Status of the Combustion Devices Injector Technology Program at the NASA MSFC

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Focus on Three Areas of Injector Development

- **<u>Heat Transfer</u>**
  - Improve 3-D heat transfer analysis capability
  - Reduce combustor local peak heat flux due to injector
- **<u>Ignition</u>**
  - Improve capability to analyze ignition transient
  - Improve injector ignitability
- **<u>Combustion Stability</u>**
  - Improve capability to analyze acoustic, non-linear effects
  - Improve stability margin

Emphasis on:

- Upper stage and in-space engine conditions and environments
- Liquid/gaseous propellants at injector
  - oxygen/hydrogen, oxygen/methane

Heat Transfer Task

Heat Transfer Capability is Essential to Exploration Mission

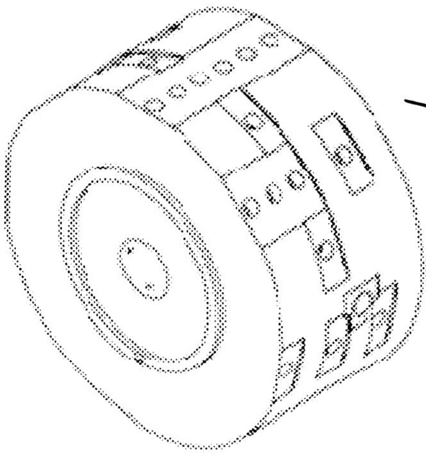
- In-space engines *must* be extremely reliable
  - Combustor compatibility and durability are critical factors in engine reliability
    - defined by *local* heat transfer, not bulk heat transfer
  - Current capability to analyze *local* heating effects from injector is insufficient and must be improved
- 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

Reduce Local Peak Combustor Heat Flux Due to Injector

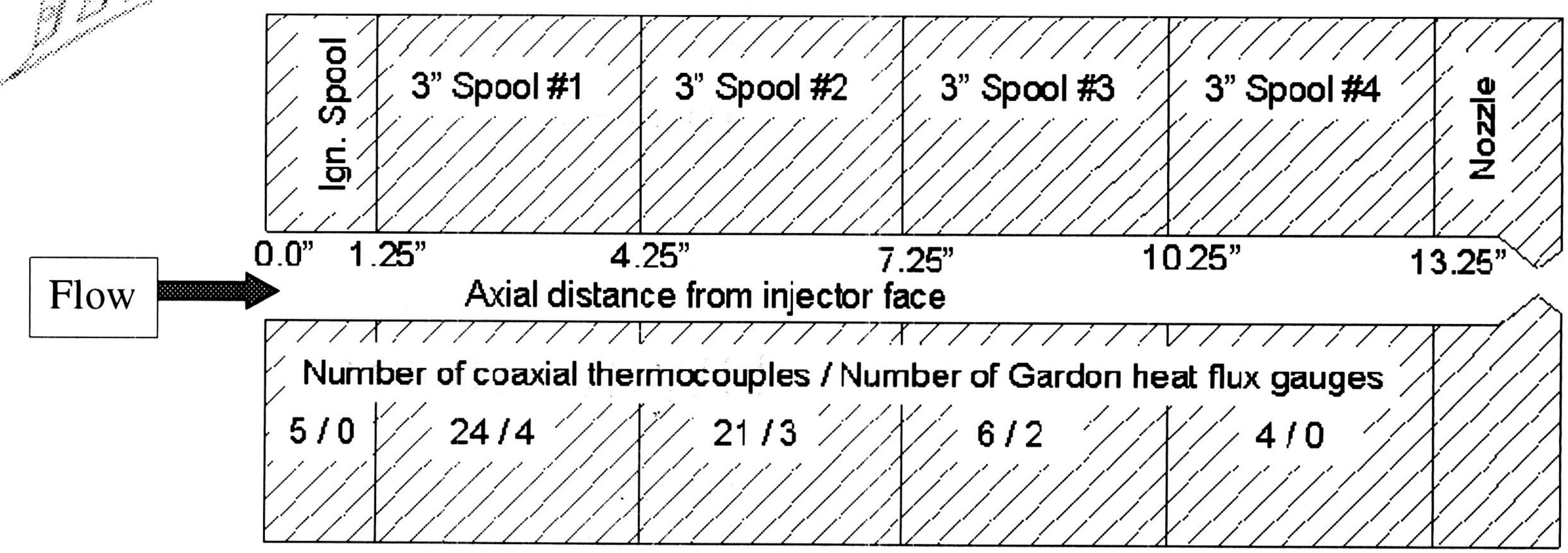
- Improve local heat transfer analysis capability
  - Current capability to analyze local injector heating effects is largely one-dimensional and empirical
  - Improve computational fluid dynamic (CFD) model capability
    - Add features for three-dimensional flows, real fluids, and faster turnaround 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

Compatibility/Heat Transfer Combustion Chamber

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



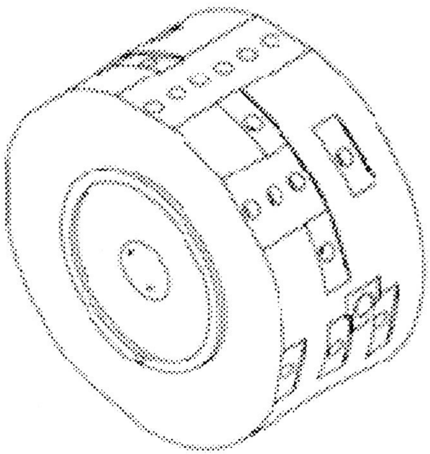
Individual Chamber Spool



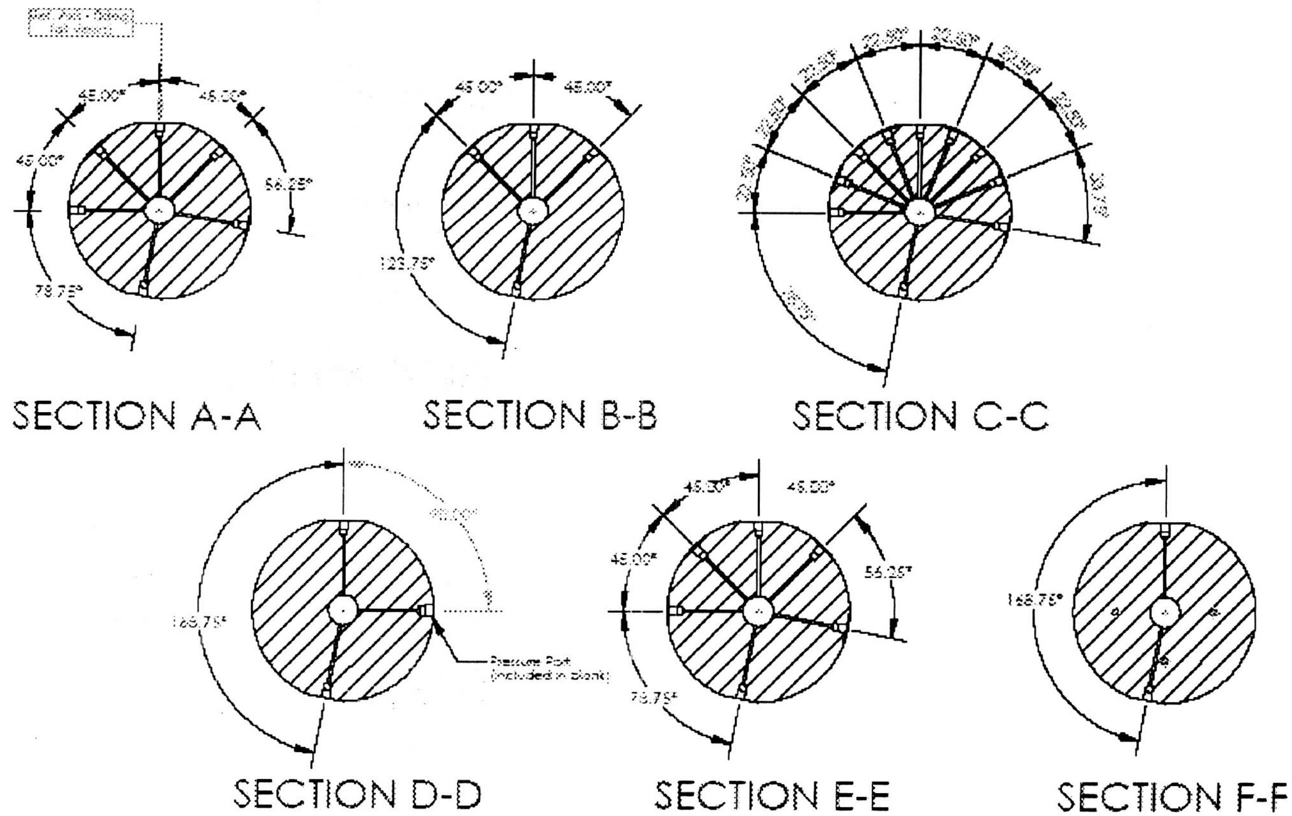
Layout of Chamber Spools with Instrumentation

Examples of Coaxial Thermocouple Layouts at Different Axial Locations

- Up to 10 sections per spool



Individual Chamber Spool



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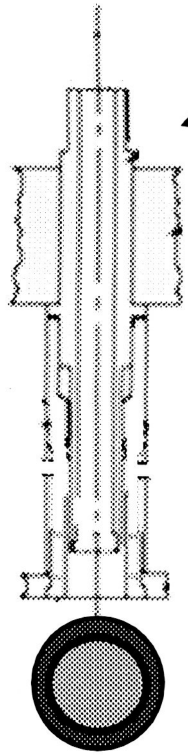
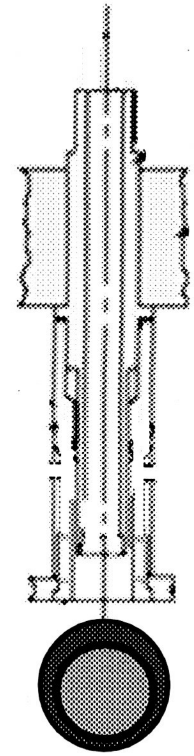
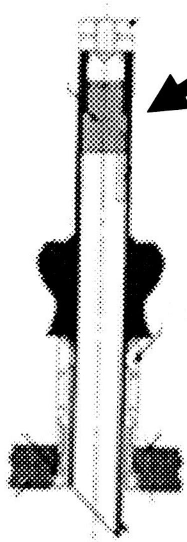
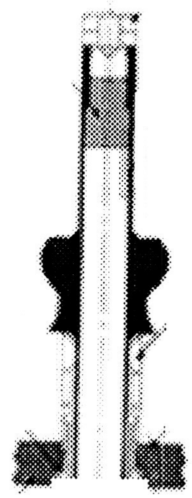
Conventional Injector Element Types to be Tested as Single Elements

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









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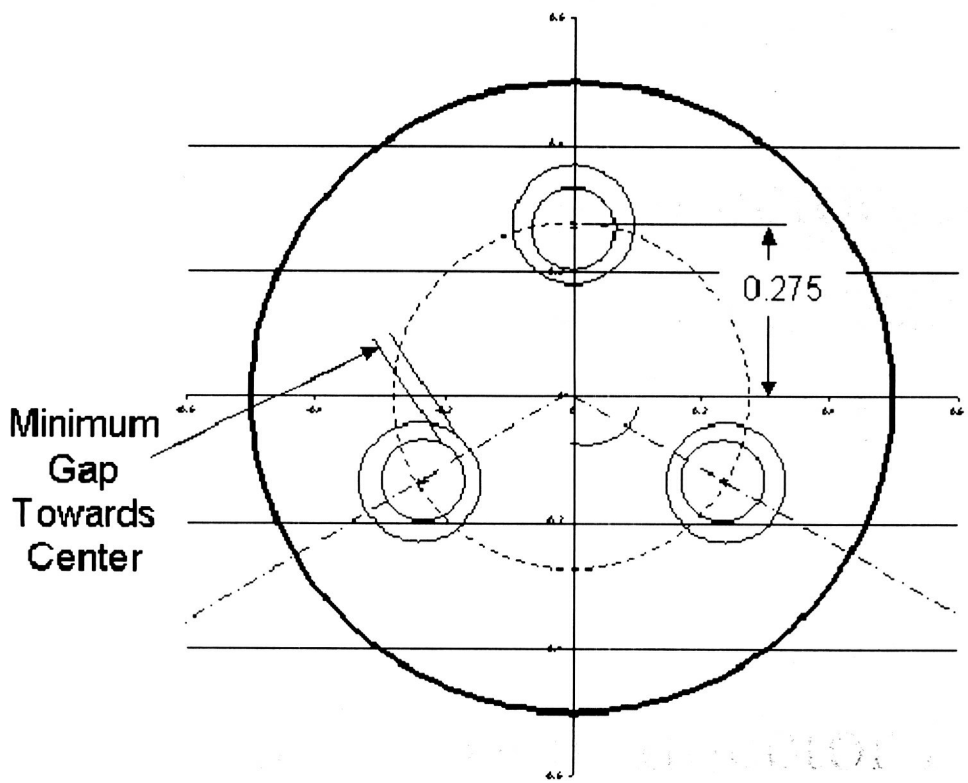
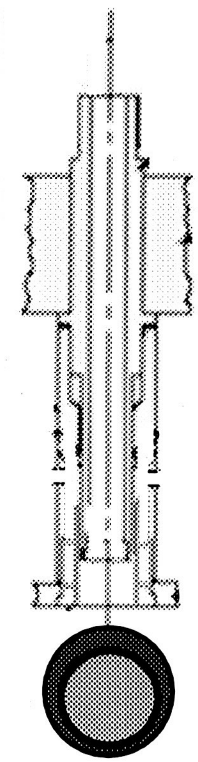
Conventional Injector Element Type to be Tested as Small Multi-element Injector





5. Off-Set Shear Coax
   (non-concentric fuel)

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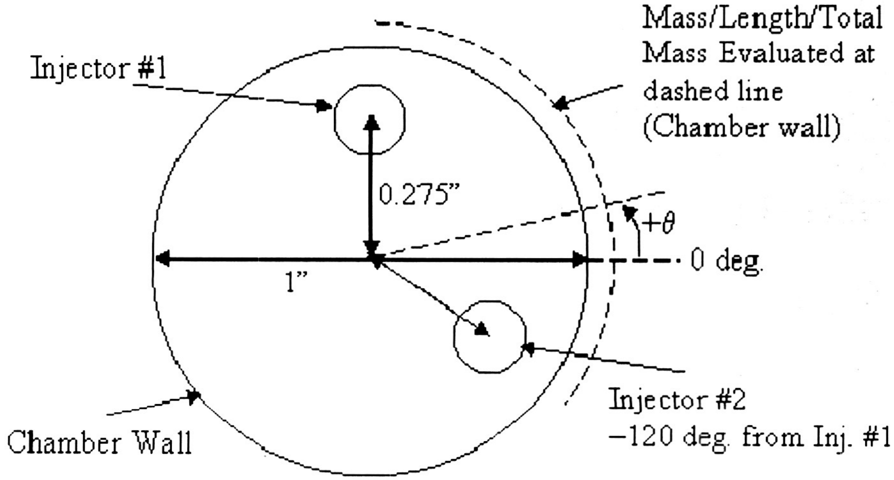
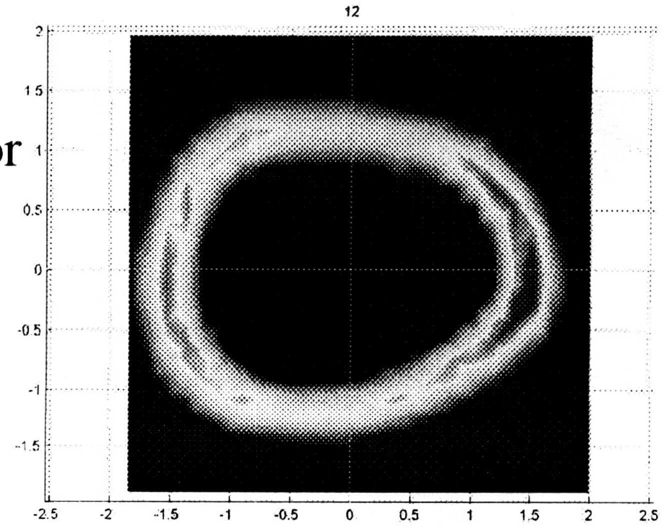
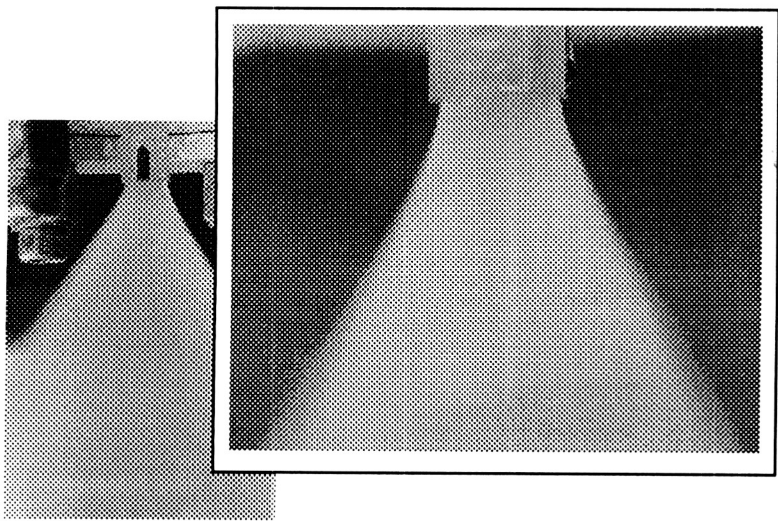
Advanced Compatibility Element Development



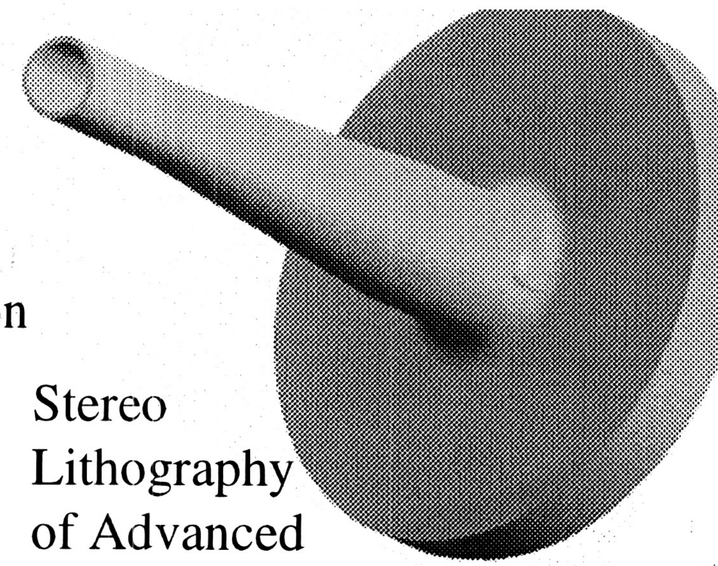
Spray Analysis Techniques

Patternator Testing





Spray Visualization



Stereo Lithography of Advanced Shapes

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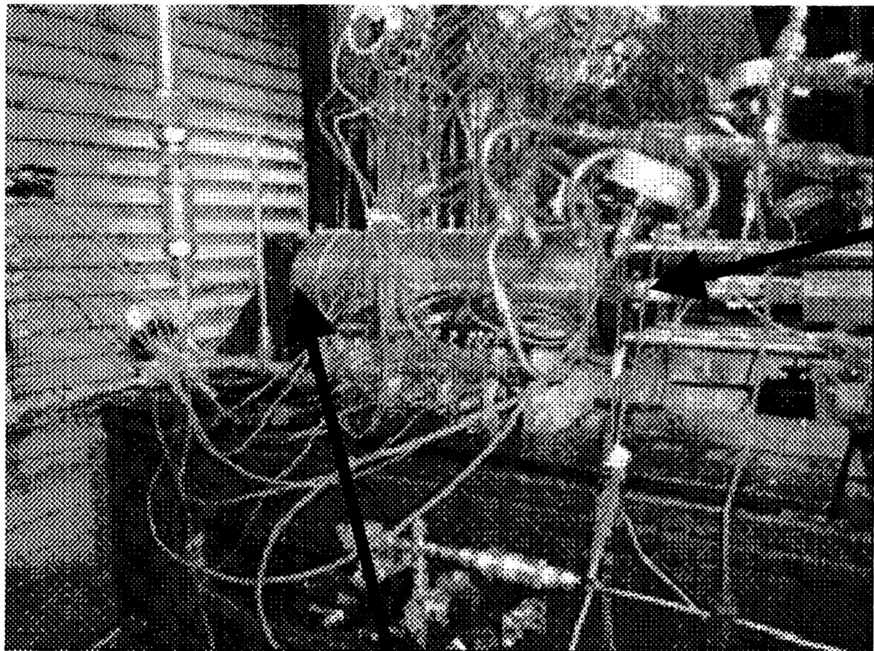
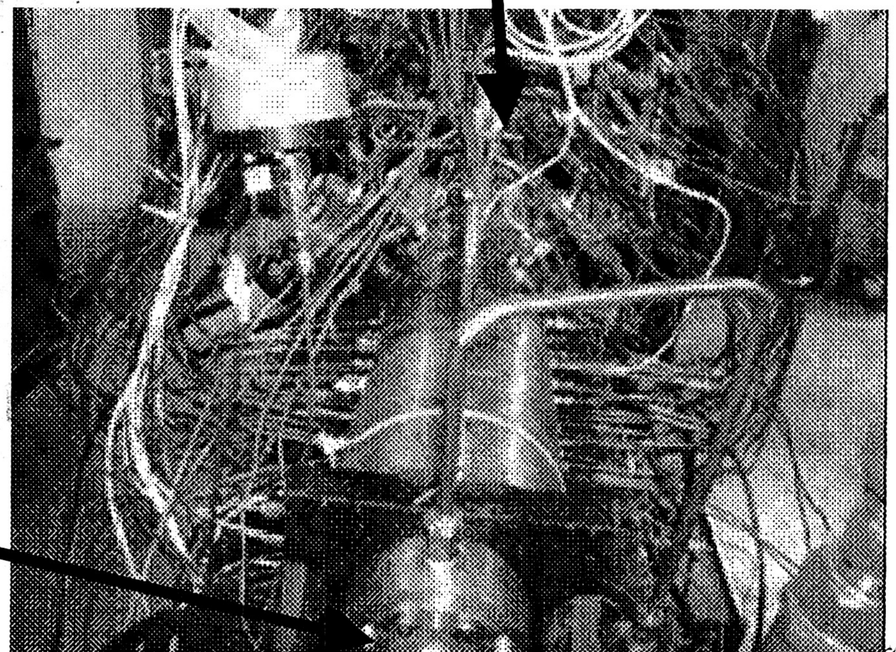
Compatibility/Heat Transfer Test Rig at The Pennsylvania State University





Injector

Nozzle

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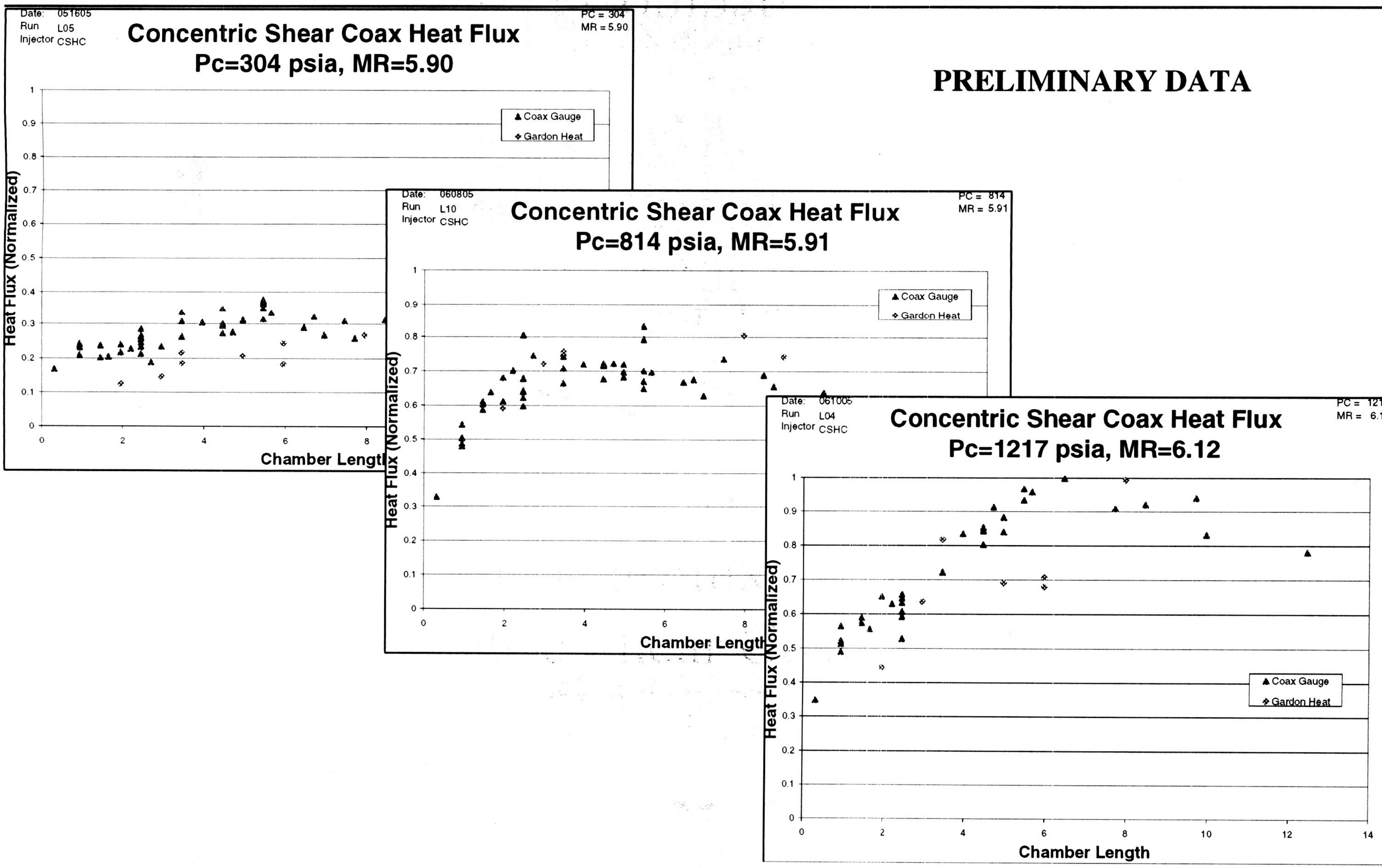
Initial Heat Flux Test Results
Concentric Shear Coaxial Element

PRELIMINARY DATA



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

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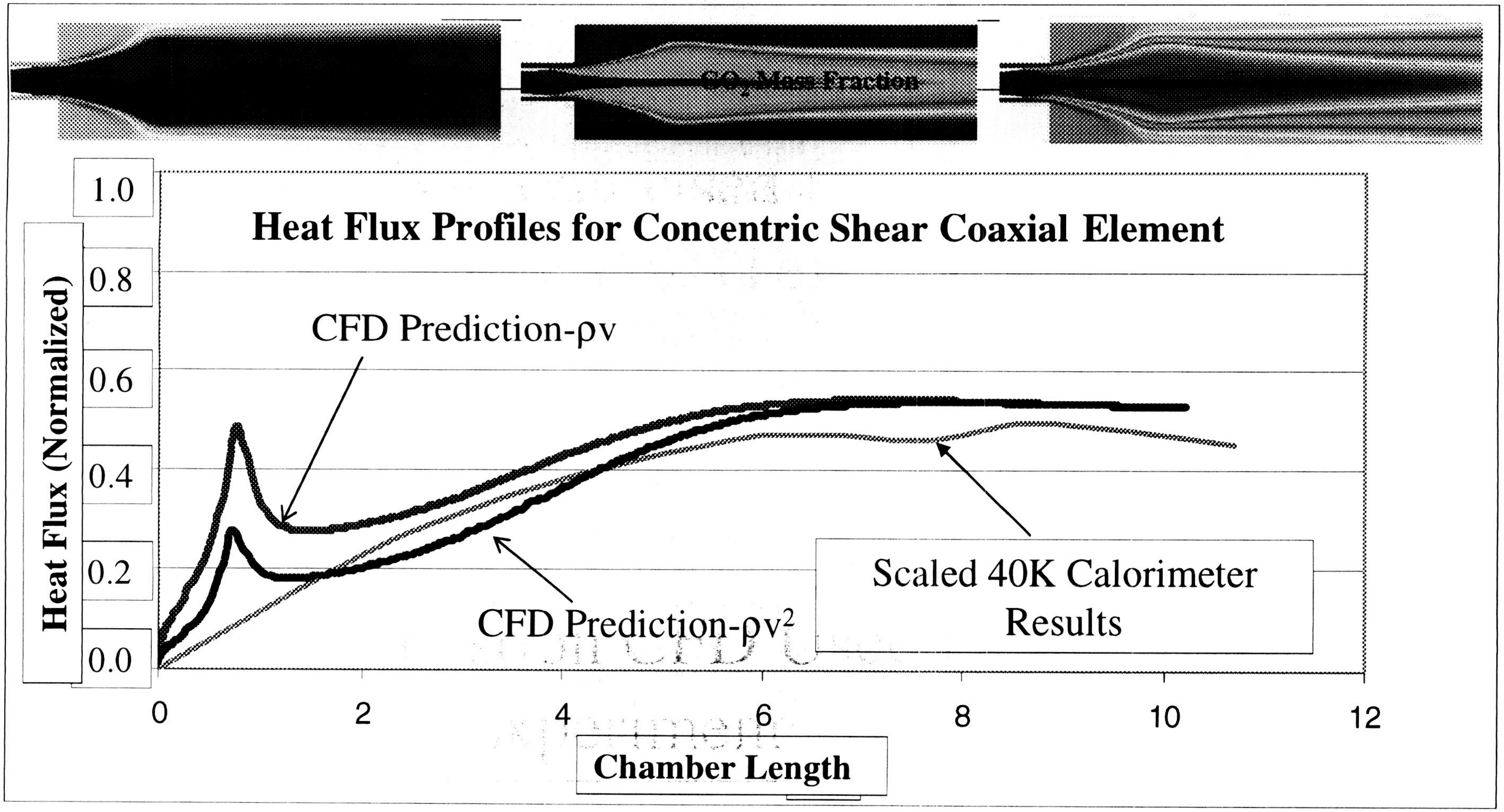
Combustion CFD Used for Pre-test Experimental Design



NOTE: Heat flux scaled by $(\rho u)_0^{0.8}$ and $(D_h)^{-0.2}$

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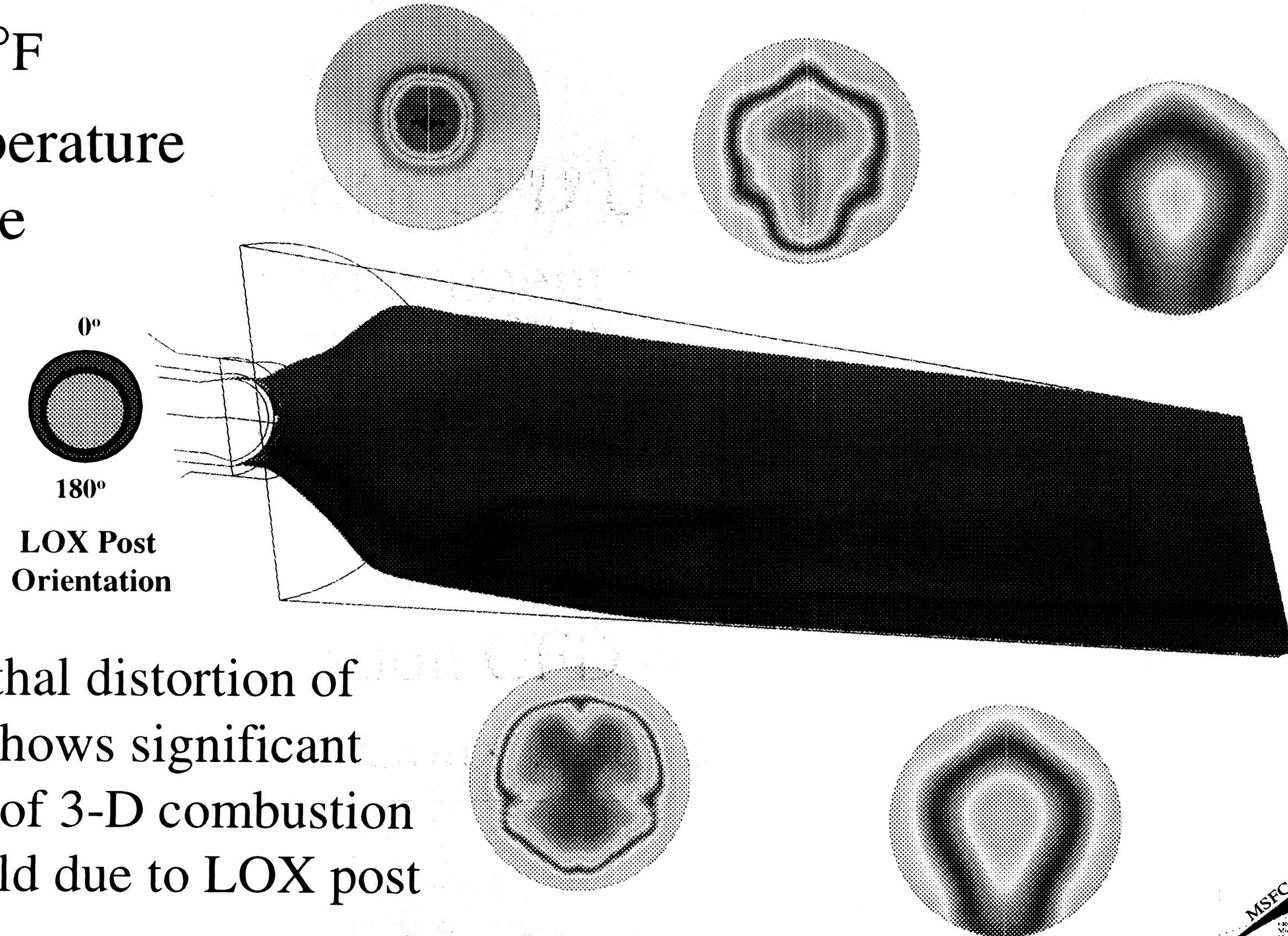
3-D Combustion CFD of Non-concentric Shear Coax Single Element

- 5000 °F

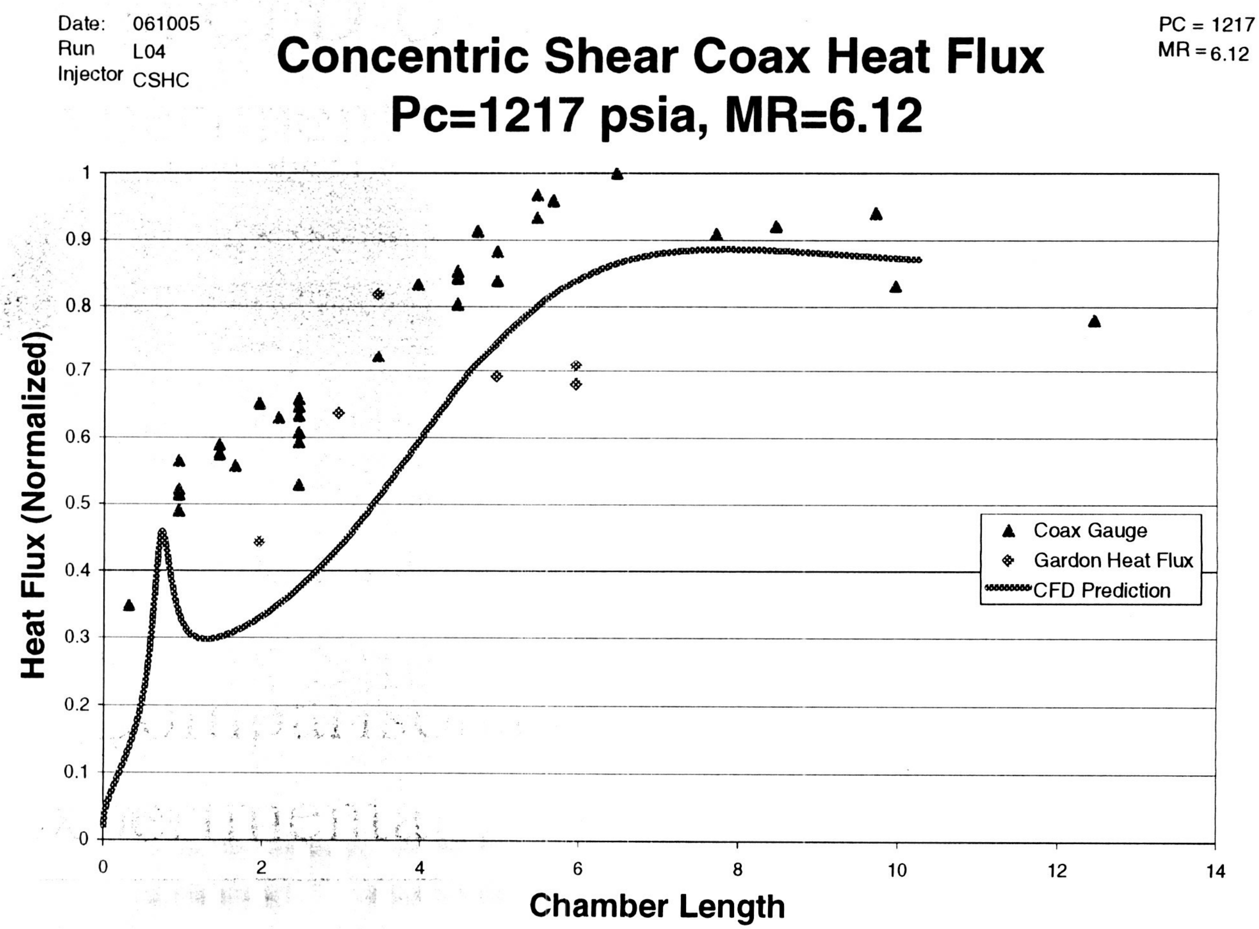
Iso-temperature surface



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

Preliminary Comparisons of Modeling to Experimental Results

- Calculations based on constant 800 °F wall temperature
- Mean level of recirculation zone not matched
- Rise rate matched OK
- Mean level in chamber matched OK



PRELIMINARY DATA

Ignition Task

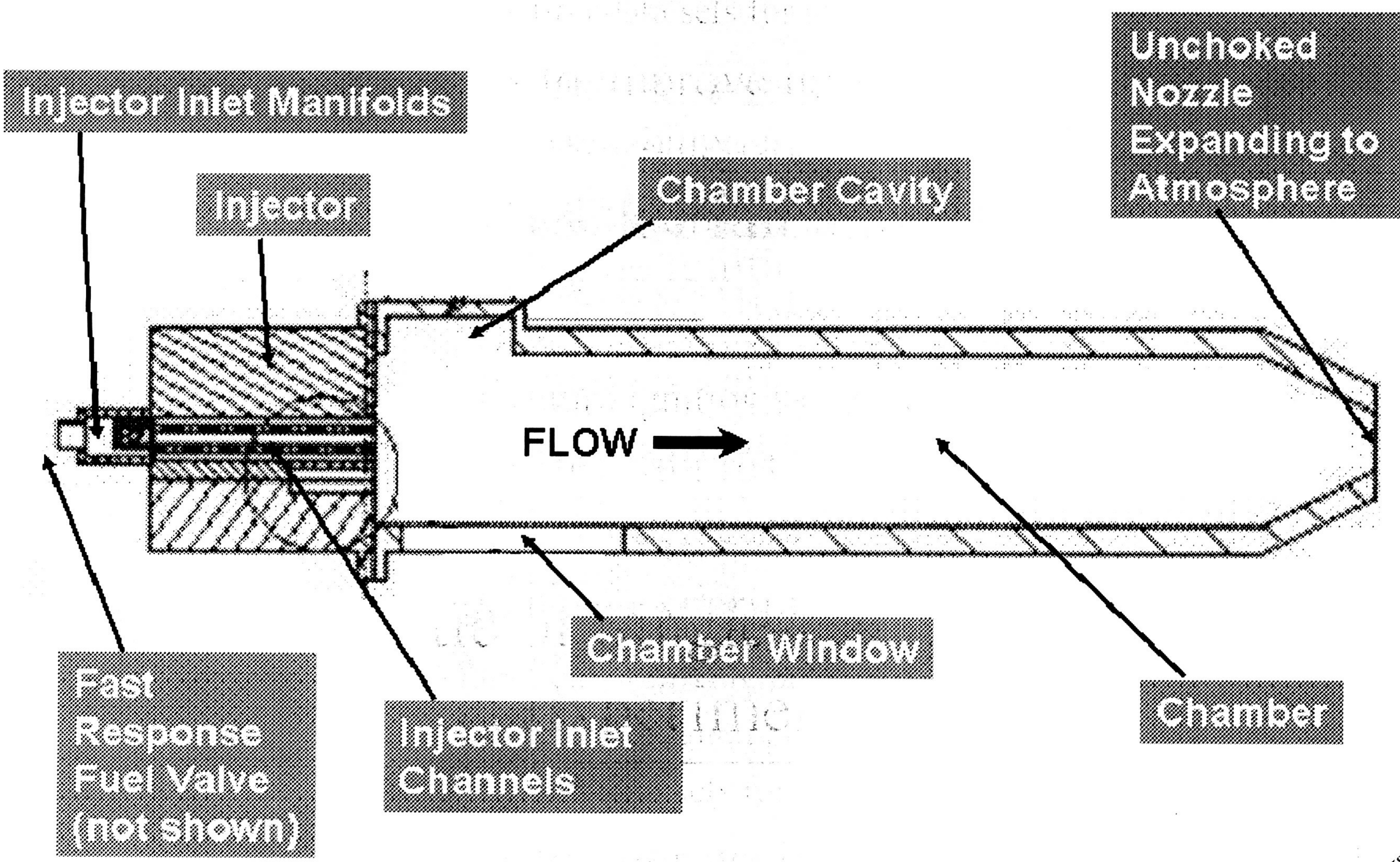
Robust Ignition is Critical for the Exploration Mission

- Upper stage & in-space engines will be required to restart
- In-space ignition of cryogenic engines will be a critical reliability issue
  - Ignition is typically highest ranked reliability issue
  - For this "must-have" reliability, Apollo used hypergolic engines (also non-cryogenic) for in-space missions
- Current cryogenic engine ignition systems have operational issues
  - Torch ignition systems require large purge or special care to preclude freezing residual water vapor
  - Ignition system development is highly empirically based (dependent on experimental input into design and trial and error testing)

Ignition Task Plan and Objectives

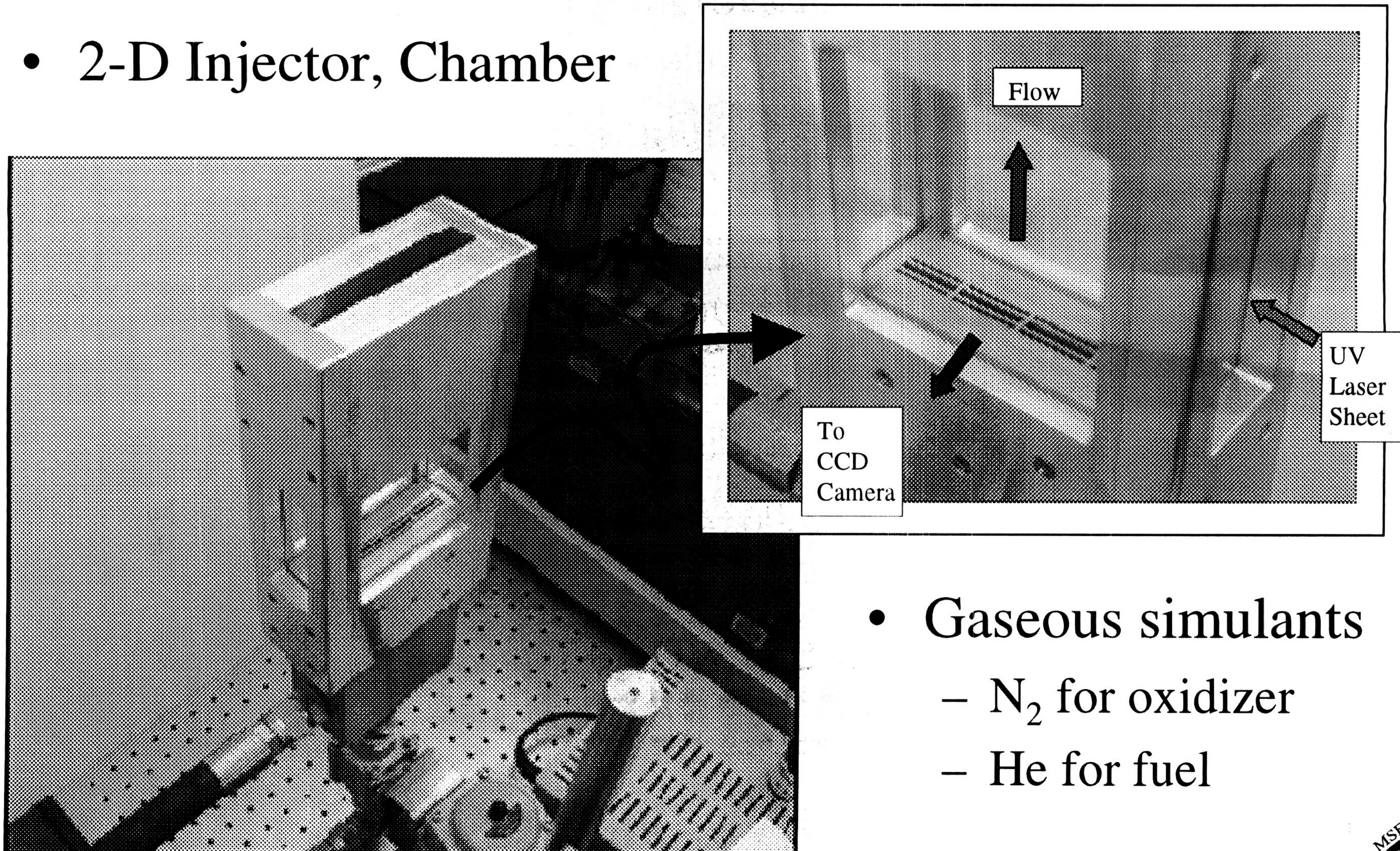
- Improve ignition analysis capability
  - Current capability to analyze *pre-ignition* and *ignition* portions of engine transient in real time is practically non-existent
  - Improve time-accurate computational fluid dynamic (CFD) model capability to analyze ignition
    - Pre-ignition propellant mixing phase (nonreacting, two-phase flow)
    - Ignition kernal generation and propagation (reacting flow)
    - Generate validation data sets for all conditions
- Develop concepts to improve ignition capability
  - Previous ignition systems developed by "test-fail-fix" methods
- Test ignition configurations in university bench-scale experiments
  - Use test data to develop and validate time-accurate combustion CFD models for future ignition system design

Schematic of Single-Phase Cold Flow Ignition Experiment Test Article



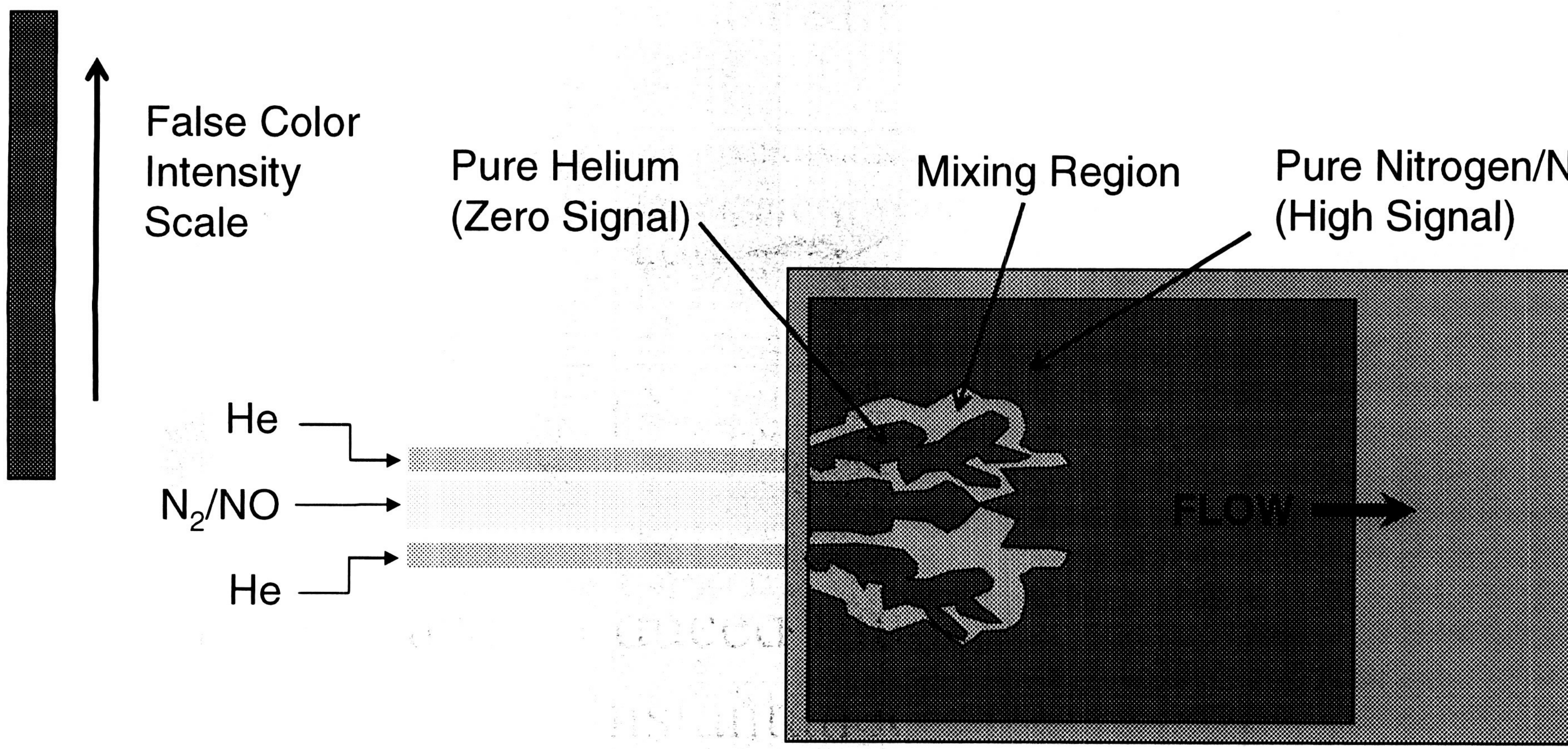
Cold-Flow Test Article

- 2-D Injector, Chamber

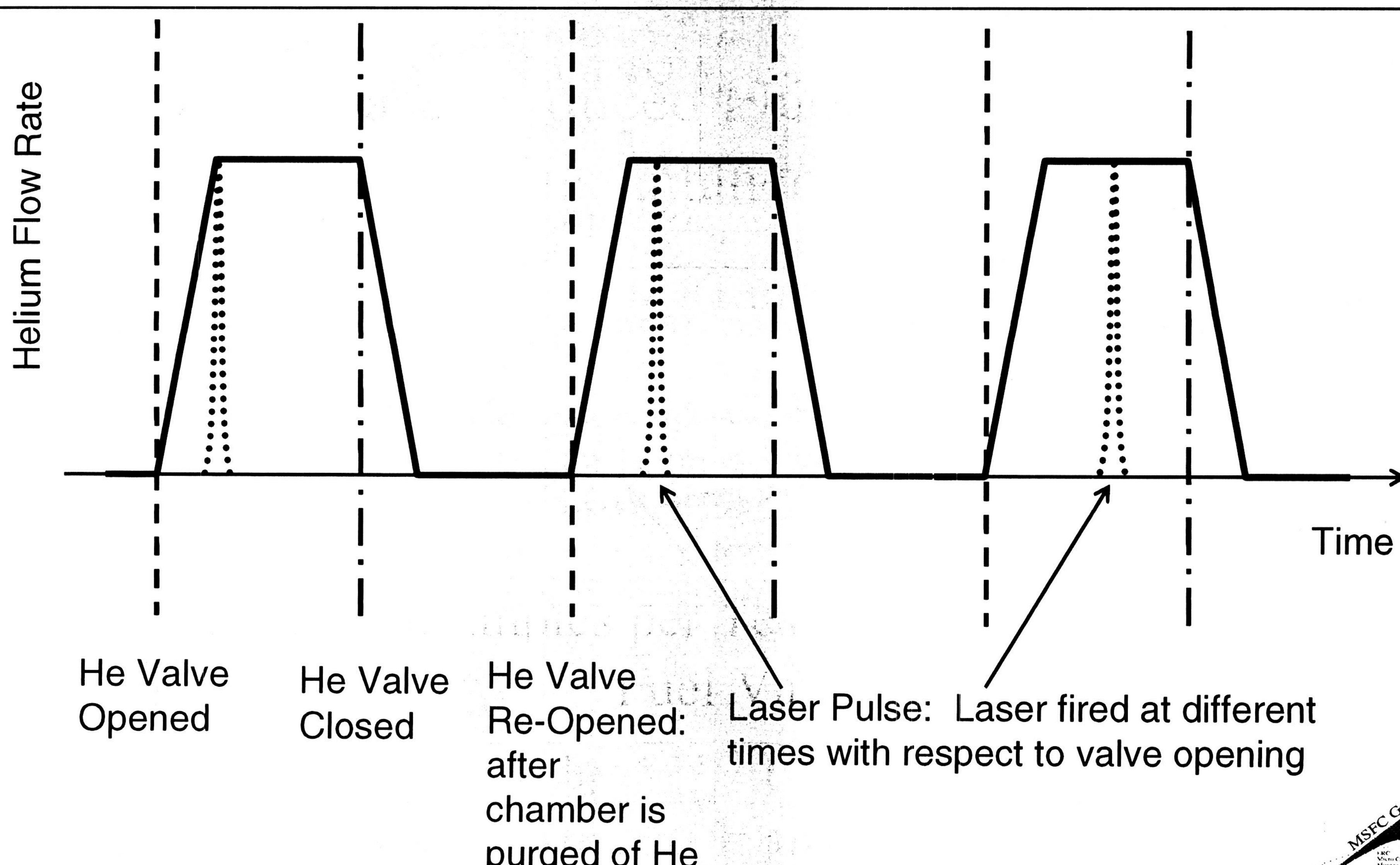


- Gaseous simulants
  - N_2 for oxidizer
  - He for fuel

Planar Laser-Induced Fluorescence (PLIF) Used to Measure Instantaneous Mixture Fraction

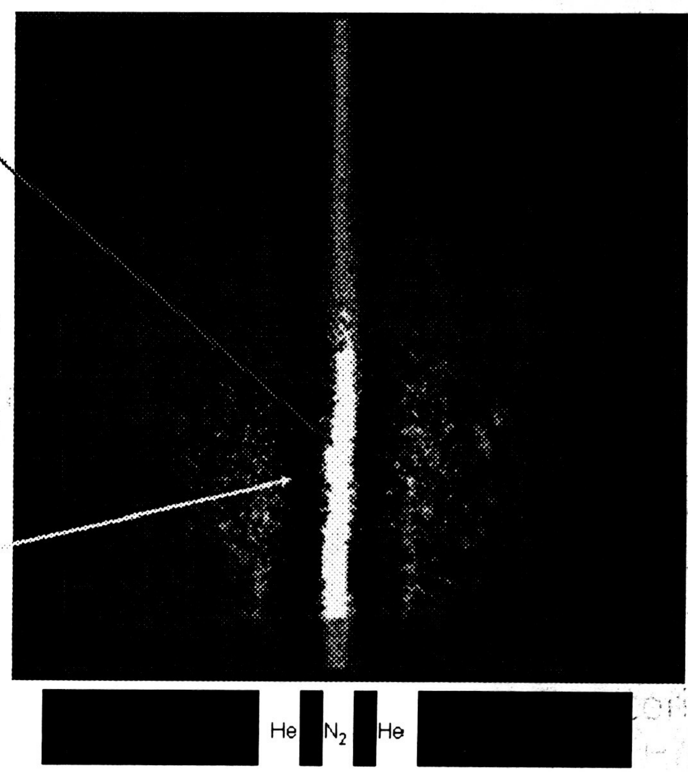


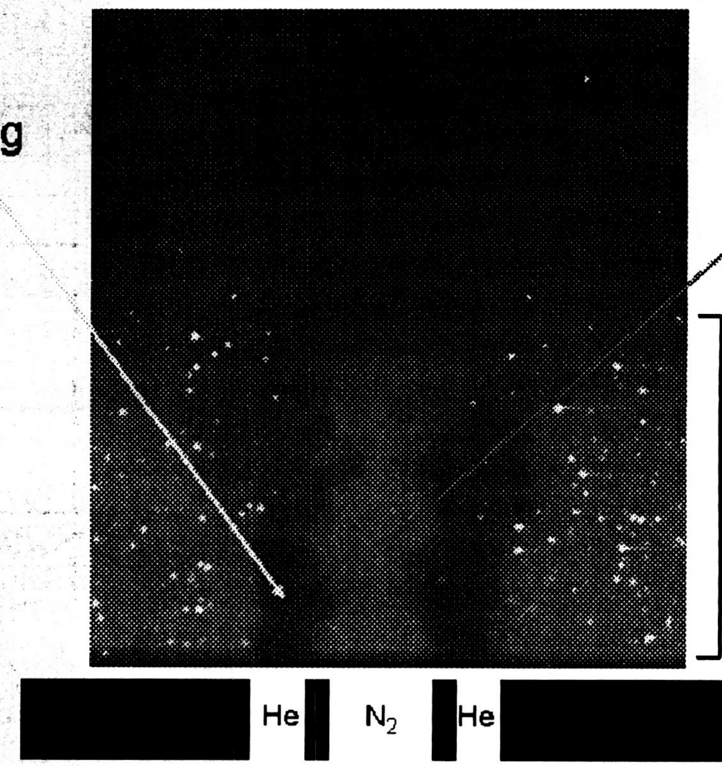
Multiple Samples per Test with Fast Response Fuel Valve



Preliminary Experimental Results

- Rayleigh Scattering
- Shadowgraph

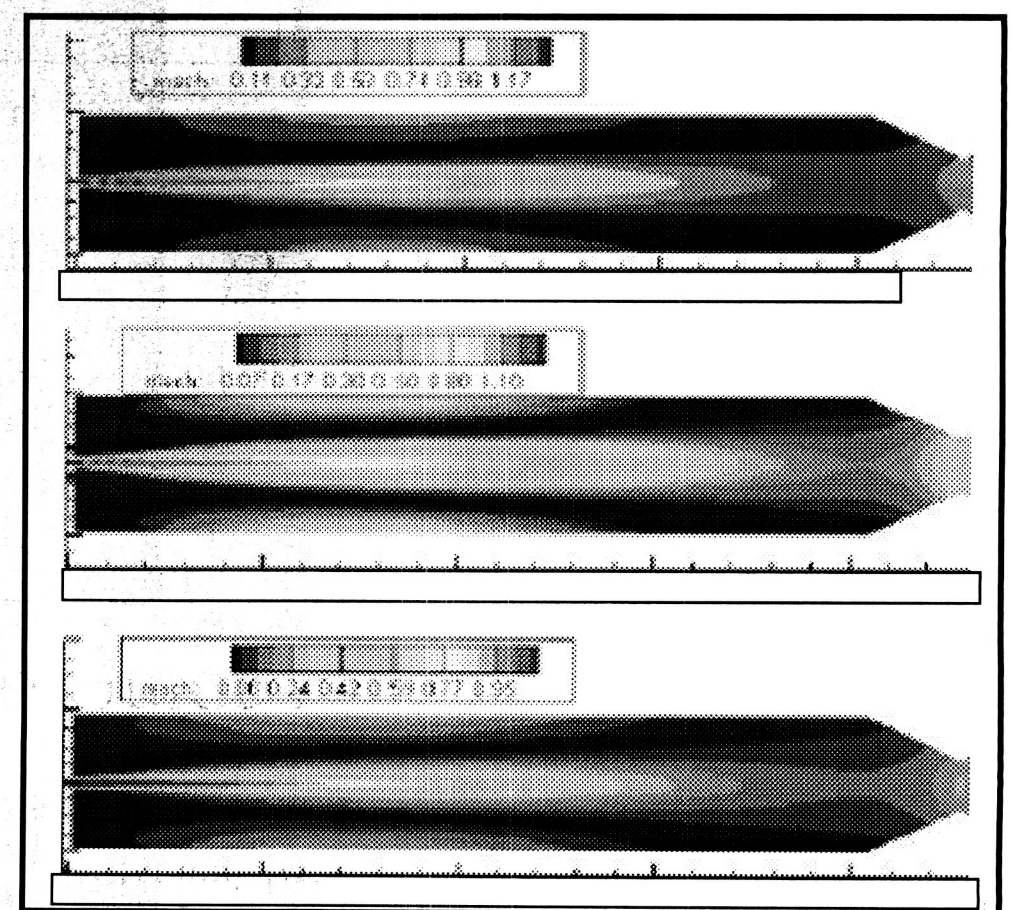




CFD Results to Guide Experiment Design

- CFD effort at Purdue using GEMS code
- Current results to guide experimental design
  - Chamber & simulant channel design
  - Flow conditions
  - Simulant valve timing
- Ultimate goal—validate CFD for the unsteady mixing process inherent in igniter design/operation

N_2 Jet only-Mach number contours as a function of N_2 channel length and chamber back pressure



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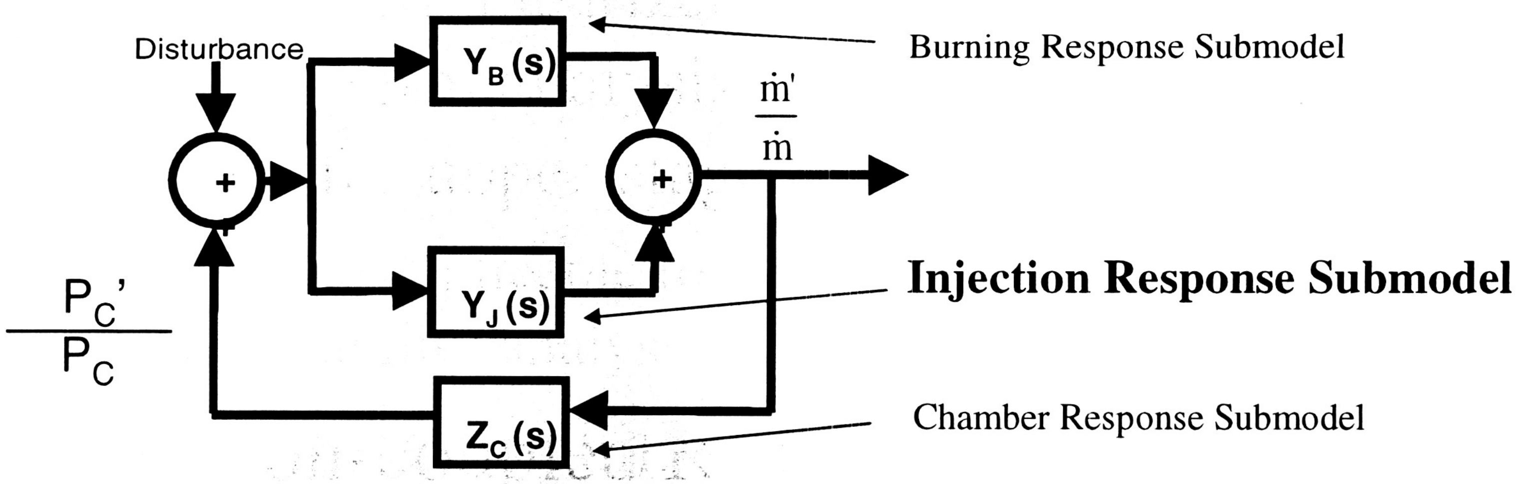
Combustion Stability Task

Improve Combustion Stability Margin

- Combustion instability has been a major design concern for *all* engines
- Develop improved linearized injector response model for near-term analysis of typical coaxial elements used for upper-stage engines
  - Submodel to be applicable to ROCCID type combustion stability analysis program
- Continue non-linear stability model development for mid-term improvements in stability analysis capability

Injection-coupled Response Model

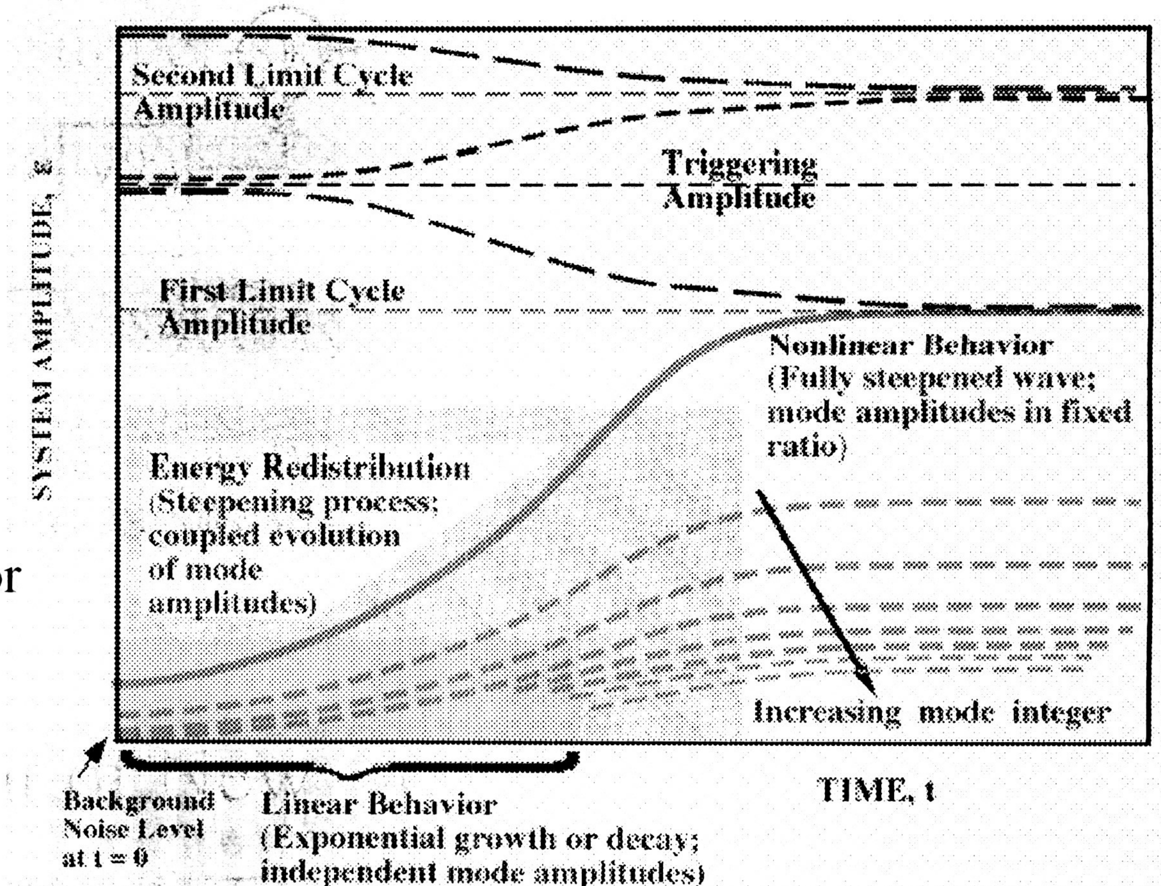
- Progressive improvement in current stability model prediction capability
  - Improve capability of injection response model calculation in ROCCID
  - Add acoustic features as are typical with coaxial injectors



- Focus on coaxial elements as typical for upper-stage and Earth Departure Stage engines

Development of New Non-linear Model

- Model development at the UTSI
- Based on non-linear asymptotic perturbation techniques
- Steepened shock-like waveforms in place of the usual acoustic modes
- Limiting amplitude behavior
- Interactions of waves with mean chamber properties
- Unsteady flow model includes rotational flow effects, heat transfer, and entropy wave generation



Summary and Conclusions

- CDIT is filling gaps in injector analysis and technology for the Exploration Mission
- Heat Transfer
  - Improve capability to analyze *local* effects of chemical reaction and flow on combustor surfaces
  - Optimize injector wall element designs
- Ignition
  - Improve capability to analyze *transient* events that define ignition processes
  - Optimize ignition system/combustor geometries
- Combustion Stability
  - Improve capability to analyze acoustic effects of coaxial elements
  - Improve non-linear predictive capability with new model

Future Plans

- CDIT is looking to secure FY 2006 funds
- Heat Transfer
  - Continue single element hot-fire
    - Elements from industry (RFI)
    - Conduct LOX/CH4 testing
  - Initiate larger multi-element hot-fire test program
    - 7-19 elements
    - LOX/H2, LOX/CH4
  - Transition from FDNS to Loci-STREAM
- Ignition
  - Conduct 2-phase non-reacting mixing experiments (FY06-07)
  - Conduct reacting flow experiments (FY07-08)
- Stability
  - Continue model development in progress

Acknowledgements

- Meg Tuma, Pete Mazurkivich, Rick Ryan, and Terri Tramel of the NASA MSFC Space Transportation Program and Projects Office
- Sibtosh Pal, Robert Santoro, and William Marshall of The Pennsylvania State University
- Charles Merkle, Robert Lucht, Jim Sisco, Scott Meyer, Waruna Kulatilaka, and Charles Tseng of Purdue University
- Gary Flandro and Joseph Majdalani of the University of Tennessee Space Institute
- Larry Jones of Medtherm

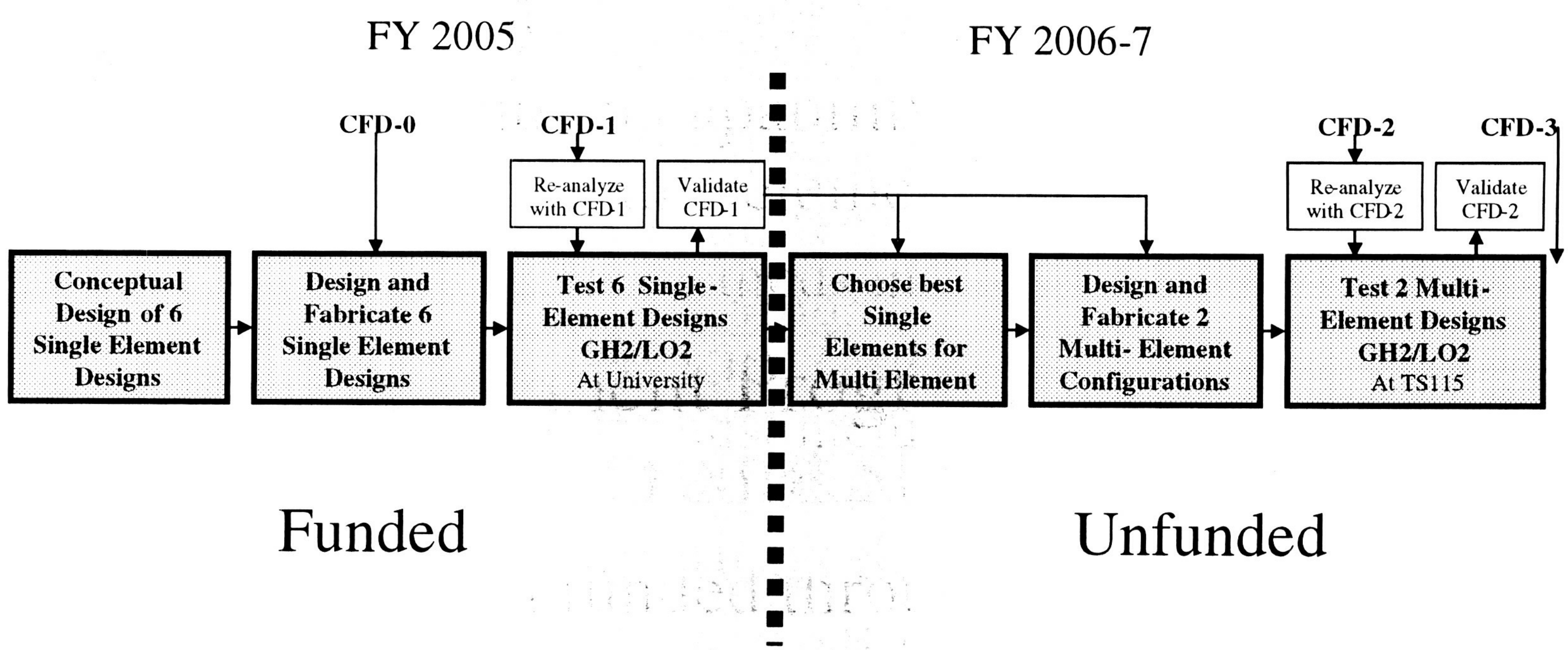
Extra Slides

Tasks Provide *Two* Deliverables

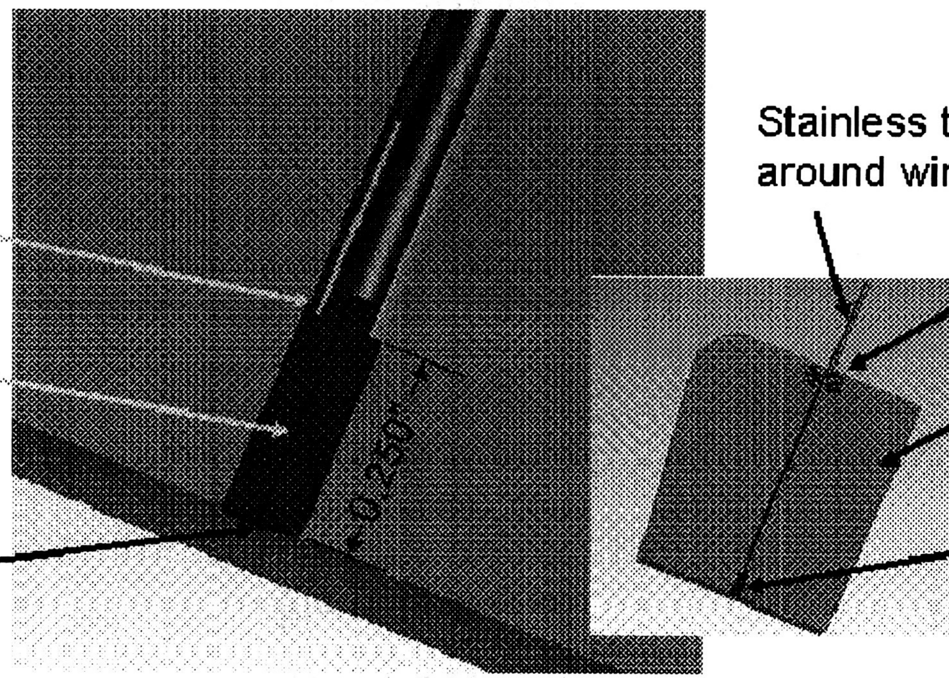
1. Technological solutions demonstrated by design, fabrication, and *test* of single element or small scale rocket injector hardware
   - Hardware is not just for tool validation
   - Test results can be used directly for injector development
2. Improvements in capability and validity to *analyze* large, multi-element injectors
   - Current analysis methods in injector design are largely 1-D and empirical
   - Future capability must include 3-D and multi-element effects

Single Element Program Flowchart

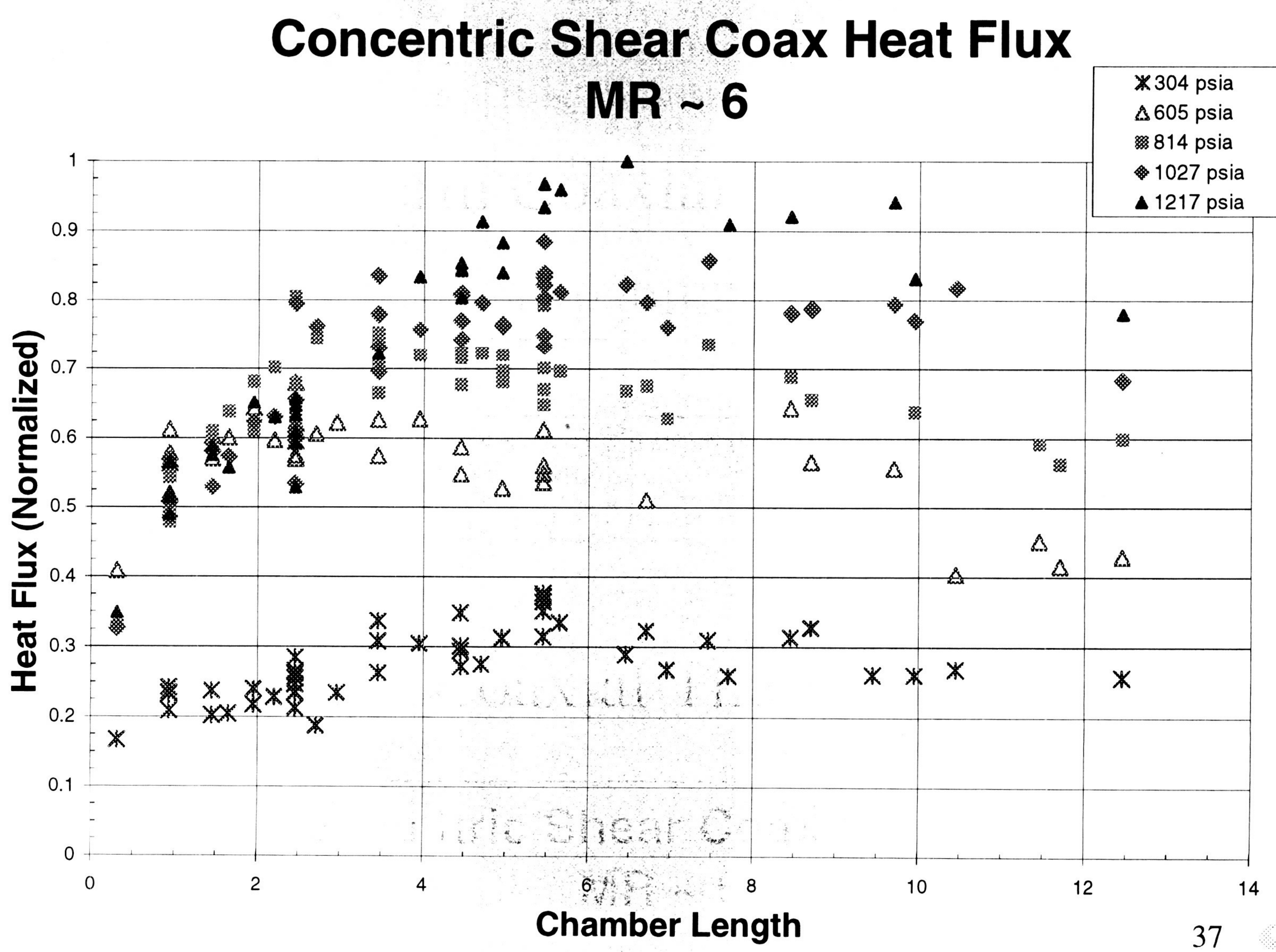
- 3 year program funded through Sept 2005
- Built on previous 3 year SCIT effort
- CFD code development funded thru SBIR



Medtherm Coaxial Thermocouple



Combined Coaxial Thermocouple Data



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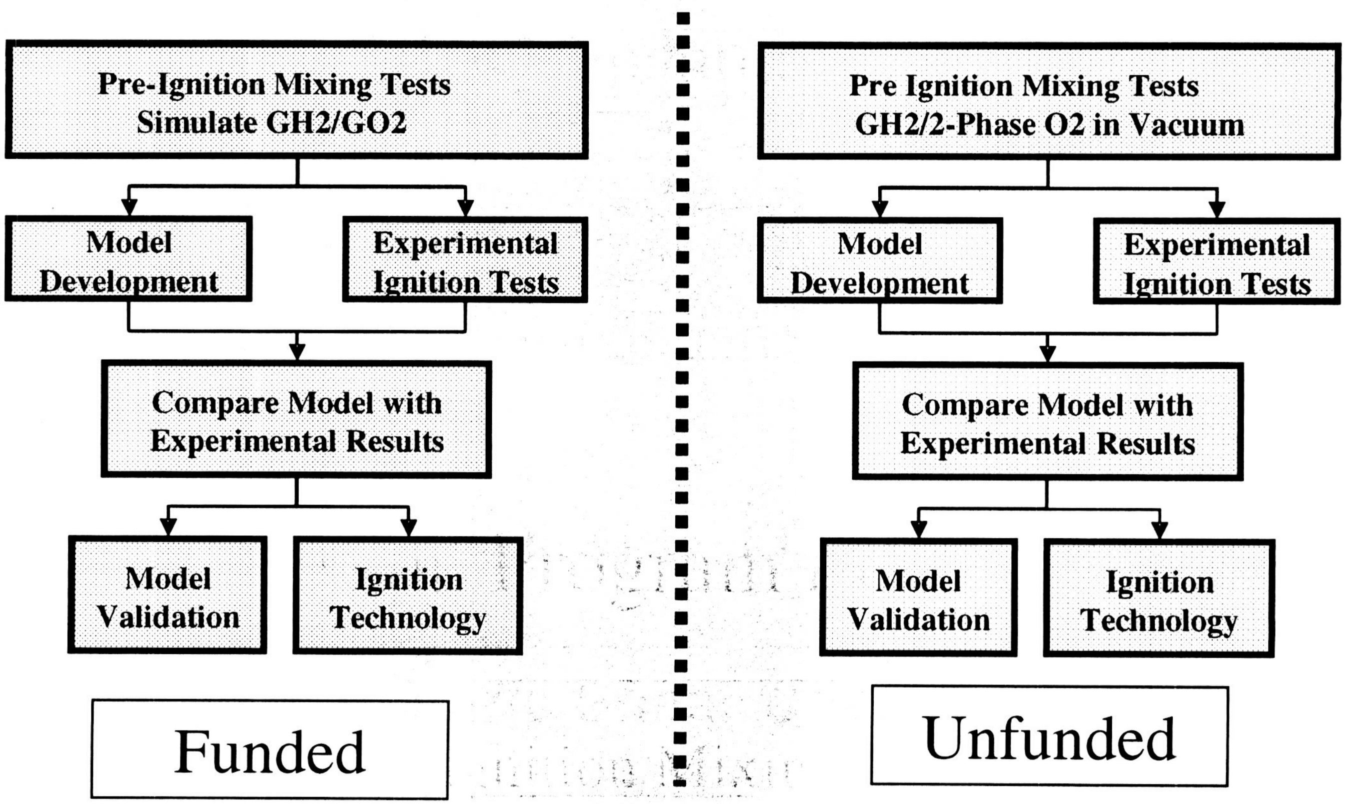
Ignition Program Flowchart

Direct Ignition Mixing Experiments

(Evaluate Spatial/Time Dependent MR map for a representative Ignition geometry/environment)



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Transient CFD Analysis Showing Fuel Simulant Entering Chamber