Astrox Studies and Experience with the Reusable Booster Systems and Two-Stage-to-Orbit Concepts

Presented to:

National Research Council

Aeronautics and Space Engineering Board

February 2012

By:

Astrox Corporation

Dr. Christopher Tarpley

Colorado Springs, CO 80917

Dr. Ajay P. Kothari

College Park, MD 20740

Acknowledgements

- Dr. Mark Lewis, Ex-Chief Scientist, Air Force
- Dr. Werner Dahm, Ex-Chief Scientist, Air Force
- Dr. Donald Paul, Chief Scientist – Rtrd, AFRL/RB
- Mr. Bruce Thieman, AFRL/RB
- Mr. Barry Hellman, AFRL/RB
- Mr. John Livingston, ASC/XR
- Mr. Glenn Liston, AFRL/RZ
- Mr. Dan Risha, AFRL/RZ
- Dr. Kevin Bowcutt, Boeing Huntington Beach
- Dr. Ray Moszee, SAF/AQR, Pentagon

Background

- Astrox experience with Access-to-Space (ATS) and high Mach cruise configurations covers almost two decades of work primarily with Air Force and NASA
- Astrox has been developing tools for vehicle design and quantitative analysis since 1990
- Studies have covered:
  - SSTO and TSTO Systems
  - RP, JP, Methane and LH2 Systems
  - Payloads from 2,000 to 60,000 lbs
  - Rocket, Turbine, Ram/Scramjet Engines
  - Air Launch, Horizontal and Vertical Takeoff Configurations

Relevant Studies Performed

Inward Turning Inlet	1990-1992	ASC/XR
Inward Turning Flowpath and Vehicles	1993-2000	NASA/LaRC
HADO and HySIDE Code	1995-1997	ASC/XR
Inward Turning SSTO Designs	1997-1999	NASA/MSFC
Access-to-Space / FAST* 1	2004 - 2006	AFRL/VA
TSTO Architectures	2005	AFRL/VA
Aerial Refueling	2006	AFRL/PRS
Prompt Global Strike	2006	AFRL/PRS
Hybrid Launch Study	2007	AFRL/PRS
TSTO Study	2007-2008	AFRL/PRS
FAST* 2	2008	AFRL/RB
Joint System Study	2009	AFRL/RB

*FAST – Fully Reusable Access-to-Space Technology

Recent Relevant Publications

1. **Kothari, A., Livingston, J., Tarpley, D. Hood, V., Bowcutt, K., Smith, T., Drayna, T., Dwenger, A., and Jacobsen, L., “Resizing of RBCC TSTO with Incorporation of Level 2 Results”, Presented at the 5^{th} CRASTE Conference, Atlanta, GA, October 2011.**
2. **Kothari, A., Livingston, J., Tarpley, C., Raghavan, V., Bowcutt, K., and Smith, T., “Rocket Based Combined Cycle Hypersonic Vehicle Design for Orbital Access”, AIAA paper no. 2011-2338, Presented at the AIAA International Space-planes and Hypersonic Technology Conference, San Francisco, CA, April 2011.**
3. **Bowcutt, K., Smith, T., Kothari, A., Raghavan, V, Tarpley, C., and Livingston, J., “The Hypersonic Space and Global Transportation System: A Concept for Routine and Affordable Access to Space”, Presented at the AIAA International Space-planes and Hypersonic Technology Conference, San Francisco, CA, April 2011.**
4. **Tarpley, C., Kothari, A., Raghavan, V., and Hellman, B., “Aerodynamic Analysis on the Rocket Based Combined Cycle Hypersonic Vehicle”, Presented at the 4^{th} CRASTE Conference, San Francisco, CA, October 2010.**
5. **Kothari, A., and Webber, D., “A Possible Route to Large Markets for Orbital Space Tourism by Using Reusable Rocket and Hypersonic Architectures”, Presented at the 4^{th} CRASTE Conference, San Francisco, CA, October 2010.**
6. **Kothari, A., Livingston, J., Tarpley, C., Raghavan, V., Bowcutt, K., and Smith, T., “A Reusable, Rocket and Airbreathing Combined Cycle Hypersonic Vehicle Design for Access-to-Space”, AIAA paper no. 2010-8905-918, Presented at the AIAA Space 2010 Conference, Anaheim, CA, August 2010.**

Recent Relevant Publications

7. Kothari, A., and Webber, D., "A Possible Route to Large Markets for Orbital Space Tourism by Using Reusable Rocket and Hypersonic Architectures", AIAA paper no. 2010-8600-366, Presented at the AIAA Space 2010 Conference, Anaheim, CA, August 2010.
8. Kothari, A., "Dual Flowpath Inward Turning RBCC Design as Second Stage of Fully Reusable TSTO System", Presented at the 3rd CRASTE Conference, Dayton, OH, October 2009.
9. Kothari, A., Raghavan, V., and Tarpley, C., "Future Responsive Access to Space Technologies Vision Vehicles Study – 18 Options", Presented at the 3rd CRASTE Conference, Dayton, OH, October 2009.
10. Kothari, A. "Technology Uncertainty Impact on Fully Reusable Launch Vehicle Systems", Presented at the 2nd RASTE Conference, Dayton, OH, May 2008.
11. Dissel, A., Kothari, A., Livingston, J., and Lewis, M., "Weight Growth Study of Reusable Launch Vehicle Systems", Journal of Spacecraft and Rockets, AIAA, Vol. 44, No. 3, May-June 2007, pp. 640-648.
12. Kothari, A., Raghavan, V., and Tarpley, C., "RBCC Upper Stage Modeling for Refueled FASST Concept", Presented at the 54th JANNAF Propulsion Meeting, Denver, CO, May 2007.
13. Dissel, A., Kothari, A., and Lewis, M., "Investigation of Two-Stage-to-Orbit Air-Breathing Launch Vehicle Configurations", Journal of Spacecraft and Rockets, AIAA, Vol. 43, No. 3, May-June 2006, pp. 568-574.
14. Dissel, A., Kothari, A., and Lewis, M., "Comparison of Horizontally and Vertically Launched Air-breathing and Rocket Vehicles", Journal of Spacecraft and Rockets, AIAA, Vol. 43, No. 1, Jan-Feb 2006, pp. 161-169.

Agenda

- Methodology
- 3 Studies
  - Access-to-Space - AFRL
  - TSTO Study - AFRL
  - Joint System Study – JSS (AFRL/NASA)
- RBS Applications

Methodology

- Integrated Design and Analysis - HySIDE
  - Parametric Geometry Synthesis
  - Aero, Engine, Thermal, TPS, Weights, Trajectory/Mission, Available Volume
  - Inside the Sizing / Closure Loop
  - Libraries of Reusable Components
  - Inverse Design, MOC, Reference Temperature, 1-D Combustor, Shock Expansion, POST, MissileDatcom
- Costing done Using Transcost
- Export to NURBS Geometry for CAD/CFD

Transcost 7.2

- *Handbook of Cost Engineering for Space Transportation Systems*
- Dr. Dietrich Koelle
- Historical Database of Launch System Costs
- Uses ManYear as a Costing Unit
- Based on System Weights
  - Development Cost
  - First Unit Production Cost
  - Updated by Gstattenbauer Thesis
- Maintenance based on Wetted Area - Rooney

Benchmarking HySIDE Results

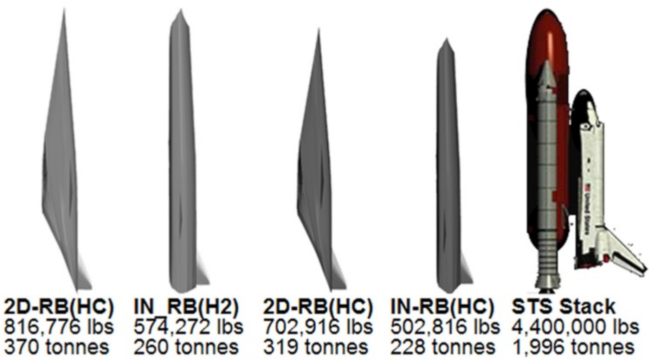
- US3D/RJPA/Vulcan Analysis by GHI
  - Isp within 6% across Mach 5 – 10 range
- Aerojet Robust Scramjet Isp
  - Consistent with expected JP/Methane Difference
- SRGULL Work for NASA LaRC
  - Thrust/Isp within 6%
- Inlet Euler CFD
  - Pressure and Mass Capture within 7%
- NASP Weights
  - Subsystem Weights based on NASP report
- Delta IV Medium
  - HySIDE system weights within 5%

Access-to-Space Study

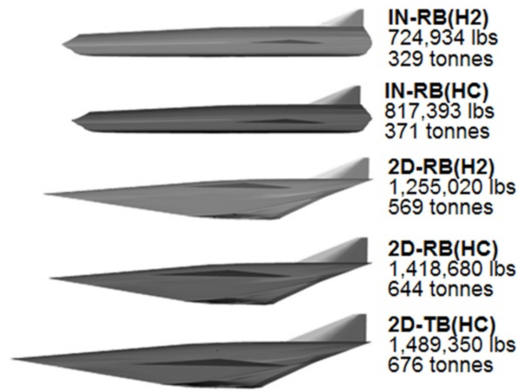
- Done for AFRL Air Vehicles Directorate
- 2006
- Compared 18 Configurations
- 20,000 lbs Payload to LEO
- SSTO & TSTO
- Horizontal & Vertical Launch

18 Access-to-Space Options Considered

SSTO-VTHL

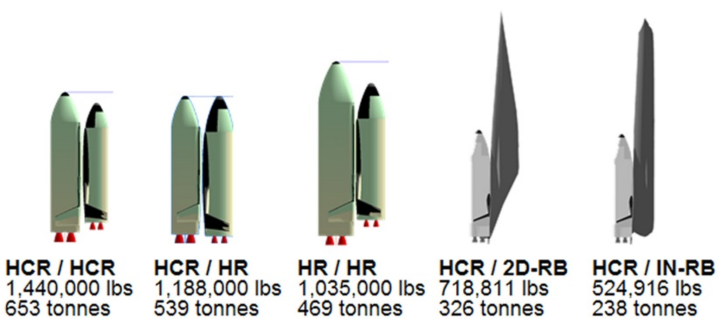


SSTO-HTHL

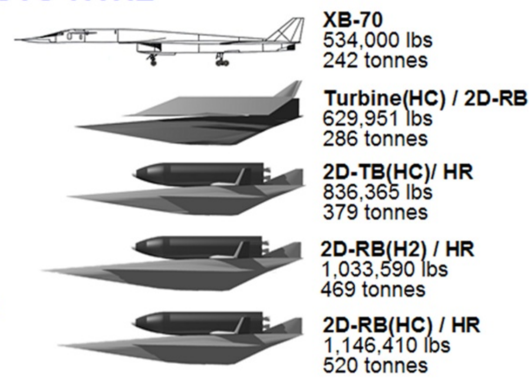


From :
Dissel, A., Kothari, A., Livingston, J., and Lewis, M., "Weight Growth Study of Reusable Launch Systems", Journal of Spacecrafts and Rockets, AIAA, Vol. 44, No. 3, May-June 2007

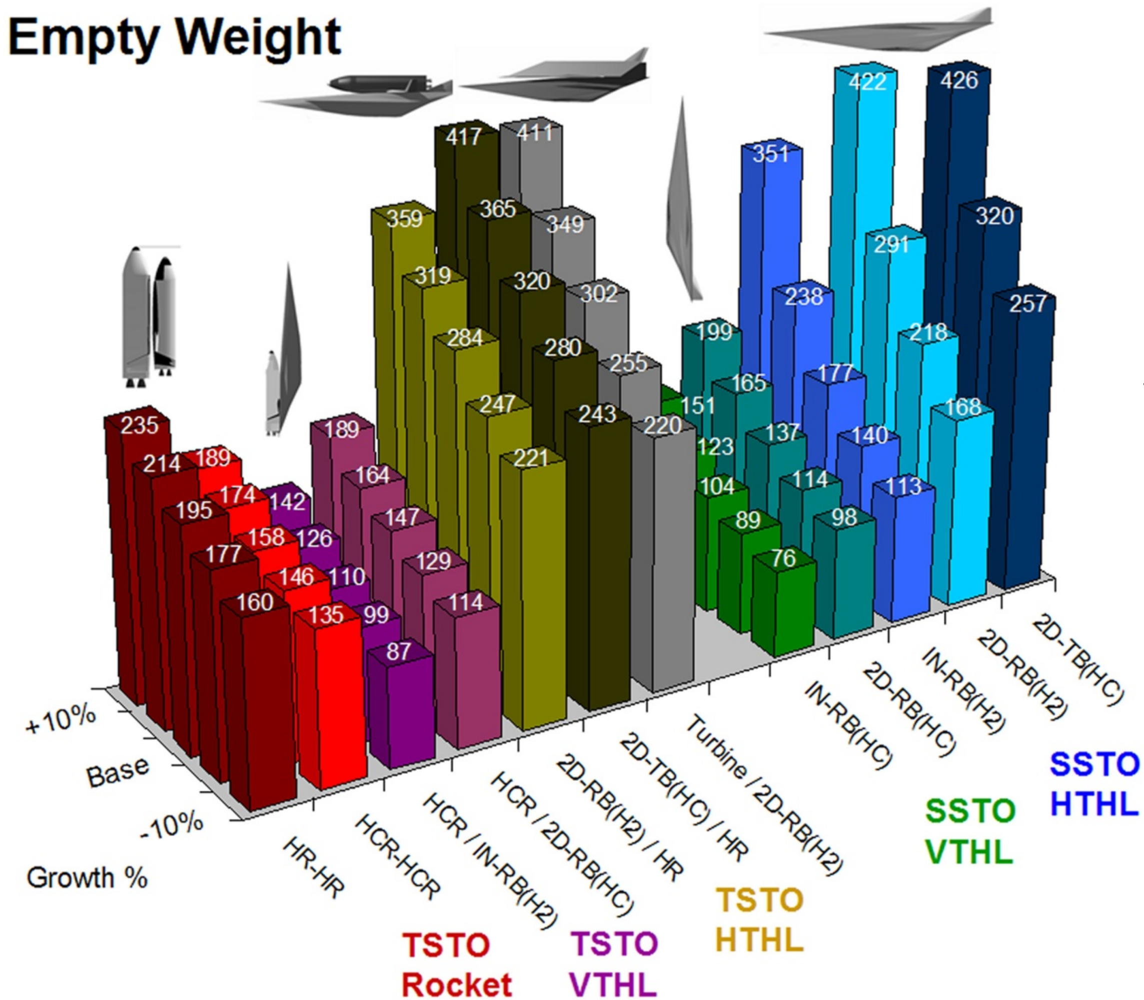
TSTO-VTHL



TSTO-HTHL

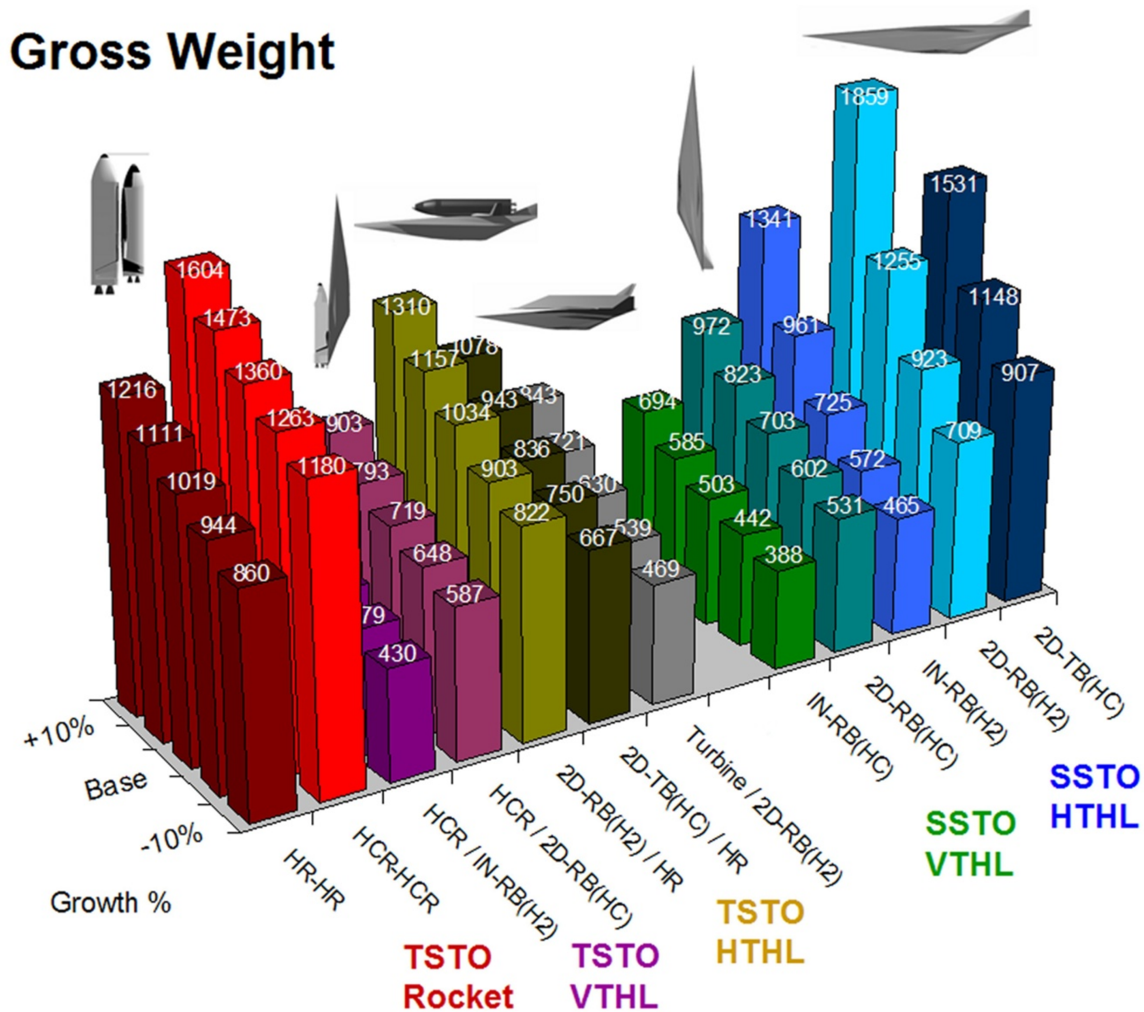


Empty Weight



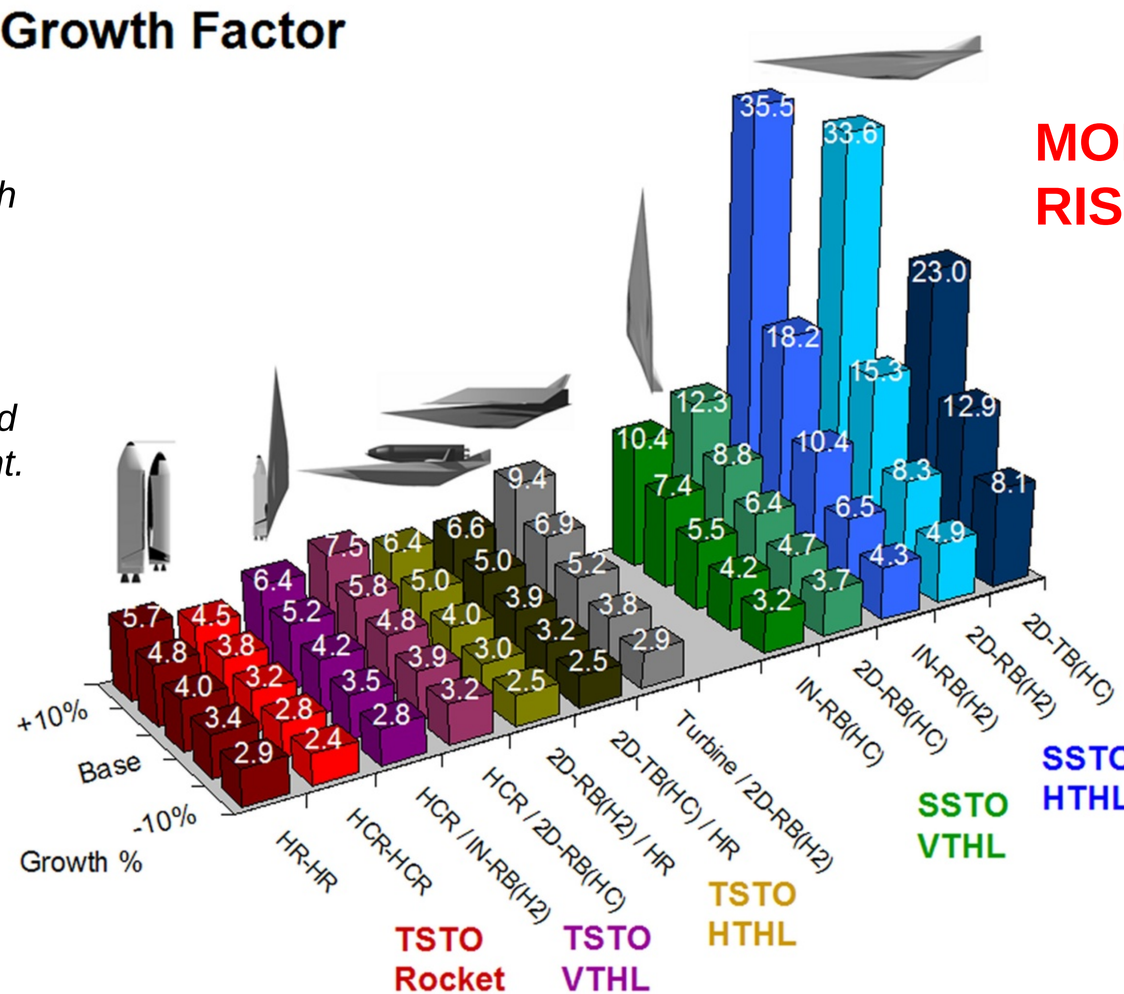
From :
Dissel, A., Kothari, A., Livingston, J., and Lewis, M., "Weight Growth Study of Reusable Launch Systems", Journal of Spacecrafts and Rockets, AIAA, Vol. 44, No. 3, May-June 2007

Gross Takeoff Weight



Growth Factor – Risk Measure

An empty weight growth factor is a measure of the scaling response in vehicle empty weight due to an increase in either the vehicle's fixed weight or scaling weight.



MORE RISKY

LESS RISKY

Access-to-Space Conclusions

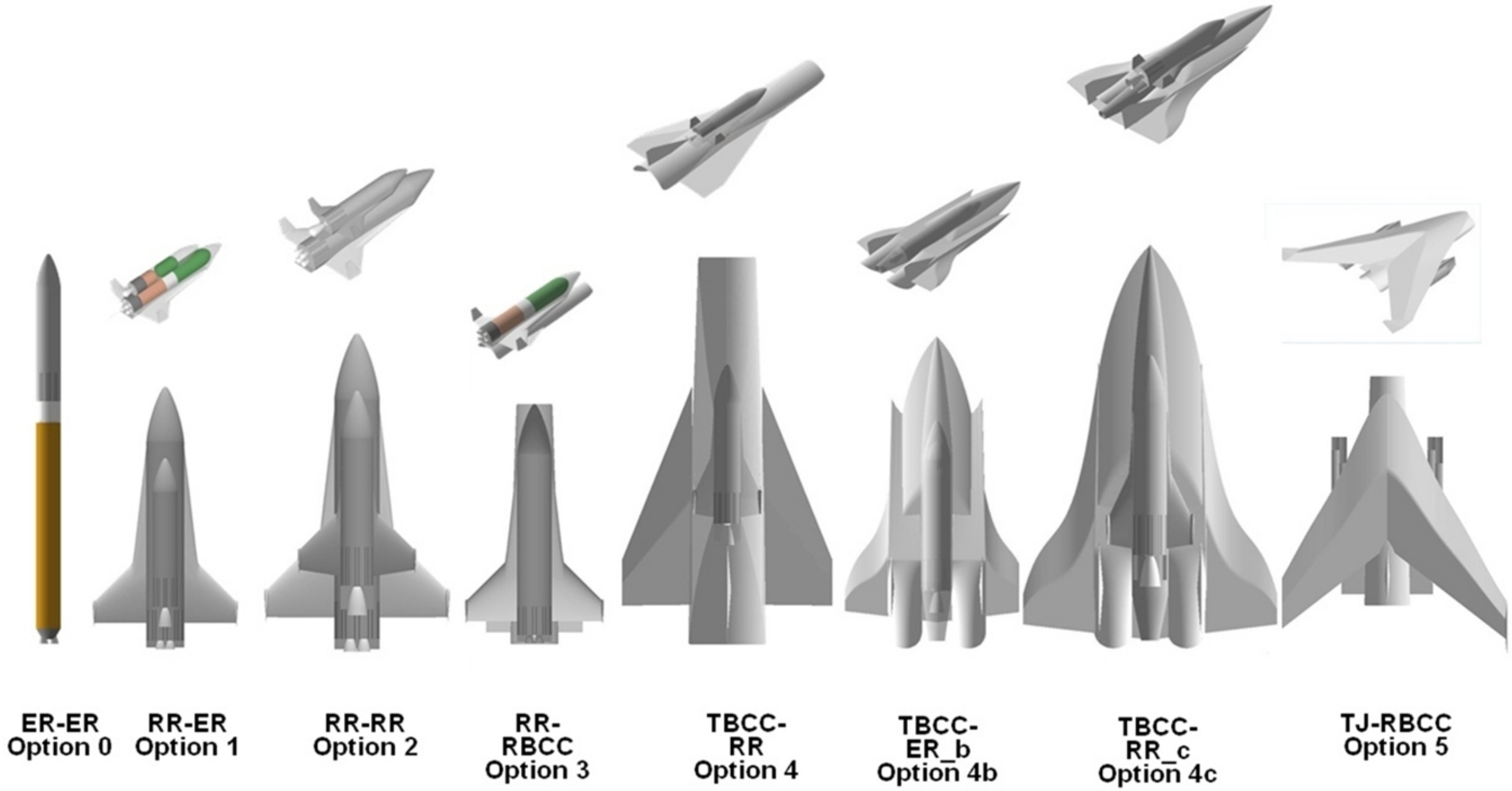
- Paper (#11) listed in the slide 6 which was published in JSR allowed us to judge the relative merits of various designs in terms of the their risk
- But it also allowed us to compare the relative GTOW and Empty Weights of Hydrocarbon boosted concepts as opposed to Hydrogen
- While the GTOW were heavier, the Empty Weights were smaller as can be seen from slide 13.
- LHC/LOX booster consistently proved more attractive than the LH2/LOX even for the Airbreather TSTO
- A higher density fuel is better suited for launch boost even if its ISP is lower.
- It was also found to be quite the opposite for the orbit insertion

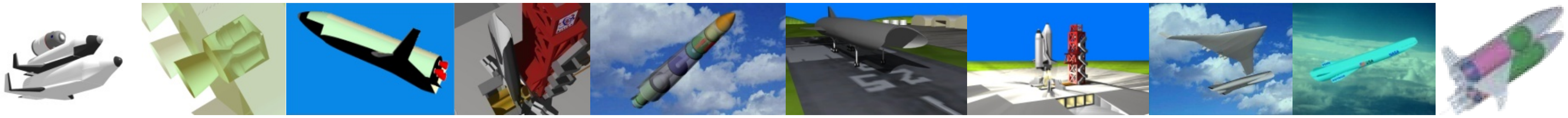
TSTO Study

- **TSTO Study For the Office of Air Force Chief Scientist**
- **Initiated by Dr. Mark Lewis and Dr. Ray Moszee**
- **2007**
- **Also Access-to-Space**
- **20,000 lbs Payload to LEO**
- **Eight Options**
  - **Expendable & Reusable**
- **Developed Cost Model Using Transcost**

TSTO Options

These Options Done for the US Air Force, AF/ST

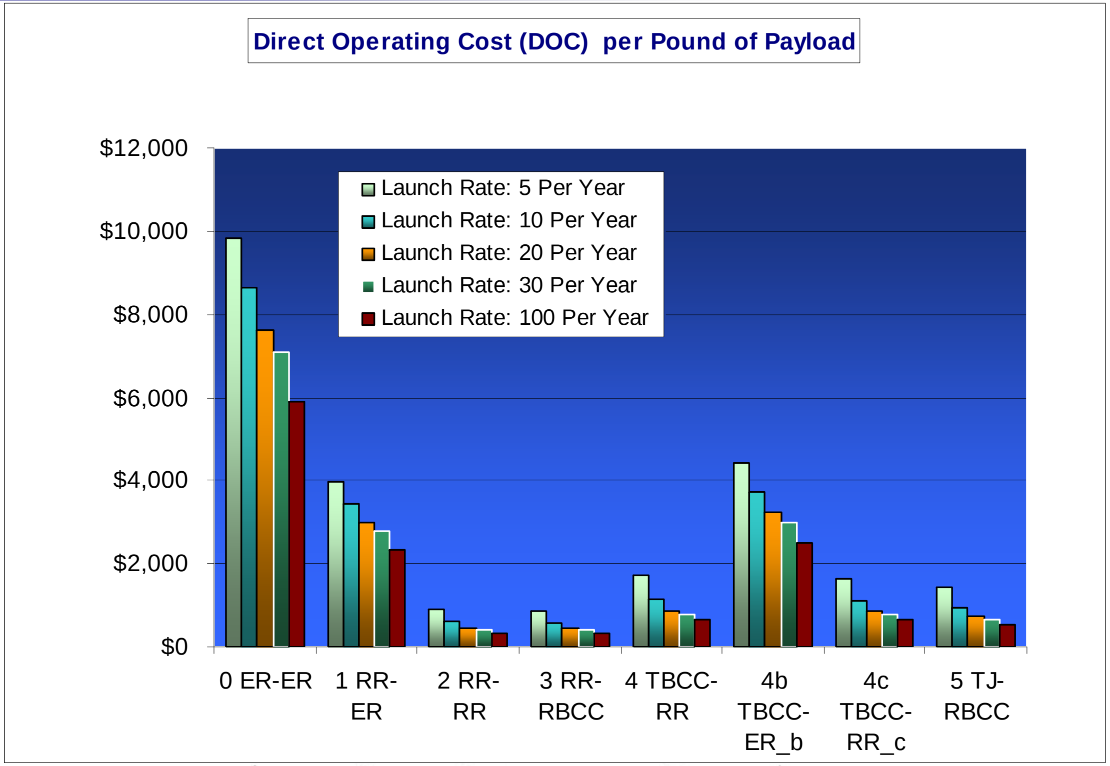


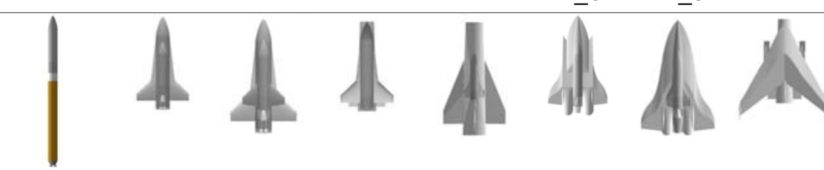


Distribution A: Approved for public release; distribution unlimited

Direct Operating Cost (DOC) per Pound of Payload for Different Launch Rates

Expendables have much higher DOC per pound of Payload





Hybrids have mid level DOC per pound of Payload

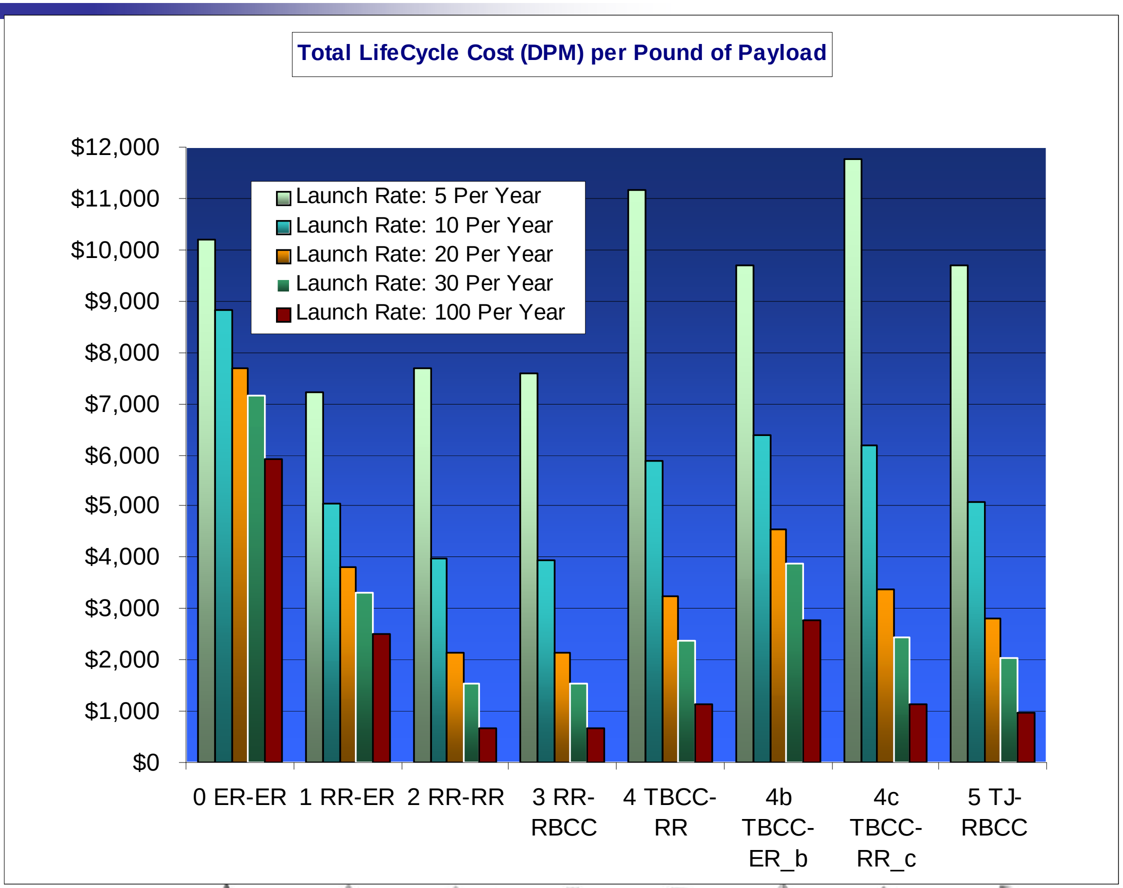
~$340 per pound price achievable with rate of 100+ flights with reusable architecture

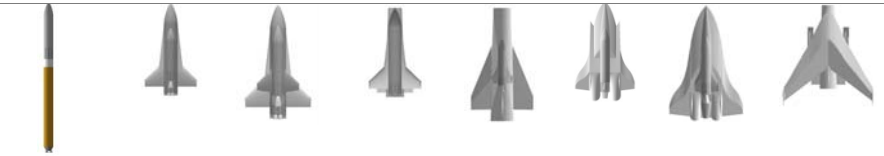
Reusables are the only way to drastically reduce the DOC per pound of Payload

Options 2 & 3 have the lowest DOC regardless of flight frequency

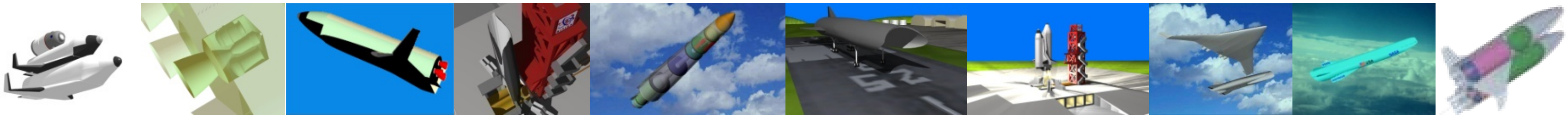
Total Development, Procurement & Maintenance Costs (DPM) per Pound of Payload for Different Launch Rates

Hybrids have lowest DPM for about 5 flights per year rate but Options 2 & 3 are quite competitive





Option 2 & 3 have the lowest DPM Cost for 10 or greater launch rates



Distribution A: Approved for public release; distribution unlimited

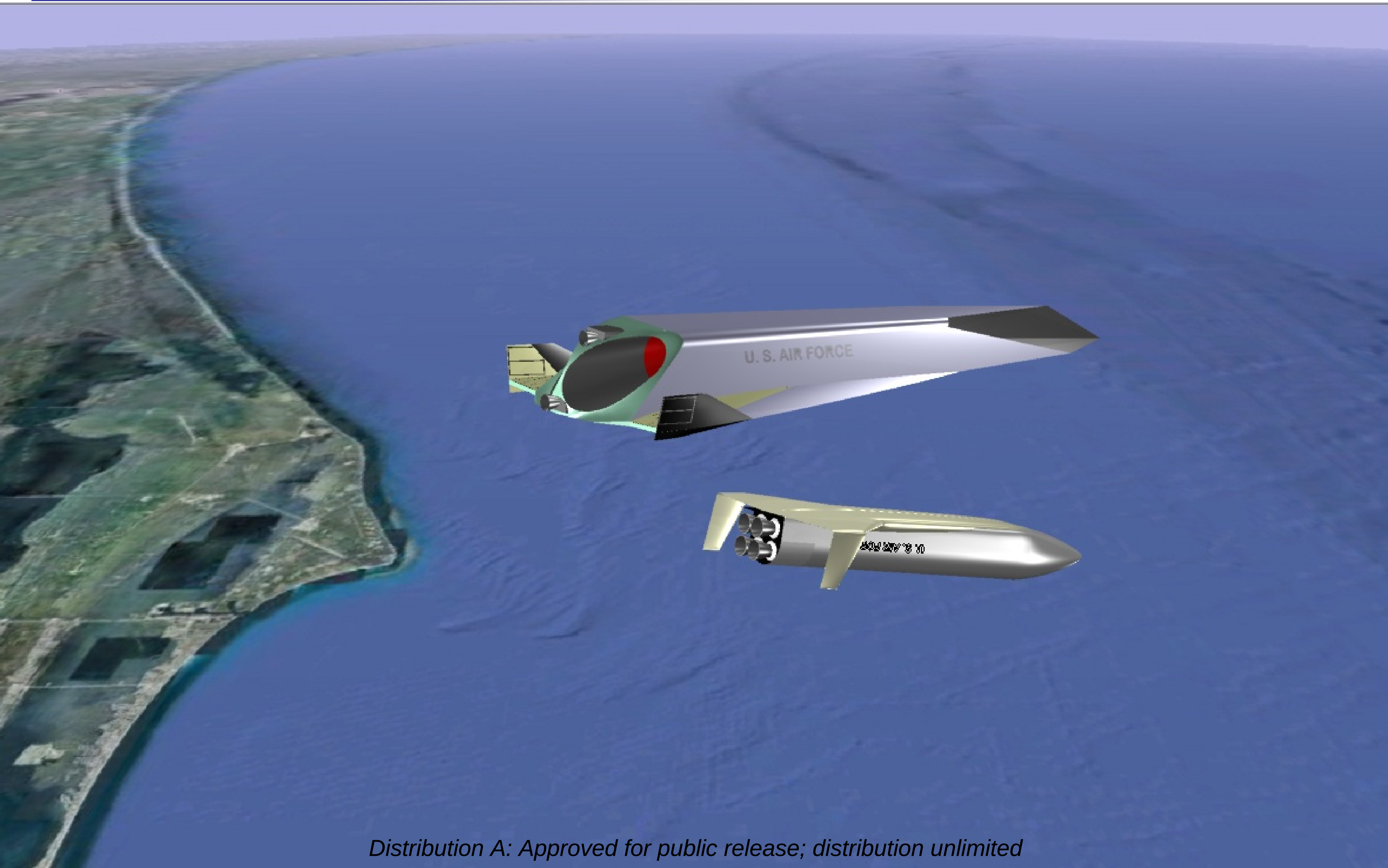
TSTO Study Conclusions

- **The decrease in Direct Operating Cost (DOC) by employing FULLY REUSABLE architecture is quite significant**
- **While this would entail significant Development Cost, when combined with DOC, the benefits still bear out for greater than approximately 10 flights a year rate**
- **The study concluded that the development of hybrid system makes sense and that the fully reusable system should be the next step**

Air Force / NASA Joint System Study

- AFRL / NASA – 2009
- Co-Chaired by Dr. Werner Dahm with participation of Dr. Moszee
- Access-to-Space - 20,000 lbs
- Tools Assessment via 3 Configurations
  - RR/RR
  - TBCC/RR
  - RR/Scramjet 2nd Stage
- Astrox led Team developing last of above three options and the design of the Scramjet 2nd stage

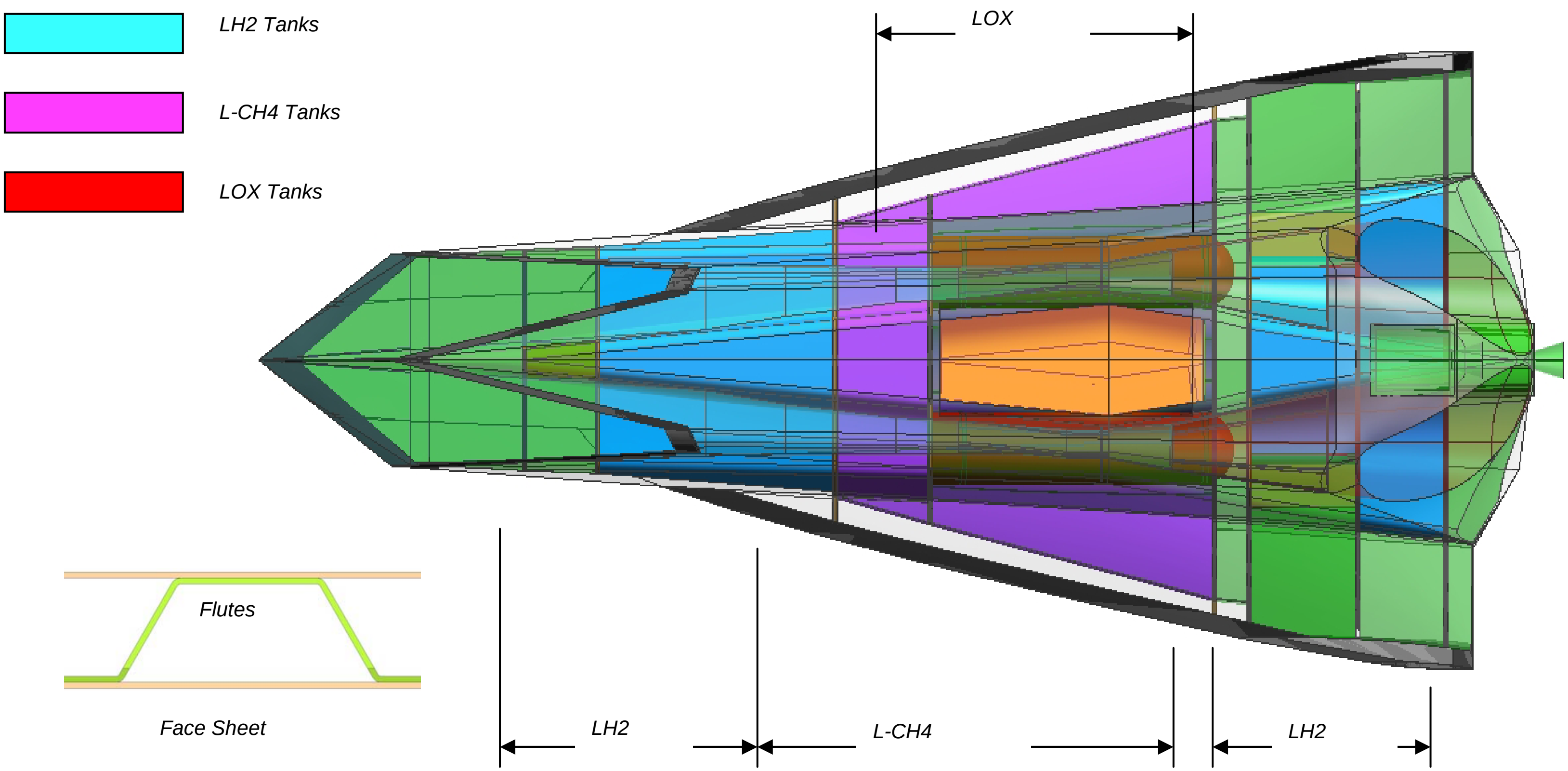
2nd Stage Scramjet / RBS



Reusable Upper Stage – Innovative Design Features

- Engine-on-top helps at staging, reentry and landing
- Dual flowpath reduces the engine size and provides usable volume
- Inward turning Inlet
- LE shaped for Vehicle Configuration Optimization
- Methane for airbreathing, ~6.2 times denser than LH2
- Heavy TPS needed only on one side
- Smaller wings and landing gear (designed for landing instead of takeoff)
- Rocket weight much smaller than turbine weight/volume

2nd Stage Scramjet Tank Layout



Distribution A: Approved for public release; distribution unlimited

Both Stages Summary (older results)

	Booster	Orbiter	Together
Payload (lbs)	None	20,000	20,000
Empty Weight with DM (lbs)	67,460	117,492	184,952
Dry Margin (lbs)	10,119	17,624	27,743
Gross Weight (lbs)	642,650	558,152	1,200,802
Startup Propellant (lbs)	13,835	0	13,835
Length (ft)	101.24	157.85	163.57
Width (ft)	52.92	66.71	66.71
Height (ft)	15.73	22.18	31.38

Joint System Study Conclusions

- Analysis is Incomplete
- Assumptions need to be cross-checked
- Force Accounting
  - Cowl-to-Tail or Tip-to-Tail
  - Allocate $ to Change Systems

Other Applications of the RBS Capability

In Addition to Access-to-Space, RBS Enables:

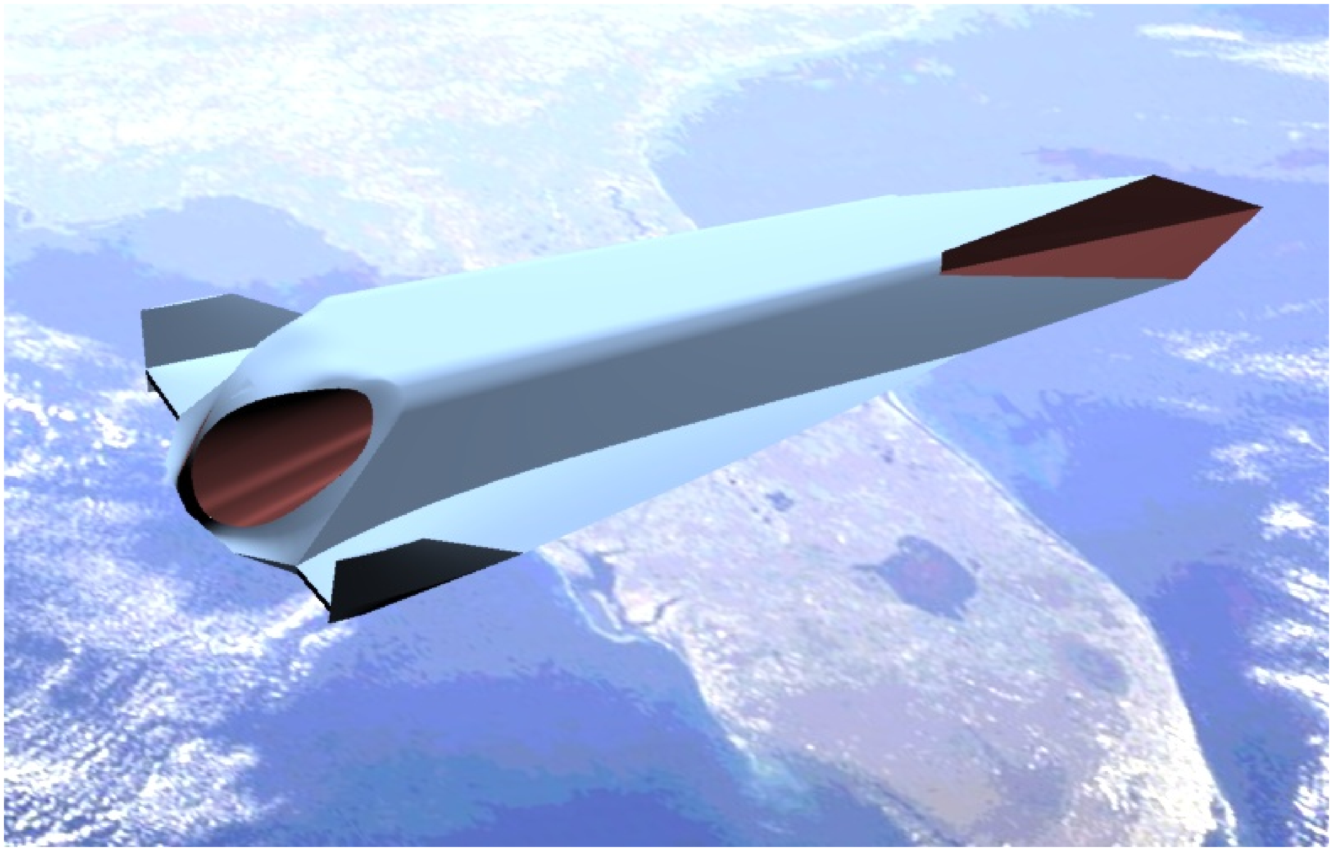
1. **ISR platform: As the booster stage for a hypersonic scramjet vehicle**
2. **Forward Based Global Strike: As the booster stage for a two stage system with second stage being a hypersonic scramjet vehicle**
3. **Global Strike from CONUS: As the booster stage for a two stage system with second stage being an expendable or reusable rocket OR a hypersonic once around scramjet vehicle**
4. **Commercial Orbital Tourism: As the booster stage for a two stage system with second stage being a reusable rocket OR a hypersonic once around scramjet vehicle**

Other Applications of the RBS Capability

- **When the ATS use is combined with the above, greater than 10 flights a year rate may be eminently possible and a considerable saving can be realized**
- **It is the "Reusable" element in RBS that makes this possible**

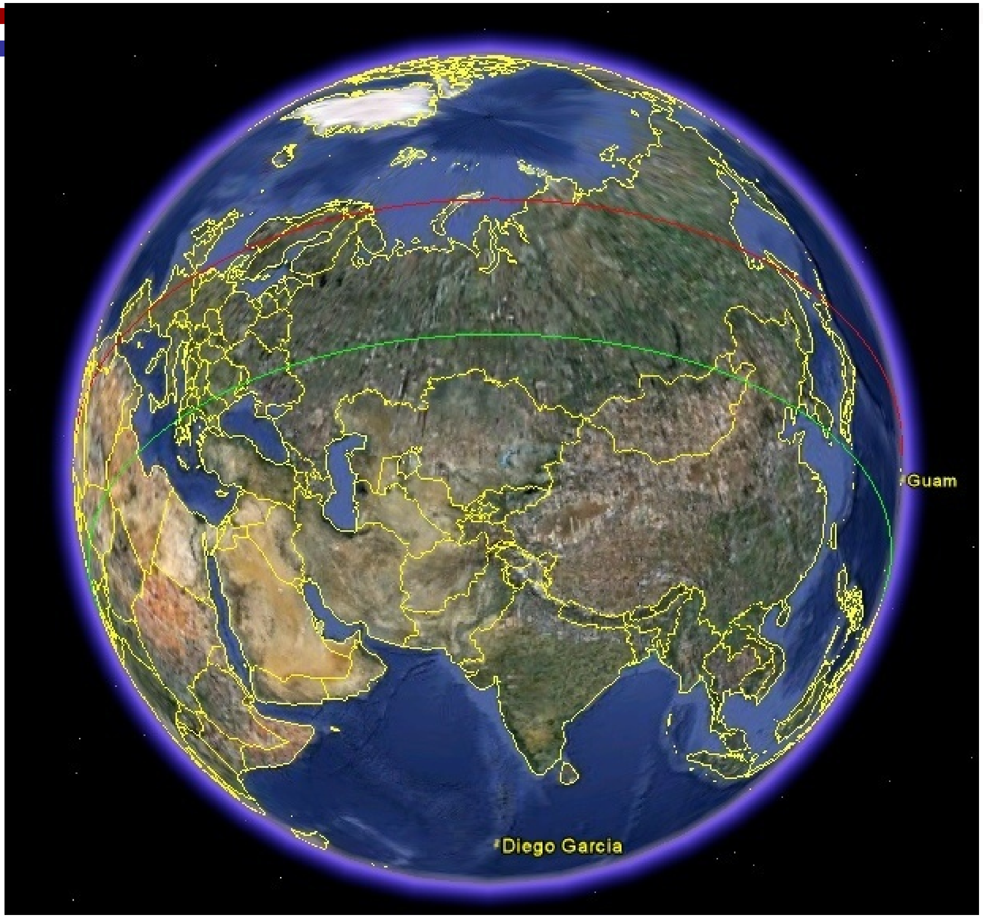
In the ISR application shown in the next three slides, the rockets are reusable and are embedded in the single stage herein. Separating the booster rocket segment using an RBS would make the system lighter and less sensitive to growth as seen from slide 13

Scramjet as ISR Platform

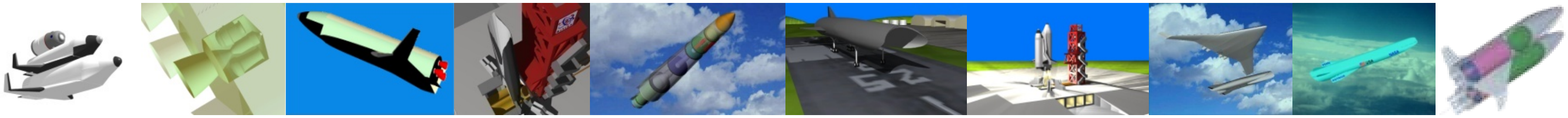


Ref: Technology Horizons Report, US Air Force, 2010

Scramjet as ISR Platform



Red: 5000 nm Great Circle from Diego Garcia
Green: 4000 nm Great Circle from Diego Garcia



Conclusions

- Hydrocarbon booster is more attractive than a LH2/LOX booster
- Full reusability significantly reduces the DOC cost
- Full reusability substantially reduces even the DPM cost
- Applications such as ISR and Global Strike in addition to the ATS can have an impact by increasing the frequency
- Commercial Space Transportation (e.g. Fuel Depot, Space Tourism, Space Debris Removal) will benefit from the technology
- Multiple beneficial impacts from RBS development