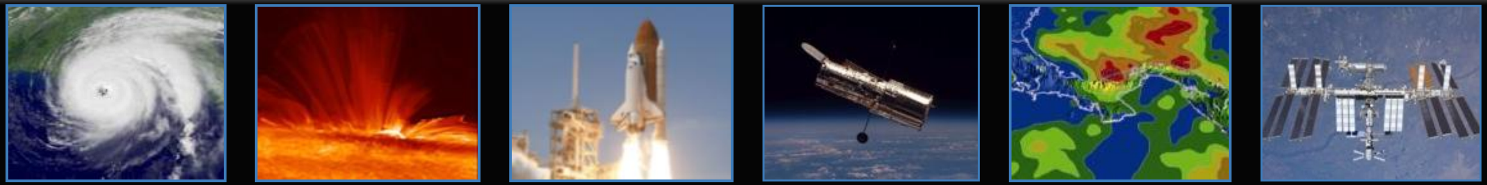
National Aeronautics and Space Administration

NASA’s Reusable Stages and Liquid Oxygen/Hydrocarbon (LOX/HC) Engines

Garry Lyles
Space Launch System (SLS) Chief Engineer
Marshall Space Flight Center

February 17, 2012

Space Launch System



Advancing the U.S. Legacy of Exploration

NASA Experience with LOX / RP-1 Propulsion

- **NASA systems**
  - RP-1 experience spans a significant period of Agency history
  - Strong heritage of h**ardware design**, development, analysis and **test exists within the agency**
  - MSFC has significant capabilities in supporting disciplines such as materials, manufacturing, and test
- Industrial base strengthened through NASA programs and technology transfer
  - History of partnering with industry in various capacities has further advanced the U.S. knowledge base
  - Transfer of key design codes, test and materials data, analytical results
  - **Recent F-1 disassembly work, both at MSFC and at PWR, ensures the next generation has an understanding of RP-1 propulsion**

History of LOX/RP-1 Engine Development
MSFC Partnered with Industry

1955 - 1973
F-1
Gas Generator Cycle
Prime: Rocketdyne

Flew on Saturn V

F-1A
In development at the end of the program

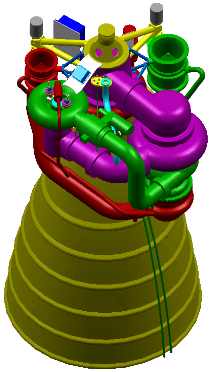
Upgraded Turbomachinery

2001 - 2004
TR107
Ox- Rich Stage Combustion
Prime: TRW

Engine to CoDR fidelity

Subscale (5k) Pintle Test at Purdue

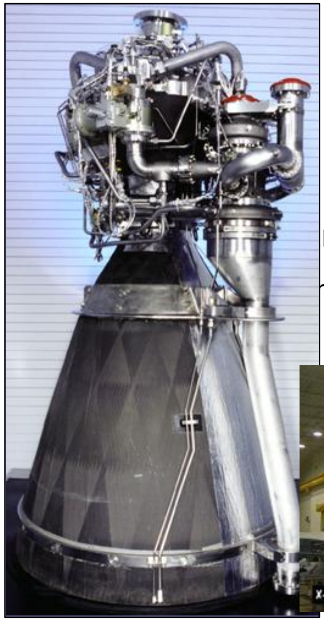
250 k Preburner Built, not Tested



1996-2001
Fastrac (MC-1)
Gas Generator Cycle
Government Design
Hardware Prime: Summa
Vehicle Prime: Orbital

ngine was Fully Developed

ngine assembled into the X-34 vehicle but did not fly



2001 - 2004

RS-84
Ox-rich Stage Combustion
Prime: Rocketdyne

Engine to IDR
(nearly CDR fidelity)

Significant subscale testing completed

History of LOX/RP-1 Engine Development

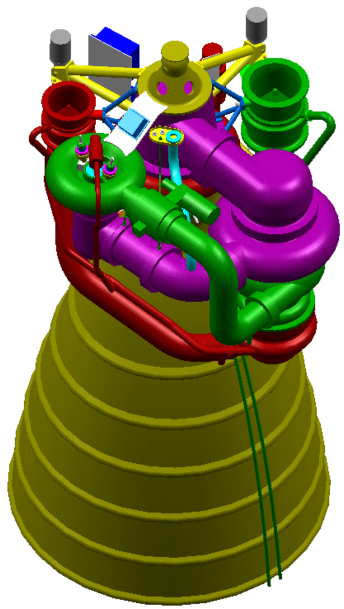
Engine Size Comparison

LOX/Hydrogen

LOX/Kerosene

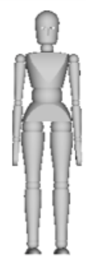
Fastrac

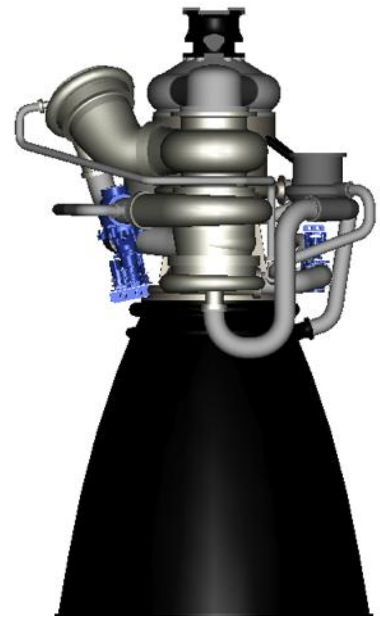
Tsl = 60 Klbf
Tvac = 63.9 Klbf
Isp (sl) = 300 sec
Isp (vac) = 314 sec
Pc = 652 psia
Wt = lbm
T/W (sl/vac) = / L ="
Nozzle ID = 45.7"
MR = 2.17



TR107

Tsl = 1,000 Klbf
Tvac = 1,074 Klbf
Isp (sl) = 300 sec
Isp (vac) = 327 sec
Pc = 2500 psia
ε_e = 25:1
Wt = 11,300 lbm
T/W (sl/vac) = 88 / 95
L = 180"
Nozzle ID = 92"
MR = 2.7





ORSC-RS84

Tsl = 1,050 Klbf
Tvac = 1,155 Klbf
Isp (sl) = 305 sec
Isp (vac) = 335 sec
Pc = 2700 psia
ε_e = 30:1
Wt = 15,925 lbm
T/W (sl/vac) = 65 / 73
L = 168"
Nozzle ID = 95.5"
MR = 2.7

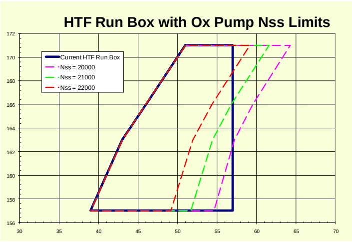
F1

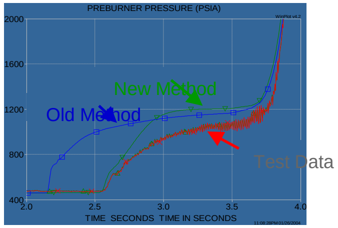
Tsl = 1,522 Klbf
Tvac = 1,748 Klbf
Isp (sl) = 265.4 sec
Isp (vac) = 304.1 sec
Pc = 982 psia
ε_e = 16:1
Wt = 18,616 lbm
T/W (sl/vac) = 82 / 94
L = 220"
Nozzle ID = 140"
MR = 2.27

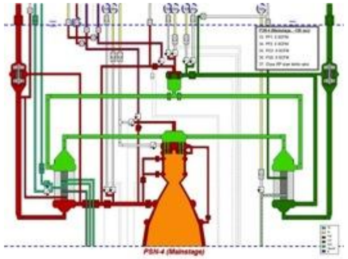
History of LOX/RP-1 Propulsion

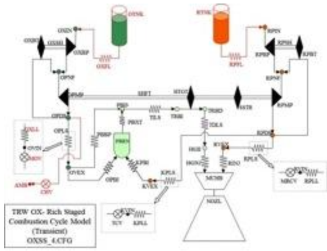
Engine System and Component Design and Analysis

Engine Systems

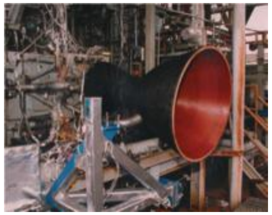


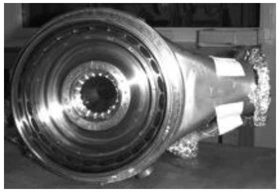


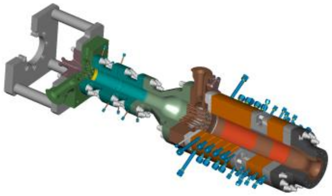


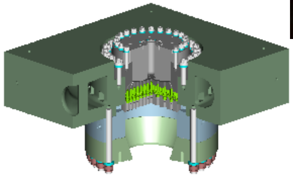


Turbomachinery Combustion Devices Lines, Valves, Actuators Detail Design

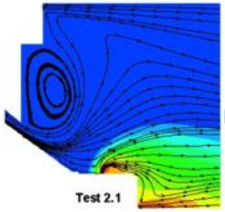


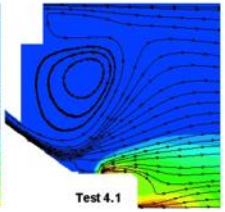


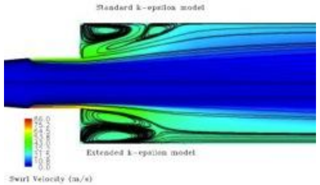


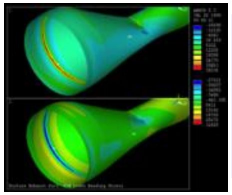


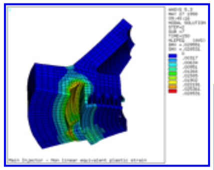
Stress, Life Assessment, Loads and Dynamics, Thermal, Acoustics, and CFD Analysis

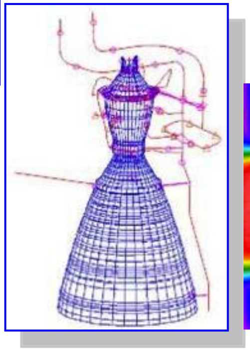


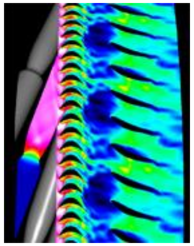


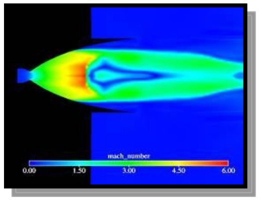


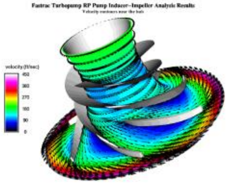


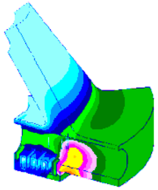


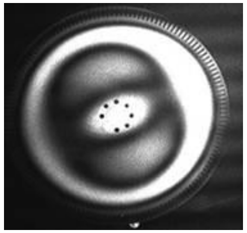


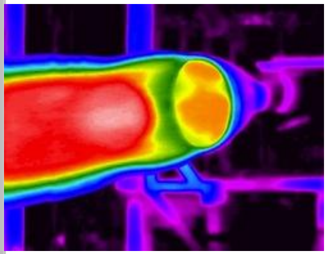












History of LOX/RP-1 Propulsion

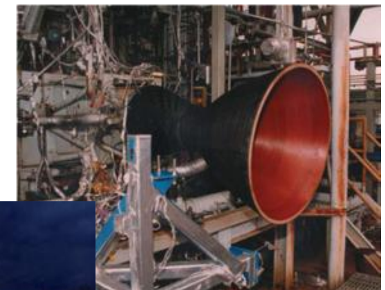
Fastrac Engine and Stage Testing and Integration

	HTF	PTA	Alfa 1	ALL
Total Tests	*35*	*5*	*17*	*57*
Total Hot Fires	*27*	*3*	*12*	*42*
Total Main Stage Tests > 5 sec	*15*	*2*	*8*	*25*
Total Seconds	*428*	*138*	*322*	*888*
Main Stage Sec	*330*	*126*	*276*	*732*
Early Cuts for Engine Causes	*9*	*0*	*2*	*11*

History of LOX/RP-1 Propulsion

Component Testing Provides Critical Risk Reduction

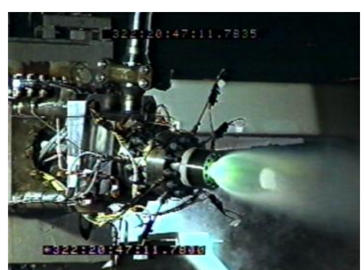

Purdue TR107 5k ORPB Testing




MSFC Fastrac Component Testing



RS84 Testing at MSFC and SSC

History of LOX/RP-1 Propulsion

Unique Test Facilities Aid Industry

East Test Area

- Subscale and component level high-pressure testing of injectors, nozzles, pumps, thrust chambers
- TS115, TS116

Materials Lab

- Failure investigation
- Comprehensive Materials Testing
- State of the Art Welding, Brazing techniques
- Structured light
- Advanced Manufacturing

North Test Area

- Unique, low-cost, quick-turnaround fluid flow tests
- Turbine, Inducer, Pump, and Nozzle test facilities

SSC

- LOX/RP1 Engine Systems Testing
- LOX/RP1 Large component testing
- Stage Testing

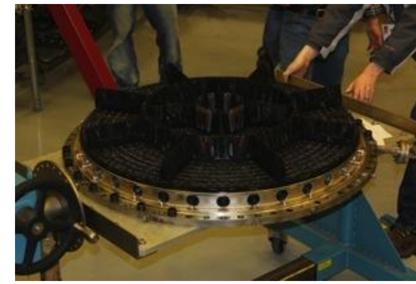
Component Development Area

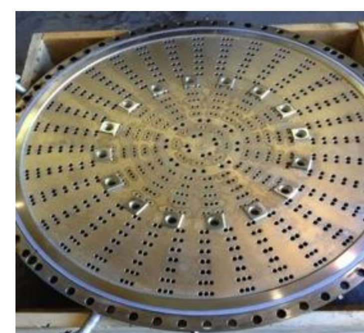
- Unique propulsion system component technology assessment
- Focused on valve, regulator, solenoid, and seal development

History of LOX/RP-1 Propulsion

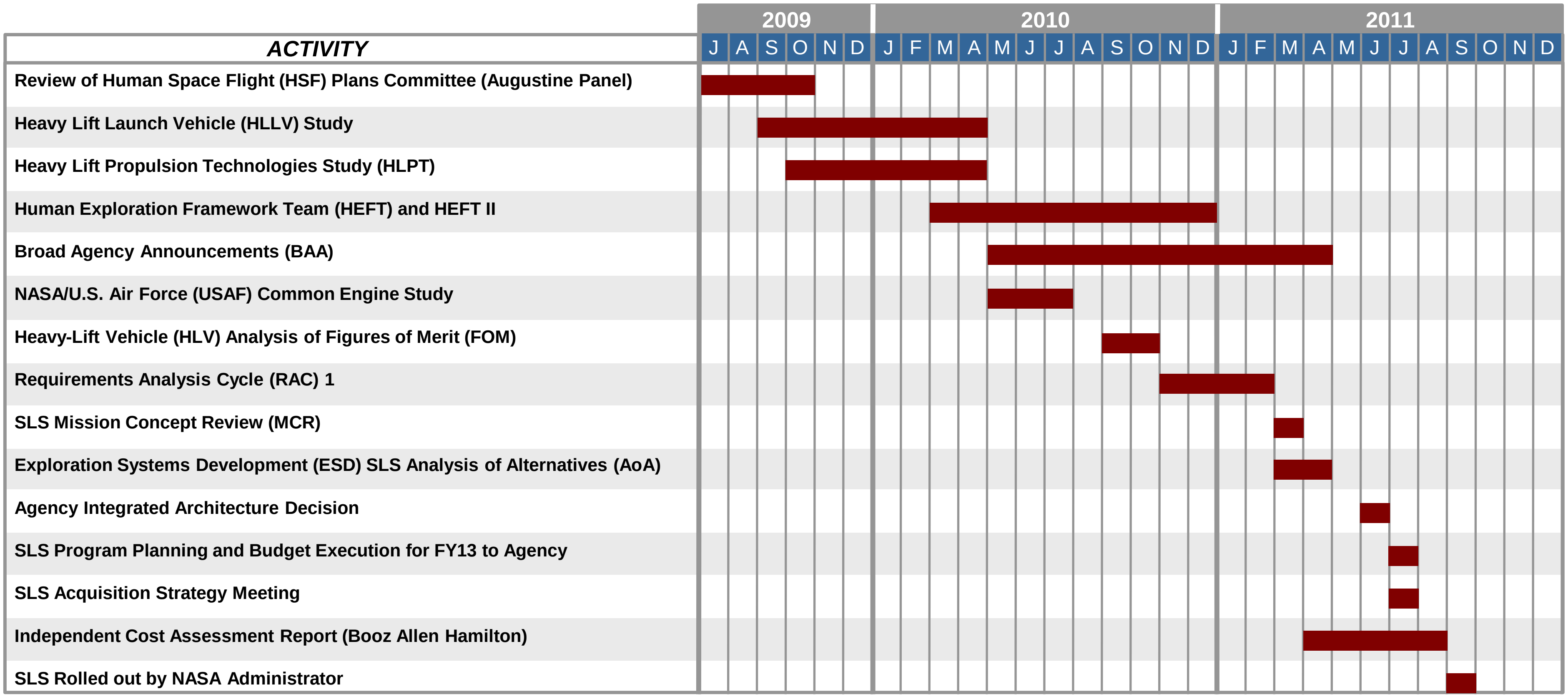
Recent F-1 Disassembly

Prepares Government and Industry Workforce for SLS Advanced Booster NRA





Studies & Activities Leading to the SLS Decision



Engineering and Business Analyses Validated SLS Architecture Selected by the Agency

NASA Authorization Act of 2010

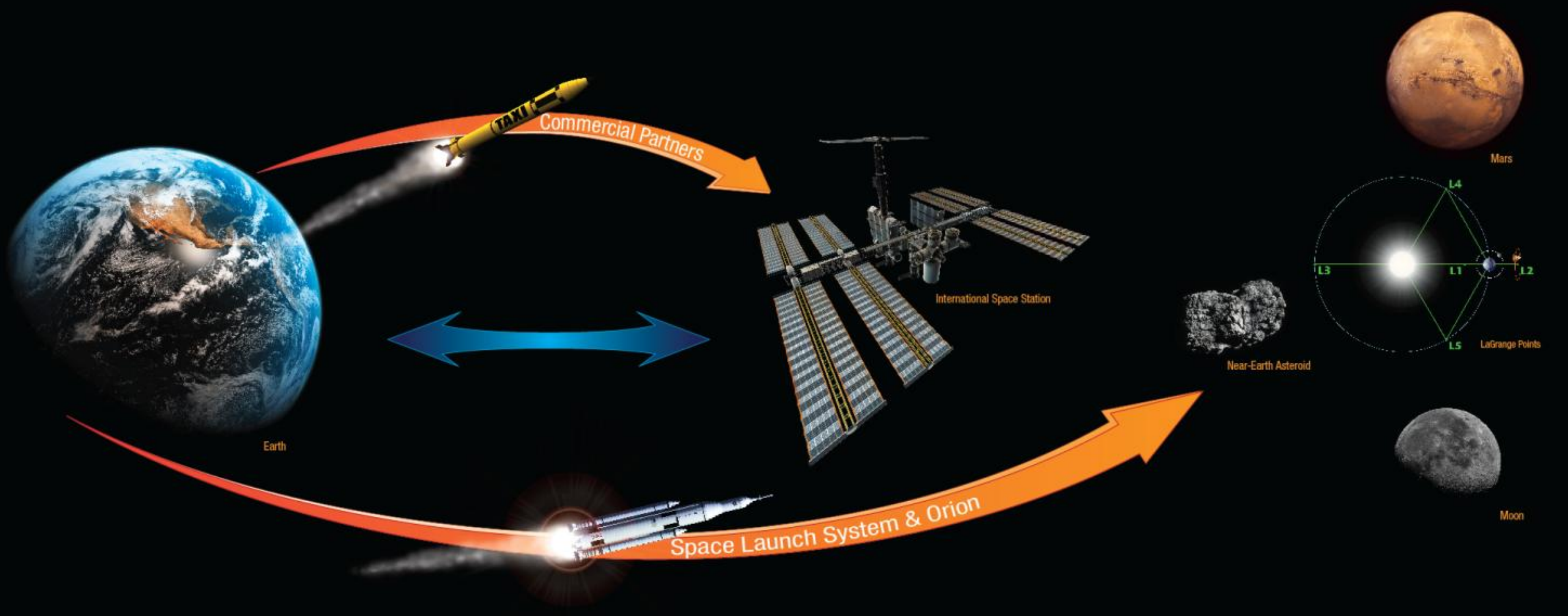
- **The Congress passed and the President signed the National Aeronautics and Space Administration Authorization Act of 2010.**
  - Bipartisan support for human exploration **beyond low-Earth orbit (LEO)**

- **The Law authorizes:**
  - Extension of the International Space Station (ISS) until at least 2020
  - Strong support for a commercial space transportation industry
  - **Development of Orion Multi-Purpose Crew Vehicle (MPCV) and heavy lift launch capabilities**
  - A “flexible path” approach to space exploration, opening up vast opportunities including near-Earth asteroids and Mars
  - New space technology investments to increase the capabilities **beyond Earth orbit (BEO)**

This rocket is key to implementing the plan laid out by President Obama and Congress in the bipartisan 2010 NASA Authorization Act.
— NASA Administrator Charles Bolden
September 14, 2011

Delivering on the Laws of the Land … and Obeying the Laws of Physics

The Future of Exploration



My desire is to work more closely with the human spaceflight program so we can take advantage of synergy…We think of the SLS as the human spaceflight program, but it could be hugely enabling for science.

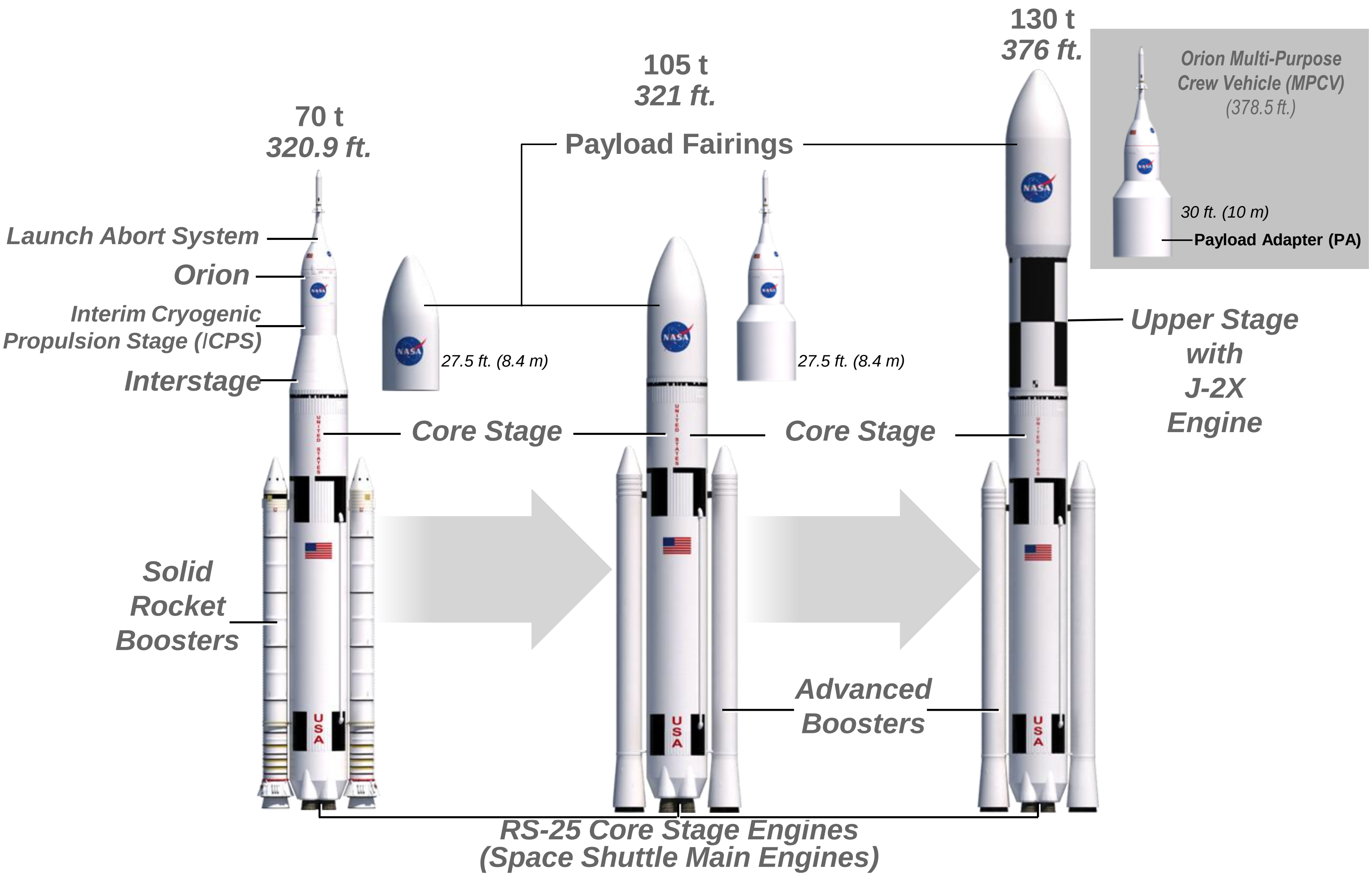
— John Grunsfeld, Associate Administrator
NASA Science Mission Directorate
Nature, Jan 19, 2012

SLS Driving Objectives

- ♦ **Safe: Human-Rated**
- ♦ **Affordable**
  - Constrained budget environment
  - Maximum use of common elements and existing assets, infrastructure, and workforce
  - Competitive opportunities for affordability on-ramps
- ♦ **Sustainable**
  - Initial capability: 70 metric tons (t), 2017–2021
    - Serves as primary transportation for Orion and exploration missions
    - Provides back-up capability for crew/cargo to ISS
  - Evolved capability: 105 t and 130 t, post–2021
    - Offers large volume for science missions and payloads
    - Modular and flexible, right-sized for mission requirements

Flexible Architecture Configured for the Mission

SLS Evolutionary Block Upgrades

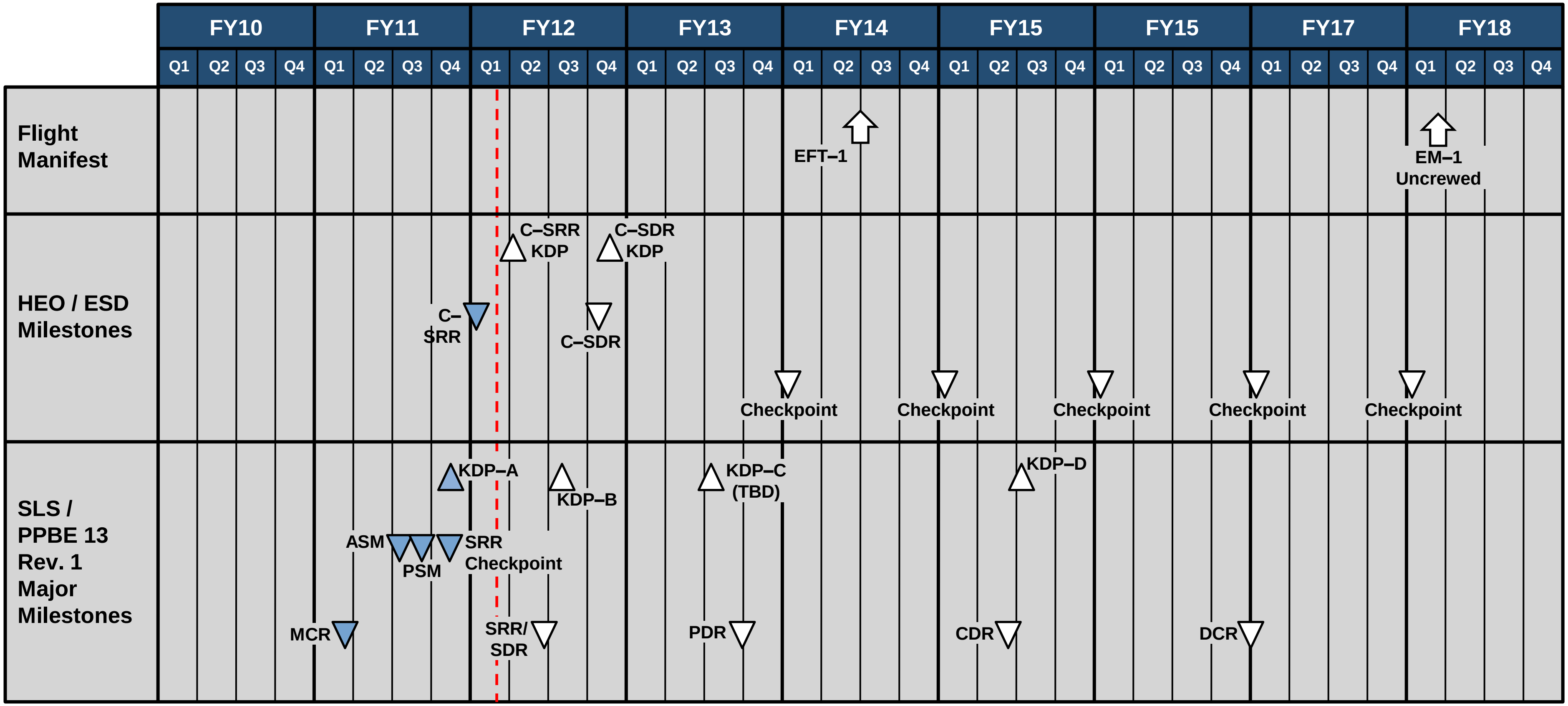


Incremental Capabilities Delivered within the Planned Budget

Assets in Inventory and Testing in Progress

First Flight 2017

Key Milestones



SLS-SCHED-69

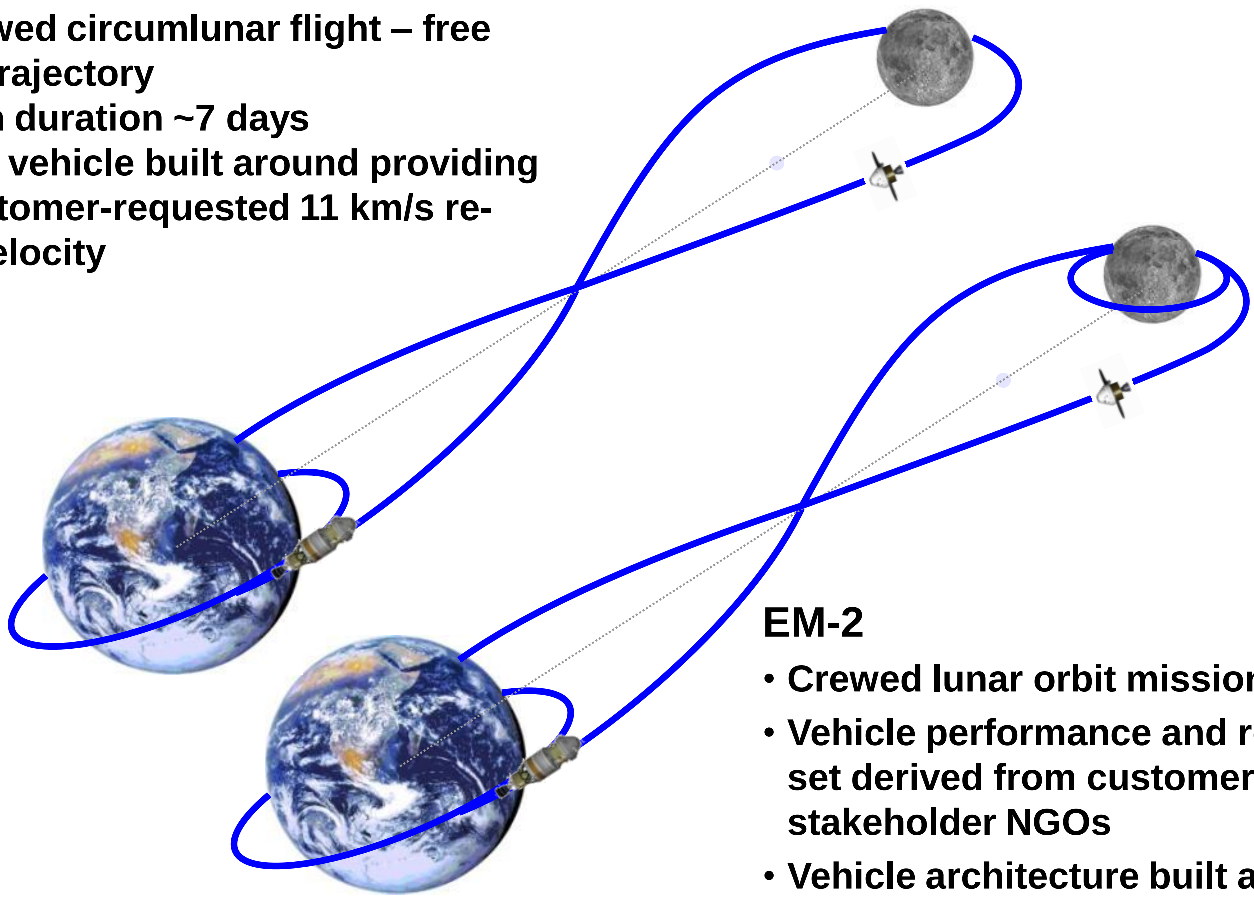
Approved: Nov 17, 2011

LEGEND:

ASM	Acquisition Strategy Meeting
C-SDR	Cross-Program System Definition Review
C-SRR	Cross-Program System Requirements Review
CDR	Critical Design Review
DCR	Design Certification Review
EFT	Exploration Flight Test
EM	Exploration Mission
ESD	Exploration Systems Development
FY	Fiscal Year
HEO	Human Exploration and Operations
KDP	Key Decision Point
MCR	Mission Concept Review
PDR	Preliminary Design Review
PPBE	Program Planning & Budget Estimate
PSM	Procurement Strategy Meeting
SDR	System Definition Review
SRR	System Requirements Review
TBD	To be determined

Early Exploration Missions

EM-1
- Un-crewed circumlunar flight – free return trajectory
- Mission duration ~7 days
- Launch vehicle built around providing the customer-requested 11 km/s re-entry velocity



EM-2
- Crewed lunar orbit mission
- Vehicle performance and requirement set derived from customer needs and stakeholder NGOs
- Vehicle architecture built around customer-required performance with fully capable spacecraft

Requirements built around customer values, initial missions, and stakeholder needs, goals, and objectives.

SLS Booster 3-Phase Development Approach

Full and Open Competition

Advanced Booster Design, Development, Test, and Evaluation (DDT&E)

- Scope: Follow-on procurement for DDT&E of a new booster
- Date: RFP target is FY15
- Capability: Evolved at 130 t
- Contract: Full and Open Competition (Liquids or Solids)

Full and Open Competition

Advanced Booster Engineering Demonstration And/Or Risk Reduction NRA

- Scope: Award contracts that reduce risks leading to an affordable Advanced Booster that meets the evolved capabilities of SLS and enable competition by mitigating targeted Advanced Booster risks to enhance SLS affordability
- Date: ***Issue draft NRA Dec 12, 2011; award targeted for Oct 1, 2012***
- Capability: Leading to 130 t
- Contract: NRA Demonstrating Specific Technologies and Affordability Risk Reduction for Advanced Boosters
  - Liquid Rocket Boosters or Solid Rocket Boosters

Booster Fly-out for Early Flights through 2021

- Scope: Build two 5-segment SRB Flight Sets
- Date: In progress
- Capability: Initial 70–100 t
- Contract: Mod to Ares contract with ATK

Moving Forward from Initial to Evolved Capability

Advanced Booster NRA Technical Summary

Requirements relative to SLS vehicle and booster sizing

- **Performance**
  1. **Mass to Orbit - 130 metric tons (286,601 lbm) to LEO**
  2. **Vehicle Dynamic Pressure < 800 psf**
  3. **Vehicle Acceleration < 4.0 g's**

- **Vehicle Configuration**
  4. **Booster-Core Interface**
     - Forward and aft mechanical attach points similar to Space Shuttle
  5. **Booster-Ground Interface**
     - Vehicle mates to 8 mechanical liftoff posts on Mobile Launcher (ML), similar to Space Shuttle
     - Vehicle fits to plume hole on ML
  6. **Load Path**
     - Boosters support vehicle mass / loads (on ML) during assembly, rollout, prep, and tanking
     - Boosters carry bulk of liftoff and ascent loads through forward attach points to the Core
  7. **Height – Booster max height limited to 235 ft based on Kennedy Space Center's Vehicle Assembly Building (VAB) lift constraint**
  8. **Vehicle Width – Core stage + boosters limited to 67.5 ft due to VAB constraint**

Advanced Booster NRA Reference Launch Vehicle

- **Booster mass and propulsion**
  - Liquid – LOX/RP, with six 1M lbf class high-performance hydrocarbon engines

    or
  - Solid – HTPB solid motor thrust trace
- **Core Stage mass and propulsion information**
  - LOX/LH2 with five RS-25E engines
- **Upper Stage mass and propulsion information**
  - LOX/LH2 with two J-2X engines (288k lbf with smaller epsilon nozzle)
- **Non-propulsive payload element**

Advanced Booster NRA Reference Missions

- **Launch site – KSC LC-39B (geodetic references, latitude, longitude, altitude)**
- **Ascent description and timeline**
  - Liftoff, pitch/roll maneuvers, gravity turn, propulsion assumptions for tailoff or shutdown, and staging information
- **Ascent environments**
  - GRACE gravitational models
  - GRAM atmosphere and winds
- **Control**
  - Assuming basic 3-DOF trajectory analysis
  - Control authority maintained if control torques remain 2x aero torques due to angle of attack (AoA) and side-slip variations (+/- 8 deg)
- **Guidance (similar to Shuttle)**
  - Open loop prior to booster separation
  - Closed-loop algorithm (PEG) after booster separation
- **Trajectory states**
  - At booster separation
    - Solid: Net booster thrust equals 80,000 lbf
    - Liquid: Propellant depletion
  - At mass injection to LEO
    - -47 x 130 nm orbit at 28.5 degrees inclination, with insertion at 77 nm altitude

Advanced Booster NRA Target Areas

Notional Target Areas for Engineering Demonstration and/or Risk Reduction
Large Booster Component Development/Fabrication
Modular/Common Booster Component Development/Fabrication
Oxygen-Rich Materials/Technologies Development
Refined Petroleum (RP) Combustion Performance and Stability Advancement
Potential Recovery and Reuse of Salt Water Recovered Engines and/or Booster Systems
Structural Testing of Low Mass-to-Strength Ratio Material
Non-Destructive Evaluation of Low Mass-to-Strength Ratio Material Structures
Damage Assessment of Solid Propellant/Liner/Insulation Integrity (during fabrication up until launch)
Solid Booster Propellant Formulations
Advanced Manufacturing Process Demonstration
Advanced Material Selection and Test
Thrust Vector Control (TVC) Systems/Components
Booster-to-Core Interface Attach Point Methods/Locations

SLS Is Open to All Potential Solutions

Advanced Development Goals and NRA Summary

Full and Open Competition

Advanced Development NRA

- Concept Development (Trade Studies and Analyses)
- Propulsion
- Manufacturing, Structures, and Materials
- Avionics and Software

Goals

Advanced Development

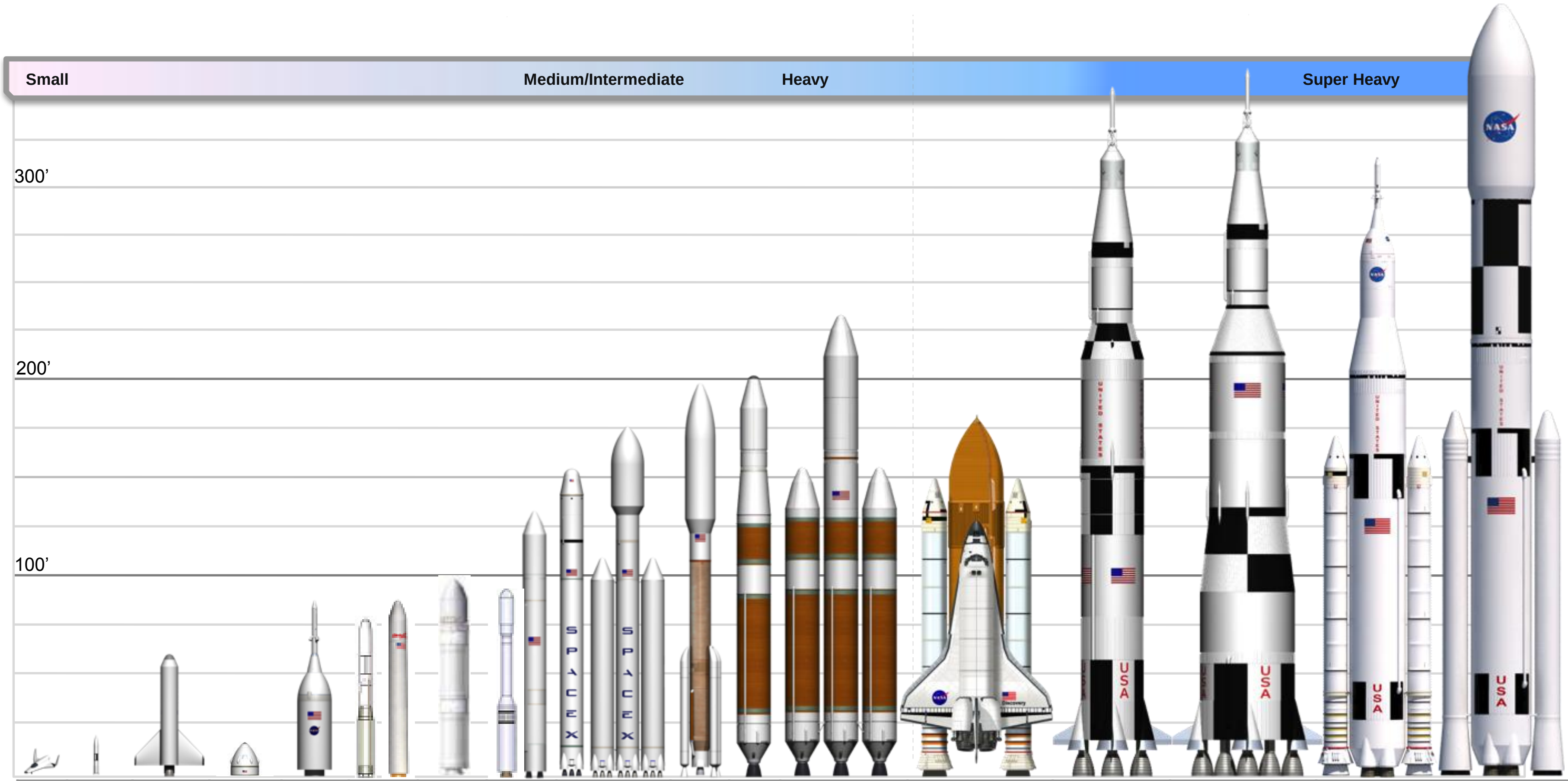
- Support SLS Safety, Affordability, and Sustainability
- Seek out innovative and creative solutions
- Reduce the risk of evolving SLS through block upgrades
- Engage small businesses, academia, and other partners

Initial Capability
2017 – 21

- Builds on current capabilities
- Engages U.S. workforce and aerospace facilities
- Provides a firm foundation for the human and scientific exploration of space

Moving Forward from Initial to Evolved Capability

SLS Will Be the Most Capable U.S. Launch Vehicle



	XCOR Lynx	Masten XA-1.0	AFRL RBX Pathfinder	NESC MLAS	Orbital AA-2	Orbital Minotaur IV & V	ATK Athena II C	Orbital Taurus I & II	SpaceX Falcon 9 & 9H	ULA Atlas V 551	ULA Delta IV M	ULA Delta IV H	NASA Space Shuttle	NASA Saturn V	NASA Nova (Concept Only)	NASA SLS 70 t 130 t
Status	Prop.	Prop.	Prop.	Prop.	Prop.	Prop.	Prop.	Prop.	Active & Prop.	Active	Active	Active	Active	Inactive	Reference	Proposed
FS Thrust (lbf)	12K	3.5K	338K	4.2K	361K	496K	383K	383K/734K	1.1M/3.4M	650K	650K	1.9M	6.8M	7.6M	12M	11.9M

Some Proposed and Fielded U.S. Systems

NASA's Space Launch System Summary

- **SLS is vital to NASA's exploration strategy and the Nation's space agenda.**
- **SLS key tenets are safety, affordability, and sustainability.**
- **Prime contractors have been selected and UCAs have been signed, engaging the U.S. aerospace workforce; Government/contractor Integrated Acquisition Team validation work is in progress.**
- **Existing hardware (RS-25 core stage engines) is being positioned for integration and testing with the core stage.**
- **Advanced hardware testing (five-segment solid rocket boosters and J-2X upper stage engine) is in progress.**
- **Competitive opportunities for advanced boosters and developments that support affordable performance upgrades are in progress.**
- **SLS design and development is on track for first flight in 2017.**

For More Information

www.nasa.gov/sls