IN-SPACE PROPULSION

AMBR* Engine for Science Missions

NASA In Space Propulsion Technology (ISPT) Program

****Advanced Material Bipropellant Rocket (AMBR)***

NASA

July, 2008

Outline

- Overview
- Objectives
- Benefits
- Heritage
- Results To-Date
- Remaining Tasks

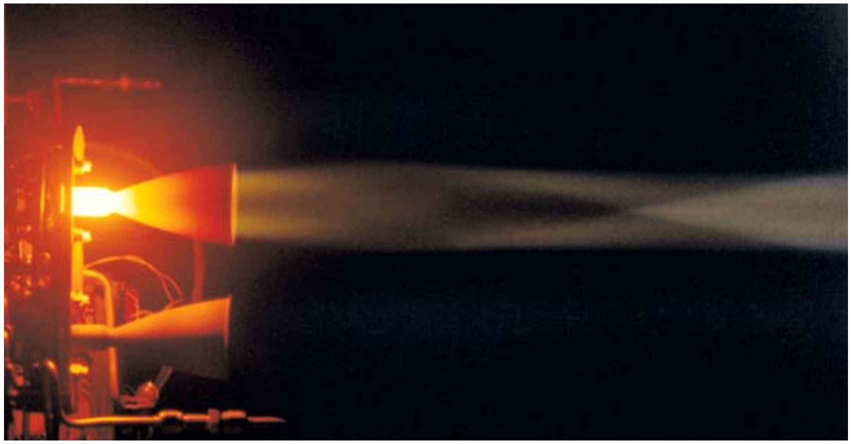
NRA High Temperature Bipropellant Thruster (AMBR)

Objective

•Improve the bipropellant engine Isp performance by fully exploiting the benefits of advanced thrust chamber materials

•Goals

* 335 seconds Isp with NTO/N2H4
* 1 hour operating (firing) time
* 200 lbf thrust
* 3-10 years mission life



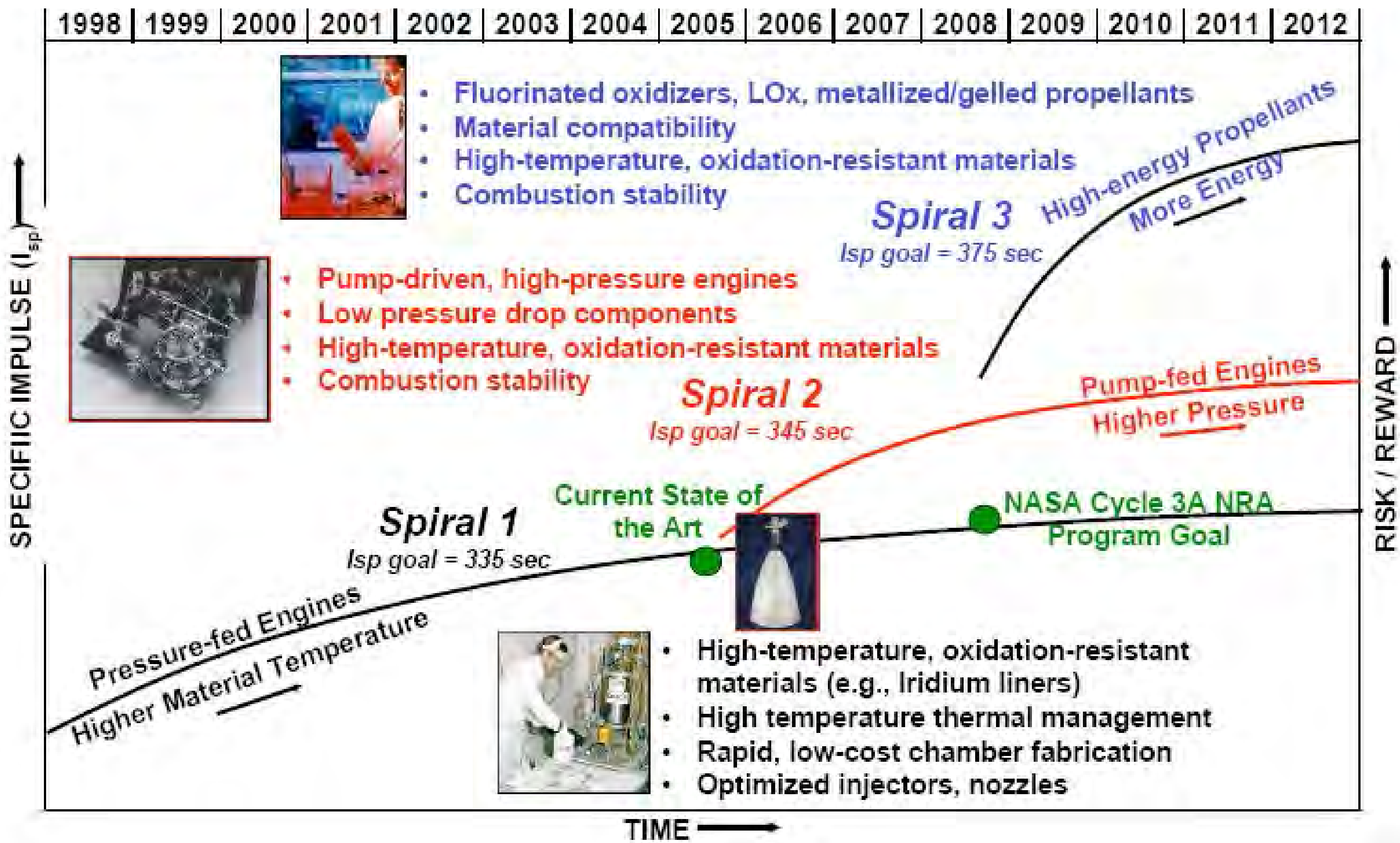
Approach

- Adopt operating conditions to allow the thruster to run at higher temperatures and pressures
- Test a baseline engine for model development
- Evaluate materials and fabrication processes
- Develop advanced injector and chamber design
- Fabricate and test a prototype engine
- Environmental testing: life hotfire, vibe, and shock tests

Key Milestones / Upcoming Events

• Kickoff	Sept 2006
• Mission and System Analysis TIM	Dec.
• Baseline Testing	Feb. 2007
• Risk Mitigation Chamber Testing	Nov.
• Prototype Engine Testing	Sept. 2008
• Environmental Testing	Nov.

Technology Advancement Spirals



Goals for AMBR Thruster Development

Primary Goal

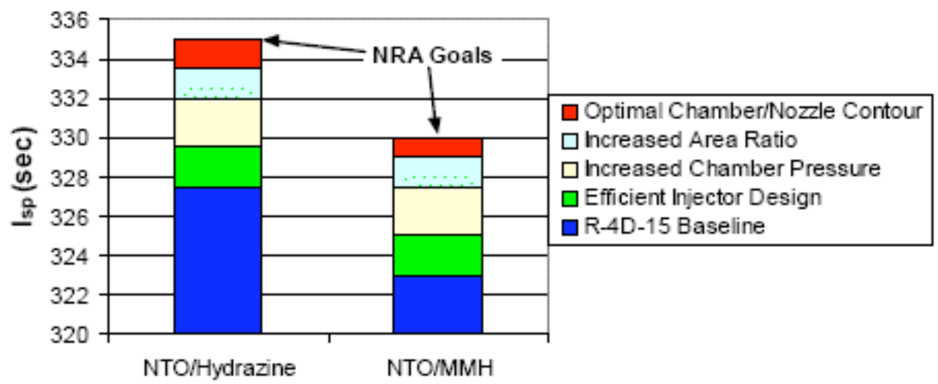
- Design and test an Ir-lined Re storable bipropellant apogee class engine to demonstrate
  - 335 seconds steady-state Isp with NTO/N2H4
  - 3-10 years mission life (by analysis & similarity)
  - 1 hour operating (firing) time
  - 200 lbf thrust

Secondary Goal

- Investigate viability of alternate Ir/Re fabrication processes and other related material systems
- Determine whether alternate processes offer cost, producibility, and/or performance advantages over the baseline chemical vapor deposition (CVD) Ir/Re fabrication process (El-Form has been found to reduce manufacturing cost by 30% over CVD)

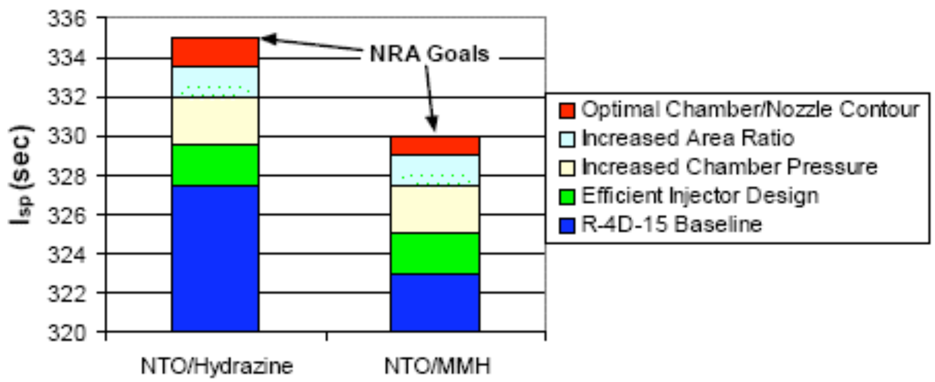
Design for Higher Performance

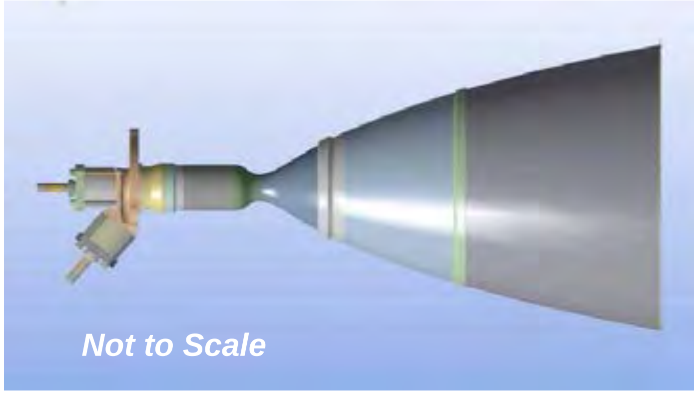
- **Modify Aerojet's state of the art engine design such that the chamber wall materials operate at their temperature limits while maintaining safety margins critical to mission integrity**
  - Optimized injector
  - Optimized chamber/nozzle contour
  - Reduced chamber emissivity
  - Increased thermal resistance between injector and chamber
- **Change engine operating conditions (within mission constraints), which will produce higher combustion gas temperatures**
  - Higher feed pressure/lower internal pressure drop
  - Higher/optimized mixture ratio



Design for Higher Performance

Design Characteristics	AMBR	HiPAT DM
• Trust (lbf)	200	100
• Specific Impulse (sec)	335	328
• Inlet Pressure (psia)	400	250
• Chamber Pressure (psia)	275	137
• Oxidizer/Fuel Ratio	1.2	1.0
• Expansion Ratio	400:1	375:1
• Physical Envelope	Within existing HiPAT envelope	
• Propellant Valves	Existing R-4D valves	





Mission and System Studies Show Benefit

- <u>Conducted mission and system studies</u> **to identify propulsion technology requirements and impacts**

•Results show increased performance can reduce the propellant required to perform spacecraft maneuvers.

•Propellant reduction implies increase of payload

AMBR Engine potential mass reduction for the missions

	Total Propulsion System Mass Reduction (Kg)				
Isp (sec)	320	325	330	332.5	**335**
GTO to GEO	0	16	30	37	**45**
Europa Orbiter	N/A	0	12	16	**24**
Mars Orbiter	N/A	0	14	22	**29**
T - E Orbiter	N/A	0	29	45	**60**

Heritage

- The AMBR technology is an improvement upon the existing HiPAT™ engine

- The HiPAT™ engine is a member of the Aerojet Corporation's R-4D Family of thrusters

- The R-4D family of thrusters carries the heritage: >1000 engines delivered, >650 flown, 100% success rate

AMBR Baseline Thruster Test

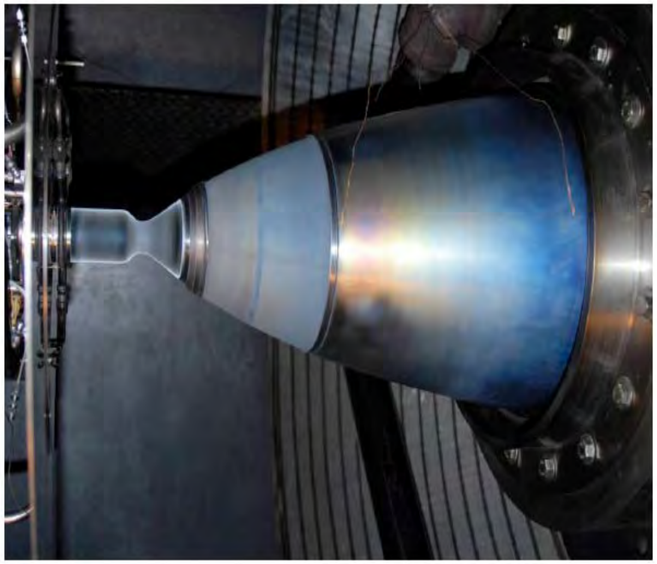
Europa DM HiPAT Development Engine

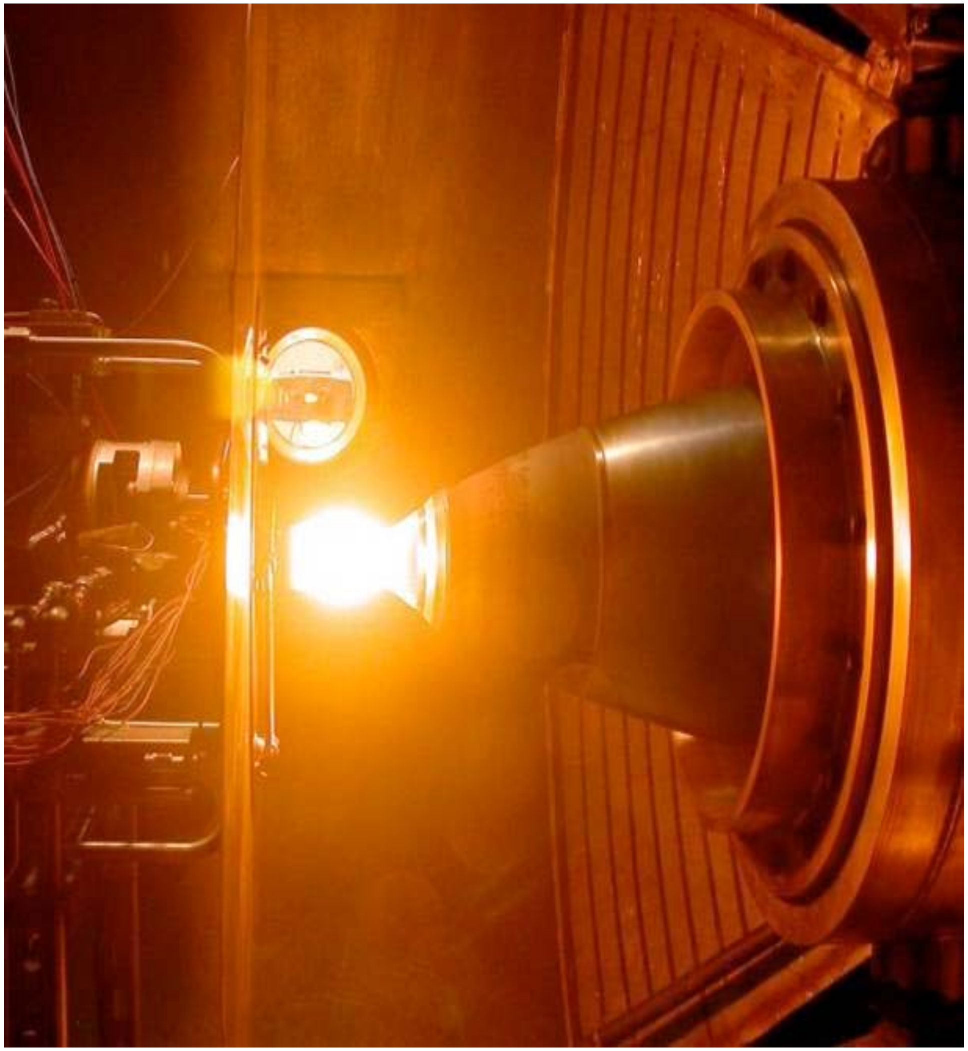
Astrium S/N 008 HiPAT Flight Engine

Baseline test article assembled from

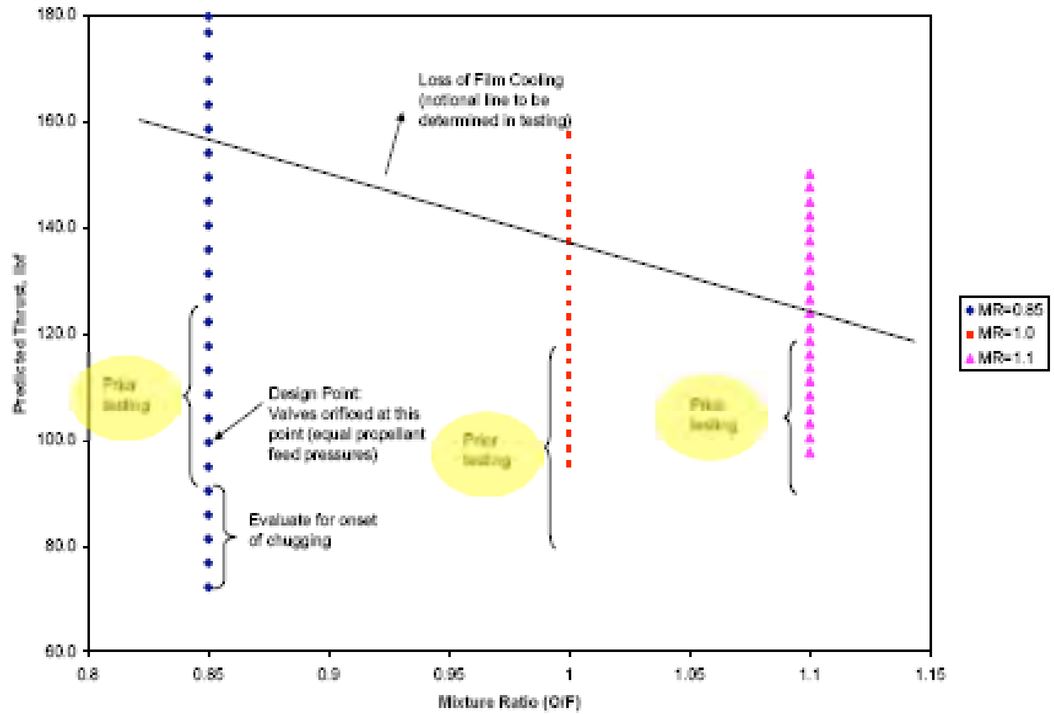
- Workhorse R-4D development valves
- Europa R-4D-15DM HiPAT development engine injector/step assembly
- Astrium S/N 008 R-4D-15 HiPAT flight engine chamber/nozzle

Thruster Installed and Fired



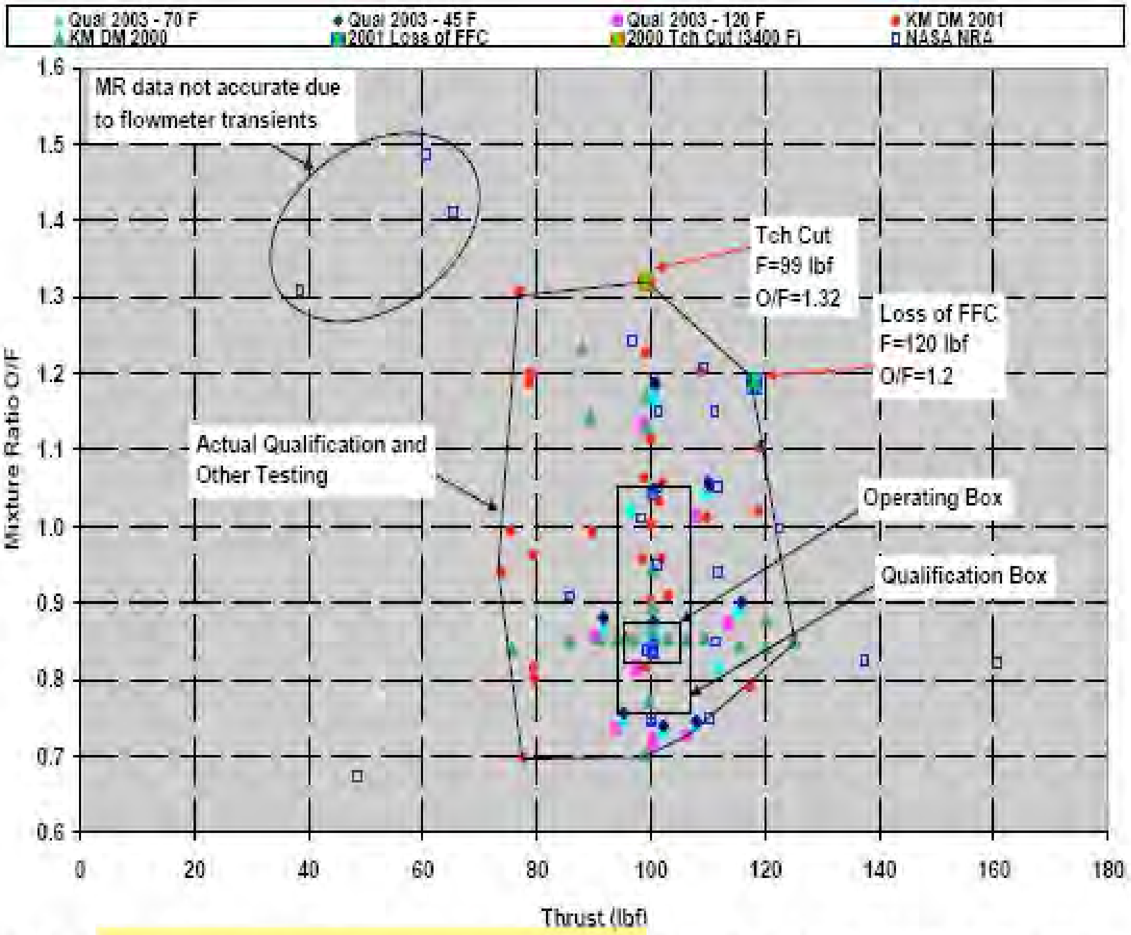


AMBR Baseline Test Matrix



- Baseline test matrix
  - Primary goal to achieve high temperature, high chamber pressure data
  - Matrix if fully realized would utilize all budgeted propellant
- Test matrix extended during test program as propellant became available
  - Not all proposed test points could be achieved due to loss of film cooling

Baseline Test Map



- R-4D-15DM tested to extreme conditions during this test program
- Higher chamber pressures could be attained with this engine with better thermal management

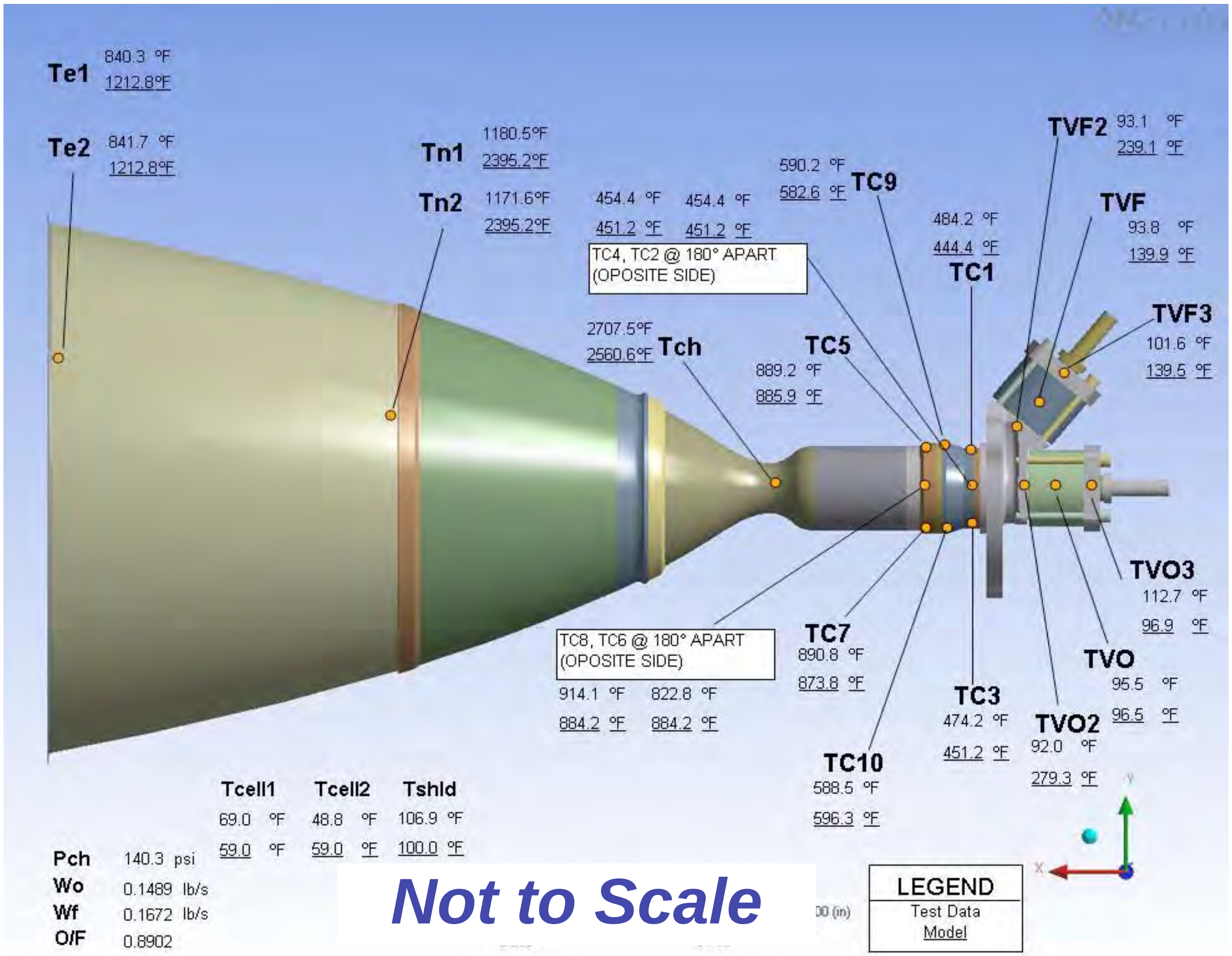
Baseline Test – Key Results Summary

- 26 hot fire runs over four days
- 2909 seconds of total burn time
- Propellant consumption
  - 472 lbm NTO
  - 569 lbm N2H4

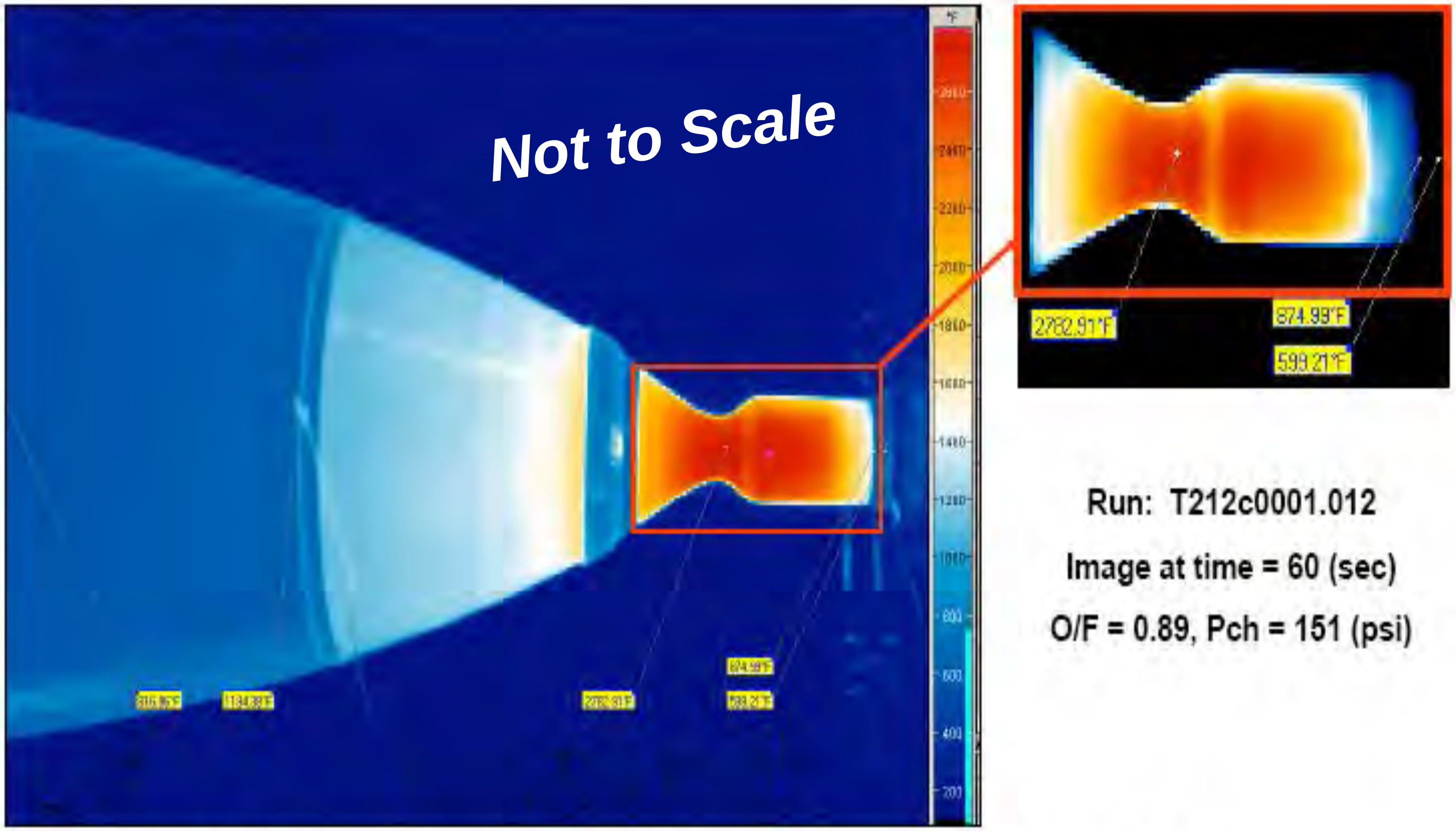
	Test Value	*New Design*
PC	217 psia	275 psia
Isp	329 sec	335 sec
TC	3673 F	4000 F--Mat'l Capability

- 3673 F maximum chamber temperature
- 217 psia maximum chamber pressure (prior max of 160 psia)
- 53.4 psia minimum chamber pressure (prior min of 99.4 psia)
- 329 seconds maximum specific impulse (prior max of 328.3 sec)
- Platinum step temperatures successfully collected (data not previously obtained)
- Exterior chamber/nozzle temperatures successfully collected via new IR camera (data not previously obtained)
- **Data collected has been very important to the subsequent prototype design**

Anchoring Thermal Model w/ Test Data



Baseline Test – Thermal Camera Output



Run: T212c0001.012

Image at time = 60 (sec)

O/F = 0.89, Pch = 151 (psi)

- Thermal Camera temperatures at each indicated point shown are correlated to thermocouple and pyrometer data. Overall temperature scale (color bar) is correlated to the chamber emissivity.

AMBR Thruster Design Detail

- **Defined internal chamber and nozzle contours**
- **Finalized iridium layer thickness and an envelope that would contain the final rhenium thickness distribution**
  - Using R-4D-15DM random vibration spectrum for structural calculations
- **Evaluated design concepts for the injector chamber interface and pre-combustor step assembly to accomplish**
  - Optimization of thermal design
    - Basic thermal model completed
    - Anchoring **thermal model** to baseline engine test data
  - Minimization of high cost materials
  - Simplification of fabrication and construction
- **Performed additional injector development test with copper chamber to mitigate risk during the design phase**
  - Injector performance and chamber length validated via C*
  - Resonator design verified
  - Goal of Isp 335 second is achievable

Selection of High Temperature Chamber Materials & Fabrication

- ❑ Iridium coated Rhenium (Ir/Re) chamber selected
- ❑ Assessed: Chemical Vapor Deposition (CVD), electroforming (El-Form™), Low Pressure Plasma Spray (LPPS) and Vacuum Plasma Spray (VPS)
- ❑ CVD is the incumbent process used to fabricate the R-4D-15 HiPAT™ thrust chambers
- ❑ El-Form has been used to fabricate an Ir/Re chamber for a bipropellant engine
- ❑ LPPS and VPS were dropped due to low technical maturity.
- ❑ Figures of Merit used for the decision matrix were:
  - ❑Producibility
  - ❑Cost – Recurring & nonrecurring
  - ❑Schedule – Recurring & nonrecurring
  - ❑Performance – Mechanical properties, thermal, oxidation resistance, & mass
  - ❑Heritage/Risk – Design & manufacturing
- ❑ **The El-Form process was down selected** primarily due to the low production cost

Chamber Materials Candidate Evaluation

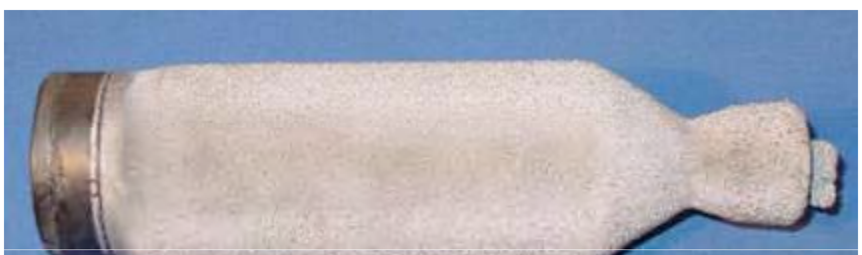
Candidate Material/Process	Cost/Schedule	Pros	Cons
Engineered EL-Form Rhenium (Re)	▪ High (but likely in scope)	▪ Improved YS and UTS	▪ Process repeatability compared to traditional EL-Form Re not known ▪ Elevated temperature strength and life not known
Thick EL-Form Ir layer	▪ Moderate	▪ Improved life	▪ Increased chamber life not demonstrated
Functionally graded ceramic lined Ir/Re (HfO_2 or ZrO_2)	▪ Out of Scope	▪ Increased operating temperature and life ▪ Improved oxidation resistance	▪ Low TRL ▪ Significant process development/testing needed
VPS Ir/Re	▪ Out of Scope	▪ Low cost ▪ High tensile strength ▪ Thicker Ir	▪ Significant process development and testing required
HIP bonded Ir /Re	▪ Out of Scope	▪ Thicker Ir ▪ Improved Re process repeatability ▪ Improved properties	▪ Thrust chamber fabrication process not well known ▪ Complex fabrication ▪ High cost
Dispersion strengthened Mo/Re or other advanced alloy	▪ Out of Scope	▪ Reduced weight ▪ Lower cost ▪ Improved elevated temperature strength	▪ Significant development and testing required ▪ Joining characteristics not well known

Life Test Scheduled…

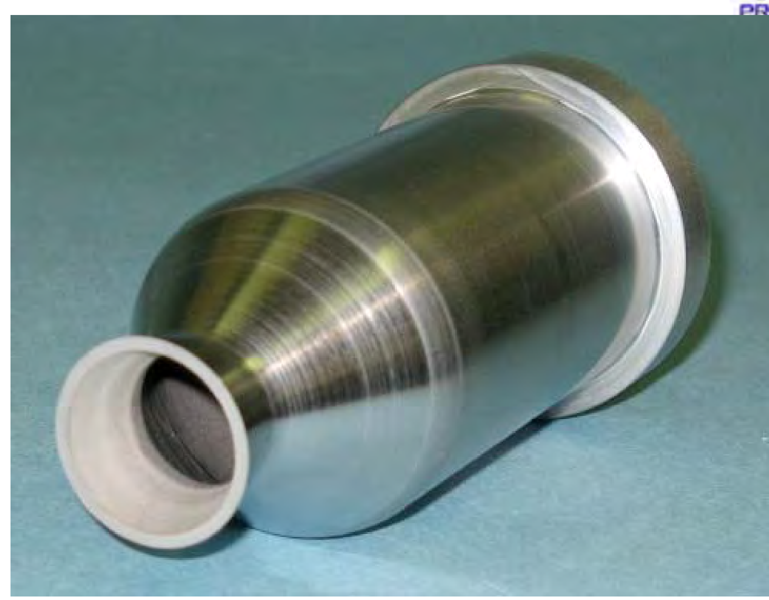
El-Form^{TM} Chamber Fabrication Process

Graphite mandrel for electroforming

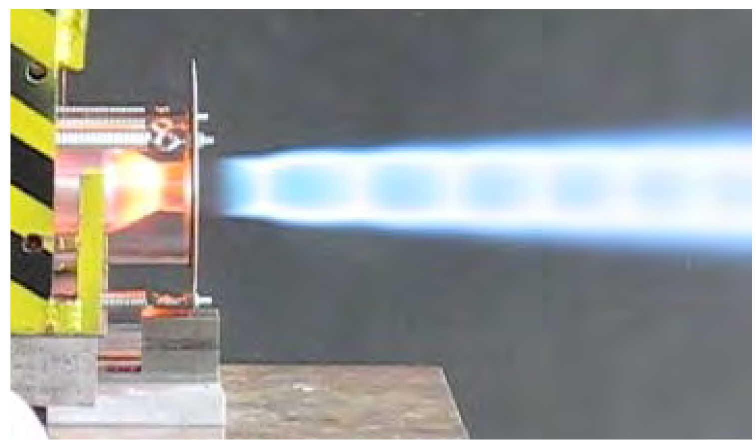
Ir Layer Applied to Mandrel with El-Form



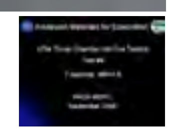
Ir/Re Applied to Mandrel with El-Form (prior to machining)



Completed EL-Form Ir/Re Nozzle



Hot-fire Test



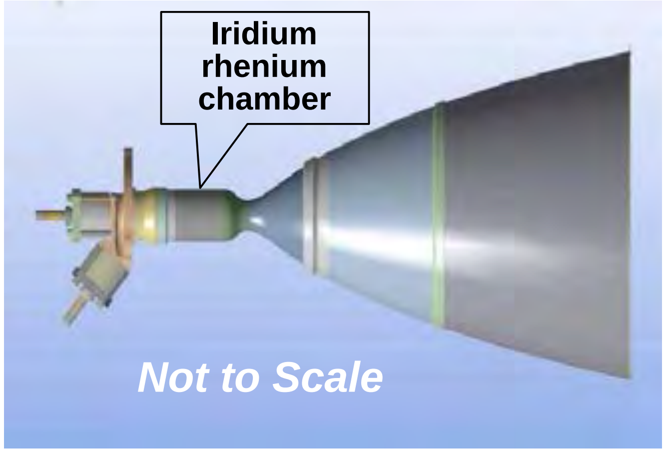
Selection of Advanced Chamber Materials & Fabrication

CVD

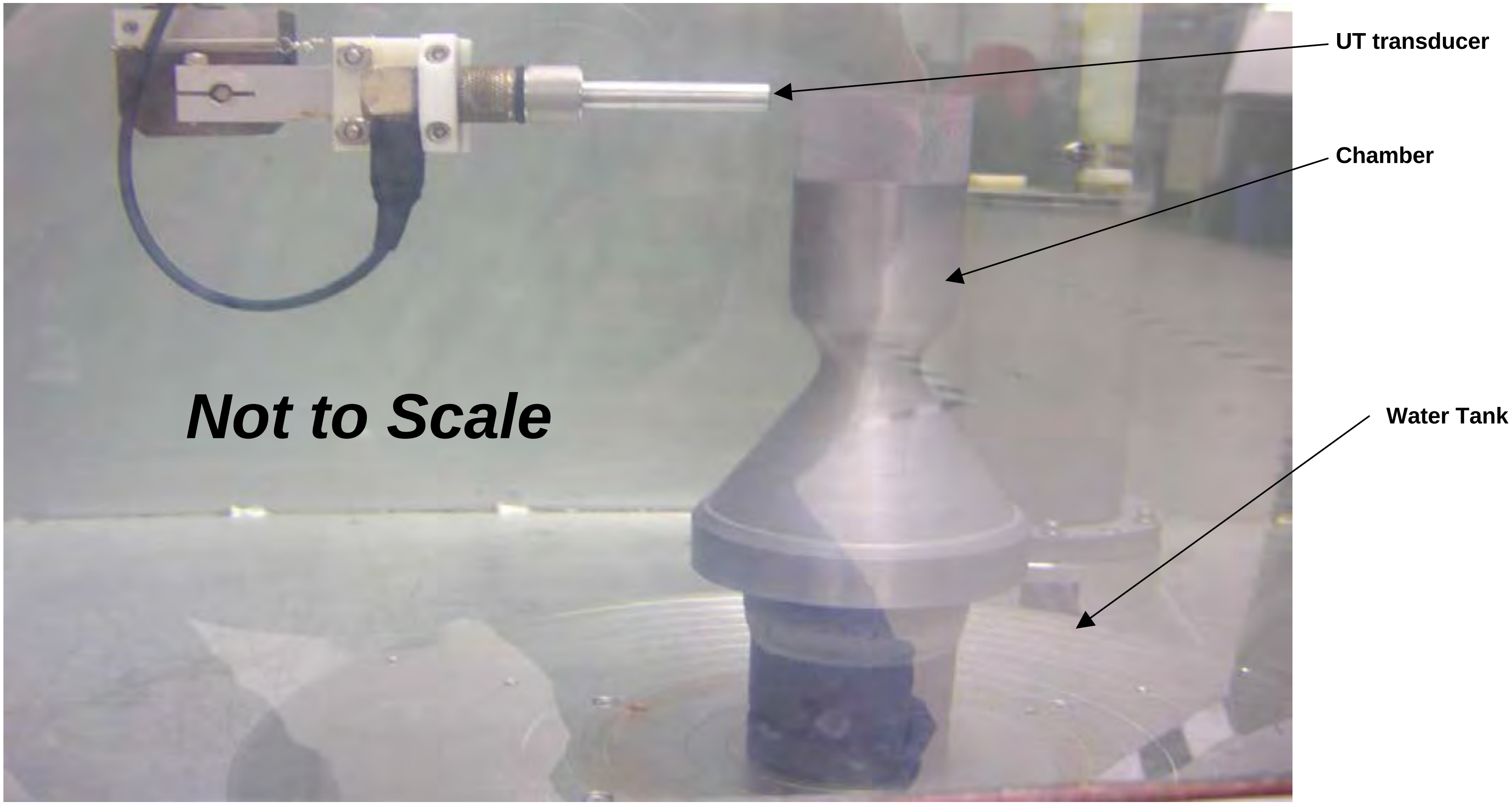
- ❑ Present State of the art method for manufacturing iridium/rhenium chamber
- ❑ Manufacturing yield rate needs improvement

EL-Form

- ❑ The method used to manufacture AMBR prototype
- ❑ 30% improvement on production cost (based on vendor quotations & invoice)



AMBR Thruster Chamber Undergoing Ultrasonic Testing



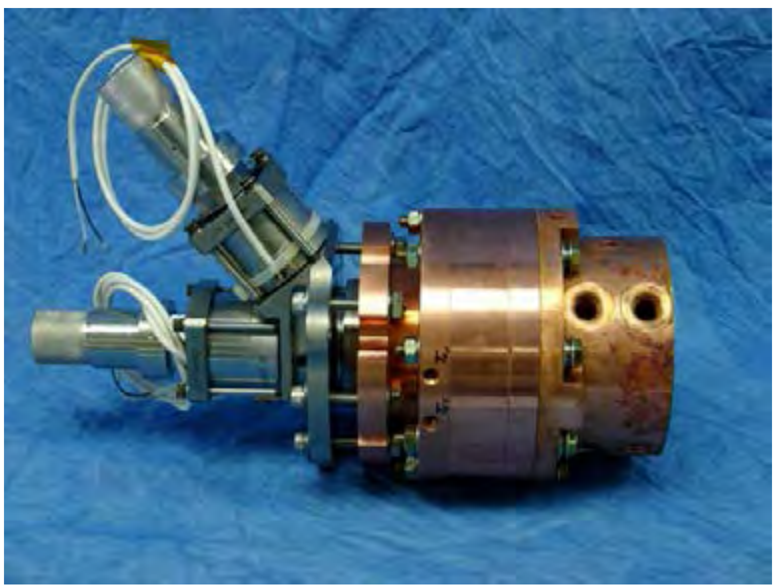
Risk Mitigation Test Objectives

- **Validate core engine design characteristics using a work horse chamber before committing to final engine build**

  - Verify performance of injector design (via c* measurements)
  - Verify resonator design (via accelerometer measurements)
  - Finalize chamber length (via c* measurements)

Test Setup – Workhorse Chamber

- ❑ **Copper chamber with water cooling jacket**
  - Used to shorten turnaround time between runs, not for active cooling
- ❑ **Bolt-together construction enables swapping injector**
- ❑ **Flight-like valves and injector**
- ❑ **Truncated nozzle eliminates expense of heat resistant materials and fabrication plus thermal expansion mismatch with cooled chamber**
- ❑ **Nozzle performance extrapolated from known engine data**



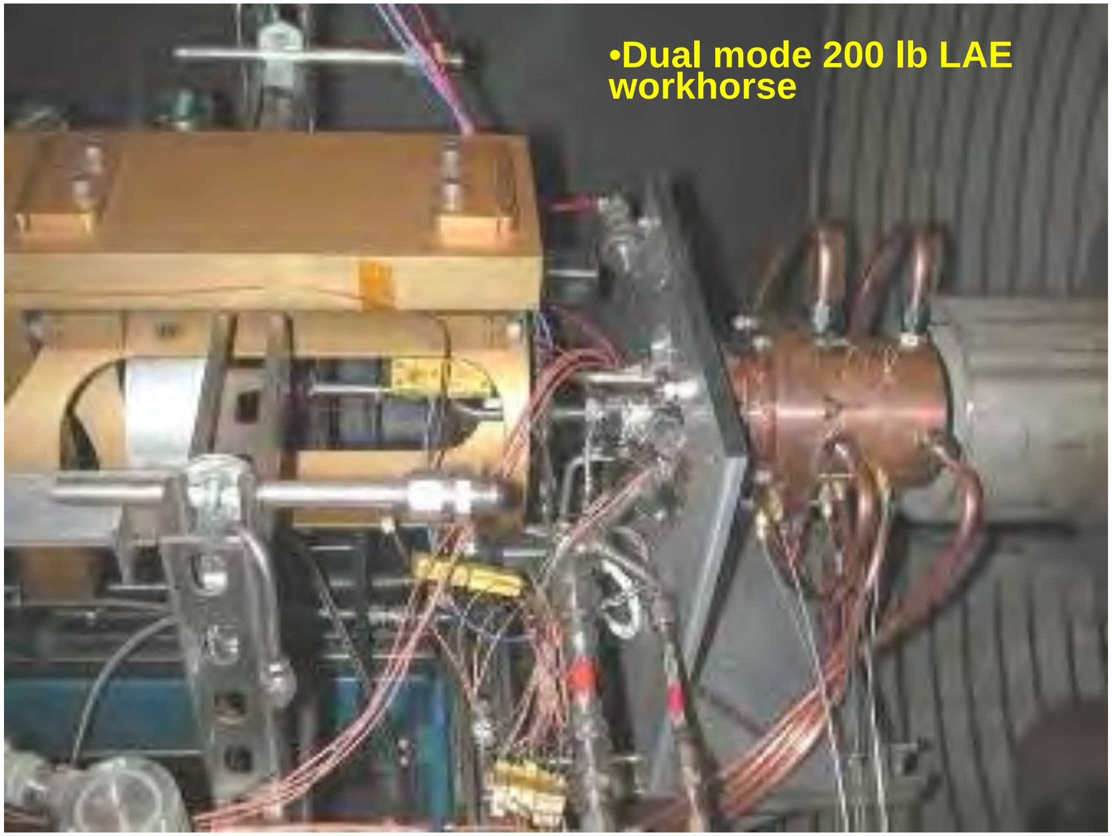
Test Setup – Engine Configuration

- **Full scale flow paths**
- **Variable length combustion chamber**
  - 2.6, 3.1. 3.6 and 4.1”
- **Propellants**
  - N_2O_4 Oxidizer and N_2H_4 Fuel
- **Injector**
  - Flight-like titanium
  - Multiple unlike doublet
  - Fuel film cooling
  - Helmholtz resonators
- **Design nominal conditions**
  - Chamber Pressure: 275 psia
  - Thrust: 170 to 210 pounds
- **No flow calibration restrictors**
  - Pressure drop minimized
  - OF set by facility

Test Setup – Aerojet Redmond Altitude Test Cell

•Altitude cell and stage one diffuser and ejector

•Gas-fired boiler, cooling towers and 2 additional ejector stages

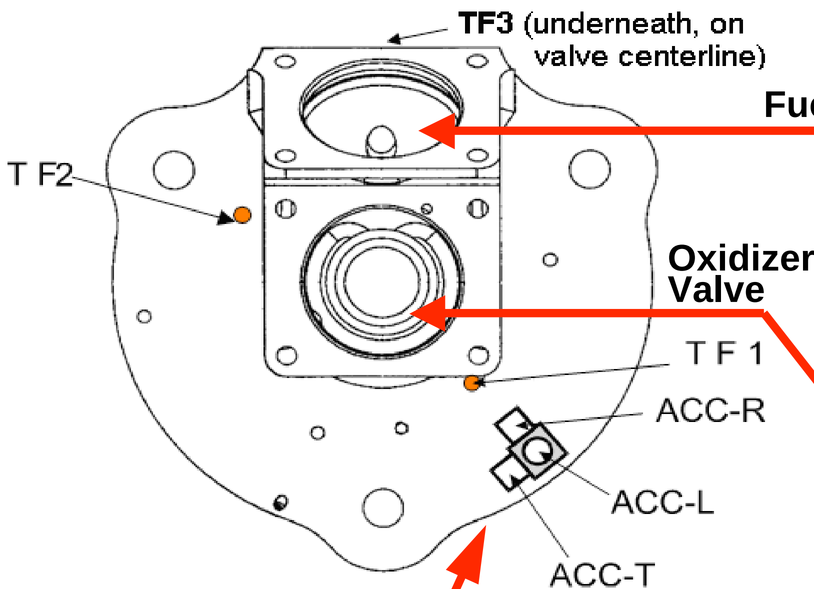


•Similar engine to AMBR in altitude cell, with cooling lines attached, poised to fire into diffuser

•Cell maintains less than 0.07 psia throughout firing for up to 330 pounds thrust bipropellant engines

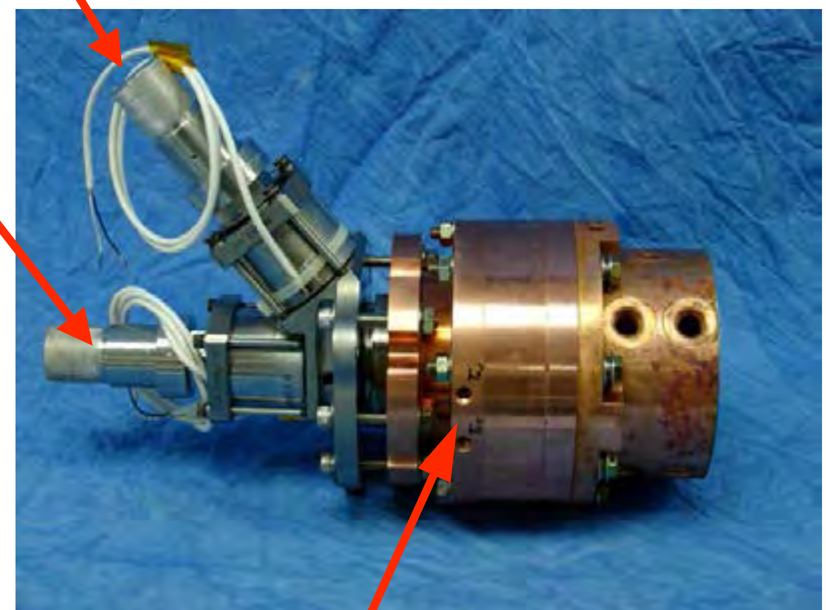
Test Instrumentation

Thermocouples located to anchor thermal model



Fuel Valve

Oxidizer Valve



- **Three-axis accelerometer to measure ignition oscillation and damping for combustion stability monitoring**

Thermocouple ports

Additional instruments/measurements:

- **propellant inlet pressures**
- **engine chamber pressure**
- **propellant flow meters**

Test Plan

Sequence Dash number	ON (sec)	OFF (sec)	Total Firings	PMO ±5 (psia)	PMF ±5 (psia)	O/F	Ox/Fuel Temperature ±5 (°F)	Comments
Trim	2	-	AR	428	430	1.200	70	
1	3	-	2	433	435	1.207	70	Nominal Pc, Nominal O/F
2	3	-	2	343	350	1.204	70	Low Pc, Nominal O/F
3	3	-	2	438	429	1.301	70	Nominal Pc, High O/F
4	3	-	2	328	365	1.046	70	Low Pc, Low O/F
5	3	-	2	430	465	1.125	70	High Pc, Low O/F
6	3	-	2	358	335	1.398	70	Low Pc, High O/F
7	3	-	2	440	422	1.308	70	Nominal Pc, High O/F
8	3	-	2	460	465	1.192	70	High Pc, Nominal O/F
9	3	-	2	422	439	1.164	70	Nominal Pc, Low O/F

Note: PMO = oxidizer feed pressure measured upstream of the propellant valve.
PMF = fuel feed pressure measured upstream of the propellant valve.

- **Inlet pressures of 328-460 (oxidizer) and 335-465 (fuel) psia tested**
- **OF ratio of 1.046 to 1.398 tested (stoichiometric OF for N_2O_4 / N_2H_4 is 1.44)**

Test Objectives

❑Characterize injector performance while varying:

- Feed pressures
- Mixture ratio
- Chamber length

❑Demonstrate:

- Fast response
- Stable ignition
- Steady-State injector operation (dynamic)

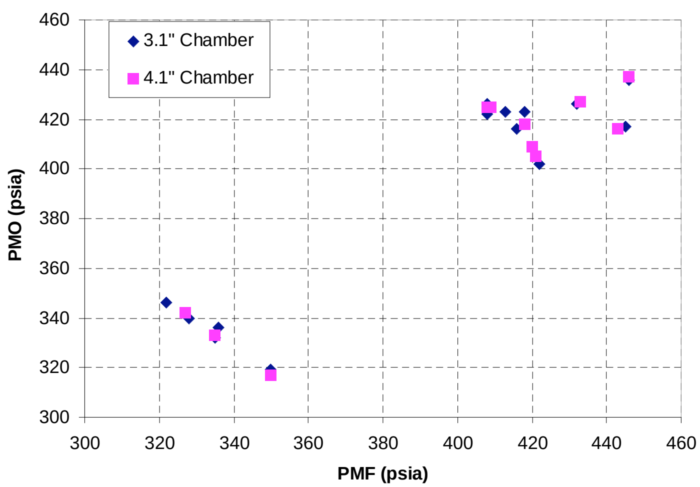
❑Performance goals:

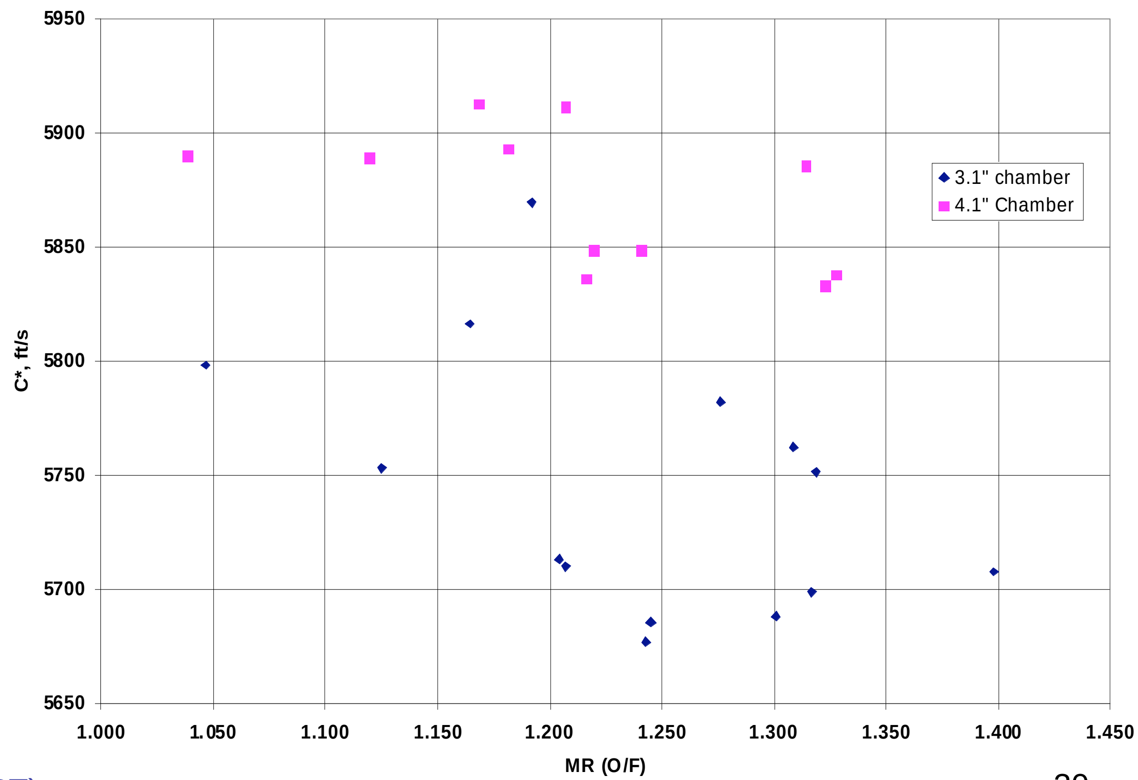
- 335 seconds Isp

Test Results

- 3.1 and 4.1 inch chambers tested
- Maximum performance seen at OF ~1.200 in 4.1” chamber
  - C* = 5849 ft/s at design point
  - Design inlet pressure 430 psia
  - Max C* 5913 ft/sec = 1802 m/s
  - Isp (est.) > 335 sec

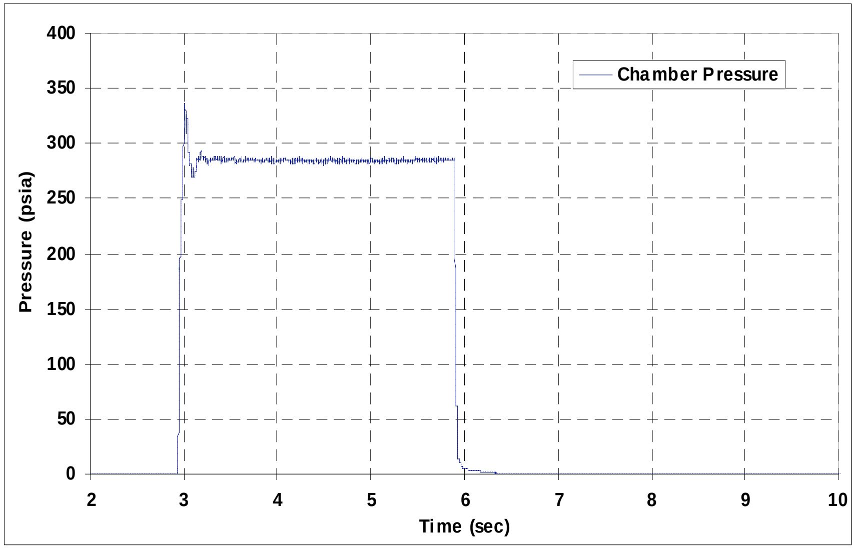
$$c^* = \frac{P_c \cdot A_t \cdot g_0}{(W_o + W_f)}$$

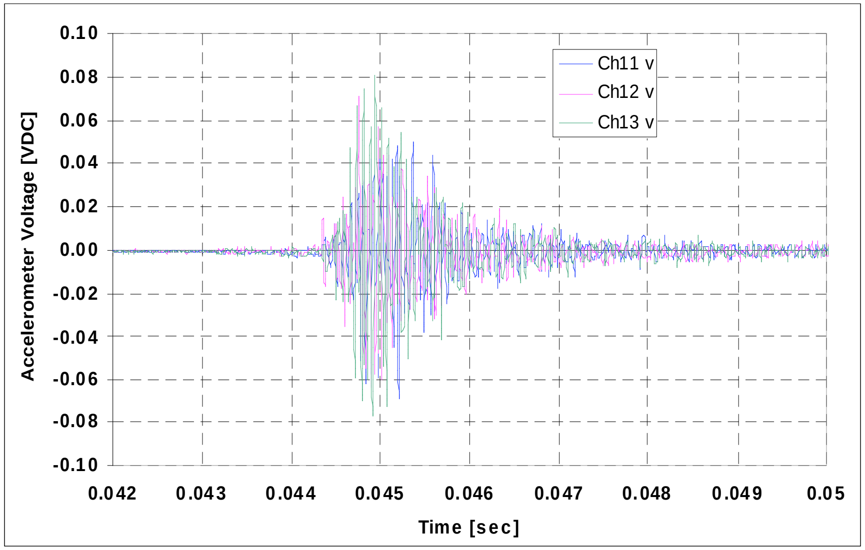




Test Results (Continued)

- Dynamics and Combustion Stability
- Roughness approximately 3% peak-to-peak
- Start response time to 90% thrust ~60 msec
- Stop response time to 10% thrust ~30 msec
- Accelerometer trace shows damping from start transient within 5 msec





Highlights of 2007 & Early 2008

- **Successful Baseline test** laid foundation for AMBR engine design
  - Thermal data,
  - Chug information,
  - and pressure, MR, and thrust information beyond baseline engine operating envelope collected for anchoring models
- **Engine performance target has been verified** in the risk mitigation test
- Prototype engine fabrication near completion
- Preparation in progress to **infuse AMBR thruster into planetary missions**

Remaining Tasks

- **Complete AMBR fabrication (3rd Quarter 2008)**
  - Injector assembly, combustion chamber, nozzle, and nozzle extension
- **AMBR performance envelope testing (4th Quarter 2008)**
- **Environmental Testing (2008/2009)**
  - Vibration (Aerojet)
  - Shock (JPL)
  - Hotfire life test (Aerojet)