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Space Launch System Advanced Development Office, FY 2013 Annual Report

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December 2013

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LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS

ABEDRR	Advanced Booster Engineering Demonstration/Development and Risk Reduction
ADO	Advanced Development Office
AE	acoustic emission
AES	Advanced Exploration System
AFRL	Air Force Research Laboratory
Al	aluminum
Al_2O_3	aluminum oxide
AM	additive manufacturing
AMRDEC	Aviation and Missile Research Development and Engineering Center
ARC	Ames Research Center
ATP	authority to proceed
AUSE	advanced/affordable upper stae engine
AUSEP	Advanced/Affordable Upper Stage Engine program
CCHP	constant capacitance heat pipe
CCTD	Composite Cryotank Technologies and Demonstration
CDR	Critical Design Review
CE	Chief Engineer
CFD	computational fluid dynamics
COTR	contracting officer's technical representative
CPS	Cryogenic Propulsion Stage
CPST	Cryogenic Propellant Storage and Transfer
CSO	Chief Safety Officer

LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

CT	computed tomography
CTS	composite tank set
DAC	design analysis cycle
DCR	Design Certification Review
DDT&E	design, development, test, and evaluation
DESLA	dual-expander, short-length aerospike
DFMEA	design failure mode and effects analysis
DFRC	Dryden Flight Research Center
DoD	Department of Defense
ECS	Environmental Control System
ED	Engineering Directorate
EELV	evolved expendable launch vehicle
EHA	electrohydrostatic actuator
EMA	electromechanical actuator
EMC	electromagnetic compatibility
EMI	electromagnetic interference
ESD	Exploration Systems Development
ETE	end to end
EUS	Exploration Upper Stage
FEM	finite element modeling
FOM	figure of merit
FSC	fluid-structure coupling
FSW	friction stir welding

LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

FWC	filament wound case
FY	fiscal year
GCSC	gas-centered swirl-coaxial
GG	gas generator
GH_2	gaseous hydrogen
GIM	generalized instability model
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
GWP	Global Warming Potential (rating)
H_2	hydrogen
HAT	Human Spaceflight Architecture Team
HCB	hydrocarbon boost
HEX	heat exchanger
HIP	hot isostatic press
HM	health management
ICPS	Interim Cryogenic Propulsion Stage
IGBT	insulated gate bipolar transistor
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
JSC	Johnson Space Center
KDF	knockdown factor
KSC	Kennedy Space Center
LaRC	Langley Research Center

LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

LES	large eddy simulation
LH_2	liquid hydrogen
Li	lithium
LN_2	liquid nitrogen
LOX	liquid oxygen
LPFP	low pressure fuel pump
LPOP	low pressure oxidizer pump
LPT	Lagrangian particle tracking
LTUS	low thrust upper stage
MAF	Michoud Assembly Facility
MCC	main combustion chamber
MPCV	multipurpose crew vehicle
MPS	main propulsion system
MRL	Manufacturing Readiness Level
MSFC	Marshall Space Flight Center
NBR	nitrile butadiene rubber
NCPS	Nuclear Cryogenic Propulsion Stage
NDE	nondestructive evaluation
NESC	NASA Engineering and Safety Center
NGAS	Northrop Grumman Aerospace Systems
NGE	next generation engine
NRA	NASA Research Announcement
OCST	Office of Commercial Space Transportation

LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

ORSC	oxidizer-rich staged combustion
PAUT	phased array ultrasonic technology
PBI	polybenzimidazole
Pc	pressure chamber
PCM	phase change material
PDR	Preliminary Design Review
PI	principal investigator
PLI	propellant liner insulation
PM	Program Manager
PPA	powerpack assembly
PP&C	Program Planning and Control
PSK	phase-shift keying
PWR	Pratt & Whitney Rocketdyne
RANS	Reynolds-averaged Navier stokes
ROCCID	rocket combustor interactive design
ROCETS	Rocket Engine Transient Simulator
ROI	return on investment
RP	rocket propellant (kerosene)
S&MA	Safety and Mission Assurance
SBKDF	shell-buckling knockdown factor
SC	staged combustion
SEM	Systems Engineering Management
SEMP	Systems Engineering Management Plan

LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

SLM	selective laser melting
SLS	Space Launch System
SRB	solid rocket booster
SRM	solid rocket motor
SRR	System Requirements Review
SSC	Stennis Space Center
SSFC	supersonic film cooling
STTR	Small Business Technology Transfer
TCA	thrust chamber assembly
TIM	Technical Interchange Meeting
TM	technical monitor
TPA	turbopump assembly
TRL	Technology Readiness Level
TVC	thrust vector control
ULA	United Launch Alliance
USAF	United States Air Force
USET	upper stage engine technology
VAB	vertical assembly building

TECHNICAL MEMORANDUM

SPACE LAUNCH SYSTEM ADVANCED DEVELOPMENT OFFICE, FY 2013 ANNUAL REPORT

1. INTRODUCTION

The Advanced Development Office (ADO), part of the Space Launch System (SLS) Program, provides the SLS with the advanced development needed to evolve the vehicle from an initial Block 1 payload capability of 70 metric tons (t) to an eventual capability Block 2 of 130 t (fig. 1), with intermediary evolution options possible. ADO takes existing technologies and matures them to the point that insertion into the mainline program minimizes risk.

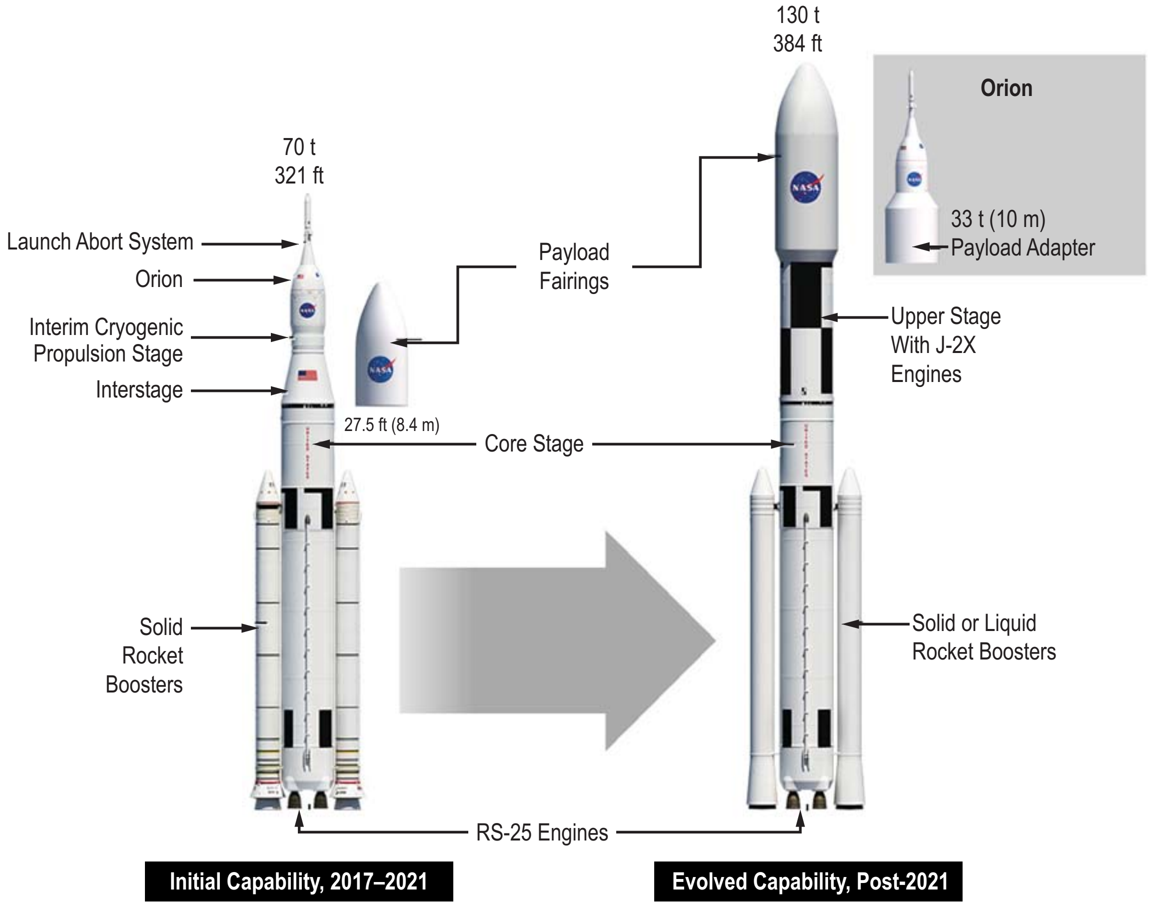


Figure 1. SLS evolvable capability.

The technology maturation path is referred to as the ‘Valley of Death.’ The Valley of Death is where ‘push’ technologies normally die due to lack of sponsorship (fig. 2). The adoption of the technology by a program transforms it from a push to a ‘pull’ technology and helps it to traverse the Valley of Death. Usually, during this period, the funding transitions from the Technology office to the Program office.

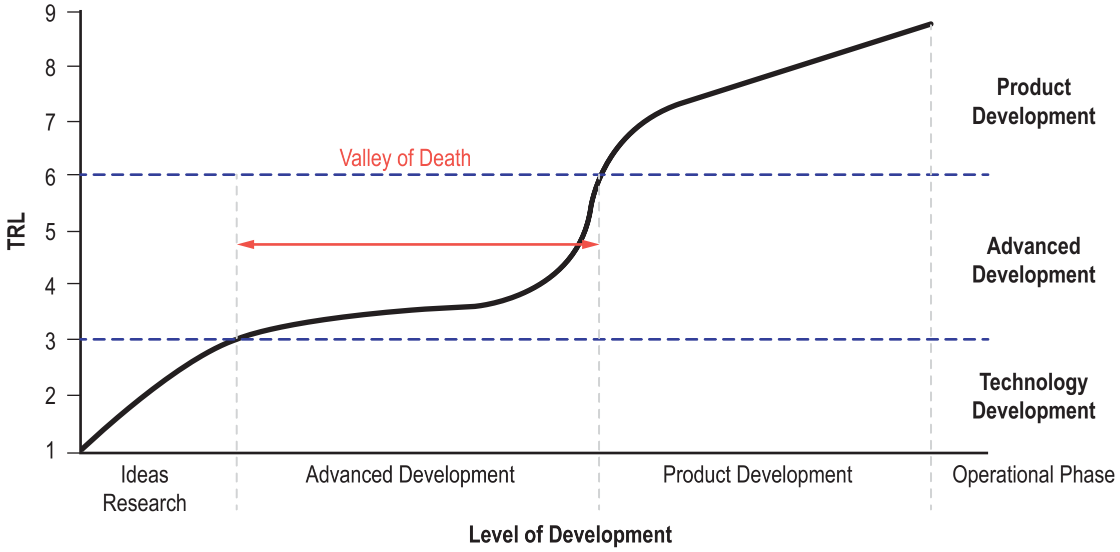


Figure 2. Technology transition.

In order to understand whether or not advanced development is required, it is necessary to systematically assess the maturity of each system, subsystem, or component in terms of the architecture and operational environment. Advanced development defined in the broadest sense can range from a laboratory experiment to the normal development process experienced in a program such as the SLS.

The term ‘technology,’ as used by NASA, is a reference to hardware maturity. The term Technology Readiness Level (TRL) is used by NASA to measure the maturity of the hardware in relation to where it should be in a normal program lifecycle. Based on the definitions of TRL (appendix A), the hardware maturity could range from basic principles to the hardware being used in an operational system. Normally, the Valley of Death is considered TRL 3 through 6. The notional flow of ADO transitioning advanced development activities to the SLS hardware elements is shown in figure 3.

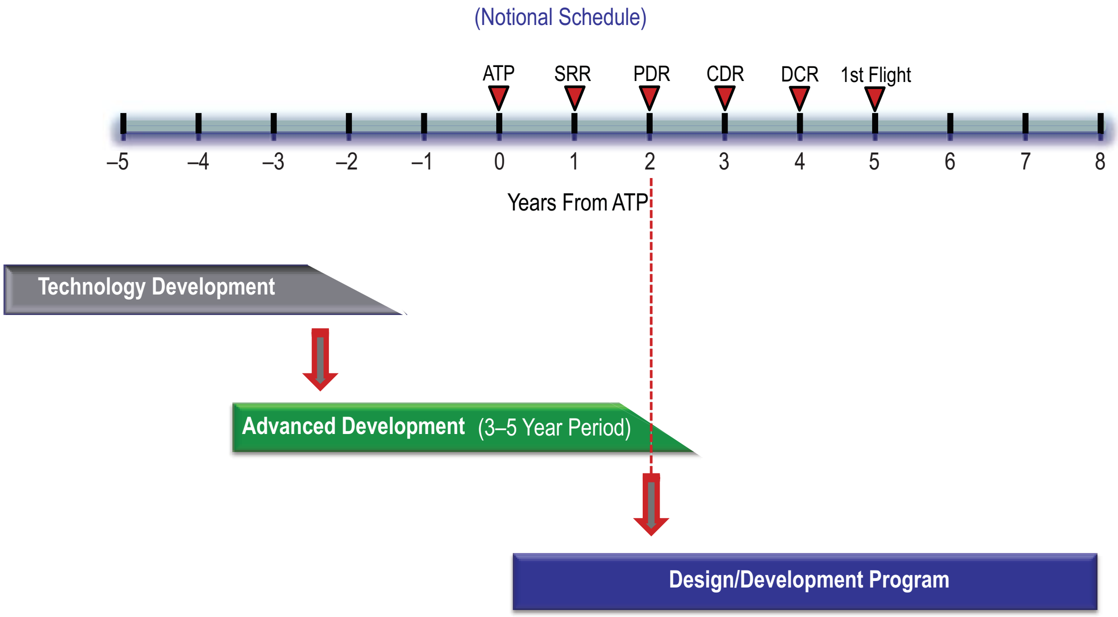


Figure 3. Technology transition to Development program.

The task selection process used by ADO depends upon whether the tasks are conducted in-house or contracted. The selection process for the in-house tasks is discussed in section 2. The contracted tasks were selected initially by issuing NASA Research Announcements (NRAs), and then competitively selecting and awarding selected tasks via a Source Evaluation Board.

1.1 Background

ADO was chartered at the initiation of the SLS program in September 2011. The main tenants of ADO's charter are outlined below:

- Manage the advanced development and block upgrades required to evolve the launch vehicle to a 130-t lift capability. ADO will work with the SLS program manager (PM) and stakeholders to define the requirements for future block upgrades.

- Work with the Marshall Space Flight Center (MSFC) Engineering Directorate (ED) and the SLS Element offices to define the block upgrade configurations.

- Work with ED to mature the configurations and define the resources and schedules for the block upgrades.

- Prioritize the development and block upgrade challenges which enable the launch vehicle to evolve to a 130-t lift capability. Advanced development may include grants, in-house and inter-Center activities, and government/industry hybrid model projects.

Based on this charter, ADO issued a call for in-house tasks in February 2012. The in-house tasks were awarded in April 2012. In early fiscal year (FY) 2012, NRAs were issued soliciting industry and academia responses to the Advanced Boosters Engineering Demonstration and Risk Reduction (ABEDRR) and SLS Advanced Development. As a result of the NRAs, tasks were awarded. A summary list of all the Advanced Development tasks is shown in figure 4.

In-house Tasks:

- Cryogenic Propulsion Stage (CPS) Systems Analysis & Definition
- AL2195 T8 Gore Development
- Characterization of SLM Materials for SLS Engine Components
- Cryoinsulation Mat'ls & Process Development - Mitigate Obsolescence
- Hexavalent Chromium Free Primer for Cryo
- MPS Low Profile Diffuser
- SLM Integral Valve/Injector - Valve Proposal
- SLM Integral Valve/Injector - Injector Proposal
- SLM Integral Valve/Injector Integrated Hot Fire Testing in 2013
- Affordable Upper Stage Engine Program (AUSEP)
- Advanced Passive Avionics Cooling
- Advanced Telemetry System
- H_2 Gas Sensor
- Fluid-Structure Coupling Damper
- Shell-Buckling Knockdown Factors
- Ullage Collapse & Capacitance Probe
- Advanced Booster Combustion Stability (NESC funded)
- Pyroshock Characterization of Composite Materials (NESC funded)
- Booster Interference Loads (NESC funded)

Academia Tasks:

- Auburn University: High Electrical Density Device Survey for Aerospace Applications
- Louisiana State University: Improved Friction Stir Welds Using On-Line Sensing of Weld Quality
- Massachusetts Institute of Technology: Modeling Approach for Rotating Cavitation Instabilities in Rocket Engine Turbopumps
- Mississippi State University: Algorithmic Enhancement for High Resolution Hybrid RANS-LES
- University of Florida: Development of Subcritical Atomization Models for Liquid Rocket Injectors
- University of Maryland: Validation of Supersonic Film Cooling Numerical Simulations Using Detailed Measurement and Novel Diagnostics
- University of Michigan: Advanced LES and Laser Diagnostics to Model Transient Combustion-Dynamic Processes in Rocket Engines: Prediction of Flame Stabilization and Combustion Instabilities
- University of Utah: Acoustic Emission Based Health Monitoring of Structures
- Pennsylvania State University: Characterization of Aluminum/Alumina/Carbon Interactions Under Simulated Rocket Motor Conditions

Awarded Industry Tasks:

- Exquadrum, Inc: Affordable Upper Stage Engine (AUSE) Requirements Study
- Moog/Aerojet: AUSE High Press LOX Flow Control Valve Manufacturing Study
- Northrup Grumman: System Requirements and Affordability Assessment for an AUSE
- Pratt & Whitney Rocketdyne: Requirements, Logistics, and System Assessment of an AUSE

Advanced Booster Engineering Demonstration and Risk Reduction Tasks (ABEDRR):

- Dynetics: Risk Reduction for Dual Boosters Using F-1B Engines
- Northrop Grumman: Demonstration of a Common Bulkhead LOX/RP Composite Cryogenic Tank
- ATK: Demonstration of a FWC for High-Energy Propellant SRB
- Aerojet: Risk Reduction for a LOX Rich LOX/RP Stage Combustion Booster Engine

Figure 4. ADO Advanced Development tasks.

In June 2013, Pratt & Whitney Rocketdyne (PWR) and Aerojet, both of which are performing work for the SLS ADO, merged to form Aerojet Rocketdyne. For the sake of clarity, and since the bulk of work described herein was performed prior to Aerojet's acquisition of PWR, both companies are referred to by the heritage names under which they were awarded the work.

1.2 Advanced Development Office Organization

1.2.1 Organizational Chart

The ADO is organized into three main areas: Advanced Booster, Concepts and Analysis, and SLS Cross-Cutting tasks (fig. 5). The contact list for specific tasks is provided in appendix B.

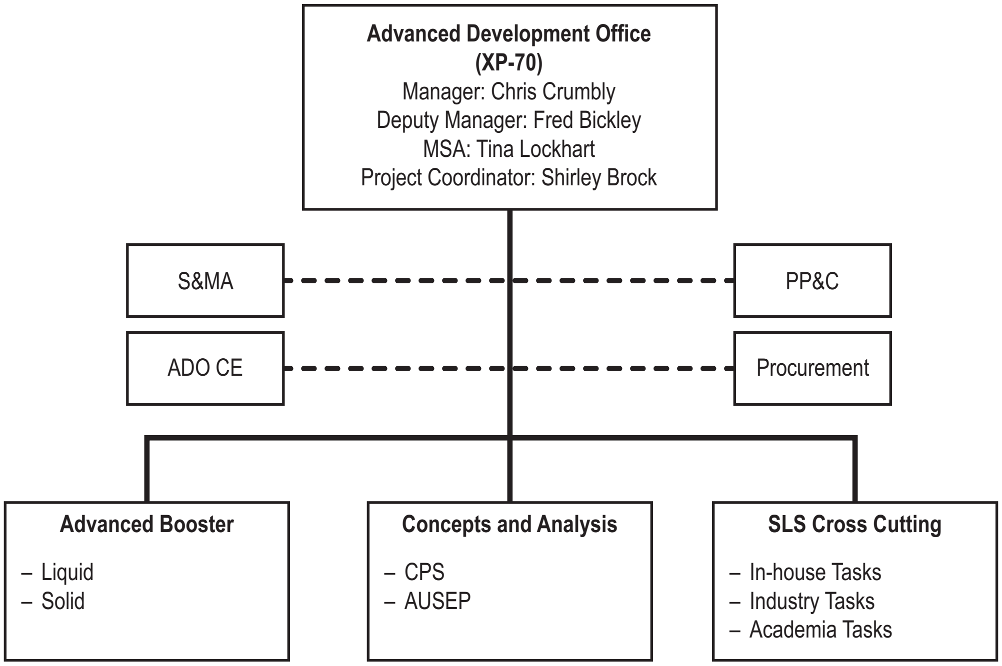


Figure 5. ADO organization.

1.2.2 Partnership

ADO has partnered with several organizations, both internal and external, in support of Advanced Development activities. The supporting partners are as follows:

- NASA
  - NASA Engineering and Safety Center (NESC)
  - National Institute for Rocket Propulsion Systems
  - MSFC ED
  - MSFC Safety and Mission Assurance (S&MA) Directorate
  - Other NASA Centers.

- Department of Defense (DoD)
  - U.S. Air Force (USAF)
  - U.S. Army—Aviation and Missile Research Development and Engineering Center (AMRDEC).

Without both NESC's and the USAF's major investments in the ADO effort, the breadth of ADO's portfolio would have been limited. Their investments have been both financial and through personnel supporting the overall effort.

1.3 Funded Tasks

In FY 2013, ADO funded the following number of tasks:

- In-house tasks: 16 (four additional tasks were funded and managed by NESC)
- Academia tasks: 9
- Industry tasks: 5
- ABEDRR: 4.

1.4 Tasks' Reference Index

For the purpose of easily finding the area of interest, all the tasks have been cross-referenced for applicability to SLS elements and engineering disciplines. The applicability for all tasks is shown in table 1.

Table 1. Tasks cross-reference matrix.

			Applicability						Discipline				
Cat-egory	Responsible Organization	Proposed Advanced Development Task	Solid Boosters	Liquid Boosters	Core Stage	Engines	EUS	Shroud	Structures	Thermal	Propulsion	Avionics	Manufac-ture
NASA In-House	MSFC	Al 2195 TB Gore Dev			🟩		🟩						
	MSFC	Cryoinsulation Materials and Process		🟩	🟩		🟩	🟩		🟩			
	MSFC	Hexavalent Chromium-Free Primer for Cryo		🟩	🟩		🟩	🟩		🟩			
	MSFC	NDE of SLM Materials				🟩					🟩		🟩
	MSFC	SLM Propulsion Hardware				🟩					🟩		🟩
	MSFC	MPS Low Profile Diffuser		🟩	🟩		🟩				🟩		
	MSFC	H_2 Gas Sensor		🟩	🟩	🟩	🟩	🟩			🟩	🟩	
	MSFC	Advanced Passive Avionics Cooling	🟩	🟩	🟩		🟩			🟩		🟩	
	MSFC	High Voltage Electronic Parts Assessment	🟩	🟩	🟩	🟩						🟩	
	MSFC	Advanced Telemetry System			🟩		🟩					🟩	
	MSFC	Fluid-Structure Coupling Damper			🟩				🟩				
	LaRC	Knockdown Factors for Shell Buckling	🟩	🟩	🟩				🟩				
	MSFC	Ullage Collapse and Capacitance Probe		🟩	🟩		🟩				🟩		
	MSFC	Bolt-on Adapter Ring for Secondary Payloads			🟩		🟩	🟩	🟩				
	MSFC	Cryogenic Propulsion Stage (CPS) Systems				🟩	🟩		🟩	🟩	🟩	🟩	🟩
	MSFC	Affordable Upper Stage Engine Program (AUSEP)				🟩	🟩				🟩	🟩	🟩

Table 1. Tasks cross-reference matrix (Continued).

Cate-gory	Responsible Organization	Proposed Advanced Development Task	Applicability						Discipline				
			Solid Boosters	Liquid Boosters	Core Stage	Engines	EUS	Shroud	Structures	Thermal	Propulsion	Avionics	Manufac-ture
	NESC	Pyroshock Characterization of Composite Materials					🟩	🟩	🟩				🟩
NASA In-House	NESC	Advanced Booster Composite Case/PBI	🟩						🟩				🟩
	NESC	Advanced Booster Combustion Stability		🟩		🟩					🟩		
	NESC	Booster Interference Loads	🟩	🟩	🟩				🟩				
Academia	Auburn University	Power Storage Devices					🟩					🟩	
	Louisiana State College	Improved FSW Using Online Sensing			🟩		🟩						🟩
	Massachusetts Institute of Technology	Instabilities in Modelling of Cavitation				🟩					🟩		
	Mississippi State University	Low Dissipation and High Order Unstructured CFD	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	Pennsylvania State University	Characterization of Al/ Alumina/Carbon	🟩								🟩		🟩
	University of Florida	Development of Subcritical Atomization Models				🟩				🟩	🟩		
	University of Maryland	Supersonic Film Cooling				🟩				🟩	🟩		
	University of Michigan	LES/Laser Diagnostics to Model Transient				🟩					🟩		
	University of Utah	Acoustic Emission HM of Structures			🟩		🟩	🟩	🟩				
Industry	Aerojet	Augmented Expander				🟩	🟩				🟩		
	Exquadrum, Inc.	AUSE Requirements Study				🟩	🟩				🟩		
	Moog, Inc	AUSE High Pressure LOX Flow Control Valve Study				🟩	🟩				🟩		
	Northrup Grumman Systems	AUSE System Requirements and Affordability Assess				🟩	🟩				🟩		
	Pratt & Whitney, Rocketdyne	Requirements, Logistics and System Assessment				🟩	🟩				🟩		
ABEDRR	Aerojet	Combustion Stability and LOX-Rich RP SC Engine		🟩		🟩					🟩		🟩
	ATK	FWC High Energy Propellant, Nozzle	🟩			🟩			🟩		🟩	🟩	🟩
	Dynetics	F-1 Engine GG/ Turbopump/P		🟩		🟩			🟩		🟩		🟩
	Northrup Grumman Systems	Common Bulkhead LOX/RP Composite Tank		🟩					🟩				🟩

1.5 Future Plans

The plan for FY 2014 is to continue the existing academia efforts, complete the industry tasks, and continue the ABEDRR tasks. Results of the initial in-house tasks are currently under review and a call was issued in May 2013 to solicit new tasks focused on an Exploration Upper Stage (EUS) and advanced manufacturing techniques. The process used is discussed in section 2.1.1.

1.6 Summary

The ADO portfolio of tasks covers a broad range of technical developmental activities supporting the evolution of the SLS launch vehicle from the initial 70 t Block 1 vehicle to the 130 t Block 2 vehicle. The ADO portfolio supports the development of advanced boosters, upper stages, and other advanced development activities benefiting the SLS program. The tasks are structured to provide off-ramps on a yearly basis in the event of budget constraints or lack of progress. The summary budget is shown in table 2. A summary schedule of tasks is shown in figure 6. The task details are discussed in section 2.

Table 2. ADO FY 2013 budget summary.

Task	FY 2013 Investment ($M)*
In-house	5.6
Academia	1.9
Industry	4.7
ABEDRR	46.5

*Substantial resources provided by NESC and the USAF.

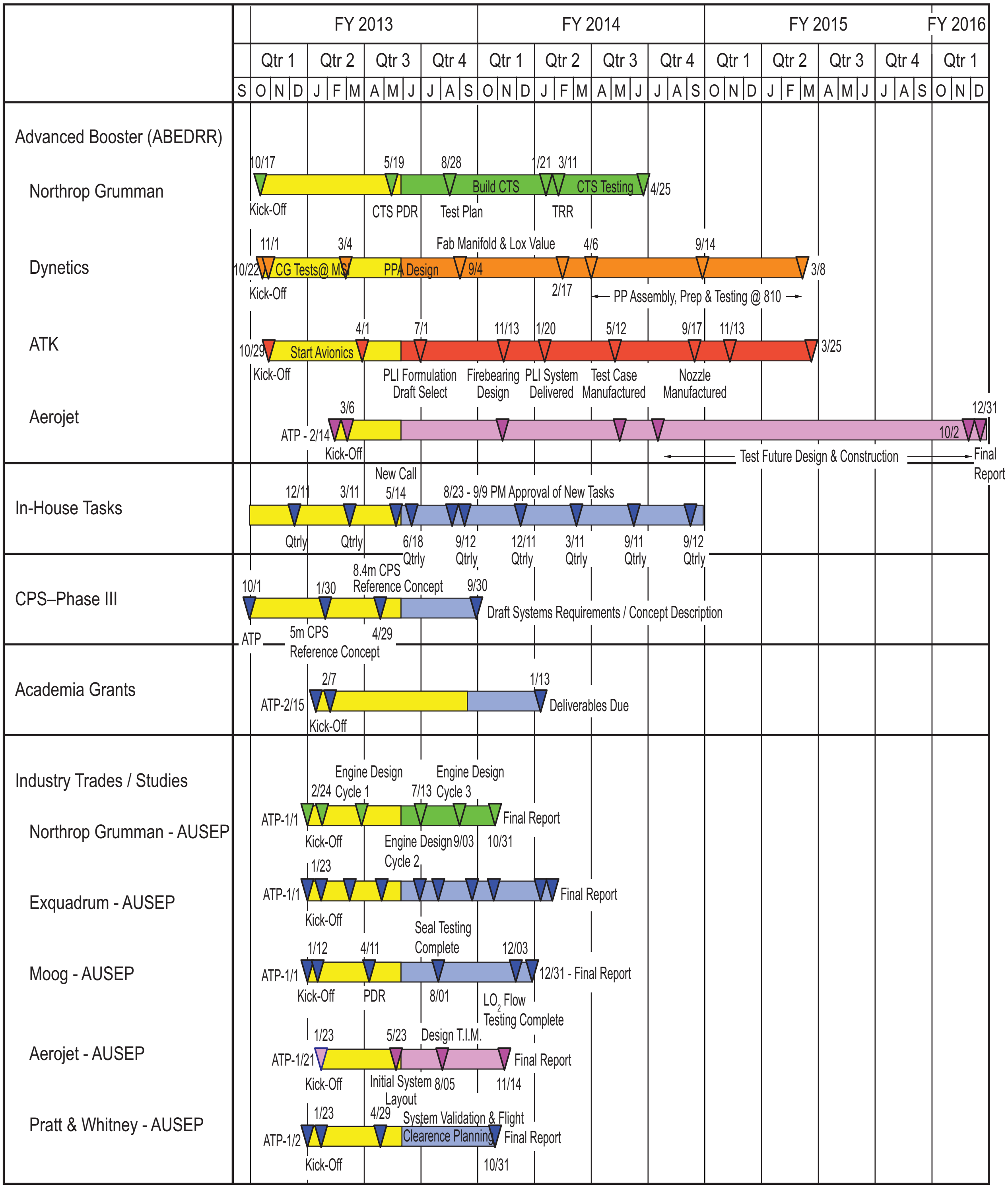


Figure 6. ADO summary schedule

2. TASK DESCRIPTION

This section covers in-house tasks, academia contracts/grants, ABEDRR contracts, and industry contracts.

2.1 In-House Tasks

ADO initially selected 19 in-house tasks. Three tasks were combined and one was transferred, resulting in a net total of 16 in-house tasks funded in 2012. They are as follows:

(1) Aluminum lithium (Al-Li) 2195 T8 Gore Development.
(2) Cryogenic Insulation Materials and Process Development.
(3) Hexavalent Chromium-Free Primer for Cryogenic Application.
(4) Nondestructive Evaluation (NDE) of Selective Laser Melting (SLM) Materials.
(5) SLM Propulsion Hardware.
(6) Main Propulsion System (MPS) Low Profile Diffuser.
(7) Hydrogen (H_2) Gas Sensor.
(8) Advanced Passive Avionics Cooling.
(9) High Voltage Electronic Parts Assessment.
(10) Advanced Telemetry System (completed).
(11) Fluid-Structure Coupling Damper.
(12) Shell-Buckling Knockdown Factors (SBKDFs).
(13) Ullage Collapse and Capacitance Probe (completed).
(14) Bolt-On Adapter Ring for Secondary Payloads (completed).
(15) Advanced/Affordable Upper Stage Engine Program (AUSEP).
(16) Cryogenic Propulsion Stage (CPS) Systems Analysis and Definition.

The last two tasks, being larger in scope than the others, are covered in sections 2.4 and 3.2, respectively.

The NESC selected to fund and manage four additional tasks not funded by ADO. These are as follows:

(1) Pyroshock Characterization of Composite Materials.
(2) Booster Interference Loads.
(3) Advanced Booster Composite Case/Polybenzimidazole-Nitrile Butadiene Rubber (PBI-NBR) Insulation Development.
(4) Advanced Booster Combustion Stability.

2.1.1 Selection Methodology

The selection process used for the in-house tasks is shown in figure 7. Initially, ADO released a call for proposals to MSFC ED with instructions to solicit inputs from other NASA Centers. The call specified that the proposed tasks must be consistent with reasonably expected technical advances and realistic budgetary constraints, and must address one or more of the following figures of merit (FOMs):

- Improvements in affordability.
- Improvements in safety.
- Improvements in reliability.
- Improvements in performance.

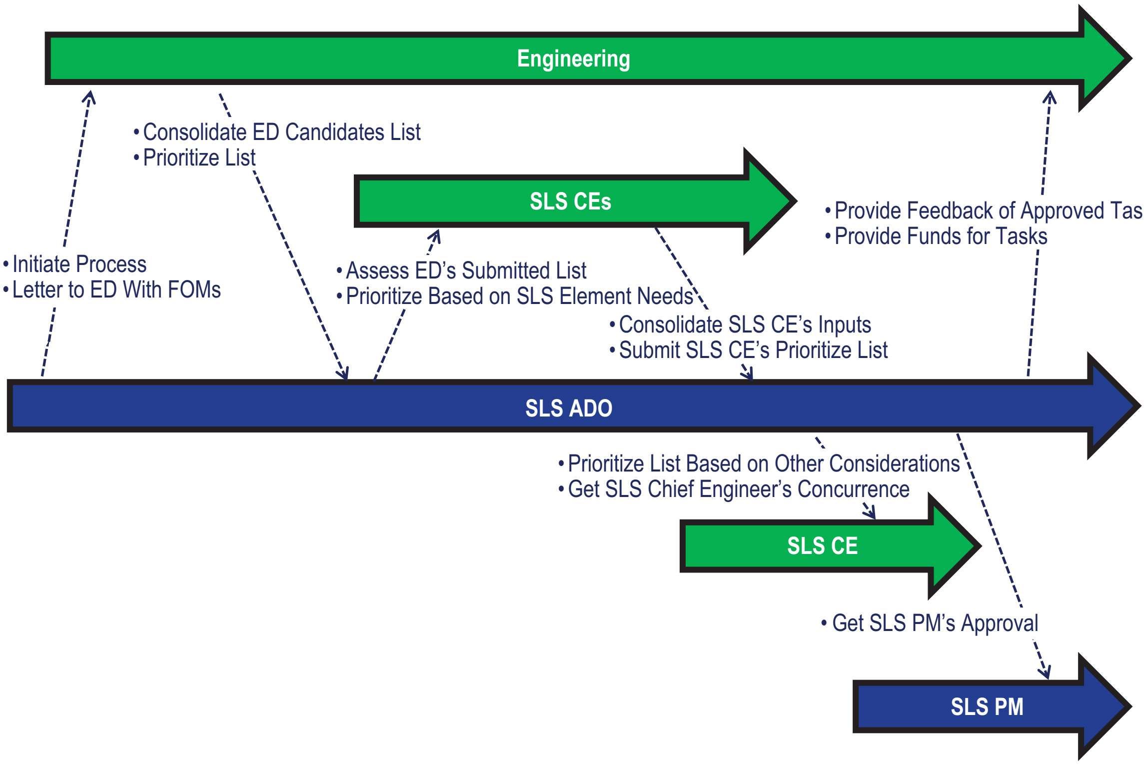


Figure 7. In-house task selection process.

The Engineering Directorate received a total of 80 proposals in the form of quad charts (the template was provided in the call from ADO). The proposals received were from MSFC, Glenn Research Center (GRC), and Langley Research Center (LaRC). Proposed NASA partnerships included LaRC, Kennedy Space Center (KSC), U.S. Army, Ames Research Center (ARC), Johnson Space Center (JSC), Goddard Space Flight Center (GSFC), Wallops Flight Facility, Michoud Assembly Facility (MAF), and Dryden Flight Research Center (DFRC).

Departments within ED reviewed and ranked the proposals. A panel of ED senior managers was convened to review and prioritize the proposed tasks. After this was completed, the results were presented to ADO. The ADO Chief Engineer (CE) then convened a panel consisting of all the SLS CEs and the SLS Chief Safety Officer (CSO) to review the proposed tasks and assess their applicability and priority to both the current Block 1 SLS vehicle and the evolved vehicle concepts. They provided their assessment to ADO by categorizing the tasks in high, medium, and low priorities.

Based on the CE and CSO inputs, ADO selected a set of 16 high-priority tasks that would fit within the allocated resources available. This final list was then vetted through the SLS CE and presented to the SLS program manager for final approval. ADO gave ED the authority to proceed (ATP) at the in-house tasks kickoff meeting on April 18, 2012.

2.1.2 Advanced Development Office-Funded Task Descriptions/Status

2.1.2.1 Aluminum-Lithium Alloy 2195 T8 Gore Development

2.1.2.1.1 Description. This task involves development of the manufacturing process to make gore panels out of Al-Li alloy 2195. These gores are then welded together to form the domes for the SLS propellant tanks. Weight is a primary design driver for the SLS, as it is in any rocket development program. The current SLS design utilizes aluminum alloy Al 2219 in the construction of the propellant tanks. Replacing Al 2219 with Al-Li 2195 gores in the propellant tank domes could save approximately 3,800 lbm for SLS Block 1B (possible interim evolution variant). Development of the stretch-forming process for Al-Li 2195 thick gores has applicability to both the current SLS design and potential future configurations. Previous Ares upper stage tasks demonstrated that material property variations in Al-Li 2195 affect the ability to successfully stretch Al-Li 2195 gores. Formability and heat treat studies need to be conducted to optimize stretch parameters.

The primary objective of this task is to optimize the heat treatment and stretch parameters for thicker gores (0.525 and 0.750 in). The upfront process optimization should reduce the downstream development cost and provide confidence for repeatable flight-qualified Al-Li 2195 gore manufacturing. To achieve these objectives, several activities have been identified that include predictive modeling, heat treatment and formability studies, mechanical property evaluation of existing thin gores (0.325 in), and stretch and property evaluation of thicker gores (0.525 and 0.750 in). Completion of these activities will provide confidence for potential replacements for Block 1B core stage gores. The test setup is shown in figure 8.

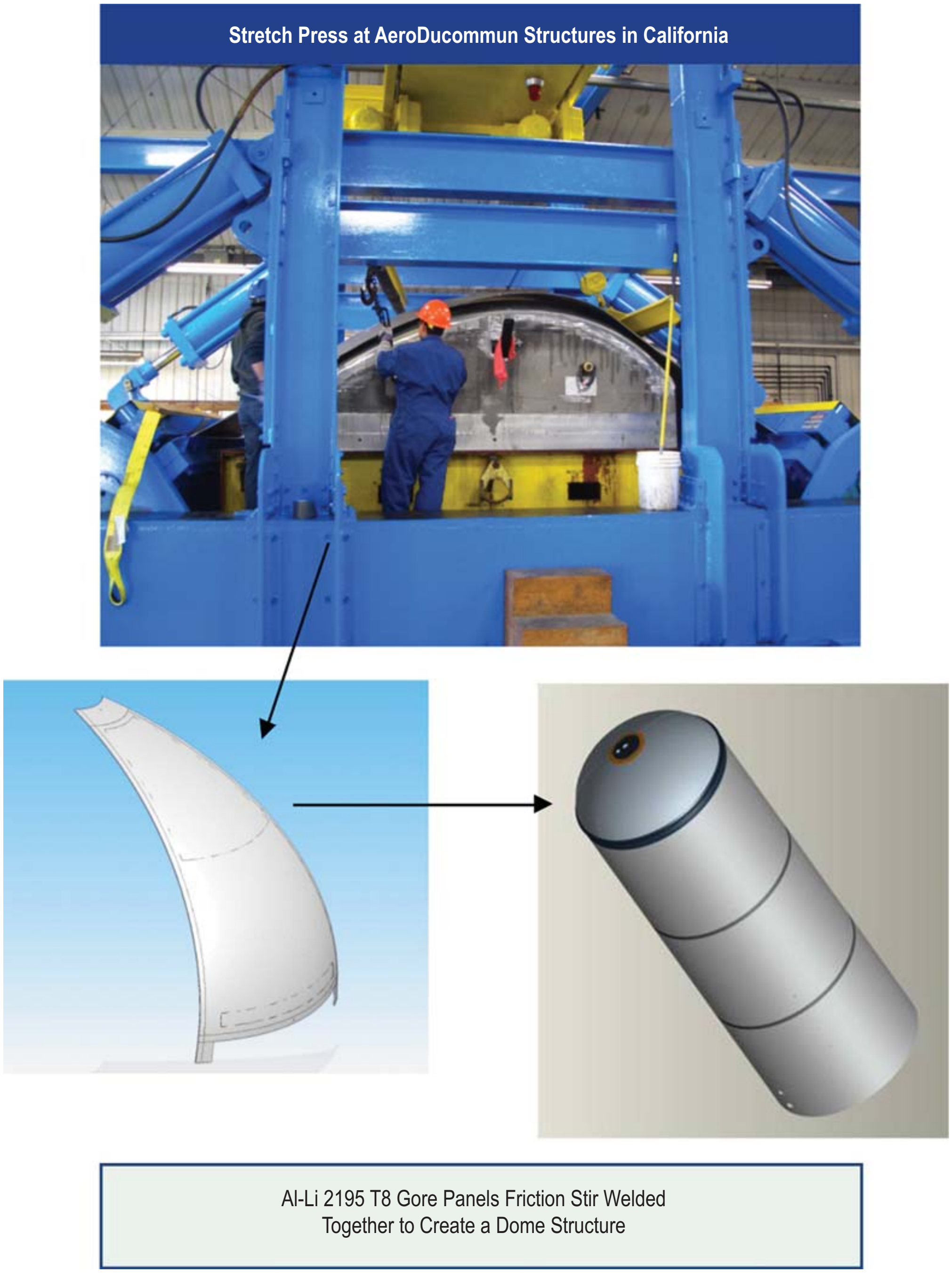
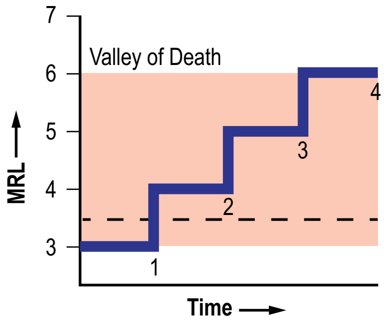


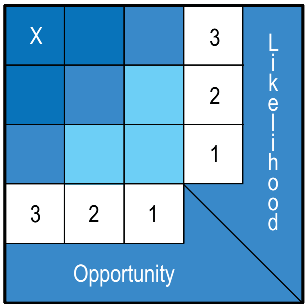
Figure 8. Ducommun test fixture.

2.1.2.1.2 Technology Readiness Level Assessment. To establish the progress desired during the execution of this task, a technology assessment was conducted to determine the end state at completion. Since the gore develpment task focuses primarily on the manufacturing process, the Manufacturing Readiness Level (MRL) was used in lieu of TRL. Milestones and investments required to improve the MRL were estimated. A 3×3 SLS opportunity matrix indicating the likelihood and opportunity for SLS was assessed. The results are presented in figure 9.



In-House Subtasks	
Event	**Description**
1	Materials properties characterization
2	Gore panels fabrications
3	Stretching of gore panels
4	Gore panel dome fabrication with welding

In-House Activity	LIKE	OPPO
Al-Li 2195 T8 Gore Development	3	3



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 9. Gore segment TRL assessment.

2.1.2.1.3 Accomplishments. The following tasks were completed:

- Mechanical testing and fracture toughness testing on 0.325-in-thick gores.
- Formability testing of 0.525- and 0.750-in plates heat-treated with NASA annealing procedure.
- Development of a finite element modeling (FEM) approach for the stretch-forming of Al 2195 gores.
- Stretch-forming of 0.525- and 0.750-in-thick gores.

2.1.2.1.4 Future Work. Future work includes the following:

- Mechanical and fracture toughness testing of 0.525- and 0.750-in-thick gores.
- Trade study to address the incorporation of thicker gores for SLS configurations, including gore manufacturability, tooling requirements, and potential heat treatment facility upgrades.

2.1.2.2 Cryogenic Insulation Materials and Process Development—Mitigate Obsolescence

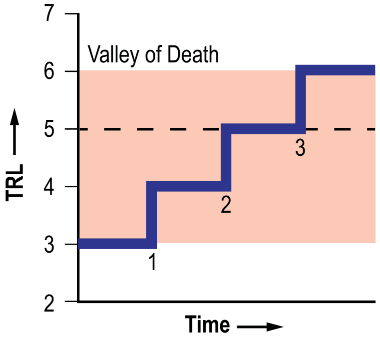
2.1.2.2.1 Description. Current cryogenic insulation materials, originally developed for the Constellation program and later transitioned to the SLS program, are classified as Ozone Depleting Substance environmentally compliant materials. These materials carry a Global Warming Potential (GWP) rating. While the Environmental Protection Agency has not begun to regulate GWP materials, it has levied a usage reporting requirement, which historically is the first step towards regulation.

It is expected that the foam industry will be testing new materials in small quantities and will likely transition them into production to avoid obsolescence-related shortages. These industry applications are different from aerospace applications, so the new foam systems will require aerospace-specific development and testing similar to that performed by MSFC for current cryogenic insulation systems.

This task is developing closeout processes for current low GWP materials and will further develop and characterize industry recommended zero GWP materials for a wide range of aerospace applications (fig. 10). Anticipated elements that may benefit from this effort include the SLS core and upper stages. These elements could be faced with a material obsolescence issue that threatens current foam system availability (historically occurs every 5 to 7 years).

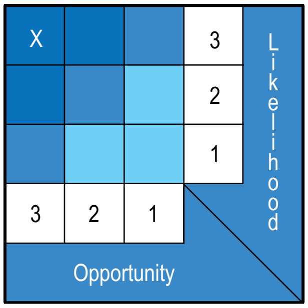
Figure 10. Foam insulated cryotank test article.

2.1.2.2.2 Technology Readiness Level Assessment. To establish the progress during the execution of this task, a technology assessment was conducted to determine the end state at completion. Also established were the milestones required to improve the TRL. A 3×3 SLS opportunity matrix indicating the likelihood and opportunity for SLS was assessed. The results are presented in figure 11.



In-House Activity	LIKE	OPPO
Cryoinsulation Material and Process Development to Mitigate Obsolescence Risk	3	3

In-House Subtasks	
Event	**Description**
1	Foam Primer Compatibility Study
1	Further define process parameters
2	Lab-scale evaluation of potential foams
3	Foam spray evaluation, vendor reformation. Boundary processing condition sprays for candidates



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 11. Cryo-insulation TRL assessment.

2.1.2.2.3 Accomplishments. The following accomplishments were made:

- All development sprays are complete and specimens are in testing.
- Foam S-180 material and process specification drafts are complete and submitted for approval.
- The foam S-180 Qualification Test Plan is complete and procurement of materials for qualification is under way.

2.1.2.2.4 Future Work. This task would continue to optimize closeout process development for current low GWP materials and further develop and characterize industry recommended zero GWP materials.

2.1.2.3 Hexavalent Chromium-Free Primer Development

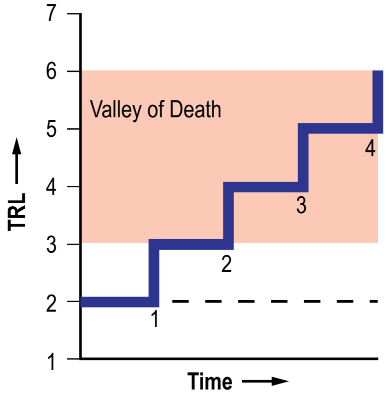
2.1.2.3.1 Description. This task involves identifying a commercially available hexavalent chromium-free primer for cryogenic applications. The need for a new primer is driven by the carcinogenic nature of, the manufacturing cost associated with, and the high potential for obsolescence of currently qualified primers that contain hexavalent chromium.

Hexavalent chromium-based primers are applied to metallic cryogenic tank structures to provide corrosion protection and promote adhesion for thermal protection system materials. Hexavalent chromium is considered a hazardous material and its availability for future programs is questionable, since its customer base is switching to nonhazardous alternatives. The primary user, the DoD, does not, in general, require cryogenic performance, so alternative materials have been made more readily available for their applications.

This effort evaluates the corrosion protection capability of several hexavalent chromium-free primers under simulated launch vehicle related conditions (fig. 12). Results will provide sufficient data to either recommend these materials for qualification testing or remove them from consideration. Applications include replacement of current hexavalent chromium primers used on the SLS structure beneath thermal protection system materials. The resulting materials will be environmentally friendly and should reduce operations costs associated with hazardous waste usage and disposal.

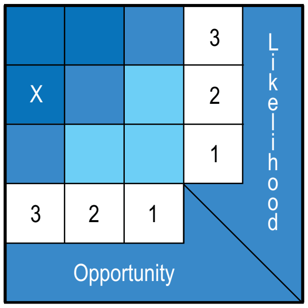
Figure 12. Hexavalent chromium-free test panels.

2.1.2.3.2 Technology Readines Level Assessment. To establish the progress during the execution of this task, a technology assessment was conducted to determine the end state at completion. Also established were the milestones required to improve the TRL. A 3×3 SLS opportunity matrix indicating the likelihood and opportunity for SLS was assessed. The results are presented in figure 13.



In-House Subtasks	
Event	**Description**
1→3	Primer test and characterization
4	Purchase commercially available materials, proceed through phased test plan to meet vehicle requirements and carry said materials towards flight certification

In-House Activity	LIKE	OPPO
Hexavalent chromium-free primer development for cryogenic applications	3	2



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 13. Hexavalent chromium-free primer TRL assessment.

2.1.2.3.3 Accomplishments. Hexavalent chromium-free primer development task personnel have been working with industry to identify potential candidates and potential modifications to these candidates to meet NASA/SLS cryogenic requirements.

2.1.2.3.4 Future Work. A 3-year test plan has been proposed to reach the goal of providing a candidate and characterize the processing boundaries for flight qualification.

2.1.2.4 Nondestructive Evaluation of Selective Laser Melting Materials

2.1.2.4.1 Description. The durability of components made from additive manufacturing techniques such as SLM, or 3-D printing, are important due to their ability to reduce manufacturing cost for components. This task provides a roadmap to assess this durability via the optimization of NDE methods and techniques. The goal is to make components that can meet the rigors of space environments in a more economical way.

The combination of structured light processes, which map the outer surface geometry of a component, and NDE mapping of the inner volume of that same part, produces data that can be merged into a mesh and mapped into a drawing used to manufacture the same part via SLM. Parts can also be reverse-engineered and reproduced.

The TRL is high for the NDE methods, but the techniques involving the down-select of a method, the production of reference standards, and understanding the effects of any manufactured defects and their cause is low, in the range of TRL 2–3.

SLM-processed components are being investigated for use in SLS engine component manufacturing (fig. 14). Initial NDE inspection of SLM-formed components has been conducted at MSFC. This effort would provide a database of NDE inspection results for candidate metals that could be used in J-2X and RS-25 engine components.

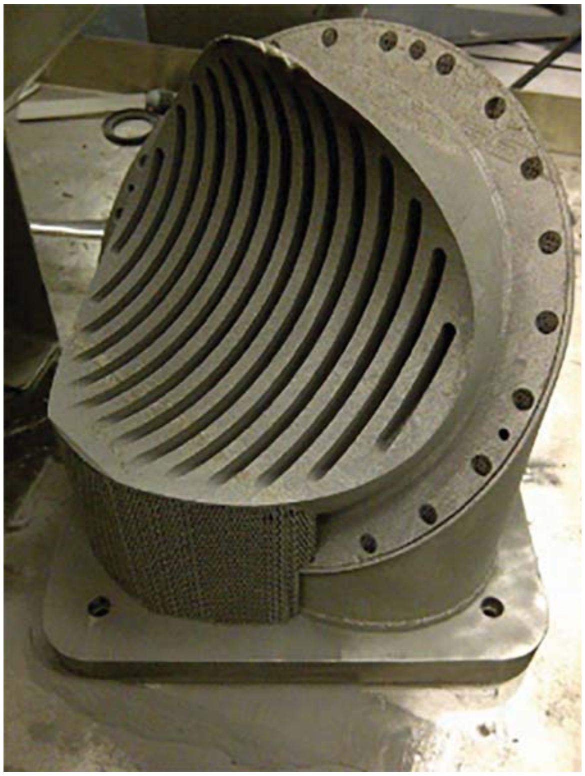
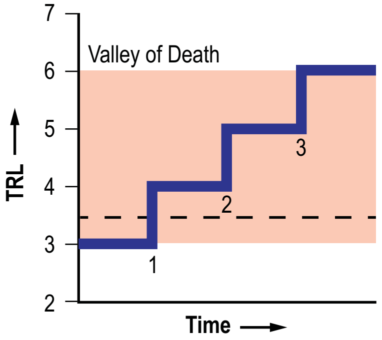


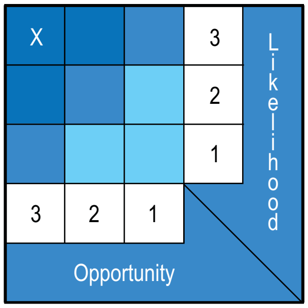
Figure 14. RS-25 Z-baffle.

2.1.2.4.2 Technology Readiness Level Assessment. To establish the progress during the execution of this task, a technology assessment was conducted to determine the end state at completion. Also established were the milestones required to improve the TRL. A 3×3 SLS opportunity matrix indicating the likelihood and opportunity for SLS was assessed. The results are presented in figure 15.



In-House Subtasks	
Event	**Description**
1→3	Characterization study of existing built components

In-House Activity	LIKE	OPPO
Characterization of SLM materials for SLS engine components	3	3



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 15. NDE of SLM materials TRL assessment.

2.1.2.4.3 Accomplishments. The task team has designed reference gauge blocks that can help merge structural light data and computed tomographic x-ray data into files that can be used to reproduce complex engine parts.

2.1.2.4.4 Future Work. The optimization of the NDE process.

2.1.2.5 Selective Laser Melting Propulsion Hardware

2.1.2.5.1 Description. This task is to design, fabricate, and cold-flow test an integral valve and injector built using SLM (fig. 16). The objective is to increase the TRL of the process through hardware fabrication demonstrators and testing. The process will eliminate the need for separate flanges and reduce the volume of fluid between the valve seat and the injector face.

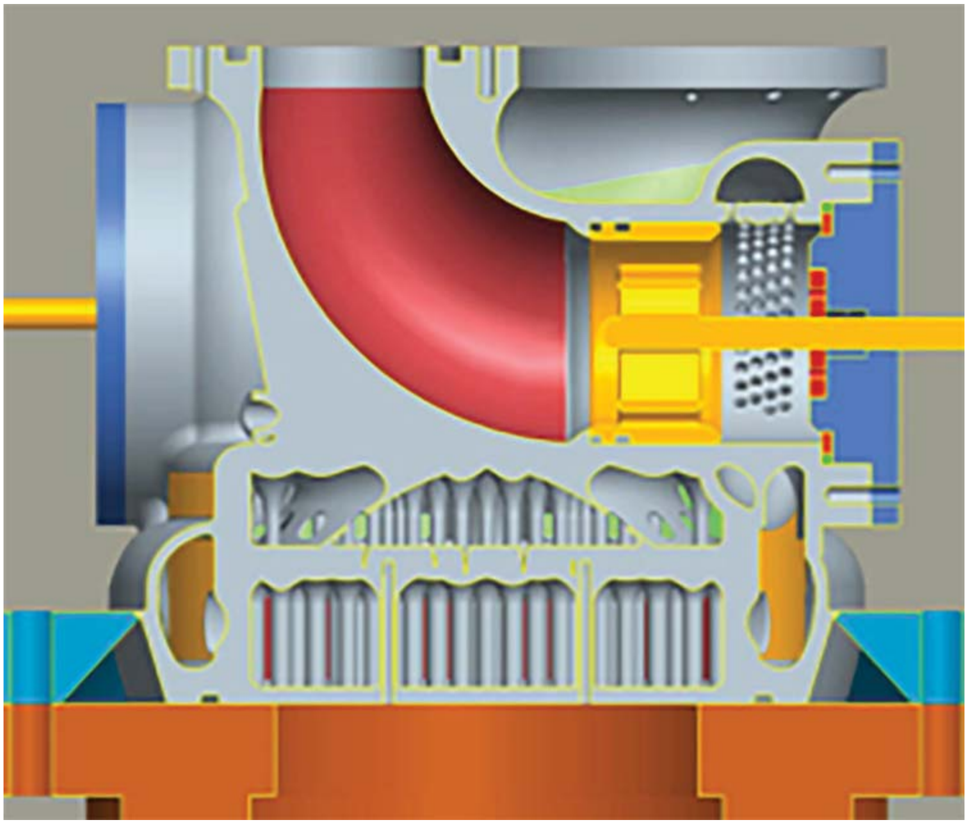
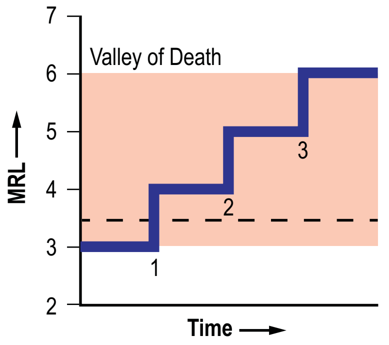


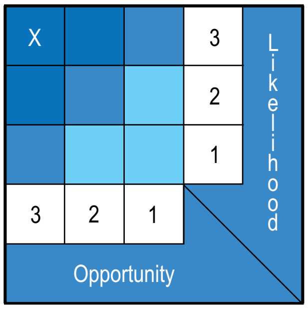
Figure 16. SLM integral valve and injector design.

2.1.2.5.2 Technology Readiness Level Assessment. To establish the progress desired during the execution of this task, a technology assessment was conducted to determine the end state at completion. Also established were the milestones required to improve the TRL. A 3×3 SLS opportunity matrix indicating the likelihood and opportunity for SLS was assessed. The results are presented in figure 17.



In-House Activity	LIKE	OPPO
Sintering laser method (SLM) integral valve/injector and hot-fire proposal	3	3

In-House Subtasks	
Event	**Description**
1	Develop a set of valves and injectors
2	Design a new body integral to an injector manifold and build the body manifold
3	Complete diffuser manufacture and prepare component development test area. Hot-fire test plan and testing
3	NDE evaluation of hardware after testing, redesign if necessary, hot-fire testing of new hardware. Data review



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 17. SLM propulsion hardware TRL assessment.

2.1.2.5.3 Accomplishments. The integral valve and injector initial design is complete and the hardware is being fabricated.

2.1.2.5.4 Future Work. Complete manufacturing and conduct both cold- and hot-flow tests.

2.1.2.6 Main Propulsion System Low Profile Diffuser

2.1.2.6.1 Description. Pressurization diffusers are used to introduce pressurization gases into a rocket's propellant tanks. This pressurization gas is used to keep the tanks pressurized as the rocket engine burns and drains the propellants. The diffuser's role is to introduce the gases into the tank without significant velocity. Typical diffusers are long and limit the amount of propellants that can be loaded into the tanks. A smaller, more compact diffuser would allow more liquid propellant to be loaded into the tank, which in turn helps increase the rocket's performance.

The purpose of this task is to create a low profile pressurization diffuser (fig. 18) that is more compact than traditional pressurization diffusers. This task uses computational fluid dynamics (CFD) to design a low profile diffuser. The flow passing through the diffuser was analyzed to determine how the exiting gases flow into the tank.

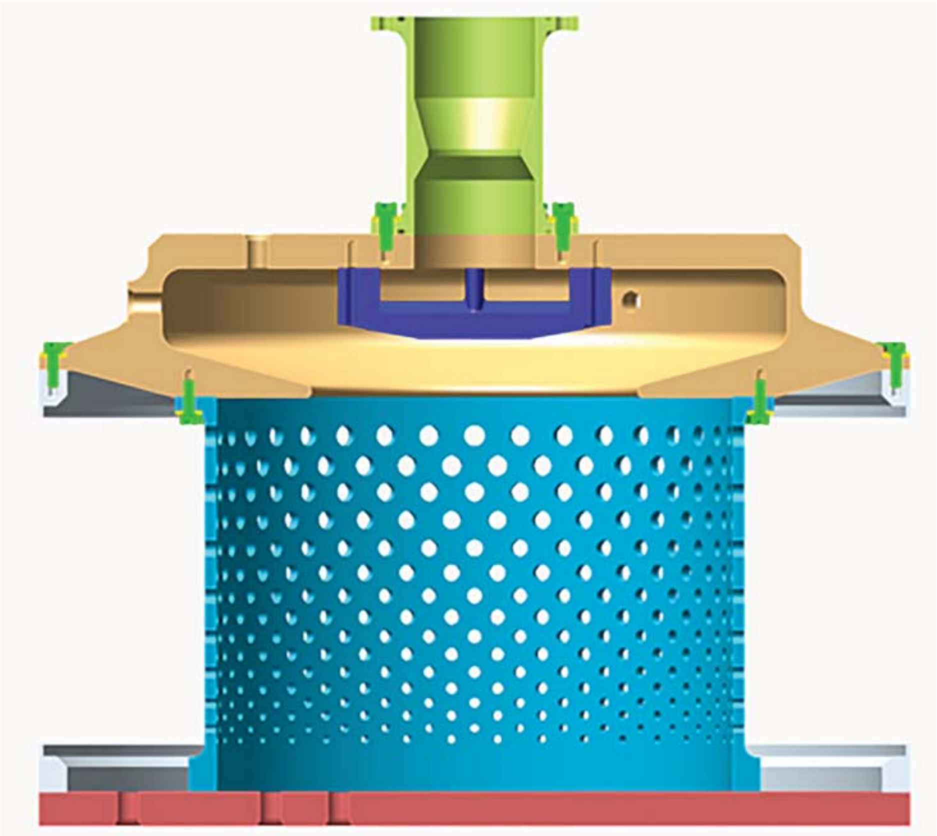
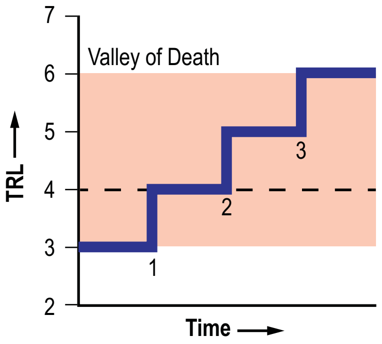


Figure 18. Low profile diffuser design.

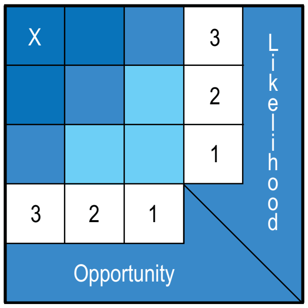
2.1.2.6.2 Technology Readiness Level Assessment. To establish the progress during the execution of this task, a technology assessment was conducted to determine the end state at completion. Also established were the milestones required to improve the TRL. A 3×3 SLS opportunity matrix indicating the likelihood and opportunity for the SLS was assessed. The results are presented in figure 19. This task began as a TRL 3. It is projected that the design will result in a TRL 6, signifying its readiness for incorporation into a test flight.



In-House Activity	LIKE	OPPO
MPS low profile diffuser	3	3

In-House Subtasks

Event	Description
1	Develop a low profile diffuser
2	Update designs, analysis of outflow conditions, diffuser manufactured
2	Complete diffuser manufacture and prepare component development test area
3	Evaluation feasibility of diffuser, flight design and manufacture, integrate into system and test



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 19. Low profile diffuser TRL assessment.

2.1.2.6.3 Accomplishments. The CFD analyses performed to date have resulted in an optimized design, which is currently being manufactured.

2.1.2.6.4 Future Work. Late in 2013, the diffuser will be tested to evaluate its flow environment. Testing will be performed at the same test facility and under the same test conditions as the current flight design for the SLS core stage. This testing will provide a direct comparison of the flow characteristics of both diffusers. The test data will allow the determination of how well the low profile diffuser will perform relative to the baseline design when installed on the flight vehicle.

2.1.2.7 Hydrogen Gas Sensor

2.1.2.7.1 Description. This task applies primarily to the core stage and engine compartment but can be used wherever there is a concern for leakage of gaseous hydrogen (GH_2) such as the upper stage, the Orion crew spacecraft, and test facilities. Vehicle safety is the major benefit provided by this sensor. The plan is to use a catalyst-based sensor or a mass spectrometer with feed lines. This design will allow real-time monitoring of GH_2. The small form factor sensor design (fig. 20) facilitates easy installation to any location in a Block 1A or Block 2 vehicle. A wireless design opens more location possibilities and is limited only by battery life.

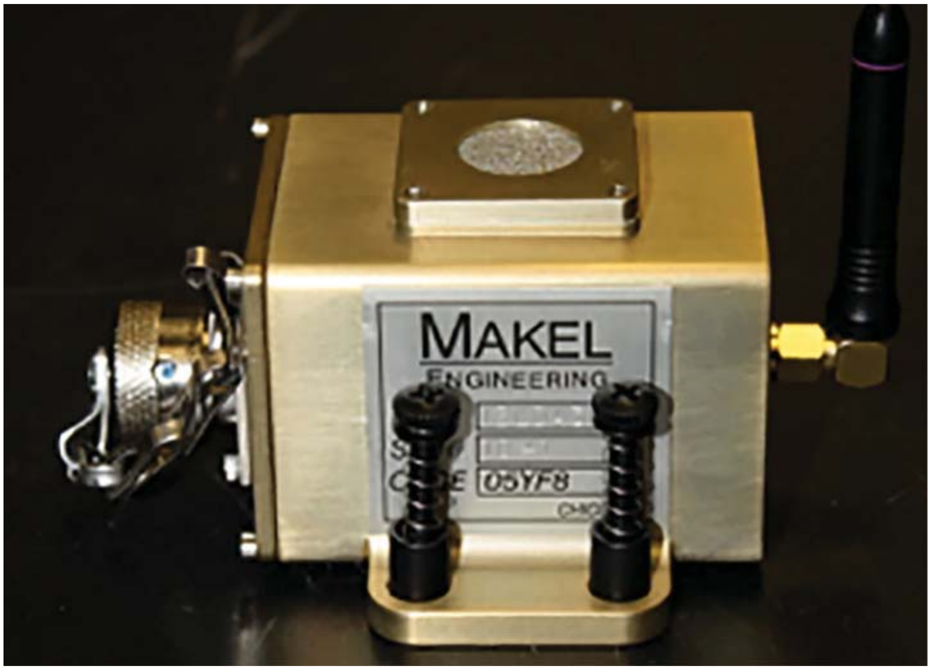
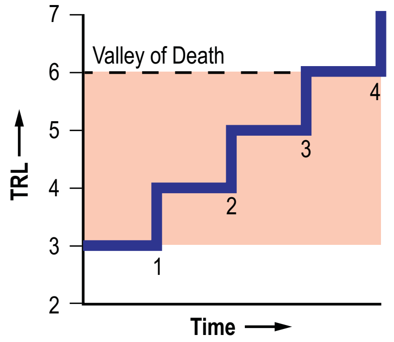


Figure 20. GH_2 sensor.

The focus of the task is to subject the GH_2 sensor to relevant SLS environments. The goal is to show that the sensor will operate successfully during pad operations, launch, and flight. The sensor design will undergo a minimum random vibration screening and a electromagnetic interference (EMI)/electromagnetic compatibility (EMC) test. The GH_2 sensor design is in use on the International Space Station (ISS) to monitor hydrogen levels in the oxygen regeneration system. The GH_2 sensor orbital replaceable unit consists of a triple-redundant sensor package, which measures hydrogen in an oxygen background with high humidity levels.

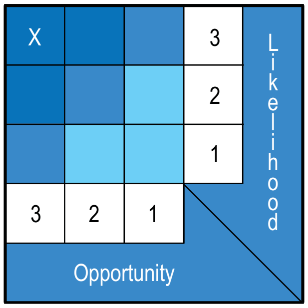
Preliminary results indicate exemplary sensor performance with no false-positive indications. This design can be packaged with other gas detection sensors that create a qualitative and quantitative in situ platform for simultaneous sensing of multiple hazardous gasses.

2.1.2.7.2 Technology Readiness Level Assessment. The current sensor's TRL is 6. The results are presented in figure 21.



In-House Activity	LIKE	OPPO
H_2 gas sensor	3	3

In-House Subtasks	
Event	**Description**
1	Combine microfabricated gas sensors with smart electronics
2	Develop sensors that can hold calibration and operate for extended periods
3	Perform testing for flight certification
4	Continue flight certification and fly aboard first flight under DFI



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 21. GH_2 sensor TRL assessment.

2.1.2.7.3 Accomplishments. GH_2 sensors have passed the minimum random vibration screening for SLS components.

2.1.2.7.4 Future Work. GH_2 sensors will be EMI/EMC tested.

2.1.2.8 Advanced Passive Avionics Cooling

2.1.2.8.1 Description. Advanced passive cooling is relevant to SLS because it provides potential low-risk solutions to localized thermal issues. In particular, isolated incidents of overheating avionics can be addressed with advanced passive techniques such as heat pipes and high conductivity plates. This allows thermal control needs to be addressed on a component level and avoids the need for installing a heavier, more costly, active cooling system to address specific avionics components. Advanced passive thermal control systems are potentially beneficial to any new launch vehicle and can be utilized in both ground and space environments (figs. 22 and 23).

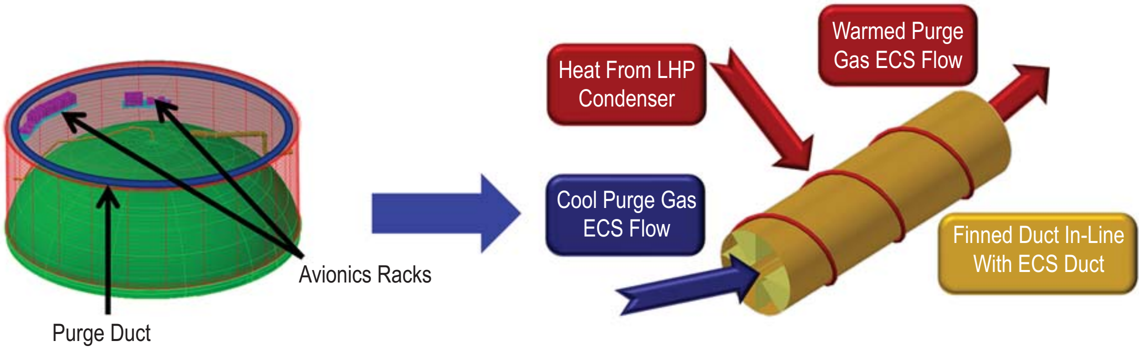


Figure 22. Advanced passive avionics cooling concept for ground.

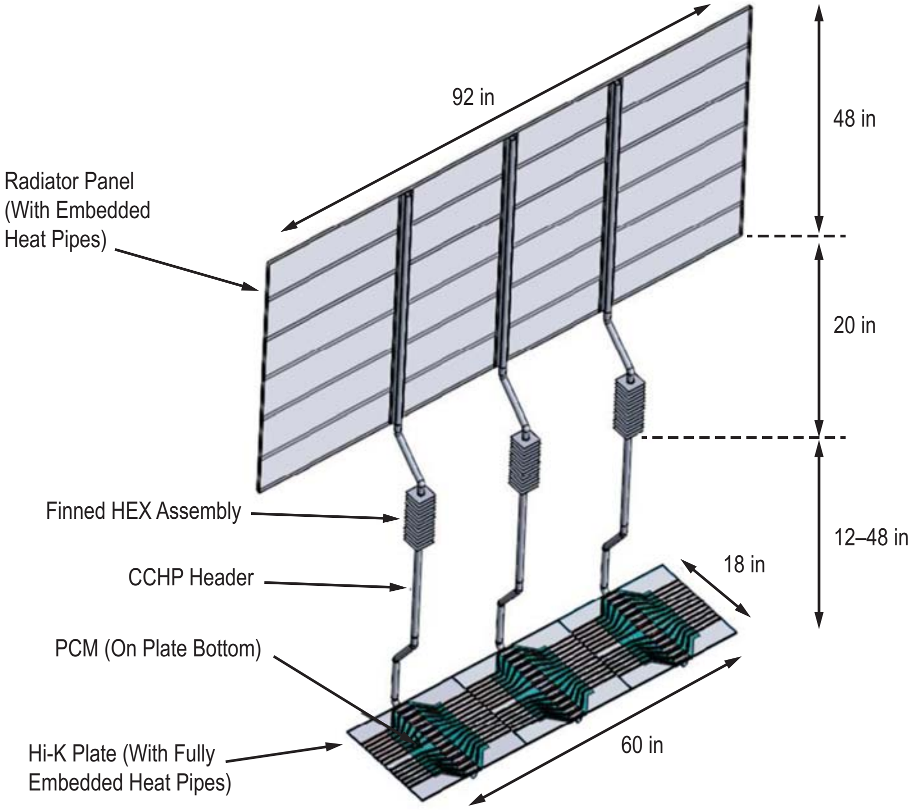
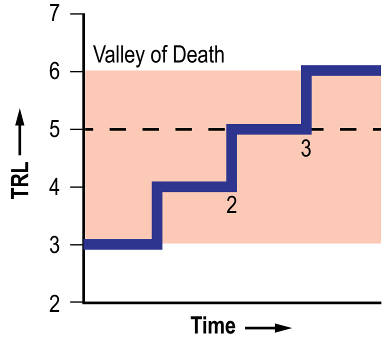


Figure 23. Advanced passive avionics cooling concept for on-orbit application.

An advanced passive approach could be used in lieu of, or as an augmentation to, the current passive system. The advanced passive approach could use state-of-the-art heat pipes, heat pipe-augmented mounting structure, and phase-change storage and rejection. The advanced passive approach could greatly enhance the cooling capability of the entire system or for individual components, resulting in improved reliability of high-power, critical electronic parts. The addition of the advanced passive approach could also facilitate layout and integration of the electronic system and components.

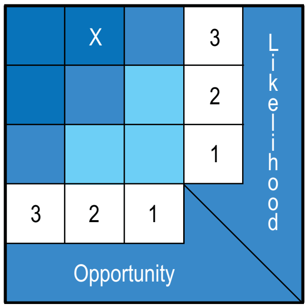
The task focus is to research various methods of passive cooling, specifically in the arena of two-phase heat transfer devices. The goal of this research is to provide low-risk solutions to specific thermal needs pertaining to SLS avionics, while making use of any current passive thermal control systems in place. Special studies are being done with companies who specialize in two-phase devices in order to gain knowledge of current technologies and to obtain hardware for characterization testing.

2.1.2.8.2 Technology Readiness Level Assessment. The task objective is to integrate existing heat pipes into a cooling concept. The current TRL of the hardware is 5. The intended TRL is 6. The results are presented in figure 24.



In-House Activity	LIKE	OPPO
Advanced passive avionics cooling	3	2

In-House Subtasks	
Event	**Description**
2	General assessment of performance and affordability of two-phase components
2	Component and system level demostration in relevant configurations
2	Hardware assessment state of art and off-the-shelf components
3	Design, fabrication to get a full-sized breadboard



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 24. Advanced passive avionics concept TRL assessment.

2.1.2.8.3 Accomplishments. The team of NASA personnel and two-phase device manufacturers has completed conceptual level trade studies and design efforts that have provided a wealth of knowledge on subject matter, and viable options for hardware systems, that directly pertain to the working architecture of the SLS avionics layout. This research has directly addressed risk reduction for the current baselines and identified potential, enhanced performance options for future vehicle configurations. Selection and procurement efforts have been initiated to fabricate demonstration units of key components identified in the earlier studies.

2.1.2.8.4 Future Work. Testing of this passive thermal control hardware is planned and will provide a working system to both demonstrate the capabilities of the hardware and characterize performance.

2.1.2.9 High Voltage Electronic Parts Assessment

2.1.2.9.1 Description. Electromechanical actuator (EMA) and electrohydrostatic actuator (EHA) technology has been discussed as a major upgrade to the existing thrust vector control (TVC) systems for launch vehicles. This upgrade could dramatically reduce weight, complexity, and operating costs; be more environmentally friendly; and have operational benefits such as simplified installation and checkout. It could be applied across many space flight applications. Work has been done in the past on the actuators, but the major roadblocks in going forward have been high-rate batteries, high voltage/high current electronic parts, and corona mitigation. This task addresses the high voltage electronic parts roadblock. The focus of this study will be insulated gate bipolar transistors (IGBTs) (fig. 25).

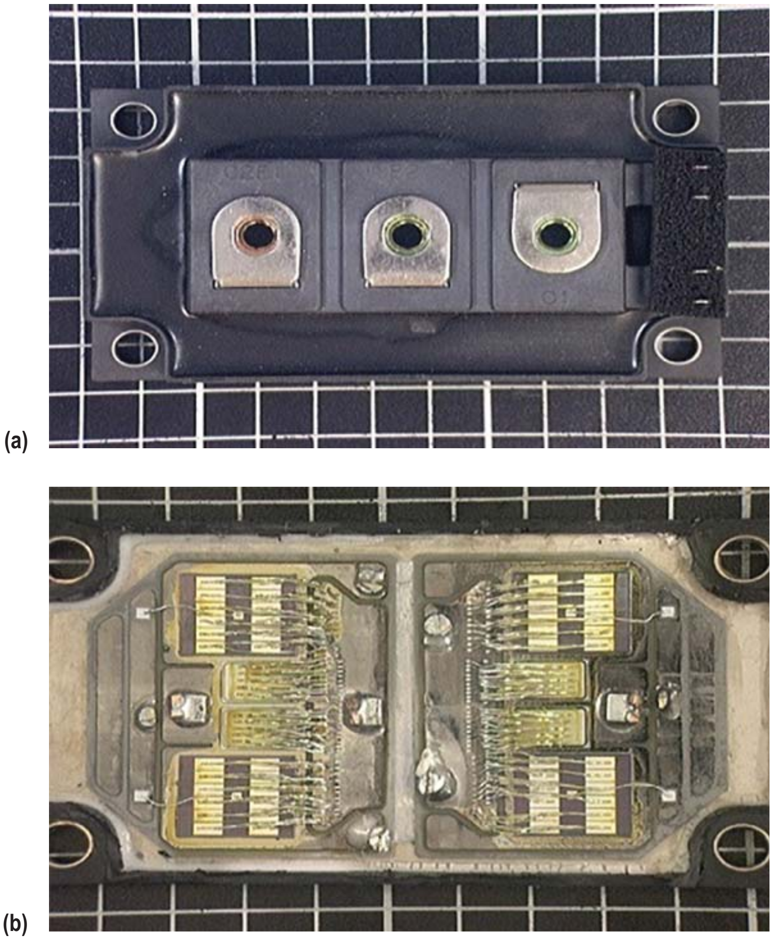
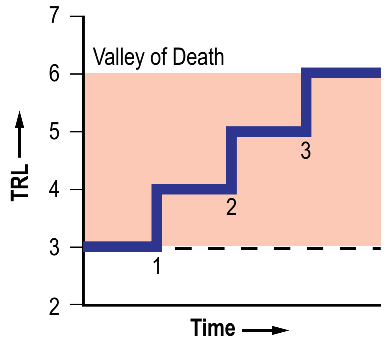


Figure 25. High voltage electronic parts, IGBT: (a) Top view encased and (b) bottom view opened.

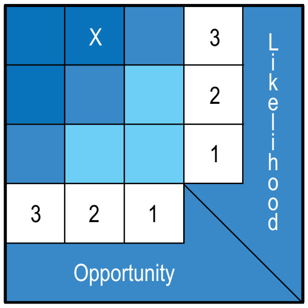
Few, if any, manufacturers of grade 2 IGBTs exist. By performing in-house testing and evaluation of these parts, this task will identify potential parts and manufacturers that could be upgraded to grade 2.

2.1.2.9.2 Technology Readiness Level Assessment. This is a component level activity only, and the assessment was conducted on that basis. The current IGBT TRL is 3, and the projected TRL is 6. The results are presented in figure 26.



In-House Subtasks	
Event	**Description**
1	Purchase IGBTs and conduct low cost mechanical, electrical, and environmental testing
2	Demonstrate and test in component and subsystem level configurations
3	System level demonstration

In-House Activity	LIKE	OPPO
High voltage electronics parts assessment	3	2



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 26. High voltage electronic parts TRL assessment.

2.1.2.9.3 Accomplishments. The task team identified one manufacturer that can produce these hermetically sealed, high voltage IGBTs.

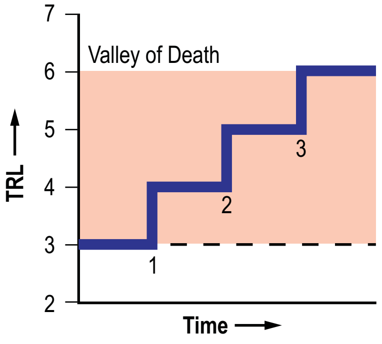
2.1.2.9.4 Future Work. The completion of the test phase.

2.1.2.10 Advanced Telemetry System

2.1.2.10.1 Description. Space launch telemetry systems have traditionally utilized the 2 GHz S band for transmission. This band is critically crowded and unable to provide all the bandwidth needed for transmission of currently forecasted SLS engineering and operational data, much less future requirements. Ares I-X was authorized 40 MHz in the S band, but was told further requests for that magnitude would not be entertained. The use of a less crowded band and/or the use of more efficient modulation/coding techniques will be required to adequately supply the near- and long-term needs of SLS and other NASA launch and science systems.

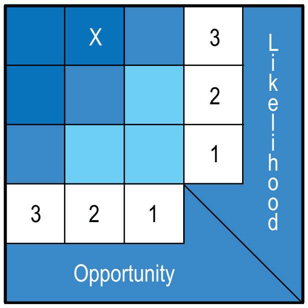
The goal of this task is to study higher order phase-shift keying (PSK) modulation, in particular, 8 PSK, in order to transmit large volumes of telemetry and video using less channel bandwidth. The study will be conducted using a modulator/receiver capable of 8 PSK modulation and low density parity check forward error correction coding. Filters will be used to band-limit the spectrum to determine the maximum achievable data rate and the power required to successfully close an 8 PSK telemetry link.

2.1.2.10.2 Technology Readiness Level Assessment. The current TRL is 3, and the projected TRL is 6. The results are presented in figure 27.



In-House Activity	LIKE	OPPO
High voltage electronics parts assessment	3	2

In-House Subtasks	
Event	**Description**
1	Purchase IGBTs and conduct low cost mechanical, electrical, and environmental testing
2	Demonstrate and test in component and subsystem level configurations
3	System level demonstration



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 27. Advanced telemetry TRL assessment.

2.1.2.10.3 Accomplishments. The task team is in the early stages of assessing 8 PSK and the capabilities of the modulator/receiver. The study has allowed SLS to become more knowledgeable of digital communication systems and forward error correction, and how filtering of the spectrum affects the communication link. The modulator/receiver has also been a significant upgrade to the task team laboratory, which will allow the team to perform more accurate radio frequency testing for future projects.

2.1.2.10.4 Future Work. This task has been discontinued because the SLS program has decided to switch from S band to C band.

2.1.2.11 Fluid-Structure Coupling Damper

2.1.2.11.1 Description. The fluid-structure coupling (FSC) technology is a highly efficient and passive method to control the way fluids and structures interact and affect the behavior of a system. This technology was developed to solve a difficult large launch vehicle structural dynamics issue.

The technology that NASA recently developed and matured is a purely passive method that controls the way fluids and a structure interact and then utilizes this controlled coupling to dictate/disrupt the response of the primary system. Originally designed to mitigate an axial response of a launch vehicle (fig. 28), the technology can be expanded to mitigate lateral and slosh responses.

Figure 28. FSC damper test setup.

The applicability is not only to launch vehicles, but also to the following commercial applications:

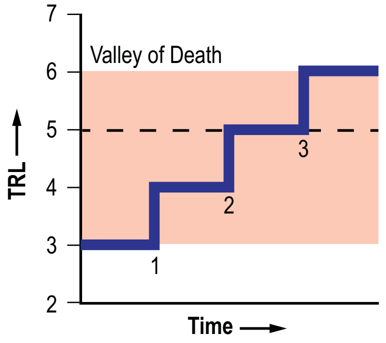
- Structural: Multistory buildings, stacks, towers, bridges, pools for spent nuclear fuel.
- Oil and gas: Offshore oil rigs, above-ground storage tanks.
- Municipal: Water tanks/towers.
- Aviation: Control of vibration transmission from wet wings and fuel sloshing.
- Marine: Multidirectional stabilization of vessels or platforms.

The goals of this task are as follows:

- Achieve a Preliminary Design Review (PDR) level design of a system to mitigate the potential axial response of an SLS vehicle.

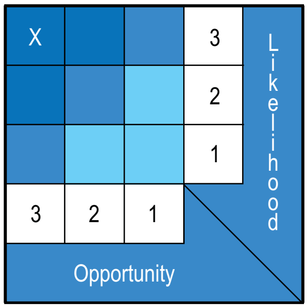
- For lateral and slosh mitigation, mature the technology from TRL 1 to TRL 5 and design a fluid structure coupler system to mitigate potential SLS vehicle responses.

2.1.2.11.2 Technology Readiness Level Assessment. For mitigation of vehicle axial modes, the technology is TRL 5. The results are presented in figure 29.



In-House Activity	L I K E	O P P O
Fluid structure coupling damper	3	3

In-House Subtasks	
Event	**Description**
1	Utilize existing infrastructure to address feasibility
2	Design and fabricate dampers and infrastructure inside exist in-house facilities
2	Test prototype under expected conditions
3	Centrifuge test under relevant conditions. Finish equations for lateral modes and test



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 29. FSC axial damper TRL assessment.

For mitigation of lateral and slosh modes, current efforts have shown great promise. The damping of axial modes is considered mature technology and no additional ADO effort is planned. Both lateral and slosh modes will be continued due to the lower TRL.

2.1.2.11.3 Accomplishments. Axial mitigation for the SLS launch vehicle has been demonstrated through testing. An FSC device weighing <200 lb successfully mitigated a potentially detrimental resonant response of a 650,000 lb structure.

2.1.2.11.4 Future Work. Lateral mitigation will be demonstrated through testing. Slosh mitigation will be researched.

2.1.2.12 Shell-Buckling Knockdown Factors

2.1.2.12.1 Description. The new SLS-specific shell-buckling knockdown factors (SBKDFs) will address many of the deficiencies in existing knockdown factors (KDFs) and guidelines. New KDFs will enable reductions in design cycle time and reworks, control mass growth, enable manufacturing cost versus performance trades, and enhance sustainability. New analysis-based KDFs will enable quantitative robustness and reliability predictions. Several independent design studies (NASA and Boeing) indicate significant mass savings potential (>3 t) in the SLS core stage. This task is to develop and validate analysis-based SBKDF updates for SLS-specific orthogrid- and isogrid-stiffened metallic cylinders. The initial KDF update in FY 2012 provided SLS-specific bounding configurations. Validation testing will be conducted in parallel on subscale and full-scale orthogrid-/isogrid-stiffened test articles at MSFC in FY 2013 through FY 2016 (fig. 30). Collaboration will occur between the NESC SBKDF project, LaRC, and MSFC by leveraging heavily off of existing test hardware, facilities, and analysis results developed by the SBKDF project from 2007 to the present.

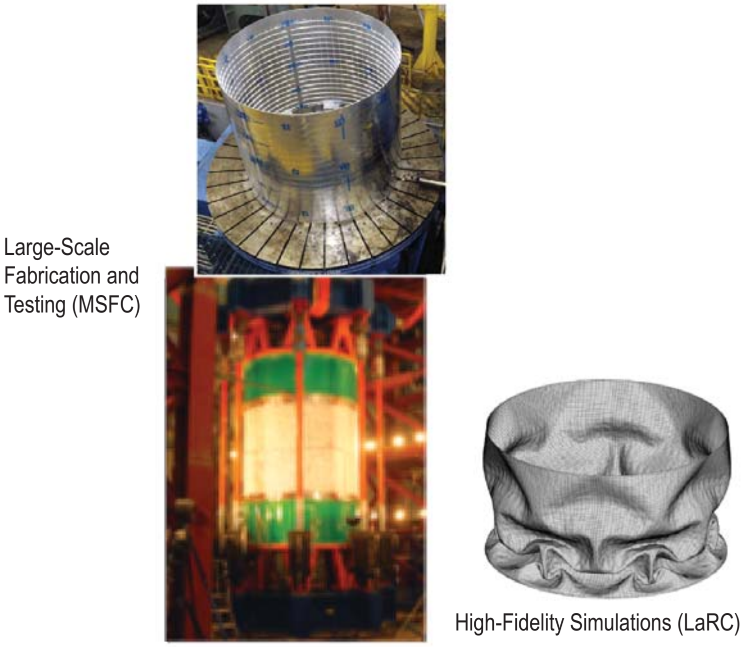
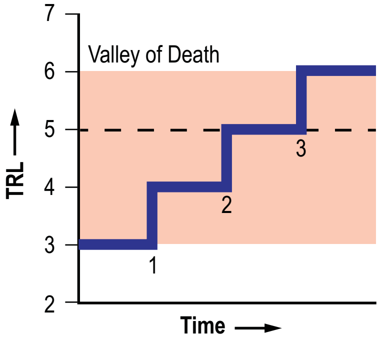


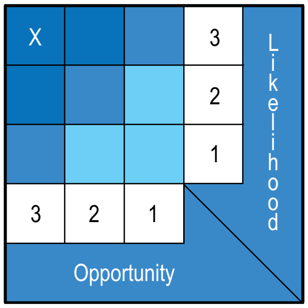
Figure 30. SBKDF activities.

2.1.2.12.2 Technology Readines Level Assessment. The current TRL is 5. The results are presented in figure 31.



In-House Activity	LIKE	OPPO
Shell buckling knockdown factors for SLS	3	3

In-House Subtasks	
Event	**Description**
1	Lower bound KDFs for SLS: geometric/ load imperfections, weld lands
2	Extend KDFs for combined mechanical, thermal, pressure loads: subscale validation testing on 4-8 ft TA
3	Tolerance based KDFs and design sensitivity data: validation testing on three subscale 8 ft diameter, one full-scale 27.5 ft TA
3	Finish subscale testing, tolerance allowables, final reports



Note:
- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 31. SBKDFs TRL assessment.

2.1.2.12.3 Accomplishments. The KDFs for combined mechanical, thermal, and pressure loads have been improved and changed from 0.65 to 0.75. Subscale validation testing on two 8-ft-diameter test articles has been completed.

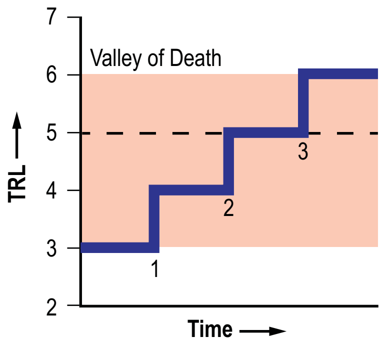
2.1.2.12.4 Future Work. No future work on SBKDF is planned for ADO.

2.1.2.13 Ullage Collapse and Capacitance Probe

2.1.2.13.1 Description. A flight-like capacitance probe was selected during the liquid oxygen (LOX) damper cryogenic testing (fig. 32) in order to gain experience in how this liquid level indication system performed. Many issues were noted, including two uncontrollable ullage collapse events occurred during liquid nitrogen (LN_2) testing that could have destroyed a flight tank and vehicle. The associated data sets need to be analyzed, reduced, and formatted for SLS consideration along with capacitance probe performance information.

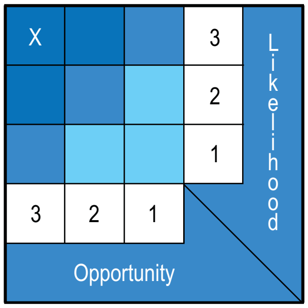
Figure 32. Ullage collapse and capacitance probe test setup (tank mounted at test stand 500).

2.1.2.13.2 Technology Readiness Level Assessment. This task has been completed and no additional ADO effort is required. The current TRL is 5. The results are presented in figure 33. If the vehicle requires this technology, it will be implemented by the SLS element offices.



In-House Activity	LIKE	OPPO
Ullage collapse/capacitance probe technical report for LOX damper LN_2 testing	3	3

In-House Subtasks	
Event	**Description**
1, 2	Pull LOX damper test data (very large data sets). Identify relevant events. Reduce and summarize data. Generate report of ullage collapse events
3	Utilize ULA-furnished flight-weight tank and KSC cost sharing for slosh and ullage scenarios



Note:

- Likelihood – Probability of Achieving Goals
- Opportunity – Benefits to Program

Figure 33. Ullage collapse and capacitance probe TRL assessment.

2.1.2.13.3 Accomplishments. The following accomplishments were achieved:

- Evaluated LOX damper test data.
- Identified relevant events.
- Reduced and summarized data.
- Generated report of ullage collapse events and capacitance probe performance, and provided engineering unit data for further consideration.

2.1.2.13.4 Future Work. No future work on ullage collapse and capacitance probe is planned by ADO.

2.1.2.14 Bolt-on Adapter Ring for Secondary Payloads

2.1.2.14.1 Description. The purpose of this trade study was to evaluate the capabilities of a secondary payload adapter ring size optimized for SLS, and to generate preliminary cost and mass estimates. In addition, the manufacturing feasibility of such a structure and its impact to the SLS vehicle will be evaluated.

The ability to carry secondary payloads in the nano, micro, mini, and medium satellite size ranges could help lower launch costs by creating payload launch opportunities for internal and external customers. The proposed modular design of the ring would minimally impact, if at all, the design of the existing SLS cargo payload adapter and make the SLS vehicle more versatile in its launch capabilities.

2.1.2.14.2 Technology Readiness Level Assessment. Since this was a study activity, no TRL assessment was conducted.

2.1.2.14.3 Accomplishments. The work has been completed and a preliminary design of the bolt-on adapter ring has been produced (fig. 34).

Figure 34. Bolt-on adapter ring concept.

2.1.2.14.4 Future Work. No future work on the bolt-on adapter ring is planned for ADO. This study has been completed.

2.1.3 NASA Engineering and Safety Center-Funded Task Description/Status

2.1.3.1 Pyroshock Characterization of Composite Materials

2.1.3.1.1 Description. Composite materials are being considered for incorporation into the evolved SLS vehicle to improve performance and affordability. The lighter materials increase the vehicle's payload capability.

This task evaluates composite materials to ensure they can withstand the stresses induced into the vehicle during launch and stage separation. Tests are performed where an explosive charge is placed on a metal plate affixed to a composite material panel. The test setup is shown in figure 35. When the charge is initiated, a shockwave is sent through the composite panel. Studying the behavior of composites when the shockwave is transitioning through the material will result in creating a model to predict how it will withstand launch stresses and shock loads.

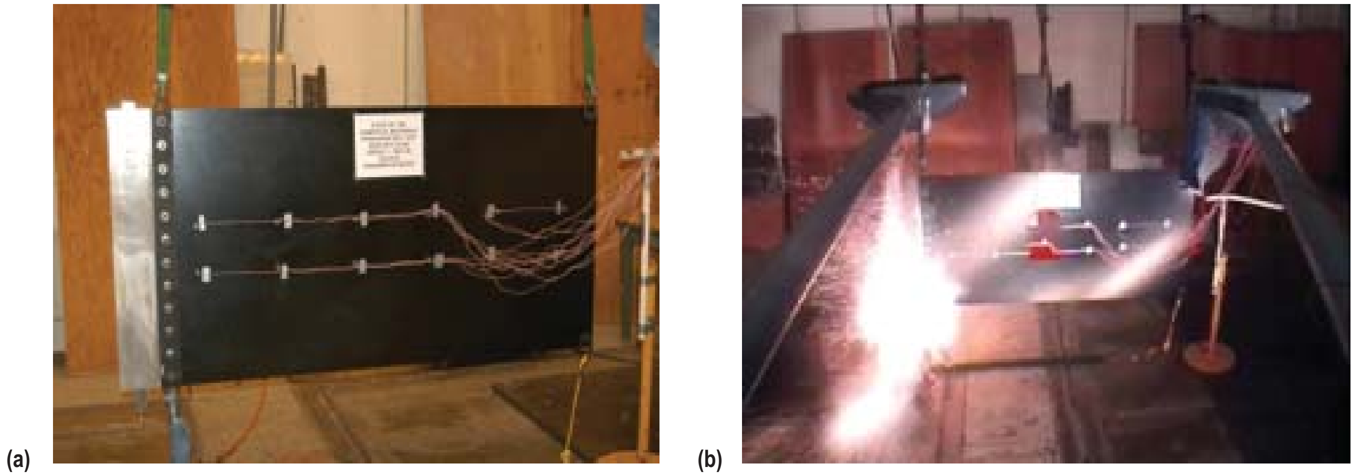


Figure 35. Pyroshock test setup: (a) Test article and (b) test.

2.1.3.1.2 Technology Readiness Level Assessment. A TRL assessment was not performed since this was a test program to evaluate the existing composite panel design response to a shock environment.

2.1.3.1.3 Accomplishments. Significant achievements include completing the pathfinder panel tests, verifying the test setup was acceptable, and completing the first group of solid composite tests, along with the analytical evaluation of test data.

2.1.3.1.4 Future Work. Testing of composite sandwich panels will begin in the near future. These panels are similar to a large launch vehicle structure such as a payload fairing, which will allow the characterization of the shock response of these materials.

2.1.3.2 Booster Interface Loads

2.1.3.2.1 Description. The interplay of shockwaves with vortex shedding at the booster/core interface creates large buffeting loads. This task investigates whether an alternative can lower the loads.

The current work combines numerical simulations with wind tunnel testing to predict buffeting loads caused by the boosters. Variations in nosecone shape, similar to the Ariane 5 design (fig. 36), are being evaluated with regard to lowering the buffet loads. The task will provide design information for the mitigation of buffet loads for SLS, along with validated simulation tools to be used to assess future SLS designs.

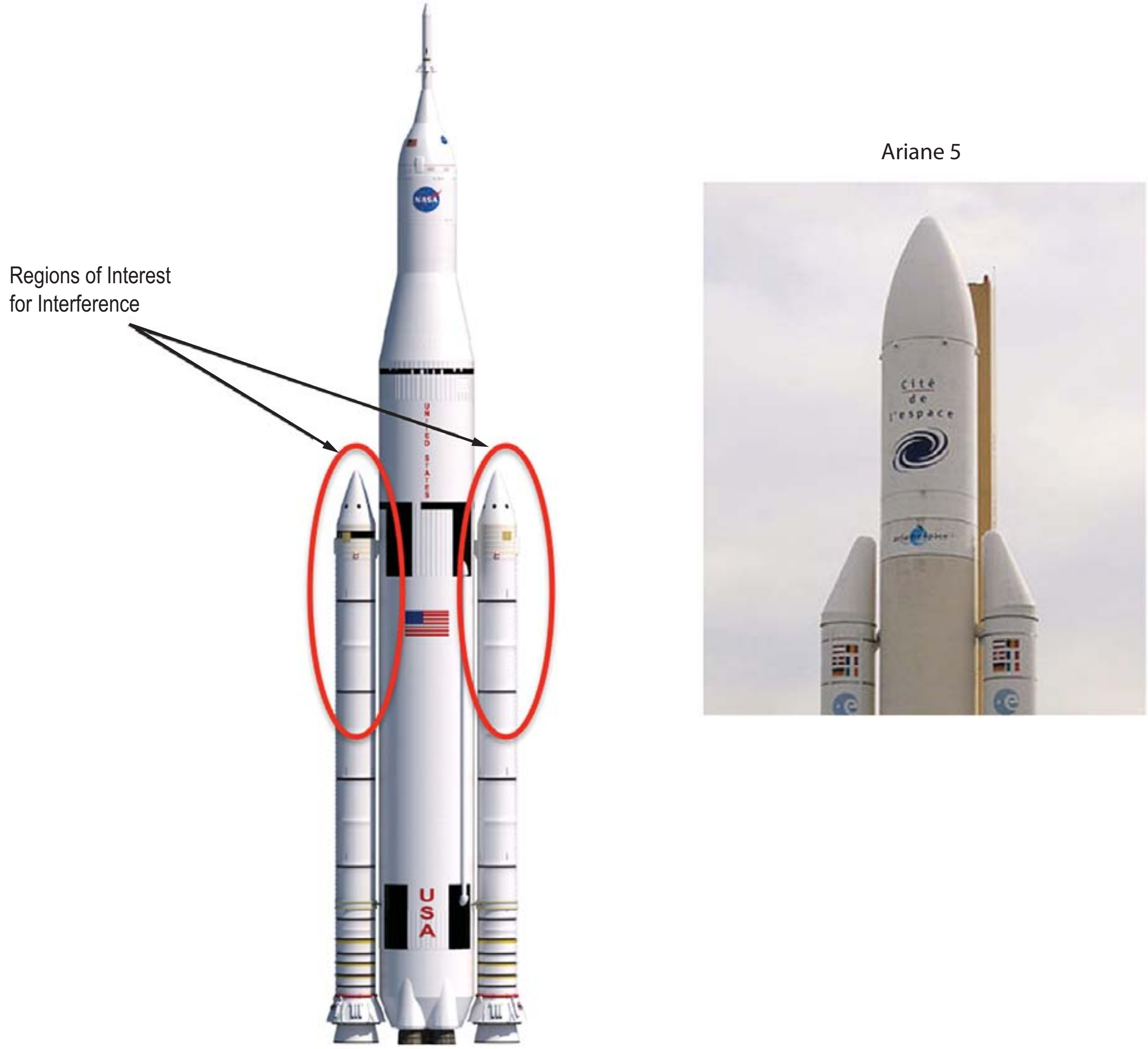


Figure 36. Booster interface loads.

2.1.3.2.2 Technology Readiness Level Assessment. A TRL assessment was not performed since this is a study to improve modeling of the environmental interactions between the boosters and the core stage.

2.1.3.2.3 Accomplishments. The project has performed initial validation checks of the buffet simulation software, and has designed wind tunnel test articles and instrumentation packages.

2.1.3.2.4 Future Work. The chief focus of this task is a wind tunnel test to be conducted at Ames Research Center (ARC). A result of the work will be the validation of numerical buffet simulation codes, which are generally applicable to any future launch system.

2.1.3.3 Advanced Booster Composite Case/Polybenzimidazole Nitrile Butadiene Rubber Insulation Development

2.1.3.3.1 Description. This work is focused on composite motor cases and higher performing solid propellants, techniques for performing NDE, and determining damage tolerance of loaded motor cases (fig. 37). This is the first of a four-phase project with the end goal of developing confidence within the NASA community in human-rating composite solid boosters. In the area of propellant processing, NASA is teamed with AMRDEC to evaluate high-energy propellant burn rates, mechanical properties, and safety requirements for advanced booster concepts.

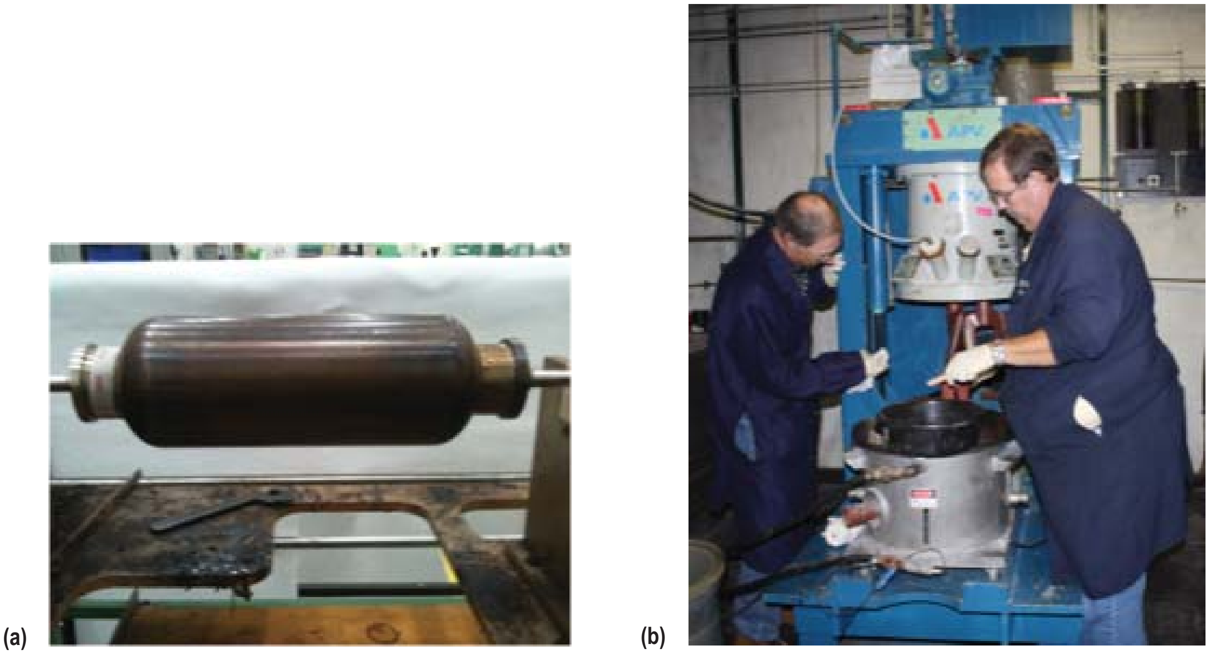


Figure 37. Advanced booster composite case: (a) Test article and (b) test setup.

2.1.3.3.2 Technology Readiness Level Assessment. Since this task was a later addition to the ADO portfolio, a TRL assessment has not been completed.

2.1.3.3.3 Accomplishments. This work began in February 2013. Currently, materials are being procured and the contract is being finalized.

2.1.3.3.4 Future Work. The first phase is a 1-year task to optimize and evaluate PBI-NBR insulation formulation and processing (i.e., co-cure versus multiple cure), candidate high-energy propellants, case fibers, and resin systems for booster design. In addition, the task will demonstrate and validate requisite NDE and damage tolerance methods required to support a human-rated composite motor.

2.1.3.4 Advanced Booster Combustion Stability

2.1.3.4.1 Description. The combustion stability tools are currently limited by the level of empiricism in both the inputs and the models. These limitations often create significant uncertainties in stability assessments and lead to increased development time and cost.

The objectives of this task are to advance the predictive capability of current state-of-the-practice combustion stability methodologies and tools used in the SLS combustion stability assessment process, facilitate identification and characterization of combustion instabilities, efficiently mitigate SLS development costs, and improve hardware robustness.

2.1.3.4.2 Technology Readiness Level Assessment. A TRL assessment was not performed since this is a study to improve modeling of the hydrocarbon-fueled booster engine combustion process.

2.1.3.4.3 Accomplishments. Based on the analysis of the design, it was determined that the proposed element does not operate like a rocket injector element. Therefore, a modified approach (fig. 38) was recommended.

2.1.3.4.4 Future Work. Implement the modified approach.

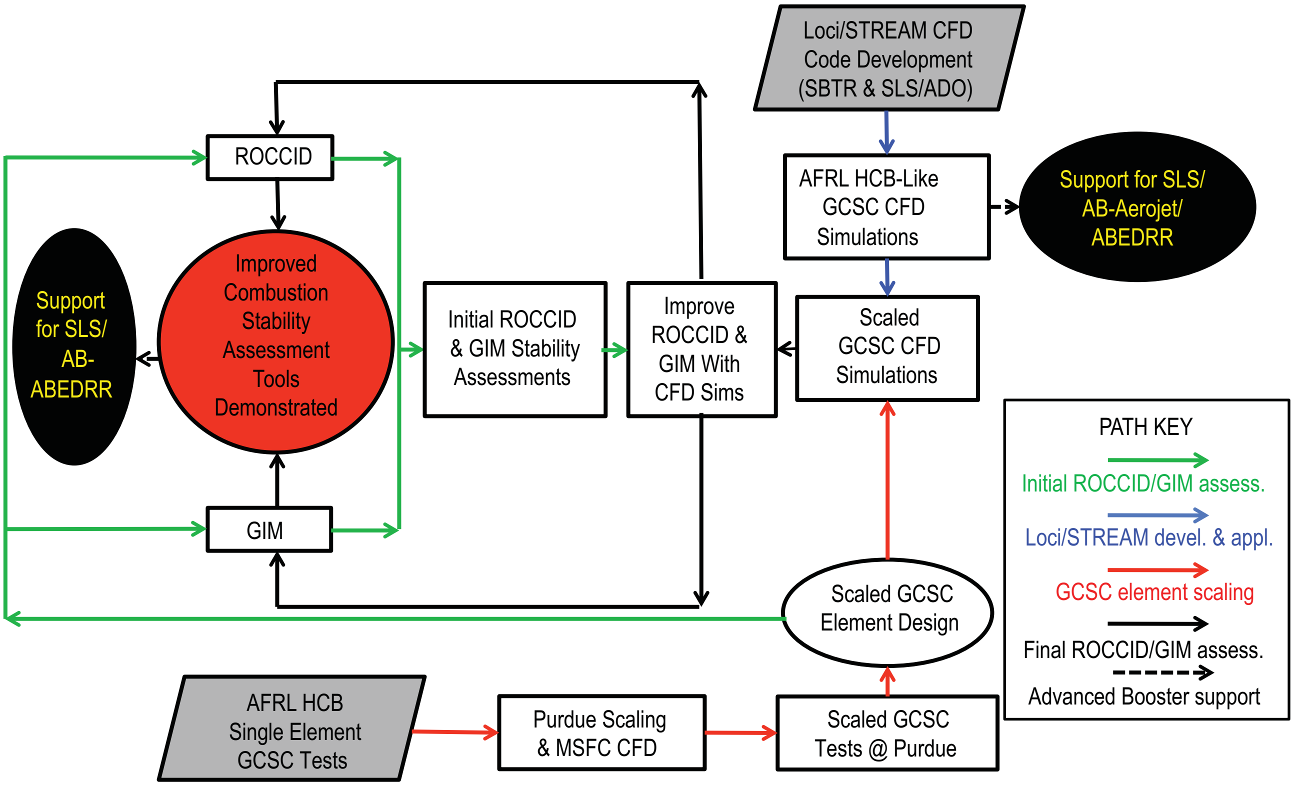


Figure 38. Advanced booster combustion stability modified plan.

2.2 Academia Contracts/Grants

Academia contracts/grants were awarded in early 2013. The tasks have a 1-year base effort with two 1-year options. Nine universities have direct grants with NASA, while Stanford University has a subtask supporting the University of Michigan. The geographical distribution is shown in figure 39.

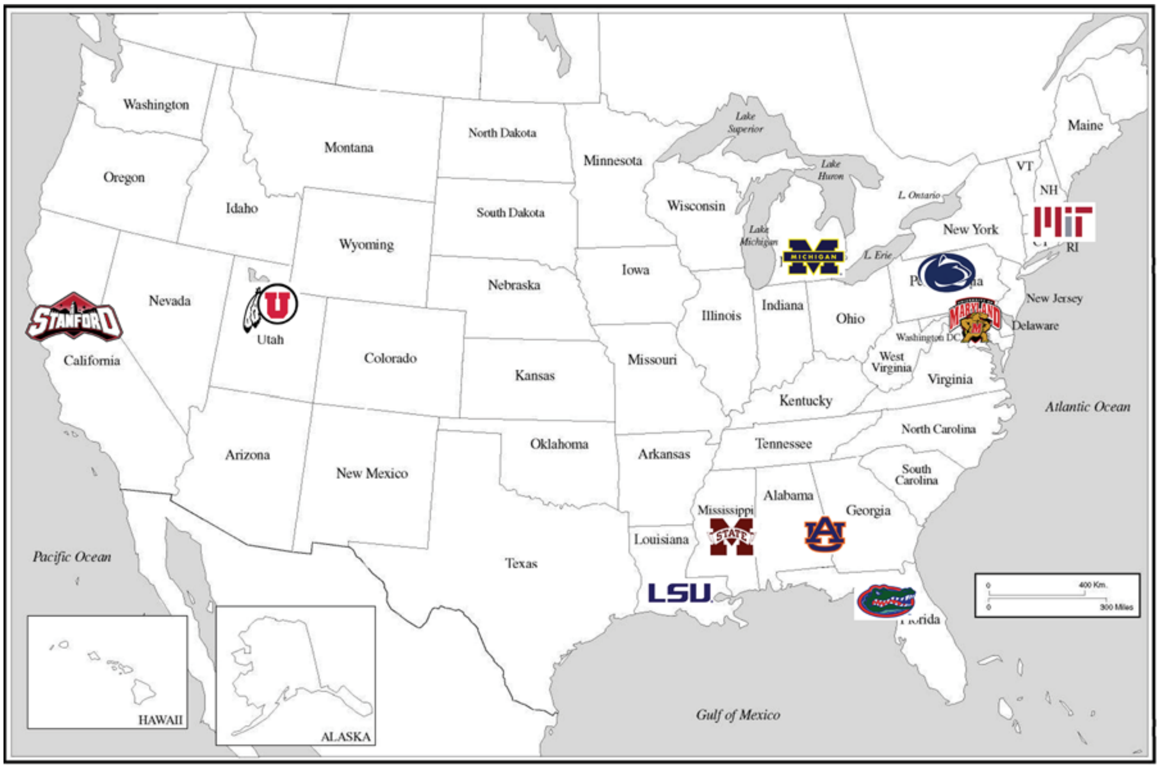


Figure 39. Academia contracts/grants for geographical distribution in the United States.

Four of the nine grants deal with improving or utilizing the Loci family of CFD/FEM codes. Loci is a C++ library and declarative programming framework that efficiently maps numerical algorithms onto parallel architectures. The approach is logic based so that it allows a description of what the code should accomplish, but it does not dictate how to accomplish it (as in imperative programming). Loci is thus a flexible, rule-based programming model for numerical simulation that allows runtime scheduling of the appropriate subroutine calls required to obtain a user-specified goal.

The Loci family of codes was developed in 1999 by a National Space Foundation funded effort. The architecture was designed at Mississippi State University. The framework and most of the modules are open access; however, there are some modules with ITAR restrictions. These codes are designed such that very large simulations can be run efficiently on multiple processors utilizing supercomputers (e.g., the ARC Pleiades supercomputer). The overall framework is such that the codes are conducive to independent/third party module development resulting in development and implementation of multiple high-fidelity modules. Loci currently has the following four major areas:

(1) Loci/CHEM (most mature and developed first).
   - Advanced turbulence, heat transfer, structural analysis, and droplet models.
   - Nonideal equations of states found in high pressure environments.
   - Overset meshes for complex geometry and object-in-motion problems.

(2) Loci/STREAM (originally developed at the University of Florida, funded by MSFC 2004–present).
   - Geometric complexity using unstructured or moving grids.
   - Real-fluid modeling for cryogenic propellants.
   - Unsteady cavitation, multiphase flows, and flamelet models.

(3) Loci/BLAST (relatively new CFD code funded by the U.S. Army).
   - Modeled blast-soil interactions (landmines buried in sand).
   - Modeled the structural effects of blast on vehicles.
   - Validated for blast events that would simulate failed motor ignition on test stand.

(4) Loci/THRUST (research).
   - CFD code for acoustic modeling.

Sections 2.2.1 through 2.2.9 provide a brief overview of each of the grants.

2.2.1 High Electrical Energy Density Devices for Aerospace Applications (Auburn University)

2.2.1.1 Principals:

- Principal Investigator (PI): Z.Y. Cheng, Ph.D.
- Co-PI: B.A. Chin, Ph.D.
- MSFC Technical Monitor (TM): Jeff Brewer

2.2.1.2 Description. This effort is to develop a database of the characteristics and specifications of commercially available electrical energy devices and to experimentally determine the characteristics and specifications of these devices. Additional activities include:

- Using different electrical loads to simulate different applications in aerospace environments.
- Identifying the most promising candidates for use on space vehicles.
- Identifying emerging technologies in the energy storage device discipline and their potential applications.

The size and weight of energy storage devices has been a challenge in previous space programs. The development of an ongoing database of suitable choices with early identification of potential revolutionary emerging technologies is important to the SLS program for optimizing performance and affordability.

2.2.2 Challenges Towards Improved Friction Stir Welds Using Online Sensing of Weld Quality (Louisiana State University)

2.2.2.1 Principals:

- PI: Muhammad Wahab, Ph.D.
- MSFC TM: Arthur Nunes, Ph.D.

2.2.2.2 Description. This activity will develop an online real-time system to determine weld quality for friction stir welds. The overall effort is depicted in figure 40.

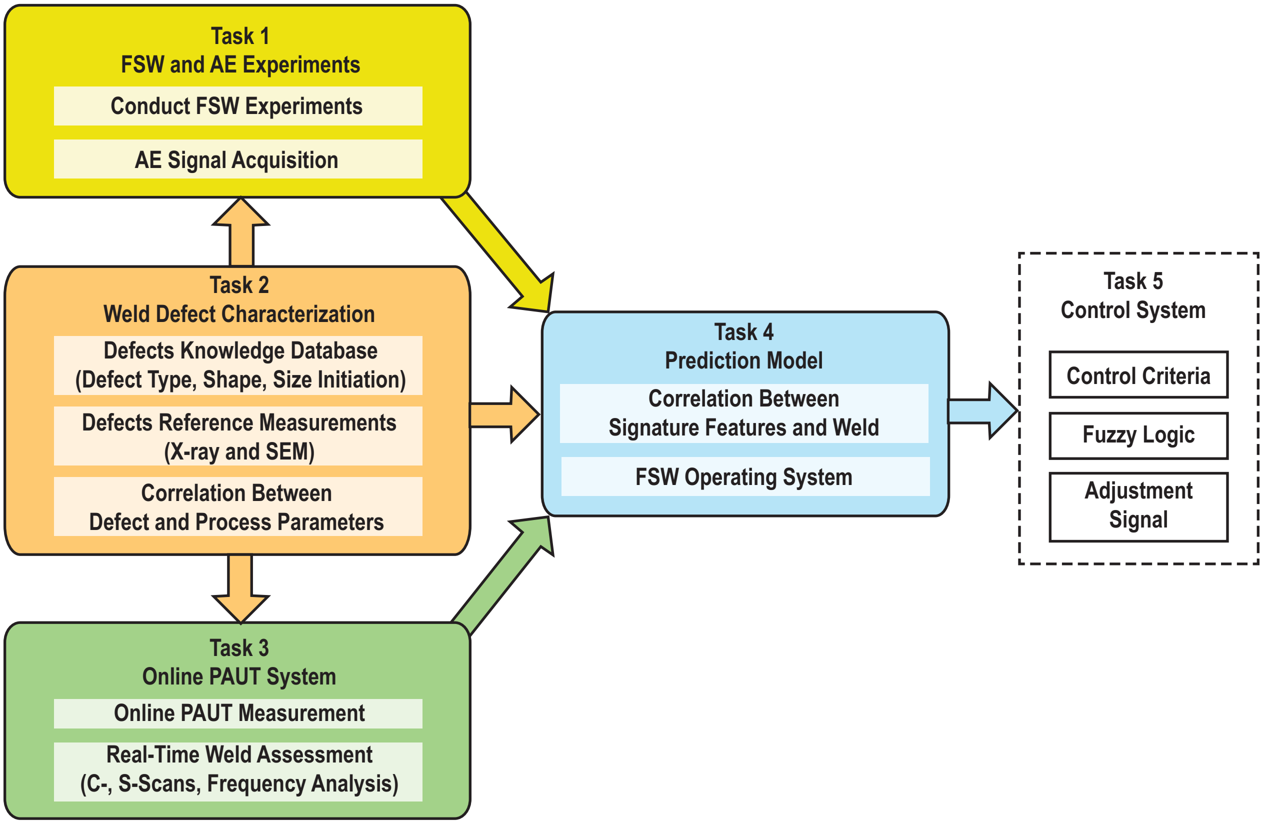


Figure 40. LSU activity flow chart.

The detection of defects as they form during friction stir welding (FSW) enables online repair and/or avoidance of defects. It may ultimately eliminate or reduce unforeseen or sudden failures in lightweight welded structures, increase cost effectiveness, and decrease risk.

2.2.3 A New Modeling Approach for Rotating Cavitation Instabilities in Rocket Engine Turbopumps (Massachusetts Institute of Technology)

2.2.3.1 Principals:

- PI: Z. Spakovszky, Ph.D.
- MSFC TM: Andrew Mulder and Thomas Zoladz

2.2.3.2 Description. This activity will develop a new methodology for quickly assessing inducer designs to suppress rotating cavitation instabilities (fig. 41) by leveraging a recently developed method for assessing jet engine compressors using body force-based modeling. PWR will act as advisors. A known geometry, pseudo-RS-25 low pressure oxidizer pump (LPOP), will be used to benchmark the methodology.

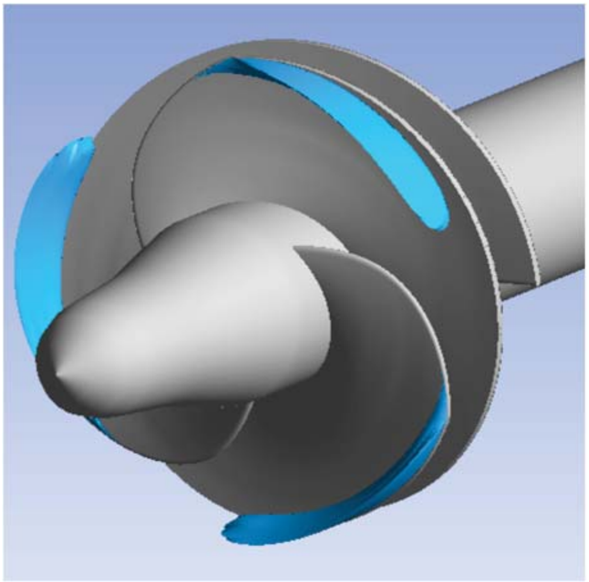


Figure 41. Inducer rotating cavitation instabilities.

An inducer will be designed and fabricated using data from the new simulation capability. The inducer will be tested in The Aerospace Corporation’s water flow test facility, completing the physics-based portion of the activity.

Mitigation of higher order cavitation in SLS turbomachinery (RS-25 LPOP and low pressure fuel pump (LPFP), J2-X LOX pump) will improve rocket engine reliability and performance. Any liquid propulsion system would benefit from this tool.

2.2.4 Low Dissipation and High Order Unstructured Computational Fluid Dyamics Algorithms to Complement the Use of Hybrid Reynolds-Averaged Navier Stokes/Large Eddy Simulation Algorithms (Mississippi State University)

2.2.4.1 Principals:

- PI: Keith Walters, Ph.D.
- Co-PI: Ed Luke, Ph.D.
- MSFC TM: Chris Morris, Ph.D.

2.2.4.2 Description. This activity will develop a new methodology to predict loads (steady and unsteady) and heating for the SLS vehicle by using a hybrid Reynolds-averaged Navier Stokes (RANS)/large eddy simulation (LES) approach to directly capture turbulent fluid motion in parts of a simulation. This will significantly improve CFD predictions (fig. 42) for the following:

- Rocket engine exhaust plumes and associated acoustic noise.
- Vehicle base flows, plume interactions, and recirculation.
- Flow over vehicle protuberances and associated acoustic noise.

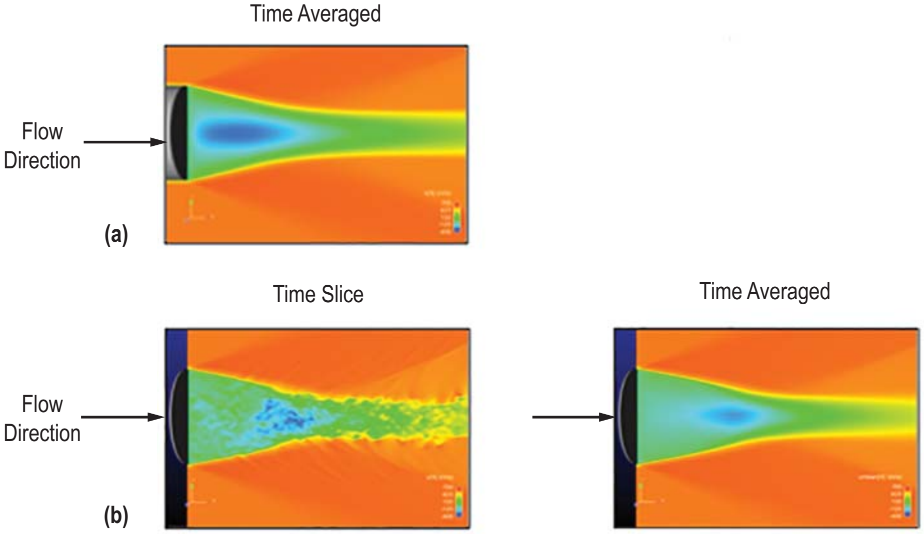


Figure 42. Fluid motion: (a) Current capability versus (b) improved simulation techniques.

The current hybrid RANS/LES capability in the Loci/CHEM code is suboptimal and has been identified for several years as an area that needs improvement. An improved prediction capability of loads on the SLS vehicle and components will enable higher fidelity environments definition, resulting in more efficient design.

2.2.5 Development of Subcritical Atomization Models in the Loci Framework for Liquid Rocket Injectors (University of Florida)

2.2.5.1 Principals

- PI: Siddharth Thakur, Ph.D.
- Co-PI: Mrinal Kumar, Ph.D.
- MSFC TM: Jeff West, Ph.D.

2.2.5.2 Description. This activity will develop a methodology to enable accurate simulation and modeling of subcritical combustion, modeling of subcritical atomization close to the injector, prediction of combustion instabilities, and determination of heat transfer coefficients for two-phase flows of cryogenic propellants during line chill-down and fluid transport (fig. 43). Both steady and unsteady atomization will be addressed.

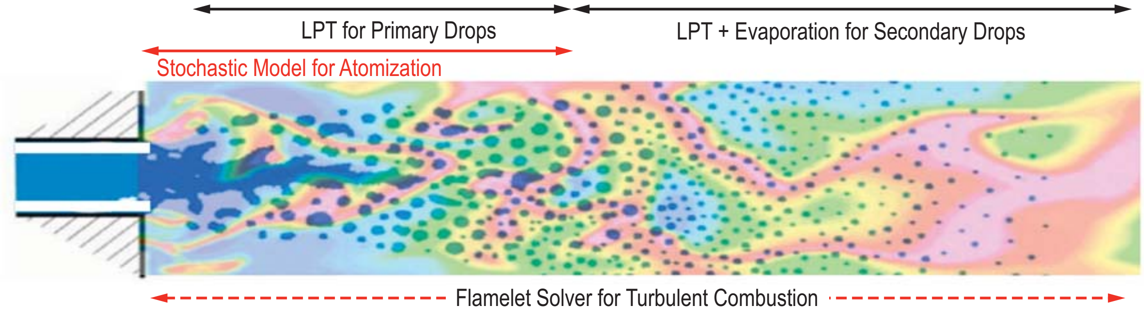


Figure 43. Injector subcritical atomization simulation.

Monte Carlo techniques will be used to capture the shape, size, and surface location of the unsteady liquid core, as well as the distribution of position, velocity, size, and temperature of formed droplets.

This activity will ultimately result in a model that enables better understanding of the critical physics in SLS liquid propulsion systems, improved combustion efficiency, the development of higher fidelity designs for injectors, and the reduction of environment uncertainty.

2.2.6 Validation of Supersonic Film Cooling Numerical Simulations Using Detailed Measurement and Novel Diagnostics (University of Maryland)

2.2.6.1 Principals:

- PI: Chris Cadou, Ph.D.
- MSFC TM: Joe Ruf

2.2.6.2 Description. This activity will develop a methodology to enable validation of supersonic film cooling (SSFC) numerical simulations using detailed measurement and novel diagnostics. The task will develop experimentally validated techniques for predicting film cooling performance through the use of existing numerical simulation tools RANS/LES (Loci/CHEM), conducting wind tunnel experiments in relevant environments for comparison data, developing new diagnostics for supersonic flows (Schlieren particle imaging velocimetry), and developing automated image interrogation techniques.

SSFC could protect the J-2X nozzle extension. Improvement in the tools that define the environments, and effectiveness of the SSFC, could result in significant engine nozzle weight savings (fig. 44).

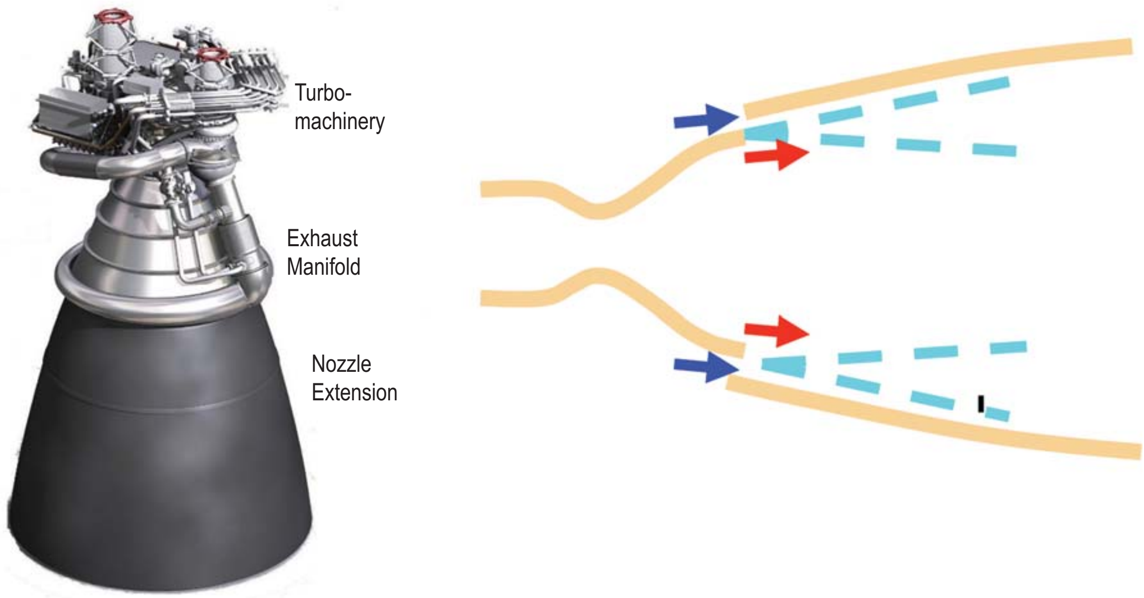


Figure 44. J-2X film-cooled nozzle extension.

2.2.7 Advanced Large Eddy Simulation and Laser Diagnostics to Model Transient Combustion-Dynamical Processes in Rocket Engines: Prediction of Flame Stabilization and Combustion-Instabilities (University of Michigan)

2.2.7.1 Principals:

- PI: Jim Driscoll, Ph.D., University of Michigan
- Co-PI: Matthias Ihme, Ph.D., Stanford University
- MSFC TM: Kevin Tucker

2.2.7.2 Description. This activity will develop a methodology to enable advanced LES and laser diagnostics to model transient combustion-dynamic processes in rocket engines. The following specific areas are being investigated:

- Predict flame stabilization and combustion instabilities (fig. 45).

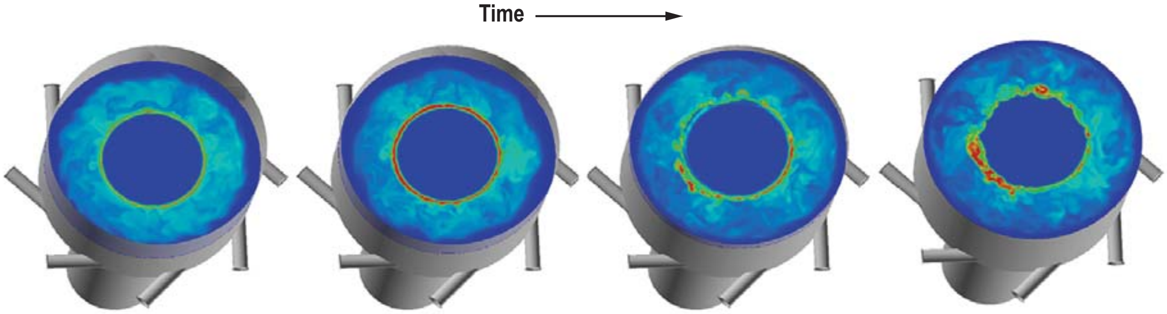


Figure 45. Unsteady burning in the cup of a coaxial element.

- Combine existing flamelet capability with a detailed chemistry description for accurate characterization of complex combustion physics associated with combustion stability.

- Implement the new chemistry capability into Loci/STREAM.

- Acquire a comprehensive experimental database to enable systematic validation of high-fidelity combustion models.

- Validate the new capability in Loci/STREAM using the experimental database.

Replacing empirically-based inputs with higher fidelity physics-based inputs in the combustion stability assessment process will provide improved injector performance and heat transfer predictions.

2.2.8 Characterization of Aluminum/Alumina/Carbon Interactions Under Simulated Rocket Motor Conditions (Pennsylvania State University)

2.2.8.1 Principals:

- PI: Kenneth Kuo, Ph.D.
- MSFC TM: Matthew Cross, Ph.D.

2.2.8.2 Description. This activity will investigate the reactions of aluminum and alumina with carbon in typical solid rocket motor (SRM) environments while considering realistic liquid residence times on carbon-containing insulation/nozzle materials surfaces. The effort will use test rigs simulating the internal conditions and Al/aluminum oxide (Al_2O_3) environment of an SRM. Some of the specific tasks to be conducted are as follows:

- Evaluate material samples exposed to liquid Al/Al_2O_3 at controlled temperature conditions using carbon dioxide laser heating.

- Utilize rocket-driven test rigs (fig. 46) to provide realistic thermal, pressure, and two-phase flow environments for characterizing material response.

Figure 46. Rocket-driven test rig.

- Conduct extensive post-test material analysis to characterize the environment and material response.

This research task will characterize reactions of Al/Al_2O_3 propellant combustion products leading to a better understanding of recently observed anomalies and improved erosion models.

2.2.9 Acoustic Emission-Based Health Monitoring of Space Launch System Vehicles (University of Utah)

2.2.9.1 Principals:

- PI: V. John Mathews, Ph.D.
- Co-PI: Dan Adams, Ph.D.
- MSFC TM: Alan Nettles, Ph.D.

2.2.9.2 Description. This task will develop, refine, and validate a method for locating and characterizing impact points in anisotropic structures. The following are specific tasks to be conducted:

- Develop a method for sensor placement such that the sensor distribution is sparse, monitoring of the complete structure is possible, and accuracy of location estimation is maintained.

- Determine from sensor waveforms whether the impact has produced damage to the structure, and be able to classify the damage type as fiber breakage, matrix cracking, or delamination (fig. 47).

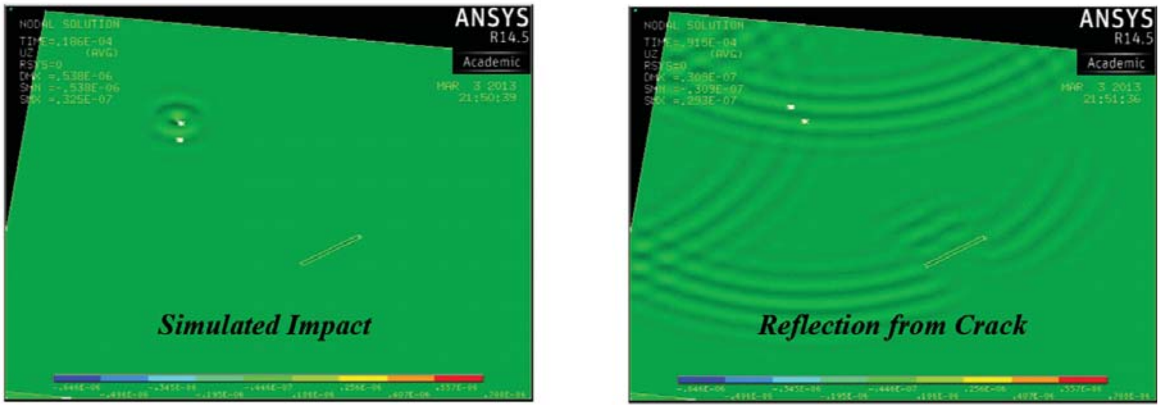


Figure 47. Impact waveform identification.

- Validate experimentally, using an impact testing system, the methods for locating the sources of acoustic emission on realistic composite structures.

The ability to locate and characterize impacts to composite parts either during manufacture, transport, or assembly will greatly reduce the cost of inspection, eliminate unnecessary repair, and lower the overall risk of this material choice.

2.3 Advanced Booster Engineering Development Risk Reduction Contracts

The SLS will provide an entirely new capability for human exploration beyond Earth orbit. Designed to be flexible for crew or cargo missions, the SLS will be a safe, affordable, and sustainable capability to continue America's journey of discovery from the unique vantage point of space.

The SLS ABEDRR activity intends to reduce risks leading to an affordable advanced booster that meets the evolved capability requirements of the SLS, and enable competition by mitigating targeted advanced booster risks to enhance affordability.

The ABEDRR contracts were selected and awarded in late 2012 and early 2013. The tasks have a 1-year base effort with two 1-year options. Sections 2.3.1 through 2.3.4 have brief desriptions of the four industrial partners selected.

2.3.1 Aerojet

2.3.1.1 Description. Although successfully developed by the former Soviet Union, a LOX/kerosene oxidizer-rich staged combustion (ORSC) engine has never been developed and flown by the United States (kerosene fuel is generally referred to as rocket propellant or RP). One of the largest risks in the development of this type of engine is combustion instability. The purpose of this task is to reduce the risk and improve technical maturity of fielding a LOX/RP ORSC booster.

The Aerojet effort has three primary tasks: (1) Risk reduction for a LOX-rich LOX/RP staged combustion booster engine, (2) combustion stability, and (3) injector design. Aerojet's Advanced Booster concept utilizes its proposed AJ1E6 LOX/RP-1 ORSC engine with two 550,000-lbf thrust chambers. This effort will build a single, full-scale AJ1E6 550,000-lbf class main injector and thrust chamber assembly and test rig and prepare it for future testing to measure performance and demonstrate combustion stability.

The USAF is also interested in LOX/RP ORSC technology. The USAF is conducting a hydrocarbon boost (HCB) program aimed at developing and demonstrating ORSC hardware and models. NASA and Aerojet have partnered with the USAF to leverage use of HCB hardware in the ABEDRR test setup.

The Aerojet test configuration is comprised of two 250,000-lbf class preburners feeding a single 550,000-lbf class main injector and thrust chamber. The USAF will supply the preburners. The main injector, chamber, and overall test rig (fig. 48) will be designed and fabricated by Aerojet and their major subcontractor, Teledyne Brown Engineering. The test rig will be designed to interface with the E-1, cell-1 test stand at Stennis Space Center (SSC). By the end of the task, Aerojet will have completed fabrication of a complete ready-to-test assembly.

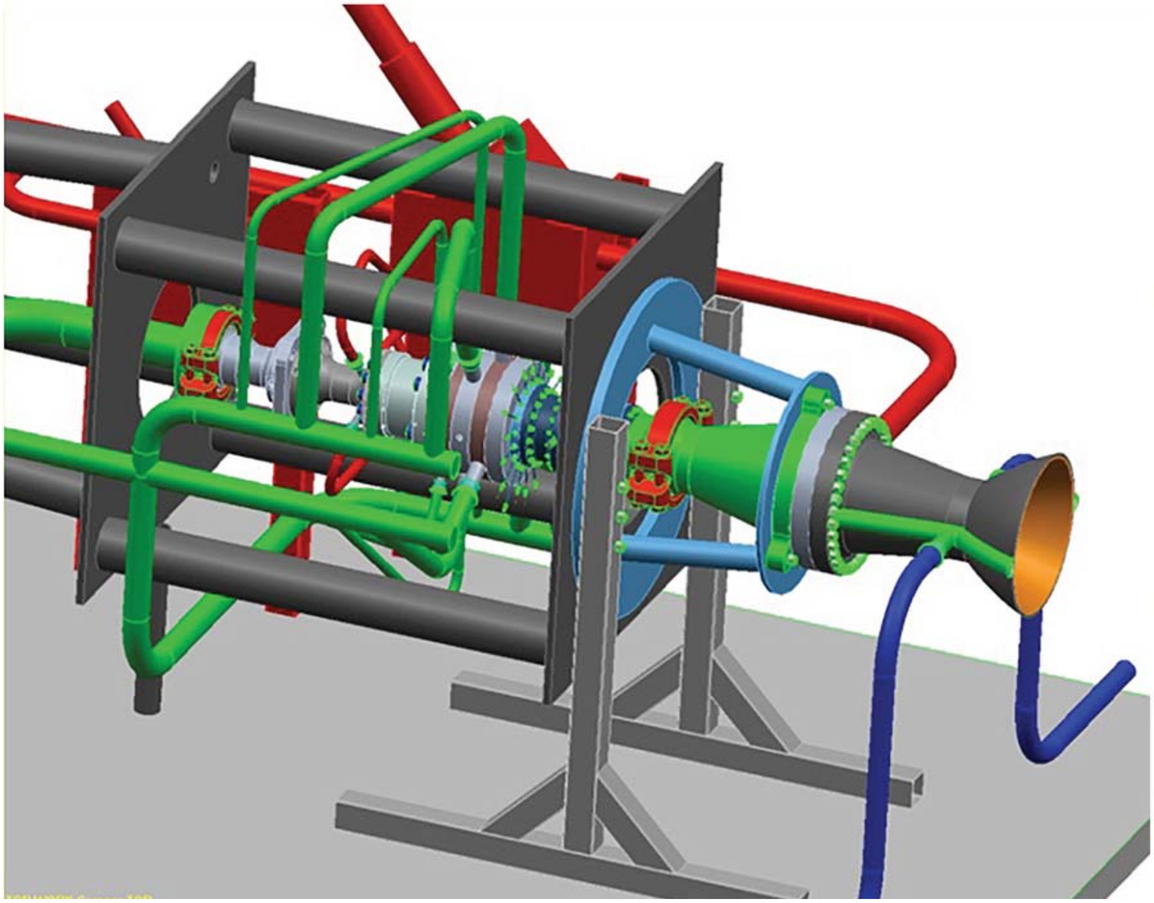


Figure 48. Aerojet ABEDRR test rig.

2.3.1.2 Technology Readiness Level Assessment. To establish the progress that will occur during the execution of this task, a technology assessment was conducted to determine the end state at completion and how it would phase in with the evolution path of the SLS vehicle-projected Block 1A/B PDR date. Both the current approach and a risk mitigation approach are shown in figure 49. The projected TRL at the end of the current effort in 2015 is 6, assuming that the engine will have been tested.

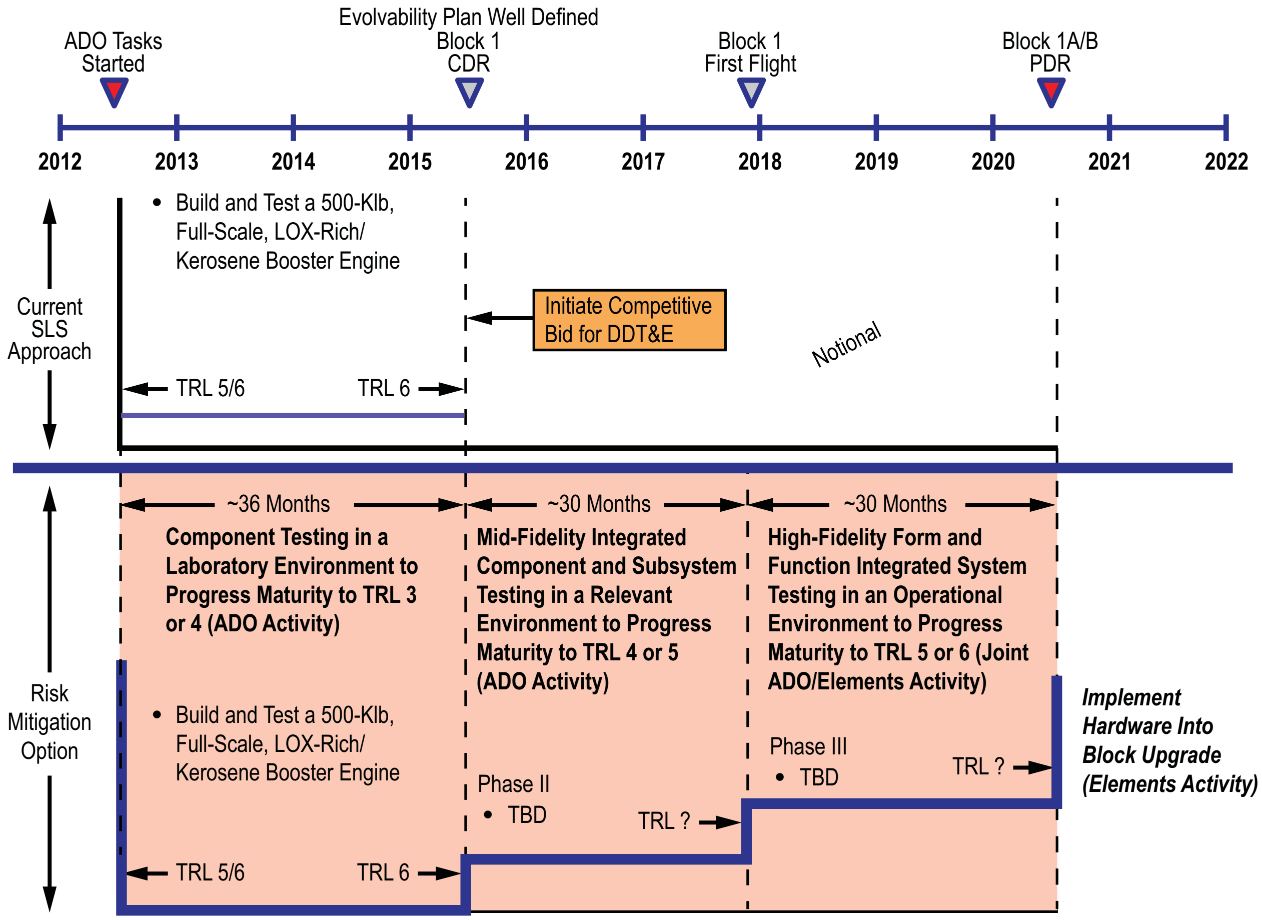


Figure 49. Aerojet ABEDRR TRL assessment.

2.3.1.3 Accomplishments. System requirements have been developed and a preliminary design initiated.

2.3.1.4 Future Work. Over the remainder of the contract, Aerojet will complete hardware design and fabrication. The USAF will provide preburners from their HCB program in early FY 2016. Aerojet will then integrate the components to prepare the integrated assembly for test.

Aerojet has also contracted with MSFC for combustion stability modeling. MSFC will provide an analytical assessment of the preliminary design. If testing of the hardware is conducted, the data will be used to refine and validate the analytical models.

2.3.2 ATK

2.3.2.1 Description. The goals of ATK ABEDRR activities are to benefit advanced booster development with improved performance, reliability, and affordability. The knowledge gained in the awarded tasks will advance the state of critical large booster systems and provide measurable data to assess a future advanced booster design, development, test, and evaluation (DDT&E) competition.

One task is an integrated booster static test article that is a 92-in analog of the contractor's advanced booster concept (fig. 50).

Figure 50. ATK ABEDRR LSC-1 92-in-diameter test motor.

The propellant, liner, and insulation task is geared towards developing a tailored thrust trace across a range of propellant family formulas that improve performance and mechanical properties while assessing a more producible booster at a more affordable cost. The goal is to gain an indepth understanding of propellant, liner, and insulation compatibilities.

A new nozzle flex bearing design will eliminate the need for the current flex boot and enable the use of a lower torque TVC system. This enables a lower weight and lower cost system that is significantly easier to process at the launch site.

The damage tolerance and detection task for a composite case is another enabling activity for ensuring the advanced booster case is safe for flight. This task is to gain an understanding of damage tolerant design solution effectiveness and give confidence to critics of composites.

The avionics and controls task is to assess power systems that are capable of driving an electric TVC system, provide the control system components, and assess different electric TVC technologies.

At the conclusion of the ATK ABEDRR activities, the contractor and government should gain an extensive amount of data, designs, processes, and capabilities to make informed decisions on future Advanced Booster design concepts for a more robust and affordable system.

2.3.2.2 Technology Readiness Level Assessment. To establish the progress that will occur during the execution of this task, a technology assessment was conducted to determine the end state at completion and how it would phase in with the evolution path of the SLS vehicle projected Block 1A/B PDR date. Both the current approach and a risk mitigation approach are shown in figure 51. The projected TRL at the end of the current effort in 2015 is TRL 5, with a Manufacturing Readiness Level (MRL) of 6.

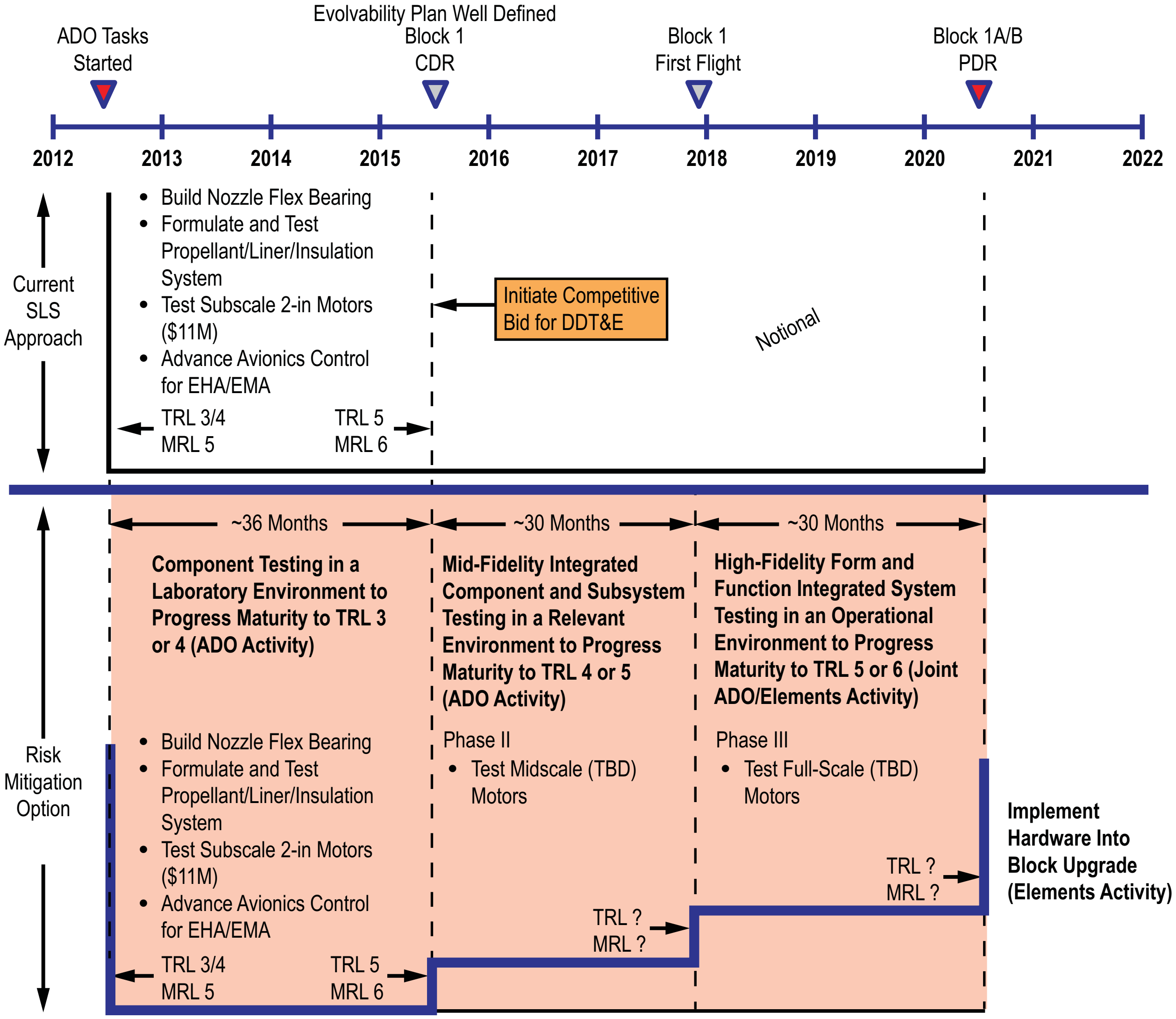


Figure 51. ATK ABEDRR TRL assessment.

2.3.2.3 Accomplishments. The following accomplishments were achieved:

- Propellant liner insulation (PLI)—Defined the propellant design of experiment; tailored liner formulation; tested and analysis four propellant formulations of pint, 1-gallon, and 5-gallon mixes; and tested PLI bondline.

- Case damage tolerance—Released drawings for the manufacturing of 92-in composite case for trial impact testing; assessed surface treatments, structural health monitoring, and NDE options; and defined the design of experiments.

- Nozzle flex bearing—Designed and released drawings of the assembly and primary components.

- Avionics and controls—Defined the test methods, assessed the actuator sizing, and assessed designed requirements.

- Static fire test—Developed the static fire test plan and built a composite case igniter.

2.3.2.4 Future Work. Future activities for ATK are as follows:

- PLI—Down-select of PLI system for 92-in static fire test motor and perform PLI system characterization.

- Case damage tolerance—Build, test, and assess impact trial test case; assess structural health monitoring and NDE systems; and build, test, and assess burst cases.

- Nozzle flex bearing—Build, test, and assess flex bearing and perform kettle tests.

- Avionics and controls—Build, test, and assess lithium ion battery system, common controller, and EMA/EHA TVC systems.

- Static fire test—Build and static fire test a 92-in motor.

2.3.3 Dynetics

2.3.3.1 Description. Dynetics was awarded two major tasks. The first task is focused on analysis of modernizaton of the Saturn era F-1 engine with an objective to reduce cost risks in four critical areas. The second major task deals with cryogenic tanks, with the objective to reduce cost risk by designing, manufacturing, and testing a cryogenic tank assembly.

2.3.3.2 F-1B Engine Task Description. The objective of this task is to reduce cost risk in four critical areas: (1) Gas generator (GG) build and test, (2) turbopump assembly (TPA) build, (3) power pack assembly (PPA) testing using the GG and TPA, and (4) main combustion chamber (MCC) build. The F-1 design will be updated (designated F-1B) to incorporate lower cost component designs and materials. Modern and more affordable manufacturing processes will demonstrate significantly reducing development time and production cost. Existing engine components will be updated with the new parts for testing to establish performance, throttling, and transient characteristics. The F-1B GG injector design will be produced using SLM low-cost manufacturing techniques (fig. 52).

Figure 52. Dynetics ABEDRR SLM GG injector design.

A full-scale, modern thrust chamber assembly (TCA) will be manufactured using lower cost construction methods (fig. 53).

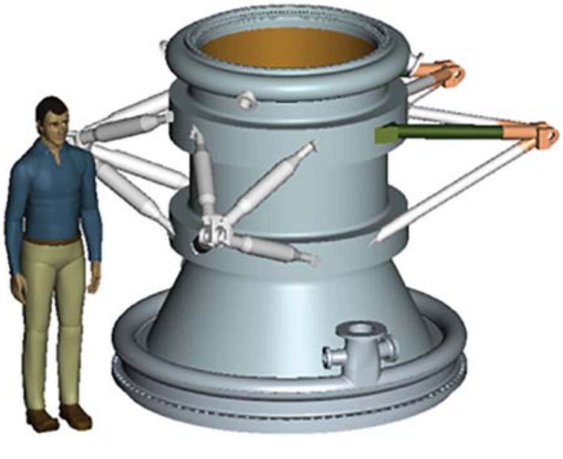


Figure 53. Dynetics ABEDRR F-1B MCC.

A new LOX pump volute, a turbine manifold, and turbine blade castings will be manufactured with the objective to demonstrate the ability to reproduce full-scale F-1 hardware that have high cost and schedule risks to DDT&E. All three parts are in final design, and developmental castings have been fabricated (fig. 54).

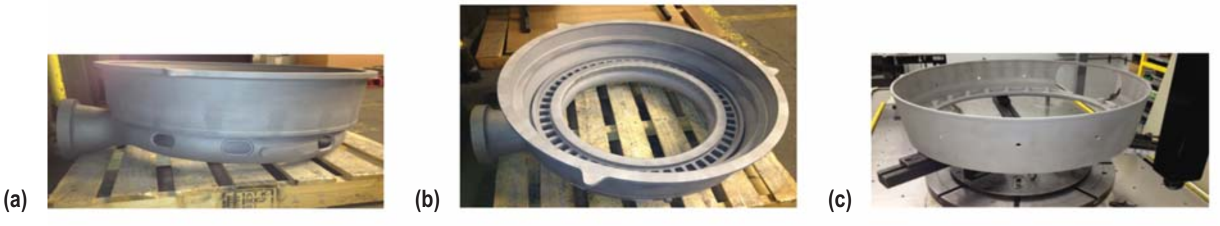


Figure 54. Dynetics ABEDRR turbopump activity: (a) Volute—side view, (b) volute—top view, and (c) volute—in fixture.

In addition, a hot-fired GG and a simplified turbopump will be integrated into a PPA for hot-fire testing. The PPA will integrate the refurbished turbopump and the previously tested GG into a test skid.

2.3.3.3 Structures Task Description. The objective of this task is to reduce cost risk by designing, manufacturing, and testing a cryogenic tank assembly. In this task, affordable manufacturing processes are used to produce and test a full-scale, flight-weight cryotank and intertank (fig. 55) to demonstrate the design and and/or manufacturing tools and processes. The cryotank will be integrated with the intertank, instrumented, and installed in a vertical test stand for static proof pressure and cryo-thermal cycle testing.

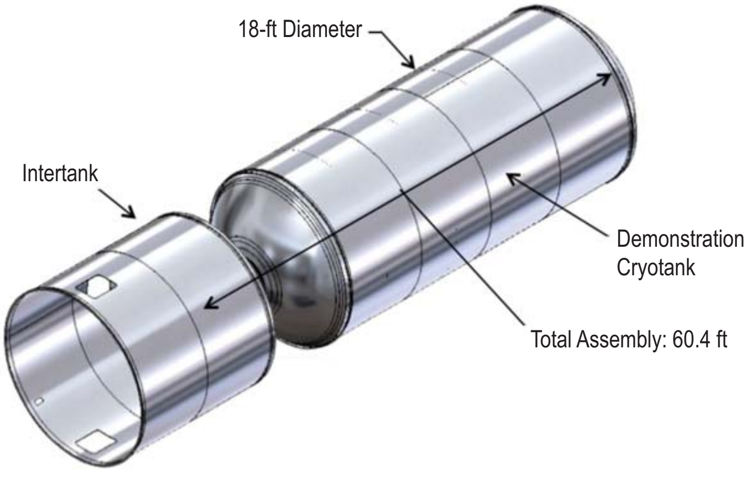


Figure 55. Dynetics ABEDRR cryotank/intertank assembly.

MSFC's FSW facilities and tooling will be utilized in Buildings 4755 and 4707. Tanks will be designed and built to validate low-cost materials and methods to produce booster structures for DDT&E. Thick-walled monocoque construction eliminates the cost and risk from machining large, complex grid panels and expensive T-ring forgings.

Common tank domes and one-piece barrels reduce parts count and improve reliability. The cryotank assembly build systematically addresses the risks associated with the design, materials, manufacturing, and NDE processes selected to produce structures. This task will also confirm that the manufacturing facilities and equipment at MSFC are suitable for building full-scale tanks and structures, validating DDT&E and production cost savings from utilizing these facilities.

2.3.3.4 Technology Readiness Level Assessment. To establish the progress that will occur during the execution of this task, a technology assessment was conducted to determine the end state at completion and how it would phase in with the evolution path of the SLS vehicle projected Block 1A/B PDR date. Both the current and risk mitigation approaches are shown in figures 56 and 57.

2.3.3.4.1 F-1B Engine. The projected TRL at the end of the current effort in 2015 is TRL 4 with an MRL of 6 (fig. 56).

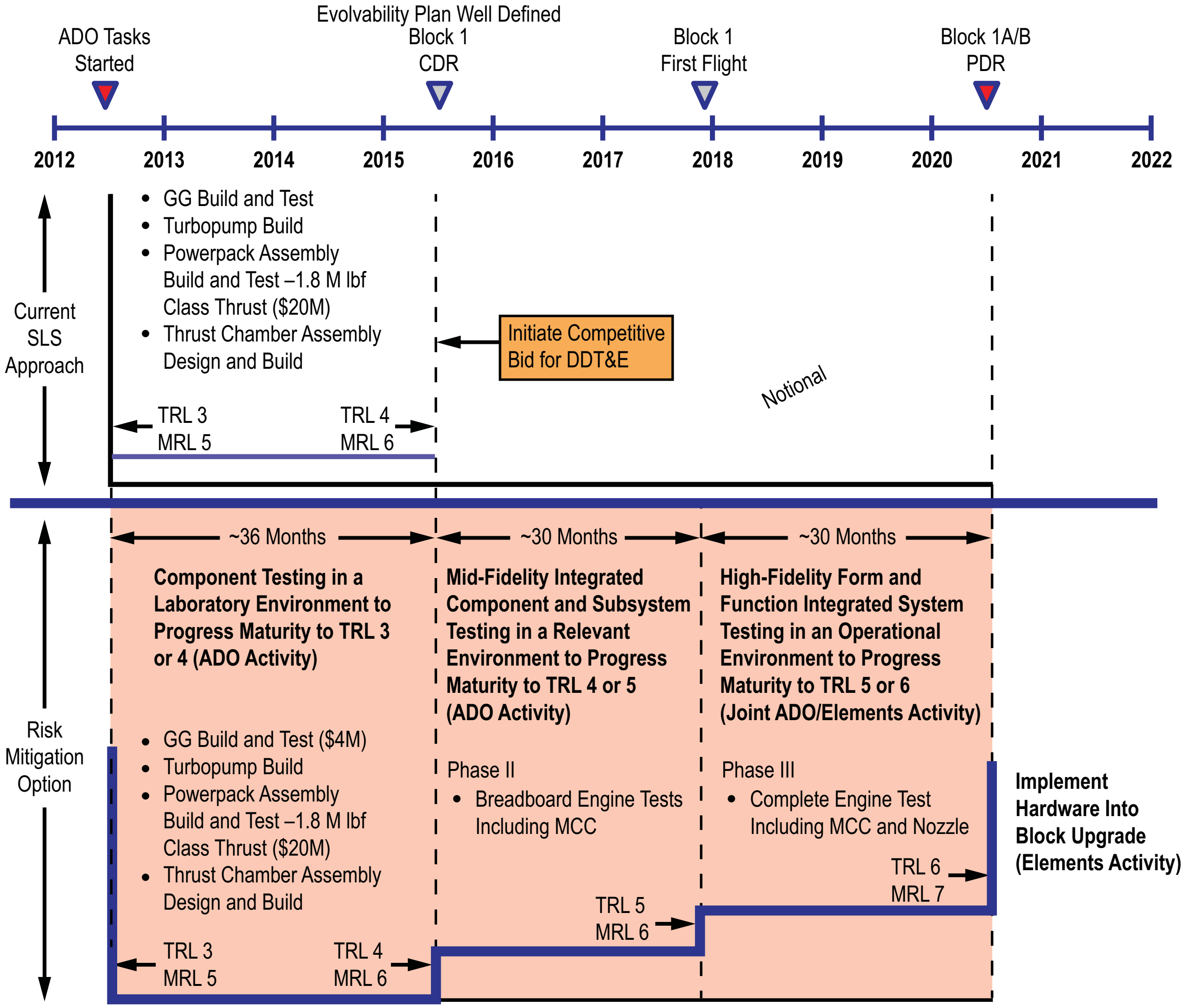


Figure 56. Dynetics ABEDRR F-1B engine TRL assessment.

2.3.3.4.2 Structures. The projected MRL at the end of the current effort in 2015 is MRL 6 (fig. 57).

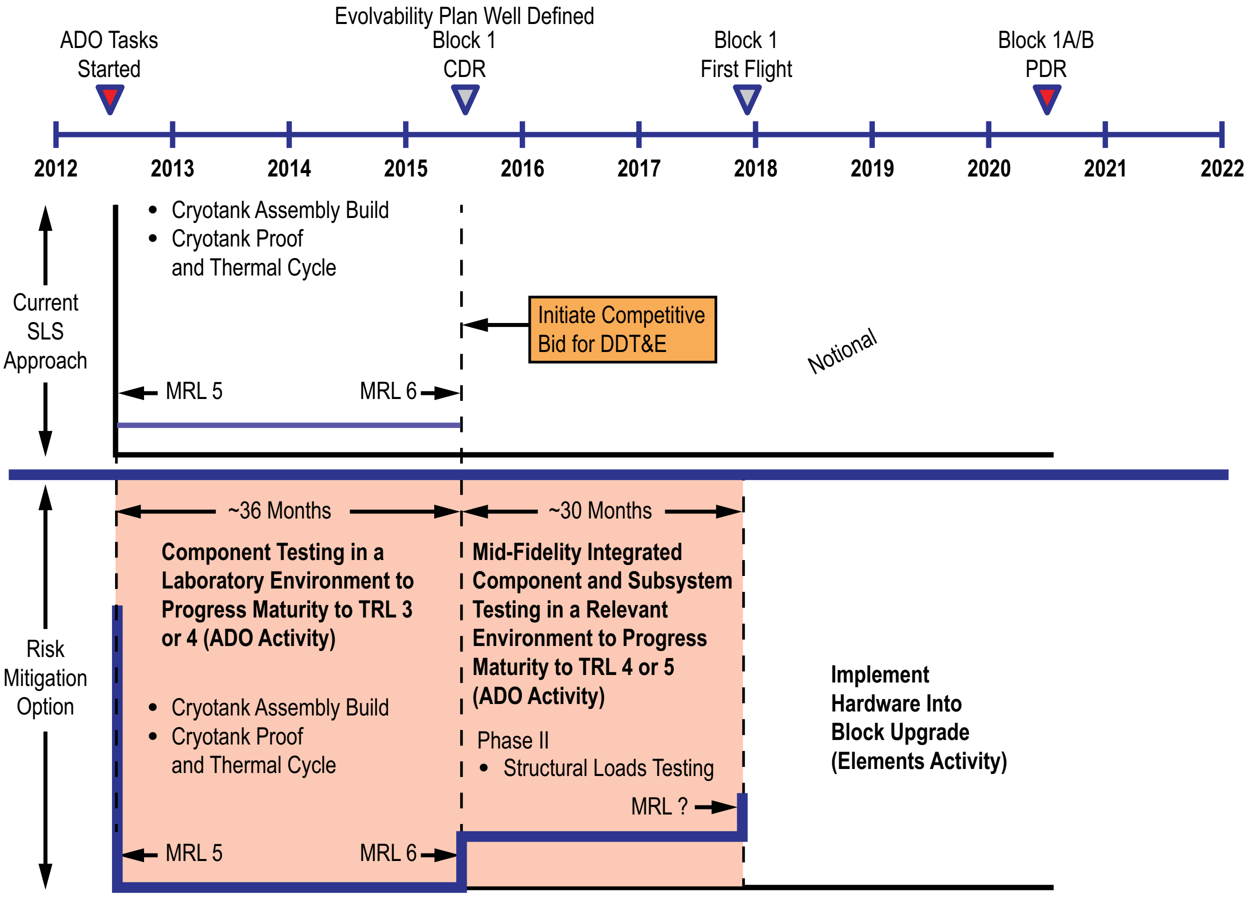


Figure 57. Dynetics ABEDRR structures TRL assessment.

2.3.3.5 Accomplishments. Accomplishments achieved for the F-1B engine and structures are given in sections 2.3.3.5.1 and 2.3.3.5.2.

2.3.3.5.1 F-1B Engine.

- A heritage gas generator was successfully hot-fired at MSFC's test stand 116 (fig. 58). The test article was an F-1 GG assembly from F-1 engine F-6049, a flight spare from Apollo 12. The test series successfully demonstrated the operating characteristics of the GG injector and chamber hardware at F-1B nominal and throttle conditions. Ten tests were conducted at the target chamber pressure and mixture ratio conditions with no test terminations or test article hardware anomalies. The test article was removed from the test stand.

Figure 58. Dynetics ABEDRR GG testing at MSFC.

- The design of an F-1 GG injector produced with low-cost manufacturing techniques was completed. Demonstration 'pie slices' of the injector were produced with SLM techniques and successfully water flow tested.

- A heritage F-1A turbopump assembly (Mk-10A) has been disassembled and hardware inspections and analysis are underway.

- A PDR was completed for the PPA.

- A PDR was completed for the F-1B MCC.

2.3.3.5.2 Structures. Achievements include the following:

- Completed structures final design review and released all cryotank structures drawings.

- Completed the first series of weld schedule development with the University of South Carolina, which tested 0.750-in-thick 2219 aluminum with a conventional FSW technique.

- Tested schedules for welding the domes to the dome/tank end rings on the Production Development System in MSFC Building 4755.

- Delivered ¾-in aluminum plate from Alcoa to Major Tool and Machine where they will be rolled into one-piece barrel sections. Delivered ¾-in aluminum plate from Alcoa to Spincraft where they will be spun into 18-ft-diameter domes.

2.3.3.6 Future Work. Future work for Dynetics involves the F-1B engine and structures as given in sections 2.3.3.6.1 and 2.3.3.6.2.

2.3.3.6.1 F-1B Engine.

- A final design review will be held in late 2013 and testing will be performed at NASA SSC E1, cell 2 in 2015:

- The F-1 GG test article will be refurbished in preparation for the powerpack test at SSC in 2015.

- The F-1 injector test article will be manufactured utilizing the SLM process in December 2013 and water flow tested at MSFC in February 2014.

- A new LOX pump volute, a turbine manifold, and turbine blade castings will be manufactured with the objective to demonstrate the ability to reproduce full-scale F-1 hardware that have high cost and schedule risk to DDT&E. All three parts are in final design, and developmental castings have been fabricated. The reassembled turbopump with incorporation of the new parts will be used in powerpack testing in 2015.

- The MCC liner configuration uses ring-rolled and spun NARloy-Z castings. Hot isostatic press (HIP) technology will be used to fabricate the MCC. HIP brazing of the liner and jacket will be followed by final machining, NDE, proof pressure testing, and flow testing. Successful completion will validate F-1B MCC manufacturing processes and will enable low-risk transition into DDT&E. The article is scheduled to be complete in early 2015.

- The PPA will integrate the refurbished turbopump and the previously tested GG into a test skid. in 2015.

2.3.3.6.2 Structures. The following structures will be built:

- FSW of the barrels, domes, and rings is scheduled to begin at MSFC in late 2013, continuing into 2014, culminating in hydrostatic and cyro-thermal testing in 2015.

- Spincraft will manufacture the 18-ft-diameter domes.

2.3.4 Northrop Grumman Aerospace Systems

2.3.4.1 Description. Northrop Grumman Aerospace Systems (NGAS) will conduct a subscale version of its composite common bulkhead tank set to demonstrate its SLS Advanced Booster concept. The contractor will deliver a final technical report summarizing the demonstration and include an updated affordability plan.

The primary objective of this project is to design and test a composite demonstration subscale article that has been fabricated using out-of-autoclave cure processes. The study will demonstrate the affordability and reliability benefits of the following composite tank set features: composite common bulkhead; an in situ out-of-autoclave cure process; unitized tank shells with barrel, dome, and skirt; and an evacuated core sandwich construction.

The NGAS team will choose a composite tank set (CTS) scale that represents the engineering and manufacturing challenges for the objective system while minimizing costs and providing best value to the customer. The scale is expected to be approximately 8 ft in diameter, or about 50% of the objective system (fig. 59).

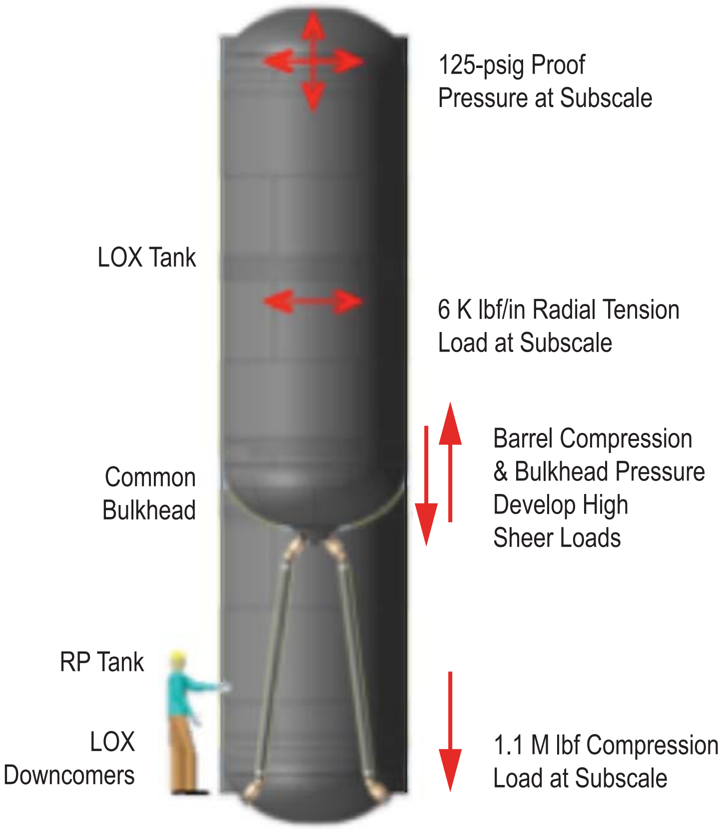


Figure 59. NGAS ABEDRR CTS demonstrator.

NGAS will collect affordability and reliability data during the design, build, and demonstration test series, and correlate the results back to the NGAS affordability plan. By successfully conducting the CTS demonstration, this effort will show the potential for reducing or eliminating dome parasitic mass from natural path lamination, eliminating longitudinal joints with the production of unitized barrels, domes, and cones, and reducing facility costs and requirements with a single footprint facility approach. The overall effort also demonstrates the scalability of the in situ manufacturing and out-of-autoclave cure process to form the 8-ft-diameter CTS pathfinder to larger structures. The NGAS CTS manufacturing system is shown in figure 60.

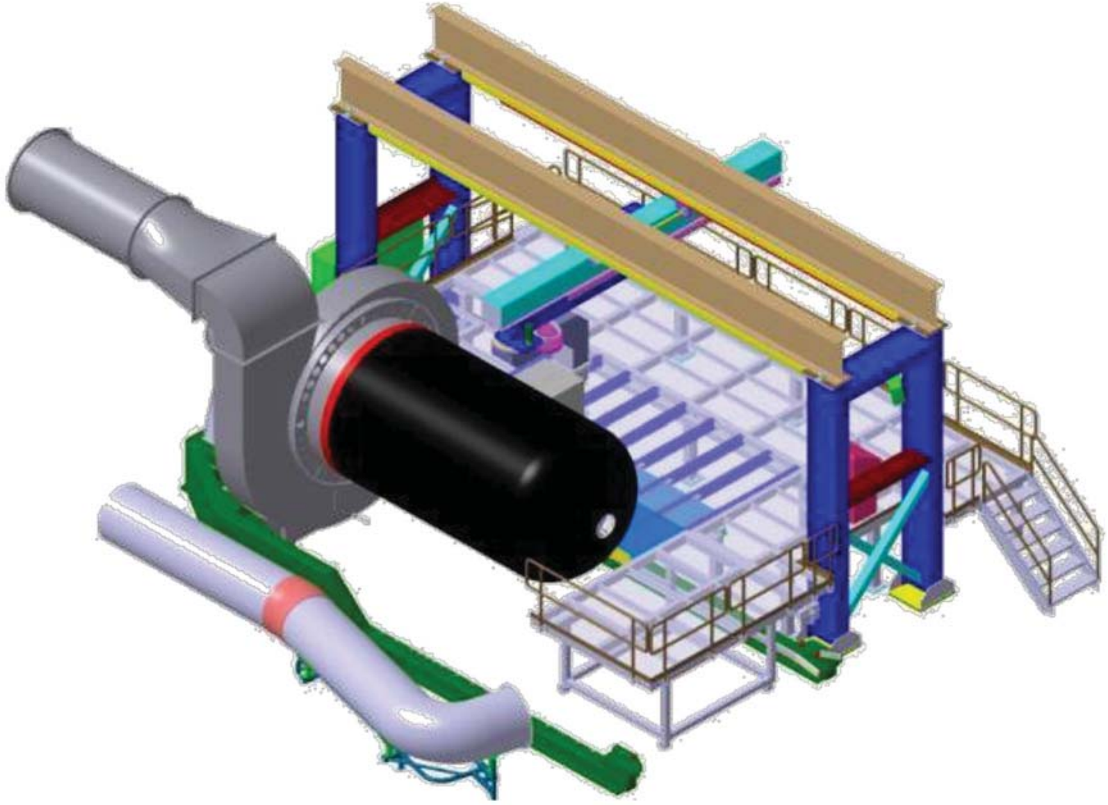


Figure 60. NGAS ABEDRR CTS manufacturing system.

The NGAS demonstration effort will provide the cost and reliability benefits of a common bulkhead composite tank for the SLS Advanced Booster and future space exploration elements. The most significant challenge facing the NGAS team is the curing of components of large unitized composite structures. Autoclave processing results in reliable components with low void content because the component is cured while under pressure; however, autoclaves are costly to build and operate.

2.3.4.2 Technology Readiness Level Assessment. To establish the progress that will occur during the execution of this task, a technology assessment was conducted to determine the end state at completion and how it would phase in with the evolution path of the SLS vehicle projected Block 1A/B PDR date. Both the current and risk mitigation approaches are shown in figure 61.

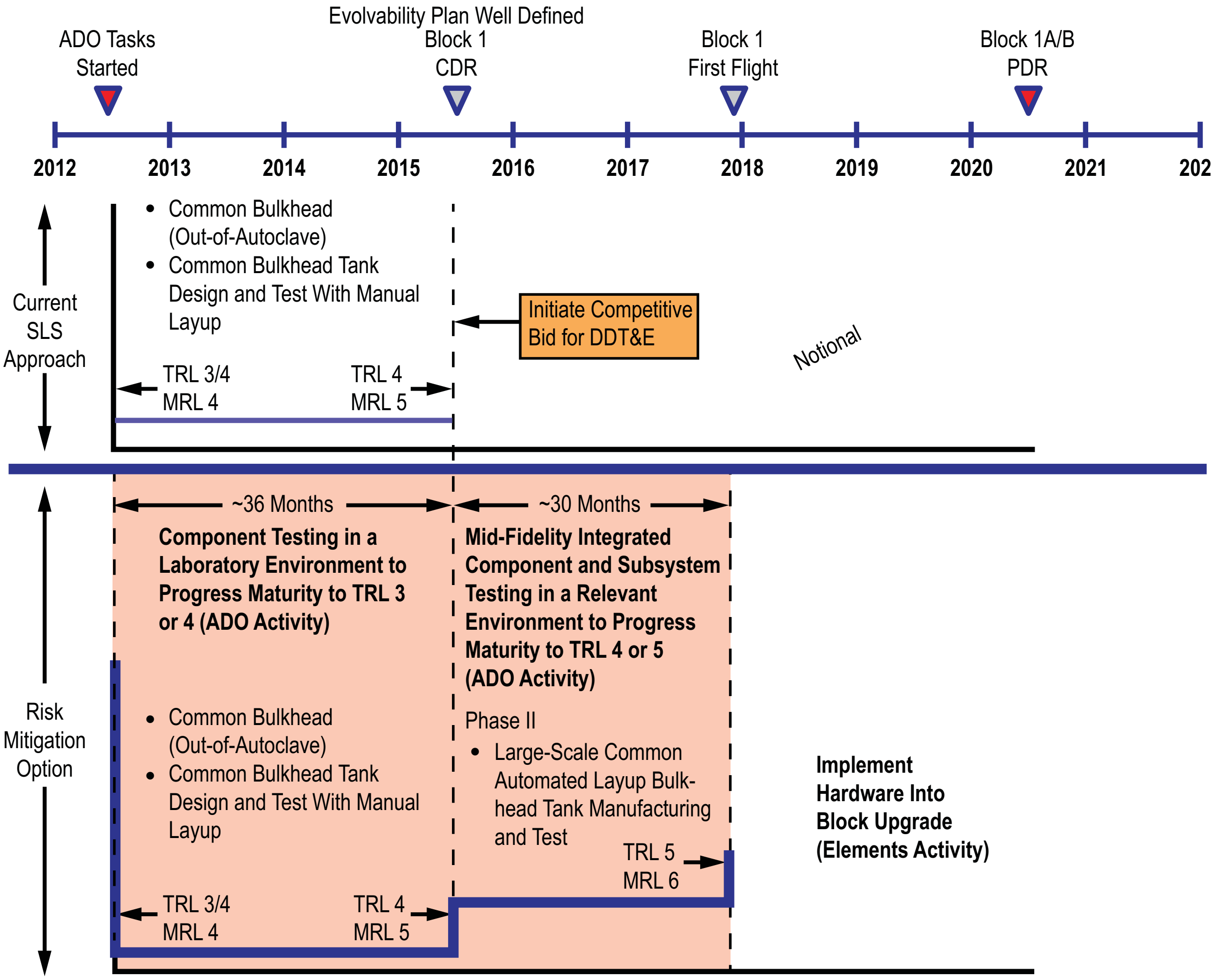


Figure 61. NGAS ABEDRR CTS TRL assessment.

2.3.4.3 Accomplishments. Achievements include the following:

- Successful demonstration design review was held in early 2013.
- Test fixture build kickoff was held at Griffon Aerospace in Madison, Alabama.
- Successfully built out-of-autoclave test panels with <1% void content.

2.3.4.4 Future Work. Future work of NGAS includes the following:

- Fabricate the test fixture and integrate the substitute fuel (diesel) supply tank.
- Design and fabricate test fixture components and test sequence.
- Perform composite tank set demonstration.

2.4 Industry Contracts

The Air Force's AUSEP is an initiative to develop an affordable upper stage engine that will be a replacement for the RL10 engine. The AUSEP engine has the requirement for 30,000 lb of thrust with the performance of the RL10B-2 that can be packaged in the envelope of an RL10A-4 to support USAF evolved expendable launch vehicle (EELV) missions using existing Atlas and Delta launch vehicles.

AUSEP has additional goals for increased thrust and reduced size and weight for the SLS CPS to provide additional mission capture. The Human Spaceflight Architecture team (HAT) analyzed the AUSEP requirements for crewed missions beyond Earth orbit. The AUSEP requirements were found to be an enabler for the CPS.

The industry contracts were awarded in late 2012 and early 2013. Contracts were awarded to five industrial partners. A brief description is provided in sections 2.4.1 through 2.4.5.

2.4.1 Aerojet

2.4.1.1 Description. The Aerojet AUSEP effort will perform a design study with emphasis on their next generation engine (NGE) system configuration that will develop the top-level system requirements and specifications for the overall AUSEP engine cycle. The work includes a system engineering trade study focused on the affordability, performance, and technological maturity of their AUSEP configuration.

The study effort will provide draft program plans, including initial estimates of recurring and nonrecurring costs and schedule to design, develop, test, and manufacture a flight-certified system within a reduced cost and constrained schedule environment.

2.4.1.2 Objectives and Scope. The study addresses three primary categories through its enhanced assessment of Aerojet's NGE in-house development as a viable replacement for the current RL10 upper stage engine. The study establishes the necessary engine performance requirements and verification, provides a flight engine design supported by the appropriate analyses and trades, and establishes cost and schedule estimates for DDT&E of a suitable replacement flight engine system.

To accomplish these objectives, the Aerojet AUSEP team will define engine system requirements and allocate them to the major NGE subsystems and components via an engine system functional analysis. Using engine system requirements, the study will establish top-level DDT&E and manufacturing planning and initial cost and schedule assessments for engine production and integration. The study will use a single design and analysis cycle to refine the AUSEP engine system concept based on Aerojet's NGE-augmented expander cycle development work completed to date (fig. 62).

Figure 62. Aerojet AUSEP engine concept.

The Aerojet team will define several FOMs as a set of selection criteria, factors, and weights to support the trade studies and analysis down-selection process, with an increased emphasis on the affordability aspects of the AUSEP replacement engine concept. As part of the overall study, the Aerojet AUSEP team will perform the culminating cost and schedule estimates required to produce the engine system. These estimates will include a development, qualification, and production schedule, and recurring and nonrecurring lifecycle costs. The overall study flow is shown in figure 63.

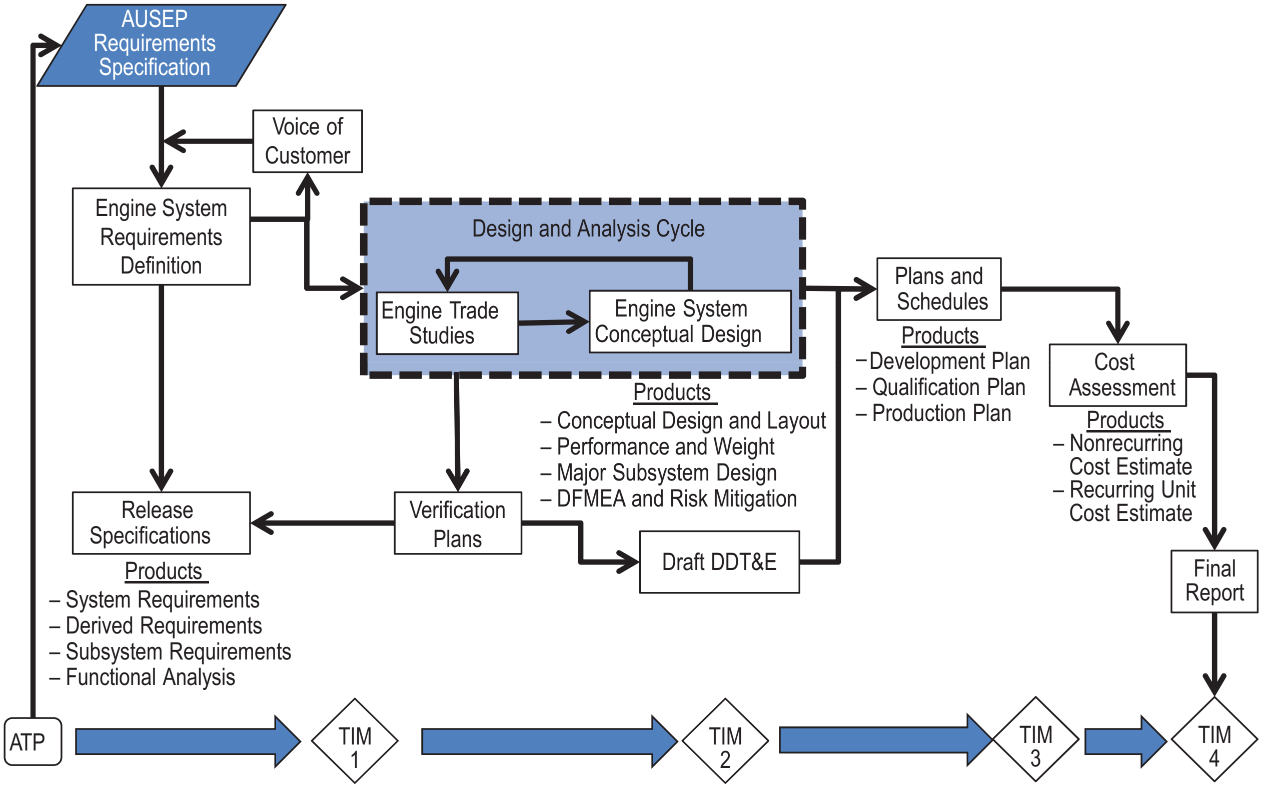


Figure 63. Aerojet AUSEP engine study flow.

2.4.1.3 Accomplishments. Aerojet accomplishments include the following:

- Finalized the initial major subsystems requirements documents along with associated verification requirements.
- Completed the series of power balance analyses for the AUSEP.
- Finalized FOM weight values to reflect increased importance of AUSEP affordability aspects.
- Established recurring and nonrecurring cost and schedule initial ground rules, assumptions, risks, and estimating methodology.

2.4.1.4 Future Work. The following is a list of planned future work:

- Refine and update the AUSEP subsystem and component development logic and plan.
- Develop the flight engine production schedule.
- Complete the remaining AUSEP power balance trades for the off-design operation and for the additional SLS mission capture studies.
- Complete integration of the gimbal arrangement and document the vehicle systems impacts (structure and actuators) arising from gimbal selection.
- Perform component level analyses and trade studies.
- Finalize and deliver the flight engine layout with isolation valve models, bellows arrangements, and nozzle profile that match the performance requirements.

2.4.2 Exquadrum

2.4.2.1 Description. Exquadrum, along with teammates WASK Engineering and ATK, is developing the dual-expander, short-length aerospike (DESLA) upper stage engine concept. The engine is being developed using a design for manufacture and assembly approach. Key features of the DESLA engine include simplification due to reduction in hardware size, which enables TCA development to be performed at full-scale affordably; a modular TCA, which enables high volume production for a low volume engine; a dual expander cycle, which enables separate optimized turbopumps and eliminates the need for an interpropellant seal; utilization of the Air Force Research Laboratory (AFRL) upper stage engine technology (USET) turbopump, which significantly reduces development technical and cost risk; and a short aerospike nozzle, which provides the surface area and heat transfer necessary for the cycle without the need for a deployable nozzle extension.

The modular thrust chamber is a key technology that enables cost-efficient manufacturing for a low production engine. It replaces a single, large, expensive TCA that requires significant tooling, touch labor, and nonconformance disposition cost, with approximately 200 small, inexpensive thrust chambers manufactured with conventional machines, minimal-touch labor, and no nonconformance disposition cost. The size of the modular thrust chamber also enables emerging manufacturing processes, such as direct metal laser sintering and SLM.

2.4.2.2 Objectives and Scope. The overall objectives of this effort are to perform trade studies in response to the requirements, mature the resulting LOX/liquid hydrogen (LH_2) engine configuration, generate recurring and nonrecurring cost, and schedule estimates to develop and produce the resulting engine configuration. Also, a conceptual design will be developed for a 60-Klb, LOX/RP aerospike engine including a detailed design of a modular thrust cell suitable for manufacture using the SLM process.

To achieve these objectives, several subtasks have been identified. Trade studies to optimize chamber pressure and nozzle area ratio have been identified to meet the maximum engine diameter requirement. Trade studies to evaluate nozzle configuration and length have been identified to meet engine performance and maximum length requirements. These trade studies will identify the engine configuration that best meets AUSEP requirements. This configuration will then be modeled in the Rocket Engine Transient Simulator (ROCETS) application for steady state and transient analysis to establish a high-fidelity engine power balance.

The resulting configuration will also be used to generate an engine conceptual design. The conceptual design will be used to evaluate packaging within the Centaur stage. The engine weight will be calculated from the 3-D solid models of the engine conceptual design. The conceptual design will also be used to generate a drawing package to obtain manufacturing cost and schedule estimates. Additionally, a detailed design of a modular thrust cell will be generated for manufacture using the SLM process.

Cost and schedule estimates will be generated. Quantities and quality variables will be used to bracket the analysis. Engine quantities will be varied for development, certification, and production. Quality requirements will include commercial, USAF EELV, and NASA human-rated spaceflight requirements.

2.4.2.3 Accomplishments. Significant progress has been achieved thus far. Thousands of trade studies have been completed to identify the optimum engine configuration. Detailed thermal analyses of the regeneratively cooled nozzle and thrust chambers have been conducted for use in the ROCETS model. Pump hydrodynamic and turbine aerodynamic analyses have been conducted to generate pump and turbine maps for the fuel and oxidizer turbopumps for inclusion in the ROCETS model. The ROCETS model has been created and is being used to generate a high-fidelity power balance and to conduct transient analyses.

Incorporating the lessons learned from the AFRL test program, the conceptual design of the DESLA engine has been completed and a 3-D solid model has been generated including a modified USET turbopump housing to reflect a flight weight configuration. The engine weight has been calculated from the solid models, and verified to meet requirements. Turbopump general arrangement and component manufacturing drawings have been generated and quality requirements identified to begin obtaining cost and schedule estimates.

An approach has been developed to obtain cost and schedule estimates that vary quantities and quality requirements ranging from a commercial program, to USAF EELV, to NASA human rating. A detailed design of a modular thrust cell has been generated and provided to NASA to fabricate using the SLM process. A 3-D solid model of the Centaur stage engine envelope has been obtained from United Launch Alliance and is being utilized to validate the engine packaging.

2.4.2.4 Future Work. The engine general arrangement drawing will be generated, along with the manufacturing drawings for the thrust ring and nozzle. Transient analyses using the ROCETS model will be completed and the high-fidelity power balance generated. The cost and schedule estimates will be completed.

2.4.3 Moog

2.4.3.1 Description. Moog will design, develop, manufacture, and test a high-pressure, cryogenic LOX, variable flow control valve for propulsion systems and engines sized for use on a cryogenic upper stage. The valve design will be based on input requirements from potential upper stage engine developers. The design is intended to be scalable to allow a single actuator/controller to be utilized on both the thrust control valve and mixture ratio control valve.

2.4.3.2 Objectives and Scope. The primary objective of this program is to design and test a developmental valve that meets the derived flow and pressure requirements in both LN_2 and LOX flow environments (fig. 64).

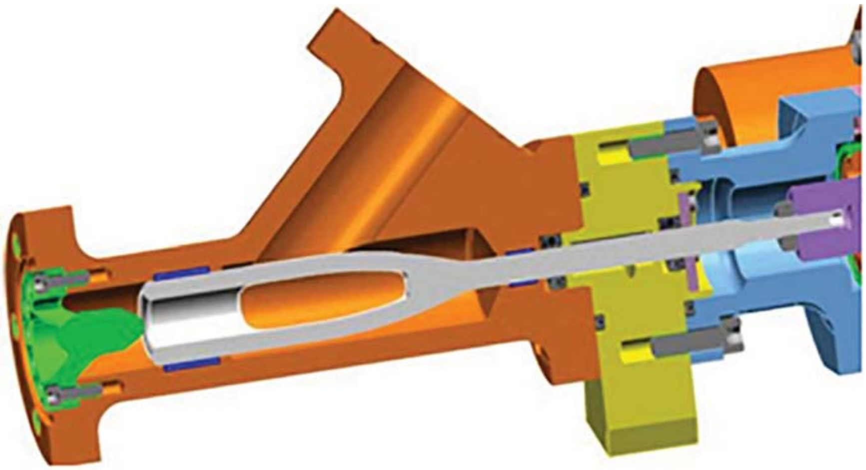


Figure 64. Moog AUSEP design concept, high pressure LOX control valve.

To complete the developmental valve design, certain key items will be tested separately prior to full-scale valve testing. First, Moog will measure flow characteristics of the metering element by conducting water flow tests at Moog. This testing will give an early indication of flow versus pressure drop at multiple valve positions before progressing to the full development valve fabrication and test phase. Second, Moog will characterize dynamic seal performance in a cryogenic environment in order to quantify the friction characteristics of the seals at LOX temperatures and examine the tradeoffs between both seal leakage and seal life versus friction.

Moog will follow parallel paths in the design of the valve body. A Monel K500 body will be produced through standard production methods, along with a parallel path of creating an Inconel 718 valve body using an advanced manufacturing process. The intent is to advance Moog's understanding of additive manufacturing and to further assess and advance the overall viability of additive manufacturing methods.

2.4.3.3 Accomplishments. The following achievements were made:

- As of the end of May 2013, Moog completed the valve design effort to support the initial build of a development LOX flow control valve based on the flow and pressure parameters given to Moog by potential upper stage engine developers. A PDR was completed with the USAF and MSFC, which included an oxygen compatibility assessment and a review of Moog's valve design and planned testing activities.

- All risk mitigation hardware designs have been completed and test hardware is on order to conduct valve element flow testing and seal design friction and leakage testing (fig. 65). The valve element flow tests are intended to allow an initial characterization of the valve flow element prior to full-scale valve testing on LN_2 and LOX high-pressure systems. The seal friction and leakage testing is intended to allow a down-selection and/or redesign cycle of the valve's critical dynamic seal utilizing seals from three different vendors.

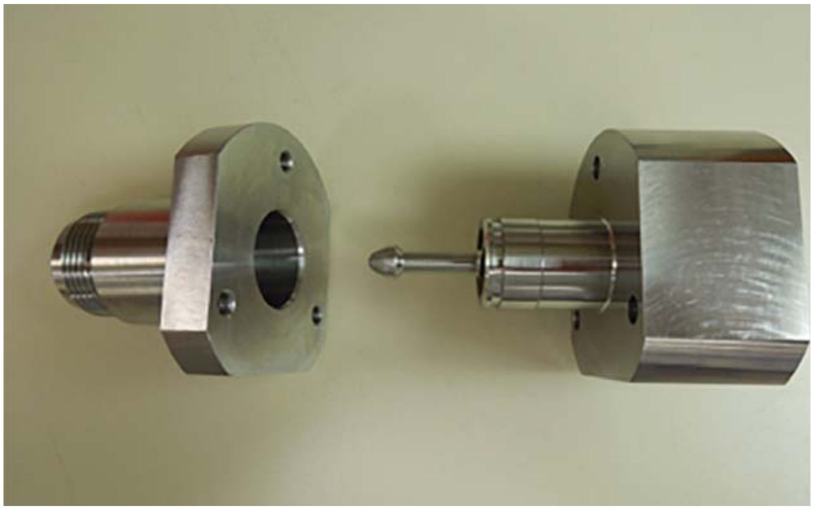


Figure 65. Moog AUSEP valve element flow test fixture.

- All valve component drawings and analyses have been completed to support the production of development valve hardware. Following the PDR meeting, the manufacturing activities were initiated at Moog and the valve hardware was added to the model shop manufacturing queue for scheduling.

- A valve body designed for SLM additive manufacturing processes has been created (fig. 66) with the technical and management support of the MSFC component and materials groups. The SLM valve body has completed its initial build, with a number of other activities (computed tomography (CT) scan, HIP, heat treat, etc.) to follow before delivery to Moog.

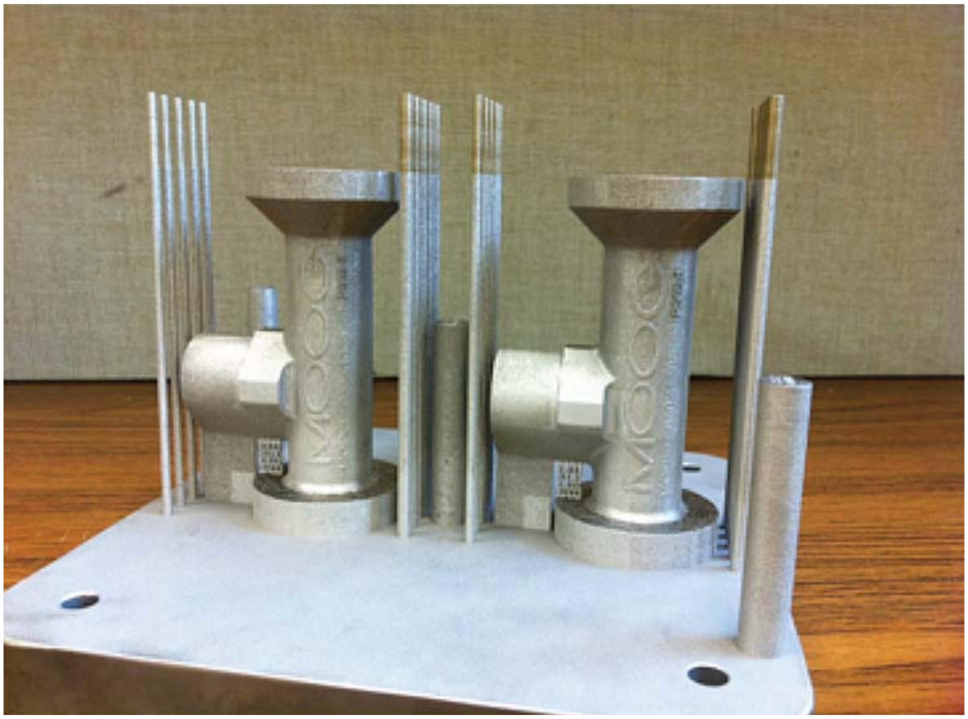


Figure 66. Moog AUSEP SLM valve body produced at MSFC.

2.4.3.4 Future Work. Future work includes the following:

- Near-term valve tasks involve completion and assembly of the valve hardware and development of internal test procedures. In parallel, Moog will work closely with the MSFC testing groups to finalize LN_2 and LOX test plans and procedures.

- In the late FY 2013 timeframe, the two valves (Monel® body and SLM Inconel® body) will be assembled and pressure/leak tested at Moog prior to LN_2 testing at MSFC. After this testing is conducted, the valves will be disassembled and examined, and one will be rebuilt for LOX testing in late 2013.

- Moog will conduct its valve element water flow testing with the completed hardware.

2.4.4 Northrop Grumman Aerospace Systems

2.4.4.1 Description. Under an SLS NRA and in collaboration with the USAF, ADO awarded NGAS a contract for an upper stage liquid engine requirements study. The NGAS AUSEP effort will perform a systems engineering trade study to identify an affordable, reliable, and technologically mature upper stage engine configuration. The study effort will provide draft program plans, including rough estimates of recurring and nonrecurring costs and schedule to design, develop, test, and manufacture a flight-certified system within a reduced cost and constrained schedule environment.

2.4.4.2 Objectives and Scope. The program will initiate the design of a 30,000-lbf thrust class LOX/LH_2 affordable upper stage engine through an engine system requirements study phase. The study will be performed to identify the most cost-effective, technically mature alternatives to the RL10 engines. The study will identify the modern design solutions that can make the replacement engine affordable, consistent with performance and reliability objectives.

The study will provide a conceptual engine design that is responsive to the SLS NRA upper stage engine study requirements, approaches, and strategies applicable to the full-scale replacement engine program in the areas of systems engineering; risk management; verification, test, and evaluation; field and launch support; and schedule and lifecycle cost estimates. If lifecycle affordability gains can be shown, engine system concepts that require modification of requirements will also be considered.

2.4.4.3 Accomplishments. NGAS achievements include the following:

- Reviewed and performed functional decomposition of AUSEP system requirements and trade space definition document.

- Established a study team and completed planning of all project activities.

- Completed broad engine system trades involving alternate cycles, sizing studies, nozzle options, and turbopump configuration.

- Initiated engine concept detailed trades and design studies.

- Selected and began the refinement of a point of departure engine system concept.

- Performed thrust chamber trades and analyses (injector type, regenerative cooling circuit layout, nozzle cooling, igniter).

2.4.4.4 Future Work. Future work includes the following:

- Continue turbomachinery trades and analyses (number of stages, shaft configuration, bearing type and arrangement, material selection).

- Perform nozzle analyses and trade studies to finalize optimum configuration (deployable designs, candidate materials, joint to cooled chamber, etc.).

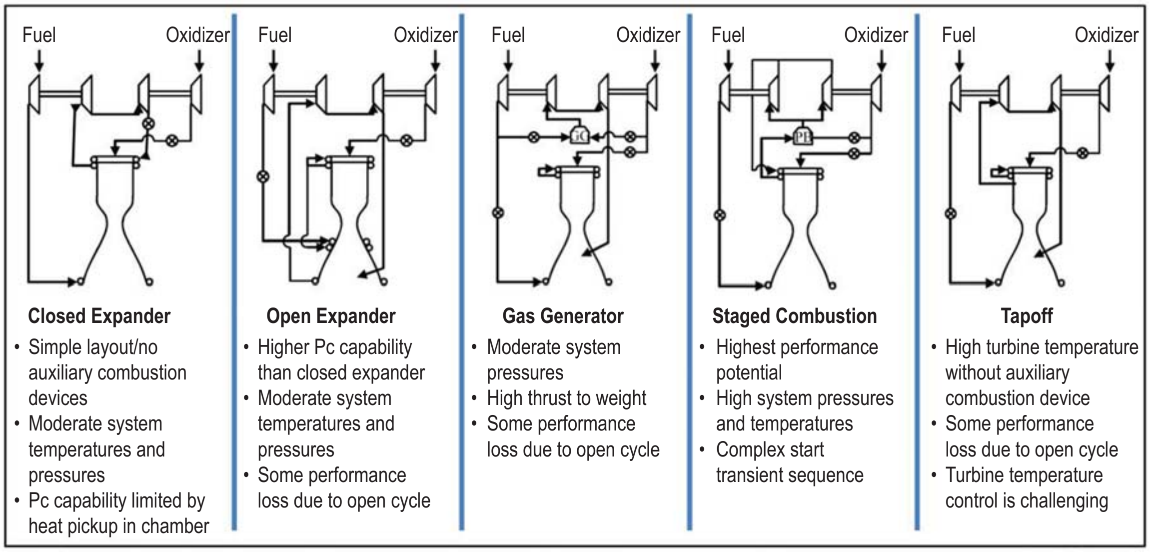
- Finalize and deliver the recurring and nonrecurring cost and schedule estimates for the design, development, test, and evaluation of an advanced upper stage engine.

2.4.5 Pratt & Whitney Rocketdyne

2.4.5.1 Description. The PWR AUSEP effort will perform a systems engineering trade study to identify an affordable, reliable, and technologically mature upper stage engine configuration. The study effort will provide draft program plans, including rough estimates of recurring and nonrecurring costs and schedule to design, develop, test, and manufacture a flight-certified system within a reduced cost and constrained schedule environment.

2.4.5.2 Objectives and Scope. The study will balance affordability, reliability, and performance through the use of a proven utility analysis process that employs interviews with the stakeholders to derive a qualitative relationship to describe the customer's utility preferences. The study will determine the AUSEP configuration with the optimum combination of performance, operability, development cost, and technical maturity.

Numerous configurations within the five cycles illustrated in figure 67 will be evaluated. The performance trade will be conducted using PWR's well established cycle prediction methodology. Physics-based power balance models will permit the rapid, accurate estimation of design and off-design characteristics using historically validated routines to predict the performance of pumps, turbines, nozzles, and other engine components.



Closed Expander
- Simple layout/no auxiliary combustion devices
- Moderate system temperatures and pressures
- Pc capability limited by heat pickup in chamber

Open Expander
- Higher Pc capability than closed expander
- Moderate system temperatures and pressures
- Some performance loss due to open cycle

Gas Generator
- Moderate system pressures
- High thrust to weight
- Some performance loss due to open cycle

Staged Combustion
- Highest performance potential
- High system pressures and temperatures
- Complex start transient sequence

Tapoff
- High turbine temperature without auxiliary combustion device
- Some performance loss due to open cycle
- Turbine temperature control is challenging

Figure 67. PWR AUSEP engine cycle trades.

PWR will then down-select to a smaller set of promising engine system concepts for detailed analyses. System trades will be made assuming the current state-of-the-art of production rocket engines to establish a baseline against which proposed technology enhancements may be measured. As part of the component level phase of the study, the PWR AUSEP team will then determine the benefits and costs of technology insertion, including advanced manufacturing technology, for these baseline cycles.

2.4.5.3 Accomplishments. The following achievements were made:

- Evaluated all planned cycles and created power balance models for all candidate architectures.
- Utilized USAF and NASA customer interviews to create a utility function balancing the main trade factors for cost, reliability, weight, specific impulse, etc.
- Established draft Systems Engineering Management Plan.
- Established recurring and nonrecurring cost estimates for the various candidates from the rocket engine cost model.

2.4.5.4 Future Work. The following future work is planned.

- Down-select to a specific set of candidate configurations.
- Perform component level analyses and trade studies to finalize optimum configuration, including identification of potential technology insertion opportunities (with estimated benefits, costs, and risks identified).
- Finalize and deliver all draft program plans.
- Complete validation plan and establish the potential development program schedules.

3. SPACE LAUNCH SYSTEM EVOLUTION PATH

The SLS program approach to achieving an evolvable architecture has been to focus on the SLS Block 1 configuration (referred to as the inner loop) and to assess the SLS evolvability path by establishing an outer loop analytical capability. The outer loop analysis runs parallel with the inner loop, thus is assessed at each major milestone review by the SLS chief engineer.

3.1 Objectives

The objective of the Evolvability (referred to as the Outer Loop) team is to define, evaluate, and maintain cost, schedule, and technical characteristics of evolution paths from the SLS Block 1 system. The primary performance driver beyond Block 1 is to increase (or evolve) payload delivery from 70 t in low Earth orbit to 105 and 130 t, thus fully enabling a national exploration capability. To meet the objective of evaluating how well these evolutionary paths correlated with the NASA mission and with mission capture intent, additional research and analyses was performed for various mission destinations. These mission destinations include those defined in NASA's Exploration Systems Development Division Concept of Operation, the recent Waypoint Study led by JSC to place a space station at Earth-Moon Lagrange point 2, and various other human and science exploration class missions.

Assessments performed by the team are full lifecycle in scope, considering both technical and programmatic impacts of future vehicle upgrade decisions. These assessments also include impacts to the current Block 1 vehicle baseline to accomplish a particular path. Starting with the current Block 1 vehicle, a benchmark was performed to calibrate the analytical analysis approach and resulting performance predictions. From the benchmark, potential vehicle evolvability paths were defined and evaluated for performance and cost, along with impact to the baseline Block 1 vehicle design. The results of this comparison provides a basis for potential recommended changes to the Block 1 SLS in order to effectively accommodate a preferred evolution. This systematic approach, focused on launch vehicle capability and mission capture, allows the trade space to iteratively converge on an optimized solution that considers a full complement of both technical and programmatic factors.

A schematic of the landscape within which the Outer Loop team operates is shown in figure 68. It should be noted that the team has three significant integrating functions internal and external to SLS that are carried out during each iteration of the outer loop: SLS Block 1 (internal), mission design (external), and technology readiness selection and prioritization (internal and external). Each iteration of the outer loop collects data across each of the integration nodes and an assessment/analysis is performed. Subsequent iterations are performed at increasing levels of maturity, further increasing the confidence level of the analysis and/or the concept design.

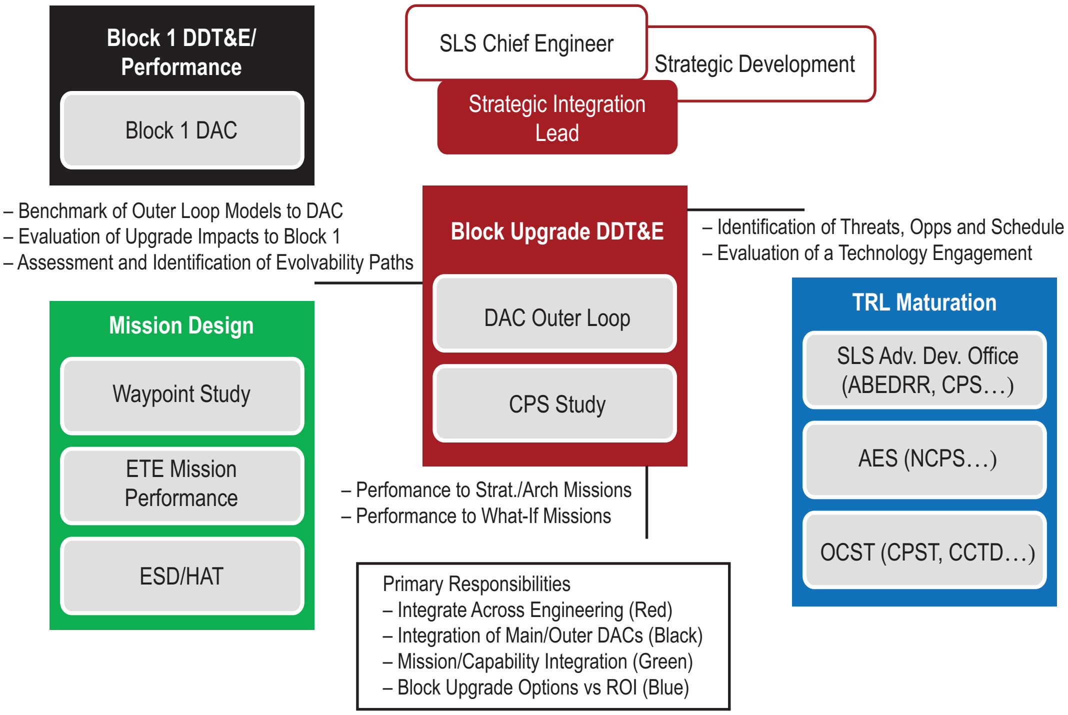


Figure 68. Outer loop design analysis cycle landscape of team operations.

Evolvability path option results will be substantiated via analysis. Additional analyses will further define maturation of the concept configuration(s) along with comments and considerations on sequencing of the architectural pieces.

3.2 Cryogenic Propulsion Stage Concepts

MSFC has been involved in the definition of the CPS for over 2 years through its involvement in the HAT. Since April 2011 the CPS team has involved MSFC Engineering and multiple Centers for subsystem definition. Between HAT mission reassessments and budget constraints, CPS definition is unclear. An evolutionary approach to address an affordable option for CPS (i.e., the Interim Cryogenic Propulsion Stage (ICPS) has been considered, but little system level definition has been performed beyond the ICPS (or Delta Cryogenic Second Stage). Addition of the CPS would improve the SLS Blocks 1, 1A, and 2 capabilities, especially its in-space performance. The CPS has been studying two major options: (1) In-space configuration of the CPS and (2) an EUS that would perform orbital insertion in addition to in-space operations (fig. 69).

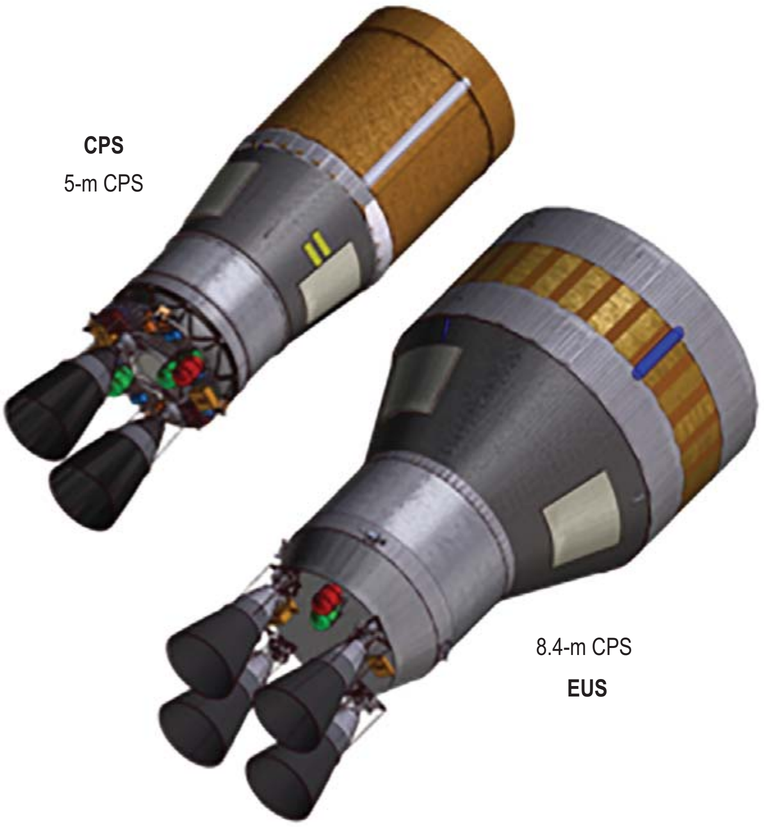


Figure 69. Cryogenic propulsion stage main concepts.

3.3 Evolution Roadmap

The SLS vehicle evolution path has many possibilities to achieve the final 130-t capability. The prime approaches being considered by the Evolvability team are the phasing of new developments (fig. 70) to remain within the flat budget profile of the SLS program. The upper path in figure 70 assumes that advanced booster development occurs first, while the lower path assumes the upper stage/CPS is developed first.

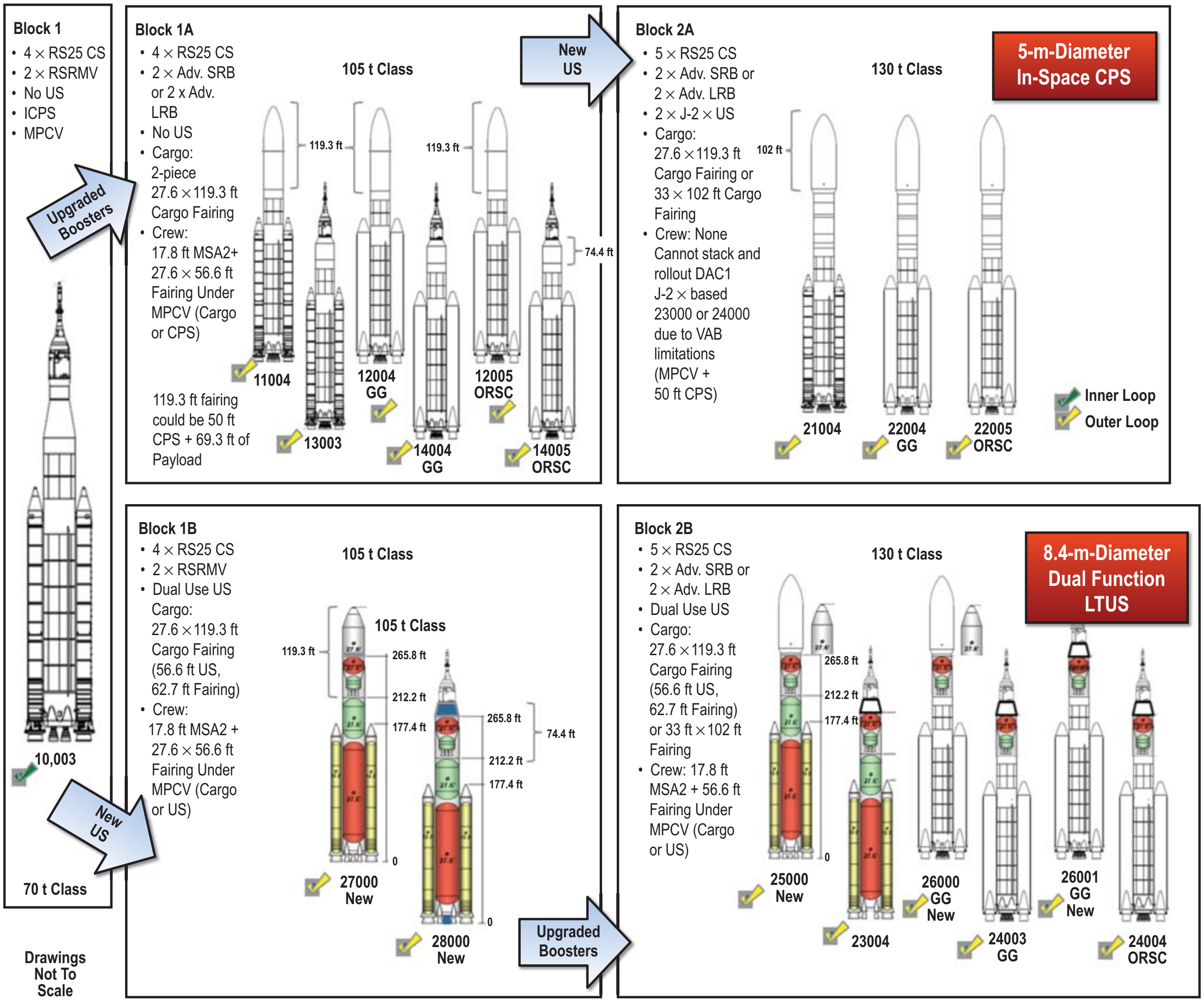


Figure 70. Cryogenic propulsion stage main concepts.

4. FUTURE PLANS

The ADO plans for FY 2014 are to continue the existing academia activities, to complete the industry tasks, and to continue the ABEDRR tasks. In addition, the initial in-house tasks will be reviewed, some will be continued, and new ones will be selected using a similar process as before.

5. SUMMARY

The ADO portfolio of tasks covers a broad range of technical developmental activities supporting the evolution of the SLS vehicle. The tasks are structured to provide off-ramps on a yearly basis in event of budget constraints or lack of progress. A summary schedule of all the tasks is shown in figure 71. The summary budget was shown in table 2, section 1.6.

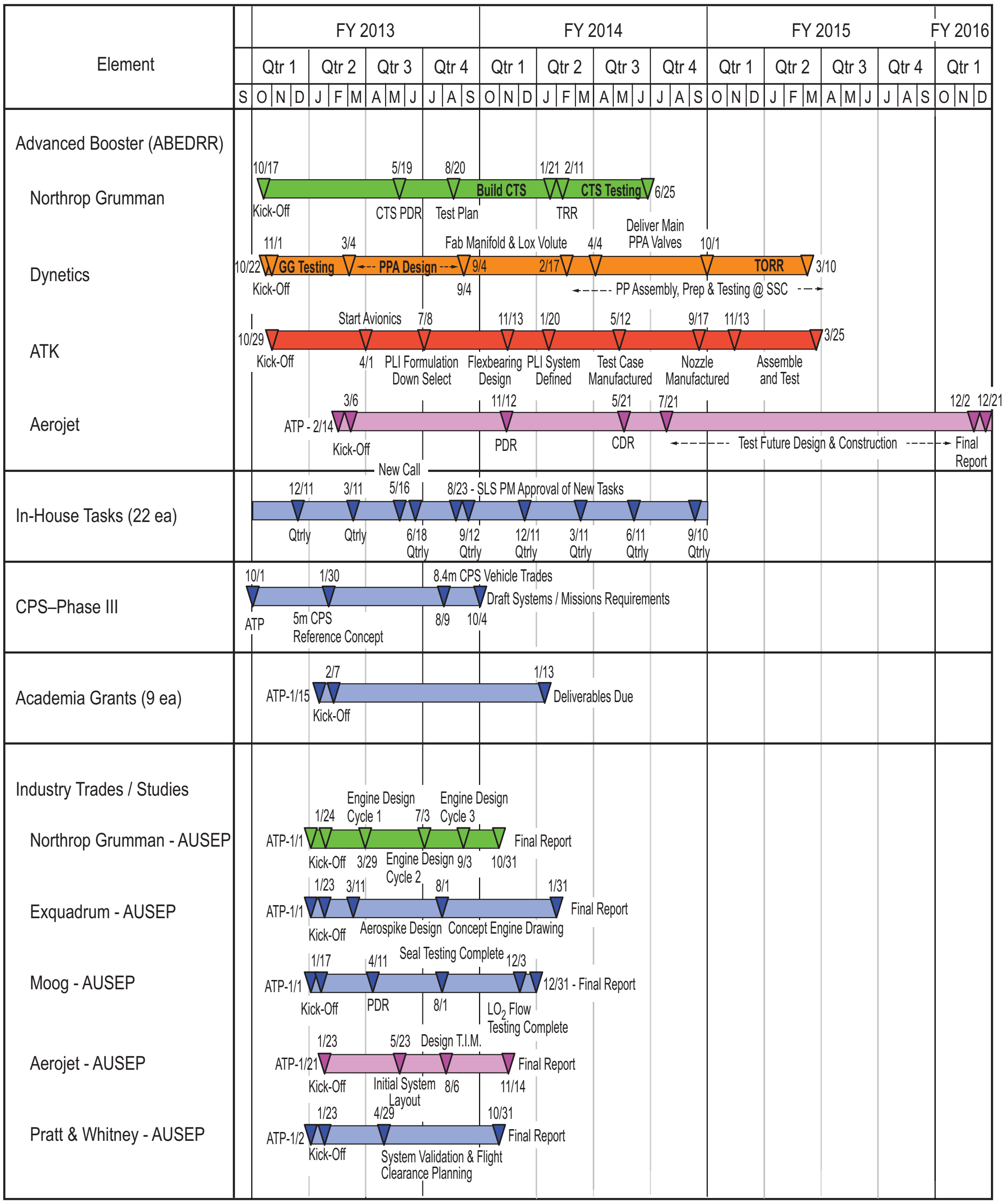


Figure 71. ADO summary schedule.

Through its broad portfolio of in-house activities and partnerships with academia and industry, the SLS ADO is laying the groundwork for the future evolution of the vehicle from its initial capability through its eventual development into the most capable launch vehicle ever flown (fig. 72). It will be able to carry astronauts on missions of exploration into the solar system and enable unprecedented scientific missions and other payloads. Engineering development and risk reduction work on advanced boosters during FY 2013 has already yielded not only a better understanding of potential booster concepts, but also has produced demonstration hardware that resulted in engine test firings. Concept studies on upper stage architecture and engines have opened new possibilities for greater and earlier mission capture as SLS evolves. Both in-house and academia research are producing results that will not only help make SLS a truly state-of-the-art vehicle, but could provide benefits for the American space industry as a whole.

Figure 72. SLS launch vehicle.

APPENDIX A—TECHNOLOGY READINESS LEVEL DEFINITIONS

The definitions for TRLs 1–9 are given in table 3.

Table 3. TRL definitions.

TRL	Definition	Key Focus
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3	Analytical and/or experimental critical functions and/or characteristics proof of concept	At this step in the maturation process, active R&D is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute 'proof-of-concept' validation of the applications/concepts formulated at TRL 2.
4	Component and/or breadboard demonstrated in a laboratory environment	Following successful 'proof-of-concept' work, basic technological elements must be integrated to establish that the 'pieces' will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is relatively 'low fidelity' compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory.
5	Component and/or brassboard demonstrated in a relevant environment	At this level, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-, subsystem-, or system-level) can be tested in a 'simulated' or somewhat realistic environment.
6	System/subsystem engineering model demonstration in a relevant environment	A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model, prototype system, or system—which would go well beyond ad hoc, 'patch-cord,' or discrete component level breadboarding—would be tested in a relevant environment. At this level, if the only 'relevant environment' is the environment of space, then the model/prototype must be demonstrated in space.
7	High-fidelity functionality and scaled form/fit demonstrated in its operational environment	Prototype near or at planned operational system. TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. The prototype should be near or at the scale of the planned operational system and the demonstration must take place in space. Examples include testing the prototype in a testbed aircraft.
8	Final product in mission configuration qualified through test and evaluation	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this level is the end of true 'system development' for most technology elements. This might include integration of new technology into an existing system.
9	Final product in mission configuration proven in actual flight	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last 'bug fixing' aspect of true system development. This TRL does not include planned product improvement of ongoing or reusable systems.

APPENDIX B—POINTS OF CONTACT

Table 4 lists the points of contact.

Table 4. Points of contact.

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14. ABSTRACT

The Advanced Development Office (ADO), part of the Space Launch System (SLS) program, provides SLS with the advanced development needed to evolve the vehicle from an initial block 1 payload capability of 70 metric tons (t) to an eventual capability block 2 of 130 t, with intermediary evolution options possible. ADO takes existing technologies and matures them to the point that insertion into the mainline program minimizes risk. The ADO portfolio of tasks covers a broad range of technical developmental activities. The ADO portfolio supports the development of advanced boosters, upper stages, and other advanced development activities benefiting the SLS program. A total of 34 separate tasks were funded by ADO in FY 2013.

15. SUBJECT TERMS

advanced development, launch vehicle, NASA, Space Launch System, technology

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