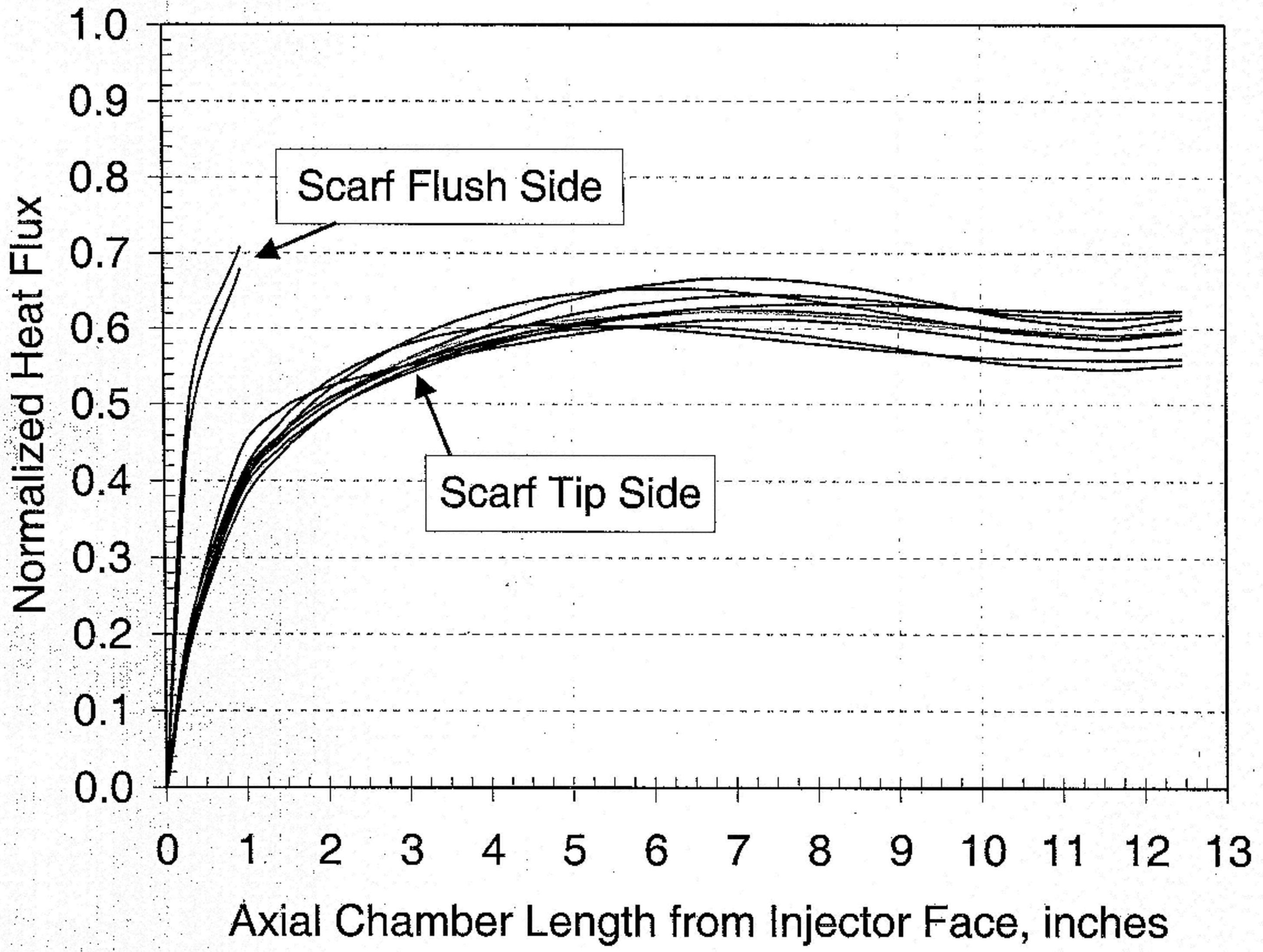


Scarf Swirl Coax Nomenclature

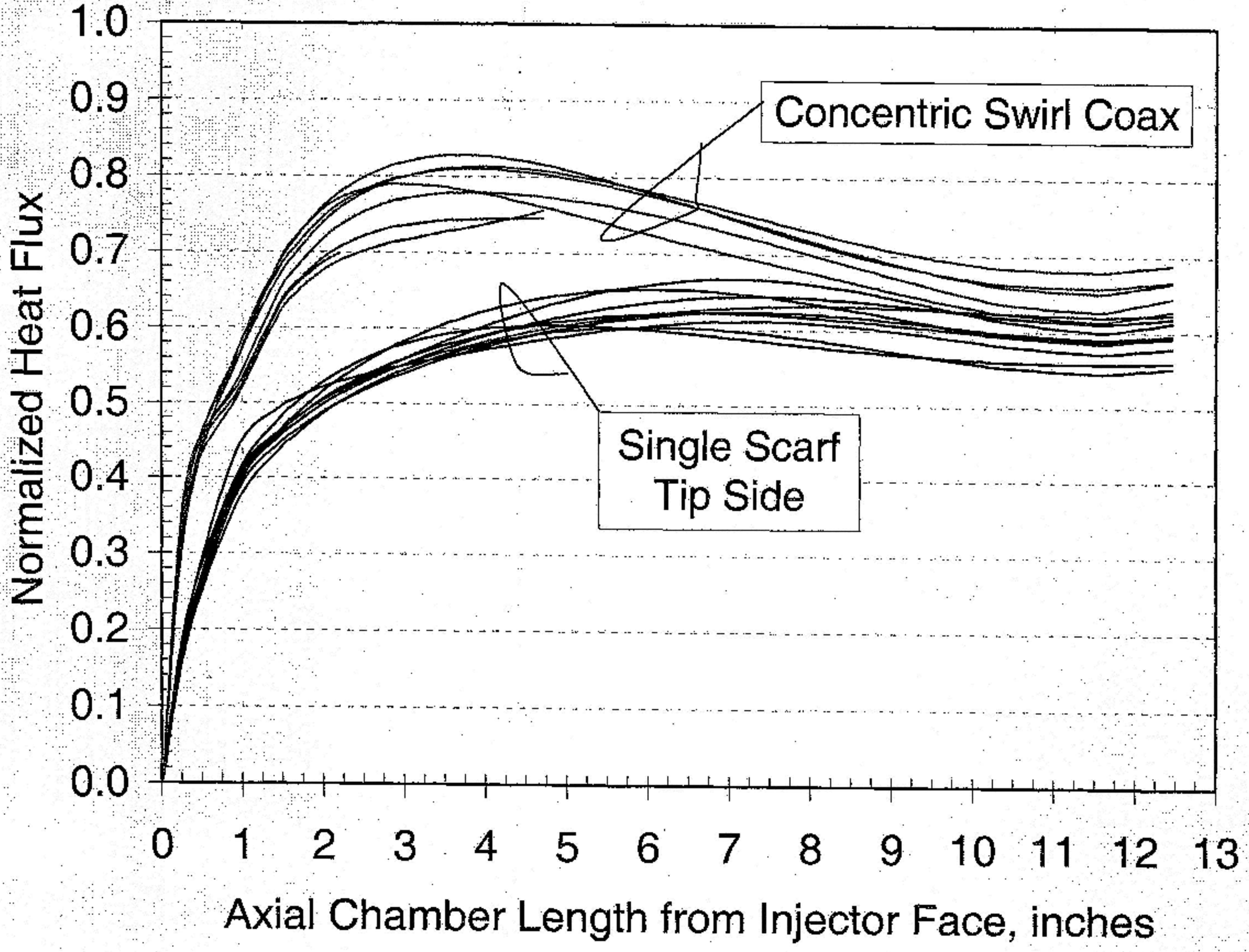




Single Element Scarf Swirl Has Large Circumferential Heat Flux Variation



"Tip" Side of Scarf Swirl Reduces Heat Flux From Concentric Swirl Coax



Summary and Conclusions

- Heat transfer analysis will play a critical role in definition of exploration mission reliability
- Must improve capability to analyze *local* effects of heat transfer and chemical reaction on combustor surfaces
- 1-element and 3-element injectors tested in small diameter chamber with highly resolved heat flux measurements
  - Shear coax injector designs – concentric and offset
  - Swirl coax injector designs – concentric and scarf
  - 109 tests conducted with 10 element designs
  - Heat flux generally collapses in the mixed out region of the chamber using $Pc^{0.8}$
  - Mixture ratio is a small effect between 5.0 and 6.5
  - 1-element shear coax heat flux profiles show sensitivity to the LOX critical pressure near the injector.
  - Heat flux from concentric elements is axisymmetric within +/- 3%
  - Element wall spacing and element scale are more powerful drivers on wall heat flux than offsetting the element.
- Wall element designs can be optimized !

Acknowledgements

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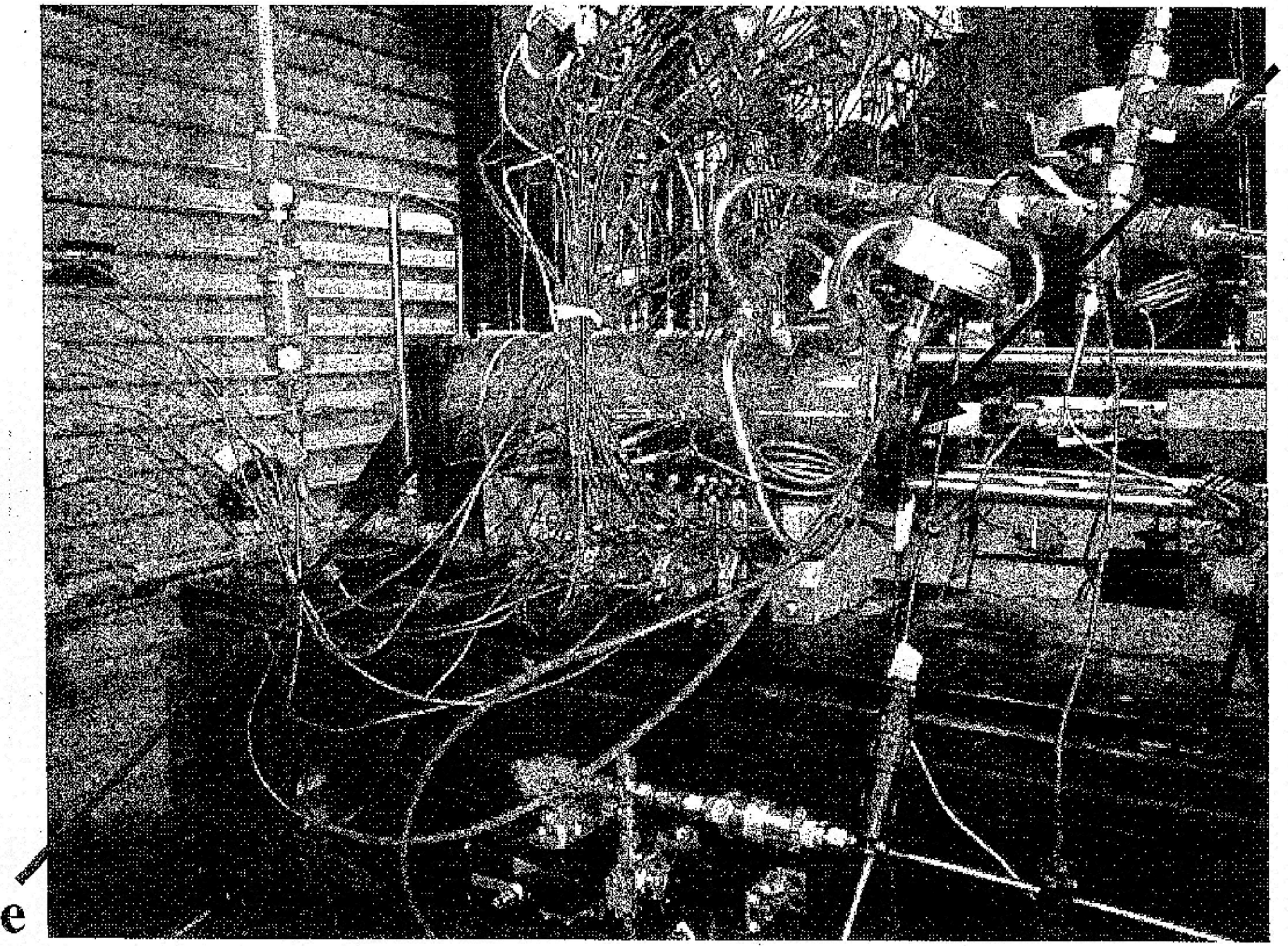
  - Meg Tuma, Pete Mazurkivich, Steve Kurtz, Rick Ryan, and Terri Tramel of the NASA MSFC Space Transportation Program and Projects Office
- Testing
  - Sibtosh Pal, Robert Santoro, and William Marshall of The Pennsylvania State University
  - Larry Jones of Medtherm

Extra Slides

Compatibility/Heat Transfer Test Rig at The Pennsylvania State University



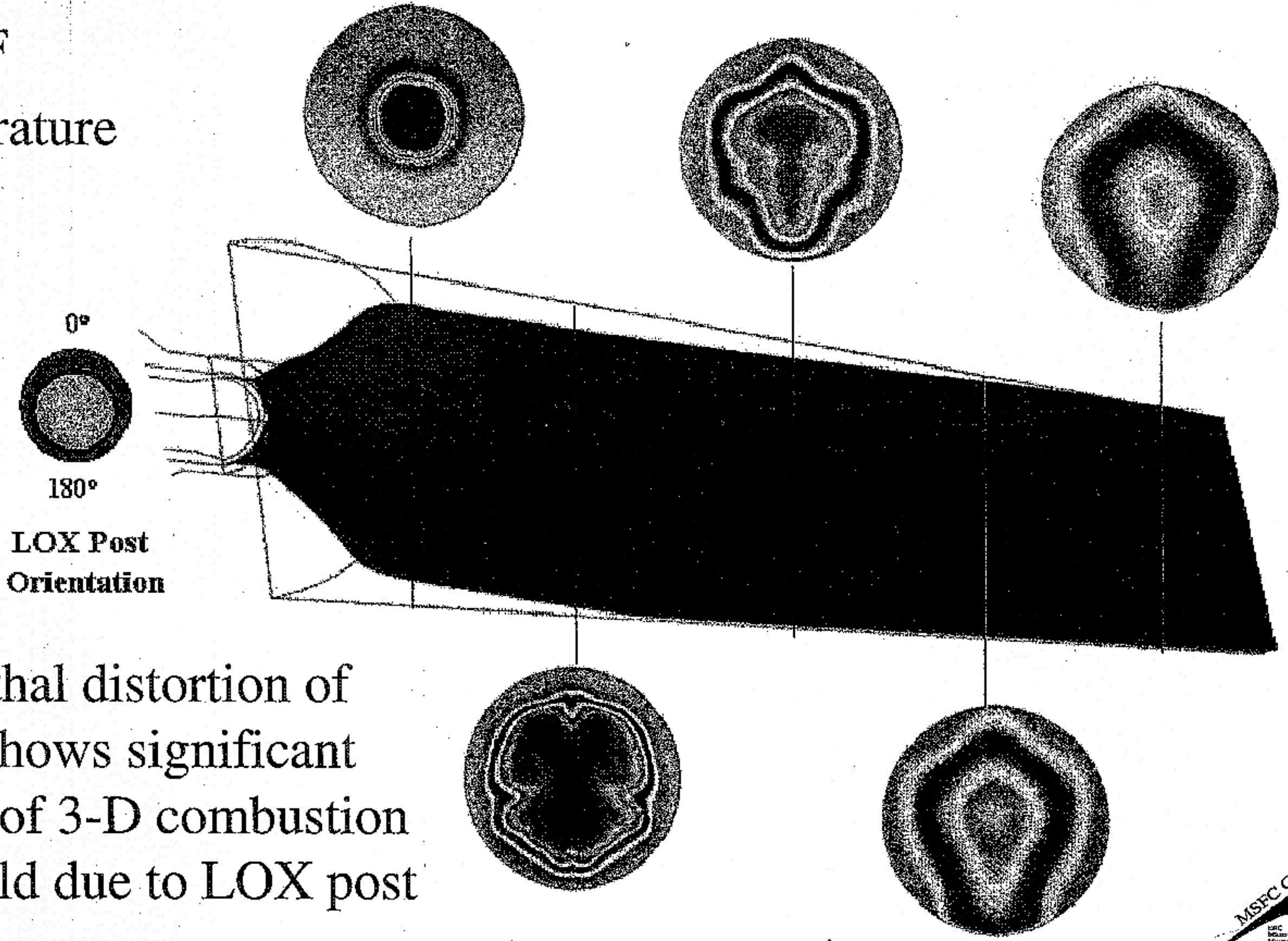
Combustion CFD Used for Pre-test Experimental Design & Post-Test Code Validation

- Role of CFD in CDIT
  - Pre-test -
    - Guide the experimental design
    - Evaluate scaling relationships
    - Examine injector flowfield features
  - Post-test -
    - Perform code validation
    - Evaluate experimental data quality
- CFD Codes
  - FDNS (Finite Difference Navier Stokes)
    - Used on all calculations to date
    - Benefits - real fluids model, chemistry, previous use for reacting flows
    - Disadvantages - limited to structured grids, inefficient in parallel mode
  - Loci-STREAM
    - To be used pending release
    - Benefits - generalized grids, scales well, Loci-framework
    - Disadvantages - applicable release not available until Fall 2005

3-D Combustion CFD of Offset Shear Coax Single Element

- 5000 °F

Iso-temperature surface



- Azimuthal distortion of flame shows significant effects of 3-D combustion flowfield due to LOX post offset

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Heat Flux Data Reduction Methodology

Flat Plate → Cylinder

Steady State
Heat Conduction

$$\dot{q} = \frac{k\Delta T}{\Delta x}$$

Steady State
Heat Conduction → **Steady State Heat Conduction Including Capacitance**

$$\dot{q} = \frac{k(T_{i2}-T_{o2})}{R_i \ln(R_o/R_i)}$$

$$\dot{q} = \frac{k(T_{i2}-T_{o2})}{R_i \ln(R_o/R_i)} + \frac{\rho c_p \Delta T(R_o^2-R_i^2)\ln(R_o/(R_i+\Delta r))}{2R_i \Delta time \ln(R_o/R_i)}$$

where ΔT is:

$$\Delta T = \{(T_{i2}-T_{i1}) - (T_{o2}-T_{o1})\}\left[\frac{1}{4\ln(R_i/R_o)} - \frac{R_i^2}{2(R_i^2-R_o^2)}\right] + (T_{o2}-T_{o1})/2$$

subscripts:

i => inside diameter; o=> outside diameter;
1=> time #1; 2=> time #2

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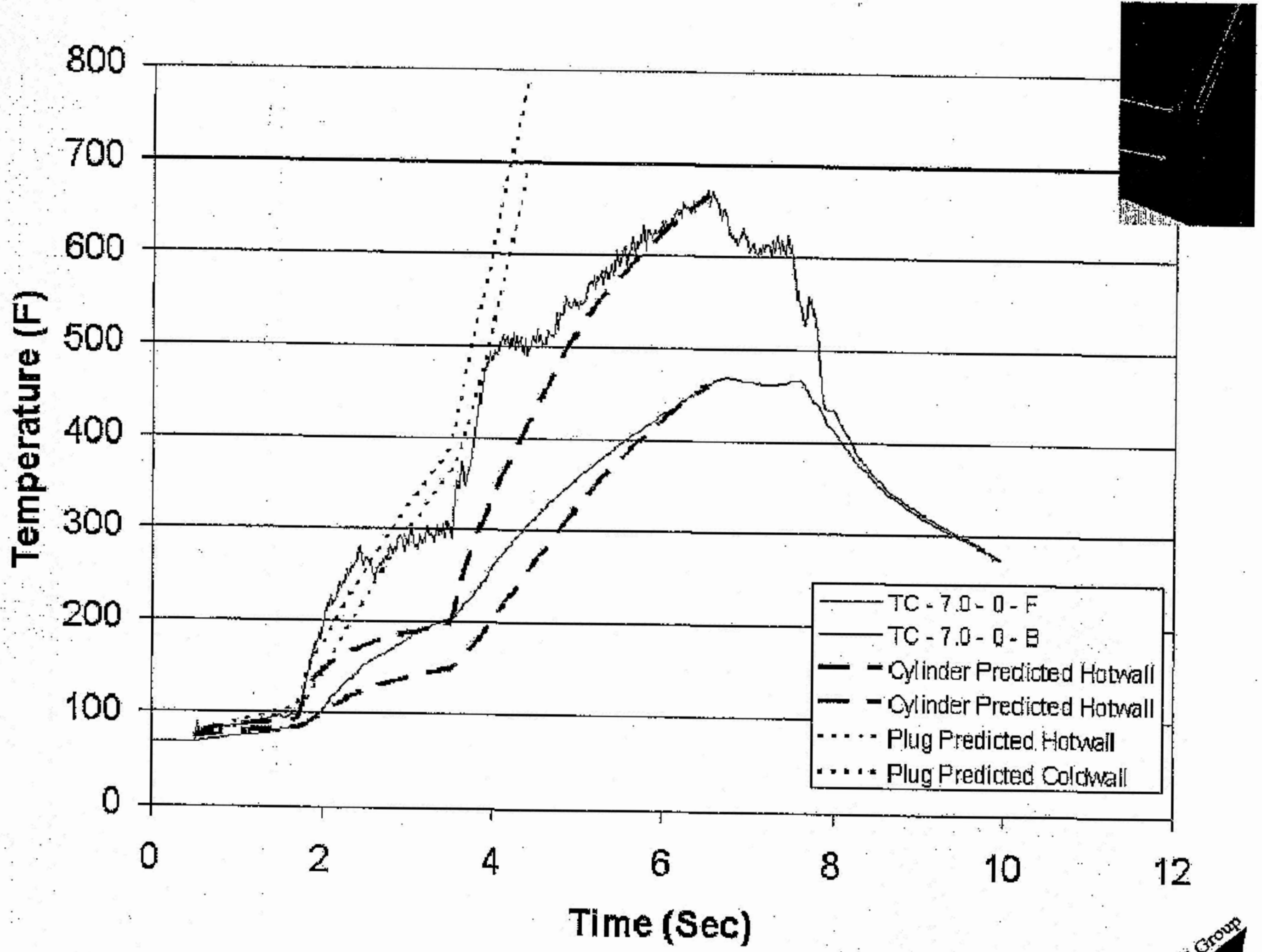
Analysis of Penn State Gas/Gas Data Shows Effects of Instrument Body Conduction

- During initial portion of test firing, instrument body is not conducting
- After some time, body becomes well attached to chamber wall
- Near end of test firing, body begins to conduct heat to chamber



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