Three Generations of Aerospace Engineering:

Dr. William F. Ballhaus, Sr.  President, Beckman Instruments (ret.)
Dr. William F. Ballhaus, Jr.  President and CEO, The Aerospace Corporation (ret.)
Dr. William L. Ballhaus  President, BAE Network Systems

Stanford University
50th Anniversary of Aeronautics and Astronautics Department

May 10, 2008
Aircraft Design and Engineering
1940s – 1960s

Dr. William F. Ballhaus, Sr.
Design Approaches

• Objective prior to 1950s was to design to requirements

• Integrated systems design began in 1950s with missiles such as SNARK
A-26 Design

INLET VELOCITY 350 MPH
18" VELOCITY 79.9 MPH
OIL COOLER DRAG 313 Pounds
INBOARD OIL COOLER DRAG 16 Pounds
DRAG SAVING 297 Pounds
OIL COOLER HEATING AIR CAUSES THRUST AS EXHAUST AIR IS HIGHER VELOCITY THAN INTAKE AIR
D-558-1

Courtesy of NASA
D-558-2 (Supersonic)
D-558-2 Design
F3D-2
F4D-1
F-89 Design
SNARK Missile

![SNARK Missile Image](image-url)
SNARK Missile
HAWK Missile

Courtesy of U.S. Army
T-38

Courtesy of U.S. Air Force
F-5E

Courtesy of U.S. Air Force
Single Stage Earth Satellite
Affordable Space Launch
1970s – 2000s

Dr. William F. Ballhaus, Jr.
Affordable Space Launch

Goal…
- Operations costs and timelines like these

Present reality…
- Slow response
- High cost

The goal of affordable space lift not yet reached
The Modern EELV Workhorses

- Built on 49 years of practical experience
  - Originally, adapted ICBMs (U.S.)
  - Many low-risk step upgrades
    - Modest investment for modest improvements
  - Design, production, and operations geared toward steady-state, pre-scheduled launch of high-value payloads

Historically, ELV launch cost has been over $6,000 per pound to LEO
A Major Attempt to Revolutionize Space Transportation
The Space Shuttle (Program started in 1972)

“Space Truck”

Launch cost goal
$100 / lb
to LEO

Concept, funding, and technology insufficient to achieve goals
## Other Attempts to Revolutionize Space Transportation

<table>
<thead>
<tr>
<th>Program</th>
<th>Goal</th>
<th>Reason Canceled</th>
<th>Funds Spent (FY05 $B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>National AeroSpace Plane (NASP)</td>
<td>• Aircraft-like operations&lt;br&gt;• $100 / lb to LEO</td>
<td>Cancelled due to&lt;br&gt;• Technology&lt;br&gt;• Cost and schedule</td>
<td>2.6</td>
</tr>
<tr>
<td>Advanced Launch System (ALS)</td>
<td>• Heavy lift for SDI&lt;br&gt;• $300 / lb to LEO</td>
<td>Cancelled due to&lt;br&gt;• $16B estimated cost&lt;br&gt;• National priorities</td>
<td>0.8</td>
</tr>
<tr>
<td>X-33 / VentureStar</td>
<td>• SSTO&lt;br&gt;• $1000 / lb to LEO</td>
<td>Cancelled due to&lt;br&gt;• Technology&lt;br&gt;• Cost and schedule</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Since Shuttle, over $5.4B spent to achieve more affordable, responsive launch
Of many attempts, only Pegasus/Taurus is presently operational.

Pegasus original launch cost projection: $6M. Current projection: $27M.
Why Is This So Hard?

- Must achieve ~25,000 ft/s in under 8 minutes
- Liftoff mass grows exponentially with increasing margins
- Compared to aircraft
  - Thrust-to-weight: Greater by order of magnitude
  - Power per pound: Greater by 1–2 orders of magnitude
  - Aerodynamic loads: Greater by order of magnitude
The Challenge of Affordability

• Historically, rockets optimized for performance over operability

• Consequences
  – Sophisticated hardware with low margins
    – Maximizes power output—minimizes weight
    – Reduces operability, maintainability, reusability
  – Extensive recurring mission assurance processes
    – Maximizes reliability of low-margin, low-rate systems
    – Costly and time-consuming

Affordability requires a different approach
Spacelift Vehicle Options

- **Expendable**
- **Partly Reusable**
  - Reusable booster with expendable upper stages
- **Fully Reusable**
  - All Rocket (Two-Stage-to-Orbit (TSTO))
  - All Hypersonic (TBCC + RBCC)*
  - Rocket and Hypersonic (RBCC)

*TBCC = Turbine-Based Combined Cycle
*RBCC = Rocket-Based Combined Cycle
### % Reusable vs. % Expendable Hardware

(This example based on 15 Klb to LEO capability)

<table>
<thead>
<tr>
<th></th>
<th>Reused Hardware (Klb)</th>
<th>Expended Hardware (Klb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RLV</td>
<td>0</td>
<td>196</td>
</tr>
<tr>
<td>ELV</td>
<td>33</td>
<td>0</td>
</tr>
<tr>
<td>RBS (Reusable Booster System)</td>
<td>12</td>
<td>61</td>
</tr>
</tbody>
</table>

#### Fully Reusable RLVs
- Are big because orbiter must go to/from orbit (80% of orbited mass is the orbiter)
- Drive higher development and production costs

#### Fully Expendable ELVs
- Expend large amounts of hardware
- Drive higher recurring costs

#### RBS
- Avoids 64% of ELV’s expendable hardware
- Avoids 69% of RLV’s reusable hardware
- Balance ELV-RLV production and development costs, resulting in lower LCC for most cases

RBS has potential for more cost-effectiveness
### Design Region Sensitivity

<table>
<thead>
<tr>
<th>Propellant Mass Fraction</th>
<th>Vehicle Gross Weight (10^6 lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.76</td>
<td>0</td>
</tr>
<tr>
<td>0.78</td>
<td>1</td>
</tr>
<tr>
<td>0.80</td>
<td>2</td>
</tr>
<tr>
<td>0.82</td>
<td>3</td>
</tr>
<tr>
<td>0.84</td>
<td>4</td>
</tr>
<tr>
<td>0.86</td>
<td>5</td>
</tr>
<tr>
<td>0.88</td>
<td>6</td>
</tr>
<tr>
<td>0.90</td>
<td>7</td>
</tr>
</tbody>
</table>

**RBS Configuration**: Reusable 1st stage, Expendable upper stages

**RBS Configuration Facilitates Robust Margins**

**State-of-the-Art for Reusable Systems**

**1-Stage RLV (SSTO)**

**2-Stage RLV (TSTO)**

**Leads to Compromise of Operability**

RBS configuration facilitates robust margins
Reusable Booster System (RBS)
RBS = Reusable Booster + Expendable Upper Stages

Upper stages expended. Booster returns to launch base.
Lessons Learned: Developing Operational Capability

• Systems Engineering
  – Design for robust operations, reliability, and maintainability
  – Maintain mission assurance standards

• Development Approach
  – Take smart risk-controlled steps—Implement block approach
    – Baseline only validated technologies
    – But still invest in technology options for future blocks

• Economics
  – Recognize unpredictability of future launch rates and spacecraft weights
    – Base system on realistic launch rates
    – Select system with flexibility to affordably respond to changes in rates and weights
High-Speed Flight Environment

199 Flights (Fleet of 3)

High Speed
Mach 6.33, with Inconel hot structure

Low Recurring Cost
~$1.6M / flight (inflated to FY04)

Fast Operations
< 48 hours turn time

Robust Rocket
XLR-99: Throttleable, restartable,
24 mean flights between overhaul

Relevant government experience
45 years of development provide strong technical base for RBS development
Role of RBS Demo in Pursuing Affordability

- Turn time and manpower database
- Safe return to base
- Controllability characteristics
  - System integration and performance
    - Structure / Tanks / Thermal
    - Reusable Propulsion
    - Mechanical / Electrical / Comm
  - Autonomous flight control
  - Upper stage separation characteristics
- Create operating cost database

Uncertainties should be resolved via demonstration
Key data needed: operability and cost
Why RBS Could Succeed Where Others Failed

Prior Attempts

<table>
<thead>
<tr>
<th></th>
<th>Shuttle</th>
<th>NASP</th>
<th>X-33</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/Thermal requirements for reusable H/W</td>
<td>Mach 25</td>
<td>Mach 25</td>
<td>Mach 15–25</td>
</tr>
<tr>
<td>Operating margins for robust hardware</td>
<td>Minimal</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Mature subsystems</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Complexity (number and types of systems)</td>
<td>High</td>
<td>Extreme</td>
<td>Extreme</td>
</tr>
<tr>
<td>Technology maturity at program start</td>
<td>Low-MOD</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Affordability at realistic launch rates</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Integration and Operability</td>
<td>High</td>
<td>Extreme</td>
<td>Extreme</td>
</tr>
</tbody>
</table>

RBS

<table>
<thead>
<tr>
<th></th>
<th>Demo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/Thermal requirements for reusable H/W</td>
<td>Mach 3–7</td>
</tr>
<tr>
<td>Operating margins for robust hardware</td>
<td>Robust</td>
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<tr>
<td>Mature subsystems</td>
<td>Yes</td>
</tr>
<tr>
<td>Complexity (number and types of systems)</td>
<td>Low</td>
</tr>
<tr>
<td>Technology maturity at program start</td>
<td>HIL</td>
</tr>
<tr>
<td>Affordability at realistic launch rates</td>
<td>Yes</td>
</tr>
<tr>
<td>Integration and Operability</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

Past attempts were high risk. RBS is a lower-risk, more easily managed development.
Why Won’t Industry Fund the RBS?

SHORT-TERM RESULTS ARE IMPORTANT.

AND I EXPECT YOU TO PRODUCE THEM.
Why Won’t Industry Fund the RBS? (Cont’d)

BUT NOT AT THE EXPENSE OF OUR LONG-TERM GOAL.

QUARTERLY EARNINGS.
Government “Patient Capital” Investment

RBS Internal Rate of Return

$3.7B development (includes 10-flight orbital demo program, DDT&E, and facilities)
FY06 constant-year dollars
20 years of operations

Potentially cost-effective for realistic launch rates
The Way Ahead

• There is a need for more affordable, reliable, operable launch – but no government consensus on the way ahead

• Integrated government launch system development plan is needed now to
  – Define the next-generation system
    – 10- to 15-year lead time
  – Capture the benefit of annual government R&D investments and avoid the ineffective multi-$billion adventures of the past
  – Encourage industry investment
  – Maintain industrial base for launch system development

Government executive leadership required
Winston Churchill

“The Americans will always do the right thing... after they’ve exhausted all the alternatives.”
Integrated Networked Systems
2000s – Future
Dr. William L. Ballhaus
Since 2000, significant advances in communications and information technology

Today’s platforms increasingly operate as nodes within a broader, integrated, and networked system

Mission effectiveness is a function of platform and network performance

“Integrated System” optimization is the goal, rather than “most advanced” platforms

Unintended consequences... Cyber security is a critical concern
Computing Power Increases with Dramatic Reductions in Cost

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Server 1998</th>
<th>Server 2008</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock Cycles</td>
<td>550</td>
<td>3000</td>
<td>Computers clock six times faster today</td>
</tr>
<tr>
<td>Processing Power</td>
<td>1</td>
<td>40</td>
<td>Computers forty times faster today</td>
</tr>
<tr>
<td>Number of Chips</td>
<td>2</td>
<td>2</td>
<td>Computers have same number of processors today</td>
</tr>
<tr>
<td>Total Cores</td>
<td>2</td>
<td>8</td>
<td>Computers have four times as many cores today</td>
</tr>
<tr>
<td>Hard Drive Size (GB)</td>
<td>8</td>
<td>1000</td>
<td>Hard drives 125 times bigger today</td>
</tr>
<tr>
<td>Memory Configuration</td>
<td>512</td>
<td>16384</td>
<td>32X the memory today</td>
</tr>
<tr>
<td>$/MB</td>
<td>4</td>
<td>0.025</td>
<td>Memory 160X cheaper today</td>
</tr>
<tr>
<td># Transistors</td>
<td>19000</td>
<td>1600000</td>
<td>84X the transistors today</td>
</tr>
</tbody>
</table>
Communication Devices Have Gotten Smaller

AMPS – Advanced Mobile Phone Service
IC – integrated circuit
PCMCIA – Personal Computer Memory Card
International Association
Increasing Connectivity

Advances in Communications and Information Technology have led to an increasingly connected world.
Extending the Network to the Tactical Edge

Optimizing requires engineering the system from an operations/user perspective, rather than a platform perspective... Tough Challenge!
Networked-System Value Chain

Integrated System Capabilities Required
- System modeling and simulation
- Analysis of Alternatives
- Business process re-engineering

Optimizing the contribution of Platforms requires optimization at the “Integrated System” level
Air Domain Example: Modern Battle Spaces Demand Mission Effectiveness Augmentation

- **MEAS® is a Feedback Control System that Optimizes Mission Effectiveness**
  - Rapid, Optimized Responses Including Multi-vehicle Strategies, Tasking, Schedules, and Routes
  - Spans Single Vehicle to Heterogeneous, Multi-Vehicle Constellation Operations
  - Manned and Unmanned Vehicles
  - Variable Level of Autonomy Tailored to the Battlespace Situation

- **Example: Challenging ISR Scenario**
  - Track/ID high priority targets in challenging terrain intermixed with non-combatant vehicles
  - Synchronize ISR assets to balance track maintenance with wide-area surveillance/recce
  - Goal: extremely long track duration with highly accurate identification

<table>
<thead>
<tr>
<th>Performance of MEAS over manual</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time targets in track</td>
<td>123%</td>
</tr>
<tr>
<td>Time in track with correct label</td>
<td>168%</td>
</tr>
</tbody>
</table>
Space Domain Example:
Space Assets as an Enabler in Air, Land, and Sea Domains

- Space assets are an enabler to:
  - Critical national security capabilities (e.g., missile defense, precision strike, command and control)
  - A broad spectrum of missions from Tactical operations to National Intelligence

- The reliance on space assets and capabilities by users into multiple domains is increasing

> 50X increase in SATCOM bandwidth per soldier since 1991
Unified Ground Architecture

“As Is” Approach

Tactical
- Control
- Quality
- Product Formation

National
- Control
- Quality
- Product Formation

Future
- Control
- Quality
- Product Formation

“To Be” Approach

Sensor Dependent Strings

Common Image Framework Mission Independent

Future – Common Image Framework

Unified ground will enable near real-time sensor fusion and processing to improve mission effectiveness
Sensor Fusion Example

“Highly Capable” Asset

Commercial Satellite Raw Image

Commercial Imagery Post Processing

Enhanced performance from a commercial imaging satellite augmented with near real-time advanced ground-based processing
The Challenge… Understand and Optimize the System

“We’re going to look like damn fools if this is just a shower.”
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