Space Launch System Base Heating Test:
Sub-Scale Rocket Engine/Motor Design, Development & Performance Analysis

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Outline

♦ Test Program Background & Motivation
♦ ATA-002 Core-Stage Rocket Engine Module (CS-REM)
  • Design, Development & Performance Analysis
♦ ATA-002 Booster Stage Solid Rocket Motor (BSRM)
  • Design, Development & Performance Analysis
♦ CS-REM & BSRM Integrated Test
♦ Conclusions
ATA-002 Technical Team

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Space Launch System (SLS) Architecture

**RS-25 Engines**: LOX/LH2
**SRB**: ACP/16% Al loading
Total Vac Thrust ~8 million lb_f

2 Solid Rocket Boosters (SRBs)

Interstage

Launch Abort System

Orion

Interim Cryogenic Propulsion Stage (ICPS)

Core Stage

4 RS-25 Engines

2017 EM-1
Motivation for Ground Tests

♦ Six hot rocket plumes expanding and interacting near the vehicle base
  • Potential to generate high thermal environments within base and nozzles

♦ Base flows demonstrate complex flow physics
  • No pure analytical methods have been developed for adequate prediction

♦ New base geometry and performance requirements for SLS
  • Cannot blindly use heritage data

♦ CFD and semi-empirical methodologies show poor comparisons
  • Significant deviations in magnitude and trends

♦ Accurate base flow environment prediction needed to efficiently size TPS
  • Decreases vehicle cost and improves crew safety
Limited numerical and analytical studies have been conducted to fully characterize multi-plume base heating.

For the following reasons:
1. Complex
2. Unsteady
3. Many interacting flow features
4. Leads to many different trends, distributions and deltas

Base Flow Regimes:

**Aspirating** – Freestream air is entrained by the non-interacting rocket plumes (cooling)

**Transitional** – slight interactions by adjacent plumes leads to updraft plume component and downward aspirating jet

**Recirculating** – large interactions by highly expansive plumes leads to predominantly an updraft plume (heating)

*Mehta et al. JSR 2013*
ATA-002 SLS Pathfinder Test Program

- ATA-002 Base Heating Test Program is broken down into two sub-test programs: (1) Pathfinder and (2) Main Base Heating Test

- Goal is to develop sub-scale SLS propulsion systems similar to full-scale flight system to be used for short-duration (~100 msec) base heating tests.

- The Pathfinder Program has many difficult challenges:
  - Highly complex test program (simulate solid & liquid propulsion systems)
  - Short-duration testing
  - Different configuration/performance than Shuttle Base Heating Models
  - Not attempted in 40 years
  - Limited heritage technical resources (engineers/technicians/components)
  - Limited funding & short schedule as compared to heritage test programs

- Pathfinder Test Program is the main focus of this paper
Main Goal: To measure base flow and heating characteristics for the SLS1000x vehicle and to scale these measurements for flight predictions

Test Requirements
- 2% SLS-1000x Model
- Test in short-duration test facility – CUBRC LENS II
- Simulated altitude: 45 kft to 200 kft, Mach 2.5 to 5.5
- Configuration: full-stack and core-only stage space flight conditions
- Test Duration: ~100 msec steady-state time window
- No gimbaling of engines/motors
- No Angle of Attack
- Test Engine-Out Case
- 200 measurements within base and external nozzles
CUBRC LENS Shock Tunnels

LENS I M=7-24

LENS II M=2.5-10
(including Ludwieg Mode)

48-inch Tunnel M=8-20
[Low Density]

LENS XX
Velocity
2,500-12,000 km/sec

LENS II test run times:
200 msec – 30 msec
Rocket Combustion Chamber Failure During Ignition Start

Rocket Engine Injector Failure During Ignition Start

H2-F2 5000 lbf Engine Injector Failure

ROCKET SCIENCE IS HARD

H2-F2 5000 lbf Engine Injector Failure
ATA-002 Core-Stage (CS) Rocket Engine Module (REM) Design

♦ Initial design based on in-house engineering codes and assessment:
  • QICE – engine component sizing/design & performance
  • IBFF – state parameter time history prediction code of the model performance
  • Valve-venturi design & performance code
  • Heritage design comparisons

♦ Final design based on in-house CFD internal flow modeling of propulsion system:
  • Combustion Instability Assessment
  • CUBRC developed CAD geometry
  • Loci-CHEM – CFD Code with finite-rate chemistry
  • Led to re-design of GO2 manifold system and combustor
  • Provided performance curves

♦ Final design based on thermal modeling
  • Patran/Sinda G – Led to nozzle material and coating selection

♦ Developed nozzle specific enthalpy flow code
  • Determines the nozzle exit specific enthalpy profile, the required test duration and material selection

♦ Loads FEA

♦ Extensive design & analysis efforts were done to minimize cost and schedule risks.

Internal engine instrumentation installed by CUBRC to determine performance and validation of design methodology
♦ All performance parameters:
  • Have met design requirements
  • Show good agreement with EV33 prediction and design tools
  • Show similarity to full-scale RS-25D engine system

♦ All engine pressure measurements obtained by PCB-111 quartz gauge
CS-REM Plume

♦ MSFC camera provided high-resolution (1280 px x 800 px) and high frame-rate (16000 Hz) visible (VIS) video of CS-REM hot-fire tests
♦ MSFC infra-red (IR) camera provided long-wave IR video of CS-REM hot-fire tests
♦ Able to adequately determine the shock structure and flow physics

♦ SSME VIS video taken during static sea-level testing at NASA Stennis Space Center
CS-REM Plume Analysis

♦ CS-REM plumes:
  • Are over-expanded at sea-level conditions
  • Free-jet boundary converge toward the centerline
  • Develops a characteristic Mach disc
  • No plume-plume interactions observed

♦ CS-REM shock structure and flow physics show good similarity with full-scale RS-25D (SSME) systems.
  • Important to obtain high-fidelity base heating data

♦ Zone of silence normalized distance increases linearly with chamber pressure.

- Mach Disc
- Oblique Shocks
- Free Jet Boundary
- Shock Cell
- Zone of Silence
- Zone of Silence/De
- Zone of Silence
- Mach Disc Diameter/De
- Mach Disc Diameter
- NOZZLE FLOW SEPARATION
- NOZZLE FLOW SEPARATION

\[ \frac{P_c}{P_{\text{inf}}} \]

\[ \frac{\text{Zone of Silence}/D_e}{\text{Zone of Silence}} \]

\[ \frac{\text{Mach Disc Diameter}/D_e}{\text{Mach Disc Diameter}} \]
ATA-002 Booster Solid Rocket Motor (BSRM) Design

- **New Design**
- **Old Design**

- **Initial design based on in-house engineering codes:**
  - Conservation of mass sizing/design & performance code
  - Heritage design comparisons

- **Final design based on thermal modeling**
  - Patran/Sinda G – Led to nozzle material and coating selection

- **Developed nozzle specific enthalpy flow code**
  - Determines the nozzle exit specific enthalpy profile, the required test duration and material selection

- **Initial design did not meet performance requirements due to significant ignition delay**
  - Required trial-and-error igniter options to obtain desired ignition response time

- **CUBRC with NASA MSFC collaboration developed an innovative igniter to meet design requirements**

Internal engine instrumentation installed by CUBRC to determine performance and validation of design methodology.

ATA-002 BSRM Performance Analysis

Model Results

CERAMIC COATED NOZZLE

Model Solution

Test Data

<table>
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<th>SRM Run 006</th>
<th>PROPELLANT X</th>
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Test Rocket Motor

SRM Chamber Pressure (psia)

Run Time (sec)

CERAMIC COATED NOZZLE

Model Solution

Test Data
Integrated Core/Booster Stage Propulsion

Base View

Top View

Side View
Integrated Core/Booster Stage Hot-Fire Test
Integrated Core/Booster Stage Rocket Plumes

CUBRC VIS camera 4700 fps at 800 px x 600 px resolution

VIS and LW-IR videos show CS-REM and BSRM plumes all-firing together as designed.

All CS-REM plume Mach discs are within the same location and have the same diameter

Plumes are fully-developed and steady in less than 35 msec

Plume diameters are similar between the left and right BSRMs

No flow asymmetry observed

Showed propulsion designs are successful.
Conclusions

♦ ATA-002 Technical Team has successfully designed, developed, tested and assessed the SLS Pathfinder propulsion systems for the Main Base Heating Test Program.

♦ Major Outcomes of the Pathfinder Test Program:
  • Reach 90% of full-scale chamber pressure
  • Achieved all engine/motor design parameter requirements
  • Reach steady plume flow behavior in less than 35 msec
  • Steady chamber pressure for 60 to 100 msec during engine/motor operation
  • Similar model engine/motor performance to full-scale SLS system
  • Mitigated nozzle throat and combustor thermal erosion
  • Test data shows good agreement with numerical prediction codes

♦ Next phase of the ATA-002 Test Program
  • Design & development of the SLS OML for the Main Base Heating Test
  • Tweak BSRM design to optimize performance
  • Tweak CS-REM design to increase robustness

♦ MSFC Aerosciences and CUBRC have the capability to develop sub-scale propulsion systems to meet desired performance requirements for short-duration testing.
Acknowledgement & References

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♦ Detail information on propulsion design, fabrication, test and performance analysis will be published as a NASA Technical Memorandum.
Thank You

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