National Aeronautics and Space Administration

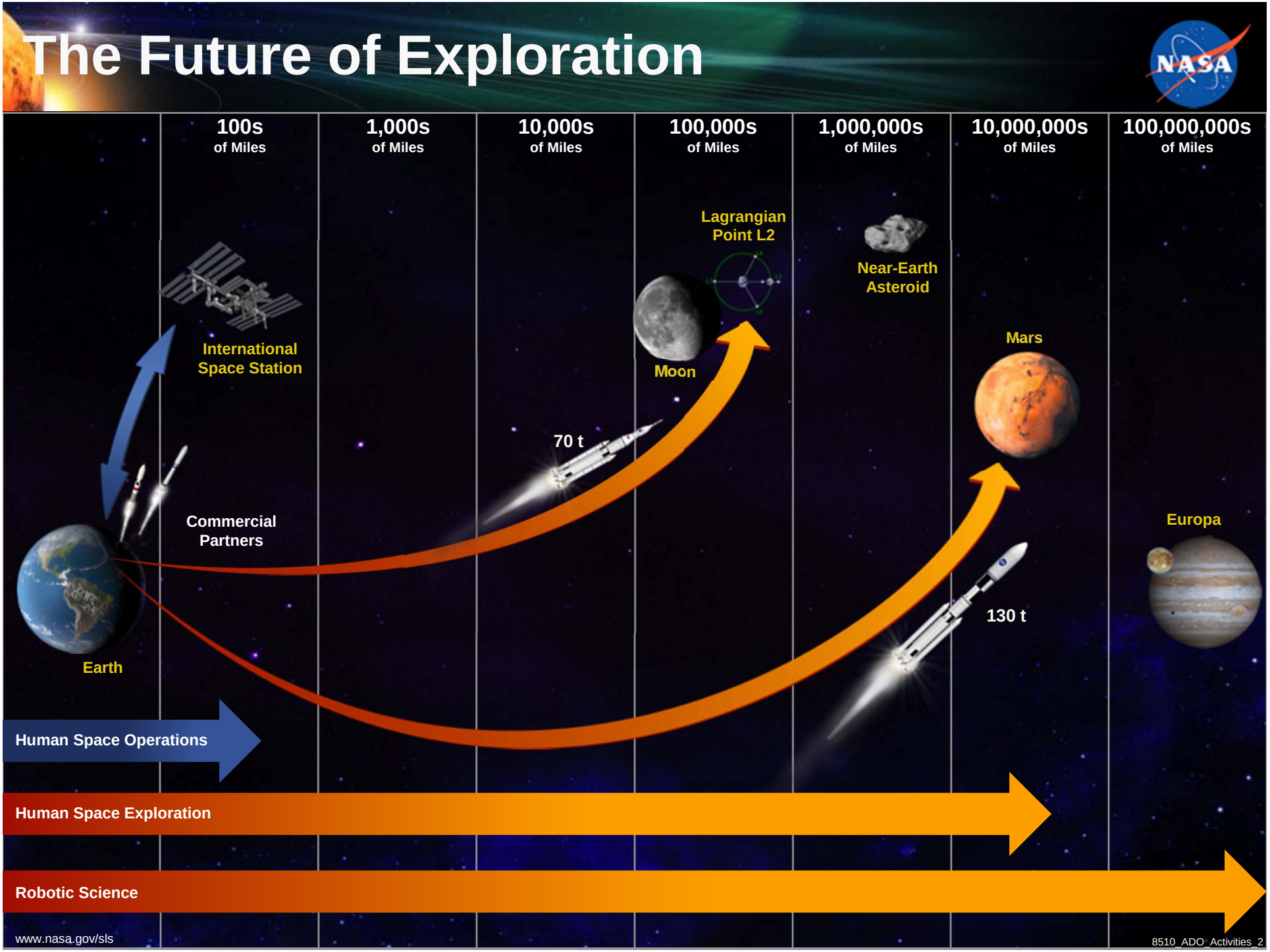
NASA Space Launch System
Advanced Developed Opportunities

Space Launch System

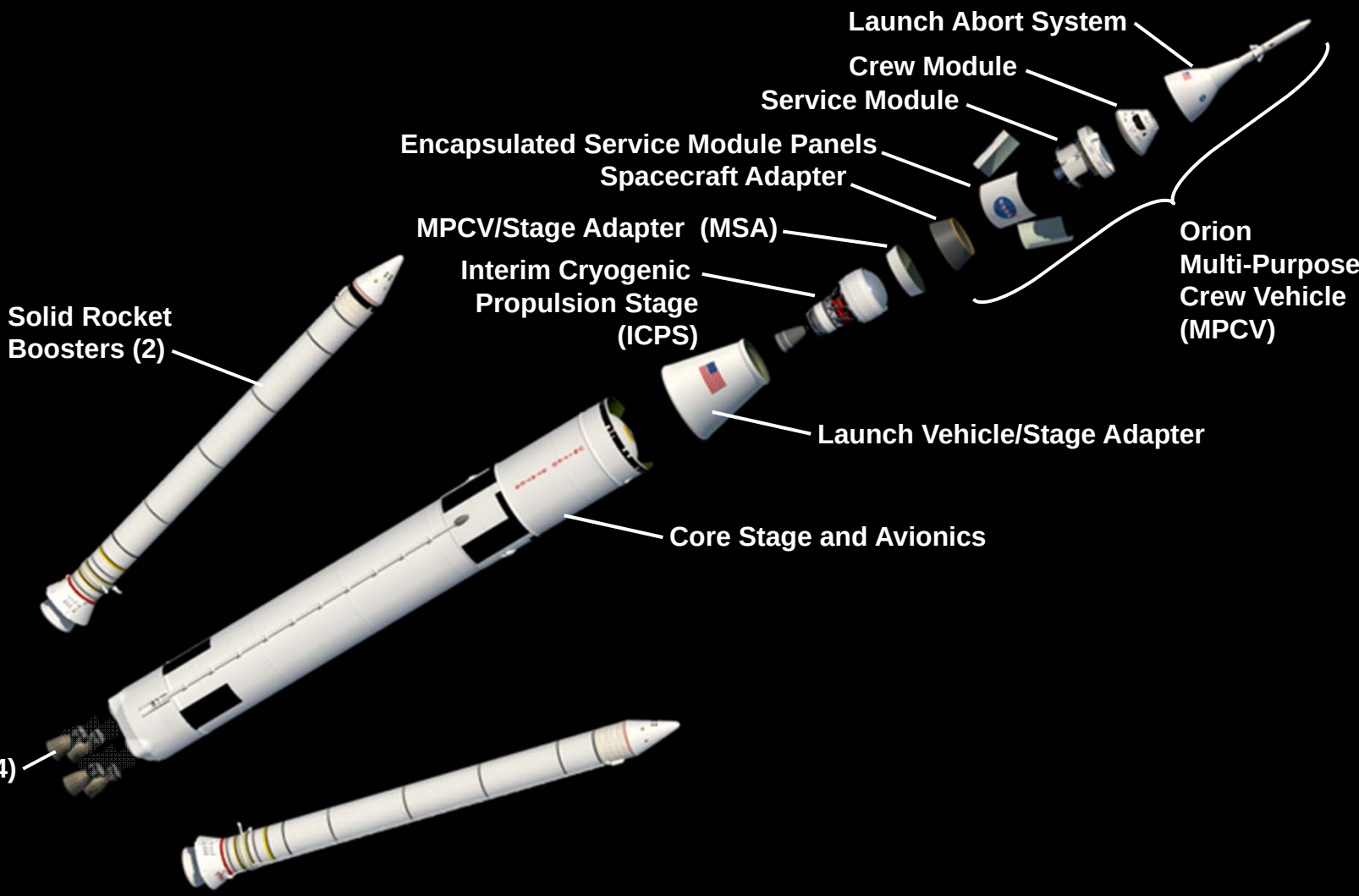
Chris Crumbly, Manager
SLS Advanced Development Office

www.nasa.gov/sls

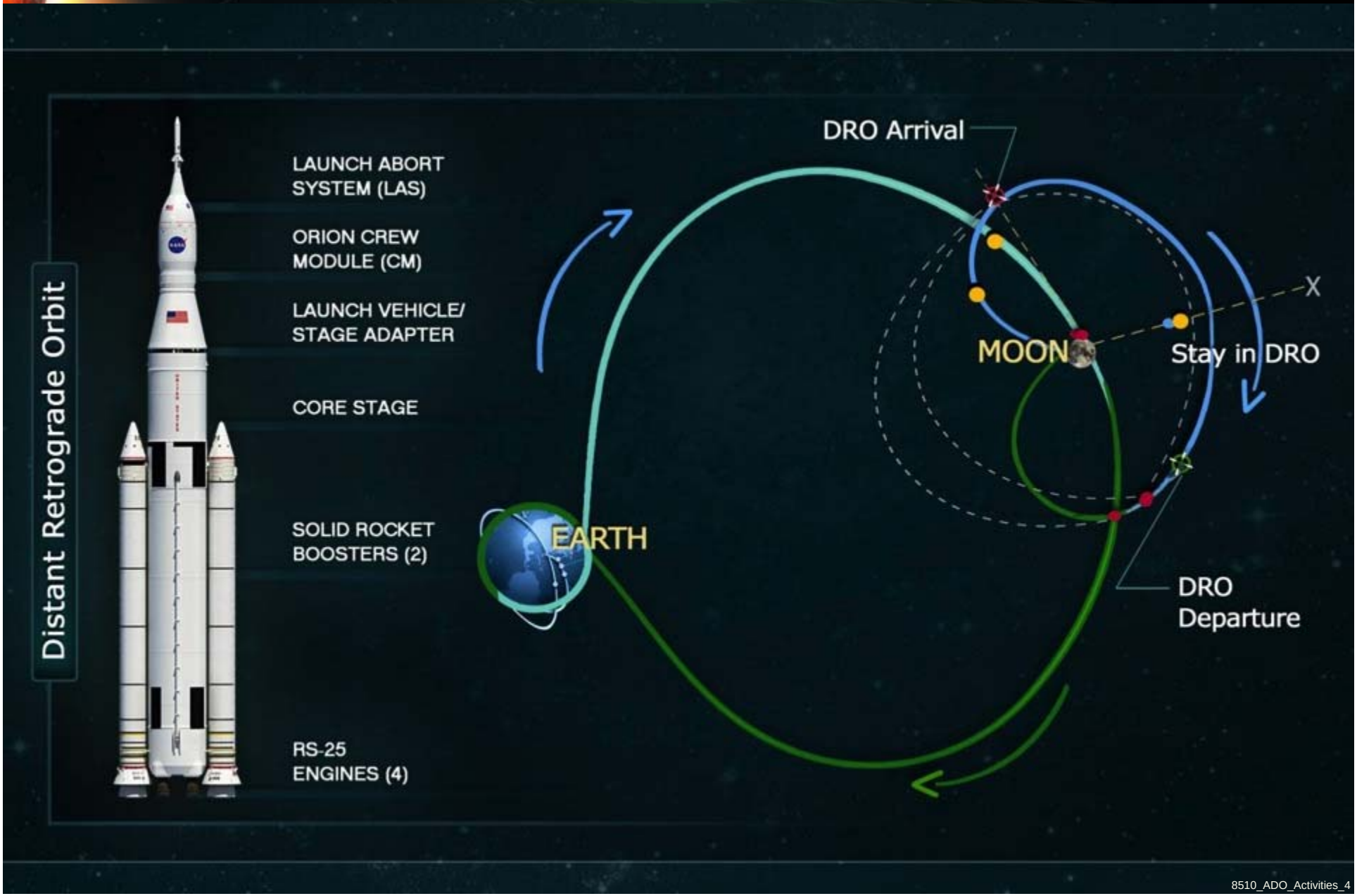
The Future of Exploration



SLS 70 metric ton Expanded View



Exploration Mission One (EM – 1)



Building to Exploration Mission-1 (EM-1)

ACCOMPLISHMENTS

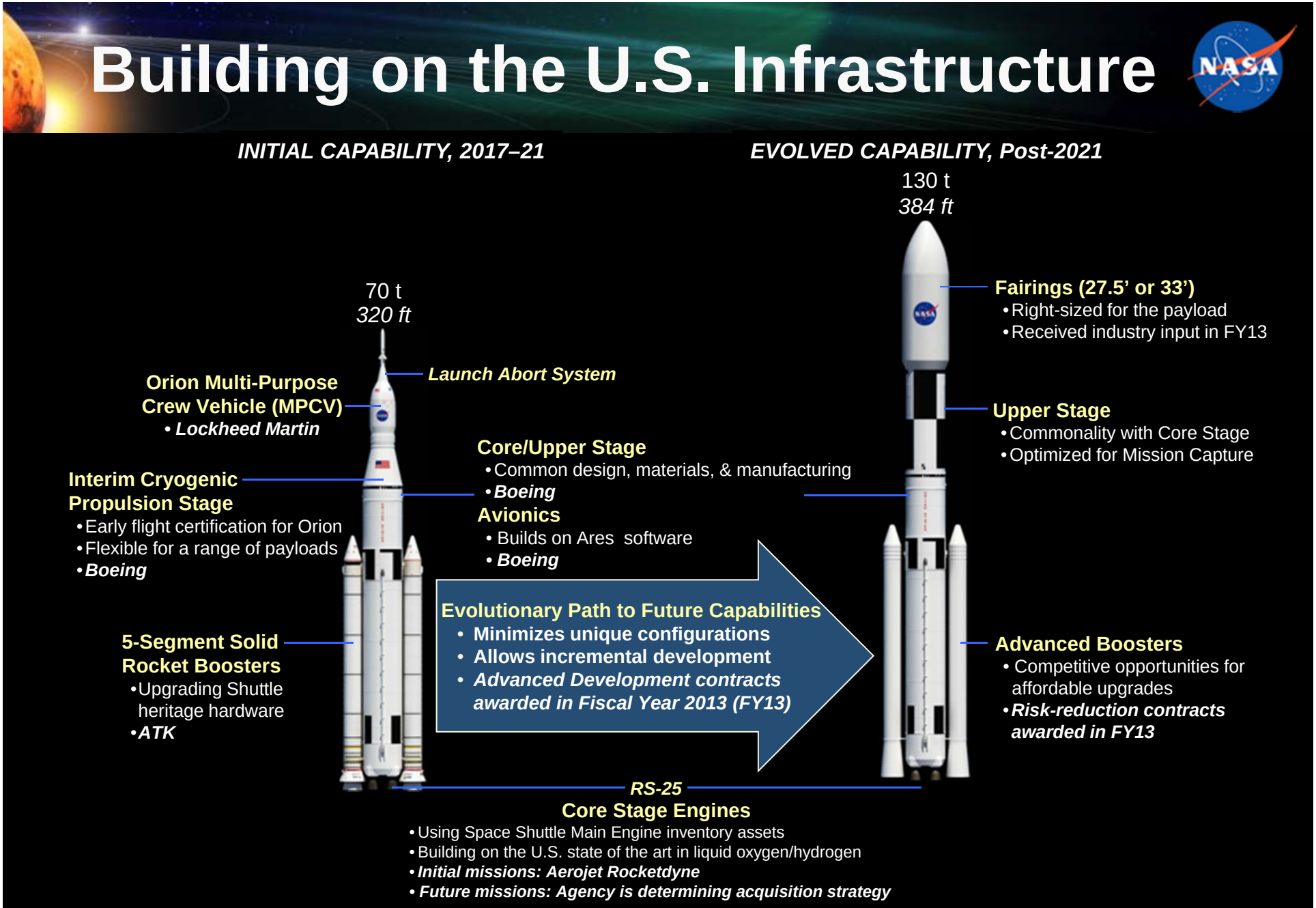
- 09/2011 Tested Booster Development Motor
- 07/2012 Delivered RS-25 Engines to Inventory
- 07/2013 Competed Preliminary Design Review
- 10/2011 - 12/2013 Tested SLS Wind Tunnel Models
- 07/2013 Completed First Confidence Barrel Section Welding
- 10/2013 Completed Thrust Vector Control Test
- 11/2013 Conducted Adaptive Augmenting Control Flight Test
- 12/2013 Completed LOX Forward Dome Manufacturing Demo
- 1/2014 Conducted Avionics "First Light" in Integration Facility
- 02/2014 Shipped Multi-Purpose Crew Vehicle Stage Adapter for EFT-1

WHAT'S NEXT

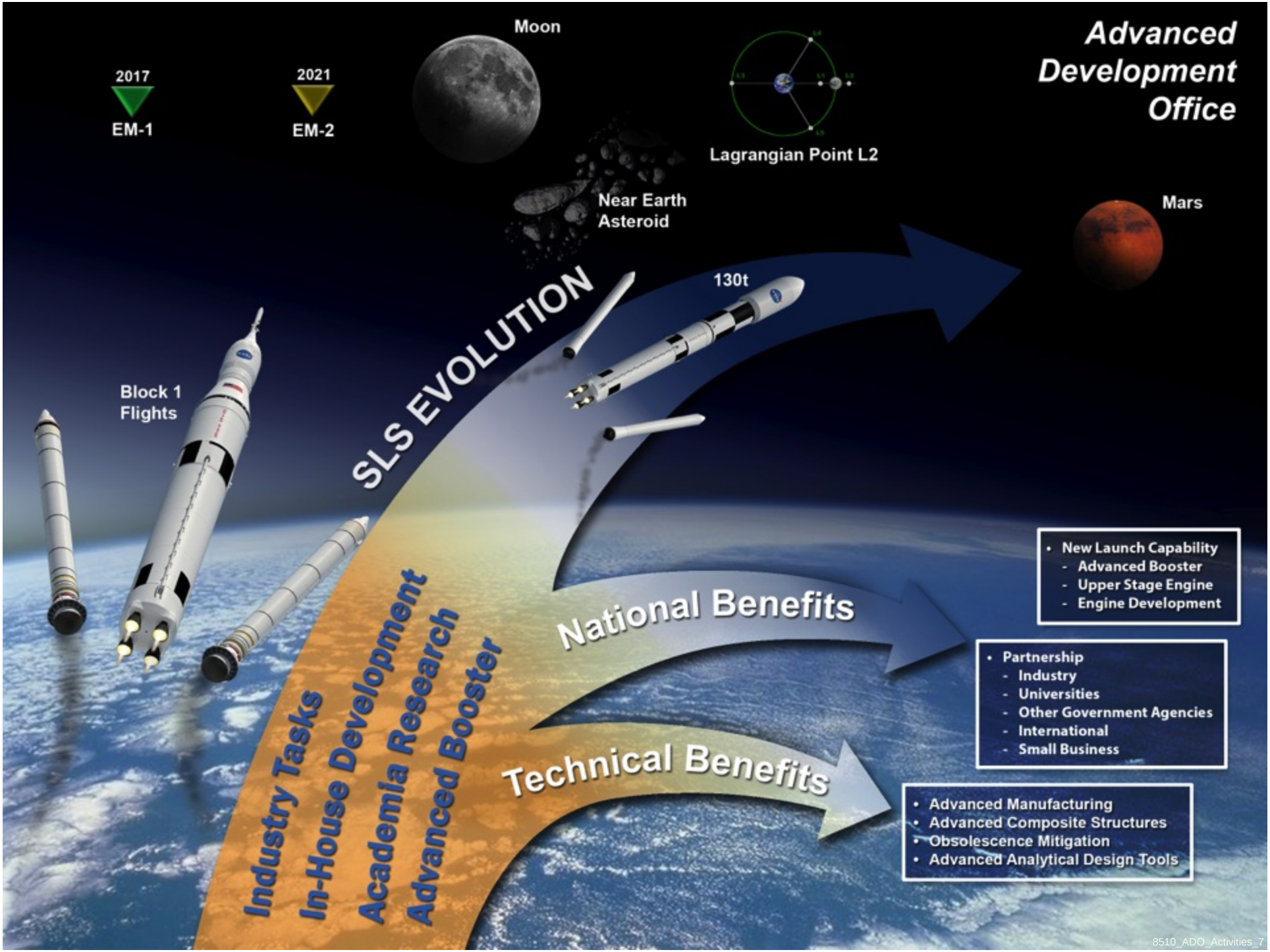
- 04/2014 Complete Manufacturing Tooling Installation
- 07/2014-15 Test Main Engines, Boosters , & Core Stage Structure
- 07/2015 Complete the SLS Critical Design Review
- 06/2016 Assemble the Core Stage Assembly and Test Fire
- 07/2017 Stack the SLS Vehicle
- 12/2017 Transport SLS from the VAB to the Launch Pad

December 2017 EM-1 Launches from KSC

Building on the U.S. Infrastructure



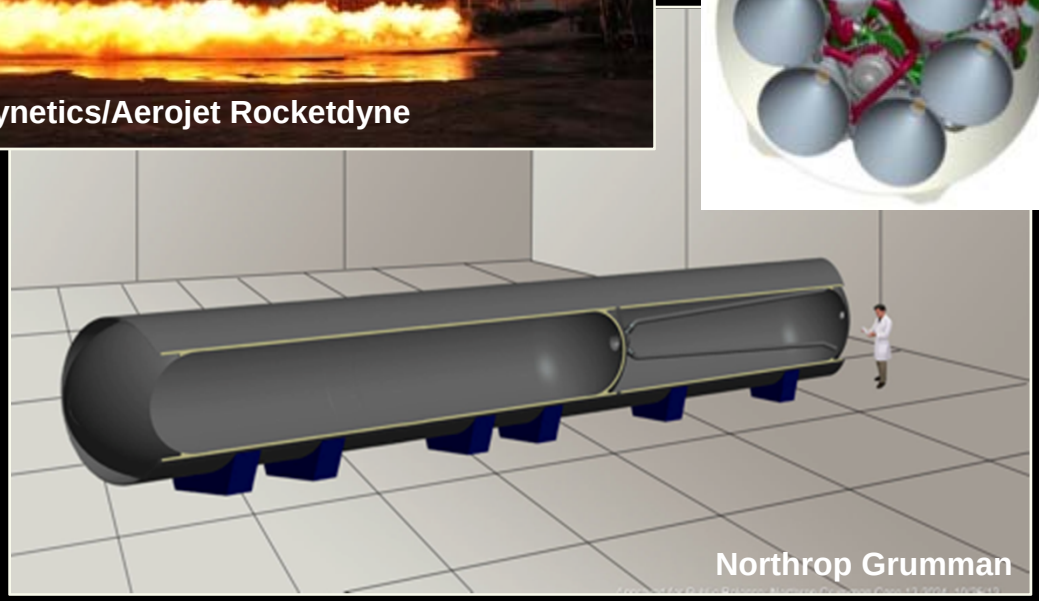
Working with Industry Partners to Develop America's Heavy-Lift Rocket


Advanced Development Office
2017
EM-1
2021
EM-2
Moon
Lagrangian Point L2
Near Earth Asteroid
Mars
Block 1 Flights
SLS EVOLUTION
130t
Industry Tasks
In-House Development
Academia Research
Advanced Booster
National Benefits
Technical Benefits
• New Launch Capability
- Advanced Booster
- Upper Stage Engine
- Engine Development
• Partnership
- Industry
- Universities
- Other Government Agencies
- International
- Small Business
• Advanced Manufacturing
• Advanced Composite Structures
• Obsolescence Mitigation
• Advanced Analytical Design Tools
8510_ADO_Activities_7

Advanced Booster Research and Development

Advanced Booster Engineering Development Risk Reduction (ABEDRR)

Program Description:
Reduce risks leading to an affordable advanced booster that meets evolved capability requirements of SLS, and enable competition by mitigating targeted advanced booster risks to enhance affordability



ABEDRR 2013 Accomplishments

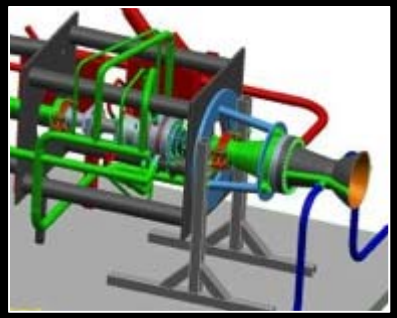
Accomplishments for 2013:

- ***Aerojet LOX/RP Engine***: Developed system requirements and initiated preliminary design

- ***ATK Advanced Booster Performance, Reliability and Affordability***:
  (1) Propellant liner insulation (PLI): tailored liner formulation; tested PLI bondline;
  (2) Case damage tolerance: released drawings for 92-in composite case;
  (3) Nozzle flex bearing: released drawings of assembly and primary components;
  (4) Avionics and controls: defined test methods; assessed actuator sizing;
  (5) Static fire test: developed test plan and built igniter

- ***Dynetics Modernized F-1 Engine and Cryotank Cost Risk Reduction***:
  (1) F-1B engine: hot-fired heritage gas generator (GG); produced F-1 GG injector; completed PDR for power pack assembly and F-1B main combustion chamber;
  (2) Cryotank structures: completed final design review and released all drawings; tested schedules for welding domes to dome/tank end rings

- ***Northrop Grumman Composite Common Bulkhead Tank***: Completed composite demonstrator design review, held kickoff for test fixture build, built out-of-autoclave test panels with <1% void content



Aerojet Test Rig

ATK Test Motor

Dynetics F-1B Main Combustion Chamber

Northrop Grumman Tank Demonstrator

Space Launch System Advanced Development Office (SLS–ADO)

In-House Tasks (Keith Higginbotham)

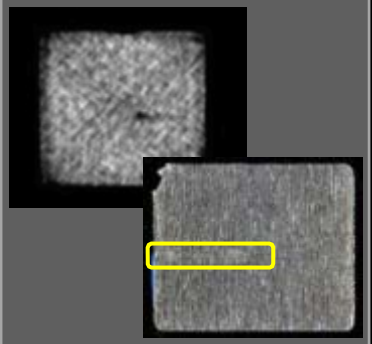
Al 2195 T8 Gore Development: Martin Volz

***Objective*:** Develop manufacturing process for making gore panels from aluminum lithium alloy 2195, to achieve weight savings for potential SLS Block 1B. Optimize heat treatment and stretch parameters for thicker panels.

***Accomplishments*:**

- Completed heat treatment and gore stretching Al 2195 plates of 0.525“ and 0.75” thickness
- Completed tensile strength and fracture toughness testing of 0.525" and 0.75” gores at room temperatures
- Verified improved mechanical properties of annealed panels

NDE of Selective Laser Melting Materials: David Brown



***Objective*:** Characterize non- destructive inspection performance on powder bed fusion materials for additive manufacturing (AM) such as selective laser melting (SLM)

***Accomplishments*:**

- Identified materials and developed specimens for NDE
- Reviewed limitations of NDE for AM parts
- Determined that Computed Tomography (CT) appears to be best method for SLM parts; work remains for planar defects

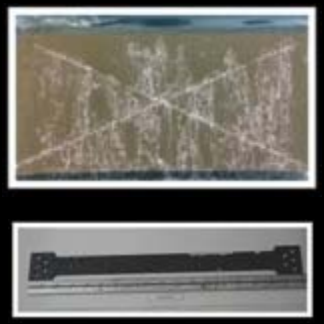
Cryoinsulation Development: Alison Protz

Objective: Develop closeout processes for low Global Warming Potential (GWP) foam insulation, and develop/characterize zero GWP materials. Develop S-180 Manual Spray Foam as risk mitigation for SLS Core Stage.

Accomplishments:

- Completed process development and specs for the S-180 manual spray foam
- Wrote manual foam sprayer organizational work instruction (OWI)
- Accomplished fab and testing of reformulated foam specimens

Chromium VI Free Primer Development: Michael Alldredge



Objective: Evaluate corrosion protection capability of multiple commercially- available hexavalent chromium-free non- hazardous primers for cryogenic applications

Accomplishments:

- Solicited industry for potential primer candidates
- Performed salt fog/ corrosion and cryoflex testing
- Selected 4 primer candidates out of 13 for further testing in second phase of project

Low-Profile Diffuser (LPD): Mike Martin

Objective: Develop a diffuser concept to replace existing types with a high performing, low profile design to enable more propellant capacity and increase SLS performance

Accomplishments:

- Used CFD methods to design LPD
- Completed machine shop work for LPD
- Developed test procedures
- Continued CFD analysis for LPD and Boeing diffuser to predict performance

Space Launch System Advanced Development Office (SLS–ADO)

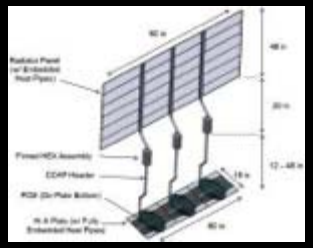
In-House Tasks (continued)

SLM Propulsion Hardware: Jason Turpin

Objective: Design, fabricate, and hot fire test an Integral Valve/Injector that is built using AM. Build partnership with Air Force for development of technologies that are synergistic with both NASA SLS and Air Force goals. Advance use of additive manufacturing (AM) technology for turbomachinery.

Accomplishments:
- Completed fabrication, water flow and hot fire testing of 28-element injector
- Completed fab of inducer, shrouded impeller, and shrouded turbine

Advanced Passive Avionics Cooling: Jeff Farmer



Objective: Develop and test advanced passive thermal control techniques to assess performance and affordability. Provide enhanced avionics cooling benefits for SLS baseline and upgrades.

Accomplishments:
- Completed survey of two-phase cooling technologies and identified concepts for SLS application
- Established design requirements for passive heat rejection through passive sublimator driven coldplate
- Received hardware based on findings of Phase 1 studies; obtained test area

High Voltage Electronic Parts: Trent Griffin

Objective: Obtain high voltage electronic parts and conduct low-cost mechanical, electrical and environmental testing. Compile construction analysis of these parts and a documented qualification path for use on SLS future TVC upgrade.

Accomplishments:
- Completed construction analysis
- Received off-board parts and materials
- Completed circuit boards
- Inspected & removed rod end and roller-screw mechanism

GH2 Sensor Development: James Currie

Objective: Deliver flight ready gaseous hydrogen (GH2) detection sensors operable for use on SLS Block 1A. Produce stand-alone leak detection systems with minimal size, weight, and power consumption.

Accomplishments:
- Completed electromagnetic interference/ compatibility (EMI/EMC) and ESD testing
- Completed random vibration screening
- Completed sensor calibration
- Completed algorithm for both GN2 and air

Fluid Structures Coupling Damper: Rob Berry

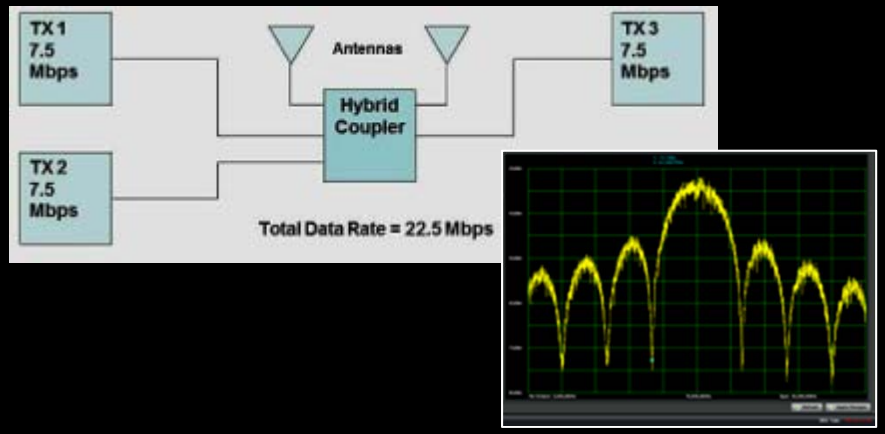
Objective: Assess feasibility and effectiveness of fluid structures coupling damper technology to control vehicle lateral modes, mitigate slosh, and SLS- unique axial mitigation

Accomplishments:
- Developed prototype design for mitigating vehicle axial modes
- Demonstrated axial mitigation for SLS through testing
- Derived lateral equations and correlated with test
- Anchored analytical abilities to properly capture physics

Space Launch System Advanced Development Office (SLS–ADO)

In-House Tasks (continued)

Advanced Telemetry System: Patrick Campbell and Bill Hopkins

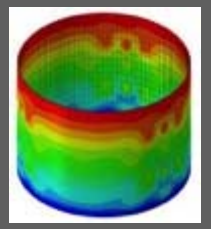


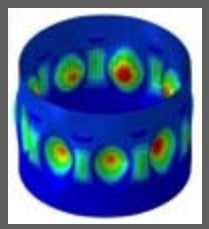
Objective: Investigate the use of advanced modulation techniques that allow (1) more data to be transmitted in a channel and (2) the use of fewer radios. Since SLS will use traditional RF telemetry systems to transmit data to the ground, high data rate requirements will necessitate multiple radios or high-bandwidth channels. Cost and spectrum constraints could make this approach difficult. This project could provide the telemetry solution.

Accomplishments:

- Received the receiver/modulator hardware capable of up to 8 Phase Shift Keying (PSK) modulation and low-density parity check (LDPC) forward error correction
- Evaluated spectrum and developed RF architecture

Shell Buckling Knockdown Factors: Mark Hilburger





Objective: Develop and validate analysis-based shell buckling knockdown factor (KDF) updates for SLS- specific orthogrid and isogrid stiffened metallic cylinders. Seek reductions in design cycle time and reworks, enhance safety/reliability, and enable significant mass savings potential in the SLS core stage (>3-4mt).

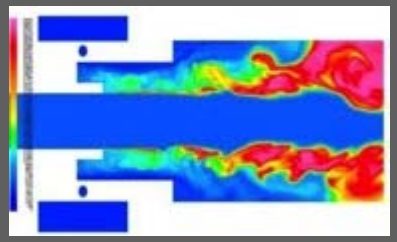
Accomplishments:

- Designed, fabricated, and tested two orthogrid 8-ft diameter cylinder test articles
- Designed two isogrid 8-ft diameter cylinder test articles
- Completed buckling analysis
- Improved knockdown factors for combined mechanical, thermal, and pressure loads

Space Launch System Advanced Development Office (SLS–ADO)

In-House Tasks (NESC Funded/Managed)

Advanced Integrated Combustion Stability Capability: Kevin Tucker



Objective: Advance the predictive capability of tools used in SLS combustion stability assessments; facilitate identification/mitigation of combustion instabilities during SLS propulsion system development; reduce development costs

Accomplishments:
- Completed CFD simulations of gas centered swirl coax injector elements
- Identified engineering tool needs for higher- fidelity inputs & model
- Completed scaling of hydrocarbon boost element; held CDR for testing of this element

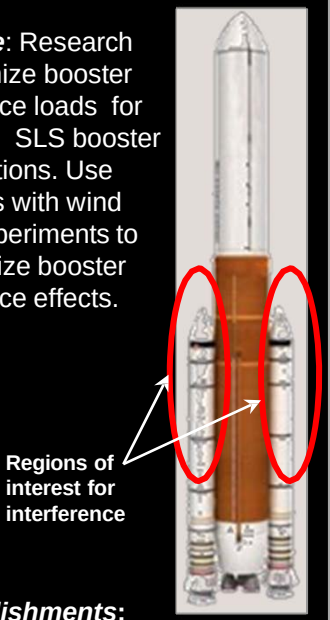
Pyroshock Characterization of Composite Materials: David Ordway

Objective: Support potential use of composites in the evolved SLS vehicle; evaluate materials to insure they can withstand launch loads and pyroshock-induced stresses during stage separation

Accomplishments:
- Completed pyroshock testing for solid and honeycomb composite panels
- Developed algorithms for export of data for statistical analytical tools
- Used output from the algorithms as input for the statistical analyses

Booster Interface Load Analysis: Greg Brauckmann

Objective: Research and optimize booster interference loads for advanced SLS booster configurations. Use CFD tools with wind tunnel experiments to characterize booster interference effects.



Accomplishments:
- Completed pre-test numerical simulations
- Completed wind tunnel test
- Supported Buffet Loads Mitigation Team; provided CFD results to guide testing options
- Briefed CFD and testing results to chief engineer
- Provided buffet simulation results to SLS Aero team

Block IA Advanced Booster Composite Case/ Internal Insulation: Jessica Chaffin

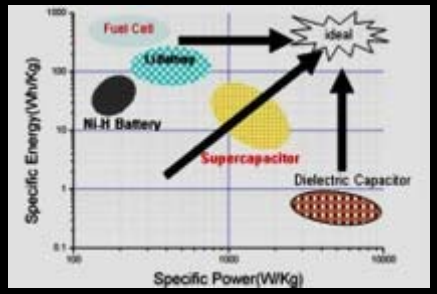
Objective: Evaluate processing through tensile strength, impact peel strength, and water burst testing. Develop NDE damage standards; determine NDE methods best suited to large-scale loaded motors. Evaluate high-energy propellants.

Accomplishments:
- Evaluated 3 propellant types through testing for hazards, burn rate, tensile properties; selected 2 propellant candidates or scale-up
- Manufactured and scale-up Manufactured and completed NDE for 38 oven cured bottles
- Determined applicability of NDE methods for composite bottles

Space Launch System Advanced Development Office (SLS–ADO)

University Grants (Mindy Nettles)

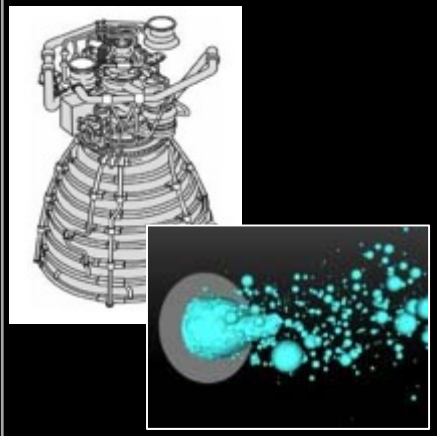
High Electrical Density Device Survey: Auburn



Objective: Conduct an assessment and develop database of commercial energy storage devices, to meet future SLS power requirements and minimize mass/volume

Accomplishments:
- Completed survey of commercially available batteries, dielectric capacitors, and supercapacitors, and determined critical parameters
- Surveyed newly developed technologies
- Assessed new dielectric composites-based energy storage devices

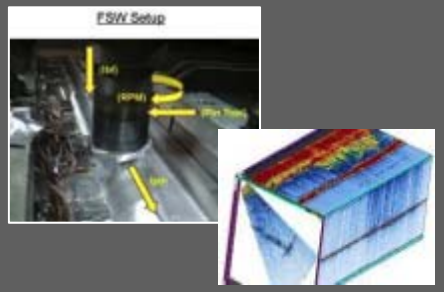
Development of Atomization Models for Liquid Rocket Injectors: Florida



Objective: Deliver improved high-fidelity design tool for SLS liquid engine injectors, help improve combustion efficiency of the SLS liquid propulsion systems, and predict combustion instabilities

Accomplishments:
- Completed stochastic modeling of subcritical primary atomization for steady case
- Integrated primary atomization stochastic model into Loci-CHEM

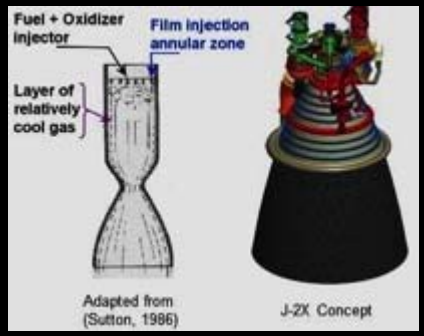
Improved Friction Stir Welds Utilizing On-line Sensing of Weld Quality: LSU



Objective: Create an on- weld quality sensing system to aid the manufacturing process of friction stir welding, and expedite the process to determine defect- free welding parameters

Accomplishments :
- Determined that process variables are coupled, and that changing one variable alters entire weld
- Correlated initial data with theoretical models
- Determined that x-ray data and Phased Array Ultrasonic Testing (PAUT) results agree
- Proved that PAUT is best choice for on-line detection

Supersonic Film Cooling Numerical Simulations: Maryland



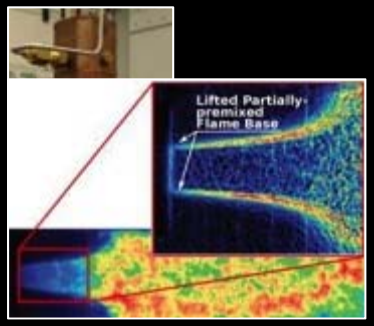
Objective: Develop a detailed understanding of film cooling fluid dynamics so that predictive CFD approaches can be developed

Accomplishments:
- Compared measured to simulated wall heat flux
- Developed high frequency pitot probe for measuring velocity fluctuations in supersonic stream
- Developed high intensity pulsed light source for Schlieren images
- Validated simulation for film cooling flows

Space Launch System Advanced Development Office (SLS–ADO)

University Grants (continued)

Transient Combustion Processes in Rockets: Michigan and Stanford

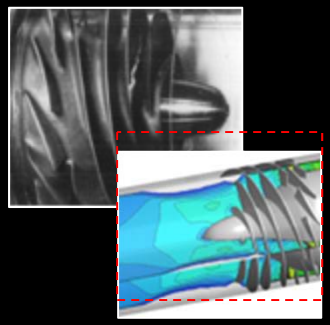


Objective: Accomplish computational and experimental research to develop validated simulation techniques for accurate prediction of unstable combustion processes in rocket engines

Accomplishments:

- Brought planar laser-induced fluorescence (PLIF) system online for diagnostics; made progress on particle image velocimetry (PIV) system
- Worked toward PIV/ PLIF system with wall temperature and chamber pressure measurements
- Developed combustion model with flame- normal heat-loss effect

Cavitation Challenges in Turbopump Inducers: MIT Gas Turbine Lab

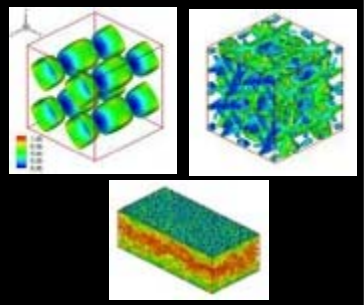


Objective: Mitigate higher order cavitation in SLS turbomachinery to improve rocket engine reliability and performance. Develop new methodology for quickly assessing inducer designs to suppress cavitation

Accomplishments:

- Defined new turbopump inducer blade passage model and established body force methodology
- Designed inducer and verified performance agreement with SSME
- Computed cavitation performance of inducer

Enhancements for Hybrid RANS-LES: Mississippi State



Objective: Achieve improvement to hybrid Reynolds Averaged Navier Stokes/Large Eddy Simulation (RANS/LES) CFD modeling, for practical solutions to problems of interest to SLS

Accomplishments:

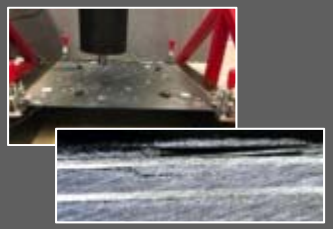
- Implemented a kinetic-energy- consistent algorithm into Loci-CHEM
- Implemented a high-resolution gradient calculation method into Loci-CHEM
- Delivered updated CHEM version to NASA; further testing and validation ongoing

Aluminum/Alumina Carbon Interactions in Rockets: Penn St.

Objective: Develop fundamental understanding of Al/Al_2O_3/carbon thermochemical reactions likely to be important for SLS motor applications by performing basic experiments

- ***Accomplishments***: Conducted CO2 laser heating experiments for Al/Al_2O_3/carbon using graphite crucible
- Observed general behavior with temperature using video, along with gas sampling and post-test sample analysis performed on select test samples

Acoustic Emission-Based Health Monitoring of SLS Structures: Utah



Objective: Develop a structural health monitoring system for SLS structures. Increase reliability of the structure by accurately identifying location and type of damage due to impacts during transportation and assembly

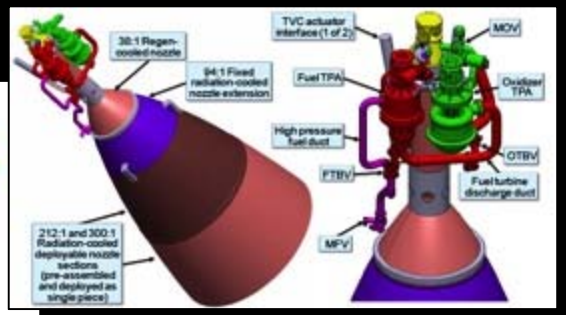
Accomplishments:

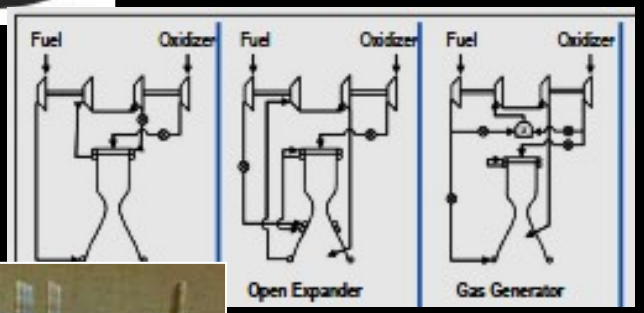
- Examined sensor response on panels due to actual and simulated impacts
- Evaluated acoustic emission sensors
- Conducted impacts at different temperatures and evaluated location algorithm
- Continued work on location estimation

Areas of Common Interest

Common Needs	Opportunities
Advanced Upper Stage Engines	Affordable Upper Stage Engine Program Studies
Booster Hydrocarbon Engines	American Kerosene Engine Studies
Advanced Manufacturing	Selective Laser Melting Materials Characterization

Affordable Upper Stage Engine Program





Program Description:

Develop affordable upper stage engine as replacement for RL10, providing a new capability benefiting muliple stakeholders in the US launch industry, including NASA and U.S. Air Force

MSFC Role:

Program Management (Brian Barley)

Accomplishments for 2013 include:

- ***Aerojet Rocketdyne Next Generation Engine System Study***: Finalized initial major subsystem requirements documents; completed power balance analyses for AUSEP; finalized figure of merit weighting to emphasize affordability
- ***Aerojet Rocketdyne Engine Trade Study***: Evaluated all planned cycles and created power balance models for candidate architectures; created utility function balancing factors such as cost, reliability, performance
- ***Exquadrum Dual-Expander Aerospike Engine***: Completed trade studies to identify optimum engine configuration; completed conceptual design of engine; developed modular thrust cell design
- ***Moog High Pressure LOX Control Valve***: Completed valve design based on flow/pressure parameters from potential upper stage developers; completed PDR; produced valve body using additive manufacturing at MSFC
- ***Northrop Grumman Liquid Engine Requirements Study***: Completed broad engine system trades; initiated detailed trades and design studies; selected point of departure engine system concept; performed thrust chamber trades
- Results being analyzed and integrated by Booz Allen Hamilton with final report due spring 2014

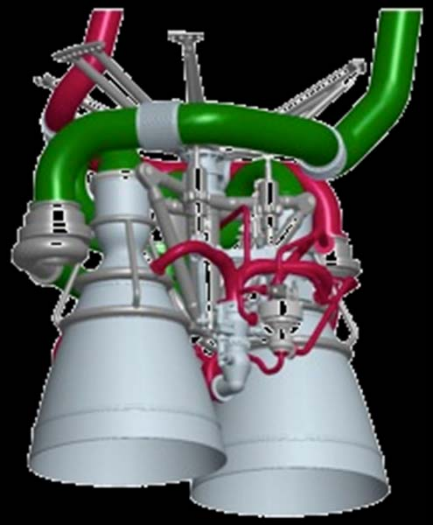
American Kerosene Engine Studies

- **NASA and USAF Space and Missile Systems Center (SMC) have partnered to study potential synergy on an American Kerosene Engine. Multiple partners involved:**
  - **Aerojet Rocketdyne**: Looking at multiple concepts for AKE opportunities, based on SLS ABEDRR efforts. (Potential study on RD-180 co-production put on hold.)
  - **Northrup Grumman:** Studying concepts for hydrocarbon aerospike engine, proposed for possible utilization for SLS advanced boosters.
  - **Georgia Tech University:** Performed study on oxygen-rich staged combustion engine technology. *Results are being presented at this conference.*

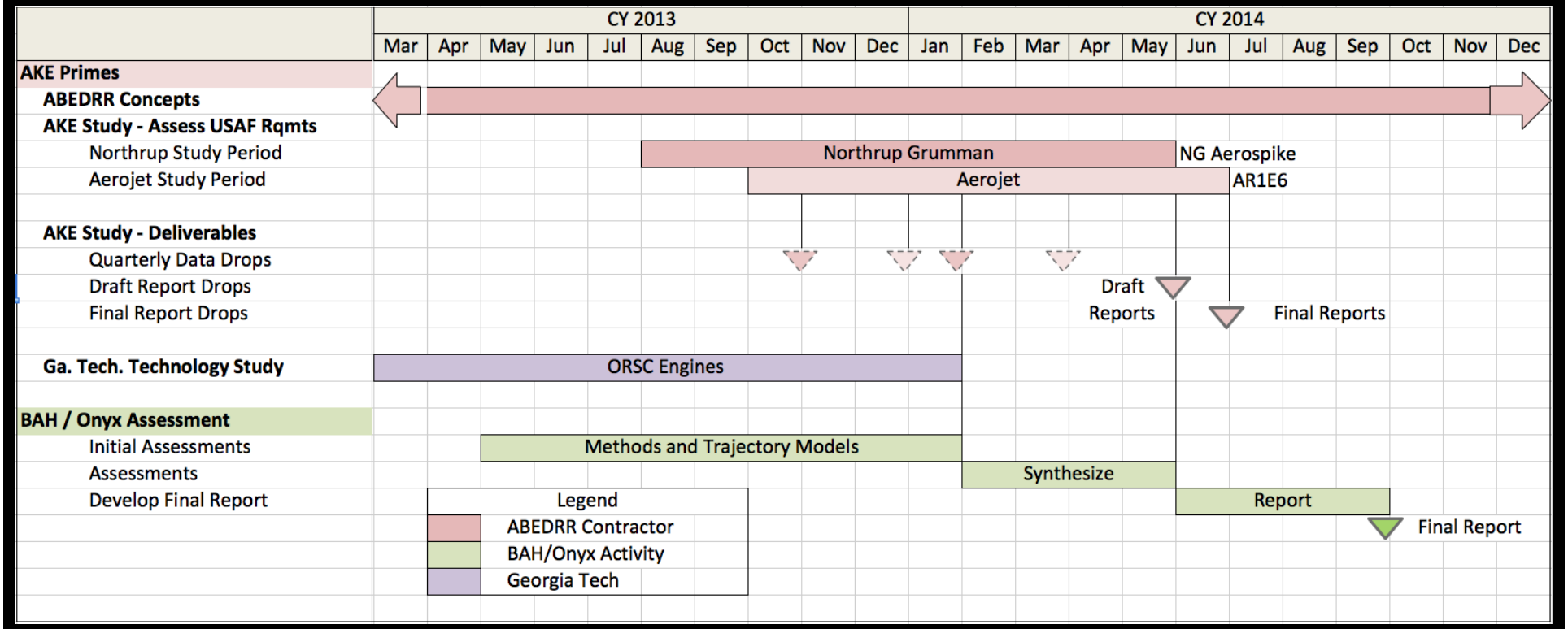
- **ABEDRR contractors to study extensibility of SLS Advanced Booster liquid engine concepts to AF EELV architectures**

- **Key study objectives –**
  - Technical feasibility, DDT&E plans and risks
  - Cost and schedule estimates

- **Results being analyzed and integrated by Booz Allen Hamilton and Onyx Aerospace with final report due spring 2014**



AKE Study Timeline



Selective Laser Melting Road to Flight

Component Development

Built and hot-fire tested J-2X gas generator discharge duct

J-2X fuel turbine exhaust duct maintenance port plug is being built for engine hot-fire testing

Successfully built RS-25 internally tied bistra

Will build and water flow test RS-25 POGO Z-baffle.

Plans in work to green run and certify SLM POGO Z-baffle for use on RS-25

Material and Process Development

Created draft SLM Engineering and Quality Guidelines document

Developing inspection techniques

Procurement of SLM machine for MSFC Materials Lab

Mechanical testing of material samples, developing materials verification matrix

Working with Army and Air Force on material development

Build flight rationale

Fly SLM components in 2017

Additional MSFC Activities

Participation in 3 separate proposals for Air Force Broad Agency announcement, pilot Additive Mfg Innovation institute

Engineering Development:

- Unique tooling fabrication
- injector elements and various other components for MSFC component test bed
- Turbopump components
- Small thruster development

Activity Completed

Activity in work

Selective Laser Melting Examples