Review and Assessment of Reusable Booster System for USAF Space Command

Aeronautics and Space Engineering Board

Committee Chair: David Van Wie

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Review and Assessment of RBS

- Tasking and Committee Membership
- Reusable Booster System Concept
- Technology Challenges
- Cost Estimation Methodology
- Findings and Recommendations
- Summary

Background

- Current Air Force medium and heavy launch capability provided by Evolved Expendable Launch Vehicles (EELV)
  - Atlas V and Delta IV launch vehicles
  - Manufactured and operated by United Launch Alliance (ULA)
- Rising launch costs have led to interest in potential alternatives
- Air Force Space Command (AFSPC) identified long-term Science & Technology challenge to provide full-spectrum launch capability at dramatically lower costs
- The Space and Missile Systems Center (SMC), in conjunction with the Air Force Research Laboratory (AFRL), has developed the concept of a Reusable Booster System (RBS)
  - Intended to significantly decrease launch costs by reducing the amount of expendable hardware that must be produced, tested, and processed

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Statement of Task

- Review and assess the U.S. Air Force Reusable Booster System (RBS) concept.
- Among the items the committee will consider are:
  - Criteria and assumptions used in the formulation of current RBS plans
  - Methodologies used in the cost estimates
  - Modeling methodology used to frame the business case for an RBS capability
  - Technical maturity of key elements critical to RBS implementation
  - Ability of current technology development plans to meet technical milestones

RBS Committee Membership

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Presentations Received

- **U.S. Air Force**
  - AFSPC/ST
  - AFSPC/A5
  - SMC/XR/LR
  - AFRL/RQ
- **NASA**
  - Kennedy Space Center
  - Marshall Space Flight Center
- **FFRDC**
  - The Aerospace Corporation
- **Commercial Aerospace Companies**
  - Aerojet
  - Andrews Space
  - Astrox Corporation
  - Lockheed-Martin
  - Orbital Sciences Corporation
  - Pratt & Whitney Rocketdyne
  - The Boeing Company

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Reusable Launch System Programs

U.S.

Space Shuttle

NASP

X-33

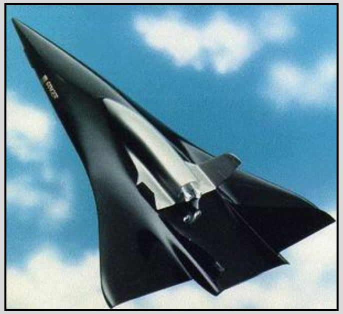
X-34

Kistler K1

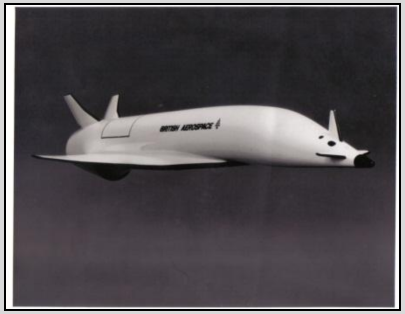
International

Buran

Saenger



HOTOL

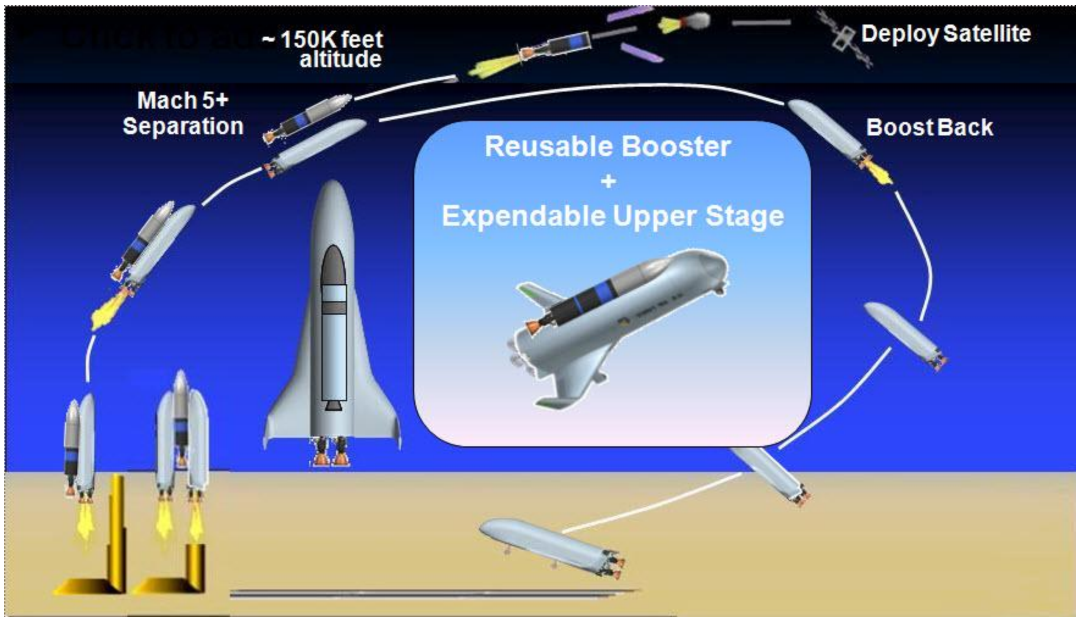


Skylon

Angara

Reusable launch vehicle objectives largely unmet in previous programs. Why could the RBS concept lead to a different result?

Reusable Booster System (RBS) Concept



<u>Key System Features</u>

- Reusable 1st stage
  - Lower thermal protection system requirements
- Expendable upper stage
- Hydrocarbon-fueled booster engine
- "Rocketback" return-to-launch-site (RTLS) maneuver

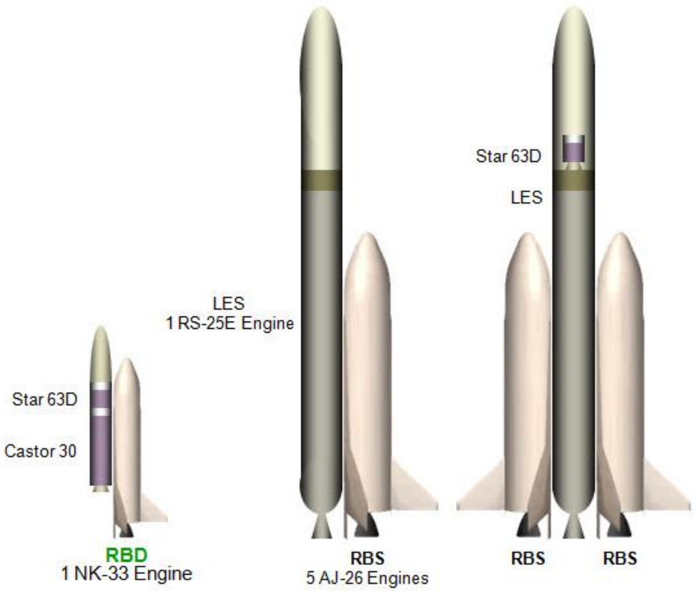
Basic premise: Hybrid reusable launch system will reduce amount of expendable hardware, which will lead to reduced launch costs

Key Aspects of Baseline RBS Architecture

Launch Requirement Model

Satellite Type	Orbit Requirement	EELV Used	Average Annual Rate
Communications	GTO	Atlas V 531	0.64
Meteorological	GTO	Atlas V 501	0.25
	SSO	Delta IV M	0.32
Navigation	MEO	Atlas V 401	1.96
Missile Warning	GTO	Atlas V 411	0.31
	SSO	Delta IV M	2.12
Intelligence	LEO (High Inclination)	Delta IV M+(4,2)	0.20
	LEO (High Inclination)	Delta IV H	0.29
	LEO (High Inclination)	Atlas V 541	0.20
	HEO	Atlas V 551	0.29
	Polar	Delta IV H	0.29
	Polar	Atlas V 401	0.16
	GTO	Delta IV M+(5,4)	0.50
	GEO	Delta IV H	0.50
Average Annual Launch Rate			**8.00**

RBS Launch Configurations



Key system development requirements:

RBD – Reusable Booster Demonstrator – Provides residual small launch capability
RBS – Based on use of AJ-26 (“Americanized” version of NK-33 engine)
LES – Large Expendable Stage – Assumes one RS-25E LO2/LH2 rocket engine
SES – Small Expendable Stage – modeled as Star 63D/Castor 30
Heavy payload launch – requires two RBS booster stages

Comparing RBS to Atlas V

Atlas V

RBS

	RBS (Approx)	Atlas V-551
Booster	5 AJ-26	1 RD-180
Inert Mass (klb)	105	41.7
Propellant Mass (klb)	900	626.3
Thrust (klbf)	1,655	860
Solid Rocket Strap-On	n/a	5
Mass (klb)	n/a	514.7
Thrust (klbf)	n/a	1,898
Second Stage	1 RS-25E	1 RL-10
Inert Mass (klb)	38	4.9
Propellant Mass (klb)	340	45.9
Thrust (klbf)	500	22.3
Gross Lift-Off-Weight (klb)	1,340	1,298
Sea Level Thrust (klbf)	1,655	2,548

RBS and Atlas V-551 Gross Lift-Off Weight (GLOW) similar (1,340 vs 1298 lbm)
RBS expendable mass lower (38 vs 46.6 klbm plus solid rockets)
RBS 2nd stage significantly larger (378 vs 50.8 klbm)

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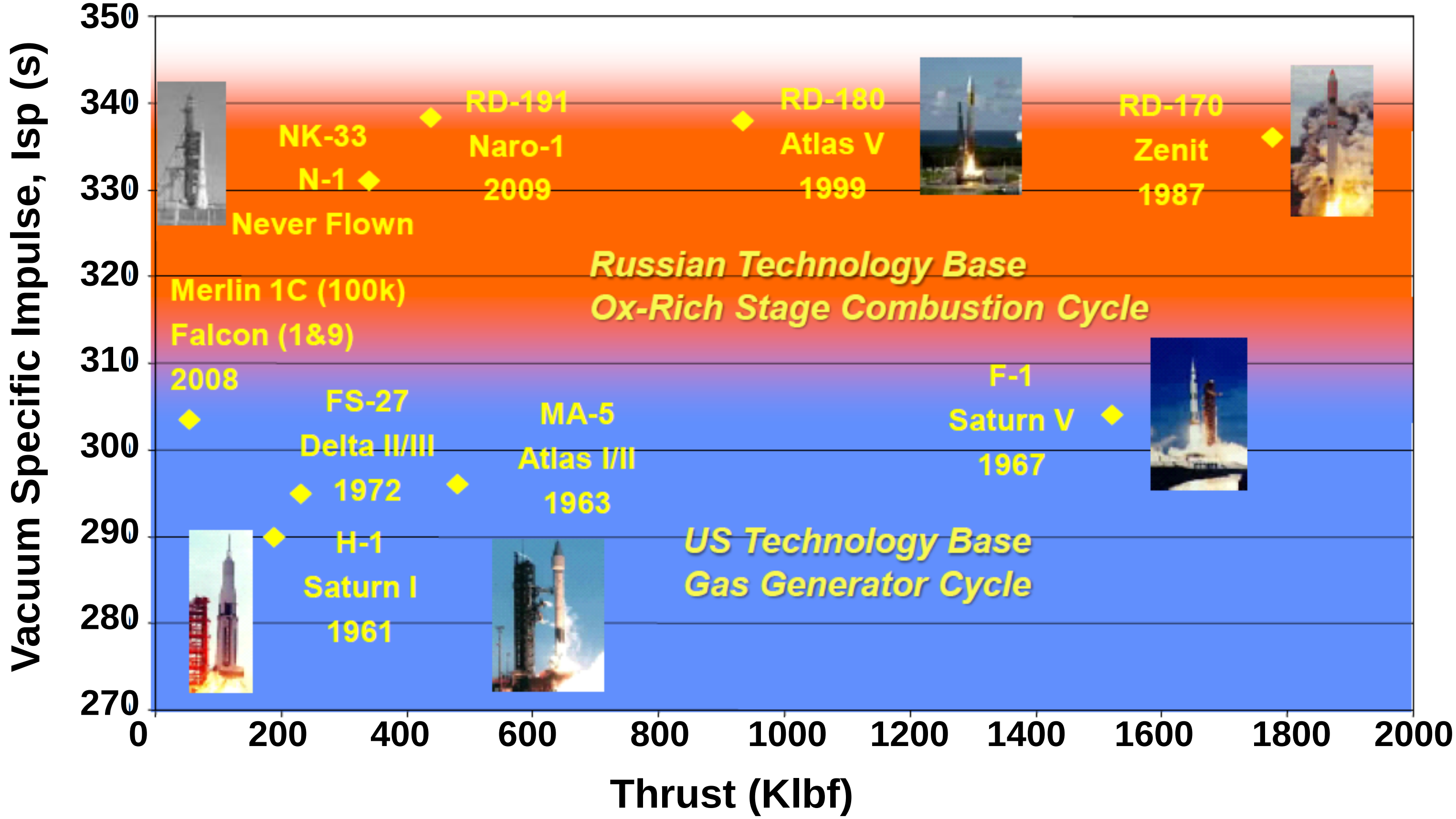
Liquid Oxygen/Hydrocarbon Fuel Boosters



- Russia is principal producer of high performance LO2/LHC rocket booster engines
- New development and testing required to produce U.S. engine

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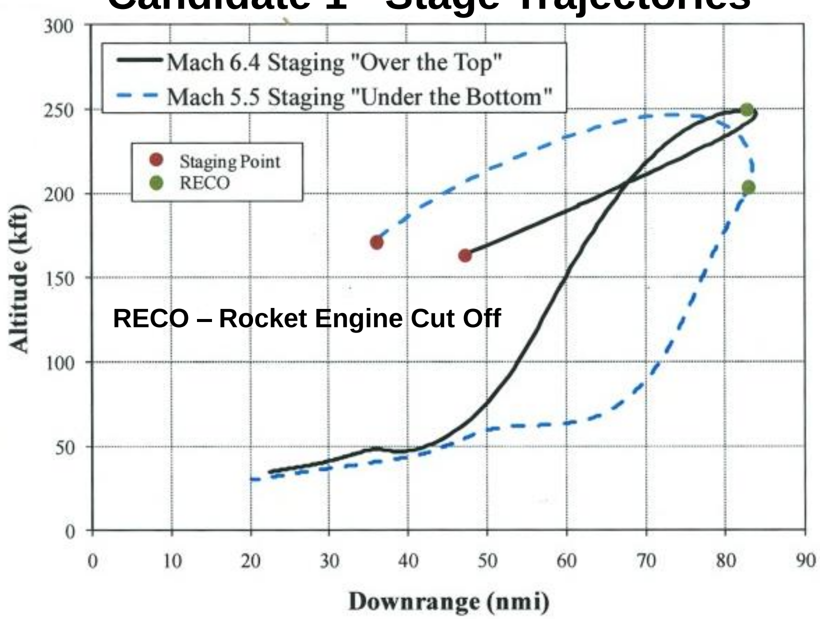
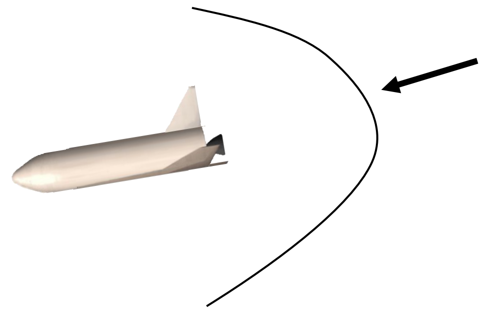
Rocketback Return-to-Launch-Site (RTLS) Operation

Candidate 1st Stage Trajectories



Ref: Hellman, B.M., et. al, AIAA-2010-8668, 2010.

Plume-Aero Interactions During Rocketback Maneuver



AFRL "Pathfinder" program aims to reduce risk using subscale flight vehicle

Rocketback RTLS maneuver technology development needs include:
- Impact of plume interactions on vehicle aerodynamics
- Propellant management within tanks during maneuver
- Effective transition to equilibrium glide trajectory

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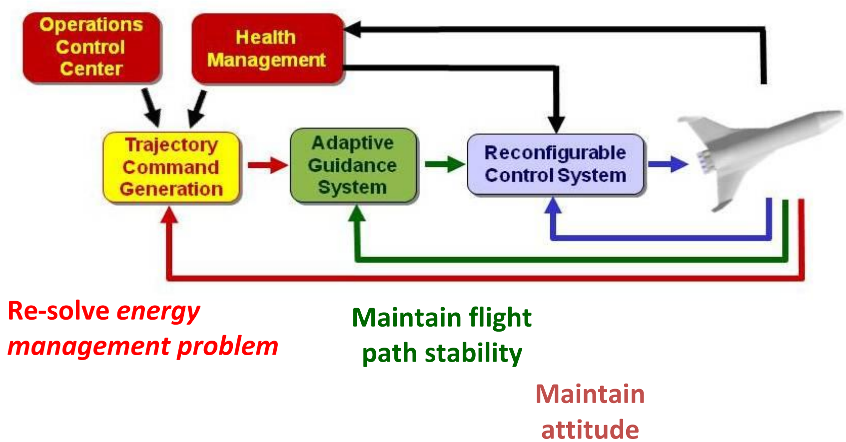
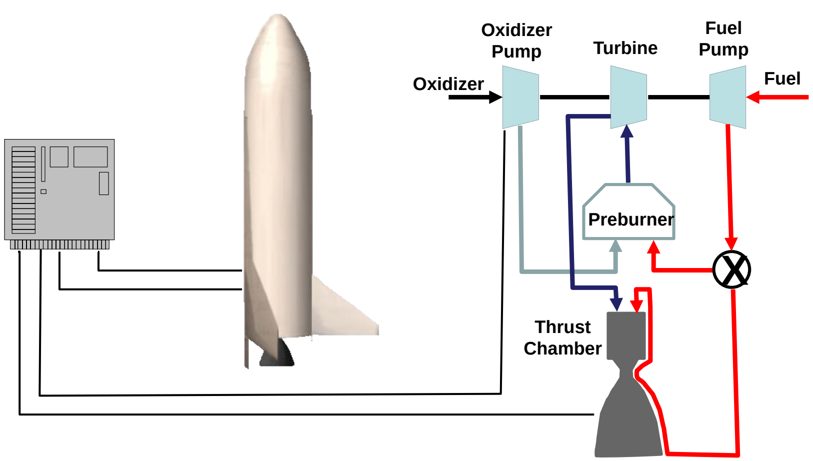
Additional Technology Challenges

Adaptive Guidance and Control



- Used to increase reliability through adapting control to account for anomalies
- Improvements needed in real-time trajectory generation and onboard processing capabilities

Vehicle Health Management System



- Diagnostic information collected in real-time
- Vehicle control adapts to current health status
- Information used to guide post-flight vehicle inspections and maintenance

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RBS Cost Methodology

Cost Category	Cost Model/Method
DDT&E	
RBD (Except NK-33 Engine)	NAFCOM
RBS	NAFCOM
AJ-26 Engine Development	Contractor Est + OGC
LES	NAFCOM
RS-25E Engine Development	N/A - NASA Developed
Castor 30 (Mods for Side Mounting)	NAFCOM*
Star 63D (Mods for Side Mounting)	NAFCOM*
ΔDDT&E (After Flight Test Program)	NAFCOM
Production	
RBS	NAFCOM
AJ-26 Engines	Contractor Est + OGC
LES	NAFCOM
RS-25E Engines	Contractor Est + OGC
Castor 30	NAFCOM
Star 63D	NAFCOM

*Used 1st Unit Production Cost as Mod Estimate
†Aerospace Model

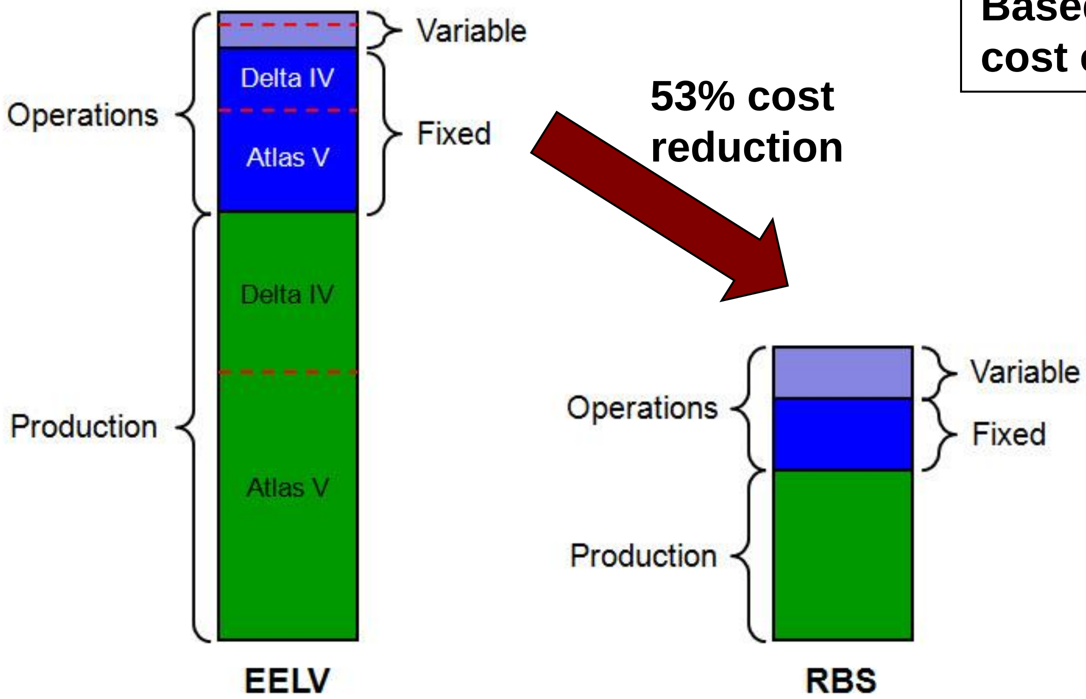
Cost Category	Cost Model/Method
Facilities	
SLC-2W for RBD (VAFB)	VAFB Estimate + OGC
SLC-3E (VAFB)	Facilities Model†
SLC-41 (CCAFS)	Facilities Model†
New Facility (CCAFS)	Facilities Model†
Operations & Sustainment	
RBD Flight Test Program	ODM†
RBS Flight Test Program	ODM†
RBS Launch Operations	ODM†
RBS Mission Integration	Based on EELV Data
RBS Transportaion	Based on EELV Data
Range Costs	Based on EELV Data
Sustainment	Based on EELV Data

CCAFS – Cape Canaveral Air Force Station
DDT&E – Design, Development, Test and Engineering
EELV – Evolved Expendable Launch Vehicle
NAFCOM – NASA-Air Force Cost Model
ODM – Operations Design Model
OGC – Other Government Costs
VAFB – Vandenberg Air Force Base

RBS cost estimates derived using various data sources and models
- Historical data, engine cost estimates, facility models, range estimates, and EELV experience

Recurring Cost Projections of RBS Compared to EELV Costs

Based on AFSMC cost estimates



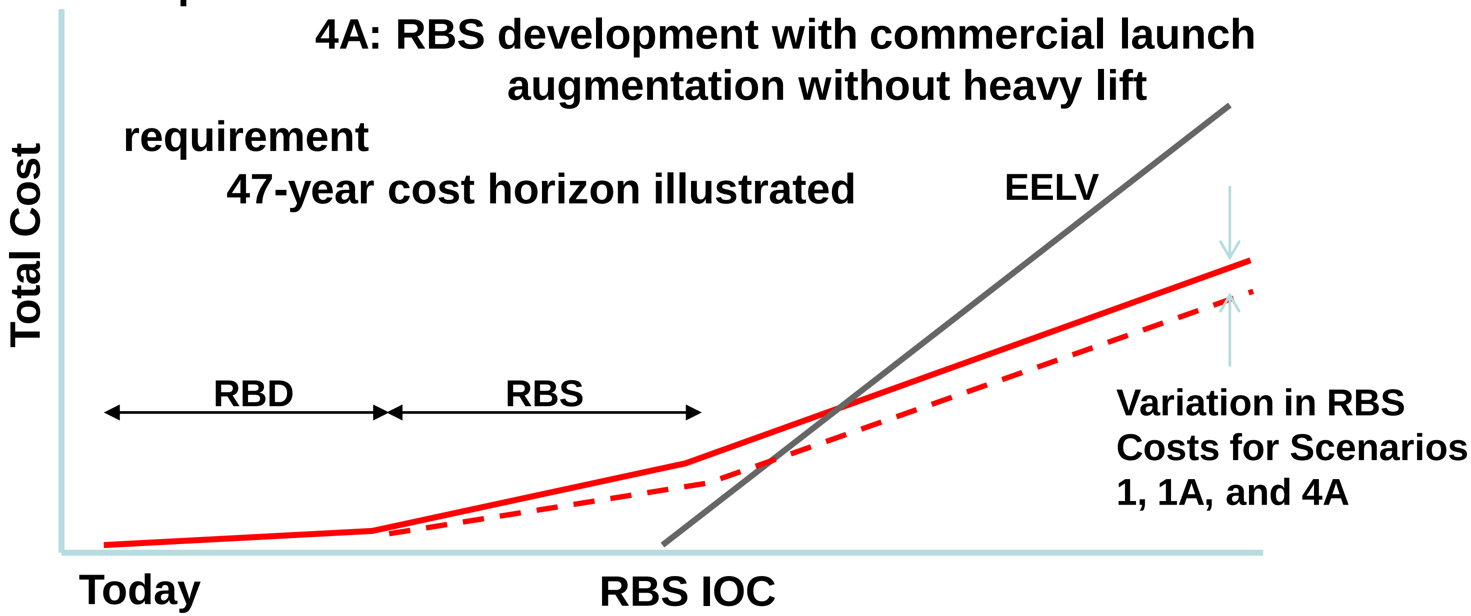
RBS business case shows 53% reduction in recurring launch costs compared to EELV costs

Comparison of Baseline RBS Costs to Extrapolated EELV Costs

Various Potential Scenarios Considered:

- 1: Baseline RBS Program
- 1A: Baseline RBS Program without heavy lift requirement
- 4A: RBS development with commercial launch augmentation without heavy lift requirement

47-year cost horizon illustrated



Using baseline inputs, cost methodology supports reduced RBS life-cycle cost compared to extrapolated EELV cost

Cost Issues Not Addressed in RBS Cost Methodology

- **New entrant commercial launch providers**
- **Single source RBS provider**
- **USAF requirement for assured access-to-space with independent launch systems**
- **Technical risks**
  - **Hydrocarbon-fueled booster engine**
  - **Rocketback Return-to-Launch-Site**
  - **Vehicle health management system**
  - **Adaptive guidance and control**

SpaceX

Orbital Sciences

Stratolauncher

Commercial launch business developing rapidly based on innovative design and entrepreneurial business approaches
- Potentially impacts USAF launch costs
- Impact of mission assurance requirements needs assessment

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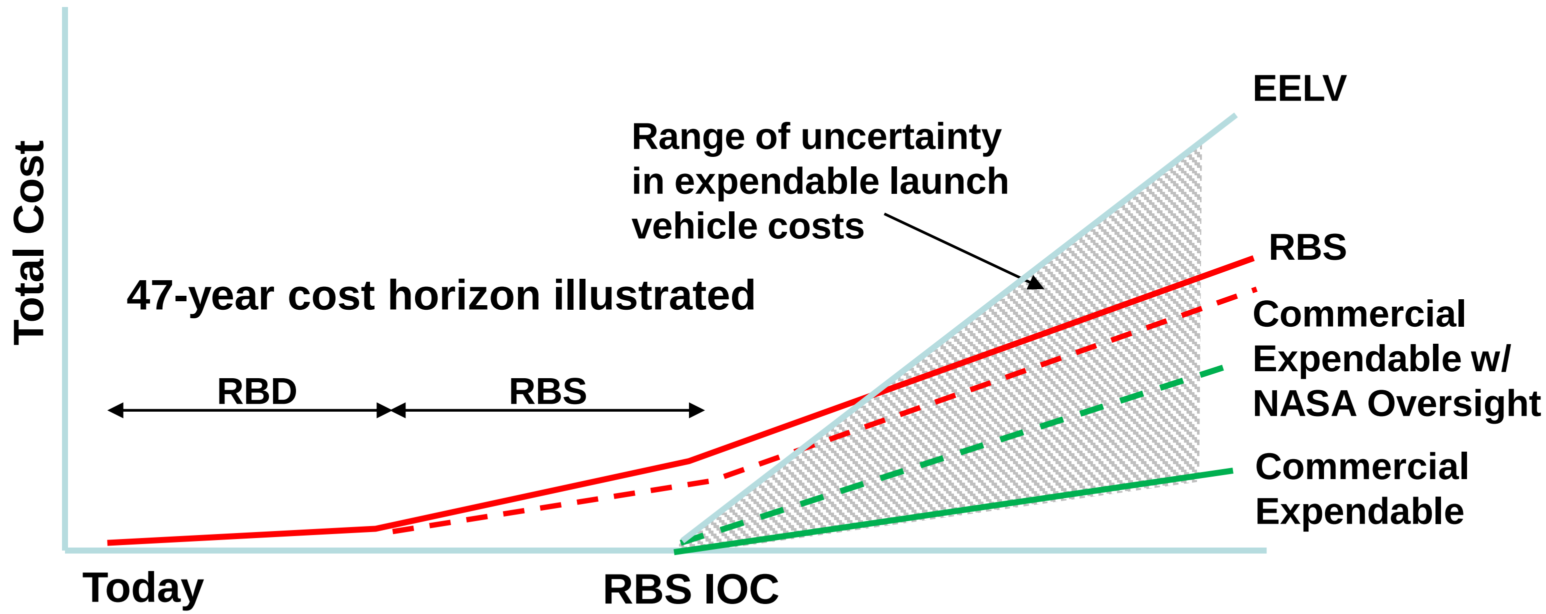
Potential Alternative Scenarios Concerning Future Launch Costs

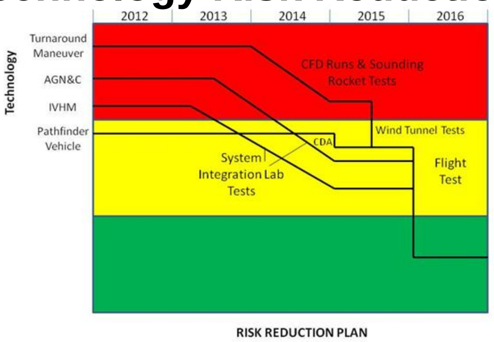


- Significant variation exists in projected costs for expendable vehicles
- RBS costs may be impacted by reduced expendable costs, but may also increase due to assumptions regarding operations costs
- RBS business case unclear due to large cost uncertainties

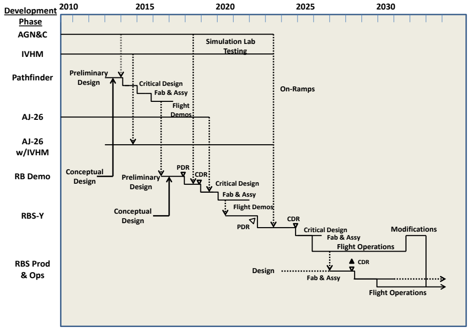
Structured Programmatic Approach Needed for RBS Development

- Integrated technology maturation and RBD development plans not available for committee assessment
- Committee-generated plans outlined for technology risk reduction and RBS development
- Technology risk reduction needed prior to significant RBD/RBS development
- Phased RBS development

Technology Risk Reduction



Phased Development Plan



Risks associated with RBS development call for structured technology risk reduction and phased development with Go/No-Go decision points

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Findings (1/2)

1. Cost estimate uncertainties may significantly affect estimated RBS life-cycle costs
2. RBS business case is incomplete and cannot be closed at present time because it does not adequately account for:
   - New entrant commercial launch providers
   - Impacts of single source suppliers
   - USAF needs for independent launch sources
   - Technical risk
3. Reusability remains a potential option for achieving full spectrum launch capabilities at reduced cost with important launch flexibility to enable significant new capabilities
4. To significantly impact USAF operations, RBS must be more responsive than current systems, but no responsiveness requirement has been identified

Findings (2/2)

5. **Technology areas identified where continued applied research and advanced development is required prior to proceeding into large-scale launch vehicle development**
   - **Oxygen-rich, staged-combustion, hydrocarbon-fueled engines**
   - **Rocketback Return-to-Launch-Site (RTLS) operation**
   - **Vehicle health management systems**
   - **Adaptive guidance and control**
6. **Given uncertainties in business case and yet-to-be mitigated technology risks, it is premature for AFPC to program significant investments in RBS development**

Recommendations (1/2)

1. USAF should establish specific launch responsiveness objectives to drive associated technology development
2. USAF should proceed with technology development in key areas:
   - Reusable oxygen-rich staged combustion hydrocarbon-fueled rocket engines
   - Rocketback return-to-launch site operations
   - Vehicle health management systems
   - Adaptive guidance and control concepts
3. AFRL should develop and fly more than one Pathfinder test vehicle design to increase chances for success

Recommendations (2/2)

4. **Decision to proceed with RBS development should be based on the success of Pathfinder and adequate technical risk mitigations in key areas:**
   - **Reusable oxygen-rich staged combustion hydrocarbon-fueled rocket engines**
   - **Rocketback return-to-launch site operations**
   - **Vehicle health management systems**
   - **Adaptive guidance and control concepts**
5. **Following successful completion of Pathfinder, USAF should re-evaluate RBS business case accounting for:**
   - **New entrant commercial launch providers**
   - **Potential impacts of single-source providers**
   - **USAF needs for independent launchers**
6. **When constructing a future RBS program, go/no-go decision points should be structured as on-ramps to subsequent stages**

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Summary

- Reusable Booster System (RBS) concept reviewed and assessed
- RBS business case cannot be closed at present due to cost uncertainties
- Continued technology development warranted
- Reusability remains an option for delivering full-spectrum launch at dramatically lower costs

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Back-Up Slides

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Findings

1. Cost estimate uncertainties may significantly affect estimated RBS life-cycle costs.
2. The RBS business case is incomplete because it does not adequately account for new entrant commercial providers of launch capabilities, the impacts of single-source providers, Air Force need for independent launch sources for meeting their assured-access-to-space requirement, and technical risk. The cost uncertainties associated with these factors do not allow a business case for RBS to be closed at the present time.
3. Reusability remains an option for achieving significant new full-spectrum launch capabilities at lower cost and greater launch flexibility.
4. For RBS to significantly impact Air Force launch operations, it would have to be more responsive than current expendable launch systems. However, no requirement for RBS responsiveness has been identified that would drive technology development.
5. Technology areas have been identified in which continued applied research and advanced development are required before proceeding to large-scale development. These areas include reusable ORSC hydrocarbon-fueled engines, rocketback RTLS operation, vehicle health management systems, and adaptive guidance and control capabilities.
6. Given the uncertainties in the business case and the yet-to-be mitigated technology risks, it is premature for Air Force Space Command to program significant investments associated with the development of a RBS capability.

Recommendations

1. Launch responsiveness should be a major attribute of any reusable launch system. To address this perceived disconnect, the Air Force should establish specific responsiveness objectives independent of the evolved expendable launch vehicle launch-on-schedule requirements that can be used to drive technology development.
2. Independent of any decision to proceed with RBS development, the Air Force should proceed with technology development in the following key areas: reusable oxygen-rich staged-combustion hydrocarbon-fueled engines; rocketback return-to-launch-site operations; vehicle health management system; and adaptive guidance and control systems. These technologies will have to be matured before they can support any future decision on RBS, and most of them will be also applicable to alternative launch system concepts.

Recommendations

3. The Air Force Research Laboratory's (AFRL's) Pathfinder project is under way to demonstrate in flight, using a small-scale vehicle, the critical aspects of the return-to-launch-site maneuver. To increase chances for Pathfinder's success, AFRL should develop and fly more than one Pathfinder test vehicle design. In addition, competition amongst RBS concepts should be maintained as long as possible to obtain the best system for the next generation of space launch.
4. The decision to proceed with the RBS development program should be based on the successful completion of the Pathfinder activities and on assurance that the technical risks associated with the reusable oxygen-rich, staged-combustion hydrocarbon-fueled engines, rocketback return-to-launch-site vehicle health management systems, and adaptive guidance and control systems are adequately mitigated.

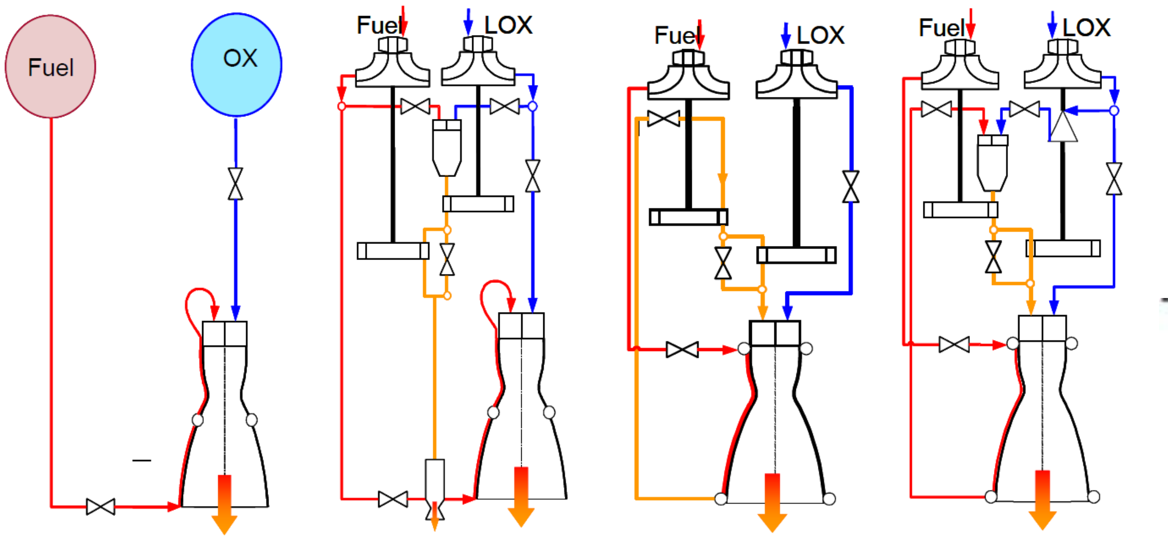
Recommendations

5. Following successful completion of the Pathfinder program, the Air Force should reevaluate the RBS business case, accounting for the following factors: new-entrant commercial launch providers; potential impacts of single-source providers; and Air Force need for independent launchers to satisfy assured-access-to-space requirements.
6. When constructing the RBS program, the decision points for proceeding from technology development to demonstration to prototype to production for RBS should be based on quantitative assessments during the successful completion of the previous phase. These go/no-go decision points should be structured as on-ramps to subsequent phases with technical underpinnings that are sufficiently well understood to proceed. The decision points for proceeding from Pathfinder and hydrocarbon boost technology risk reduction to a mid-scale demonstrator and from the demonstrator to Y-vehicle prototypes should be considered as on-ramps.

Common Rocket Engine Cycles

Pressure-fed system **Pump-fed systems**

gas generator *expander* *staged combustion*



F-1

Merlin 1C

RD-180

NK-33

Staged combustion cycles offer the highest performance for booster rocket motors

NAFCOM Model Uncertainties

- Manufacturing Method

RBD	Maximum Methods	**Significant Methods**	Moderate Methods	Minimal Methods	Limited Methods
RBS	Maximum Methods	**Significant Methods**	Moderate Methods	Minimal Methods	Limited Methods

- Engineering Management

RBD	Minimum Changes	**Few Changes**	Moderate Changes	Dedicated Team	Distributed Team
RBS	Minimum Changes	**Few Changes**	Moderate Changes	Dedicated Team	Distributed Team

- Design Level

RBD	Level 1	Level 2	Level 3	Level 4	Level 5	**Level 6***	Level 7	Level 8
RBS	Level 1	Level 2	Level 3	**Level 4**	Level 5	Level 6	Level 7	Level 8

- Funding Availability

RBD	No Delays	**Infrequent Delays Possible**	Delays Likely
RBS	No Delays	**Infrequent Delays Possible**	Delays Likely

- Test Approach

RBD	Minimum Testing	**Moderate Testing**	Maximum Testing
RBS	Minimum Testing	Moderate Testing	**Maximum Testing**

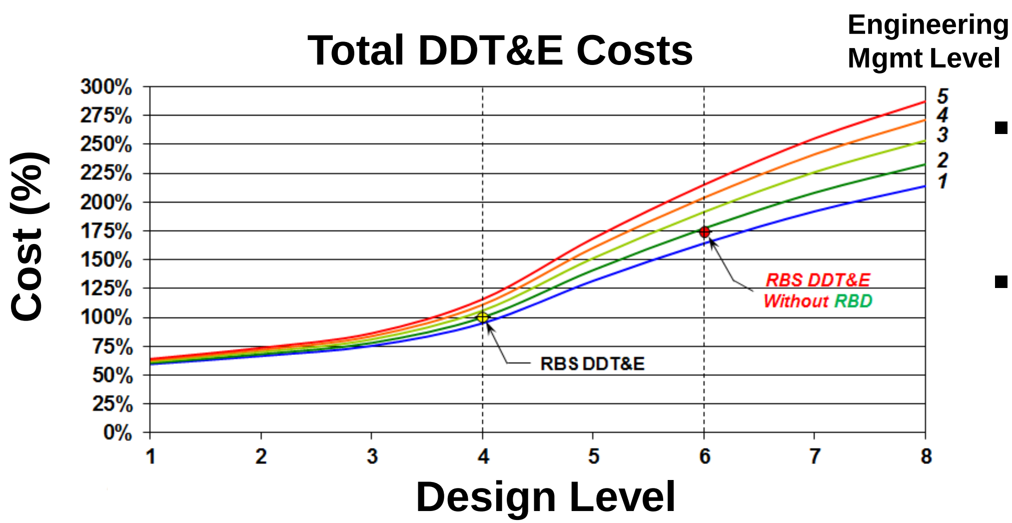
- Program Interfaces

RBD	**Minimal Interfaces**	Moderate Interfaces	Extensive Interfaces
RBS	Minimal Interfaces	**Moderate Interfaces**	Extensive Interfaces

- Pre-Development Study

RBD	**2 or More Study Contracts**	One Study Contract	<9 months of Study
RBS	**2 or More Study Contracts**	One Study Contract	<9 months of Study

- RBS development costs derived using NASA/Air Force Cost Model (NAFCOM)
- Costs correlated with dry mass
- Model inputs account for:
  - Design maturity
  - Development approach
  - Funding availability



- Sensitivity analysis provides insight into potential cost variability
- Cost uncertainties derive from:
  - Vehicle configuration uncertainties
  - Technical risk
  - Uncertainties in model inputs

Operations Costs

Category	RBS Personnel Estimates			Atlas I/II	Delta II	Titan IV
	CCAFS	VAFB	Common			
Vehicle Processing ('Hands-On Labor')	43	43	-			
Vehicle Engineering	-	-	15			
Payload Integration	8	8	4			
Flight Ops/Mission Ops	7	7	5			
Flight Software Engineering	-	-	12			
Logistics	8	8	5			
Launch Support Equipment	18	18	6			
Facilities Maintenance	14	14	8			
Landing Site Ops	22	22	-			
Adminstration	6	6	-			
Total	**126**	**126**	**55**			
	307			**325†**	**175†**	**1,336†**

*Assumes all contractor workforce

†Ref: "Cost of Space Launch Systems," C. L. Whitehair, The Aerospace Corp., June 1994

Operations costs associated with RBS

- **Experience with manned reusable Space Shuttle of limited use**
- **Bottoms up labor estimates in line with Atlas/Delta experience**
- **Impacts of mission assurance requirements with reusable system not currently understood**