AMBR* Engine for Science Missions

NASA In Space Propulsion Technology (ISPT) Program

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

April 2010

AMBR Status Information Outline

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

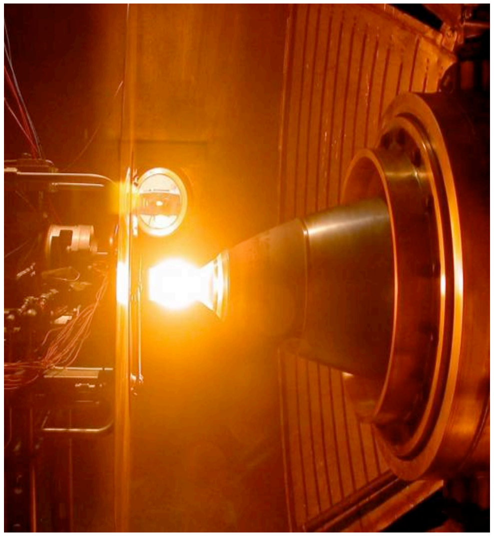
NRA High Temperature Bipropellant Thruster (AMBR)

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



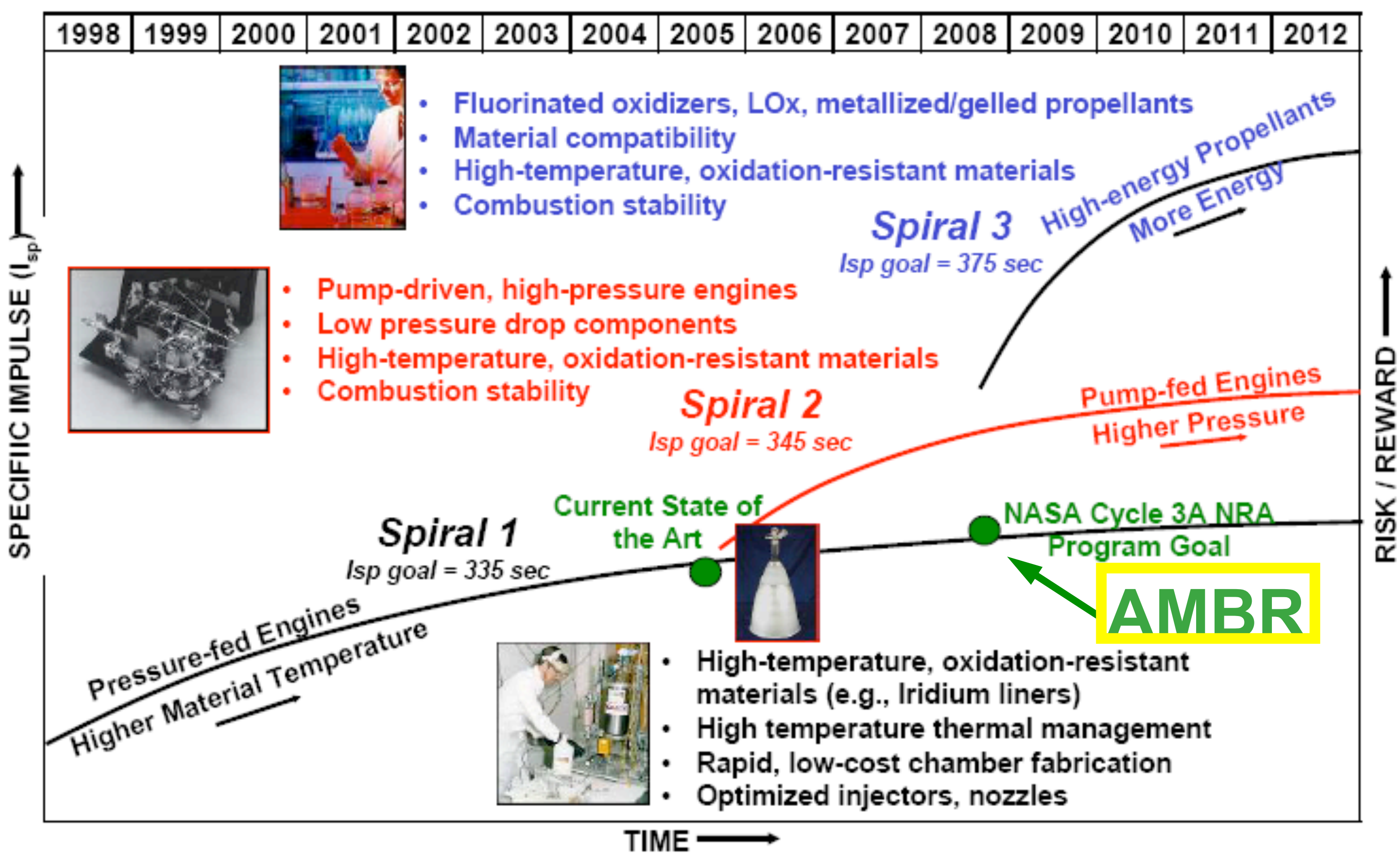
Approach

- 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.
• Engine Primary Performance Testing	Oct. 2008
• Vibe and Shock Testing	Jan. 2009
• Additional Performance Testing	Feb. 2009
• Long Duration Hotfire Testing	June 2009
• Design Model Update and Final Report	Sept. 2009

Technology Advancement Spirals



Mission and System Studies Show Benefit

- **Conducted mission and system studies to identify propulsion technology requirements and impacts**

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**

- Results show increased performance can reduce the propellant required to perform spacecraft maneuvers.
- Propellant reduction implies increase of payload

Heritage

- The AMBR technology is an *improvement upon the existing HiPAT^{TM} engine*

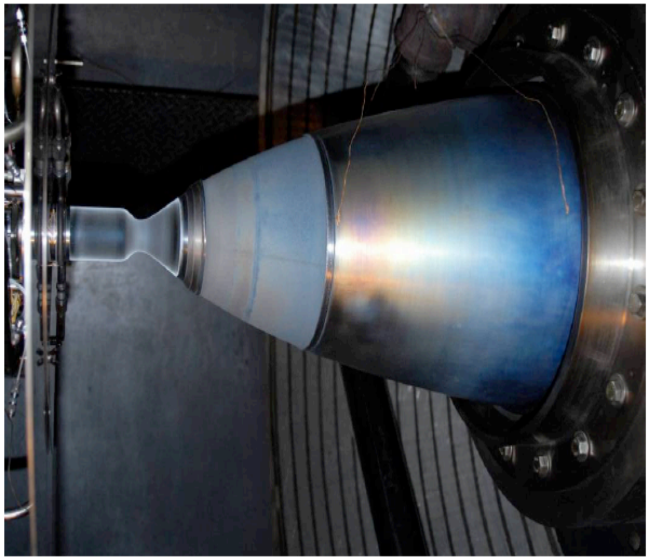
- The HiPAT^{TM} engine is a member of the *Aerojet Corporation's R-4D Family* of thrusters

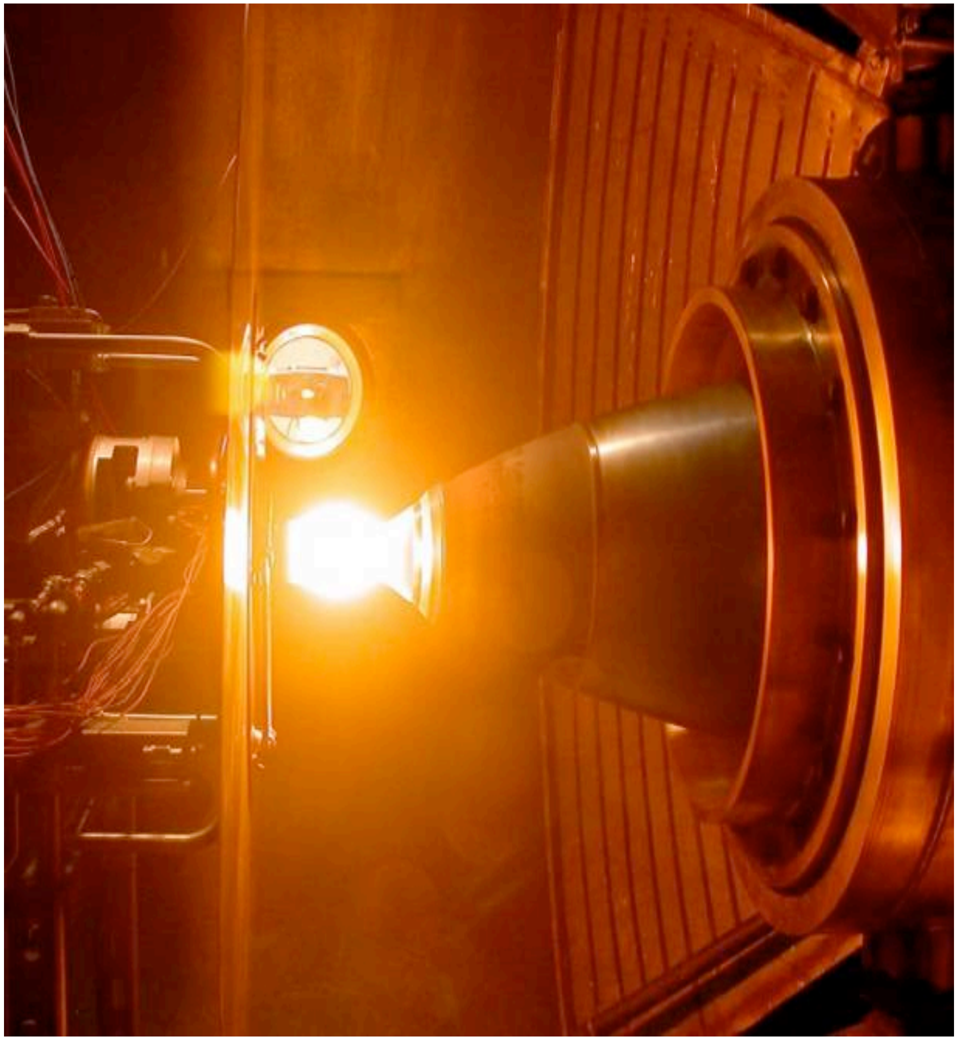
- The R-4D family of thrusters carries the heritage: *>1000 engines delivered, >650 flown, 100% success rate*

Project Evolution

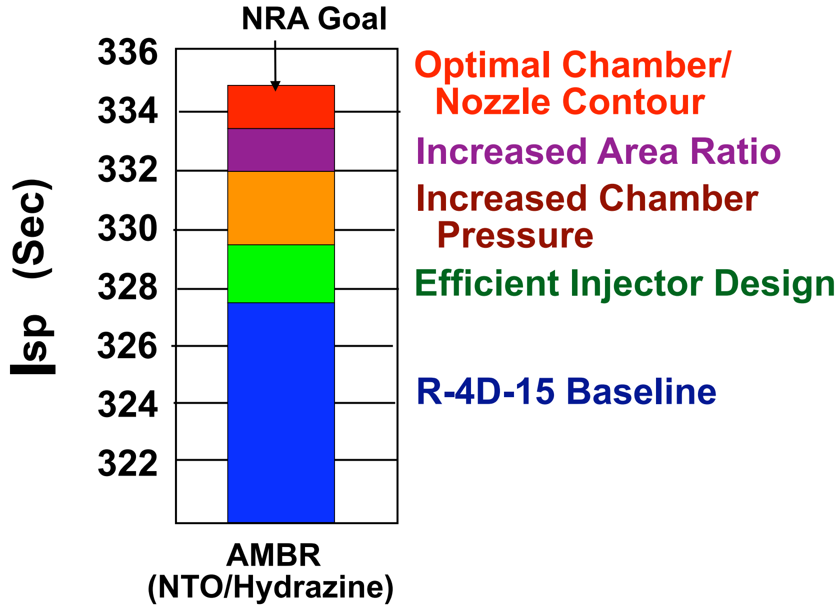
- **Original NRA objective was technology demonstration of both an NTO/Hydrazine and NTO/MMH bipropellant engines**
  - Fully utilize the advanced material potential of higher operating temperature for increased performance
    - Optimize injector and chamber, shift MR
    - Update procedure and processes for reduced cost production
  - Physical "drop-in" for the HiPAT engine
- **Performance goals were to push the technology as far as practicable, as a potential stepping stone for a higher pressure thruster (spiral 2)**
- **In 2007, SMD directed the project to close out development activities with potential product at TRL 6.**
  - Decision was made to eliminated NTO/MMH engine performance demonstration in favor of more TRL 6 validation activities
    - No expected technology challenges, engine design iteration required for NTO/MMH version
  - Added environmental testing of NTO/Hydrazine engine
  - Added increased duration testing for NTO/Hydrazine engine
  - Lowered pressure to accommodate existing tanks and subsystems to improve nearer-term applicability for New Frontiers and Discovery class missions
  - 200 lbf Thrust goal unachievable at both lower pressure and HiPAT physical envelope
- **In 2009, the AMBR engine became available for transition into full flight development and qualification program for mission infusion.**

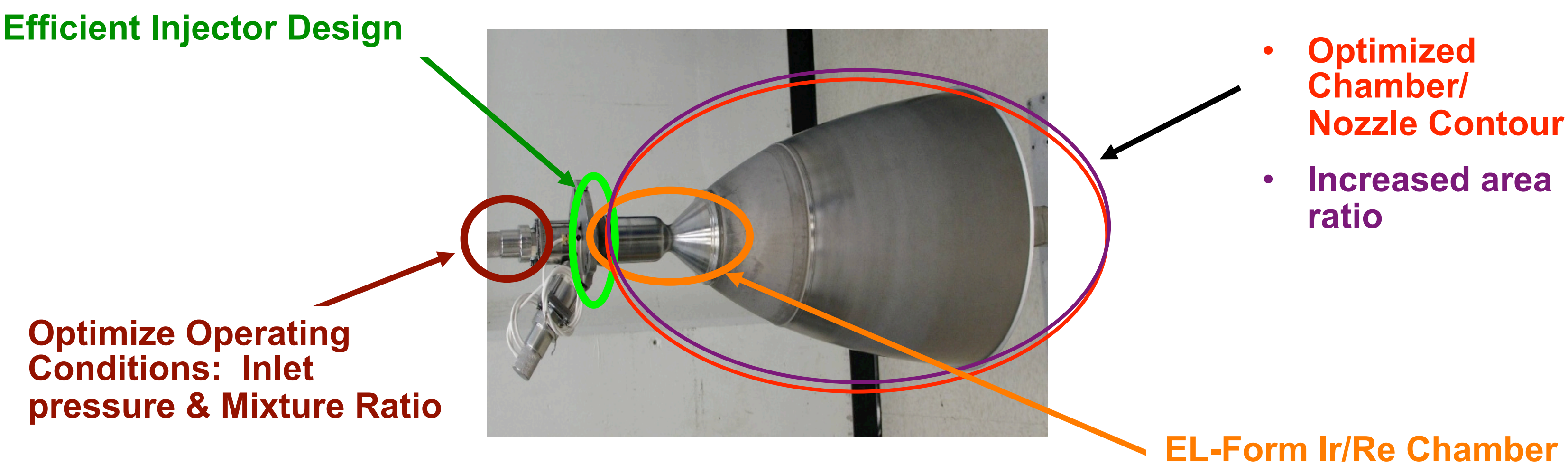
Thruster Installed and Performance Tested





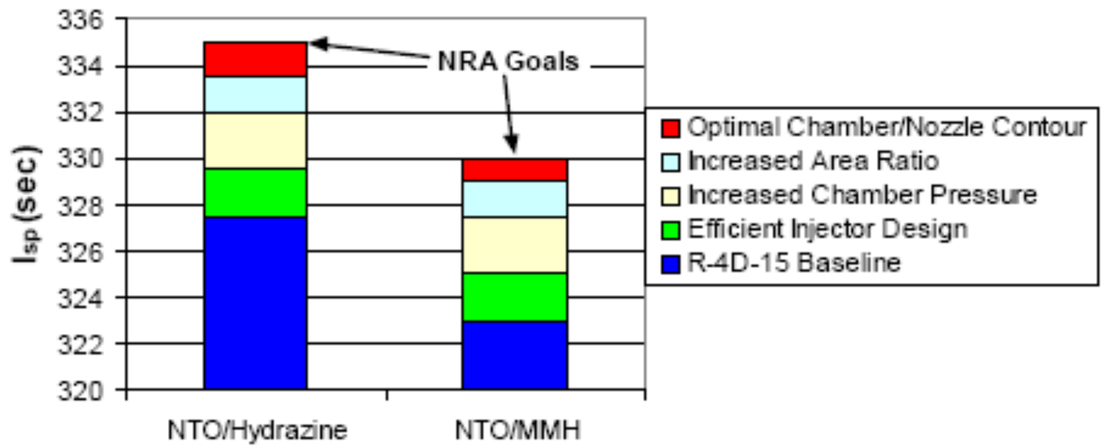
AMBR Technologies





Design for Higher Performance

- ❑ **Modify Aerojet's state of the art engine design to fully utilize the high temperature capability of the Ir/Re chamber**
  - 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



AMBR Thruster Design Detail

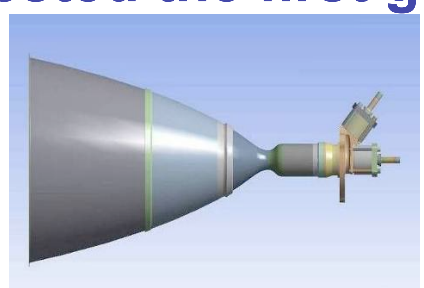
- **Defined internal chamber and nozzle contours**
- **Finalized iridium layer thickness and an envelope that would contain the final rhenium thickness distribution**
  - Using R-4D-15DM random vibration spectrum for structural calculations
- **Evaluated design concepts for the injector chamber interface 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 for an Isp gain 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 developmental bipropellant engine by Aerojet with promising result
- ❑ 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

AMBR Engine Accomplishments

Designed, fabricated, and tested the first generation AMBR engine



- **Design**
  - Thermal
  - Structural
- **Fabrication**
  - Injector
  - EL-Form Ir/Re chamber
- **Primary Performance Testing (*See next 2 charts*)**
  - Preliminary results show an **Isp of 333 seconds**— highest Isp ever achieved for the hydrazine/NTO
  - **@ Propellant inlet pressure (275 psia) and mixture ratio (1.1) allow for integration with commonly available propulsion system components**

- **Vibration Testing Completed 12/10/08**
  - Post test inspections showed no anomaly
  - Data analysis in progress
  - Used the HiPAT Qualification Level vibration test spectrum

- **Shock Testing Completed 01/22/09**
  - Post test inspections showed no anomaly
  - Data analysis in progress
  - Referenced the JUNO engine shock SRS
- **Additional Performance Testing Completed 02/17/09**
  - Primarily at lower mixture ratios
- **Long-Duration Hotfire Testing Completed 06/25/09**
  - At mixture ratio 1.1, thrust 140 lbf, fuel inlet pressure 260 psia (preliminary calculations show Isp 333 sec)

AMBR a Proven Design for Higher Performance

Design Characteristics	HiPAT DM	AMBR Design	AMBR Test Results 10/1/08	AMBR Test Results 6/25/09
Trust (lbf) (N2H4/NTO)	100		150	141
Specific Impulse (sec)	326/329		333.5	333
Inlet Pressure (psia)	250		275	250
Chamber Temperature (F)	3100	4000	$\geq$3900	3900
Oxidizer/Fuel Ratio	0.85		1.1	1.1
Expansion Ratio	300:1 / 375:1	400:1		
Engine Mass (lbm)	11.5 / 12	12		
Physical Envelope				
Length (inch)	24.72 / 28.57	25.97		
Nozzle Exit Dia (in.)	12.8 / 14.25	14.6		
Propellant Valves	R-4D Valves	R-4D Valves		

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

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

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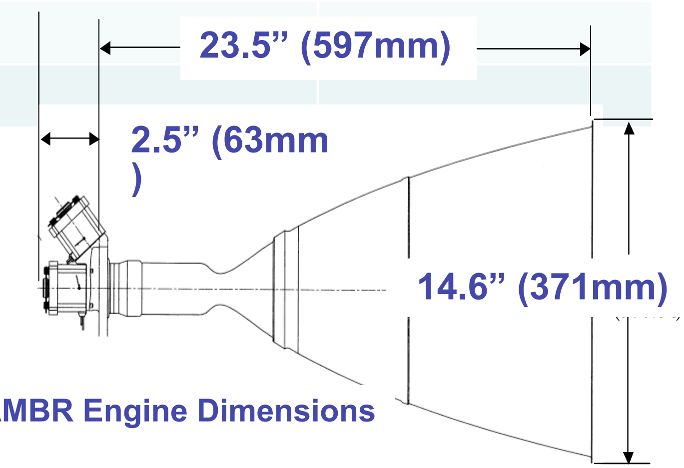


AMBR Engine Dimensions

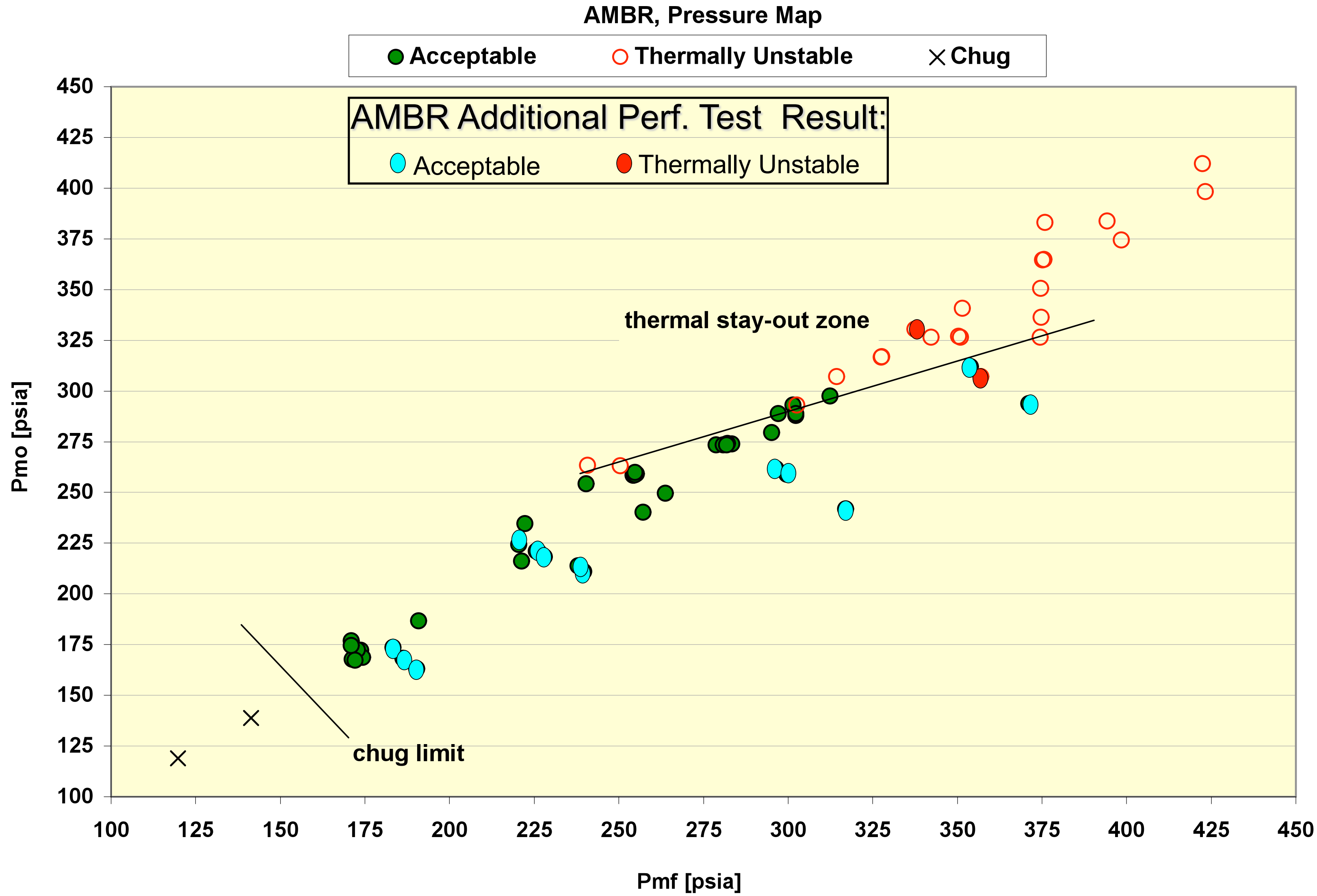
(Primary) Performance Test Summary

- ❑ **48 hot fire runs**
- ❑ **4397 seconds of total burn time**
- ❑ **Propellant consumption**
  - 1040 lbm NTO
  - 840 lbm N2H4
- ❑ **3925-F maximum sustained chamber temperature**
  - Max of 4025-F for transient
- ❑ **288.8-psia maximum chamber pressure**
- ❑ **99.1 psia minimum chamber pressure**
  - Low thrust limit for chugging
- ❑ **333.5 seconds maximum specific impulse (stable op.)**
  - O/F = 1.1 & F = 151.1-lbf
  - O/F = 1.06 & F = 158.6-lbf

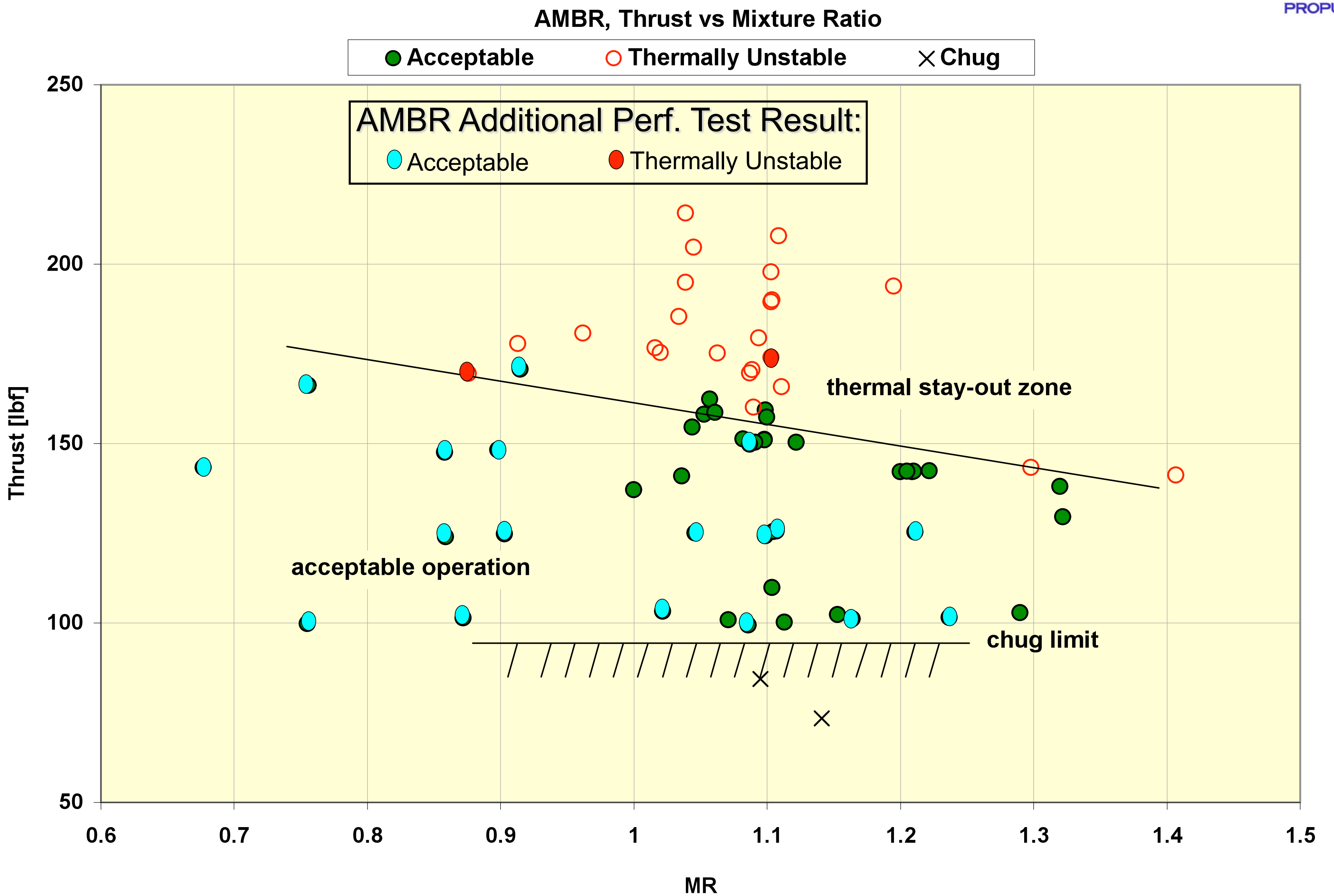
Pre Hot-Fire

Post Hot-Fire

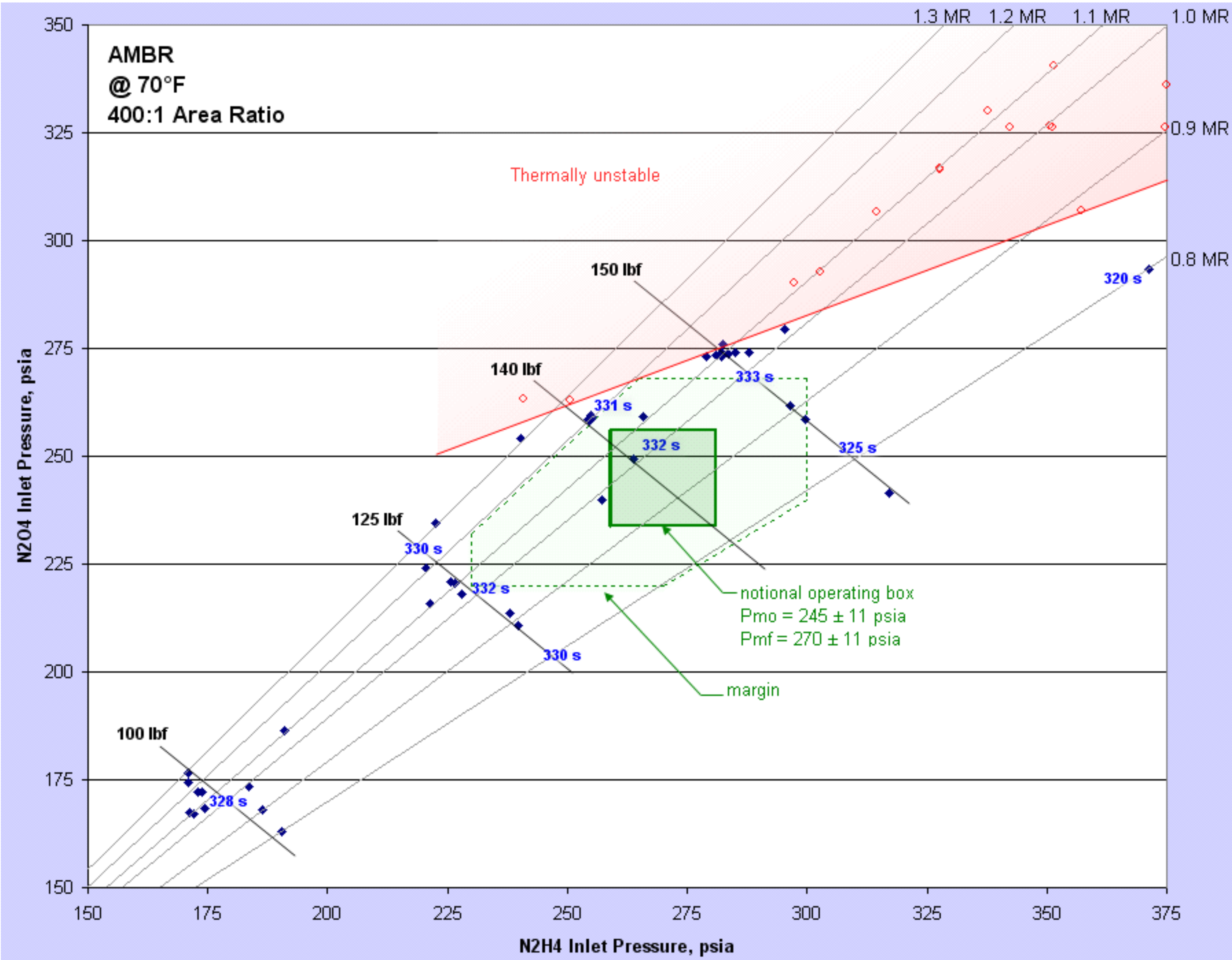
AMBR Test Result
(containing all performance test data)



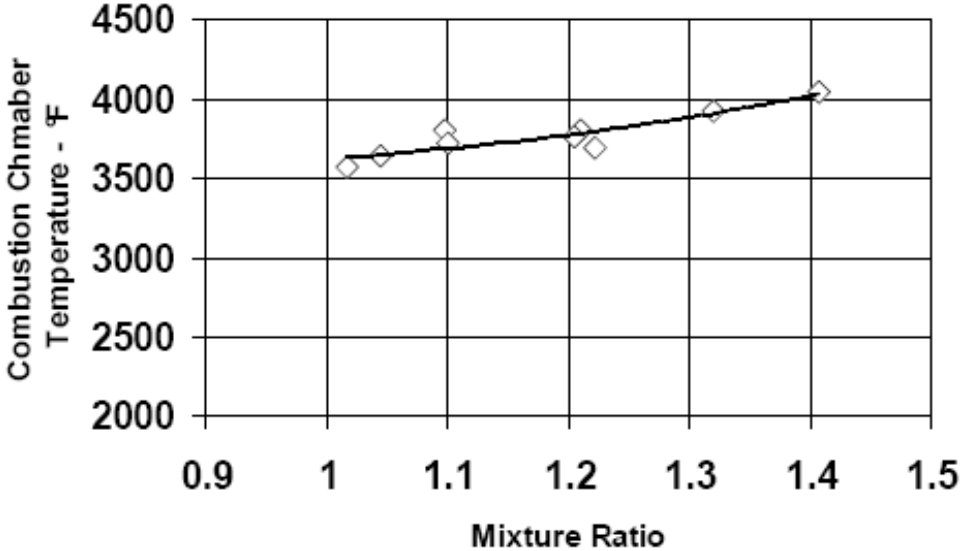
AMBR Test Result
(containing all performance test data)



Notional Operating Box for AMBR
(As of April 17, 2009)

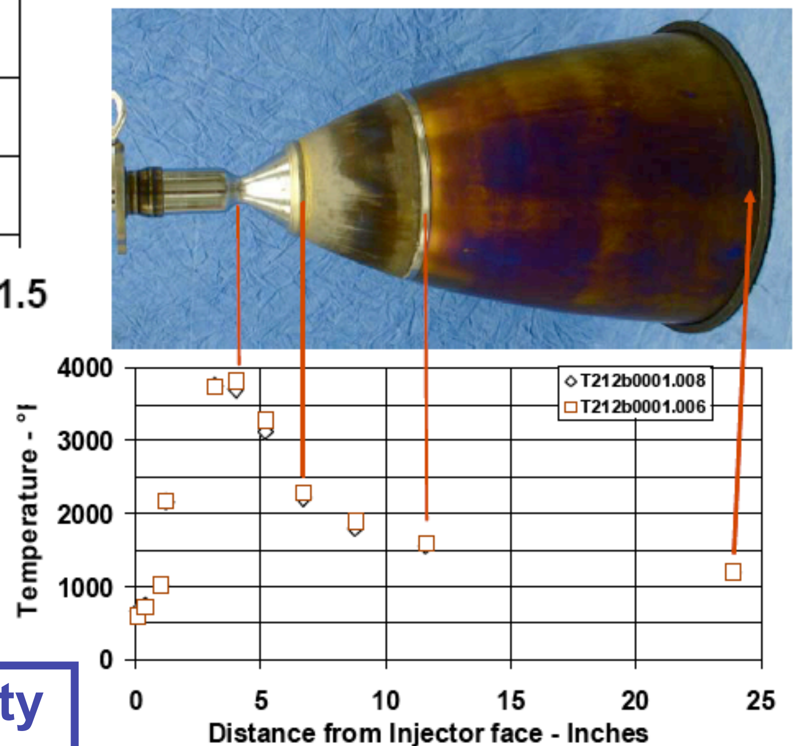


AMBR Engine Temperature During Performance Test



Combustion Chamber Temperature vs Mixture Ratio

Exterior Temperature Scan Using Pyrometer



Utilizing High Temperature Capability of Ir/Re Combustion Chamber

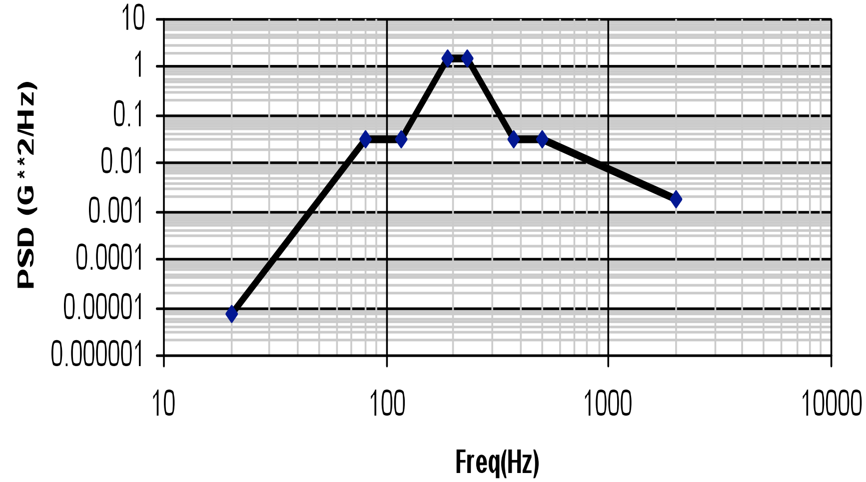
AMBR Engine Vibration Test

Setting up AMBR Engine for Vibration Test at Aerojet, Redmond

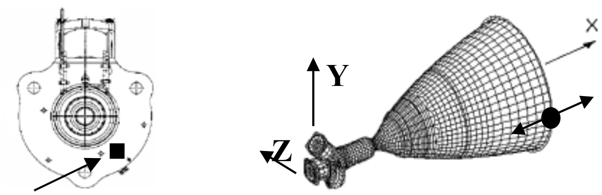
AMBR Engine Vibration Test Parameters

- **Completed AMBR vibration test on 12/10/2008**
  - —No anomaly observed
  - —Data analysis is ongoing
  - —Used the HiPAT Qualification Level vibration test spectrum

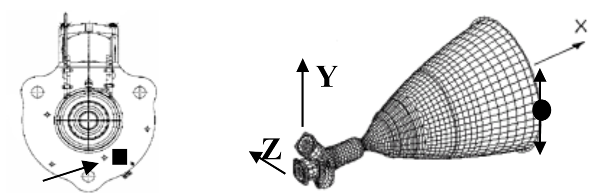
PSD ≡ Power Spectrum Density



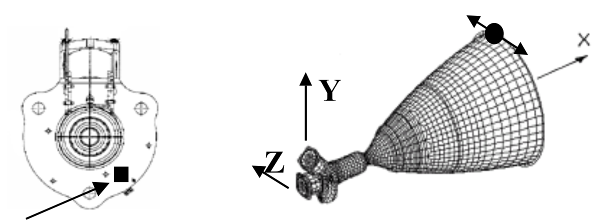
X-Axis



Y-Axis



Z-Axis

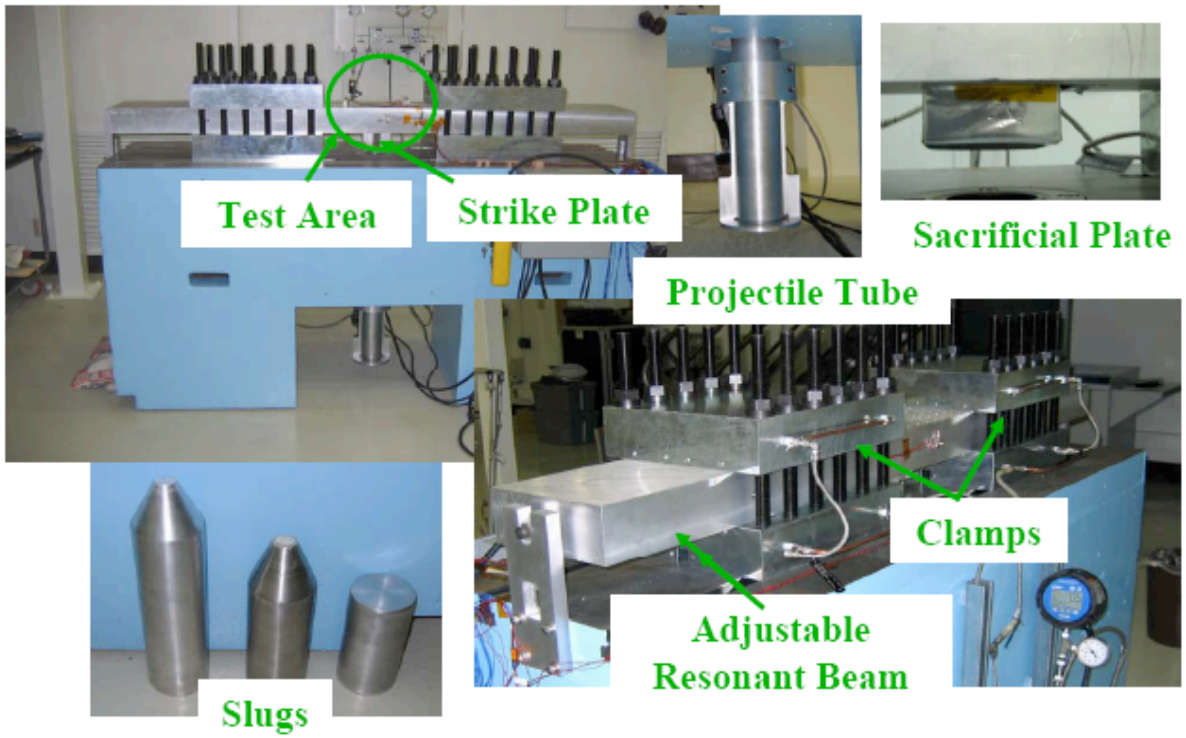


Freq (Hz)	PSD (G^2/Hz)
20	0.0000073
80	0.03
117	0.03
190	1.5
230	1.5
375	0.03
500	0.03
2000	0.0018

Spectrum for Vibration Test

Shock Test Setup at JPL

Tunable Beam Setup



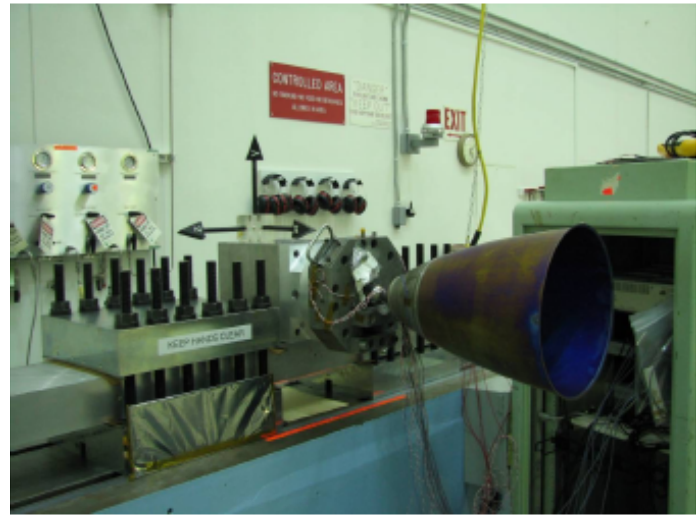
Spacecraft and Launch Vehicle Dynamic Environments Workshop

3

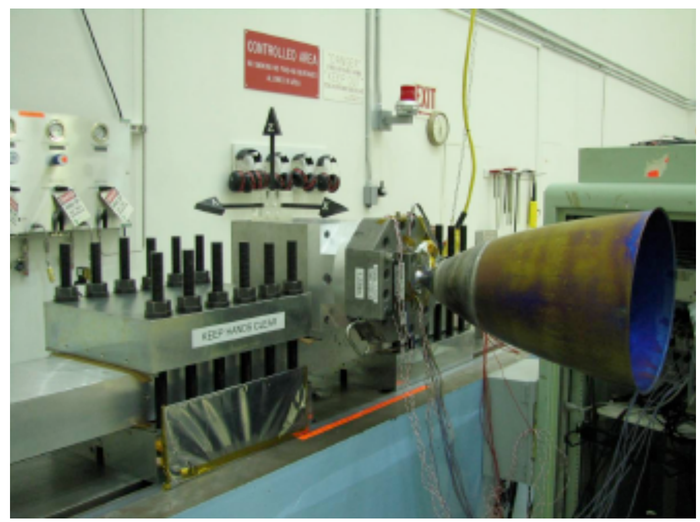
JPL

AMBR Engine Shock Testing at JPL

Shock Testing in X direction

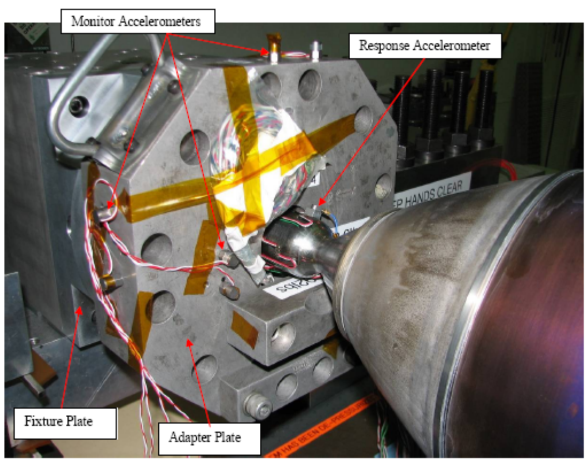


Shock Testing in Y and Z direction

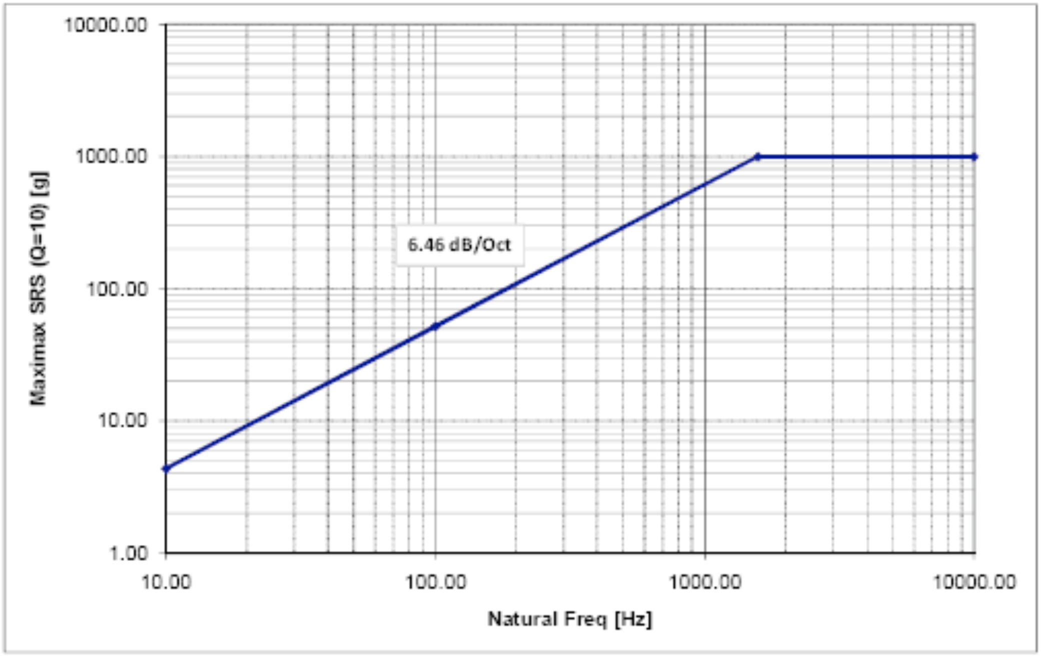


AMBR Engine Shock Test Parameters

- **Completed vibration test on 01/22/2009**
  - No anomaly observed
  - Data analysis and hardware inspection are underway
  - Used the Shock Response Spectrum (SRS) adapted from JUNO mission



AMBR engine mounted on the adapter and fixture plate



Natural Frequency [Hz]	Maximax SRS [g] (Q=10)
10	4.4
100	52
1579	1000
10,000	1000
Two shock pulses *per axis*	

Simulated Pyroshock Requirement

AMBR Points of Contact

AMBR Points of Contact at Aerojet:

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