Reusable Booster System (RBS)

Briefing to the Aeronautics and Space Engineering Board of the National Research Council

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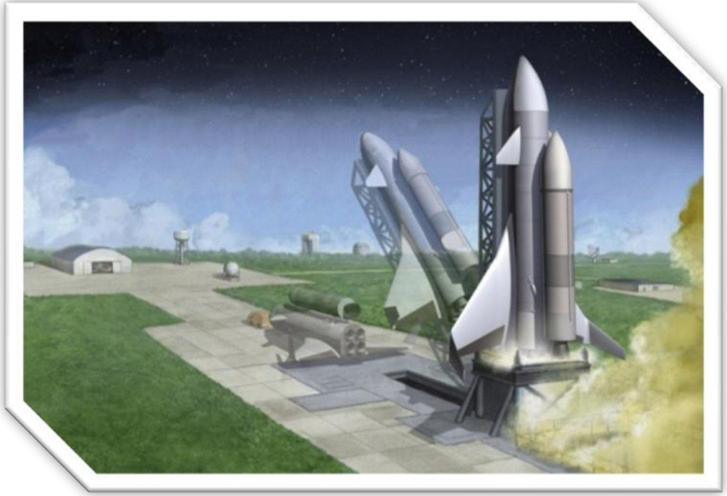
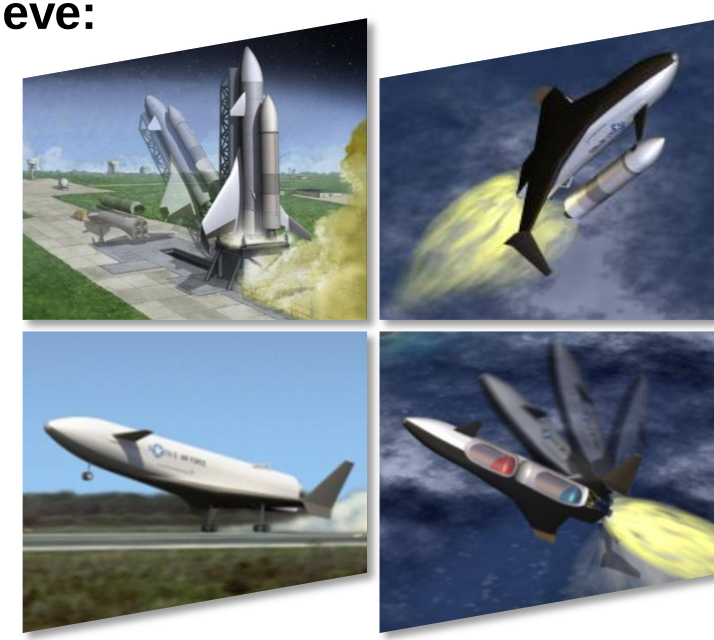
Introduction and Objectives

- **As a major developer and operator of spacecraft and launch vehicles, Lockheed Martin (LM) has appreciable experience with the realities involved in designing, costing, and implementing successful space systems that meet government requirements.**
- **LM has been continuously committed to and involved in the maturation of the Reusable Booster System (RBS) as a promising choice for future Air Force (AF) spacelift and is well aware of the technology, risk, acquisition, and advocacy hurdles that face new launch systems**
- **The purpose of this briefing is to provide the National Research Council's (NRC) Aeronautics and Space Engineering Board program committee with Lockheed Martin's perspectives and data to assist in their RBS assessment. Topics will include:**
  - **LM assumptions and methodologies used in RBS analysis and cost estimating**
  - **Cost analysis and resulting drivers**
  - **Identification of technology challenges and risk mitigation plans**



Reusable Booster System (RBS)

- **LM concurs that the RBS has the potential to be a transformational spacelift capability that embodies affordability, responsiveness, simplicity of operations, and reliability for a wide range of payload classes**
- **RBS has been identified by many industry and government studies as the most promising future spacelift concept to reduce launch costs and increase responsiveness and is considered the likely future replacement for the EELV**
- **LM analysis shows that RBS can achieve:**
  - ☑ **Rapid turn time and call-up**
    - **Turnaround time: ~50 hours**
    - **Call up time: ~28 hours**
  - ☑ **Minimal ground and flight crew**
    - **Crew size: ~48**
  - ☑ **High reliability**
    - **Equivalent to EELV (~98%)**
  - ☑ **Cost reduction: ~50%**
  - ☑ **Clean pad and minimal range**
  - ☑ **Modular / growth lift capability**



EELV – Evolved Expendable Launch Vehicle

Reusable Booster System

FUTURE OF AIR FORCE LAUNCH SYSTEMS

Responsive Space Vision

Air Force Objective

Provide continuous global operation

- Rapid adaptation to war fighter needs
- Asymmetric opposition forces present new challenges
- Shorten the delay between sensor and user
- Protect, augment, and replenish space assets on demand
- Recognize increased dependence on space services and systems
- Speed and affordability

Air Force Spacelift Attributes

- Low cost, responsive "aircraft-like" ops
  - High reliability
  - Rapid turn time and call-up
  - Minimal ground and flight crew
  - Clean pad and minimal range
  - Modular / growth lift capability
- High military utility
  - Tactical space assets
  - Conventional satellites
  - Reentry systems
  - Tactical theater-based ISR

Stated Spacelift Technologies

- Agile, responsive ranges
- Vehicle / system health management
- Autonomic logistics
- Reusable, operable engines / motors
- Etc…

Spacelift is a Key Element in Achievement of Air Force Objectives

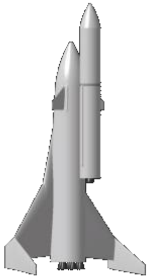
Military Spacelift Needs

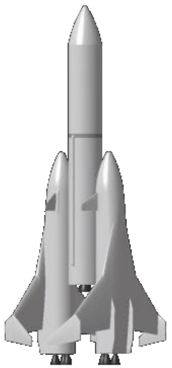
- Launch Operations for Satellite and Counter Space
  - In depth vehicle and launch operations design and analysis show RBS provides highly operable, routine spacelift capability for multiple types of payloads
- Robust and Responsive Spacelift
  - Thorough system design & discrete event simulation modeling shows RBS based launch systems can meet required responsive vehicle turnaround & call up times
- Regeneration and Augmentation of Satellite Constellations
  - Comprehensive vehicle and operations analysis shows RBS can provide rapid, routine asset launch to support surge requirements
- Terrestrial Point-to-Point Transport Through Space
  - System and operational analysis shows an RBS can support multiple upper stage types for future responsive system needs as they arise
- Sortie Military Missions
  - Detailed system effectiveness / military utility analysis in blue force vs. red force scenarios shows RBS is highly effective in an anti-access environment

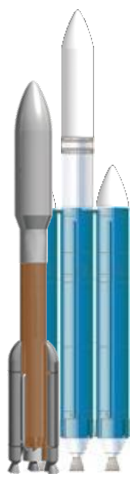
LM Analysis Shows RBS Meets Military Needs

Key Spacelift Factors

- Key evaluation factors between RBS and expendable launch vehicles:
  - Reusability & Flight Rate vs. Cost
    - Reusable systems mitigate the per-flight acquisition costs of a replaced expendable system
      - Fully reusable system – high flight rates
      - Fully expendable system – low flight rates
    - RBS is a cost optimization between fully reusable and expendable for moderate flight rates
  - System Sizing & Addressable Missions vs. Recurring & Non-Recurring Cost
    - RBS addresses a broader payload range than any single expendable launcher in order to:
      - Maximize reusable cost savings from increased flight rate
      - Minimize the number of distinct reusable elements
      - Ensure RBS investment remains relevant to uncertain future payload manifests
    - Drive system design towards highest frequency missions to maximize cost benefit
  - Other Factors
    - Reliability: RBS can achieve EELV reliability levels
    - Risk: RBS requires technology development investment
    - Industrial Base: Reusable vs. Expendables differ in implementation/impacts





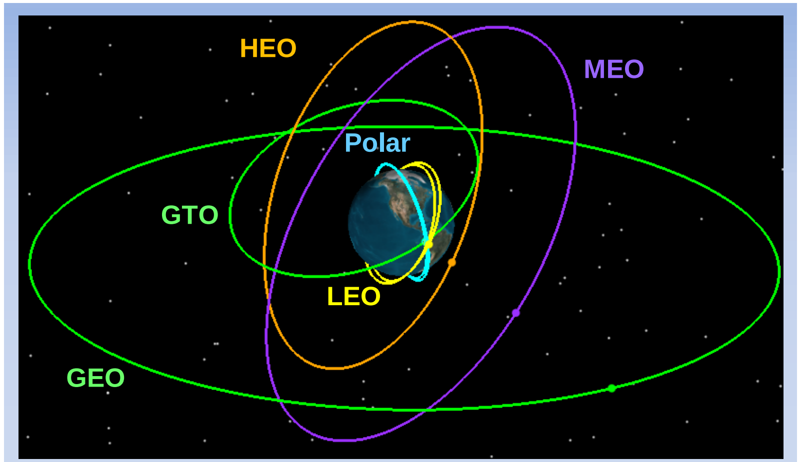


Reusable Booster System

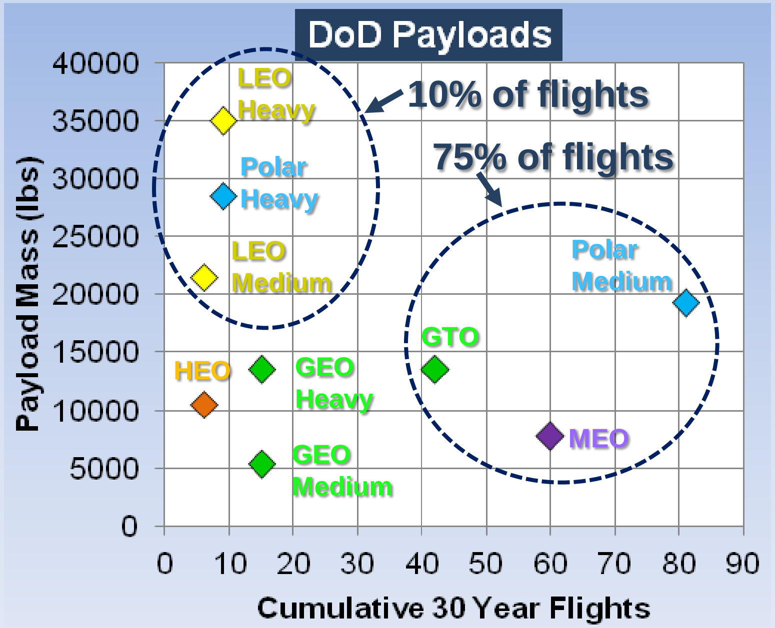
SYSTEM OVERVIEW

Mission Requirements

- **Multiple studies have shown that RBS system design and cost are highly dependent on the payloads and mission models**
- **RBS must support current EELV class mission requirements**



ORBIT	MAXIMUM PAYLOAD	INCLINATION @ SEPARATION	AVG ANNUAL LAUNCH RATE
LEO Med-Int	21,500 lbs	63.0 deg	0.2 / year
LEO Heavy	35,000 lbs	68.0 deg	0.3 / year
MEO Med-Int	7,805 lbs	55.0 deg	2.0 / year
Polar Med-Int	19,300 lbs	98.6 deg	2.7 / year
Polar Heavy	28,500 lbs	97.5-98.5 deg	0.3 / year
HEO Med-Int	10,500 lbs	63.4 deg	0.2 / year
GTO Med-Int	13,500 lbs	27.5 deg	1.4 / year
GEO Med-Int	5,300 lbs	0.0 deg	0.5 / year
GEO Heavy	13,500 lbs	0.0 deg	0.5 / year



Commercial Reusable Booster Study mission requirements

LEO – Low Earth Orbit
MEO – Medium Earth Orbit
HEO – Highly Elliptical Orbit

GTO – Geostationary Transfer Orbit
GEO – Geostationary Earth Orbit

Key System Attributes

- LM analysis indicates that RBS arch. solutions that support reduced cost spacelift and responsive operations have the following features:
  - <u>Vertical Takeoff</u>
    - Realistic options are rocket based; large masses preclude horizontal launch
  - <u>Horizontal Landing</u>
    - Low risk and most operable reusable recovery option that requires minimal ground processing
  - <u>Vehicle Stack and Return To Launch Site (RTLS) Configuration</u>
    - Serial burn, side-by-side stage attachment
    - Booster rocketback recovery
  - <u>Autonomous Flight with Adaptive Guidance Navigation & Control (GN&C)</u>
    - Unmanned system capable of robust autonomous guided ascent and return flight
  - <u>Integrated System Health Management (ISHM)</u>
    - Critical technology for reducing between flight inspection, maintenance, and checkout
  - <u>Rapid Mission Planning</u>
    - Minimizes vehicle turn timelines with preplanned mission sets
  - <u>Horizontal Vehicle Processing</u>
    - Minimizes timelines and scale of required logistics/facilities
  - <u>Offline Payload & U/S Processing</u>
    - Minimizes vehicle turn around timelines by segregating payload and upper stage integration
  - <u>Operable Subsystems</u>
    - Subsystem elements that are designed for maintainability or rapid replacement

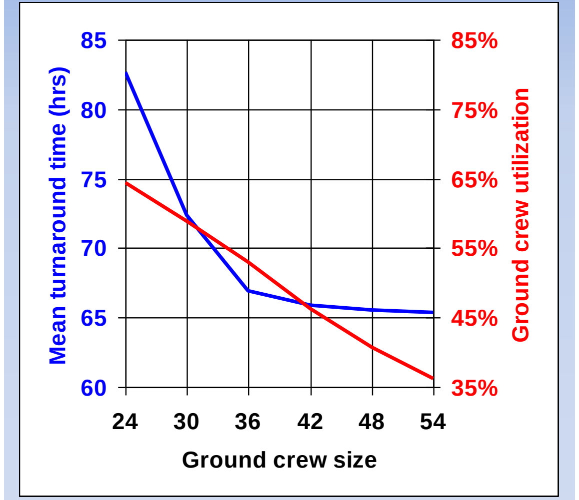
U/S – Upper Stage

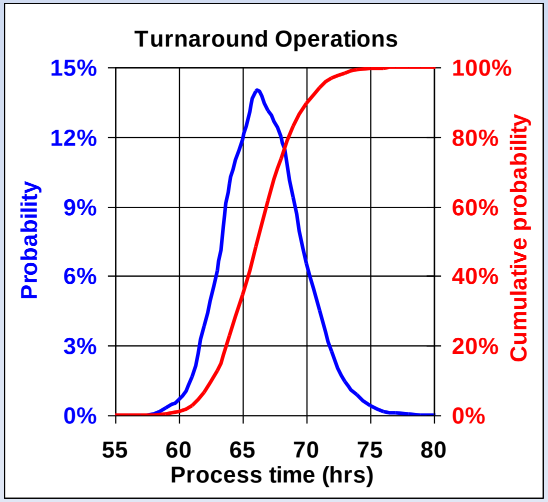
Ground Processing & Ops Analysis

- Key timesaving and manpower reduction concepts:
  - All vehicle processing, integrations, and tests performed in the hangar
  - One time only hardware and software validation and interface checks
  - All countdown preps including pyros and non-hazard fueling completed before roll to pad
  - All automated mechanical and electrical interface checks at pad mate
  - Short countdown with topping off pressurants and propellant
  - All automated tests during processing, countdown preparations, and terminal count
  - One support equipment set per vehicle to support both horizontal and vertical operations

Task Name	No ISHM	ISHM	ISHM Improvement
Ground Crew Size	36	36	---
Mean Turnaround Operations Time	102 hrs.	67 hrs.	34.3%
Mean Turnaround Operations Labor	694 hrs.	426 hrs.	38.6%
Mean Call-up Operations Time	34 hrs.	33 hrs.	2.9%
Mean Call-Up Operations Labor	165 hrs.	159 hrs.	3.7%

Operations Analysis Data With ISHM





Reusable Booster System

COST ANALYSIS

Cost Inputs and Assumptions

- Mission model
  - Utilizing EELV class mission model
    - Flight rate: 8/year
      - 243 launches over 30 year program operating life
      - Medium class missions: 7/year
      - Heavy class mission: 1/year
- Reusable booster life: 100 flights
- Launch sites: 2 (Cape Canaveral and Vandenberg)
- Fleet size: 8 total boosters; 4/launch site
- Launch and maintenance operations
  - Mix of blue suit and contractor operations
- Other key cost inputs/factors:
  - System architecture element design, development, evaluation, and testing (DDT&E)
  - Reusable booster responsiveness
  - Cost improvement and rate efficiency curves
  - Site activation
  - Upper stage development and processing
  - Base operations and support
  - Range and propellant
  - On-going annual contractor support for booster and expendable hardware

Cost Analysis & Resulting Drivers

LM Cost Models

- Comprehensive cost data from 50+ years of design, manufacture, and operations of spacelift launch systems
  - e.g. Atlas, Titan, Athena
- Applicable cost data from 50+ years of design, manufacture, and operations of manned and unmanned aircraft systems
  - e.g. F-16, F-22, F-35, C-130, UAVs
- System deployment trends and efficiency curves
- Detailed RBS developed CONOPS flows validated with subject matter experts
- In-depth CONOPS discrete event simulation analysis

LCC Analysis and Sensitivities

Life Cycle Cost Results

Booster & Upper Stage Development Cost(s)

Booster & Upper Stage Production Costs

Operations & Support Costs

Average Cost Per Flight

Marginal Cost Per Flight

Development Cost Drivers
- Commonality – # of Architecture Peculiar Vehicles/Elements
- Vehicle Mass – Development Cost
- # Launch Sites – Facilities & Infrastructure

Production Cost Drivers
- Vehicle Mass – Unit Production Cost
- Flight Rate / Responsiveness - Booster Qty
- Mission Model – Expendable Element Qty
- Commonality – Learning Curve / Rate Efficiency Benefits

Operations & Support Cost Drivers
- # Sites – Ops Personnel & Infrastructure O&S
- Responsiveness – Turnaround Operations
- Mission Qty/Rate – Ops Personnel & Infrastructure O&S
- Commonality – Flight Rate Benefits, Ongoing Contractor Support
- Booster Size – Turnaround Operations

Average Cost per Flight Cost Drivers
- # Sites – Ops Personnel & Infrastructure O&S "Fixed Cost"
- Mission Qty/Rate – Expendable Hardware Unit Cost, Flight Rate Efficiency Benefits, Ops Personnel & Infrastructure O&S
- Expendable Element Size – Upper Stage, PLF, CM Unit Cost
- Commonality – Flight Rate Eff. Benefits, Ongoing Contractor Support
- Booster Size – Turnaround Operations

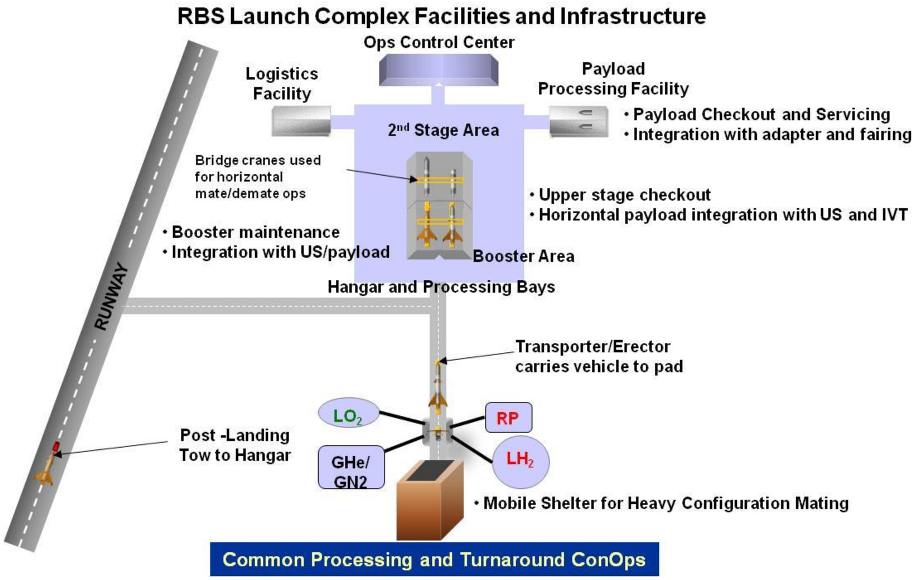
Marginal Cost per Flight Cost Drivers
- Mission Qty/Rate – Expendable H/W Unit Cost, Flight Rate Eff. Benefits
- Expendable Element Size – Upper Stage, PLF, CM Unit Cost
- Commonality – Production/Flight Rate Efficiency Benefits
- Booster Size – Turnaround Operations

Life Cycle Cost Analysis Shows RBS Can Meet Cost Reduction Target

UAV – Unmanned Aerial Vehicle
CONOPS – Concept of Operations
LCC – Life Cycle Cost
O&S – Operations & Support
PLF – Payload Faring
CM – Control Module

Infrastructure Investments

- **Launch sites**
  - **Utilize existing runways at both sites**
    - **Place processing/launch facility close to runways**
  - **New infrastructure elements include:**
    - **Reusable booster hanger facility**
    - **Off-line/adjacent upper stage processing facility**
    - **Transporter/erector system**
    - **Launch pad with automated commodity and power connections**
    - **Mechanical and electrical ground support equipment**



- **Production**
  - **New production facilities are not required**
  - **Potential for use/modification of existing test facilities**

RBS Utilizes/Improves Upon Current Launch infrastructure

Reusable Booster System

ENABLING RBS SUCCESS

RBS Development Strategy

- **LM believes that RBS technical and cost goals are achievable**
  - **LM is confident that system development is realizable without significant difficulty**
  - **Required technologies and materials within the existing state of the art**
  - **Primary unknowns are the uncertainties associated with the aerodynamics, control, and propellant dynamics during the rocketback maneuver**
- **LM agrees with and supports the Air Force development plan that achieves RBS capability through subscale demonstration and development**
  - **LM believes that two sets of subscale RBS flight demonstrators can sufficiently reduce RBS development risk for the operational system**
    - **Largest remaining RBS uncertainties are not testable via ground testing**

LM Recommends Focused Flight Demonstrations to Anchor System Development

RBS Flight Demonstration Vehicles

- **RBS Pathfinder**
  - **Provides near-term risk reduction for the most critical technology**
    - **Demonstrates successful execution of the rocketback maneuver while achieving flight conditions traceable to the vision operational RBS system**
    - **Gathers critical test data on aerodynamic interactions and propellant management**
- **RBD (Reusable Booster Demo)**
  - **Provides demonstration of the key RBS performance and operations attributes**
    - **Demonstrates successful execution of the RBS booster flight profile**
    - **Demonstrates vehicle design, material solutions, and employed technologies**
    - **Demonstrates directly analogous flight turn around operations**

Planned RBS Flight Demonstrators Mitigate Key RBS Risks

Technical Risk Mitigation Plans

#	KEY TECHNICAL RISK AREAS & MITIGATION	FAST	PF	RBD	RBS
1	Rocketback Return To Base Method Flight Dynamics				
2	Reusable & Throttleable LOx/Hydrocarbon Main Engine	Hydrocarbon Boost			
3	Advanced Low Maintenance Structures				
4	Integrated Systems Health Management / Autonomic Logistics				
5	Adaptive GN&C Flight Software				
6	Propellant Management & Slosh Dynamics				
7	Rapid Mission Planning				
8	Agile, Responsive Ranges				
9	Green/Operable RCS Propellants				
10	Operable Thermal Protection Systems				
11	Non-pyro Separation Systems				
12	Payload and Stage Separation Dynamics				
14	Operable Power Systems (Batteries & APU)				
15	Advanced Ground Processing Automation				

RBS Pathfinder Provides Critical Near-Term Technology Demonstration

FAST – Future responsive Access to Space Technologies
PF – [RBS] Pathfinder
RBD – Reusable Booster Demo

LOx – Liquid Oxygen
GN&C – Guidance, Navigation, & Control
APU – Auxiliary Power Unit

Reusable Booster System

WRAP UP AND CONCLUSIONS

Wrap Up and Conclusions

- RBS enables responsive, lower cost spacelift for Air Force key mission needs:
  - Launch operations for satellite and counter space
  - Robust and responsive spacelift
  - Regeneration and augmentation of satellite constellations
- A RBS small-scale flight demonstrator (RBS Pathfinder) project is critical in the near-term to demonstrating the rocketback return to base method
  - Key enabler of responsive next generation launch
- A RBS large-scale demonstrator program (RBD) is critical to validate RBS system attributes (i.e. design implementation, turnaround time, call up time, maintenance hours per sortie, alert hold, etc.)

"Generate the results and prove it can be done"

RBS Meets Operations And Cost Needs;
Continued Development And Demonstration Is Key