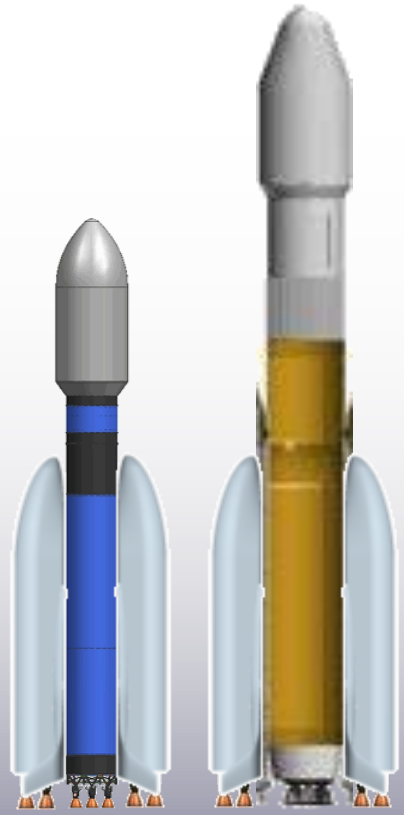
AFRL

THE AIR FORCE RESEARCH LABORATORY

LEAD | DISCOVER | DEVELOP | DELIVER

# AFRL Portfolio Responsive & Reusable Boost System (RBS)



## ASEB-NRC Briefing

*17 February 2012*

**Bruce Thieman**
**Jess Sponable**
**Air Force Research Laboratory**

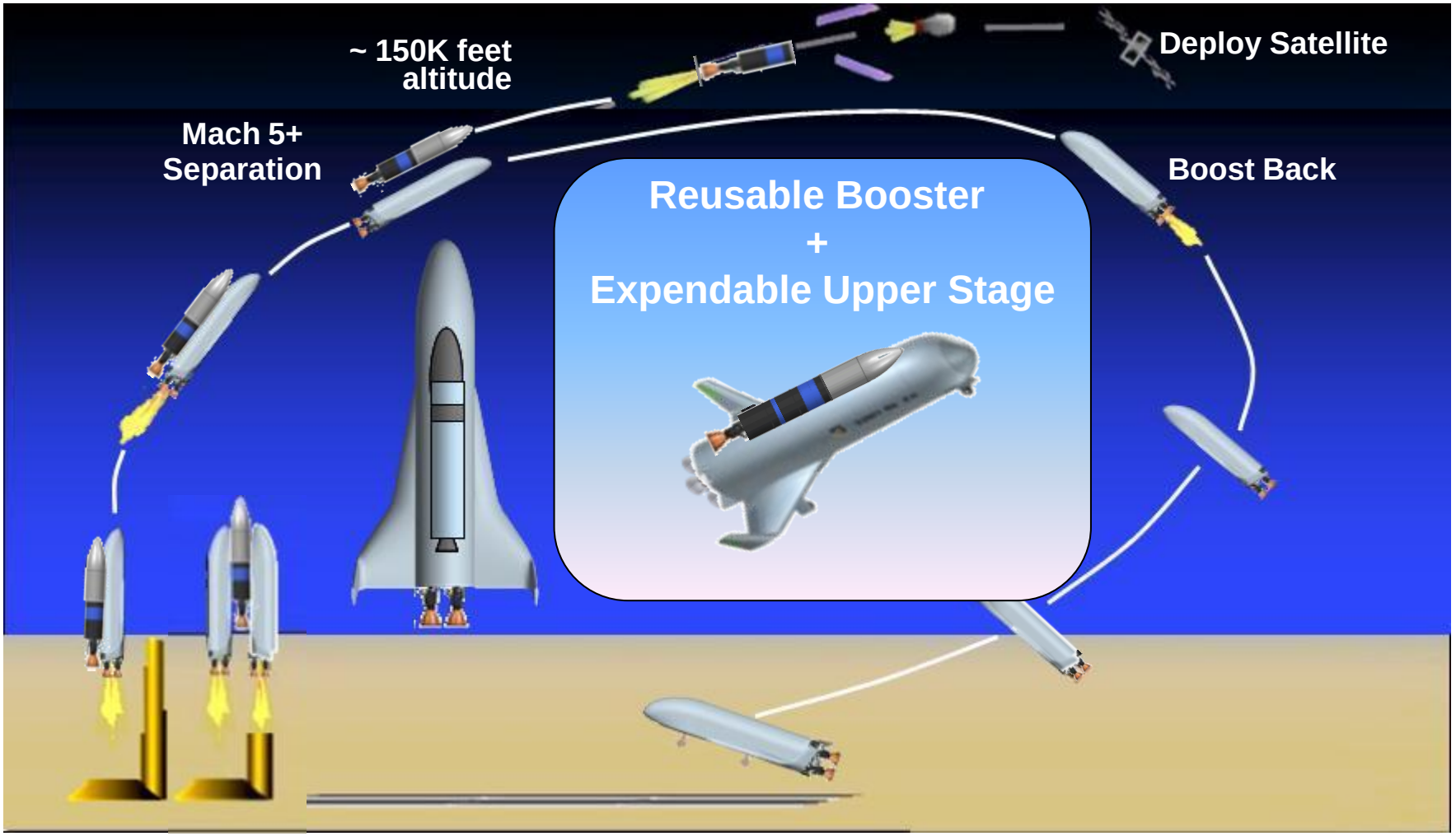
***Integrity ★ Service ★ Excellence***

# AFRL Briefings to NRC on RBS

- **AFRL Perspective on Reusable Booster Technology**
- **RBS Program**
  - S&T
  - RB-X
  - Overall Assessment
- **Hydrocarbon Boost Technology Program**

  (Tomorrow)

# Reusable Booster Launch Vehicle CONOPS

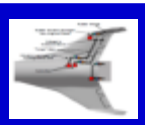


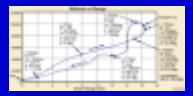
# What is Responsive Space Access?

## *A Suite of Technologies Enabling Future Capabilities*

### Component Technologies


Responsive Ops


ISHM
AG&C

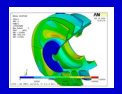


Aircraft Subsystems


NextGen Composites



TPS
Airframe TPS

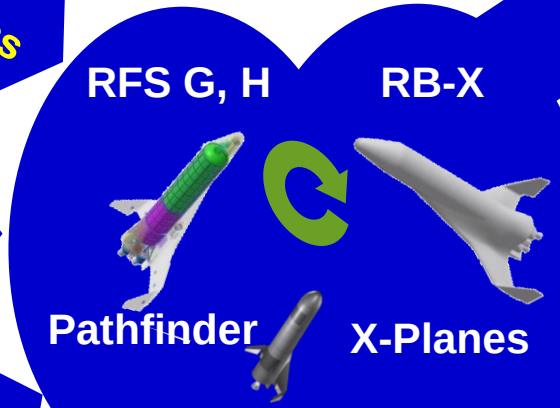
AFGE



USET
Propulsion Test



HC Boost

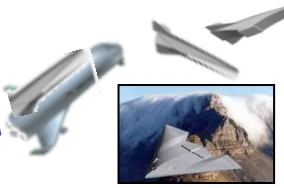
### Reference Flight Systems & X-Planes …




### … Enables Technology Integration

### Transition To Future Capability


Responsive Launch
*5-15K lbs*


Hypersonic Testbed & High Speed Aircraft


Commercial RBS


Space Sortie Vehicle



Liquid Flyback Boosters or EELV Replacement


Nano/Small-Launch

~15 ~20

RBS Flagship → Propulsion & X-Planes → Tech Transition

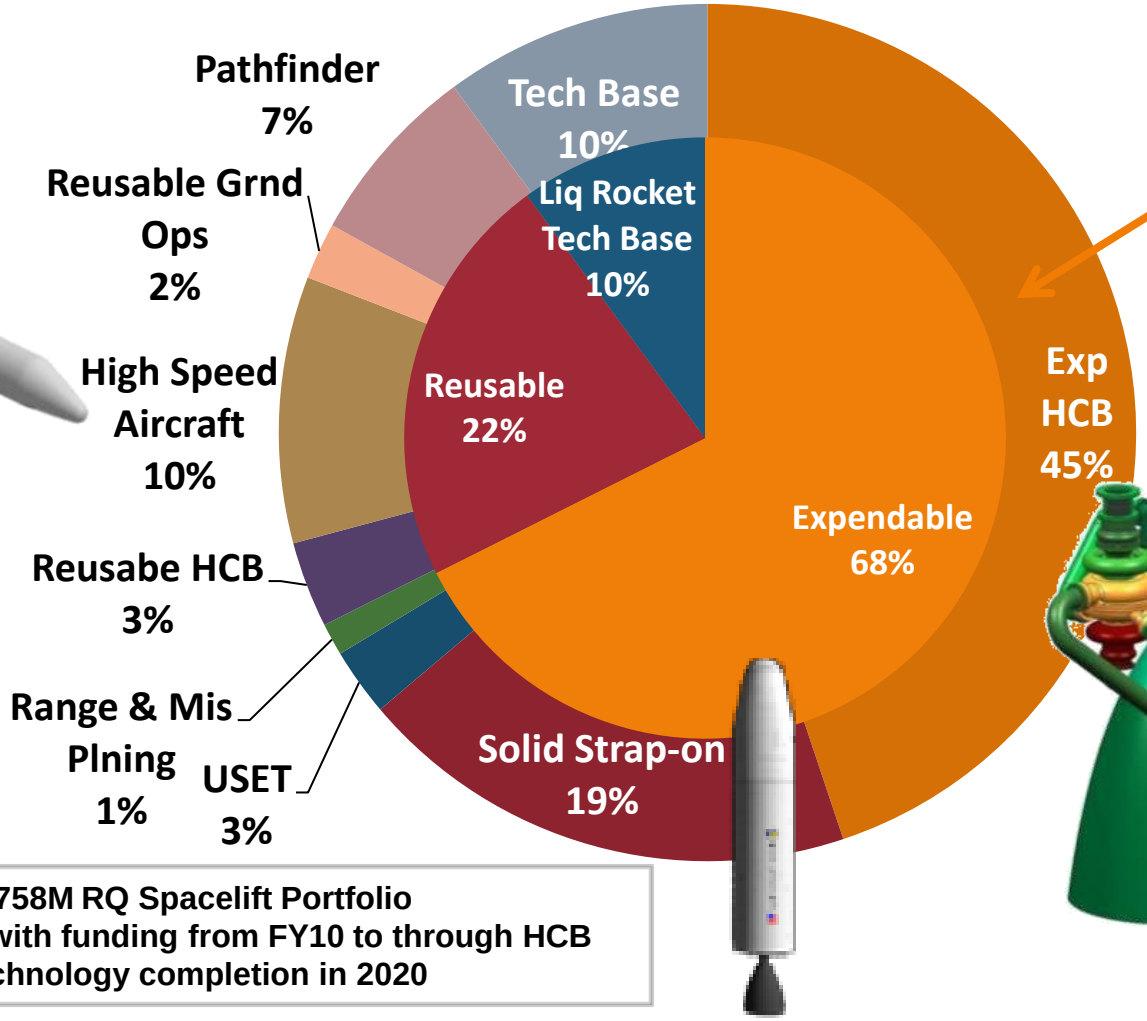
# RBS
## The Technology Challenges

- **What technology challenges need to be overcome?**
  - Current space launch ops are expensive due to expendable space access components w/manpower intensive 6-48 month call up, and launch on clear weather only
    - Maintenance intensive acreage TPS
    - Single use high temperature sensors
    - Remote control & man in loop control
    - Preplanned failure modes & response (no ISHM)
    - Maintenance intensive, single mission engines
  - Current reusable high speed structures have significantly poorer fuel mass fractions than expendables

- **What technologies are being matured as part of this Flagship?**
  - Rapid Remove and Replace TPS, Seals, and Attachments
  - Long Life High Temperature Sensors and Actuators
  - Low Cost Reliable Upper Stage
  - Reusable Rocketplane and Launch Complex Design for Operability
  - Mach 5+ Vehicle Recovery Turn
  - High Mass Fraction, Composite Lt Weight Structures
  - Adaptive Guidance & Control
  - Rapid Airframe Assessment and Maintenance
  - Long Life and Operable Rocket Engine Chamber and Turbomachinery

# RQ Spacelift Portfolio

**$169M Reusable**




**$512M Expendable**

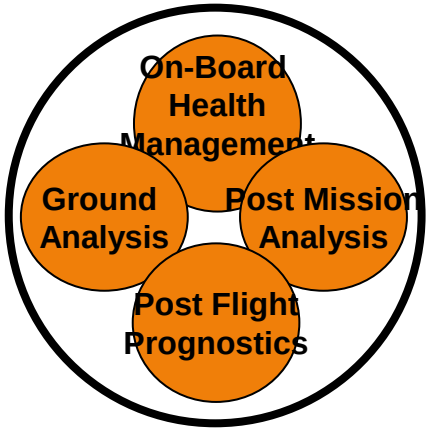


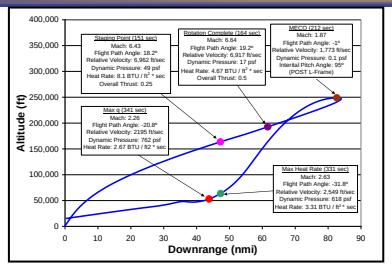
**$758M RQ Spacelift Portfolio**
**FY12 PB/BA with funding from FY10 to through HCB technology completion in 2020**

**Reusable Booster Stage Requires $538M of this Portfolio**

# Innovation – Key Technologies for Responsive or Reusable Spacelift

## Real Time Health Management



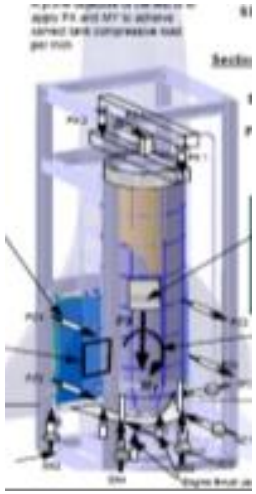




## High Speed Guidance & Control

## RTLS and Rocketback

## Thermal Protection (Area and Leading Edges) and Thermal Management

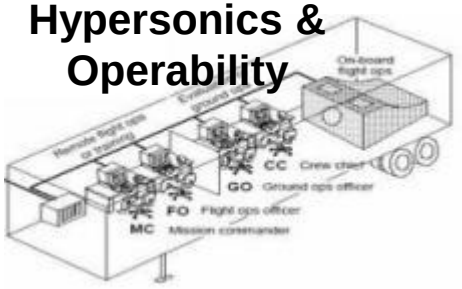
## Light Weight Structures



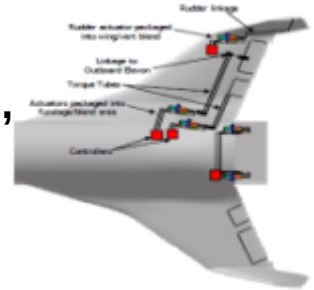
## Autonomous & Adaptive Range Ops

## CFD & AeroThermal Dynamic Design Tools

## Aircraft Like Ground Operability, Clean Pad Ops, and Design for Hypersonics & Operability




## Power, Fluid, Thermal & Actuation



## Low Cost Expendable Upper Stage and Reusable Rockets

# Incremental Steps to Responsive Lift and Launch on Schedule

Small Test Vehicle

Demo A/C-Like CONOPS

Demo Rocket Boost Back

Small Launch Options

Cost $1-3M

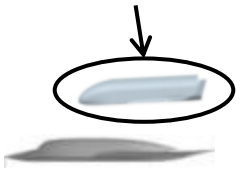
**Test**

**Build**

X-Plane(s)

X-45 (Size Ref)

Small & Affordable



## Step 1 – Pathfinder

*Residual Capability*
*Nano-sat Launch Option*
*50 Kg to LEO*

Future Capabilities

S-2

S-1

RB-X Options

F-15 (Size Ref)

5K lbs

## Step 2 – RB-X

*Small demonstrator*

*5-15K lbs to LEO*

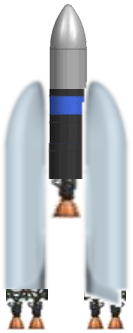
*Cost 2X < Minotaur IV*

SSV

*<15K lbs*

Potential Residual Capability Configurations

*15K lbs*



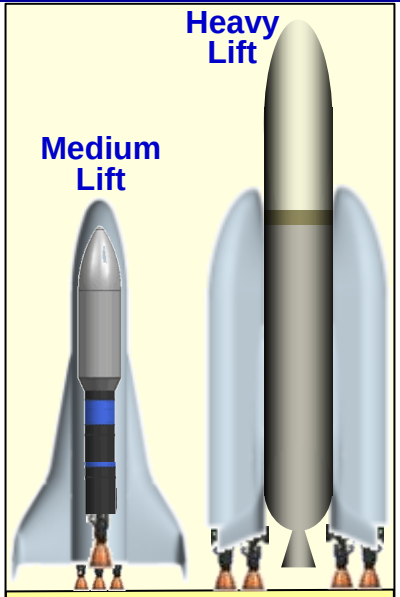
## Step 3

*Residual Capability*
*5-15K lbs to LEO*

*Cost 3X Less*

Heavy Lift

Medium Lift



## Step 4 (Options)

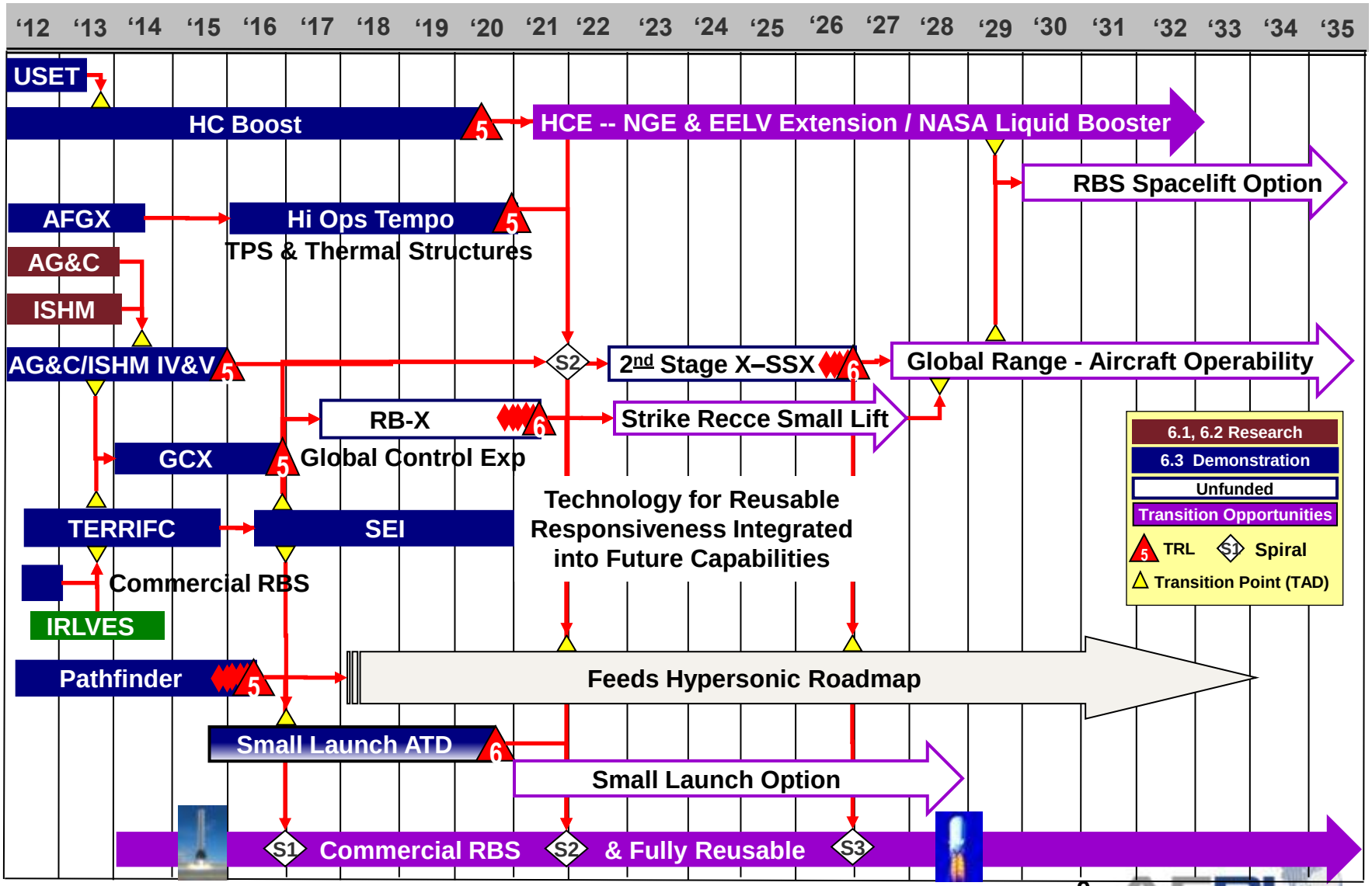
*Operational RBS*
*Up to 65K lb Payload*

*Cost 3X< EELV*

Representative Options

# Responsive Space Access

## *Roadmap & Transition Opportunities*







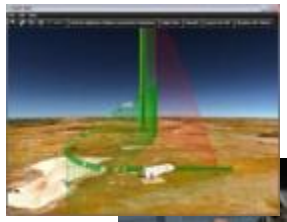

9

# Hybrid Reusable Booster Technology Maturation

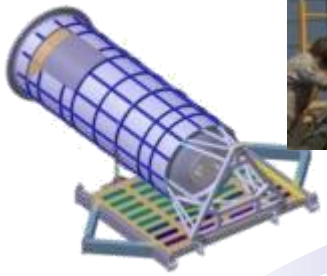
Adaptive Guidance & Control

FAST (AFRL)

Airframe Structures



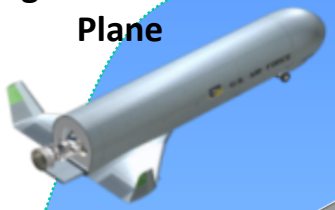
Integrated Vehicle Health Mngment



Responsive Ops Test

Pathfinder Rocket Back Demo (SMC & AFRL)

Flight Demo or X-Plane



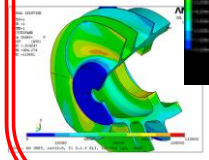
**RBS**

(AFSPC funded)

Vehicle Technologies

Engine Technologies

Physics-Based MS&A tools



USET

Vision Engine

Risk Reduction

HC Boost Demo (AFRL)

Integrated Engine Cycle Testing (250Klbs Thrust - Subscale)

Prototype & Flight Weight Engine (SMC)

**A $385 million integrated suite of ground & flight technologies**

# Hydrocarbon Stage Combustion Engine Development

Model Driven Design

Concept Design

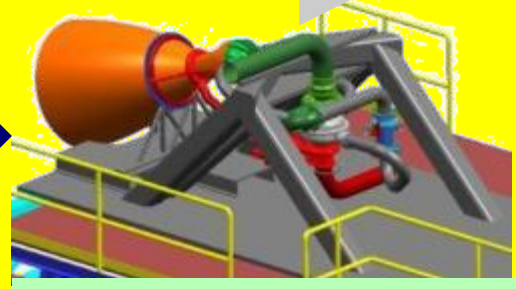
TRL 3
(2007 – 2012)

Subscale / Rig Testing

TRL 4
(2011 – 2013)

Component Testing

TRL 5
(2015 – 2018)



Integrated Engine Cycle Testing (250K)

TRL 5
(2019)

Prototype Engine (430K/860K)

TRL 6
(2022)

Flightweight Engine (860K)

TRL 9
(2025)

Uses and Refines USET design tools

Vision Engine

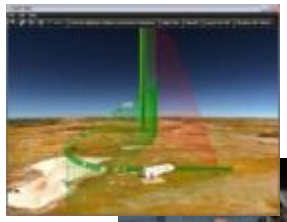
TRL 3
(2007)

Component TRL – Green
System TRL – Purple

# Hybrid Reusable Booster Technology Maturation

Adaptive Guidance & Control

FAST (AFRL) Airframe Structures



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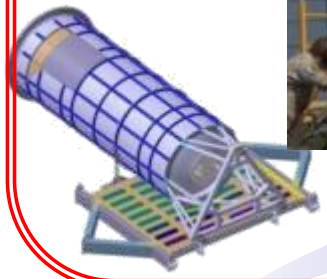

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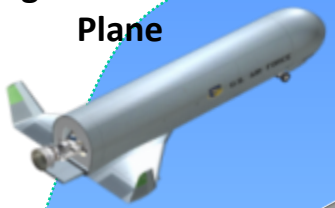

Vehicle Technologies

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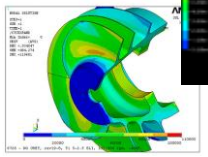


USET

HC Boost Demo (AFRL)

Vision Engine

Risk Reduction

Integrated Engine Cycle Testing (250Klbs Thrust - Subscale)

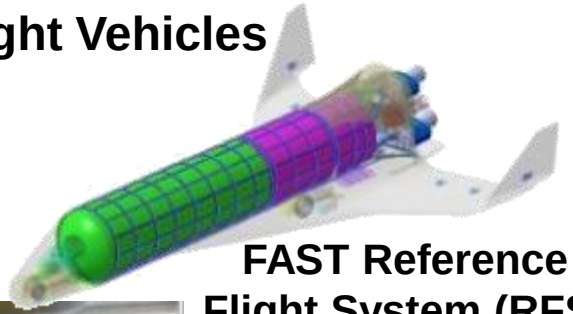
Prototype & Flight Weight Engine (SMC)

**A $385 million integrated suite of ground & flight technologies**

# Airframe Ground Experiment

- **The AFGE Program Includes the Integration of Composite Primary Structures, TPS and SHM Technologies into a Full-Scale Airframe Experiment to Reduce Critical Risks for Future Flight Vehicles**

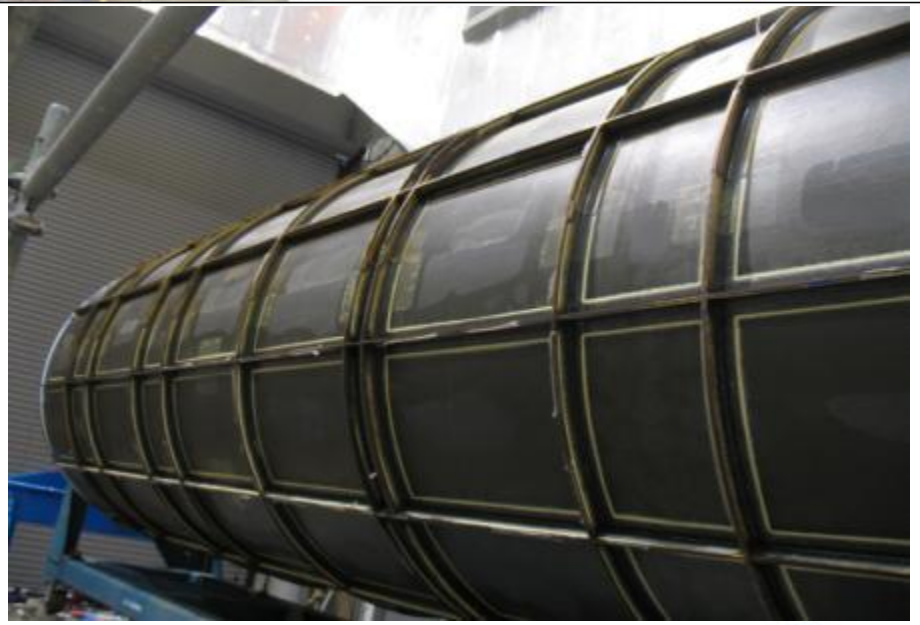
- **Major Program Elements**
  - **Mature Airframe Design of the Reference Flight System (RFS) Booster Vehicle**
  - **Design & Fabrication of an Integrated Airframe Test Article, ~7’ x 19’**
  - **Mission Cycle Testing to Evaluate Airframe Robustness, Reliability, and Reusability**
    - **Planned testing to simulate LO2/RP system (& potentially LO2/LCH4)**
    - **100 ascent/descent mission cycles with LN2 (simulated aero loads, thermal, cryo, TPS, vibration, proof, etc.)**



**FAST Reference Flight System (RFS)**

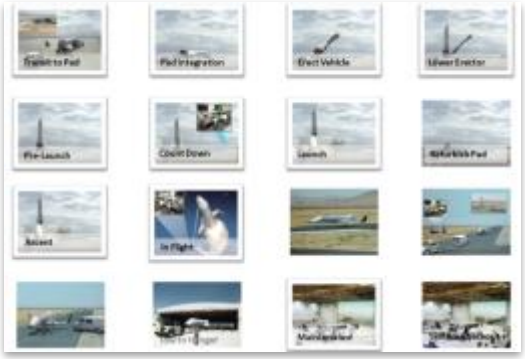
**FAST AFGE Test Article**

# AFGE Hardware Status



# Design and Operability Overview

**2008**



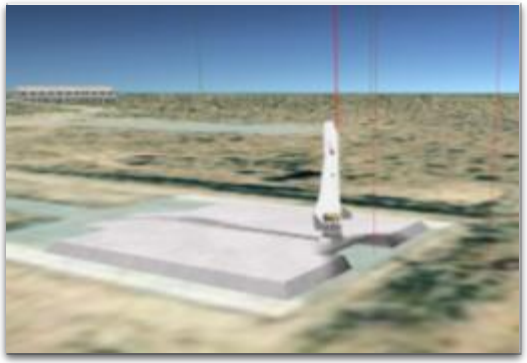
**CONOP & Functional Definition**

- Day in the life
- Sequence Diagram
- Requirements
- Test plan
- ICD
- DODAF

**2009 - 2010**

**Simulation Test Bed Design, Development, and Integration**

- Hardware
- Software
- Ops Control Center



**Conduct Experiments Simulation Scenarios**

- Nominal flight
- Abort on launch
- Engine icing during rocket back
- TPS struck non-critical

# Responsive Ops Demos

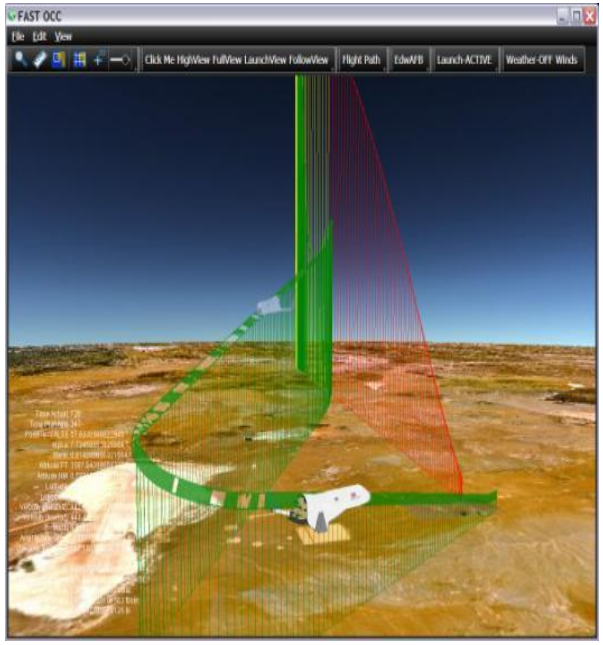
- Mission Planning
  - Rapid mission planning with range approval
  - Automated flight safety system
  - Low manpower Operations Control Center
- Rapid engine remove & replace
- Rapid TPS remove & replace
- Automated alignment, connection, and verification system
  - Element integration (Vehicle to vehicle and vehicle to pad)
    - Vehicle and ground ISHM with interactions
    - Including considerations for upper stage change-out and destacking
  - Rise-Off umbilicals
- Rapid Propellant Loading
  - Tank, line, and subsystem conditioning
  - Automated to reduce personnel requirements

Ground-Vehicle Umbilicals

**One Integrated Health Management System for Ground and Flight Operations**

# AG&C and ISHM Experiments

- **Adaptive Guidance & Control/Subsystems & Integrated Systems Health Management**
  - **Autonomous guidance and control "iron bird" flight controls, flight laws, subsystems and failure management**
  - **Integrate with flight computer, ISHM and Ground operability and maintenance planning**
  - **Demo in OCC**



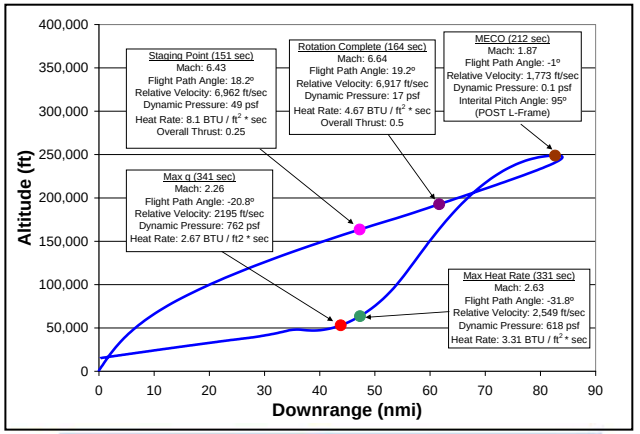


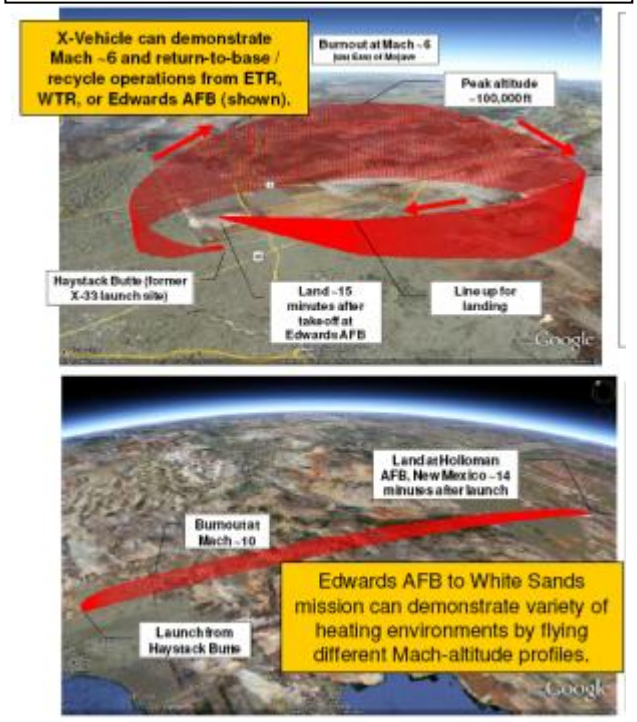


Cleared for Public Release AFRL/WS 07-0499

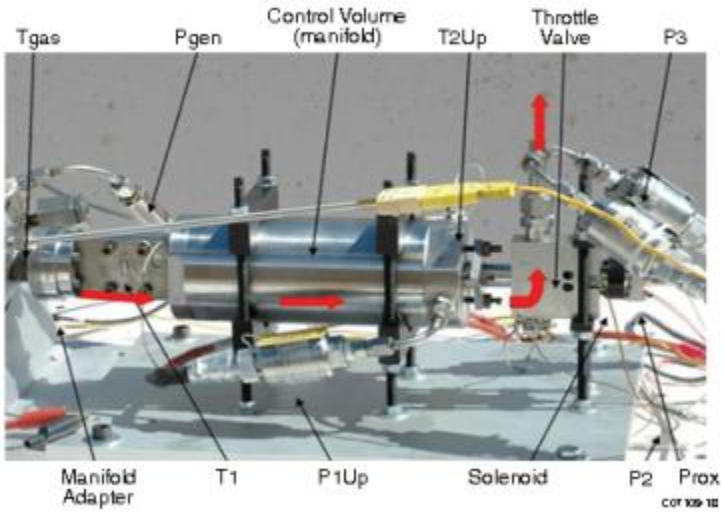
# Control & Health Management and Operability Challenges

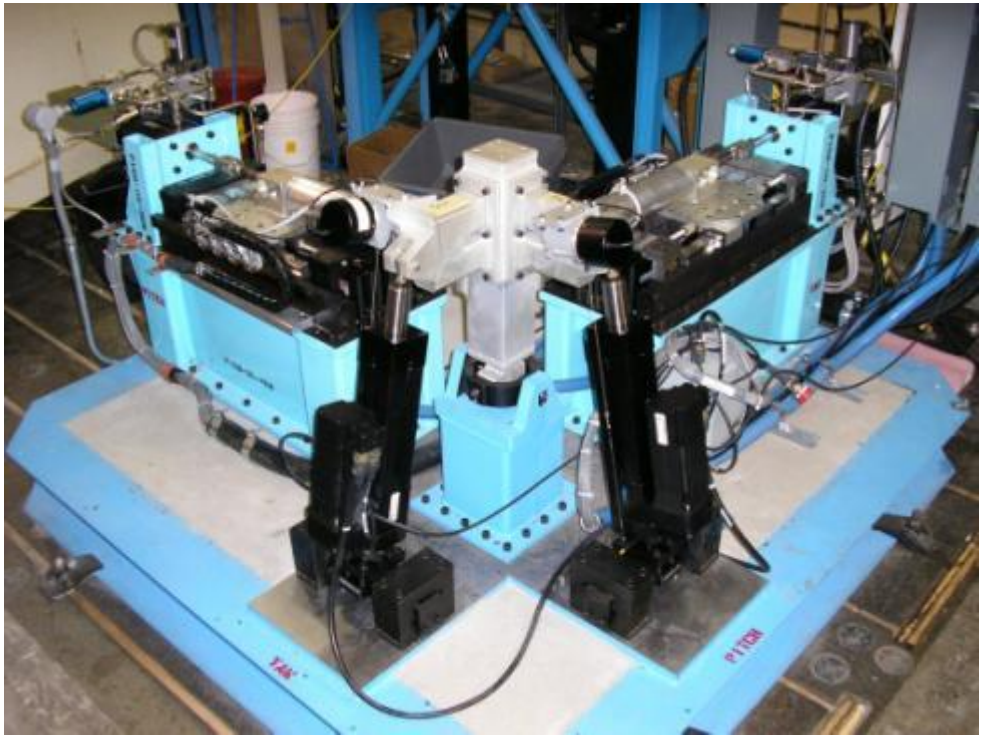
- 6DOF Control for Robust Rocket Back Maneuvers
  - Flight Envelope Limitations
  - Vehicle Orientation / Load Restrictions
  - Blended, Multiple Control Effectors
- Range Capabilities and Restrictions
  - Incremental / Extended Flight Test Program
  - Assessment of Facilities
    - CCAFS / VAFB
    - EAFB
    - WSMR
    - Commercial / Non-Federal Ranges
  - Flight Safety, Communication and Data Telemetry Requirements



# Hardware in the Loop Simulation

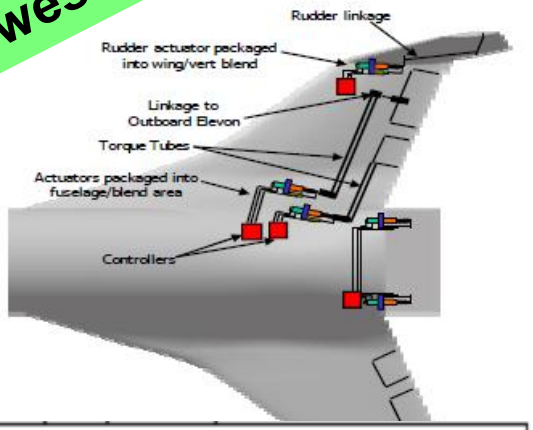


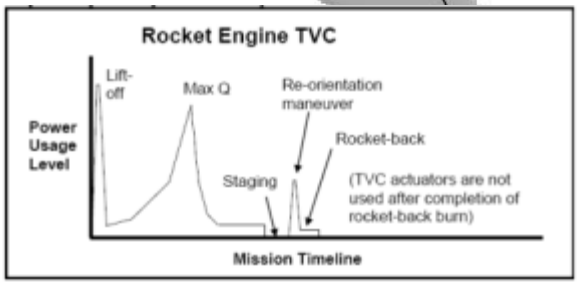



# Power, Fluid, Thermal & Actuation Challenges

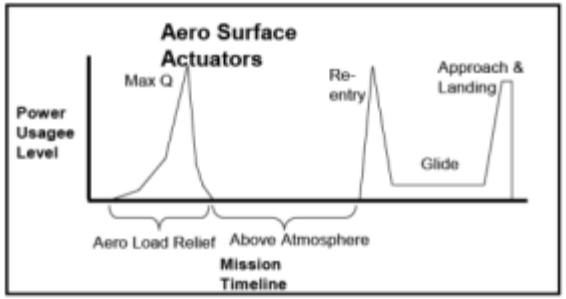
Newest Area

- Electric Power Generation, Storage and Distribution
  - Batteries (Li-Ion or Li-Polymer) or APU (Non-toxic) sizing
  - Charging / Turn-Around Operations
- Full Envelope Thermal Management
  - External and Internal Thermal Sources and Sinks
  - Ground Operations Timelines and Requirements and Weather Conditions
- Reaction Control System Sizing and Integration
  - Propellant Options
  - Thruster and Tank Sizing
  - Aft only vs Fore and Aft RCS placement




27. Power Usage vs Mission Timeline for Engine TVC

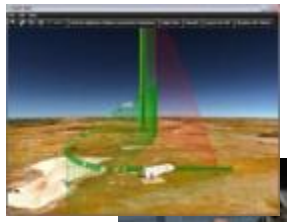



**Energy Optimized Vehicle Approach**

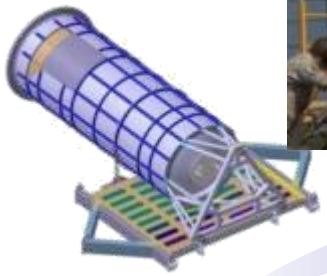
# Ongoing Technology Program
## *Delivers S&T for Future Launch*

Adaptive Guidance & Control

FAST (AFRL) Airframe Structures



Integrated Vehicle Health Mngment



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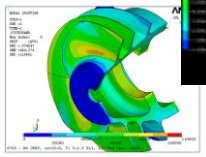

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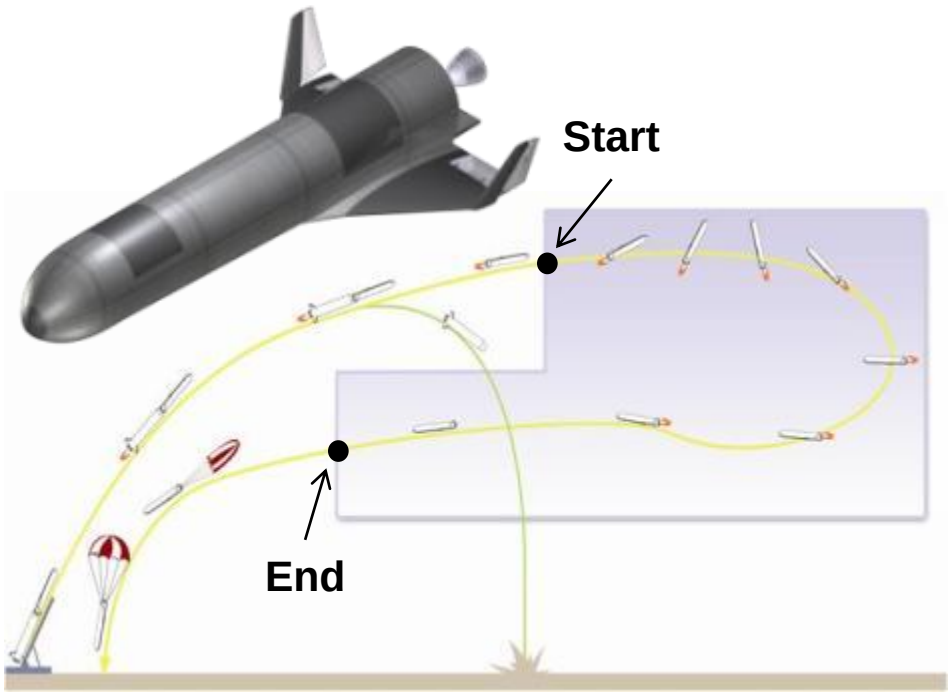
**A $385 million integrated suite of ground & flight technologies**

# Pathfinder Experiment Concept

**Objective: Demonstrate the rocketback maneuver traceable to relevant flight conditions and reduce risk in key technical areas**




*Notional RBS Pathfinder Trajectory*

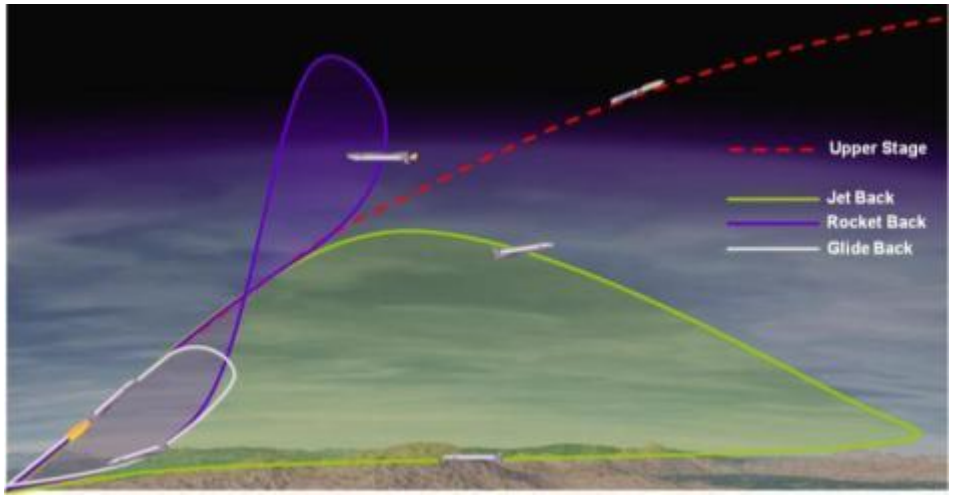
**Key Elements:**

- Sub-scale RBS Vehicle
- Vertical Takeoff Horizontal Landing
- Demo Rocketback from not possible with glideback RTLS
  - Supersonic, transonic, subsonic at low dynamic pressure and extreme AOA
  - No other previous flight test comes close to matching conditions
- Propellant management issues
- Understand control system integration issues
- Collect aero, trajectory, and control system response data to feed larger RB-X demonstrator program

**Rocketback Flight Demonstration – FY15/16**

# Why Rocketback?

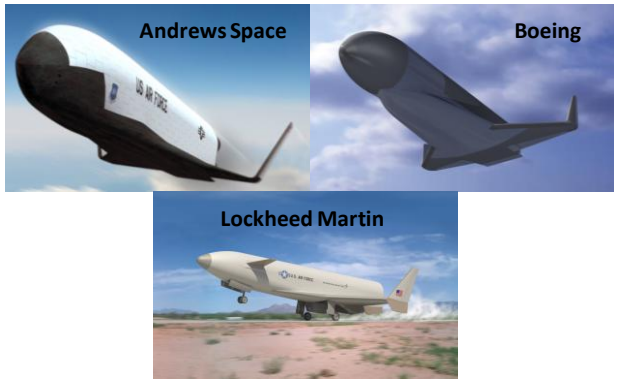
- Return-to-Base Maneuver Needed For Staging over Water and Quick Turn-Around Operations
  - Fleet Sizing and Base Concerns
- Glide-back Limits Staging Point
  - Needs Larger, More-Costly Upper Stage
  - Limited to Mach ~3 staging
- Jet-back Needs Integration of Additional Propulsion System
  - Hardware Integration Challenge
  - Increased Flight Time and More Severe Thermal Environment
- Rocketback Allows for Less Complex Vehicle
  - Less Flight Time and More Benign Thermal Environment
  - No Additional Propulsion System



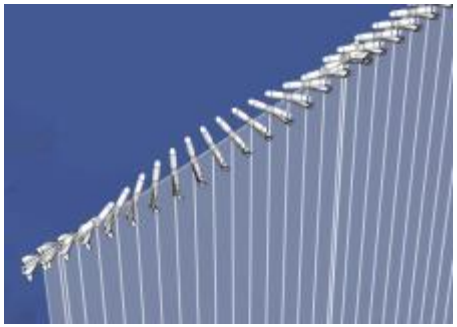

**Rocketback is a Key Enabler for Responsive, Low-Cost RBS**

# Pathfinder Flight Experiment

## Approach




- **Multiple awards – different solutions**
- **Sub-scale RBS demo vehicle**
- **Vertical Takeoff Horizontal Landing**
- **Reduce Risk**
  - Explore CONOPS
  - Demo rocketback
  - Incremental flight envelope expansion



## Technical Challenges

- **CONOPS – VTHL and O&M**
- **Flight environment**
  - Angles of attack from -180 to +180
  - Mach 3.5-6.5
  - Dynamic pressures up to 100 psf
  - Rotation rates up to 20-30 deg/sec
- **Aerodynamic phenomena**
  - Vortex shedding
  - Re-entry aeroheating
  - Shock structure
  - Plume-vehicle interactions
  - Boundary layer transition
  - Viscous interactions
  - Flow separation
  - Interaction with RCS thrusters
  - Control surface effectiveness
- **System**
  - Propellant management
  - Flight state determination
  - Multiple changes in engine throttle
  - Vehicle stability and control

**Objective: Demonstrate CONOP & rocketback maneuver traceable to relevant flight conditions and reduce risk in key areas**

# Rocketback Technical Challenges

- Challenges occur at flight conditions where existing computational models have not been validated and existing ground test facilities are unable to suitably match the conditions
- Flight environment
  - Angles of attack from -180 to +180
  - Mach 3.5-6.5
  - Dynamic pressures up to 100 psf
  - Rotation rates up to 20-30 deg/sec
- Aerodynamic phenomena
  - Vortex shedding
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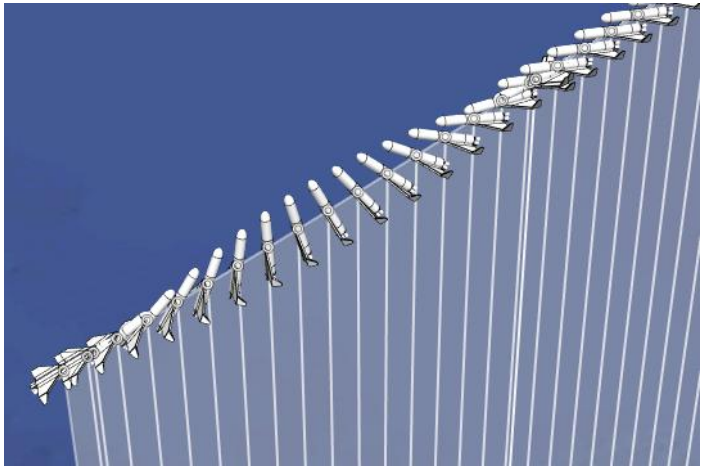
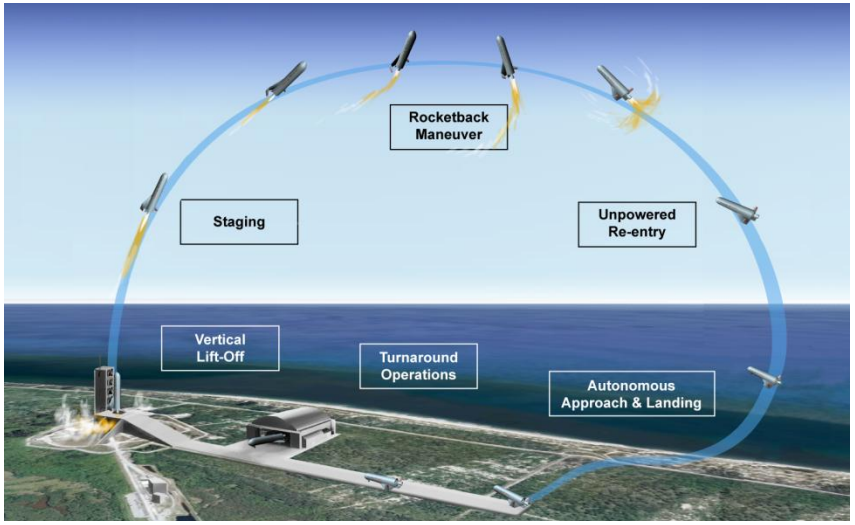


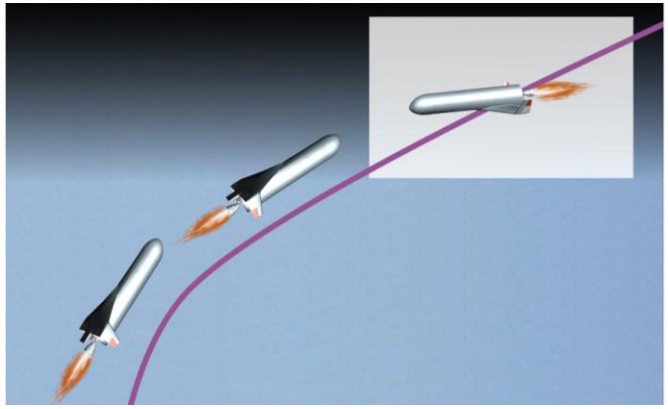
- Propellant management
- Flight state determination
- Multiple changes in engine throttle
- Vehicle stability and control

# RBS Pathfinder

- $57M partnership program between AFRL/RB and SMC/XR
- MOA signed in Dec 2010
  - SMC/XR provides $16M
  - AFRL/RB provides $41M
- Demonstrate CONOPS for RBS first stage
  - Vertical takeoff-horizontal landing (VTHL)
  - Rocketback return to launch site (RTLS) maneuver




- Explore rocketback flight envelope
  - Unexplored aerodynamic flight regimes
  - New flight control and propellant management techniques



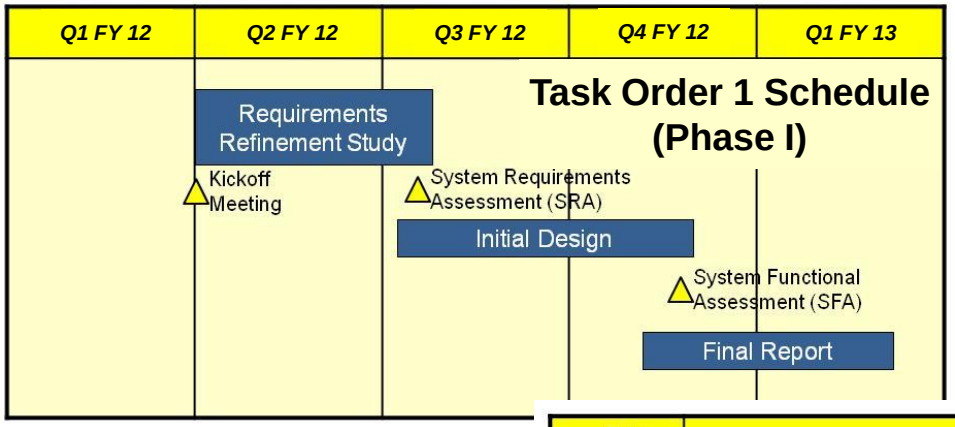
# RBS Pathfinder Program Approach

- **Task Order 1 – Concept Design Maturation (Phase I) FY12**
  - **Three contractors selected**
  - **Conduct requirements studies to refine the KPPs from the original solicitation**
  - **Conduct initial design study to verify feasibility of the revised requirements**
- **Task Order 2 – Detail Design, Fabrication and Flight Testing – Award FY13**
  - **One contractor from Phase I will be selected**
  - **Build and Demonstrate autonomous flight CONOPS of RBS rocketback return-to-base mission.**
  - **Rocketback envelope expansion flight research. Integrate with Launch Assist System (if necessary).**
  - **Flight Control and Health Management Architecture – Include software interfaces to support AFRL research activities on Integrated Adaptive Guidance & Control (IAG&C) and Integrated System Health Management (ISHM).**
  - **Program Costs – Gather data that can be used to estimate the costs of future RBS demonstration and development programs.**

- **Requirements for TO 2 will be revised as TO 1 progresses**
- **All contractors awarded the basic contract will have fair opportunity to provide revised proposals for TO 2**
- **All study results from TO 1 will be made available for awardees to bid a revised TO 2**

# Pathfinder Task Orders Schedule and Budget

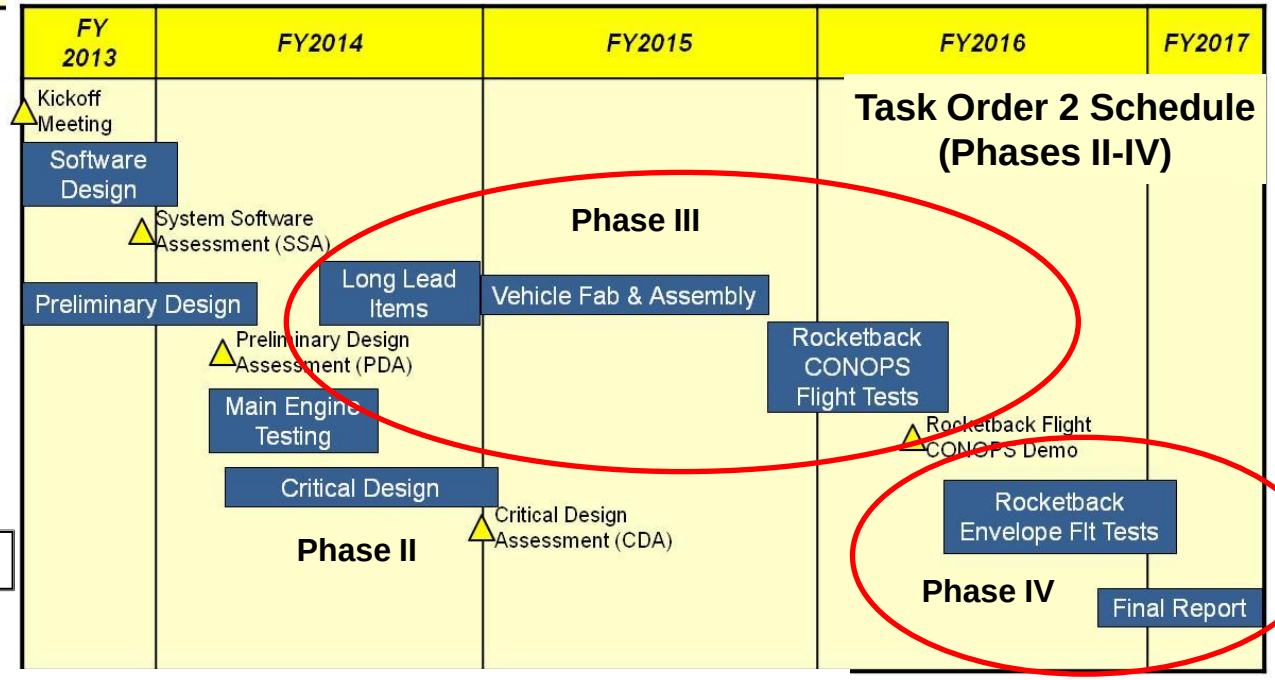
**$7.25M**




- **Proposals Received – 19 May 11**
- **Kickoff Meetings – Early Dec 11**
- **Updated Program Requirements Complete – May 12**

- **Recompete of Task Order 2 in Sep 2012**
- **Kickoff – Apr 2013**
- **First flight – Dec 2015**

**$49.95M**

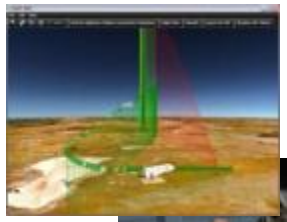



**$$ are FY12 PB**

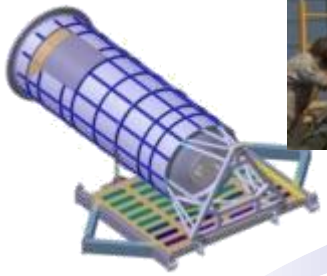
# Ongoing Technology Program
## *Delivers S&T for Future Launch*

Adaptive Guidance & Control

FAST (AFRL) Airframe Structures



Integrated Vehicle Health Mngment



Responsive Ops Test

Pathfinder Rocket Back Demo (SMC & AFRL)

Flight Demo or X-Plane

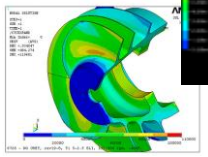
**RBS**

(AFSPC funded)

Vehicle Technologies

Engine Technologies

Physics-Based MS&A tools



USET

Prototype & Flight Weight Engine (SMC)

HC Boost Demo (AFRL)

Vision Engine

Risk Reduction

Integrated Engine Cycle Testing (250Klbs Thrust - Subscale)

**A $385 million integrated suite of ground & flight technologies**

# RB-X Demo

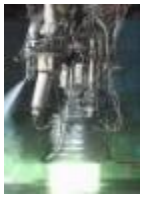
*Can leverage SpaceX Technology*

## Upper Stage

- ✓ Falcon 9 upper stage
- ✓ Mod as Demo upper stage

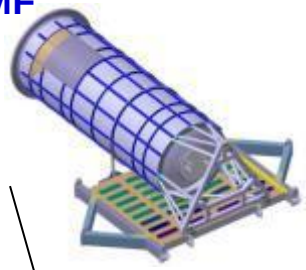
## Engine Options

- ✓ Merlin (4 to 6 engines or F9)
  - ✓ Operational, minor mods for throttle / reuse
- ✓ AJ-26 (1 or 2 engines)
  - ✓ Mod NK-33 for US Production
- ✓ Single vs Multi engine demo
  - ✓ Engine out, high reliability, etc.



## Airframe Experiment

- ✓ AFGE composite load bearing tank & structure / high PMF
- ✓ Responsive Ops
- ✓ AG&C/ISHM

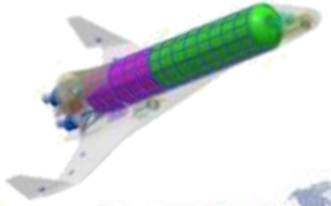


## Pathfinder

- ✓ Award in progress
- ✓ Small, affordable
- ✓ Demo boost back, VTHL CONOPS, operability, etc.

## RB-D Design

- ✓ Mature design, mass properties & performance understood
- ✓ Leverages Pathfinder & Flagship technologies
- ✓ Next step is integrated Demo design & flight



***Flagship***

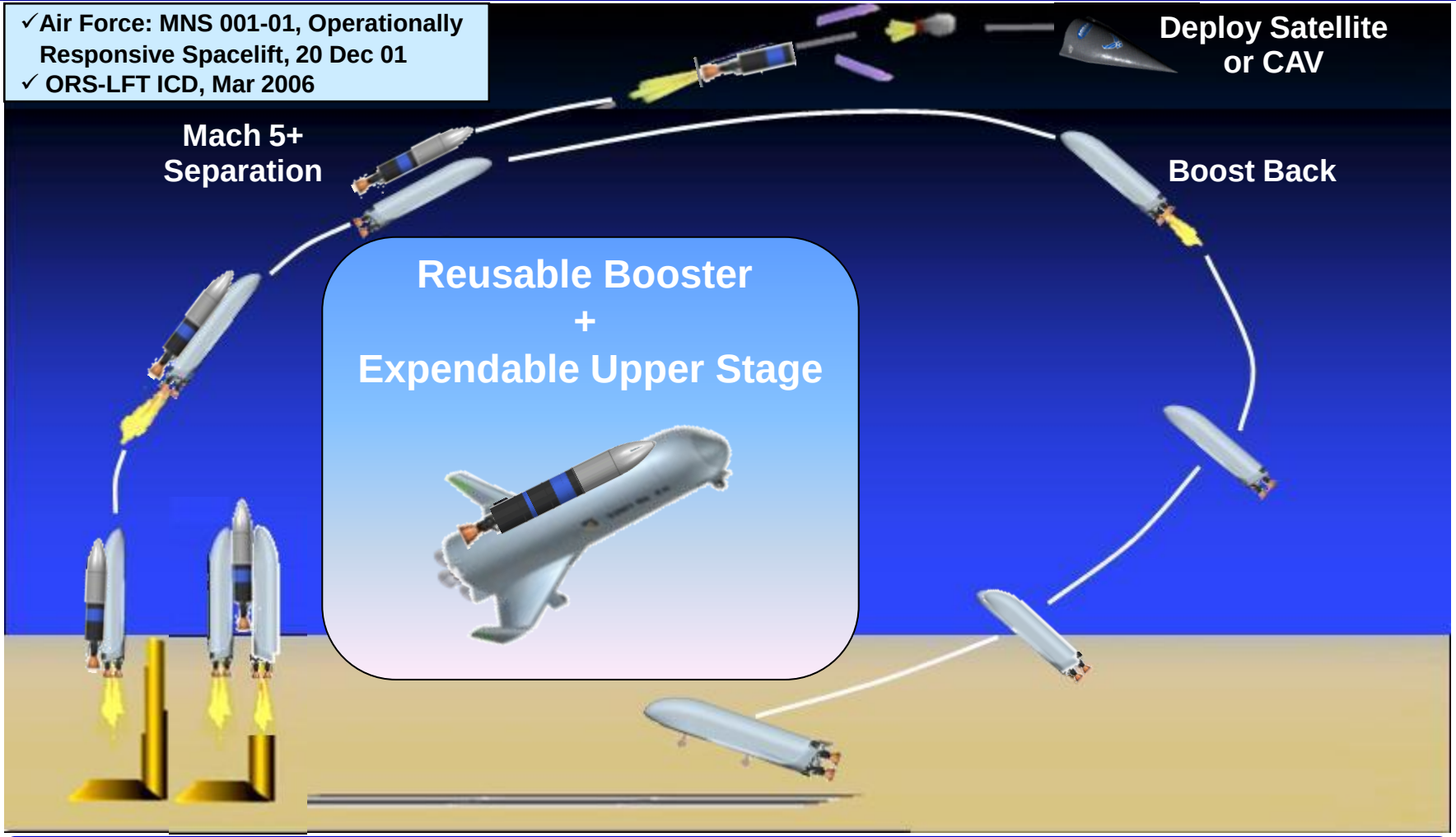
- ✓ *Ops Control Center*
- ✓ *ISHM and AG&C*
- ✓ *Grounds Ops/Spaceport CONOPS*

**Aircraft-Like Operability**



AFRL

# CONOPS




**Payload: single core *~8K lbs, dual core ~15K lbs***

# Incremental Steps to Responsive Lift and Launch on Schedule

Small Test Vehicle

Demo A/C-Like CONOPS

Demo Rocket Boost Back

Small Launch Options

Cost $1-3M

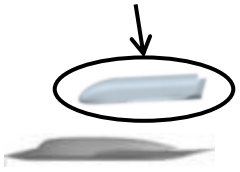
**Test**

**Build**

X-Plane(s)

X-45 (Size Ref)

Small & Affordable



## Step 1 – Pathfinder

*Residual Capability*
*Nano-sat Launch Option*
*50 Kg to LEO*

Future Capabilities

S-1

S-2

RB-X Options

F-15 (Size Ref)

5K lbs

## Step 2 – RB-X

*Small demonstrator*

*5-15K lbs to LEO*

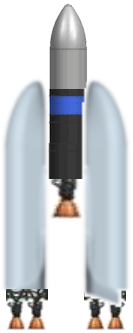
*Cost 2X < Minotaur IV*

SSV

*<15K lbs*

Potential Residual Capability Configurations

*15K lbs*



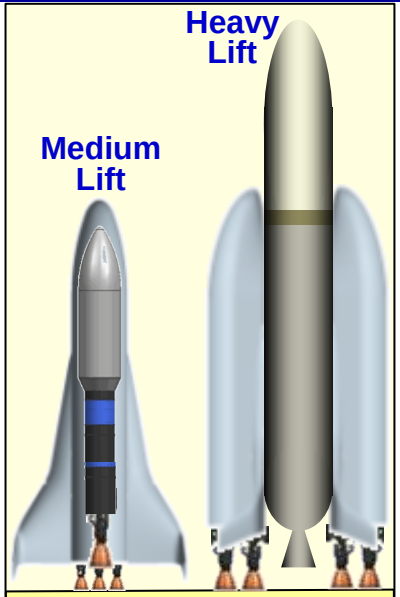
## Step 3

*Residual Capability*
*5-15K lbs to LEO*

*Cost 3X Less*

Heavy Lift

Medium Lift



## Step 4 (Options)

*Operational RBS*
*Up to 65K lb Payload*

*Cost 3X< EELV*

Representative Options

# RB-X Demo Schedule & Cost (ROM)

| Funding ($1,000's) | Yr 1 | Yr 2 | Yr 3 | Yr 4 | Yr 5 | Yr 6 | TOTAL |
|---|---|---|---|---|---|---|---|
| Assumed funding allocation over life of program | 5% | 10% | 15% | 20% | 30% | 20% | 100% |
| **Required Demonstrator Funds** | | | | | | | |
| Full Scale Demo without Upper Stage | 20,000 | 40,000 | 60,000 | 80,000 | 120,000 | 80,000 | **400,000** |

- ❑ **$360 to 450M – Proof of concept demo & flight test**
  - ✓ Single RBS concept
  - ✓ 2 units + spares
  - ✓ Flight test (no upper stage)
- ❑ **$90 to 120M – Expendable upper stage demo**
  - ✓ Modify SpaceX 1st Stage of Falcon 1 as single RBS stage
  - ✓ Flight test small payload to LEO (5-8K lbs)
- ❑ **$40-60M – Extended modular testing**
  - ✓ Flight test of medium payload to LEO (15K lbs)
- ❑ **$TBD – Additional production**
- ❑ **$TBD – Recurring annual operations & maintenance**
  - ✓ At 20 flights per year yields $12-18M/flight, $800-1200/lb
  - ✓ Projections from AF CORE O&S model modified for RBS
  - ✓ Commercial synergy may reduce

# Currently Funded Technology Plan

FY 12 POM (FY 11-17) + HCB to 2020

**Current Budget Buys**

**Cost & Ops databases** (TRL-5)

**Safe return-to-base validation** [RTB and AG&C (TRL-4)]

**Controllability characteristics** [Flight Laws (TRL-6)]

**System integration and performance**

- **Structure / Tanks / Thermal** (TRL-5)
- **Reusable Propulsion** (TRL-5)
- **Mechanical / Electrical / Comm** (TRL-4)
- **Design Tools** (TRL-5)
- **Health Management for Quick Turn** (TRL-5)

**Autonomous flight control demo** [Rocket-back Man TRL-6]

**Upper stage sep characteristics data** [Not in Current Plan]

**Risk Reduction for operational system** **[Partial]**

**Pathfinder Flight Demo $64M**

**HCB Brassboard $264M**

**RBD at SLV size moves all technologies to TRL 6**

**Demos: Integrated Guidance & Control, Main Structure, & Rocket-back Flight**

# The Missing Link

- **X-Planes**
  - **To validate technology**
  - **To validate operability/CONOPS**
  - **To validate cost and system models**

**Pathfinder is First Step Down Path of**

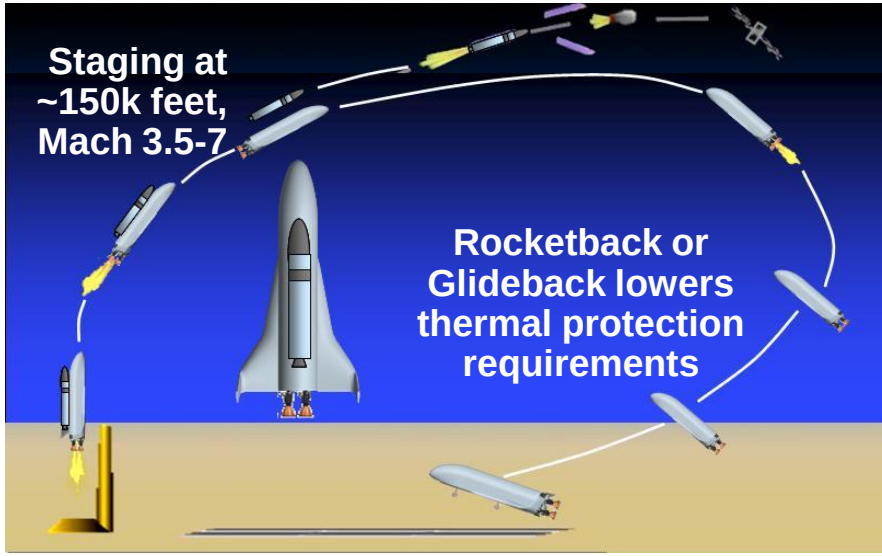
**Affordable Space Access & High Speed Flight**

# AFRL Vision…

**A 21st Century of**
**Diverse, Routine, Reliable & Affordable Space Access!**

# Reusable Access to Space Driving Functions

- Challenges
  - Escalating spacelift mission cost
  - Lack of a modular, multi-mission spacelift architecture
  - Insufficient responsiveness limiting space options
- Solution Concept: Vertical Take-off, Horizontal Landing (VTHL), Reusable Booster System
- Benefits to Warfighter:
  - > 50-66% cost reduction for launch on schedule
  - 2-8 hr callup
  - 24-48 hour turn around from call up to launch
  - 90% weather availability for assured strike and launch on demand




AFRL Addressing the Tech Needs

# Supporting Studies / Reports

| Document | Final Report Date | Creator / Leading Organization | Focus | Findings |
|---|---|---|---|---|
| ORS AoA | 1 April 2005 | AFSPC | ORS in context of all launch requirements | Hybrid-based architectures best choice based on 20-year LCC and relative risk. Advantages:<br>• Potential launch cost reduction of a factor of three, or better, below present systems<br>• Predicted 2-4 day turnaround minimizes fleet sizes<br>• Use of state-of-the-art technologies resulted in low development cost and technical risk |
| Responsive Access to Space Technology | 2003 | AFRL | | |
| Vector 1 Study | 2005 | USECAF | | |
| Future Launch Study (*US Launch Systems: History and Future Plans*) | 25 March 2006 | Aerospace for SMC | | |
| Future Launch Vehicles Study (*The Future of Launch Vehicle Systems for the USAF*) | 24 June 2010 | AF Scientific Advisory Board (AFSAB) | Options to mitigate "perfect storm" of launch problems | •Status quo not viable<br>•Develop new LOX/HC staged combustion cycle engine as a top priority<br>•RBS-type launcher offers operational flexibility, but analysis and demonstrations needed |
| Spacelift Development Plan | 2010 | SMC | Future spacelift in all weight classes | Selection of RBS as preferred net-gen option |
| Spacelift Total Cost of Ownership (TCO) | 8 July 2011 | SMC/LR & XP | analyze integrated EELV & Reusable Booster System (RBS) business cases | Phaseout of EELV for RBS will cut costs 50% or more. Lowest LCC comes with accelerated switch from EELV to RBS: Lowest NRE is developing RBS with a commercial partner. Continued EELV is the most expensive option. |