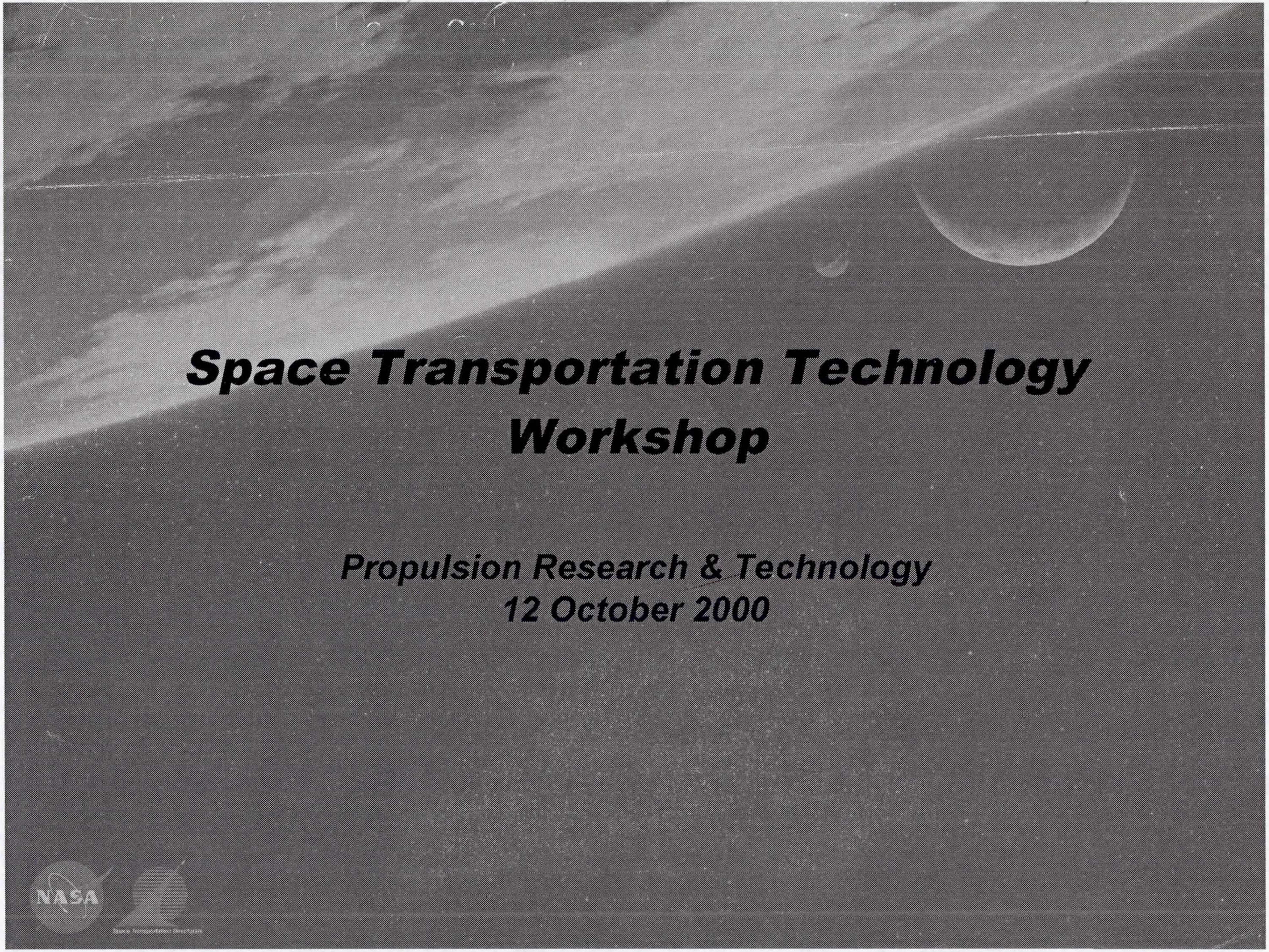
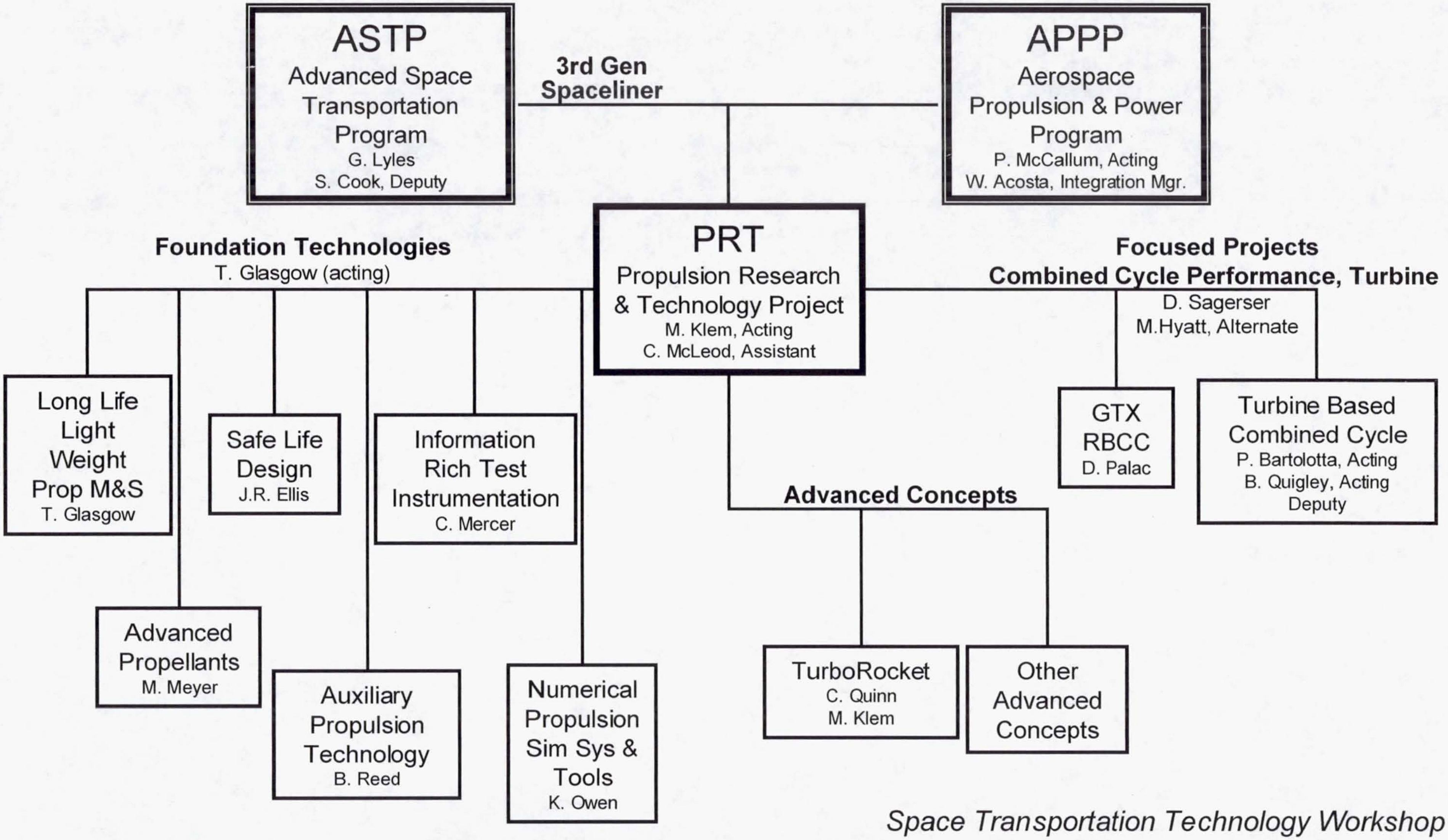
CONF PROCEEDINGS / IN 116 / PRIMARY 2076p 20000157389



Space Transportation Technology Workshop

Propulsion Research & Technology
12 October 2000



ASTP
Advanced Space Transportation Program
G. Lyles
S. Cook, Deputy

3rd Gen Spaceliner

APPP
Aerospace Propulsion & Power Program
P. McCallum, Acting
W. Acosta, Integration Mgr.

PRT
Propulsion Research & Technology Project
M. Klem, Acting
C. McLeod, Assistant

Foundation Technologies
T. Glasgow (acting)

Long Life Light Weight Prop M&S
T. Glasgow

Advanced Propellants
M. Meyer

Safe Life Design
J.R. Ellis

Auxiliary Propulsion Technology
B. Reed

Information Rich Test Instrumentation
C. Mercer

Numerical Propulsion Sim Sys & Tools
K. Owen

Advanced Concepts

TurboRocket
C. Quinn
M. Klem

Other Advanced Concepts

Focused Projects
Combined Cycle Performance, Turbine
D. Sagerser
M.Hyatt, Alternate

GTX RBCC
D. Palac

Turbine Based Combined Cycle
P. Bartolotta, Acting
B. Quigley, Acting Deputy

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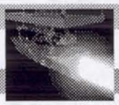
PR&T Project Level Organization

- Combined Cycle Flowpath Performance
  - –RBCC
    - GTX
    - ART
  - –TBCC
- Foundation Propulsion Technologies
  - –LLLWP Materials & Structures
  - –Safe Life Design
  - –NPSS
  - –Information Rich Test Instrumentation
  - –Advanced Propellants
  - –Auxillary Propulsion Technology
- Advanced Concepts
  - –Turbo Rocket
  - –Other Concepts

Major Milestones ▲ Commit to Flight ▲ Configuration Decisions ◆	2001	2002	2003	2004	2005	2006
	▲ 1st Demo Selected	▲ Product.Release Rocket Sys Sim.	▲ Demo reaction transfer modeled PMC	▲ 2nd Demo Selected		
Propulsion Technology & Integration						
RBCC				Mature for 3rd Demo		
GTX		▲ Baseline Combust Perf	▲ Baseline for SSTO Mixer/Combust. ▲ SSTO Nozzle Expt.	Mature for 3rd Demo		
ART		▲ Complete				
TBCC	Down.-select concept. design to concept. engine cycle & TBCC config. ▲	▲ ▲	▲ Concept. design for TBCC concept design & risk mit. strat. ▲	Mature for 3rd Demo Sub-scale demonstrator engine PDR	 Sub-scale demonstrator engine DDR ▲	*RAC, PDET, SEC Complete critical component rig testing ▲
Long Life Light Weight Propulsion Materials and Structures	Exp. design for high conductivity alloy dev. Survey of gen3 vehicle needs for leading edges	▲ Char. prototype CMC nozzle sub-elements ▲ Initiate design of high fidelity quick access rocket exhaust expos. rig	▲ Demo reaction transfer modeled PMC ▲ Therm. perform. cooled CMC panel ▲ Screen regen. cooled concepts for CMC thrust chambers Perform aeroconvective tests of first concepts	▲ Initiate funded coating development	▲ Oxidation protection scheme for CMC nozzles developed	*Ultra Safe, HOTPC, 0CO ▲ Demonstrate affordable PMC for 750°F applications
Safe Life Design	▲ Procurement of CMC(Sic/Sic) Panels-coupon level tests Est. correlation between CMC Component NDE data and coupon level data for damage dev. under mech. loading	▲ Complete screening of ultra hi-temp PMC w/optimized 3D fiber Architecture (TRL1)	▲ Complete prelim. tests /analysis of seal concept ▲ Complete dev. of life predict.model for UHTPMC's ▲ Complete verifi. of continuum damage mech.	▲ Perform coupon level deformation Y life tests under biaxial loading	Multiscale analysis of a fiber/particulate reinforced subcomponent incorporating appropriate local/global failure criteria, ▲	*Ultra Safe, OFTET Perform subcomponent testing under complex multiaxial states of stress ▲
NPSS	Product. Release Rocket Sys Sim.	▲ Roto-Stator pump CFD analysis initial capability	▲ Product. RBCC simulation ▲ Initial cavitating pump element design code			
Information Rich Test Instrumentation	Feasibility test of inorganic binder ▲		Demo multifunctional thin film sensor array ▲	Prototype Doppler Global Velocimetry sys test	▲ Enviro testing of integrated thin film sensor sys w/support electronics	
Advanced Propellants	▲ Endothermic compar. Test of HC's Rocket coking test of HC's	▲ DGH pilot plant fab ▲ Scramjet combust compar. tests of HC's	▲ DGH production demo	▲ Thermal stability & energy density screen of hi-energy propell. sturct. candidate qualified	▲ DGH subscale rocket combust. performance measured	▲ Hi-energy density propell. scramjet perform. measured
Auxiliary Propulsion Technology	▲ Start Microtube Catalytic Ignition Demo	▲ Regen. Cooled microcombuster feasibility demo	▲ Burning behavior of represent. monopropellant characterized	▲ Thermal decomp. of rep. monopropellant characterized	▲ RCS monopropellant formulation/ignition method selected ▲ Microcombus regen-cooled design/fab. param. optimized.	▲ Hi-press., regen-cooled, bipropel. microcomb. demo
Turbo Rocket	▲ Initial Feasibility		▲	Dual fluid pumping feasibility		Precombustor Feasibility ▲
Other Concepts	▲	APP NRA	▲ APP NRA		▲ APP NRA	

*Identified APP Synergistic Tasks

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Propulsion Research & Technology FY01-06 Project Roadmap

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J. Rod Ellis	Safe Life Design	216-433- 3340	John.R.Ellis@grc.nasa.gov
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Brian Reed	Auxiliary Prop Technologies	216-977-7489	Brian.D.Reed@grc.nasa.gov
Mike Meyer	Advanced Propellants	216-977-7492	Michael.L.Meyer@grc.nasa.gov
Carol Quinn	TurboRocket Sub Proj MGR	216-433- 2825	Carol.A.Quinn@grc.nasa.gov

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PR&T Points of Contact

- Foundation Technologies contains 6 Subprojects:
  - Long-Life Light-Weight Propulsion Materials & Structures (9 Tasks):
    - Process and Material Development for Fabrication of CMC Blisks
    - High Conductivity Materials
    - National Durability Test Apparatus
    - CMC Nozzles and Cooled Structures
    - Polymers and PMC's for High Temperature Propulsion Applications
    - Revolutionary Fibers and Interface Coatings(begins in FY 04)
    - Ceramic Composite Thrust Chamber Development
    - Cooled Ceramic Matrix composite Panels
    - Evaluation of Ceramic Leading Edge Concepts
  - Safe-Life Propulsion Design Technologies (6 tasks):
    - Ceramic matrix composite (CMC) life prediction methods
    - Life Prediction methods for ultra high temperature polymer matrix composites for RLV airframe and engine application
    - Enabling design and life prediction technology for cost effective large-scale utilization of MMCs and innovative metallic material concepts.
    - Probabilistic analysis methods for brittle materials and structures.
    - Damage assessment in CMC propulsion components using nondestructive characterization (NDC) techniques.
    - High temperature structural seals for RLV application.

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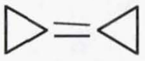
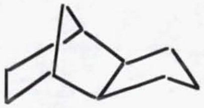
PR&T Foundation Technologies, cont'd

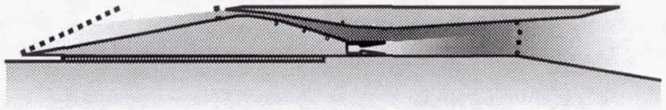
- NPSS for Space Transportation (3 tasks):
  - Numerical Propulsion System Simulations for Space Transportation Propulsion Applications.
  - Improved Rocket Engine Turbopump Design Data Base.
  - Design Process Improvement Through Enhanced Environment Prediction Capability.
- Information Rich Test Instrumentation (4 tasks):
  - Surface Heat Flux Measurements
  - Surface Temperature Measurements
  - Combustion Diagnostic Measurements
  - Gas Velocity Measurements
- Advanced Propellants (4 tasks):
  - Common HC Fuels for Combined Cycles
  - High Energy Hydrocarbons
  - Densified Gelled Hydrogen
  - Hybrid Propellants
- Auxiliary Propulsion Technologies (2 tasks):
  - Bipropellant Micro-Combustion and Heat Transfer
  - Advanced Monopropellant Decomposition and Combustion Mechanisms

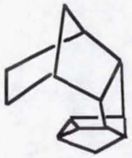


BCP

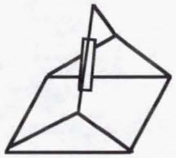


JP-10





RJ-5



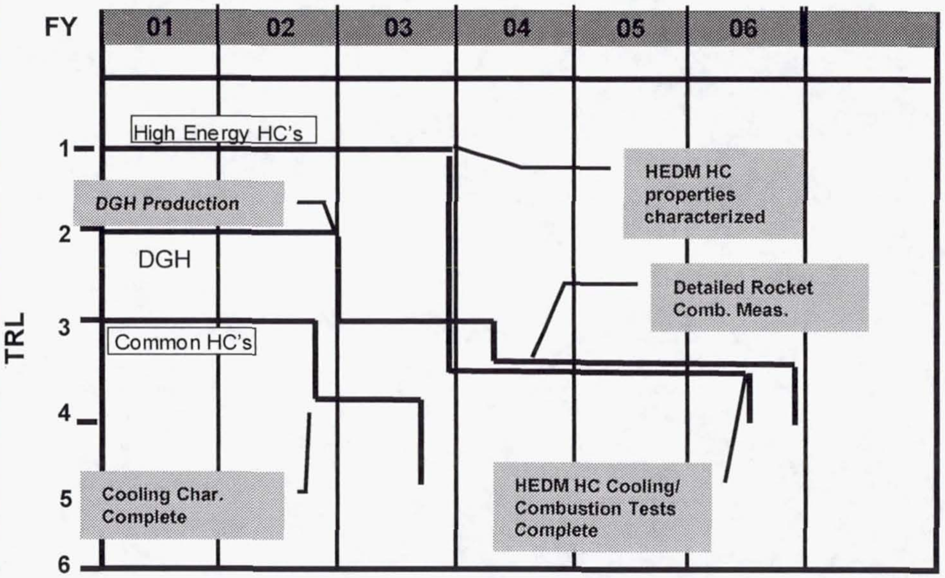
Quadricyclane

Milestones / Activities

- **Current State of the Art**
  - JP-7/RP-1, LH2
- **Benefits of Technology (Cost, Safety, Performance, etc)**
  - HC Heat Sink ~ 2000 BTU/lb
  - HC time between overhaul: hours not minutes
  - HEDM energy-density +20% over JP-7
  - 17% H2 density increase with zero Isp reduction
- **Risks/Technical Challenges with Mitigation Plans**
  - HC coking: mitigated by screening wide range of fuels and options to work additives or deoxygenation
  - producing gelled densified H2 with optimum CH4 fraction: mitigated by history of gelling LH2 and densifying H2

Milestones / Activities

- **FY'01 Milestones**
  - 2Q01: Endothermic comparison tests of common HC's
  - 4Q01: Rocket coking comparison tests of common HC's
- **FY'02 Milestones**
  - 2Q02: Scramjet combustion comparison at M=6.5
  - 4Q02: Densified Gelled H_2(DGH) production demonstrated
- **Prioritized list of Activities, e.g.:**
  - Characterize common HC's for combined cycle systems
  - Identify HEDM candidates for combined cycle systems
  - Demonstrate DGH production
  - Rocket condition thermal stability : U. Kansas grant



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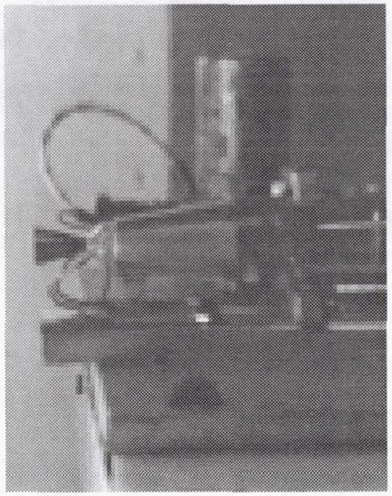
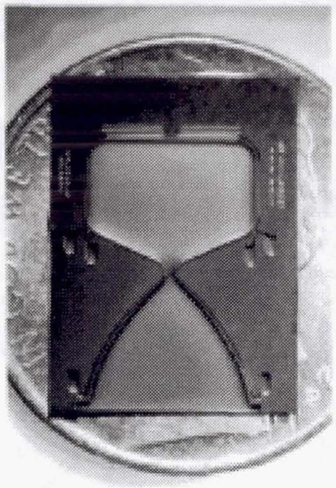
PR&T Advanced Propellants

Auxiliary Propulsion Technology: Foundation for Low-Maintenance, Low-Cost Reaction Control Systems





High-Performance (Isp > 270-s), Low-Hazard Monopropellants

↓

Simple, Single-Propellant RCS

High-Pressure, Bipropellant Microthrusters

↓

1-ft x 1-ft x 6-in, Microthruster Array RCS Panels

- 3rd Generation RLV Goals
  - Two orders of magnitude reduction in RCS servicing costs
  - Improve inherent safety and operational flexibility for RCS

- Very low-maintenance RCS concepts will address goals
  - System using Isp > 270 s, low-hazard monopropellant
    - Single-propellant, no thermal management, no vapor hazard
  - 1-ft x 1-ft x 6-in RCS panels consisting of microthruster arrays
    - Revolutionary concept would offer unprecedented redundancy, low-cost fabrication of thrusters, and 10X reduction in dry mass

- Provide technology foundation for low-maintenance RCS by investigating critical issues/challenges
  - Advanced monopropellant decomposition and combustion
  - Combustion and heat transfer in bipropellant microthrusters

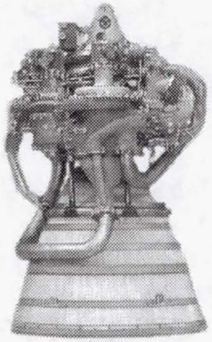
- Project Participants
  - NASA GRC : Ignition and combustion experiments
  - MIT: Regeneratively-cooled microcombustor heat transfer
  - Penn State: Monopropellant combustion experiments

- Near-Term Milestones
  - FY01 Microtube catalytic ignition
  - FY02 Regeneratively-cooled microcombustor feasibility
  - FY02 Burning behavior of representative monopropellant

- FY06 Status
  - High-pressure, regeneratively-cooled, oxygen/ethanol microcombustor demonstrated
  - Decomposition of RCS monopropellant in reactor characterized

- Auxiliary Propulsion Technology Project Contact
  - Brian Reed, 216/977-7489, Brian.D.Reed@grc.nasa.gov

Williams International
Low Cost Turbo Rocket Concept



25,000 lbf RL-10

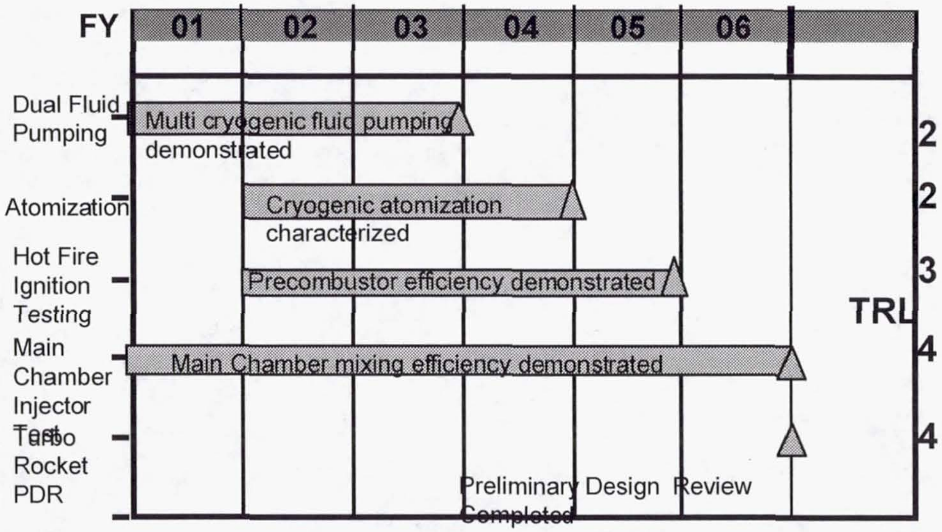
25,000 lbf Turbo Rocket
Proprietary

Milestones / Activities

- ♦ Current State of the Art
  - RL10, SSME, and FASTRAC where the TPA is integrated with the TCA through a web of plumbing
- ♦ Benefits of Technology (Cost, Safety, Performance, etc)
  - 10-50% the cost of current rocket engines
  - T/W of over 100
- ♦ Risks/Technical Challenges with Mitigation Plans
  - demonstrate ability to accelerate cryogenic fluids to speeds required for injection into precombustor
  - demonstrate ability to cool main chamber with hydrogen-rich effluent
  - adequately mix hydrogen and oxygen in precombustor and main chamber

Milestones / Activities

- ♦ FY'01 Milestones
  - 9/01 Begin Design of Dual Fluid Pumping System Rig
- ♦ FY'02 Milestones
  - 09/02 Begin Testing of Dual Fluid Pumping System
- ♦ Prioritized list of Activities, e.g.:
  - Dual Fluid Pumping Testing
  - Atomization Rig Testing



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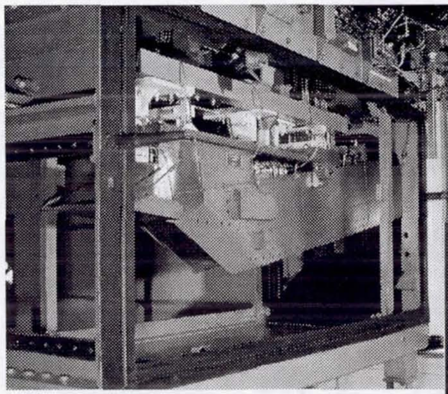
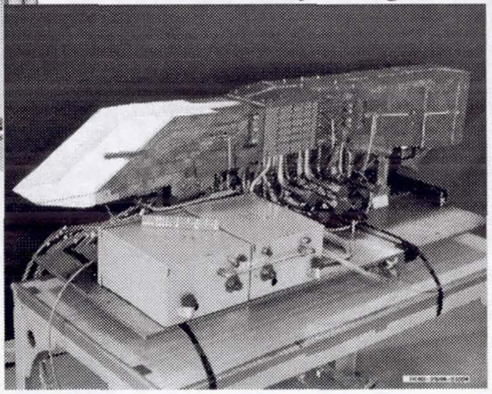
PR&T Low Cost Turbo Rocket

PR&T - Advanced Reusable Technologies (ART) RBCC Test Bed



Aerojet Strutjet

Rocketdyne Engine A5

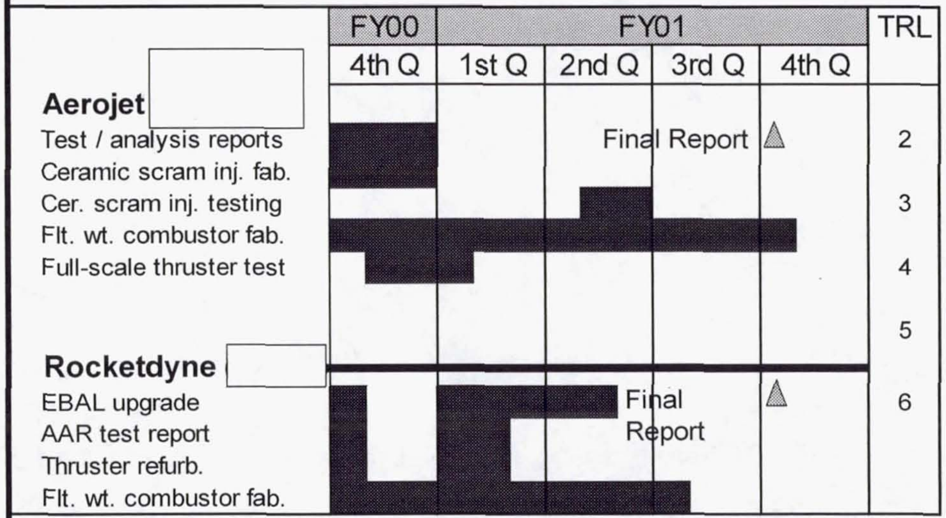


Milestones / Activities

- Current State of the Art
  - Boiler plate test hardware
- Performance Metrics
  - Completed combustor weight
  - Combustor manufacturability

Milestones / Activities

- FY'01 Milestones:
  - Phase II Final Reports
- Prioritized list of activities:
  - Complete Phase II Final Reports
  - Fabricate flight-weight combustors
  - Test ceramic scram injectors



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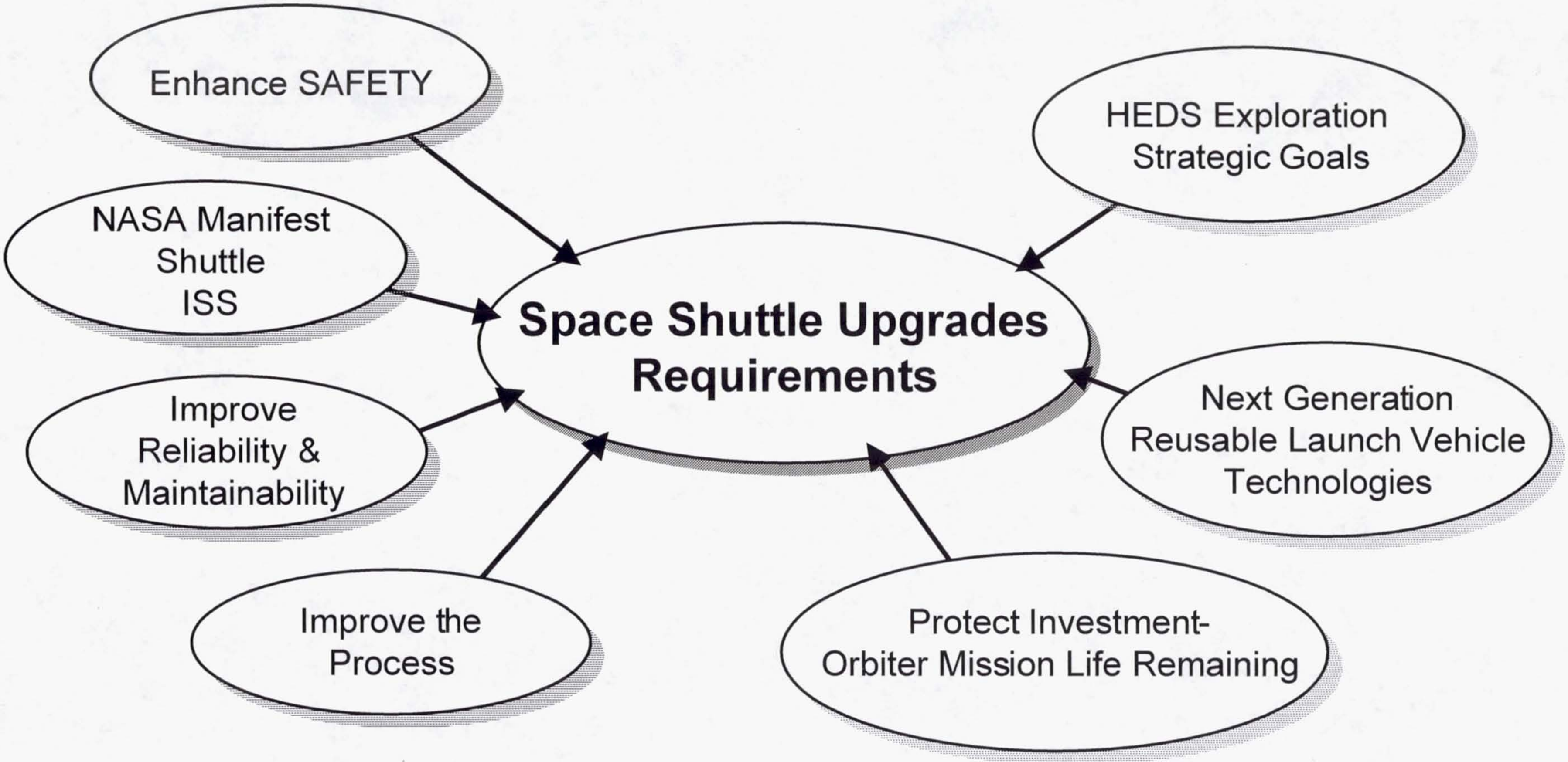
Shuttle Upgrade Plan

September 11, 2000

Why Space Shuttle Upgrades?



Space Shuttle Upgrades Requirements

Enhance SAFETY

NASA Manifest
Shuttle
ISS

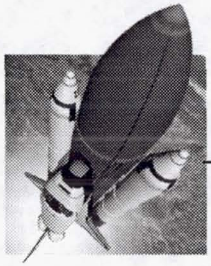
Improve
Reliability &
Maintainability

Improve the
Process

HEDS Exploration
Strategic Goals

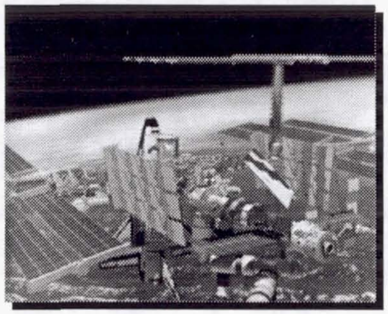
Next Generation
Reusable Launch Vehicle
Technologies

Protect Investment-
Orbiter Mission Life Remaining



Future Shuttle Manifest

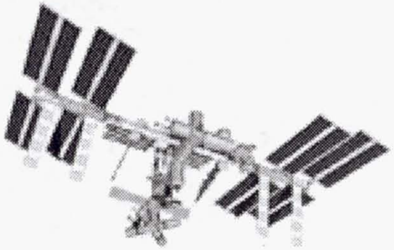
Space Shuttle Upgrades are the foundation for ISS and future HEDS Initiatives

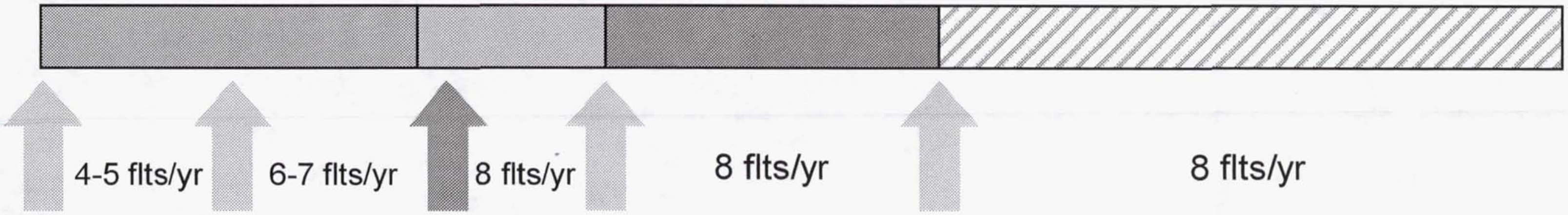


International Space Station

Assembly	Logistics and Utilization
▨	▨

STS-88
Dec '98





STS-1
1981

STS-3
1982

STS-49
1992

STS-106
2000

~STS-141
2004

~STS-222+
2012

~STS-400*
>2030

4-5 flts/yr

6-7 flts/yr

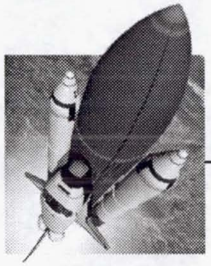
8 flts/yr

8 flts/yr

8 flts/yr

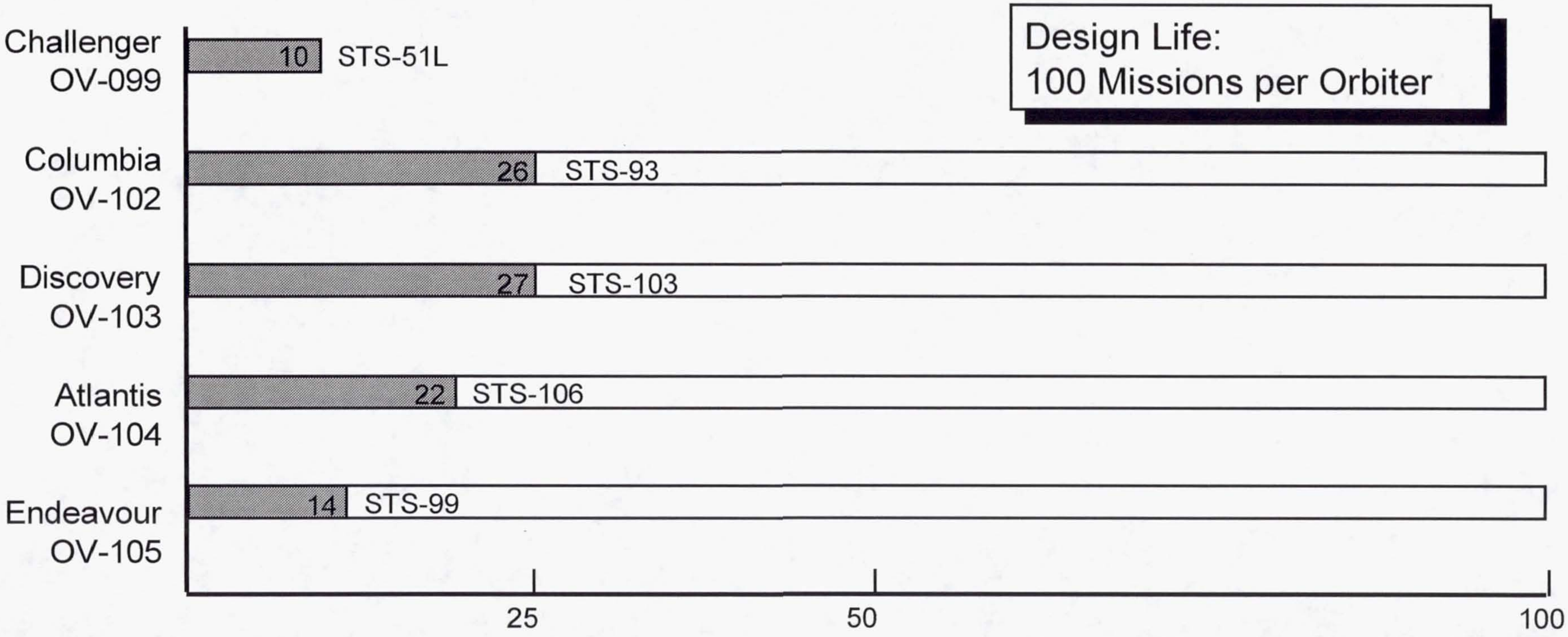
Today

* Orbiter design life 100 missions



Orbiter Mission History

Total flights to date: 99
Orbiter lifetime Remaining: 311



Design Life:
100 Missions per Orbiter

Space Shuttle Program

SSP GOALS

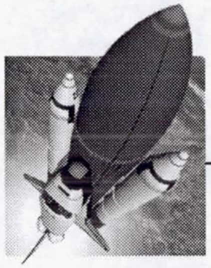
1. FLY SAFELY
2. MEET THE MANIFEST
3. IMPROVE SUPPORTABILITY
4. IMPROVE THE SYSTEM

Get with the Program !

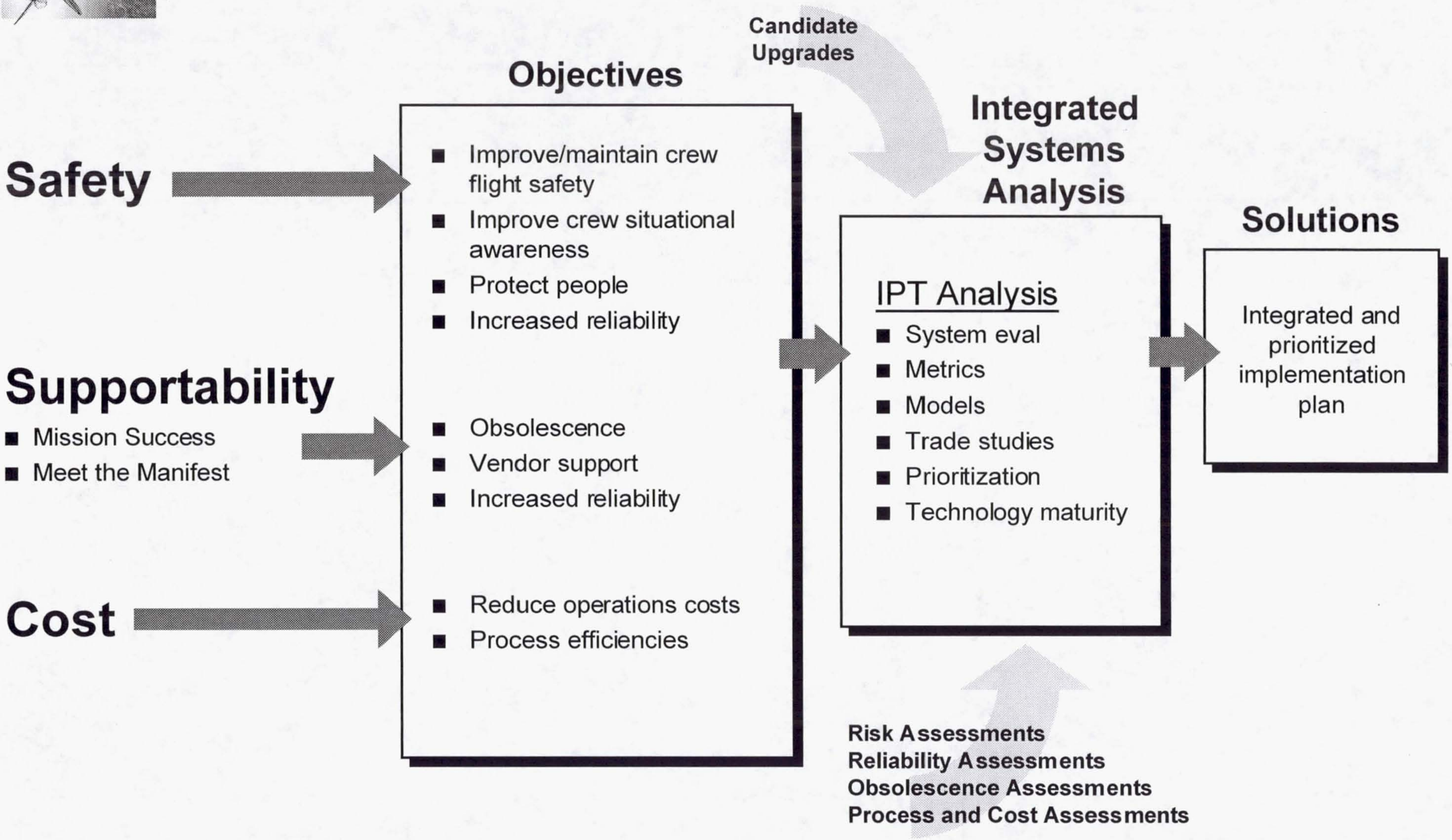
Space Shuttle Program

SSP OBJECTIVES

1. Improve the safety and reliability of the Shuttle system; identify and resolve obsolescence concerns.
    a. Decrease risk of catastrophic loss of vehicle and crew, evolving to 1/1000 loss of vehicle and 1/10,000 loss of crew.
    b. Reduce accepted risk causes of hazards.
    c. Reduce risk through implementation of industrial engineering improvements.
2. Reinvent processes/standards to increase manifest flexibility (examples include: decreased development time, reduced OPF flow, etc.)
3. Decrease the development time for new hardware for ATP to ready for first implementation.
    a. Minor: less than 8 months
    b. Major: less than 36 months
4. Achieve SSP environment compliance by FY03.
5. Plan for and provide reliable facility infrastructure to support SSP objectives.



Selection Criteria Ensures System Process



Safety

Supportability
- Mission Success
- Meet the Manifest

Cost

Objectives

- Improve/maintain crew flight safety
- Improve crew situational awareness
- Protect people
- Increased reliability

- Obsolescence
- Vendor support
- Increased reliability

- Reduce operations costs
- Process efficiencies

Candidate Upgrades

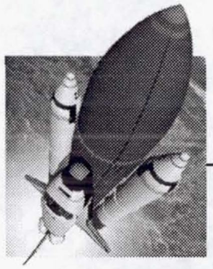
Integrated Systems Analysis

IPT Analysis
- System eval
- Metrics
- Models
- Trade studies
- Prioritization
- Technology maturity

Risk Assessments
Reliability Assessments
Obsolescence Assessments
Process and Cost Assessments

Solutions

Integrated and prioritized implementation plan



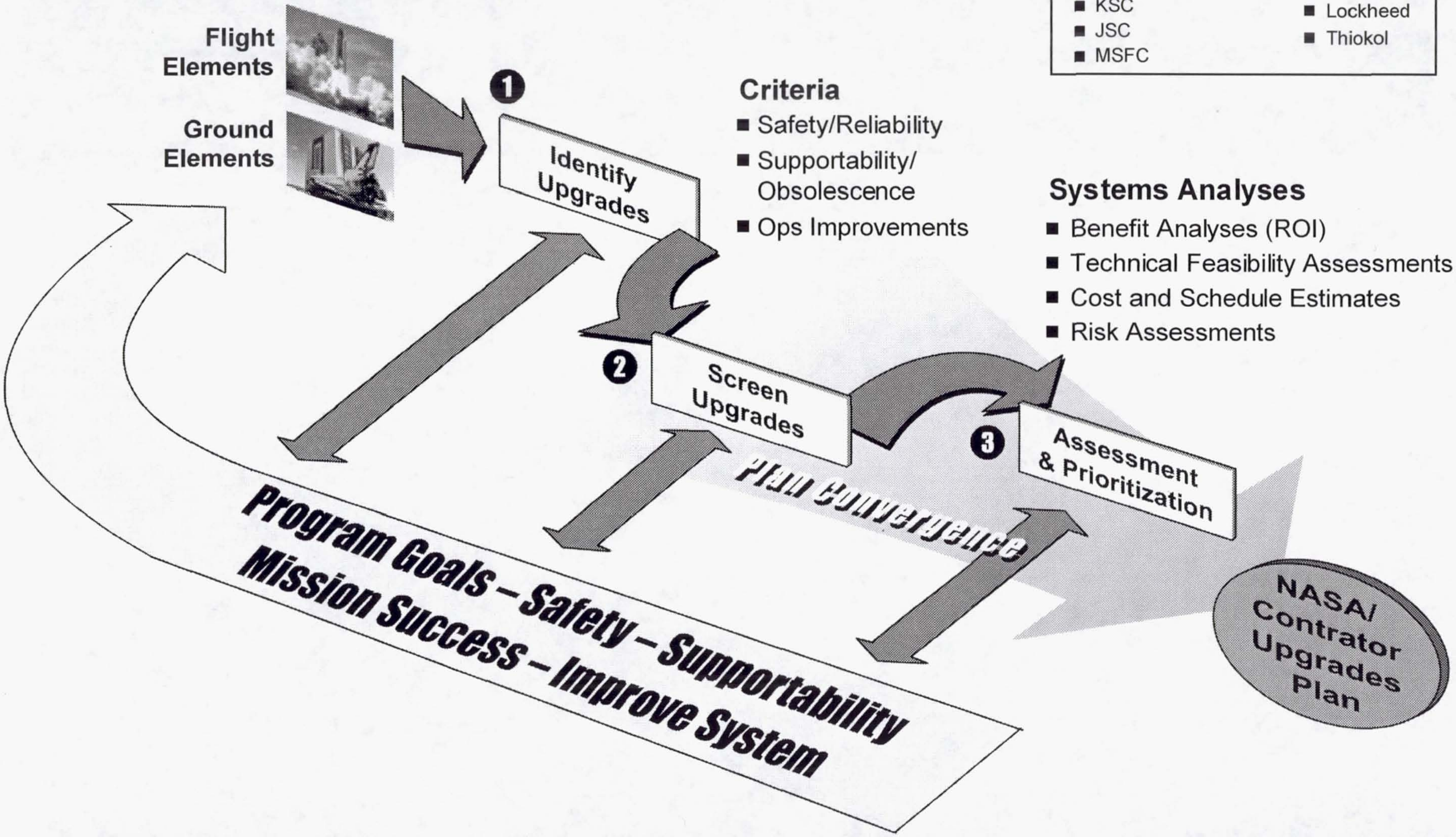
An Integrated Team Process

Integrated approach to produce a unified NASA/Industry STS upgrades plan which supports NASA's goals:

Improve Shuttle Safety - Support ISS - Support Future HEDS Initiatives

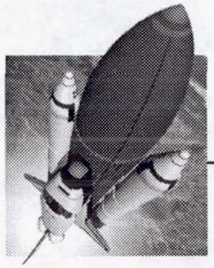
NASA
- Headquarters
- Space Shuttle Program
- KSC
- JSC
- MSFC

Industry
- USA
- Boeing
- Lockheed
- Thiokol



Criteria
- Safety/Reliability
- Supportability/ Obsolescence
- Ops Improvements

Systems Analyses
- Benefit Analyses (ROI)
- Technical Feasibility Assessments
- Cost and Schedule Estimates
- Risk Assessments



Shuttle Upgrade Plan Background

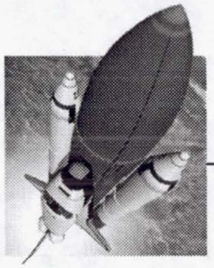
Shuttle Upgrade Strategy

Pro-active upgrade program to keep Shuttle flying ***safely*** and efficiently until the next generation vehicle to meet agency commitments and goals for human access to space

- ISS assembly and support
- Mission support for complex scientific payloads: e.g., HST, SRTM, etc...
- Testbed for new technology
- Human exploration and development of space

Safety Upgrades

Supportability Upgrades



Shuttle Upgrade Plan Background

Shuttle Upgrade Strategy

Pro-active upgrade program to keep Shuttle flying ***safely*** and efficiently to 2012 and beyond to meet agency commitments and goals for human access to space

Safety Upgrades

Risk Reduction Goals

- Major reduction in ascent catastrophic risk
- Significant reduction in orbital and entry system catastrophic failure risk
- Improve crew cockpit situational awareness for managing critical operational situations

Supportability Upgrades

Flight Hardware Availability Assurance

- Obsolescence
  - Parts availability
  - Vendor support
- Failure rates
- Repair times
- Inventory attrition

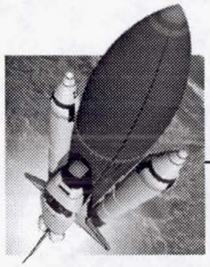
Operational Improvements

- Maintainability
- Reliability
- Mission success
- Operational simplicity\
- Turn-around time improvements
- Cost reduction

Space Shuttle *Safety* Upgrades

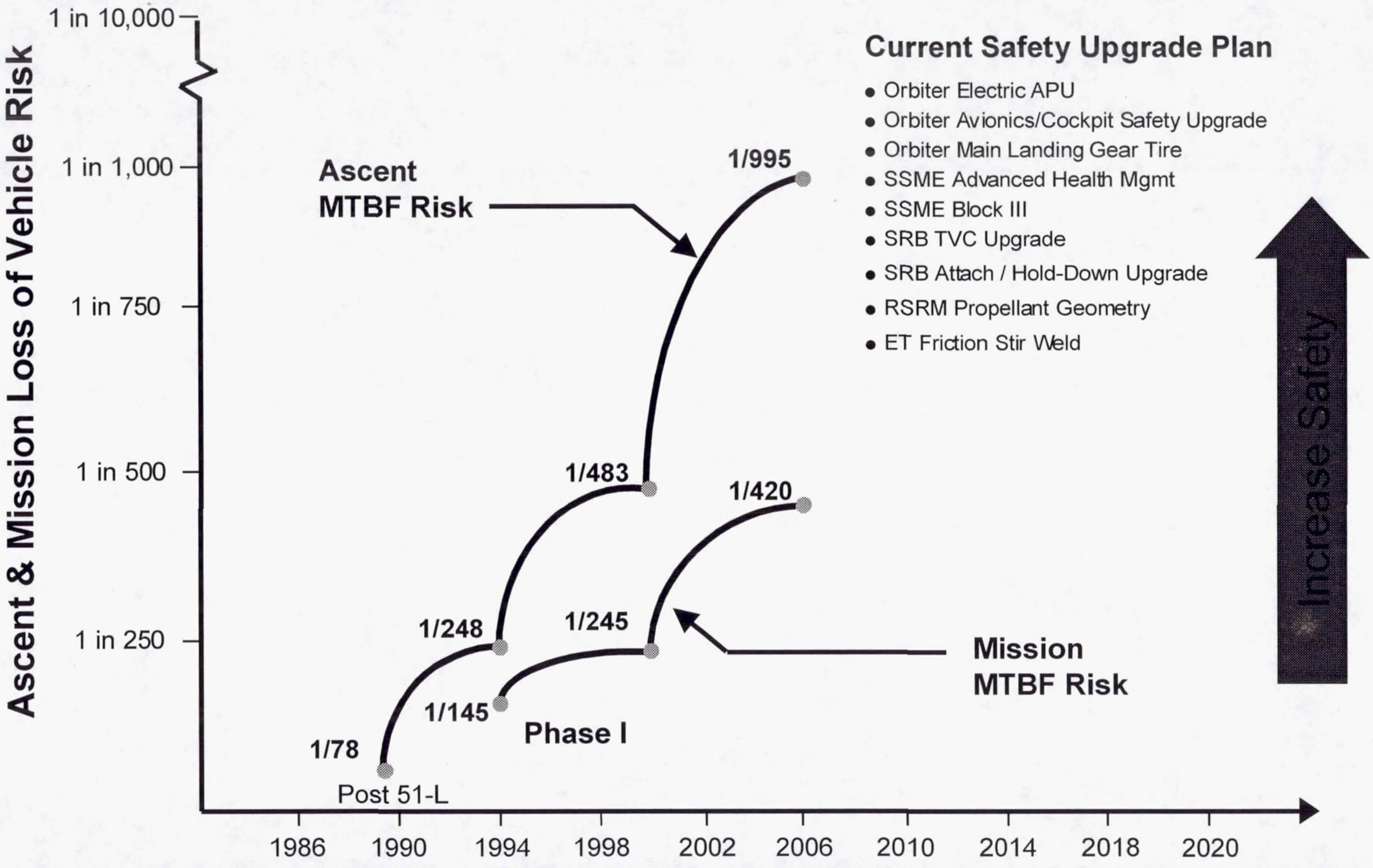
The Goals & The Challenges

- Goals
    - Major reduction in ascent catastrophic risk
    - Significant reduction in orbital and entry system catastrophic failure risk
    - Improve crew cockpit situational awareness for managing critical operational situations
- Challenges
    - All upgrades operational in the fleet by end of 2005
    - No impact to on-going Manifest support
    - Control costs to estimates provided in President's proposed budget



Safety Benefit of Planned Shuttle Upgrades

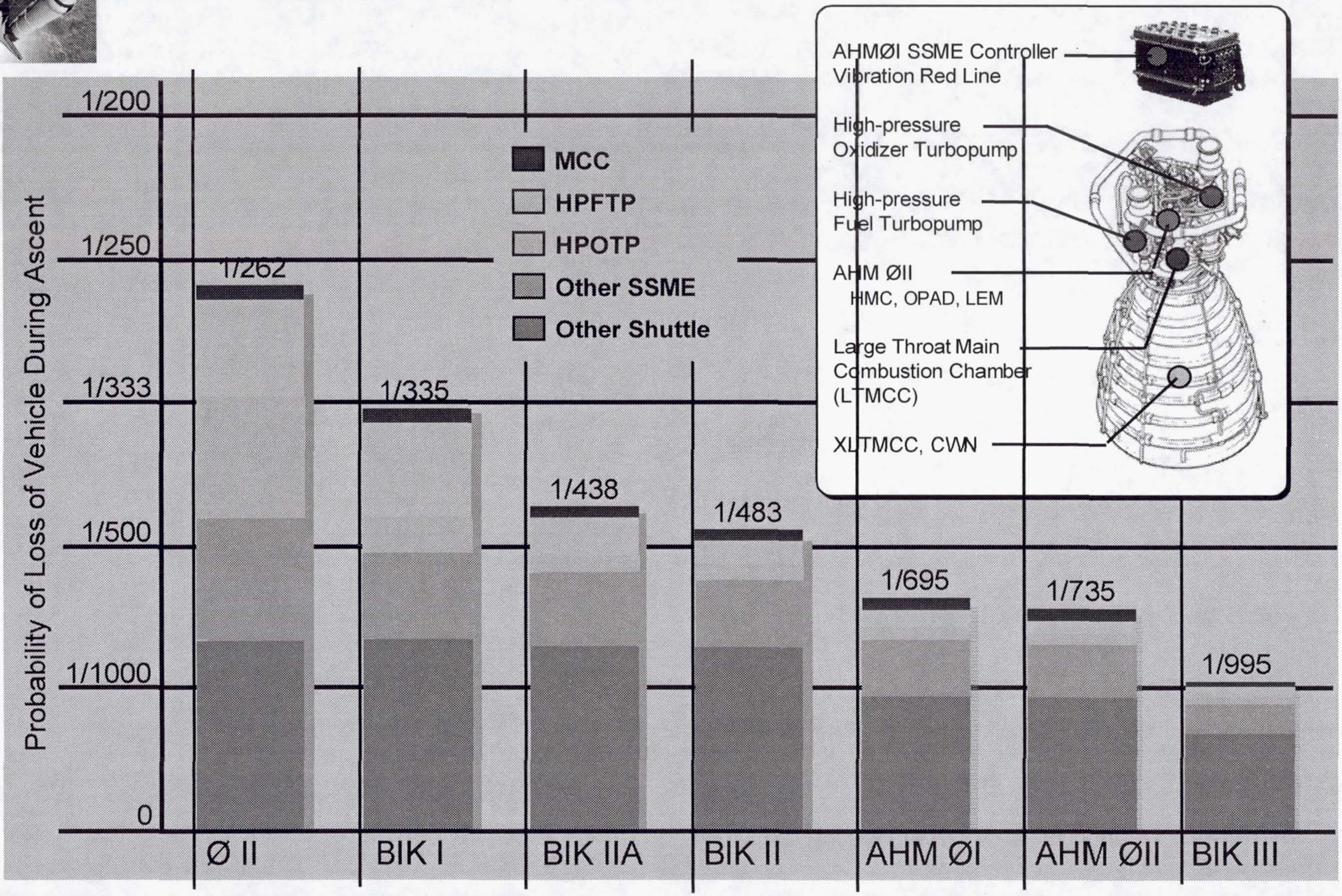
Increased Safety Through Selected Upgrades

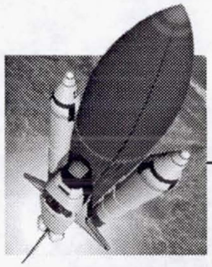


Current Safety Upgrade Plan

- Orbiter Electric APU
- Orbiter Avionics/Cockpit Safety Upgrade
- Orbiter Main Landing Gear Tire
- SSME Advanced Health Mgmt
- SSME Block III
- SRB TVC Upgrade
- SRB Attach / Hold-Down Upgrade
- RSRM Propellant Geometry
- ET Friction Stir Weld

SSME Upgrades Reduce Ascent Risk





Space Shuttle Safety and Supportability
Safety Upgrade Candidates

Orbiter Avionics

- **Cockpit**
  - Enhanced Caution and Warning
  - Crew Situational Awareness Displays
  - AFD Switch Panel Upgrade
  - Device Driver Unit Replacement (DDU)
- **Data Processing**
  - Mission Management Computer
  - Modular Auxiliary Data System
  - Modular Memory Unit (MMU)
- **Communications**
  - Ku-Band DEA
  - PCMMU
  - S-Band FM
  - Network Signal Processor
- **Navigation**
  - Trajectory Control Sensor (TCS)
  - IMU Replacement (SIGI)
- **Power Sub-Assemblies**
  - Hybrid Drivers
- **Thermal Protection System**
  - More Durable Lower Surface Tile (Study)
- **Structures & Mechanisms**
  - Crew Escape System (Study)
  - Main Landing Gear Tire Improvements
  - Micrometeoroid/Orbital Debris Mitigation (MMOD)
- **Environmental Control & Life Support Systems**
  - Hydrogen Water Separator

SRB / RSRM / ET / SSME

SRB Advanced TVC
Integrated Electronics Assembly
ABACS
ET Robust TPS
ET Digital Radiography
New O-Ring Material
Case Stiffener Segment/T-Ring
RSRM Propellant Geometry
SRB Attach/Hold Down Hardware
ET Friction Stir Initial Welds
Advanced Health Monitoring
SSME Block III
– XLTMCC and Robust Nozzle
SRB TVC Upgrades / FIV
SRB Altitude Sensor Assembly
Nozzle/Case Joint J-Leg Insulation
Integrated Receiver-Decoder (IRD)
Range Safety Distributor (RSD)

Power & Propulsion

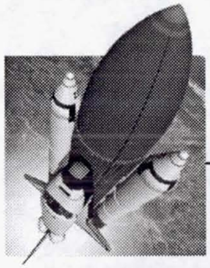
Electric APU
Enhanced Pyro Initiator Controller
Improved Pilot Operated Valve
Quad Check Valve Redesign
Long Life Alkaline Fuel Cell

Operations

- **Ground Operations**
  - Maintainability for Safety (Study)
  - SCAPE Suit Improvements (Study)
  - CLCS
- **Flight Operations**
  - PIDAE
  - Shuttle Upgrades Design Visualization
  - Robotic Situational Awareness Display
  - Human Factors/Cockpit Engineering Study
  - Expansion of MCC Landing Sites
  - AWPS
  - EECOM STS Pressure Management Tool
  - Alternatives to Hardware Based Robotics Training
  - DM Trajectory Operations Interface Redesign
- **Flight Tests**
  - Wireless Sensor
  - Laser Dynamic Range Imager HTD

Advanced Technology

Crew Escape
Reusable First Stage
Non-Tox OMS/RCS Propellants
PEM Fuel Cell
Electromechanical Actuators
Water Membrane Evaporator
Integrated Vehicle Health Mgmt
Propellant Densifications
Fiber Optics



Space Shuttle Safety and Supportability
Safety Upgrade Candidates

Safety Upgrades   Supportability Upgrades   Approved Upgrades   Advanced Technology

Orbiter Avionics

- **Cockpit**
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  - Crew Situational Awareness Displays
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  - S-Band FM
  - Network Signal Processor
- **Navigation**
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SRB / RSRM / ET / SSME

SRB Advanced TVC
Integrated Electronics Assembly
ABACS
ET Robust TPS
ET Digital Radiography
New O-Ring Material
Case Stiffener Segment/T-Ring
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SRB Attach/Hold Down Hardware
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– XLTMCC and Robust Nozzle
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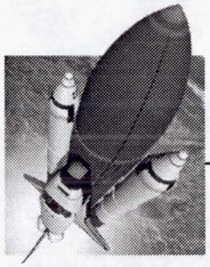
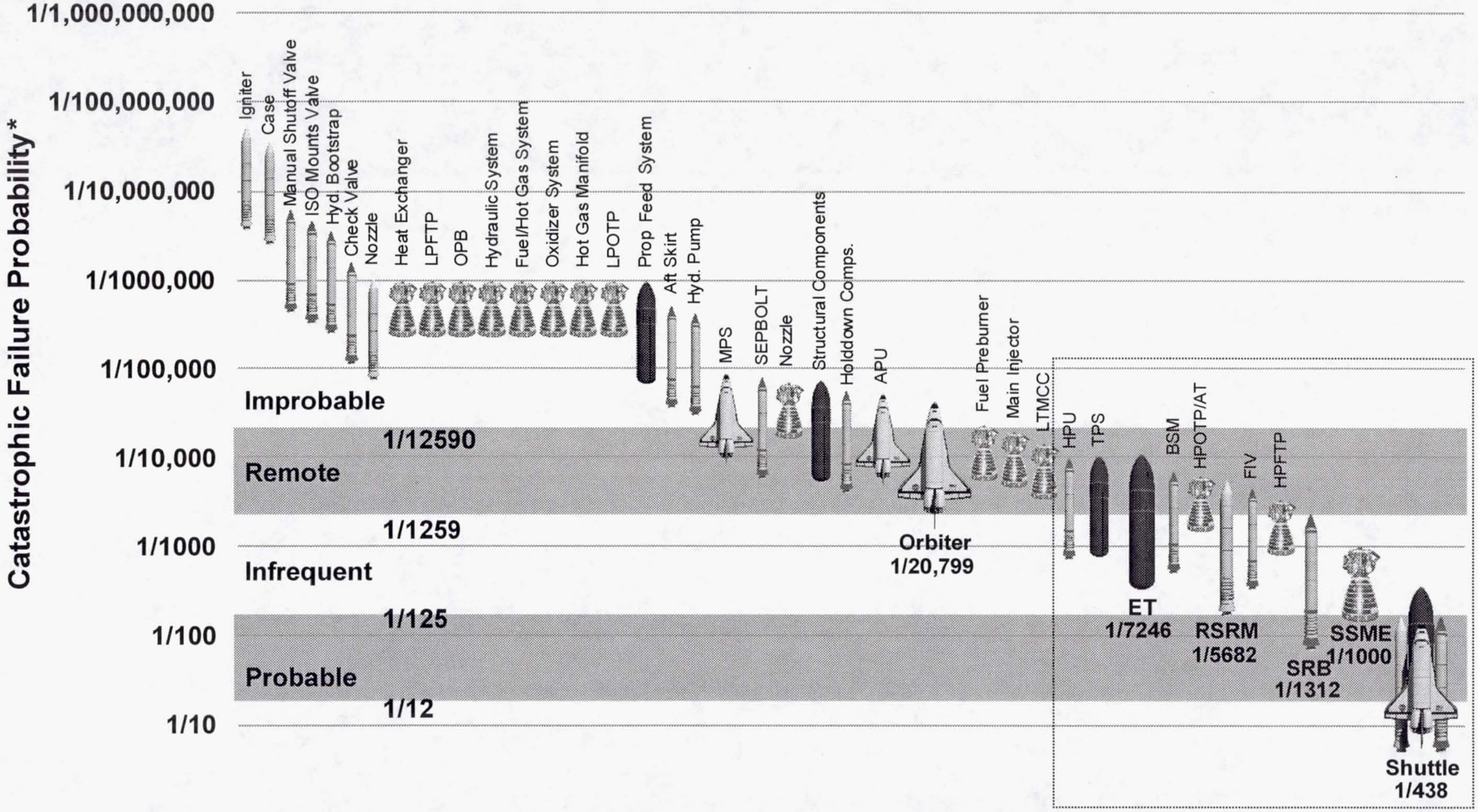
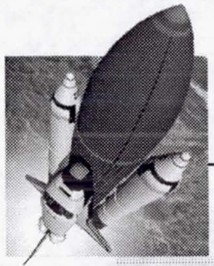


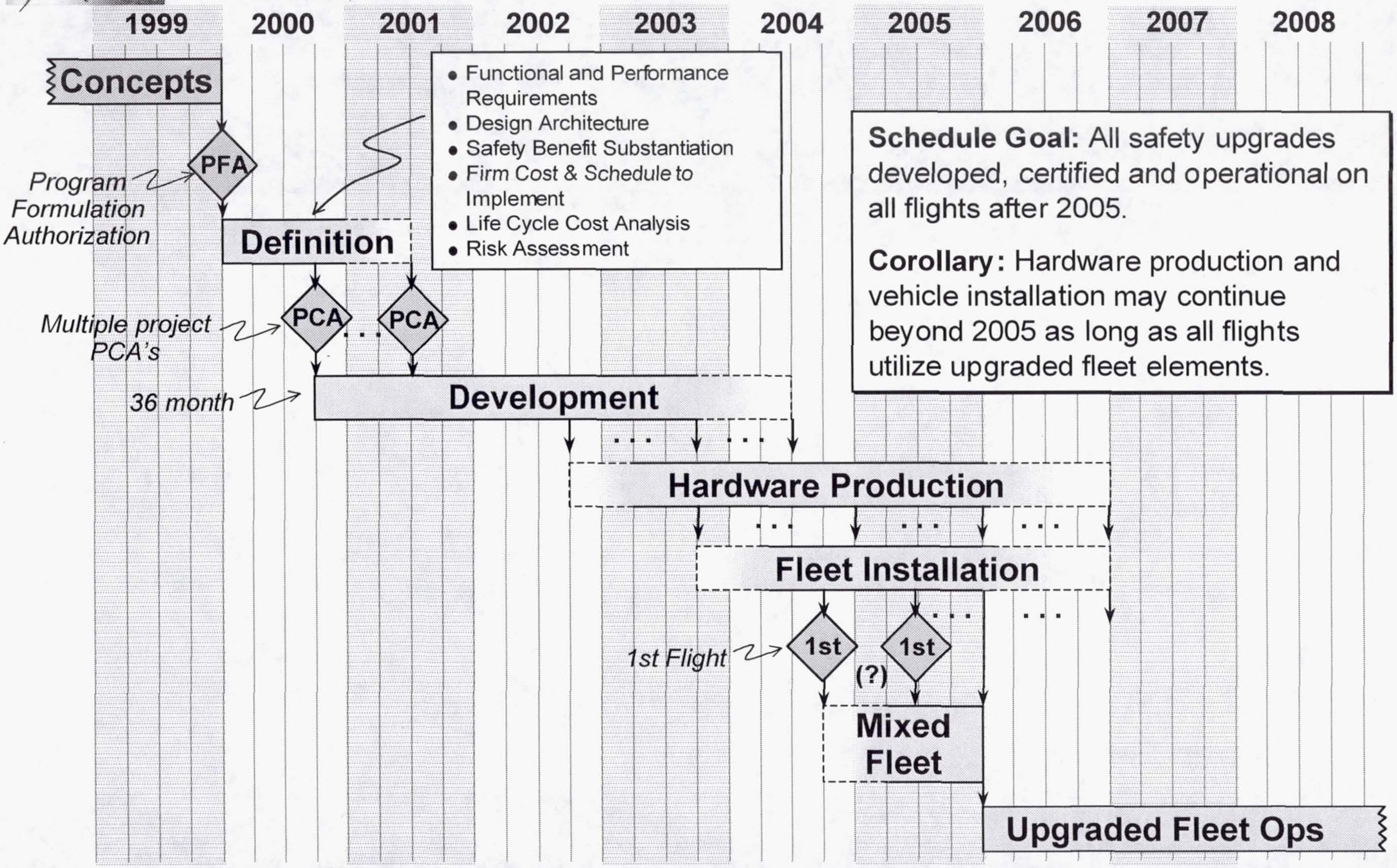
Block IIA Configuration - Ascent



* Based on 1998 QRAS



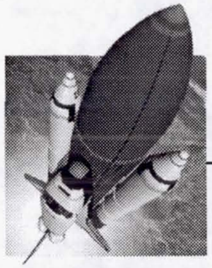
Shuttle Safety Upgrade Schedule Strategy



- Functional and Performance Requirements
- Design Architecture
- Safety Benefit Substantiation
- Firm Cost & Schedule to Implement
- Life Cycle Cost Analysis
- Risk Assessment

Schedule Goal: All safety upgrades developed, certified and operational on all flights after 2005.

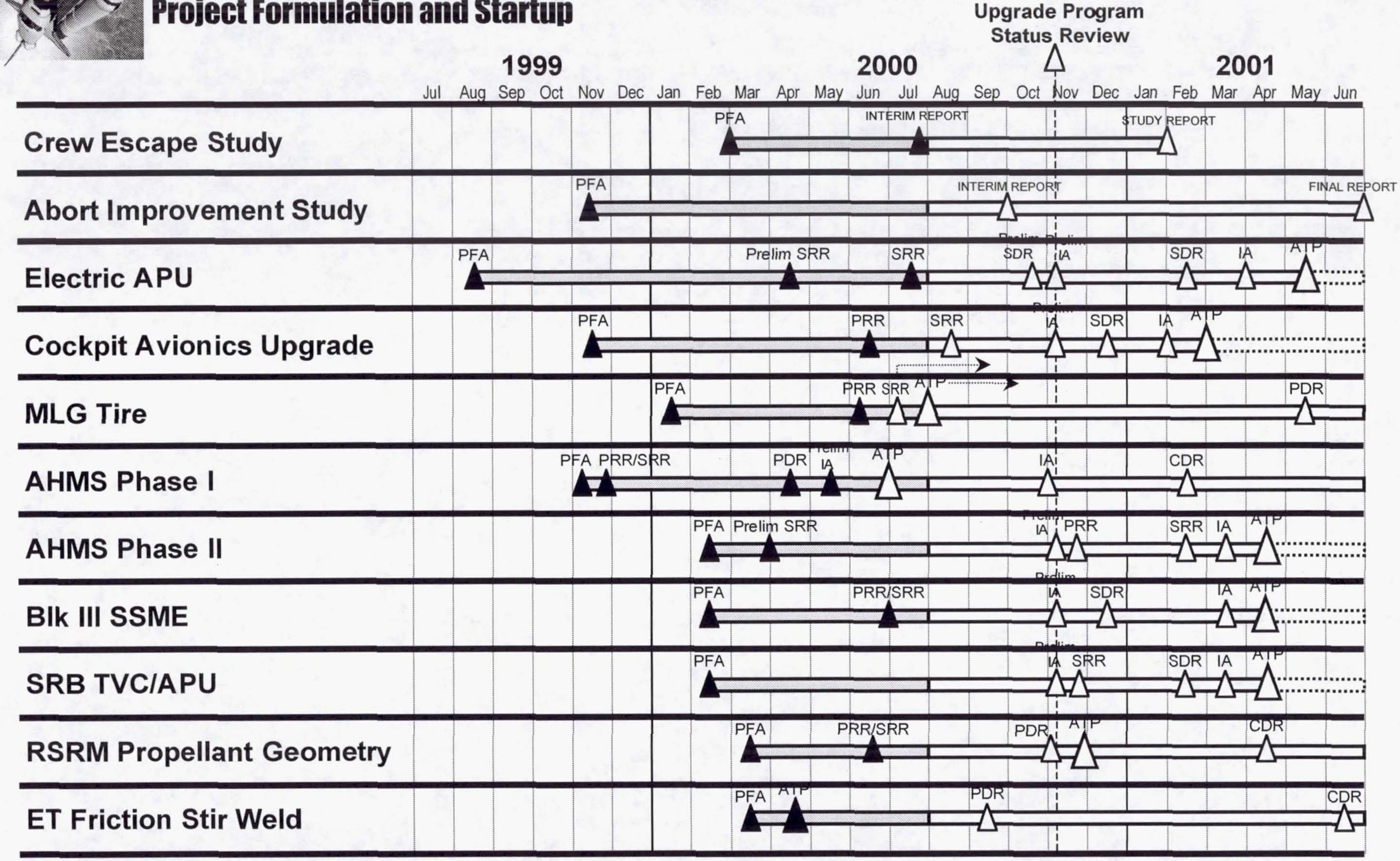
Corollary: Hardware production and vehicle installation may continue beyond 2005 as long as all flights utilize upgraded fleet elements.



Shuttle Safety Upgrade Schedules

Project Formulation and Startup

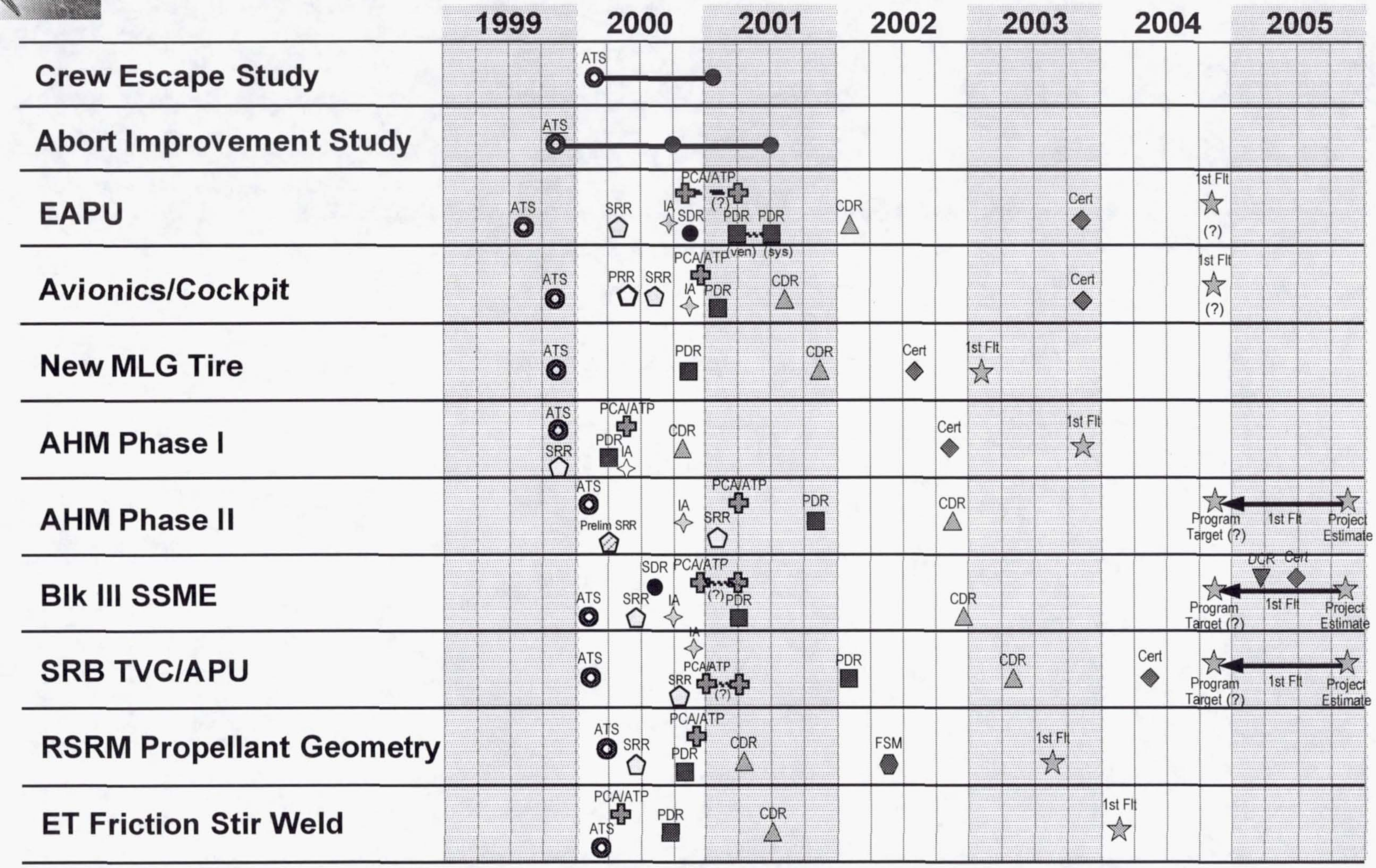
REVISION (8/1/00)



Other Studies: Maintainability for Safety, TPS, SCAPE Suit

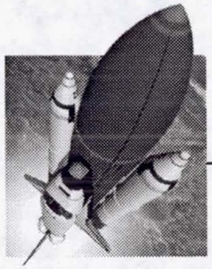
ROM Safety Upgrade Schedules

Non-Baseline Working Schedules (Calendar Year Quarters)



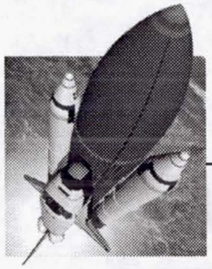
Other Studies: Maintainability for Safety, TPS, SCAPE Suit

Note: SSP Program goal is to achieve 1st Flight for all safety upgrades by 2004 or early 2005, thus supporting full fleet operations of all safety upgrades by the end of 2005.



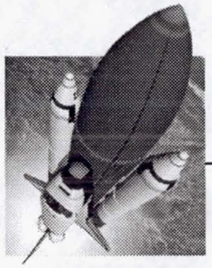
High Priority Safety Upgrades

- **Electric Auxiliary Power Unit (APU)**
  - Battery-powered electric motors replace hydrazine powered turbines to drive Orbiter hydraulic pumps
  - Eliminates hydrazine leakage/fire hazards, eliminates turbine overspeed hazards, and reduces toxic materials processing hazards
  - Simplifies APU startup/shutdown procedures and constraints
- **Avionics/Cockpit**
  - New architecture provides a symmetric cockpit, improved graphics, more data connectivity, and a new computational platform (Command Display Processor)
  - Reduces crew workload, provides enhanced caution and warning, abort/trajectory assessment, RMS workstation, flight instruments, rendezvous/proximity/docking operations thereby increasing safety
- **New Main Landing Gear Tire**
  - Redesign tire and rim to increase the low operating margins
  - Additional margin in landing speed, low temperature, and load limit



High Priority Safety Upgrades (cont'd)

- **SSME Advanced Health Monitoring Phase I**
  - Upgrade SSME Controller with real-time turbopump synchronous vibration redline capability and a new high-speed interface, fly a Health Management Computer (HMC) prototype, fly an Optical Plume Anomaly Detection (OPAD) experiment, investigate Linear Engine Model (LEM) as an MOD tool, Phase II requirements definition
  - Reduces probability of catastrophic engine failure by approx 23%, lays groundwork for Phase II
- **SSME Advanced Health Monitoring Phase II**
  - Flight HMC with advanced Real-Time Vibration Monitoring System (RTVMS), OPAD, and LEM
  - Reduces probability of catastrophic engine failure by an additional ~ 24%, increases SSME anomaly detection capabilities enhancing mission success and ground operations
- **Block III SSME**
  - New SSME Engine with an extra large throat and longer Main Combustion Chamber (MCC) and a shortened, robust, channel-wall constructed nozzle
  - Improves 3-engine catastrophic failure scenario MTBF, improves 3-engine and nozzle failure MTBF, eliminates failure modes, reduces production time and cost, and reduces nozzle maintenance



High Priority Safety Upgrades (cont'd)

- **SRB TVC/APU**
  - Develop a new SRB APU for the Thrust Vector Control system which does not use hydrazine. Downselect from three options.
  - Eliminates hydrazine leakage/fire hazards, eliminates turbine overspeed hazards, and reduces toxic materials processing hazards
- **SRB Attach/Hold Down Hardware**
  - Design more robust SRB attach/hold down hardware for use between the SRB and ET
  - Reliability improvement to 1/995 (QRAS) ascent loss of vehicle
- **RSRM Propellant Grain Geometry**
  - Modify propellant grain geometry in five locations
  - Improves structural margins of safety in the motor, reduces time spent in the hazardous motor environment, eliminates propellant trimming in areas of improvement
- **ET Friction Stir Weld**
  - Develop solid state initial weld technology to be used during ET production
  - Friction stir welding can increase weld joint strength, achieve higher weld margins, and improve fracture toughness as well as improve supportability, cost and process control

Orbiter Avionics/Cockpit Upgrades

Description

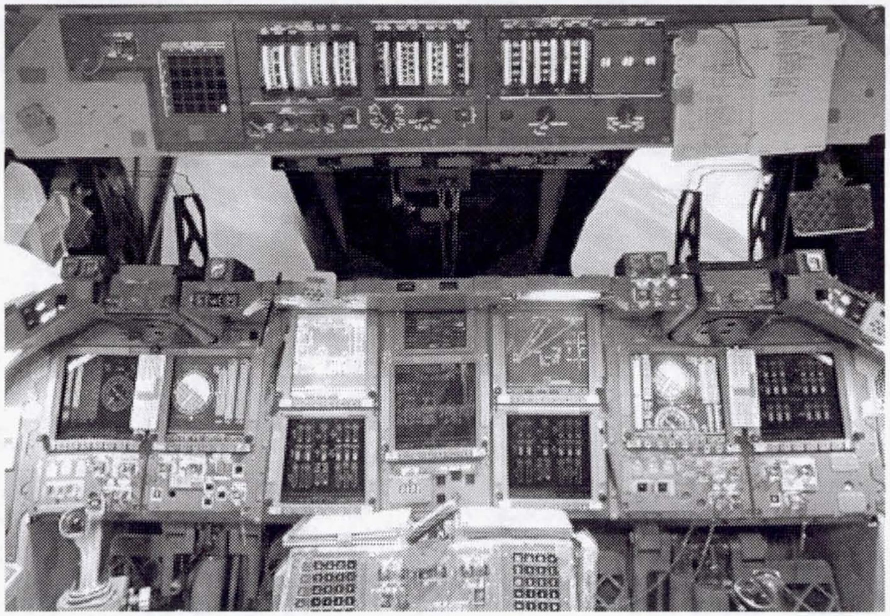
Orbiter Avionics/Cockpit safety upgrade provides

- "Smart Cockpit" … problem root cause
- A symmetric cockpit
  - Any display on any screen
  - Any keyboard commands any display
- Integrated data sources and graphics
- A new computational platform

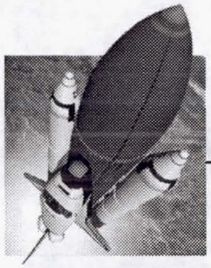
Benefits

Flight Safety

- Enhanced caution and warning
- Improved crew situational awareness
- Improved crew workload margin during critical operations



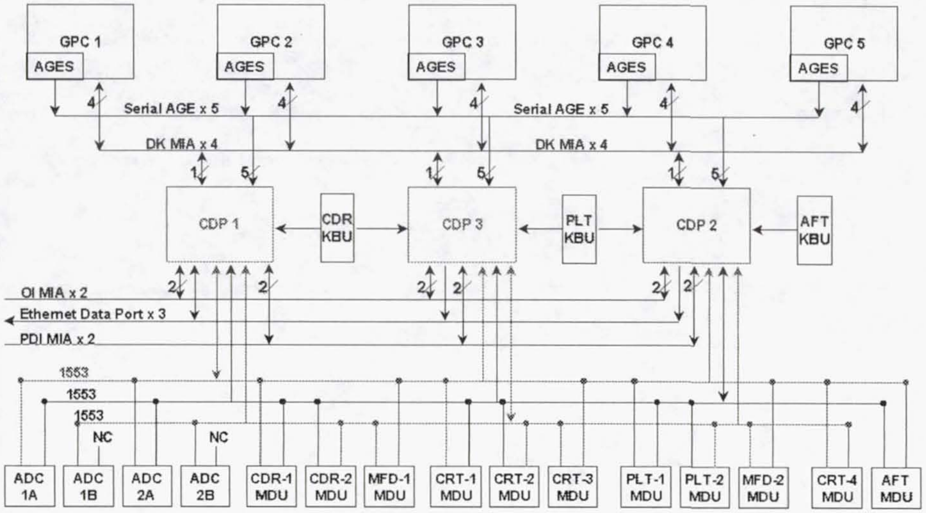
"Smart Cockpit" builds on "Glass Cockpit"



Orbiter Avionics/Cockpit Upgrades

Description

- Upgrade Orbiter Avionics/Cockpit architecture to create
    - A symmetric cockpit – any display on any MDU, any keyboard to any display
    - Connectivity to vehicle and payload data (PASS, BFS, OI, PL)
    - Integrated data sources and graphics on MDUs
    - A new computational platform (Command Display Processor) for keyboard commands, displays, enhanced caution and warning and abort/trajectory assessment
    - A low-impact implementation to allow labs to support a mixed fleet



Benefits

Flight Safety

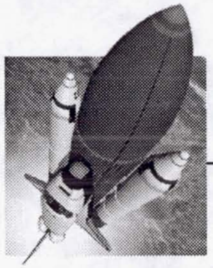
- Architecture meets highest priority Cockpit Council safety objectives and provides a growth path to further cockpit workload reductions
    - Improve crew abort/trajectory situational awareness
    - Reduce crew workload
    - Provide enhanced caution and warning to find problem root cause
    - Improve capacity margin for General Purpose Computers

Mission Success

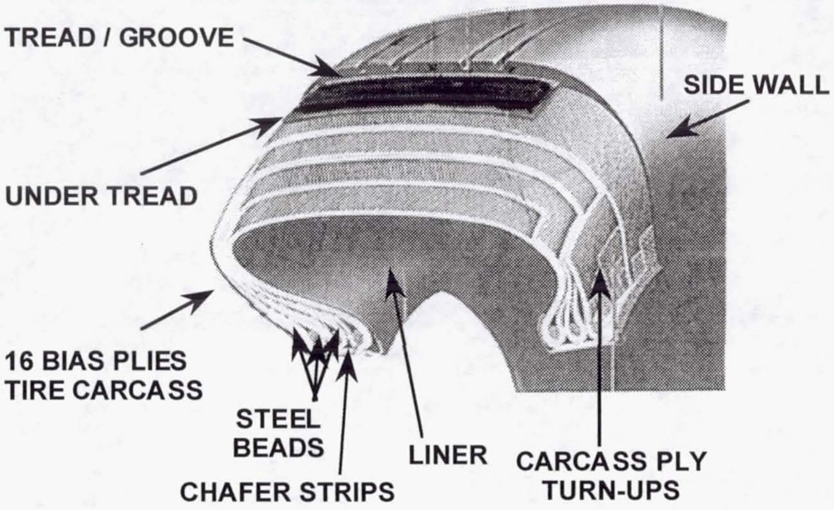
- Upgrade RMS workstation and flight instruments
    - Improved RMS/docking situational awareness
- Simplify rendezvous/proximity/docking operations
- Increased system reliability

Schedule

Avionics	FY00				FY01				FY02				FY03				FY04				FY05				FY06			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study	▨	▨	▨	▨	▨	▨	▨																					
DDT&E					▨	▨	▨	▨																				
Production									▨	▨	▨	▨	▨	▨	▨	▨												
Delivery & Installation																	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨



Improved Main Landing Gear Tire



Description

- Redesign Orbiter Main Landing Gear Tire to increase load capacity for higher speed landing capability
    - Increase safety margin
    - Increase pressure rating design
- New wheel design required after tire development is finalized

Benefits

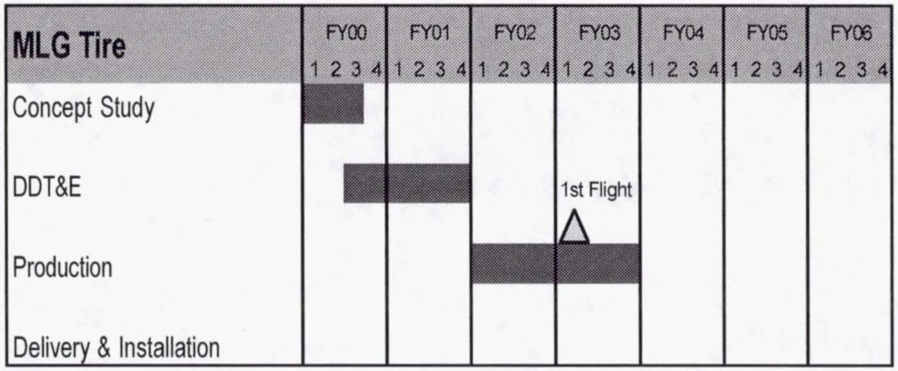
Flight Safety

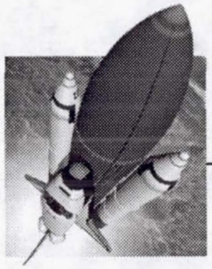
- Increase load capacity safety margin on tire
- Increase landing speed safety margin

Supportability

- Replace rubber compounds to mitigate future obsolescence

Schedule



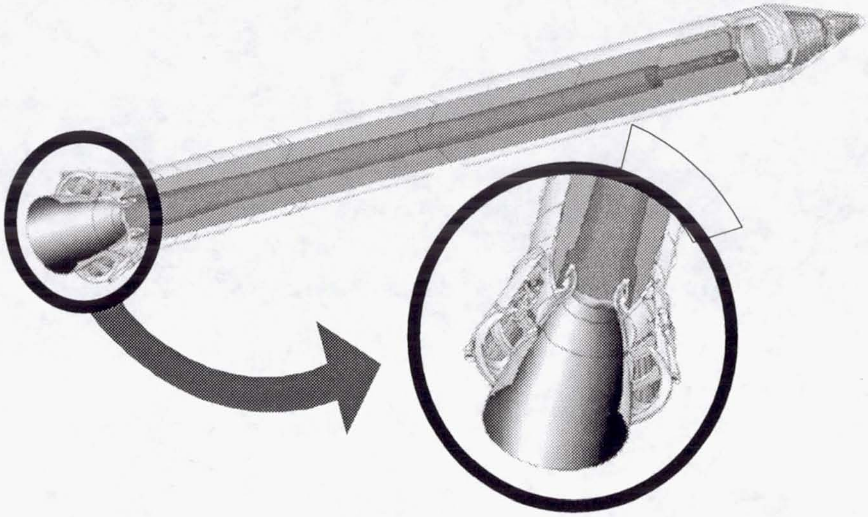


SRB Thrust Vector Control/APU Upgrades Plan

Description

SRB APU Upgrade Trade Studies

- Electric APU
- Solid Propellant Gas Generator (SSPG
- Blowdown / Reccumulation System

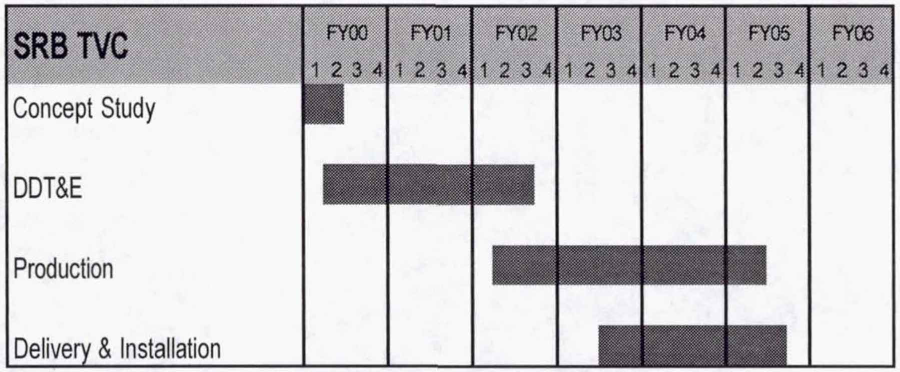


Benefits

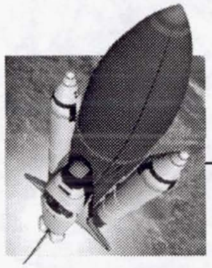
Safety

- Flight Safety - Reduces ISRB LOV (1/X) ascent risk to 1442
- Ground Safety - Reduces toxic materials processing and handling

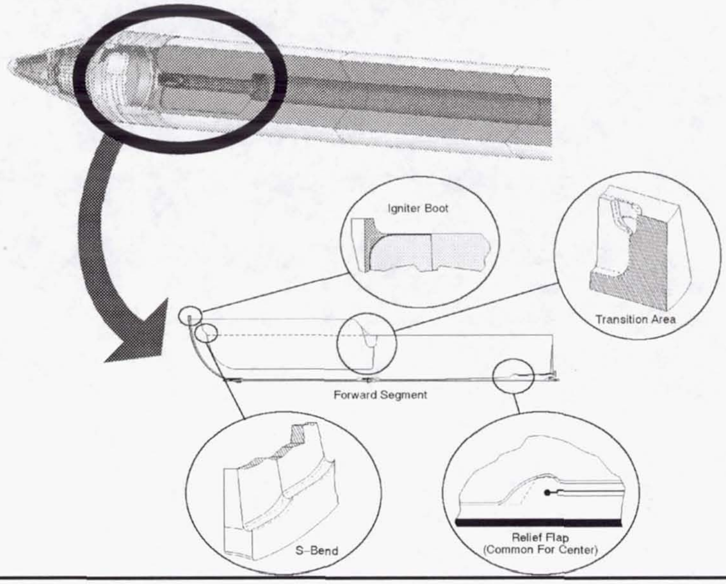
Schedule



Tentative Schedule



RSRM - Propellant Grain Geometry Modification



Description

- Modify propellant grain geometry to improve structural margins of safety (1.4 to 2).
- Modifies propellant, liner, and insulation

Benefits

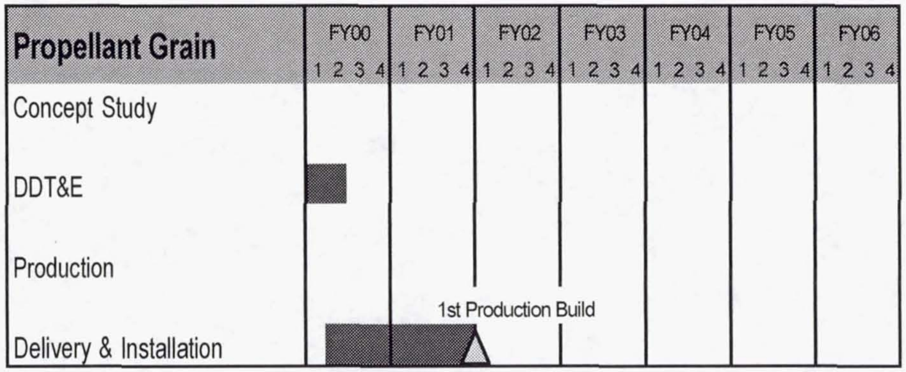
Flight Safety

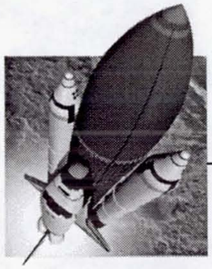
- Increase safety factor in the RSRM.
- Change hazard mitigation from inspection to design.
- **Ground Safety**
- Reduce the time operators and inspectors at Utah and KSC spend in a hazardous environment inside the motor.
  - Eliminate the need for propellant trimming
  - Eliminate inspections

Improve the System

- Eliminate the re-inspection criteria at KSC after six months storage and the associated additional segment handling.
- Robust design reduces obsolete material threats

Schedule

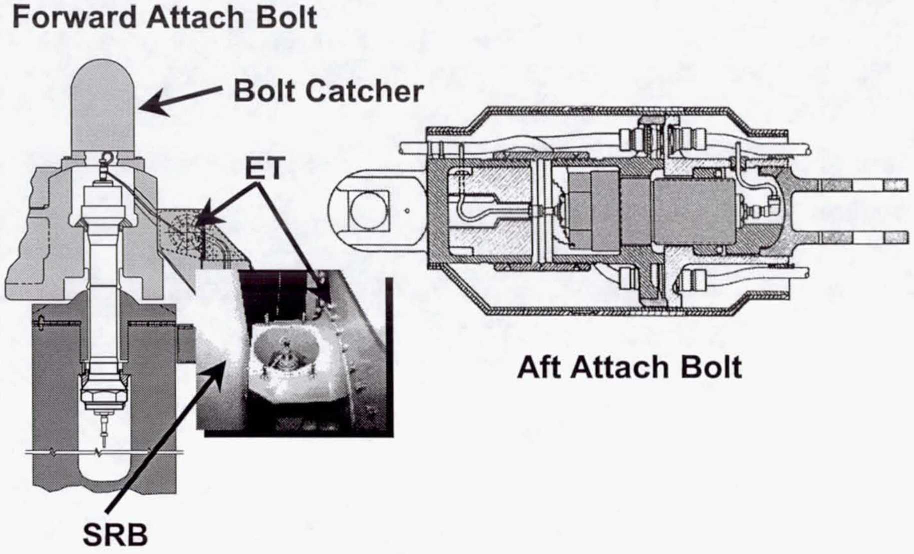




SRB Attach/Hold-down Hardware Upgrades Plan

Description

- Elements to be evaluated
  - Blast container
  - Bolt catcher
  - ET/SRB attach bolts (forward and aft)
- Performance testing to anchor analytical models
- Research of available material properties
- Process reengineering to reduce potential for human error
- Results in improved component robustness



Benefits

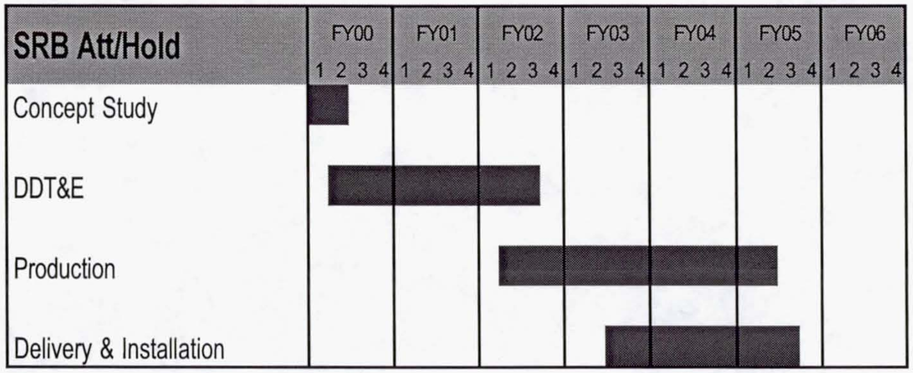
Safety

- Increased Factor of Safety (FOS) from 1.35 to minimum requirement per 07700 Vol X design factor of safety requirement
  - Current FOS is an exception to the requirement
- Improved component robustness
- Reduced potential for human error

Supportability

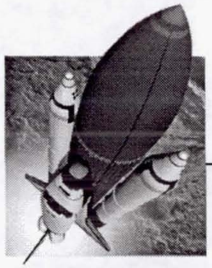
- Increased maintainability through reduction of human error

Schedule

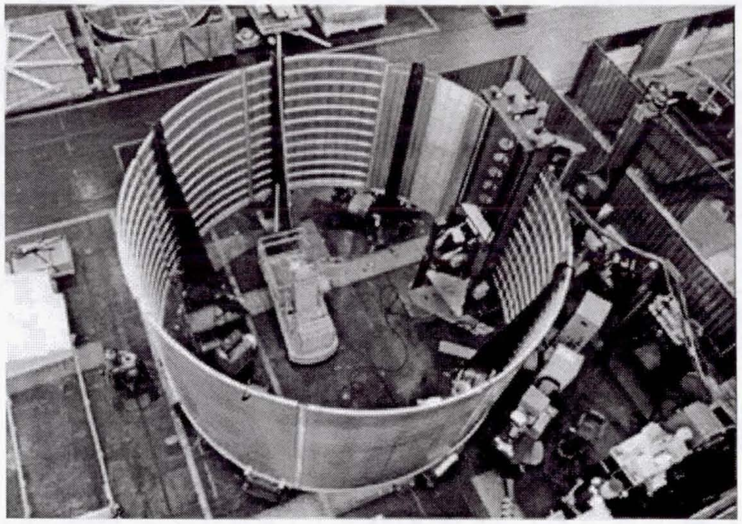


SRB Att/Hold	FY00				FY01				FY02				FY03				FY04				FY05				FY06			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study	■	■																										
DDT&E		■	■	■	■	■	■	■	■	■	■																	
Production										■	■	■	■	■	■	■	■	■	■	■	■	■						
Delivery & Installation															■	■	■	■	■	■	■	■	■					

Tentative Schedule



External Tank (ET) Upgrades - Friction Stir Weld (Barrels, Longitudinal)



Description

- Implement friction stir weld technology for External Tank longitudinal LOX and LH2 barrels
- Characterize weld process requirements and allowables
- Focus on Non-Destructive Evaluation (NDE) qualification requirements
- Develop weld process bandwidth parameters toward the goal of a 6 sigma control process

Benefits

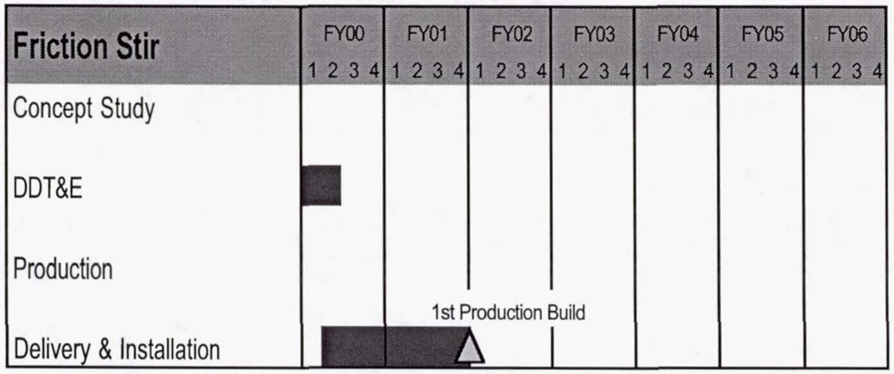
Flight Safety

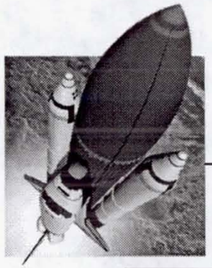
- Increases barrel reliability by improving
  - Weld joint strength
  - Weld margins
  - Fracture toughness
  - Process control

Improve the System

- Decreased ET production time
- Decreased ET production cost
- Operational demonstration of important industry technology

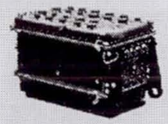
Schedule





SSME Advanced Health Management System

Phase I



SSME Block II Controller Upgrade
- Vibration redline
- DCU memory
- Communication bus

Phase IIA

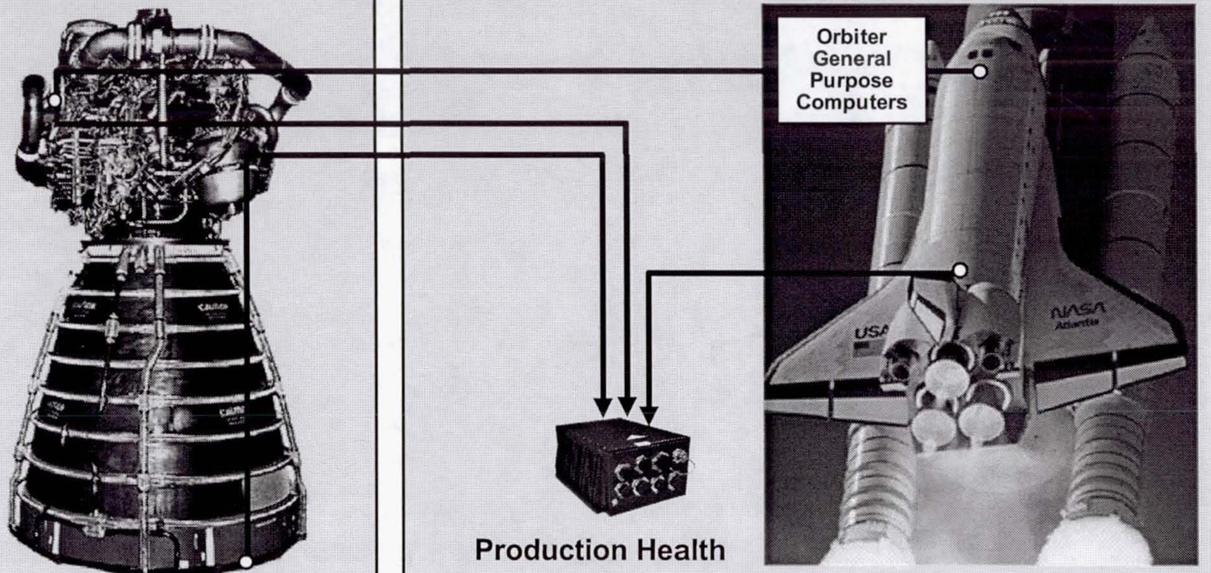
Protoflight Health Management Computer
- Design
- Development
- Vehicle integration
- Flight demo/monitor
- RTVMS, OPAD, LED flight experiments

Catastrophic Redlines

Reside in Engine Controller

23% Reduction in Failure Probability

Phase IIB



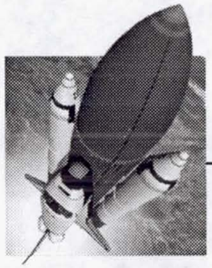
Production Health Management Computer
- Expanded vibration monitoring
- Exhaust plume monitoring
- Engine model
- Expert systems
- Vehicle & System integration

Engine Health & Advisories Recommend Action

Resides on Orbiter

Similar Risk Reductions Calculated for Phase II

Goal: Reduce risk of SSME catastrophic failure by approximately 40%



SSME Advanced Health Management Phase I

Description

- SSME Advanced Health Monitoring Phase I – Synchronous Vibration Redline
  - Modify SSME Controller
    - Reliable real-time turbopump synchronous vibration redline capability
    - High speed serial interface for external communication
  - Develop and fly prototype Health Management Computer (HMC)
  - Fly OPAD Flight Experiment
  - Develop Linear Engine Model (LEM) as a MOD tool
  - Phase II Requirements Definition

Phase I

SSME Block II Controller Upgrade

Prototype Health Management Computer

Catastrophic Redlines

Reside in Engine Controller

Benefits

Flight Safety

- Reduces SSME catastrophic failure probability approximately 23%
- Reduces Shuttle catastrophic failure probability approximately 8%

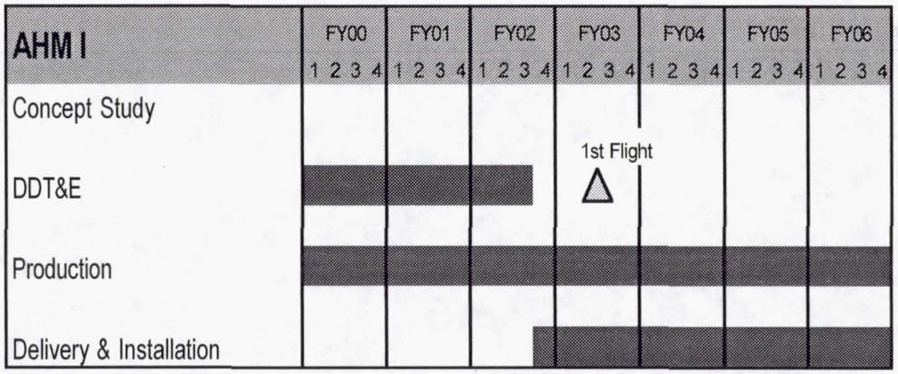
Mission Success

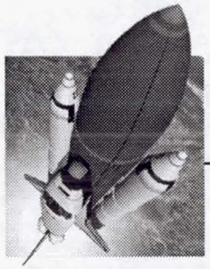
- Improved SSME Controller external communication
- Develops tool to be used by crew and MOD

Technology

- Develops technology needed for Phase II
- Integrated with and contributes to program and agency IVHM goals

Schedule





SSME Advanced Health Management Phase II

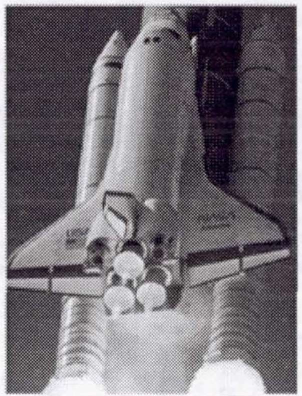
Description

- SSME Advanced Health Monitoring Phase II – Advanced Health Management System (AHMS)
  - Health Management Computer (HMC) hosts
    - Advanced Real Time Vibration Monitoring System (RVTMS)
    - Optical Plume Anomaly Detection (OPAD)
    - Linear Engine Model (LEM)
- Phase II AHMS assesses results of RVTMS, OPAD and LEM and makes an overall SSME health recommendation

Phase II

Production Health Management Computer

- **Expanded vibration monitoring**
- **Exhaust plume monitoring**
- **Engine model**
- **Expert systems**
- **Vehicle & System integration**



Engine Health & Advisories Recommend Action

Resides on Orbiter

Benefits

Flight Safety

- Reduces SSME catastrophic failure probability approximately 24%
- Phase I and Phase II combined reduces SSME catastrophic failure probability approximately 41%

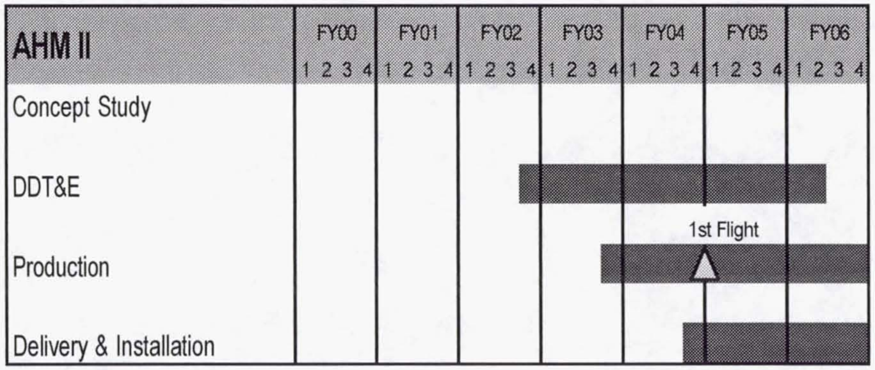
Mission Success

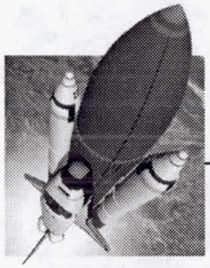
- Detects and isolates failures with high confidence and provides mitigation options which were previously unavailable
  - Mitigation of off mixture ratio operation
  - Enhances SSME operability due to additional data and automated engine health assessments

Technology

- Integrated with and contributes to program and agency IVHM goals

Schedule





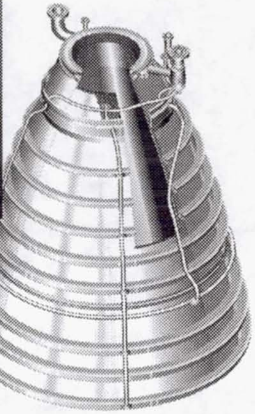
Block III SSME

Description

- Extra-Large Throat Main Combustion Chamber (XLTMCC)
  - Reduced operating environments (pressure, temp)
  - Reduced hazards in Orbiter aft compartment
  - Reduced number of critical welds and parts
- Channel-Wall Nozzle
  - Reduces hazards of current nozzle

High Performance SSME

Larger LTMCC



Advanced Nozzle

Benefits

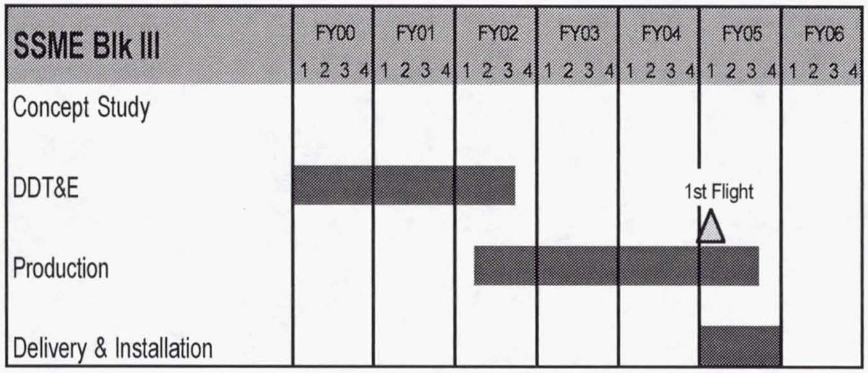
Flight Safety

- Increases SSME catastrophic failure MTBF by approximately 30-35%.
- Potential increased abort thrust capability
- Increased engine margin
- MCC/Nozzle interface is below the heat shield

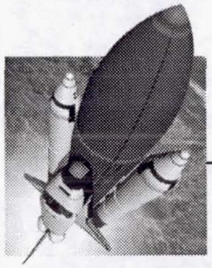
Improve the System

- Decreased production time and production costs
- Increased turbine life
- Reduced inspections

Schedule



SSME Blk III	FY00				FY01				FY02				FY03				FY04				FY05				FY06			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study																												
DDT&E	■	■	■	■	■	■	■	■	■	■	■										1st Flight △							
Production										■	■	■	■	■	■	■	■	■	■	■	■	■	■					
Delivery & Installation																					■	■	■	■				

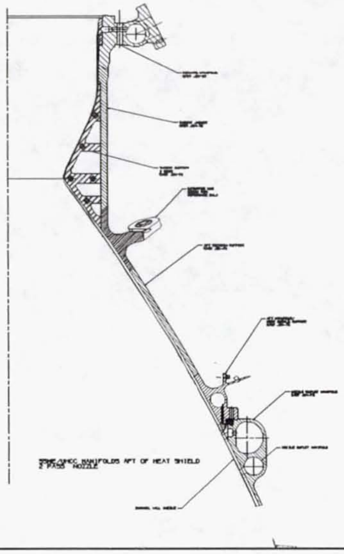


SSME Blk III X-Large Throat MCC

Description

- X-large throat MCC reduces operating environment for turbopumps and other components for increased engine reliability
- XLTMCC is ~18 inches longer to make optimum MCC/Nozzle configuration
- Has optimum RAO contour for Isp performance
- Fabricated by HIP braze process to eliminate failure modes and achieve 2X reliability improvement

- JBK-75 cast manifolds & jacket
- HIP braze close-out of channels
- Only 4 FMEA/CIL Crit 1 welds - was 23
- Only 10 parts + pins - was 20
- MCC/Nozzle interface below heat shield



Benefits

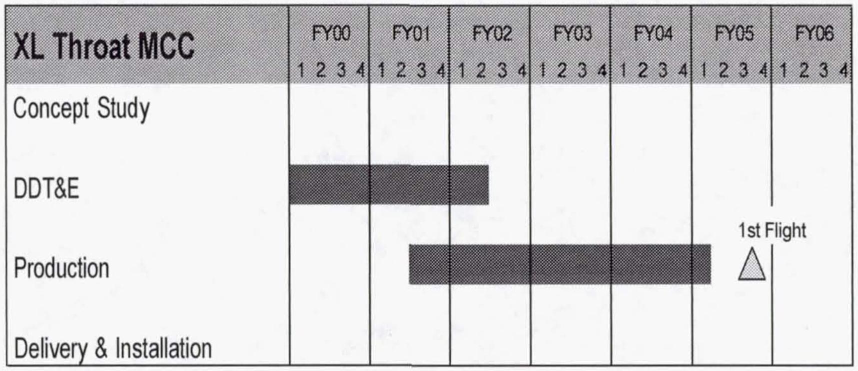
Safety & Reliability

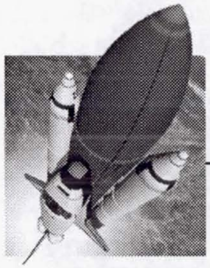
- Improves 3-engine catastrophic MTBF from 1 in 1885 to 1/2586 with reducing the operating environment
- Doubles MCC MTBF from 1 in 8,950 to 1 in 17,901

Improve the System

- Unit production cost ~$1M lower
- Production cycle time reduced ~6-12 months

Schedule



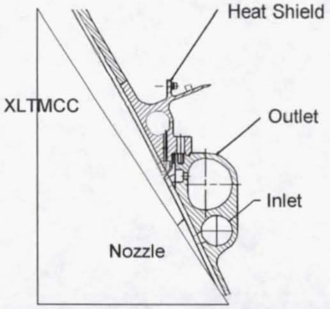


SSME Block III Channel-Wall Nozzle

Description

- Channel-wall constructed nozzle shortened by XLTMCC length increase with optimum contour
- Simplified construction - 5 major subassemblies (integral inlet / outlet casting, liner, jacket, forward end plumbing & drain lines, & TPS)
- Simple aft end flow turn-around with 1 weld -- no steerhorn feedlines
- No chamber coolant control valve/actuator
- Robust fabrication with reduced part count & welds

- Integral inlet & outlet JBK-75 cast manifolds
- JBK-75 liner & jacket
- HIP braze close-out of channels
- Eliminated ~300 welds & 5800 inches of welds
- Eliminated ~250 parts
- MCC/Nozzle interface below heat shield



Benefits

Safety & Reliability

- Improves 3-engine MTBF from 1 in 2363 to 1 in 2593 and doubles nozzle MTBF from 1 in 13,860 to 1 in 27,720
- Benign joint failures with G15 below heat shield

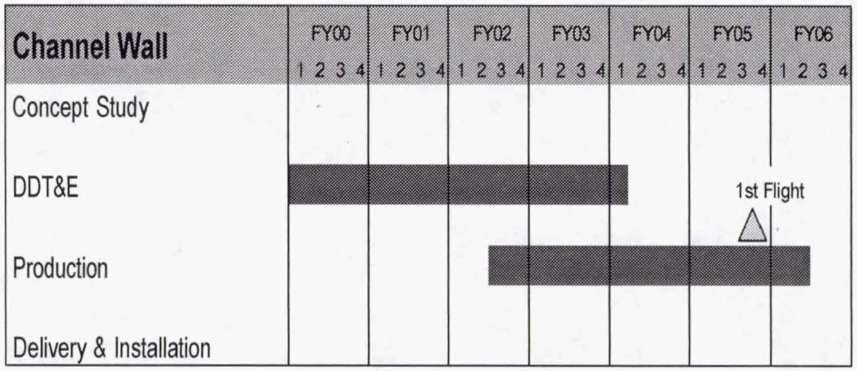
Mission Success

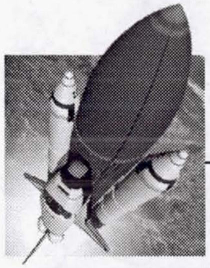
- Recover XLTMCC Isp loss with optimum contour and smooth wall (~1s)

Improve the System

- Reduce nozzle maintenance -- no leakage/repairs
- Reduces fabrication cycle time by 18 months
- Unit production cost ~$2M lower

Schedule

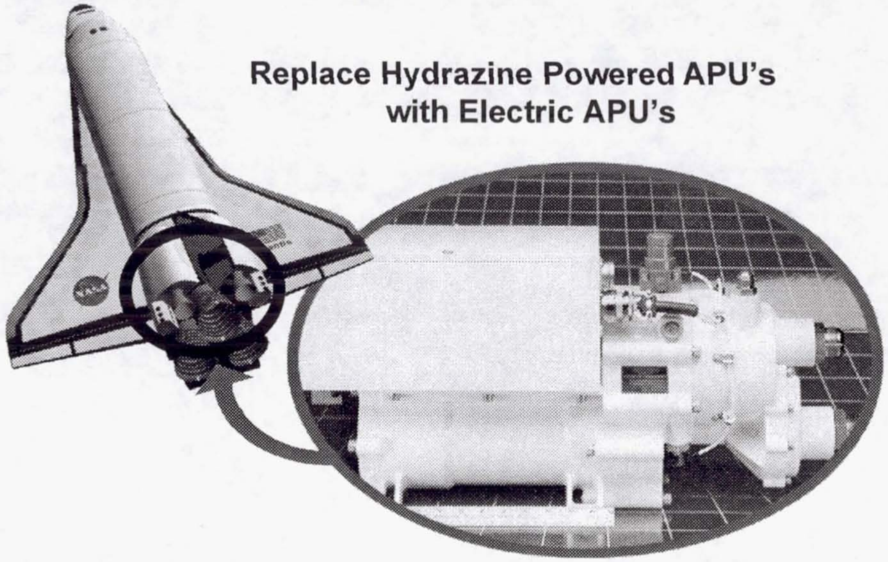




Electric Auxiliary Power Unit (EAPU)

Description

- Upgrade three existing hydrazine system/high speed turbines with three electric motor driven, hydraulic pump systems powered by batteries
- EAPU upgrade consists of three main components
  - Electro-Hydraulic Drive Unit (EHDU) and Cooling
  - Battery system
  - Electric Power Distribution & Control (EPD&C)



Replace Hydrazine Powered APU's with Electric APU's

Benefits

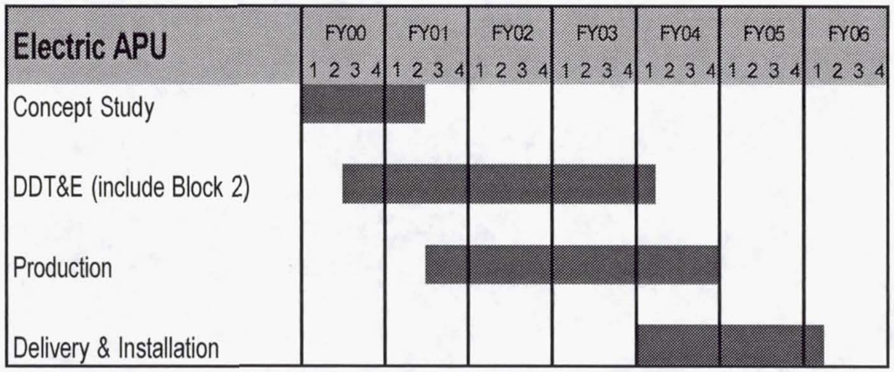
Flight Safety

- Eliminates hydrazine turbine hazards
  - Over speed
  - Hydrazine leakage
  - Re-ingestion of vented hydrazine

Ground Safety

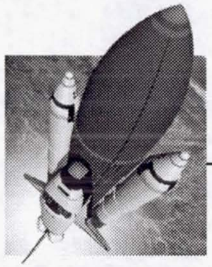
- Reduces toxic materials processing and handling

Schedule



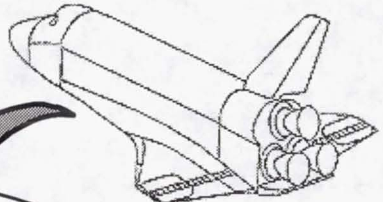
Electric APU	FY00 1 2 3 4	FY01 1 2 3 4	FY02 1 2 3 4	FY03 1 2 3 4	FY04 1 2 3 4	FY05 1 2 3 4	FY06 1 2 3 4
Concept Study	▨▨▨▨	▨▨					
DDT&E (include Block 2)	▨▨	▨▨▨▨	▨▨▨▨	▨▨▨▨	▨		
Production		▨▨	▨▨▨▨	▨▨▨▨	▨▨▨▨		
Delivery & Installation					▨▨▨▨	▨▨▨▨	▨

Safety Upgrades



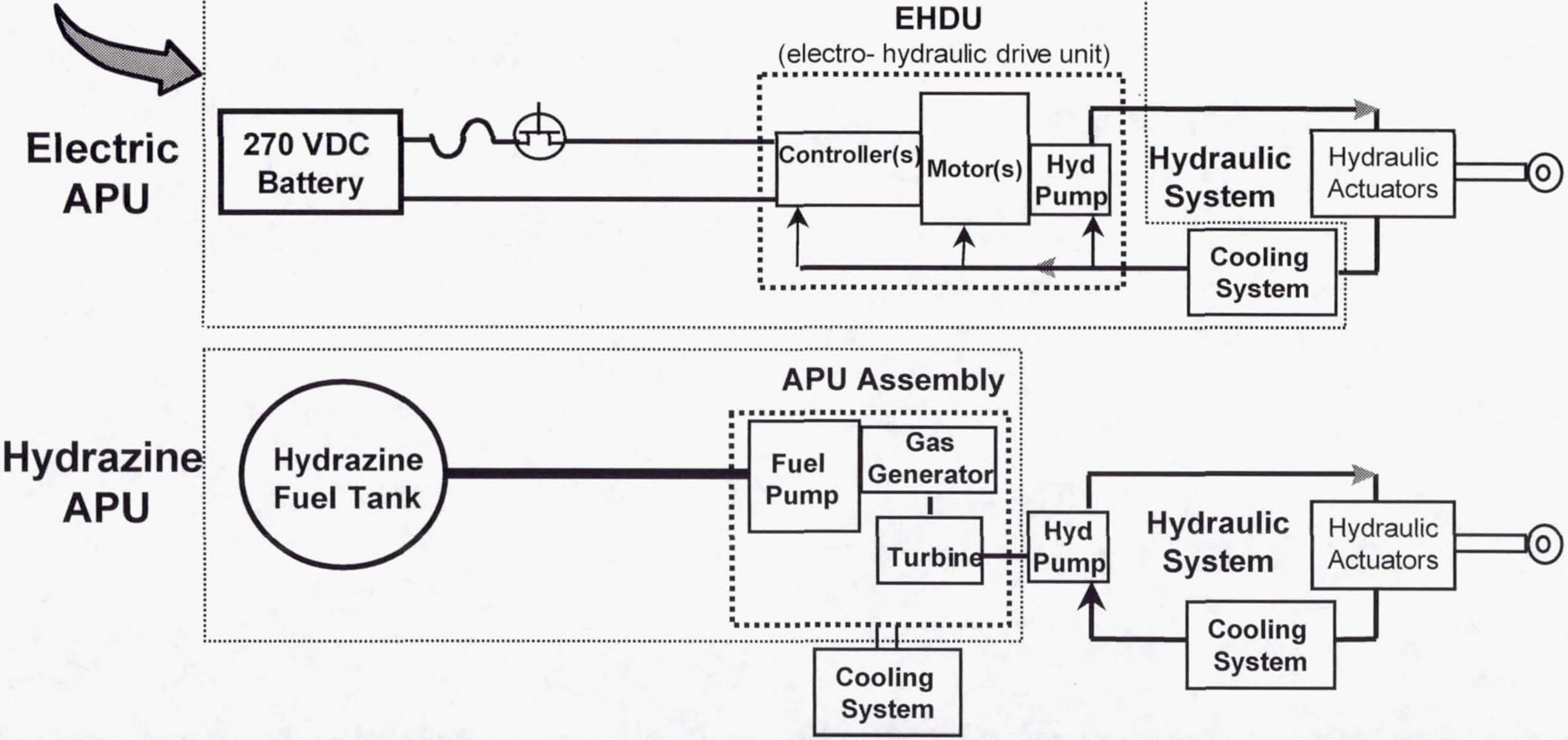
Electric Auxiliary Power Unit (EAPU)

Replace existing hydrazine and high speed turbine systems with electric motor driven, hydraulic pump systems powered by batteries



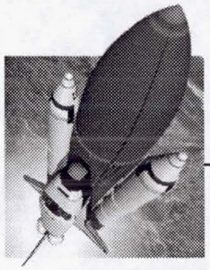
3 APUs in Orbiter Aft Fuselage Supply Power to Hydraulic System

- Takes advantage of battery advancements to minimize weight impact.
- EHDU output power will be 30 percent higher than existing system.
- Enhanced system health monitoring



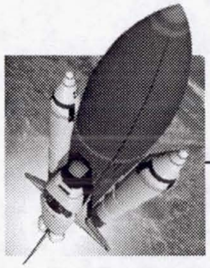
High Priority Safety Studies

- **Crew Escape Engineering Design Trade (Study)**
  - In-depth engineering study of contingency crew survival options
    - Extraction, ejection, crew module separation
  - Determine feasibility, survival utility, cost, and technical impacts
  - Increases probability of a successful crew bailout
- **TPS Lower Surface Tile (Study)**
  - Develop a more durable lower surface tile for bottom of Orbiter
  - Reduces risk of tile burn-through, reduces post-landing repair, and may provide additional MMOD protection
- **SCAPE Suit Improvement (Study)**
  - Objective is to develop a safer and more efficient SCAPE suit
    - Current suit is heavy, allows undesirable levels of CO_2, and is not efficiently cooled
  - Technical approach is to design and develop a prototype suit with decreased weight, better CO_2 scrubbing, and better cooling

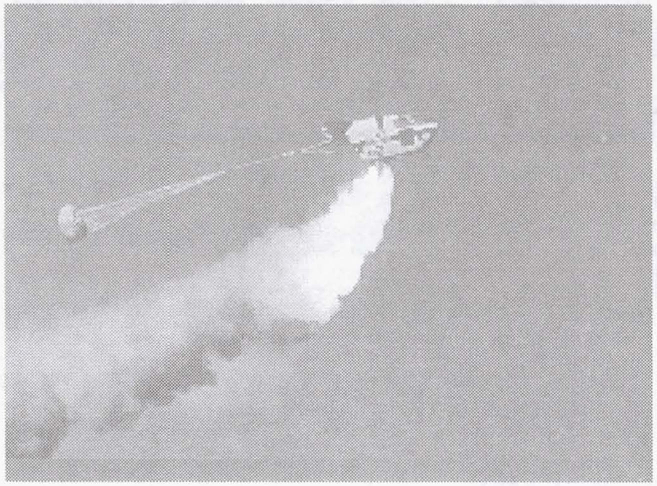


High Priority Safety Studies

- **Shuttle Abort Improvements (Study)**
  - Investigate Orbiter hardware/software/procedural improvements to eliminate/decrease two engine out blackzones and other abort scenarios
  - Reduce areas of no coverage, eliminate abort scenarios, increase probability of a successful abort
  - Investigate propulsion element improvements to eliminate/decrease two engine out blackzones and other abort scenarios
  - Reduce areas of no return, eliminate abort scenarios, increase probability of a successful abort
- **Maintainability for Safety (Study)**
  - Objective is to identify maintainability improvements which can improve safety
  - Reduce potential of collateral damage during ground processing, improve personnel safety



Crew Escape System (Study)



Description

- Enhance crew escape capability in the event that the Orbiter can not return to one of the designated landing sites.
  - Expand crew escape envelope from 20,000 ft to 150,000 ft
  - Add capability to save multiple incapacitated crewmembers
  - Expand ability to use crew escape system based on flight conditions (vehicle speed, trajectory, attitude)
- Crew Escape candidates for study are:
  - Forward fuselage/crew module separation
  - Ejection seats
  - In-place extraction system

Benefits

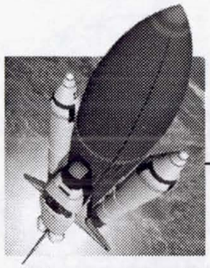
Flight Safety

- Increase probability of crew survival during loss of vehicle scenarios
  - Probabilities for the three candidates will be estimated in the study
- Increase probability of crew survival in a rapid egress scenario on the launch pad
  - Capabilities for the three candidates will be evaluated in the study

Schedule

Crew Escape study includes Phase I and Phase II

Crew Escape Study	FY00	FY01	FY02	FY03	FY04	FY05	FY06
	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
Phase I (Completed 10/99)							
Phase II (Trade Study/ Downselect)	▨						
Phase III (System Design/ Certification)		▨	▨	▨			
Phase IV (Delivery & Inst.)					▨	▨	▨



Orbiter TPS Lower Surface Tile (Study)

Description

Develop a more durable TPS tile for the orbiter vehicle's bottom fuselage region that will significantly reduce flight damage without compromising the thermal performance of the current system.

- Reduce the thermal conductivity of the current RCG/TUFI/AETB-8 tile to that of the RCG/LI-900 tile.
- Modify the TUFI process to be compatible with the LI-900 tile material
- Produce a tile system of comparable weight, catalytic performance, and thermal conductivity as the current LI-900 baseline system with enhanced durability.
- Produce a tile coating applicable to the LI-900 significantly more durable than the RCG/TUFI combination, with comparable weight and catalytic performance
- Products deliverable for FY00:
- Midterm (June 2000) and Final reports (Oct 2000) for each effort
- For each of the above efforts, no less than
    - 8 square tiles (6" square, 2" thick)
    - 4 arc jet pucks (3.875" diameter, 2" thick)

Original AETB-8 Tiles with RCG/TUFI Coating;
OV-104 Base Heat Shield Five Flights - No Damage
STS-76, STS-79, STS-81, STS-84 & STS-86

Projected Benefits

Safety & Reliability

- LOV (1/X) due to On-Orbit M/OD: Current 2197; Projected ~2800
- Reduces hazardous ground operations by elimination of re-waterproofing
- Reduced risk and increased safety for components, system and personnel; 50% Reduction in tile contribution to Orbiter risk from M/OD

Mission Success

- Increased reliability of components and systems; Significant reduction in component damage

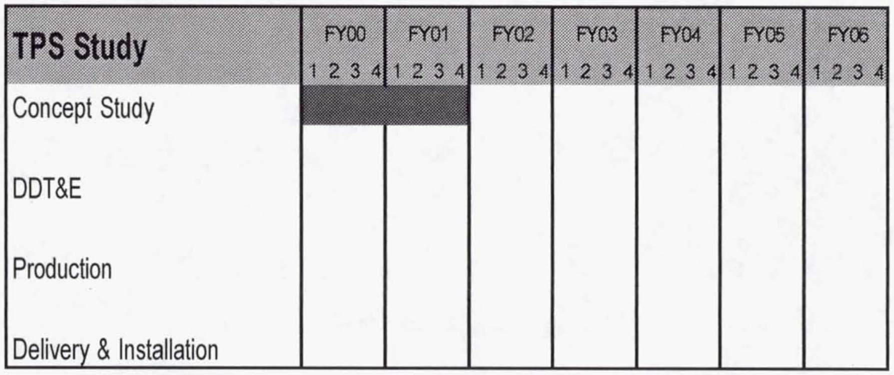
Supportability

- Maintenance free lower surface significantly decreases amount of unplanned work in OPF. Weight reduction of 200-600 pounds. Supports 30-day OPF flow

Improve the System

- Supports 30-day OPF flow

Schedule



TPS Study	FY00 1 2 3 4	FY01 1 2 3 4	FY02 1 2 3 4	FY03 1 2 3 4	FY04 1 2 3 4	FY05 1 2 3 4	FY06 1 2 3 4
Concept Study	▨	▨					
DDT&E							
Production							
Delivery & Installation							

Advanced Protective Suit Program (Study)

Description

- Redesign existing propellant handler's Self-Contained Atmospheric Protective Ensemble "SCAPE" suit which is used for protection during propellant loading operations
  - Phase 1 included development of a new 1 hour cooling dewar and then a 2 hour dewar
- Currently investigating teaming with part of the U.S. Army Soldier and Biological Chemical Command, "Natick Labs", for development of suit specifications and for suit production.

Benefits

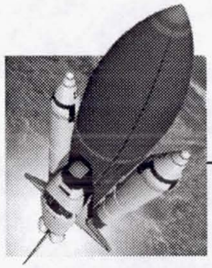
Ground Safety

- Design goals for new suit include
  - Reduce carbon dioxide levels
  - Improve thermal characteristics
  - Improve visibility
  - Improve dexterity
  - Eliminate need to be upright to maintain adequate air flow
  - Improve communications/reduce noise
  - Improve fit
  - Decrease cost
  - Decrease weight

Schedule

Advanced Protective Suit study includes Phase I and Phase II

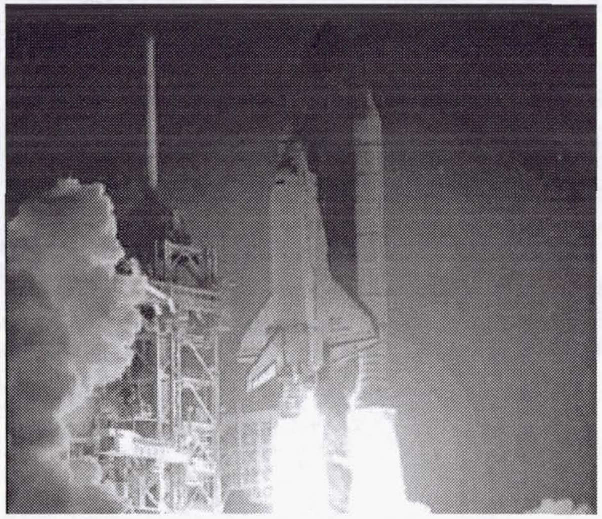
Suit Study	FY98				FY99				FY00				FY01				FY02				FY03				FY04			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Phase I (Environmental Control Unit Dev.)				▨	▨	▨	▨	▨	▨	▨																		
Phase II (Suit Specs/ Prototype Dev.)											▨	▨	▨	▨														
Phase III (DDT&E)															▨	▨	▨	▨	▨	▨								
Phase IV (Prod. & Del.)																												



Abort Improvements (Study)

Description

- Current abort capability does not include full crew and vehicle survivability coverage for some two and three engine out scenarios (black zones).
- A multidisciplinary team was formed to brainstorm possible improvements. The most promising improvements will be implemented or studied further. Study addresses
  - Vehicle capability characterization (i.e. improve vehicle models, databases, constraints or limitations that drive blackzones)
  - Improvements to software, procedures, or hardware

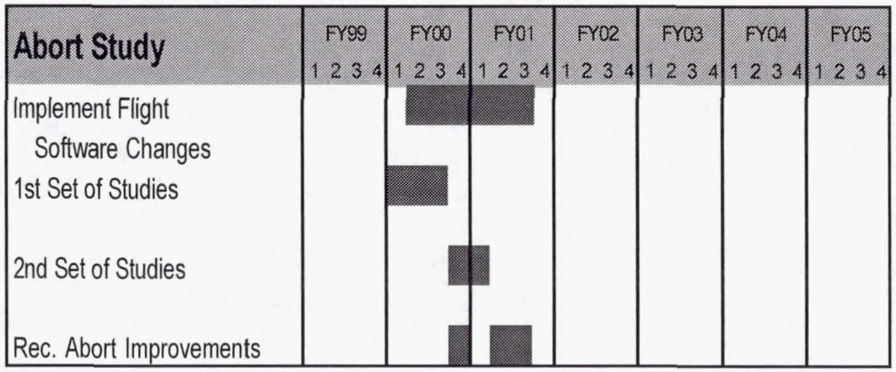


Benefits

Flight Safety

- Improve probability of a runway landing or bailout in certain loss of crew and vehicle abort scenarios
- Black zone criteria (targets for improvement)
  - ET attach structural failure for 3 SSME's out in 1st Stage (< 100 sec)
  - Loss of Control (LOC) during the pullout maneuver (qbar > 800 psf)
  - Structural failure during the pullout maneuver (Nz>3.5 g's)
  - Recontact/LOC after ET Separation near Vrel=0 on RTLS
  - Recontact/LOC for 3 SSME's out during last minute of PRTLS
  - Thermal limit and/or 3.5 g exceedance for MECO near VI=19K fps

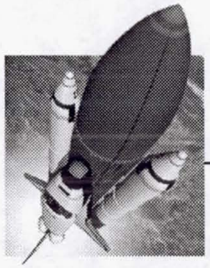
Schedule



Space Shuttle Safety Upgrade Implementation Strategy

- Space Shuttle Program is committed to implementing the major safety upgrades by 2005.

- A SSP upgrades program plan to facilitate and manage the implementation of the upgrades.



Shuttle Upgrade Plan Background

Shuttle Upgrade Strategy

Pro-active upgrade program to keep Shuttle flying ***safely*** and efficiently to 2012 and beyond to meet agency commitments and goals for human access to space

Safety Upgrades

Risk Reduction Goals

- Major reduction in ascent catastrophic risk
- Significant reduction in orbital and entry system catastrophic failure risk
- Improve crew cockpit situational awareness for managing critical operational situations

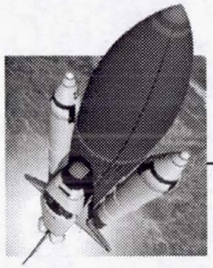
Supportability Upgrades

Flight Hardware Availability Assurance

- Obsolescence
  - Parts availability
  - Vendor support
- Failure rates
- Repair times
- Inventory attrition

Operational Improvements

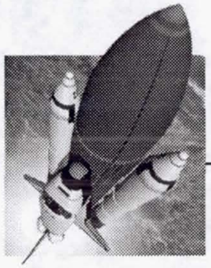
- Maintainability
- Reliability
- Mission success
- Operational simplicity\
- Turn-around time improvements
- Cost reduction



Shuttle Supportability Upgrade Priorities

- **Key flight hardware *obsolescence* assessments**
    - Orbiter communication system
    - SRB integrated electronics assembly

- **Infrastructure refurbishment and repair**
    - Modernizing the Launch Processing System at KSC
    - Currently carrying out detailed assessment of all ground support facilities



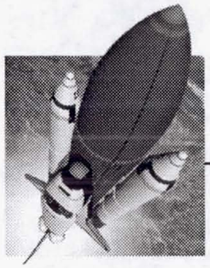
Preliminary Supportability Study Conclusions

Key near term decisions

- Strategy for funding-limited supportability upgrade plan for 2000 & 2001 assuming no additional funds before 2002
  - Key question to be resolved is relative phasing of Orbiter major communication system upgrade and SRB major avionics upgrade
- Initiate design and acquisition effort, including vendor contracts, to implement necessary upgrades for near term supportability threats

Continue to refine supportability analyses and plans

- Independent assessment of supportability analyses and plans
- Develop more in-depth analysis and rationale
  - Reliability statistical variation analyses
  - LRU unique projections (rather than by similarity)
- Revise technical plans, proposals, costs and schedules
- Develop POP2000 budget submit for additional funding needed starting in FY02 and subsequent years



Preliminary Supportability Study Conclusions

- Only minor hardware supportability issues in fluid and mechanical subsystems
- Orbiter and SRB obsolete avionics are primary threat to assured manifest support through 2012
- Necessary additional funds to accomplish prudent supportability upgrades are under review and will be handled as part of the POP2000 budget planning for FY02 and subsequent years

Process to Identify Supportability Upgrades

Identify Issues
- Parts availability
- Failure rate
- Repair time
- Attrition
- Support equipment
- Operational complexity
- Infrastructure

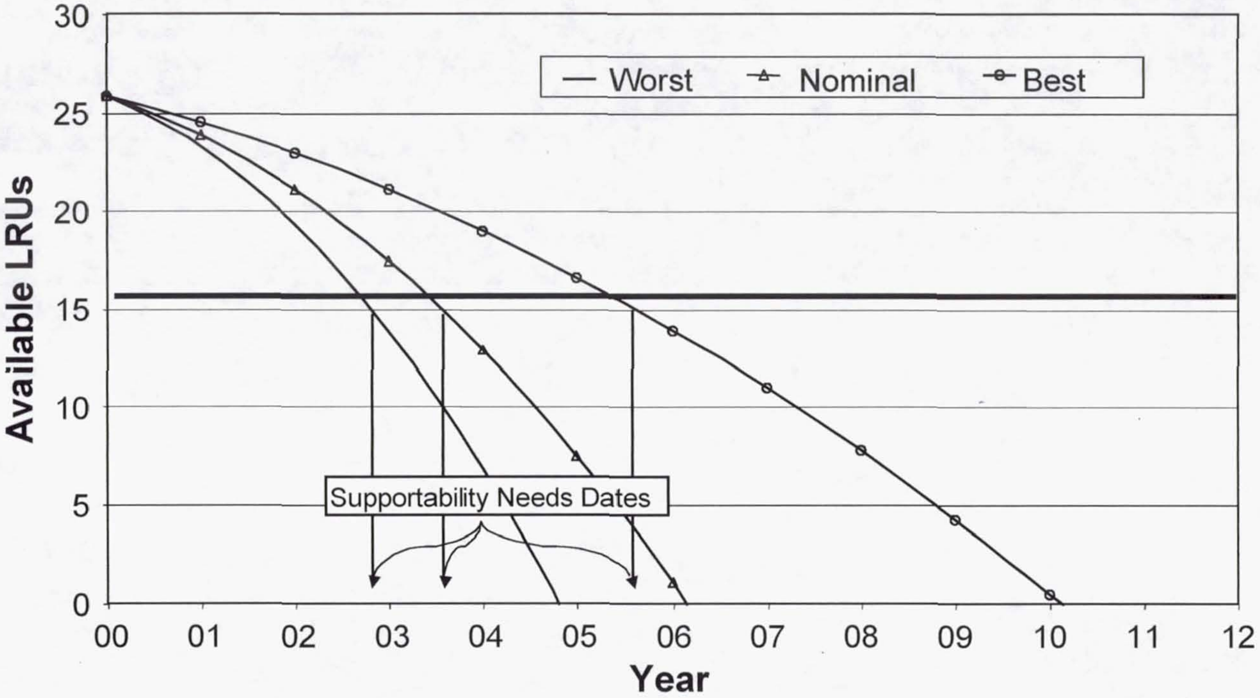
Validate Issues and Assess Consequence
- Metric/Trend data
- Best/Worst case scenarios

Identify Options
- Alternate supplier
- Substitute part
- Repair facility improvement
- LRU upgrade

Evaluate Options and Choose Preferred Solution
- Feasibility of option
- Risk
- Schedule
- Life cycle cost
- Ancillary benefits
  - Performance
  - Operations simplicity
  - Inherent reliability
  - Etc.

Prioritize and Provide Rationale for Recommended Supportability Upgrades

Example LRU Best, Nominal and Worst Cases



Nominal

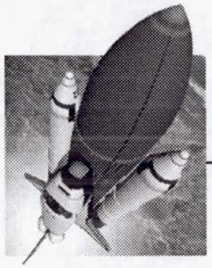
- Estimate near term demand (failures, attrition) for 8 flights per year from historical data
- Establish increasing failure rate trend from historical data or similar hardware to account for "bathtub" failure rate
- Estimate near term Repair Turn Around Time (RTAT) from NSLD assessments of historical data and mitigating circumstances
- Estimate increasing trend to account for impact of obsolete parts on RTAT
- Use historical attrition rate

Best

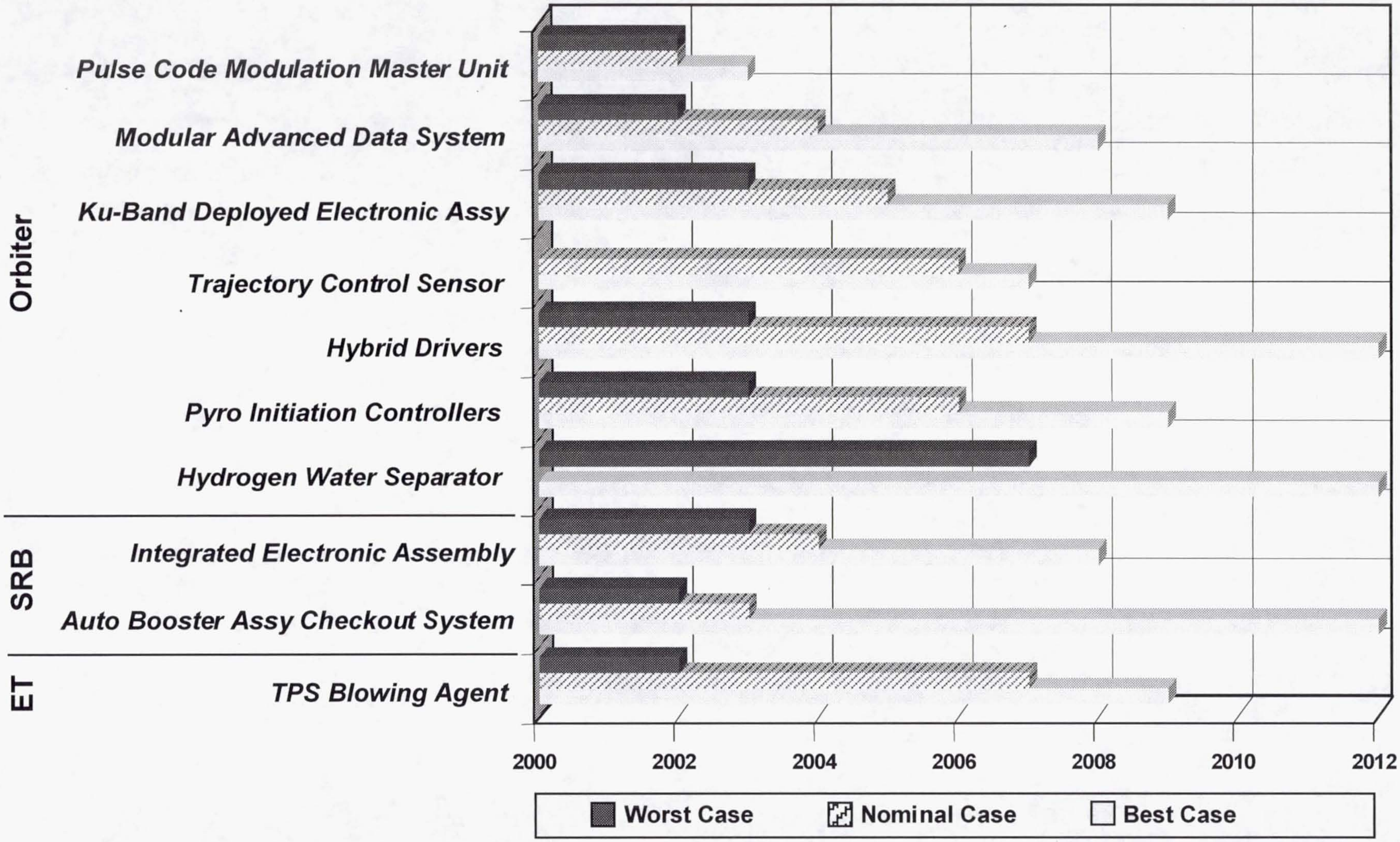
- 1/2 increase in nominal failure rate
- No change in RTAT
- Historical attrition rate

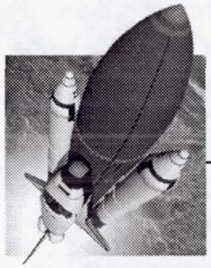
Worst

- 2x increase in nominal failure rate
- 2x increase in nominal RTAT
- Historical attrition rate



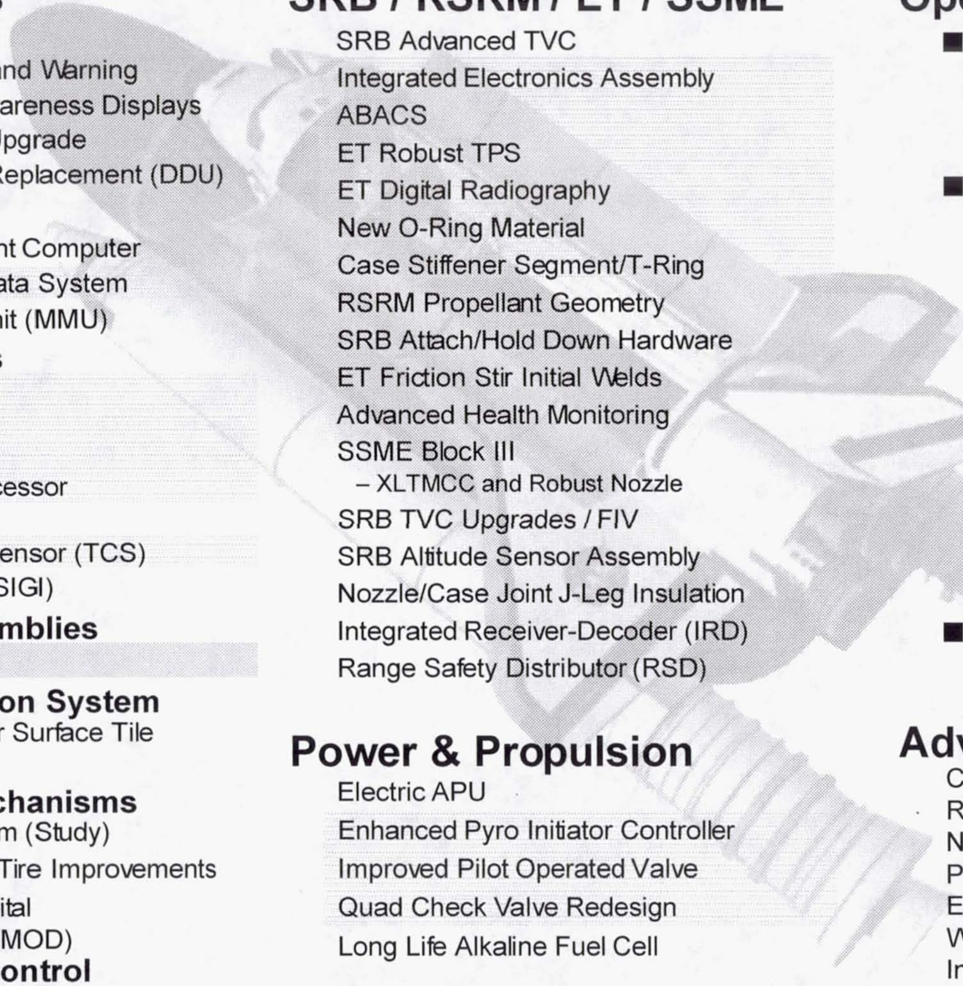
Obsolescence Mitigation Need Dates





Space Shuttle Safety and Supportability
Safety Upgrade Candidates

Safety Upgrades   Supportability Upgrades   Approved Upgrades   Advanced Technology



Orbiter Avionics

■ Cockpit
- Enhanced Caution and Warning
- Crew Situational Awareness Displays
- AFD Switch Panel Upgrade
- Device Driver Unit Replacement (DDU)

■ Data Processing
- Mission Management Computer
- Modular Auxiliary Data System
- Modular Memory Unit (MMU)

■ Communications
- Ku-Band DEA
- PCMMU
- S-Band FM
- Network Signal Processor

■ Navigation
- Trajectory Control Sensor (TCS)
- IMU Replacement (SIGI)

■ Power Sub-Assemblies
- Hybrid Drivers

■ Thermal Protection System
- More Durable Lower Surface Tile (Study)

■ Structures & Mechanisms
- Crew Escape System (Study)
- Main Landing Gear Tire Improvements
- Micrometeoroid/Orbital Debris Mitigation (MMOD)

■ Environmental Control & Life Support Systems
- Hydrogen Water Separator

SRB / RSRM / ET / SSME
- SRB Advanced TVC
- Integrated Electronics Assembly
- ABACS
- ET Robust TPS
- ET Digital Radiography
- New O-Ring Material
- Case Stiffener Segment/T-Ring
- RSRM Propellant Geometry
- SRB Attach/Hold Down Hardware
- ET Friction Stir Initial Welds
- Advanced Health Monitoring
- SSME Block III
  - XLTMCC and Robust Nozzle
- SRB TVC Upgrades / FIV
- SRB Altitude Sensor Assembly
- Nozzle/Case Joint J-Leg Insulation
- Integrated Receiver-Decoder (IRD)
- Range Safety Distributor (RSD)

Power & Propulsion
- Electric APU
- Enhanced Pyro Initiator Controller
- Improved Pilot Operated Valve
- Quad Check Valve Redesign
- Long Life Alkaline Fuel Cell

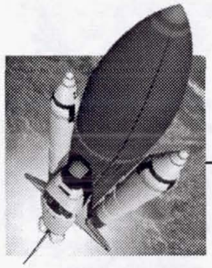
Operations

■ Ground Operations
- Maintainability for Safety (Study)
- SCAPE Suit Improvements (Study)
- CLCS

■ Flight Operations
- PIDAE
- Shuttle Upgrades Design Visualization
- Robotic Situational Awareness Display
- Human Factors/Cockpit Engineering Study
- Expansion of MCC Landing Sites
- AWPS
- EECOM STS Pressure Management Tool
- Alternatives to Hardware Based Robotics Training
- DM Trajectory Operations Interface Redesign

■ Flight Tests
- Wireless Sensor
- Laser Dynamic Range Imager HTD

Advanced Technology
- Crew Escape
- Reusable First Stage
- Non-Tox OMS/RCS Propellants
- PEM Fuel Cell
- Electromechanical Actuators
- Water Membrane Evaporator
- Integrated Vehicle Health Mgmt
- Propellant Densifications
- Fiber Optics



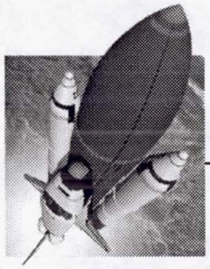
Supportability Upgrades: Requirements and Definitions

Mandatory Supportability Upgrades

- **Mandatory supportability** means “3 shipset availability” for the orbiter fleet (8 shipsets for SRB) based on 8 flights per year through 2012 and equivalent criteria for other shuttle elements
- **At the hardware LRU level** the “3 shipset _un_availability” is determined by one of the following criteria:
  1) the subject LRU contains obsolete part(s) with projected spares inventory depletion before 2012, **and** the obsolete part(s) cannot be replaced with new part(s) without redesigning the assembly or component it is used in; i.e., LRU redesign is required to keep flying after the current parts inventory is depleted. That is, we can’t get the part anymore nor can we buy a “plug and play” replacement part, so we have to redesign the LRU or at least one of its subassemblies to accommodate new parts.
  2) The projected failure rates and repair times for the subject LRU cannot be handled by the maintenance depot, even with **reasonable** depot enhancements (additional staffing and equipment); that is, the maintenance workload will overload the depot and eventually lead to hardware unavailability for flight. That assumes that we do a first order trade on enhancing our repair capability before we say we have to upgrade the flight hardware.

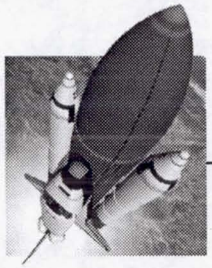
Supportability Improvements which provide significant benefits with respect to:

- Reliability
- Mission success
- Operational processing efficiency
- Life cycle cost



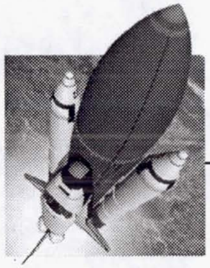
Mandatory Supportability Shuttle Upgrades

Upgrade Project	Supportability Driver
Pulse Code Modulation Master Unit	Project failure rate exceeds repair rate
Modular Advanced Data System	Failure rate is expected to exceed repair rate
Ku-Band Deployed Electronic Assembly	Projected failure rate exceeds repair rate
Trajectory Control Sensor (TCS)	Limited life item
Hybrid Drivers	Not enough hybrid drivers for approved upgrades
Enhanced PIC	Projected demand and attrition exceeds supply
Hydrogen water Separator	Increasing nickel deposits degrade performance
SRB Command Receiver Decoder	Projected failure/attrition rated impact supportability
SRB Integrated Electronics Assembly	Projected attrition rate and limited life impacts supportability
Auto Booster Assy Checkout System	Projected CPU failure/attrition rates exceed projected supply
Robust ET TPS Study	TPS foam blowing will become obsolete



Supportability Improvement Shuttle Upgrades

Upgrade Project	Supportability Driver	Payback Year	
		0% Discount	6.25% Discount
S-Band Network Signal Processor	Obsolete, wearout and degradation failures may exceed ability to repair, Opportunity for bandwidth improvement	**N/A**	**N/A**
S-Band FM Transmitter	Obsolete, wearout and degradation failures may exceed ability to repair	**N/A**	**N/A**
Improved Pilot Operated Valve	Projected reliability improvements provide return on investment	**2009**	**2011**
Quad Check Valve Redesign	Projected reliability improvements provide return on investment	**2010**	**2012**
New O-Ring Material	Projected return on investment and flow time reduction	**2006**	**2006**
Case Stiffener Segment/T-Ring	Projected reliability improvements provide return on investment	**2011**	**2013**
ET Digital Radiography	New digital process provides flow time reduction and substantial ROI	**2008**	**2010**



Modular Auxiliary Data System Recorder

Description

- Option 1: Upgrade
  - Produce new tape for both recorders for near term support
  - Replace tape function with solid state memory in the Modular Memory Unit
- Replace Pulse Code Modulators (PCMs) with high speed PCMs
- Option 2: AHM
  - Procure new tape for both recorders for near term support
  - Combine with Health Management Computer upgrade for the main engines

Benefits

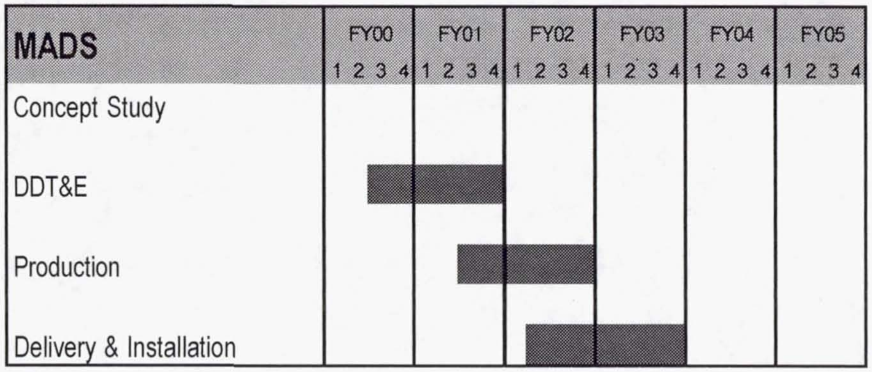
Supportability

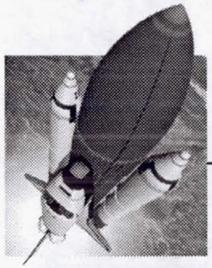
- Tape procurement mitigates near term obsolescence need
- Option 1 mitigates technological obsolescence of recorders

Improve the System

- Both options convert from tape recording to solid state memory
- Option 1 provides for high speed PCMs
- Option 2 leverages technology of SSME AHM effort

Schedule

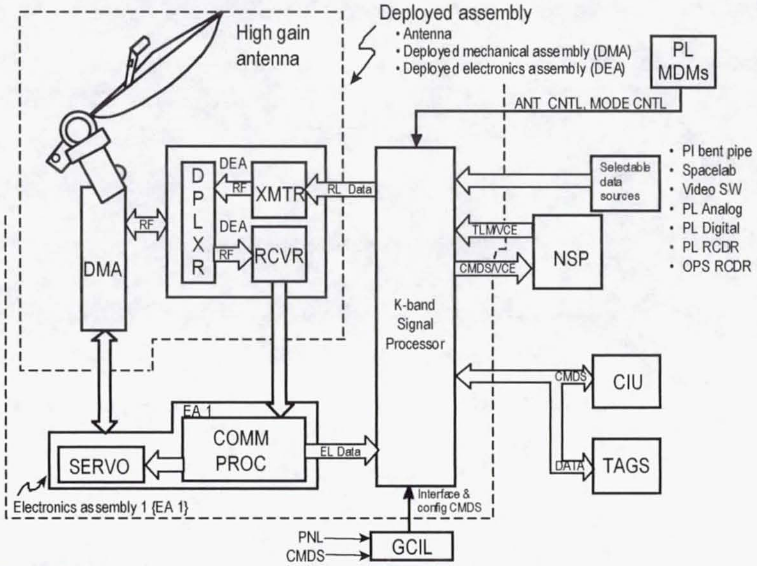




KU-Band Deployed Electronic Assembly

Description

- Replace obsolete Ku-band communications system electronics
  - Option 1: Retrofit current hardware
    - Board-level upgrade of the DEA … I.e., drop in SRU's
    - Separate rendezvous sensor from KU-band hardware
  - Option 2: Replace current deployed parabolic dish Ku-band assembly and supporting electronics with modern phased array antenna (PAA)
    - High bandwidth PAA
    - Separate rendezvous sensor
    - Includes upgrades of communications architecture



Benefits

Safety & Reliability

- PAA option eliminates Crit 1 CIL

Supportability

- Both options mitigate obsolescence issues of the Deployed Assembly
- PAA option mitigates all other obsolescence issues in communications system

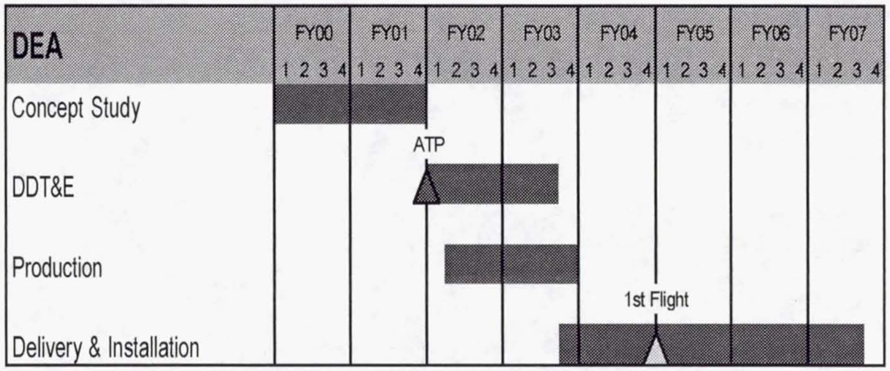
Meet the Manifest

- Provides simultaneous high bandwidth communications during rendezvous
- Improves reliability for mission success and on time launch

Improve the System

- Enables high-bandwidth communications during rendezvous operations
- PAA option is required to enable increased bandwidth capability of Network Signal Processor upgrade
- PAA option provides high-bandwidth operations without opening payload bay doors
- PAA option is an enabler for the MOD Re-invent process

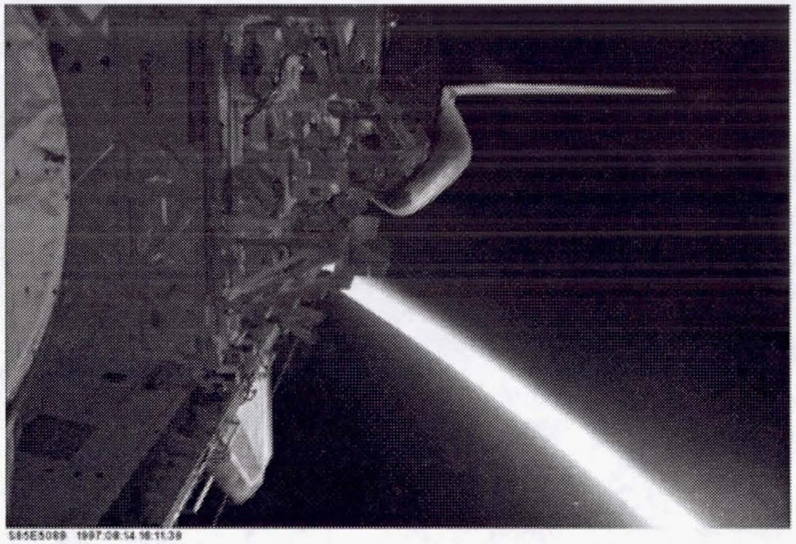
Schedule



Pulse Code Modulating Master Unit

Description

- Option 1: Replace form, fit, function with new technology
    - Reduces number of subassemblies
    - Improves reliability and performance
    - Supports increased data downlink and MOD re-invention
    - May absorb Payload Data Interleaver (PDI) function
- Option 2: Integrate with mission computer as part of safety upgrades



S85E5088 1997:08:14 18:11:38

Benefits

Supportability

- Mitigates obsolescence issues with current PCMMU

Improve the System

- May absorb Payload Data Interleaver (PDI) function
- Increase data downlink
- Supports MOD Re-invention

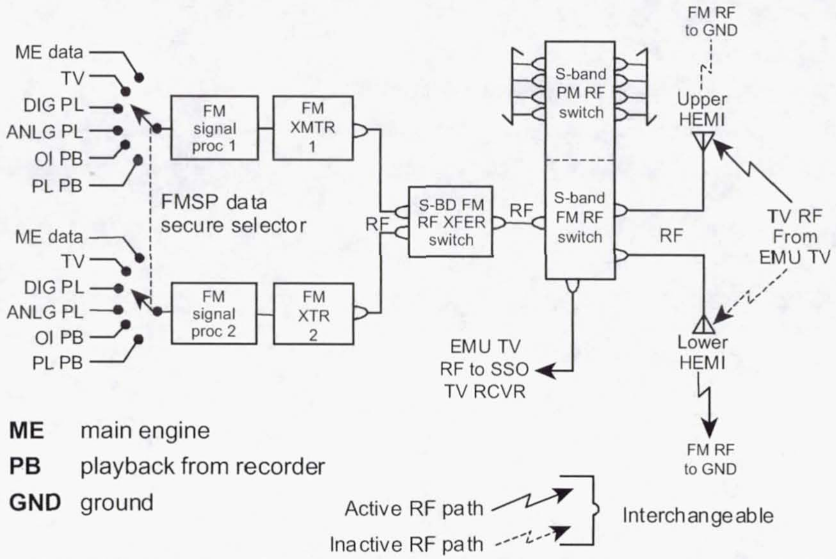
Schedule

PCMMU	FY00				FY01				FY02				FY03				FY04				FY05			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study																								
DDT&E				▨	▨	▨	▨	▨	▨															
Production								▨	▨	▨	▨	▨	▨											
Delivery & Installation												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

S-Band FM

Description

- New FM system (transmitter and signal processor)



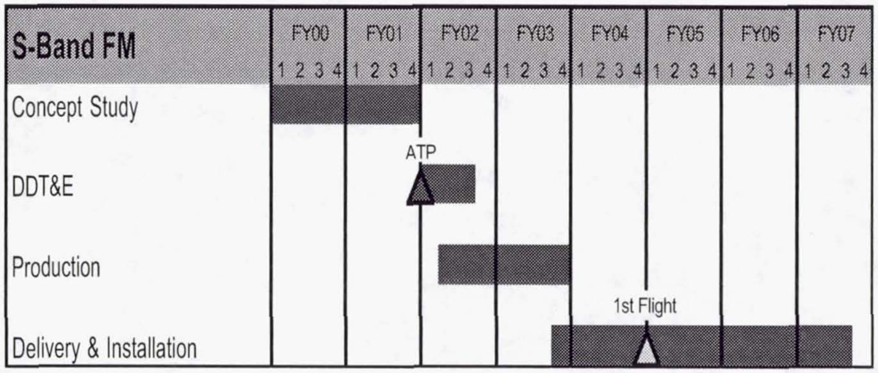
ME main engine
PB playback from recorder
GND ground

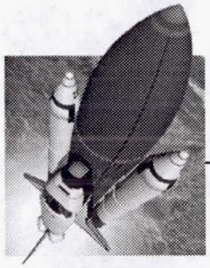
Benefits

Supportability

- Mitigate obsolescence issues of the S-Band FM System

Schedule





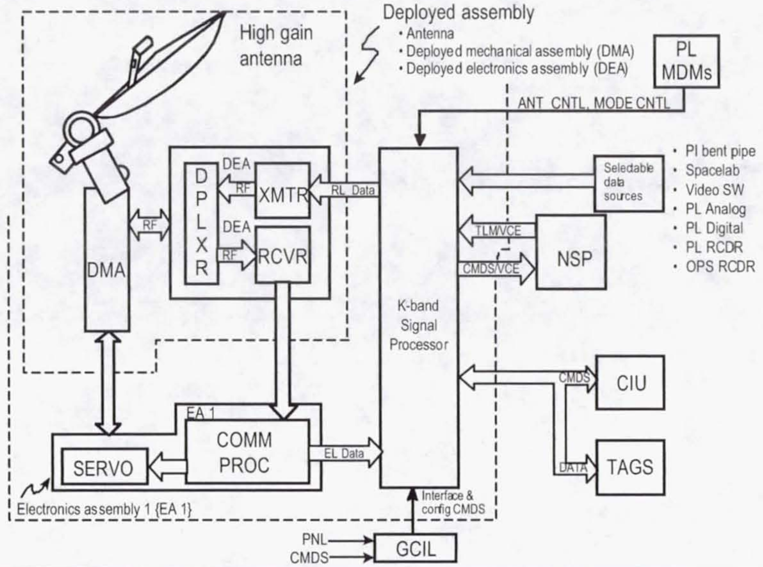
S-Band Network Signal Processor

Description

Combine signal processing and Communications Security (COMSEC) in one new LRU

Employ new voice encoding to increase data bandwidth by up to 32 Kbps

- Supports need for new telemetry without continuous scrubbing of telemetry format loads (TFLs)



Benefits

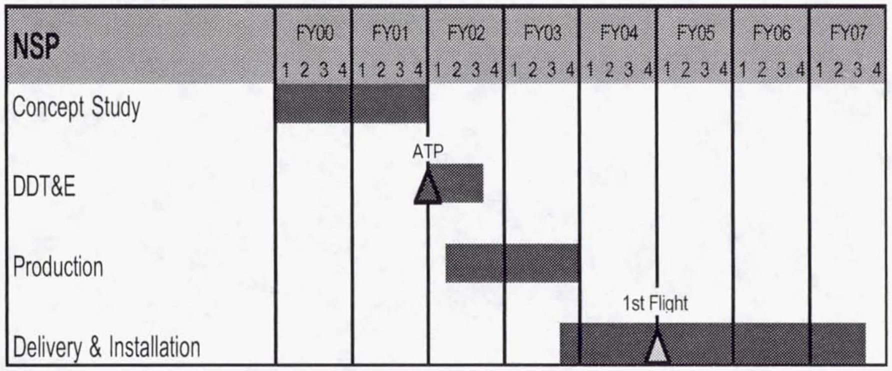
Supportability

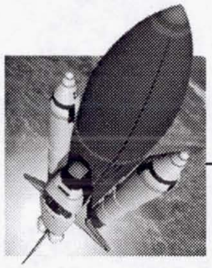
- Mitigate obsolescence issues of the Network Signal Processor

Improve the System

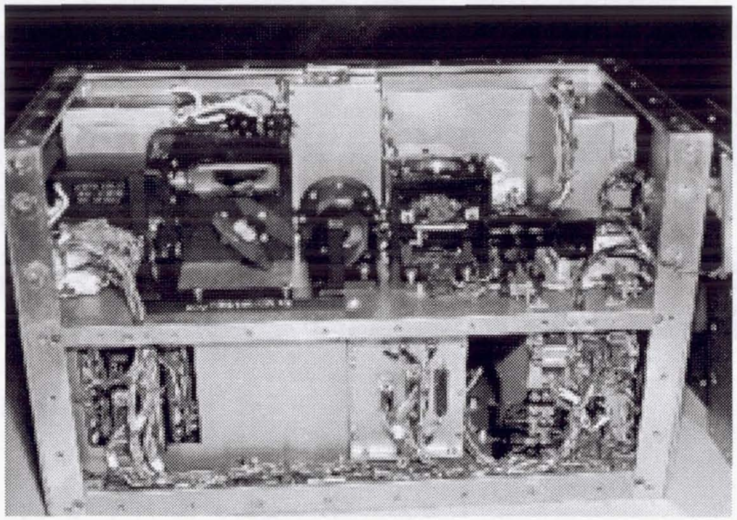
- Combines COMSEC with signal processing for more efficient LRU
- Increased bandwidth during all phases of flight
  - Requires PAA option upgrade of Deployed Electronic Assembly
- Enabler for MOD Re-invention

Schedule





Trajectory Control Sensor (TCS)



Description

TCS is a GFE rendezvous and docking sensor used inside 5000 foot range to target

Upgrade

- Replace galvanometer shaft with new solid shaft
- Purchase 1 new unit to certify all units to 30 flights

Benefits

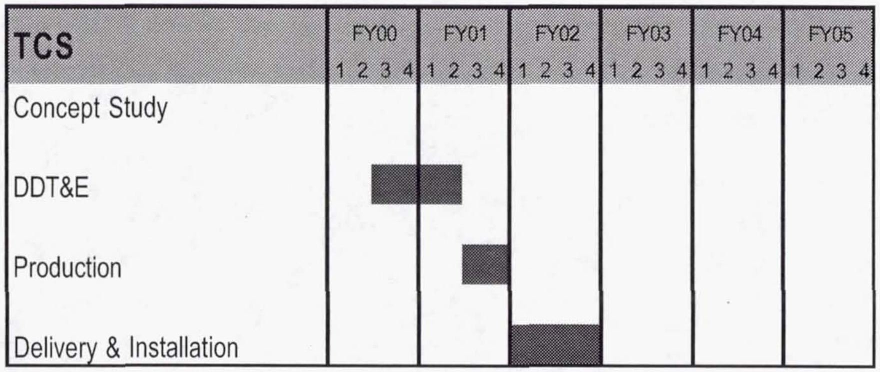
Supportability

- Mitigates obsolescence needs of current Trajectory Control System

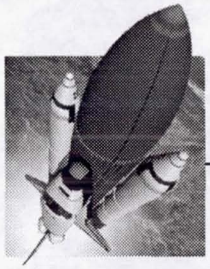
Improve the System

- Improved reliability with new solid galvanometer shaft

Schedule



TCS	FY00				FY01				FY02				FY03				FY04				FY05			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study																								
DDT&E			▨	▨	▨	▨																		
Production							▨	▨																
Delivery & Installation									▨	▨	▨	▨												



Hybrid Drivers

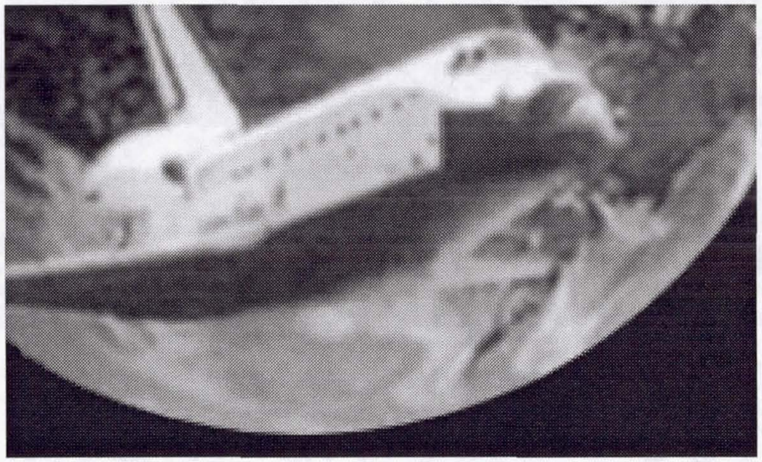
Description

Hybrid driver controllers/assemblies are solid state switching devices used to control and distribute power to Orbiter subsystems

Single programmable device which can support all requirements

Options:

- Drop in replacements for four type of Hybrid Drivers
- Four functionally equivalent types of Hybrid Drivers
- Non-preferred substitute (e.g. electromechanical relay)

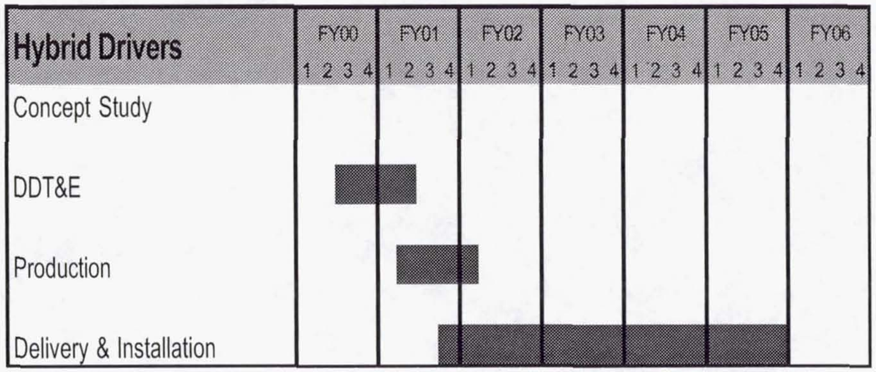


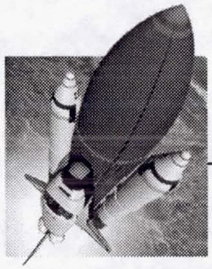
Benefits

Supportability

- Provides for Hybrid Driver needs through the course of the avionics upgrades process, other Orbiter modifications, and typical logistics demands

Schedule





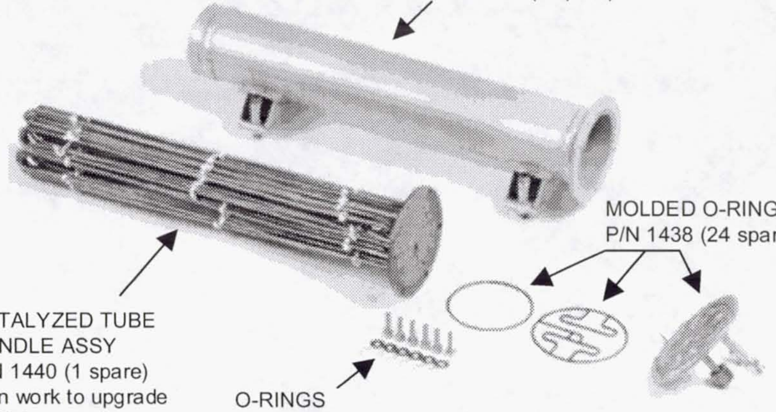
Hydrogen Water (H_2/H_2O) Separator

Description

H_2/H_20 Separator removes hydrogen gas from the potable water generated by fuel cells

Drop in replacement based upon same technology

- Water flows on the inside of tubes while space vacuum is applied to the outside of tube surfaces causing the hydrogen to pass through the solid tube wall into space vacuum

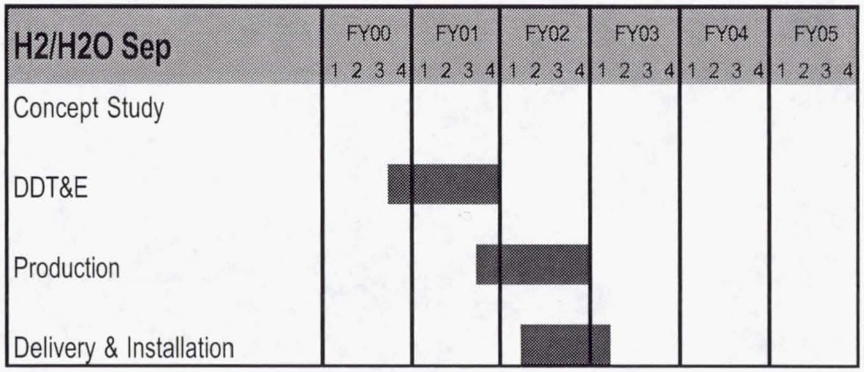


Benefits

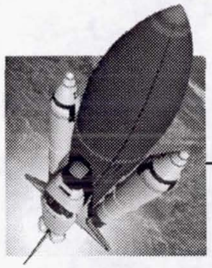
Supportability

- Mitigates obsolescence issues with current Hydrogen Water Separators
  - Efficiency degradation (acceptable efficiency: 95%)
  - Anomalous Nickel deposits
  - Spares issues (currently only 2 spares for fleet)

Schedule



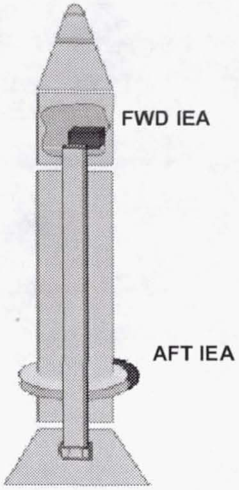
H2/H2O Sep	FY00				FY01				FY02				FY03				FY04				FY05			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study																								
DDT&E				▨	▨	▨	▨	▨																
Production								▨	▨	▨	▨	▨												
Delivery & Installation										▨	▨	▨	▨											



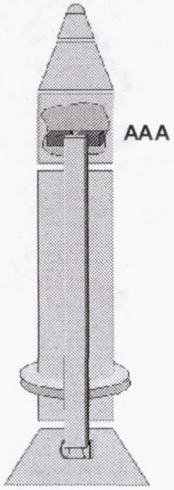
SRB Integrated Electronic Assemble Upgrades Plan

Description

- Replace obsolete 1970's vintage electronics with state-of-the-art
- Add redundancy to LCC instrumentation
- Two option in evaluation
  - IEA retrofit (interchangable with existing IEA)
  - Advance Avionics Assembly (new design to minimize life cycle cost)
- 2nd quarter FY 2000 down select



IEA Retrofit



Advanced Avionics Assembly (AAA)

Benefits

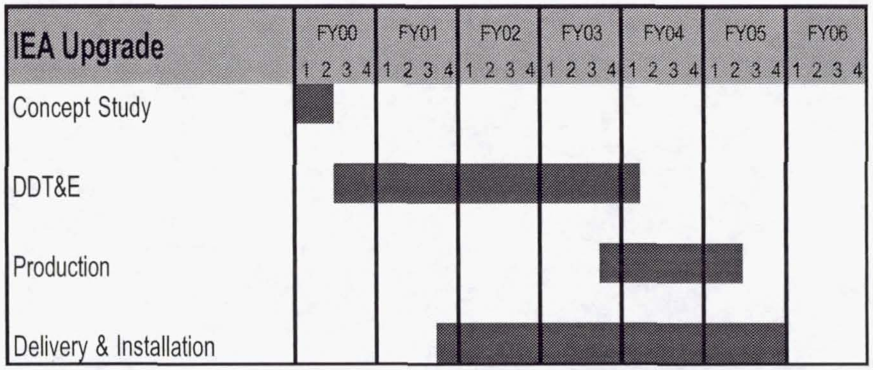
Safety

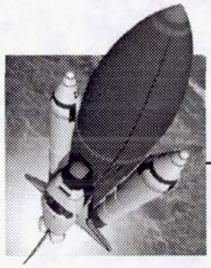
- Improved reliability and robustness
- Reduced potential for on-pad scrubs/aborts

Supportability

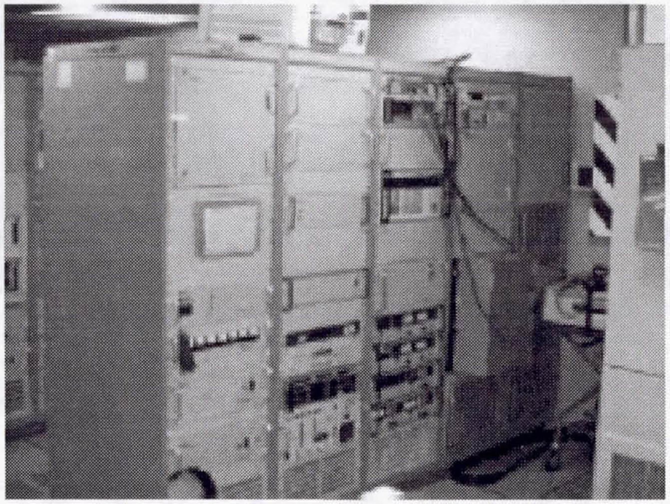
- Obsolescence, increasing failure rates, and lack of spares pose risk to SSP manifest
- No spare APU controller cards
- Onset of age-related failures risks lowering reliability
  - 20+ year old EEE parts
  - Consensus of MSFC, DoD, and industry technical communities

Schedule





SRB Automated Booster Assembly Checkout System (ABACS)



Description

- The Automated Booster Assembly Checkout System (ABACS) is used to test SRB Flight Avionics and Thrust Vector Control Systems prior to each flight
  - Replace with new technology, commercially based assemblies
  - Incremental development to preclude impact to launch processing
  - Will consider CLCS architecture as base for ABACS
- Upgrade replaces key systems affected by obsolescence
  - ABACS Controller and Emulator
  - IEEE-488 Instruments
  - Test Station Hardware

Benefits

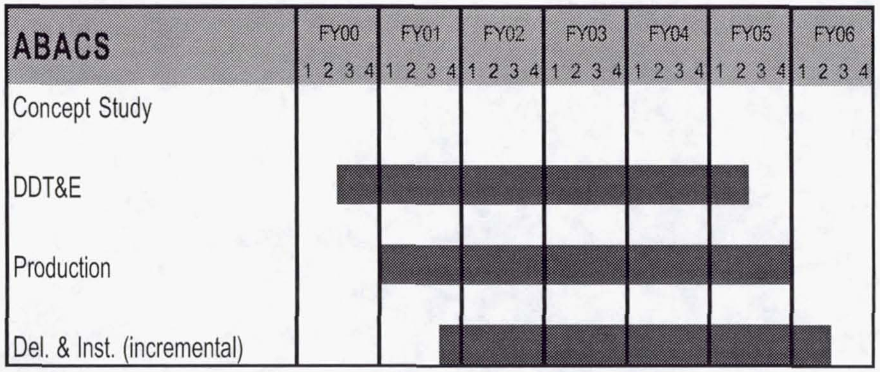
Supportability

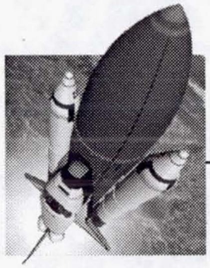
- Increases likelihood of having a required ground processing system available to support KSC operations
- Mitigates obsolescence of key components such as 8086, 8186 and 8286 CPU's

Improve the System

- Enhances ABACS maintainability

Schedule

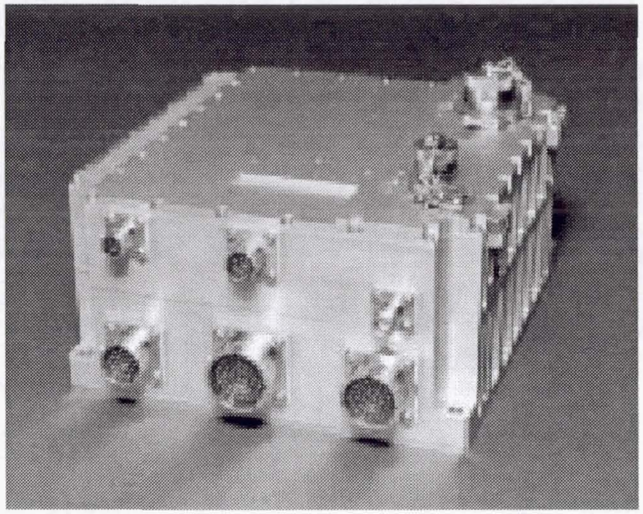




SRB Command Receiver/Decoder (CRD)

Description

- Integrated Receiver-Decoder (IRD) and Range Safety Distributor (RSD) provide reception and command of range safety instructions
  - If needed for range safety, initiates SRB self-destruct
  - DDT&E is funded and underway and 1st engineering units are in test
- Combine IRD and RSD into one unit with new design
  - New unit is the Command Receiver Decoder (CRD)
    - Achieves full EMT compliance
    - Replace PIC with direct current firing circuit



Benefits

Flight Safety

- Eliminates a criticality 1 failure mode
- Decreased destruct reaction time

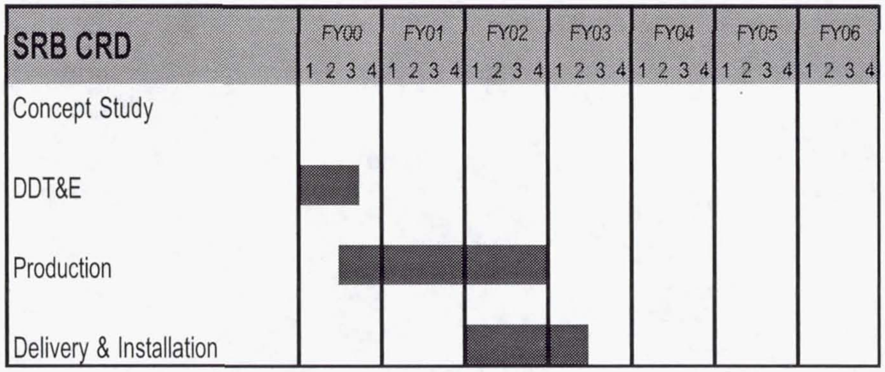
Supportability

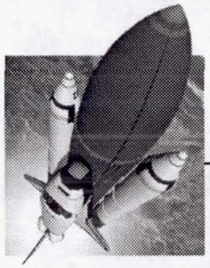
- Mitigates obsolescence of key components
  - RSD and IRD have 39 obsolete EEE parts
  - RSD Programmable Automated Test Set requires upgrade/replacement

Improve the System

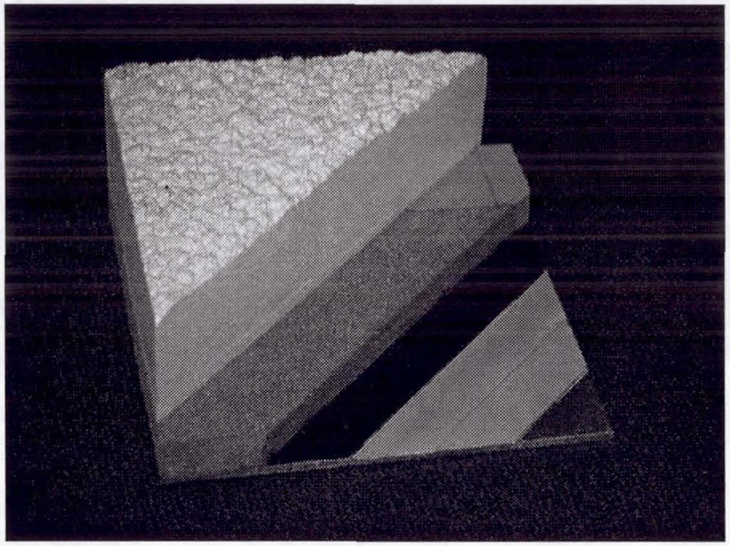
- Enhances maintainability

Schedule





ET Robust TPS (Study)



Description

- External Tank (ET) Thermal Protection System (TPS) is sprayed on as a foam and provides thermal protection to the tank
- Research how to formulate and manufacture TPS spray foam systems that are more damage resistant and have higher tensile strength
  - New TPS blowing agent will be environmentally compliant (eliminate HCFC's)
    - Manufacturers will phase out production of blowing agent (HCFC's) due to worldwide environmental agreements.
    - A waiver is being pursued to allow import of HCFC's beyond December of 2002.
    - A separate waiver may be needed to allow use of blowing agent beyond December of 2003.

Benefits

Flight Safety

- Reduces likelihood of damage to orbiter tiles during ascent
- Resolves flight performance issues
  - Intertank foam loss
  - Popcorning on liquid oxygen ogive

Meet the Manifest

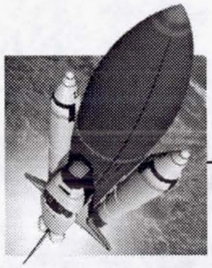
- Reduces likelihood of TPS damage by weather at the launch pad
- Eliminates risk to ET production rate due to the unavailability of an EPA compliant blowing agent

Improve the System

- Resolves foam production issues
  - Internal lacquering in spray gun
  - Problems in Cells "K" and "B/C" with low strength and blisters

Schedule

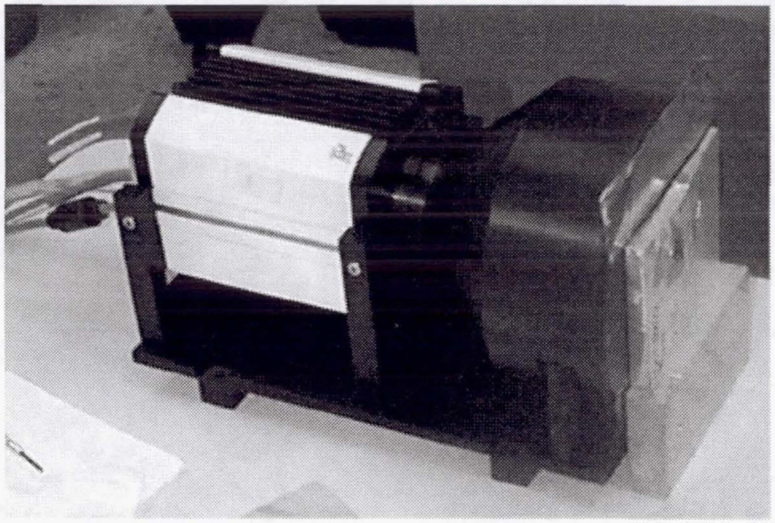
ET TPS	FY00				FY01				FY02				FY03				FY04				FY05				FY06			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study			▨	▨	▨	▨	▨																					
DDT&E																												
Production																												
Delivery & Installation																												



ET Digital Radiography

Description

- All ET welds are inspected using a film x-ray process.
  - *Process is manual and time consuming.*
  - Film must be developed before it is known if welds pass inspection.
- Replace the current film x-ray inspection process with digital x-ray inspection process for acceptance of ET welds
  - Integrate into 20 existing ET tooling stations
  - Automated weld history and defect tracking
  - Improved user interface
  - Database development and archival capabilities



Benefits

Meet the Manifest

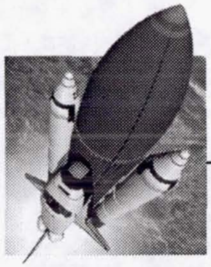
- Reduces at least 10 days of ET production critical flow time (out of 22 months)

Improve the System

- $1.8M in recurring labor and material cost savings per year, based on 8 flights per year.
- Digital images can be quickly shared electronically with engineers at other sites to aid in problem resolution.
- Improved film density range
- Eliminates potential of data loss due to degradation of archived film
- 1.9:1 Return on Investment thru 2012 ($17.2M savings on $9.0M investment)
- Cost payback is estimated to be in 2008.

Schedule

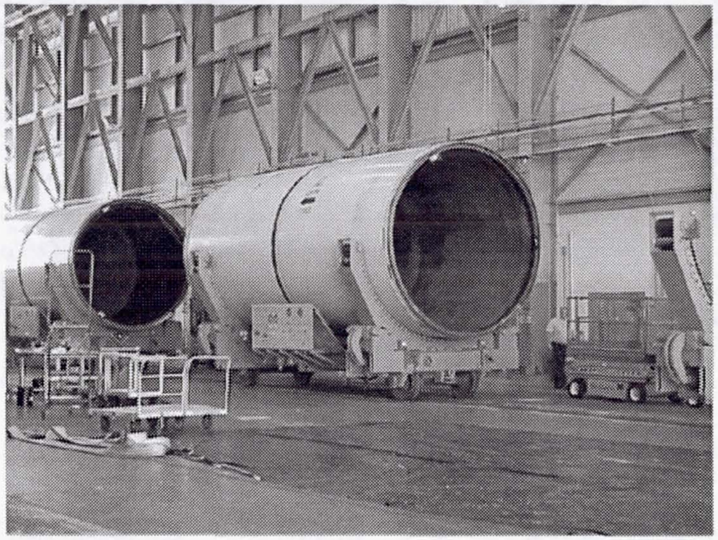
ET Digital	FY00				FY01				FY02				FY03				FY04				FY05				FY06			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study																												
DDT&E				▨	▨	▨	▨	▨	▨																			
Production						▨	▨	▨	▨	▨	▨	▨																
Delivery & Installation						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨								



New O-Ring Material/Joint Heater Elimination

Description

- The RSRM O-ring/joint heater system provides a seal between RSRM segments.
- Heater system is required to maintain O-ring temperature for cold weather launches
- Replace the current RSRM O-ring material with a new generation of polymers that allow for formulation of O-Ring materials with better physical properties, particularly low temperature resiliency
  - Joint heater system can be eliminated

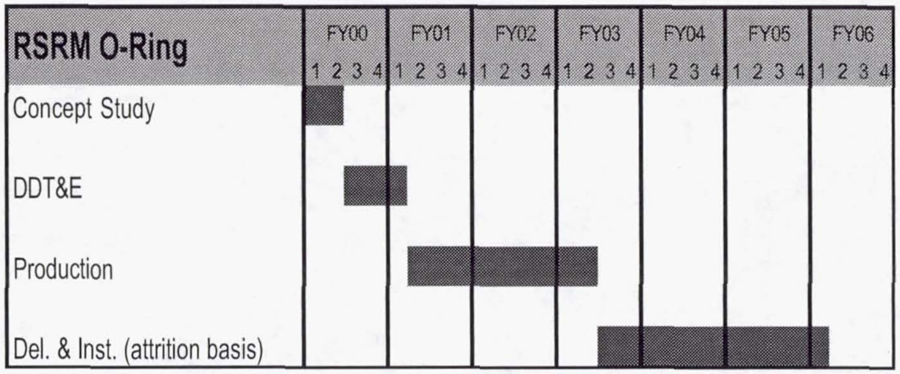


Benefits

Improve the System

- $1.6M savings in recurring costs per year by eliminating heater system build-up time and checkout.
  - 7:1 Return on Investment thru 2012
- Reduces one day of critical flow time during stacking in VAB at KSC (VAB operations no longer prevent further critical path reductions in KSC stacking operations)
- Eliminates hazards related to electrical heaters and associated power cables. *May eliminate seal related launch commit criteria* constraints due to current seal/heater system
- Saves 400 lbs. of SRB weight per mission
- Cost payback is estimated to be in 2006.

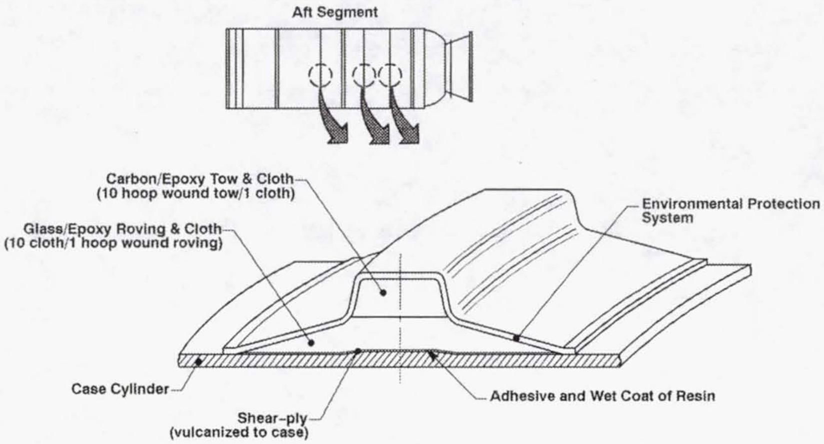
Schedule



Case Stiffener Segment/T-ring Redesign

Description

- Redesign case stiffener segment and T-rings to reduce damage to the hardware during water impact and increase proof-test demonstrated factor of safety on forward stub from 1.24 to 1.40
  - Stiffener stubs are damaged (cracked) due to cavity collapse loads during water impact



Benefits

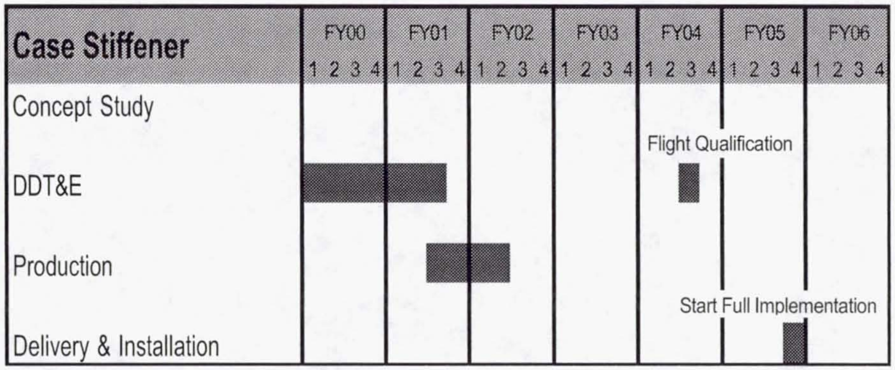
Safety/Reliability

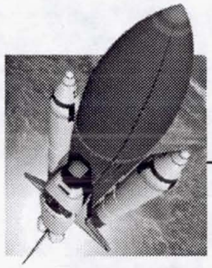
- Increase demonstrated factor of safety on forward stub from 1.24 to 1.40
- Removing stubs eliminates stub cracks during water impact and need for subsequent inspections

Supportability

- Reduce Utah refurb/repair time and KSC flow time
- Return five currently unusable segments to flight inventory
- Reduce attrition of stiffener segments

Schedule





Pyrotechnic Initiation Controllers (PICs)

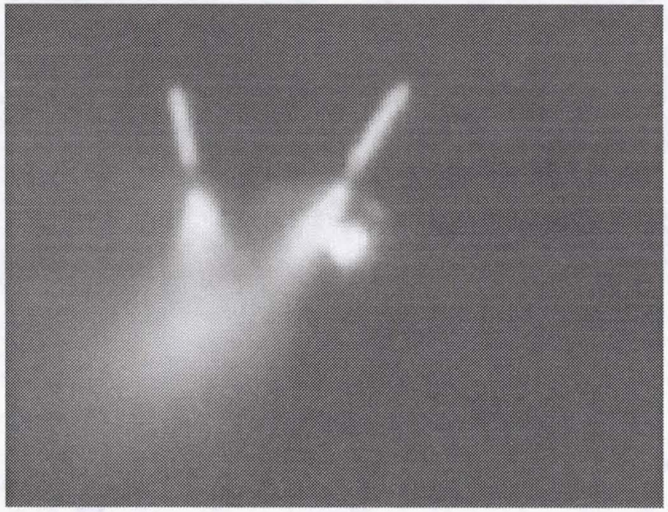
Description

PICs are capacitive discharge devices used to ignite NASA Standard Initiators for separation maneuvers

New design with same form, fit, function

- New technology & improved reliability
- 1000 units

Interdependency - Each SRB forward and aft IEA pair uses 17 PICs



Benefits

Safety & Reliability

- Improved reliability of new devices

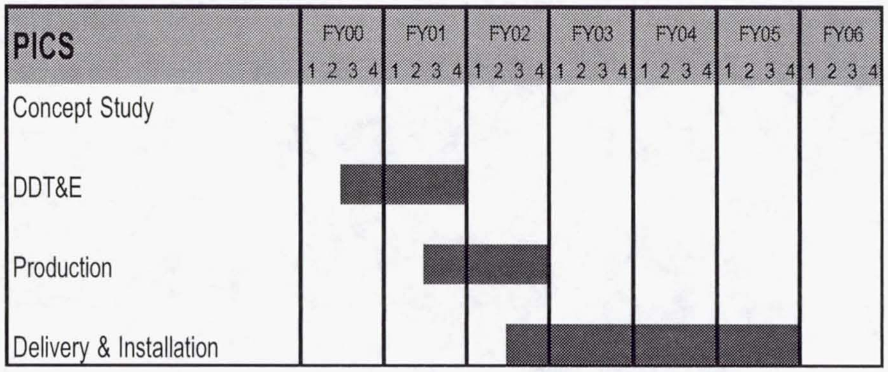
Supportability

- Mitigates obsolescence need for current PICs

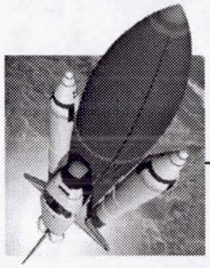
Improve the System

- Weight savings with new technology
    - 30 lbs per Orbiter
    - 25 lbs per SRB
- $500k annual savings

Schedule



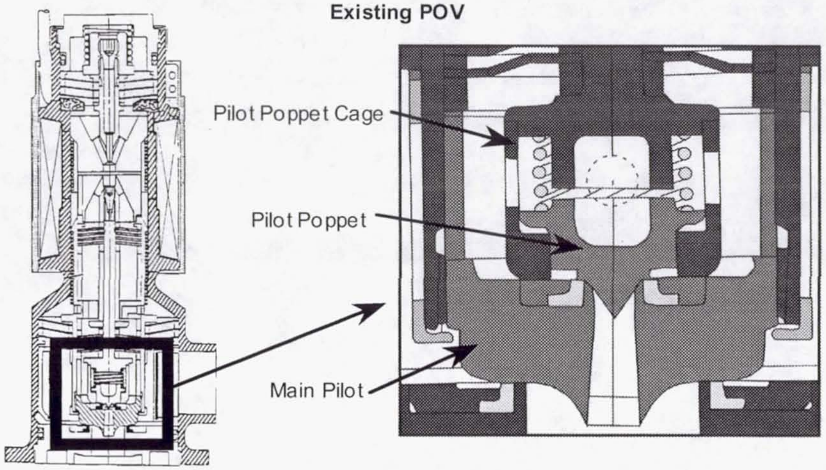
PICS	FY00				FY01				FY02				FY03				FY04				FY05				FY06			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study																												
DDT&E			■	■	■	■	■	■																				
Production							■	■	■	■	■	■																
Delivery & Installation											■	■	■	■	■	■	■	■	■	■	■	■	■	■				



RCS Improved Pilot Operated Valve (POV)

Description

- The POV controls the flow of fuel and oxidizer for the Reaction Control System primary thrusters
  - Failure modes include fail off and fail leak
  - A failure can lead to the loss of an ISS docking mission due to contamination (continued leakage) or loss of translation control
- Upgrade redesigns the POV seat and poppet to eliminate leakage and sticking
  - Significant effort will be spent to optimize the design



Benefits

Flight Safety

- Reduces likelihood of fuel or oxidizer leakage that could contaminate sensitive payload or ISS components

Meet the Manifest

- Reduces likelihood of shortening a mission due to a continuously leaking POV or a combination of failed POVs.

Supportability

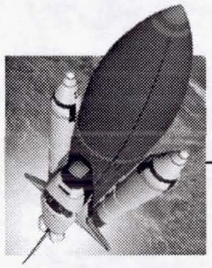
- Reduces likelihood of time-consuming POV changeout

Improve the System

- Reduces yearly maintenance cost by approximately 50%
  - 23 new valves required per year
  - 5.5 unscheduled removals per year
- Cost payback is estimated to be in 2009.

Schedule

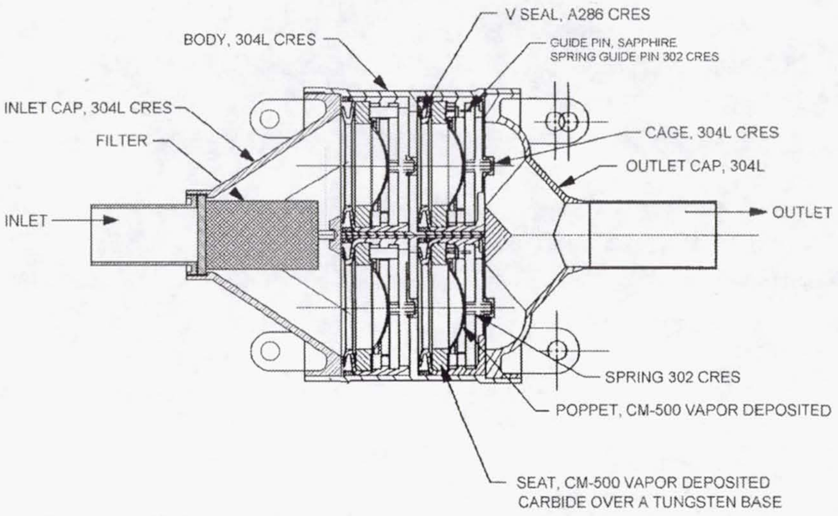
IPOV	FY00 1 2 3 4	FY01 1 2 3 4	FY02 1 2 3 4	FY03 1 2 3 4	FY04 1 2 3 4	FY05 1 2 3 4	FY06 1 2 3 4
Concept Study							
DDT&E	▨	▨					
Production		▨	▨				
Del. & Inst. (attrition basis)			▨	▨	▨	▨	▨



OMS/RCS Quad Check Valve

Description

- The OMS/RCS Quad Check Valve (QCV) prevents the back flow of propellant in the helium pressurization system.
- Upgrade redesigns QCV assembly to eliminate internal leakage and stuck-open poppets
  - Phase A study
    - Study and development testing of QCV modification and new check valve design
  - Phase B qualification test/implementation
    - Replace sapphire guide pin with diamond pin and/or increase poppet spring force



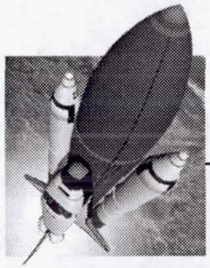
Benefits

Improve the System

- Failed QCV requires FRCS or Pod removal. These removals are time consuming and are hazardous operations.
- Since Return to Flight there have been 27 failures requiring remove and replace.
- OMRS failures require increased ground time to troubleshoot problems.
- New design estimated to have (estimate only - savings will be better quantified after Phase A study)
  - 50% maintenance savings due to decreased troubleshooting (estimated at $100K/year)
  - 50% reduction in failures requiring R&R (estimated at $300K/failure)
- Cost payback is estimated to be in 2010.

Schedule

QCV	FY00				FY01				FY02				FY03				FY04				FY05				FY06			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study			▨	▨	▨	▨																						
DDT&E						▨	▨	▨																				
Production									▨	▨	▨	▨	▨	▨	▨													
Del. & Inst. (attrition basis)													▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	



Space Shuttle Safety and Supportability
Safety Upgrade Candidates

Safety Upgrades   Supportability Upgrades   Approved Upgrades   Advanced Technology

Orbiter Avionics

- **Cockpit**
  - Enhanced Caution and Warning
  - Crew Situational Awareness Displays
  - AFD Switch Panel Upgrade
  - ▨ Device Driver Unit Replacement (DDU)
- **Data Processing**
  - Mission Management Computer
  - Modular Auxiliary Data System
  - ▨ Modular Memory Unit (MMU)
- **Communications**
  - Ku-Band DEA
  - PCMMU
  - S-Band FM
  - Network Signal Processor
- **Navigation**
  - Trajectory Control Sensor (TCS)
  - ▨ IMU Replacement (SIGI)
- **Power Sub-Assemblies**
  - Hybrid Drivers
- **Thermal Protection System**
  - More Durable Lower Surface Tile (Study)
- **Structures & Mechanisms**
  - Crew Escape System (Study)
  - Main Landing Gear Tire Improvements
  - ▨ Micrometeoroid/Orbital Debris Mitigation (MMOD)
- **Environmental Control & Life Support Systems**
  - Hydrogen Water Separator

SRB / RSRM / ET / SSME

- SRB Advanced TVC
- Integrated Electronics Assembly
- ABACS
- ET Robust TPS
- ET Digital Radiography
- New O-Ring Material
- Case Stiffener Segment/T-Ring
- RSRM Propellant Geometry
- SRB Attach/Hold Down Hardware
- ET Friction Stir Initial Welds
- Advanced Health Monitoring
- SSME Block III
  - XLTMCC and Robust Nozzle
- ▨ SRB TVC Upgrades / FIV
- ▨ SRB Altitude Sensor Assembly
- ▨ Nozzle/Case Joint J-Leg Insulation
- ▨ Integrated Receiver-Decoder (IRD)
- ▨ Range Safety Distributor (RSD)

Power & Propulsion

- Electric APU
- Enhanced Pyro Initiator Controller
- Improved Pilot Operated Valve
- Quad Check Valve Redesign
- Long Life Alkaline Fuel Cell

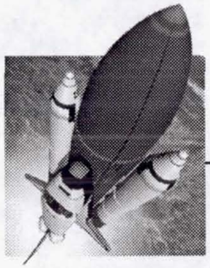
Operations

- **Ground Operations**
  - Maintainability for Safety (Study)
  - SCAPE Suit Improvements (Study)
  - ▨ CLCS
- **Flight Operations**
  - ▨ PIDAE
  - ▨ Shuttle Upgrades Design Visualization
  - ▨ Robotic Situational Awareness Display
  - ▨ Human Factors/Cockpit Engineering Study
  - ▨ Expansion of MCC Landing Sites
  - ▨ AWIPS
  - ▨ EECOM STS Pressure Management Tool
  - ▨ Alternatives to Hardware Based Robotics Training
  - ▨ DM Trajectory Operations Interface Redesign
- **Flight Tests**
  - ▨ Wireless Sensor
  - ▨ Laser Dynamic Range Imager HTD

Advanced Technology

- Crew Escape
- Reusable First Stage
- Non-Tox OMS/RCS Propellants
- PEM Fuel Cell
- Electromechanical Actuators
- Water Membrane Evaporator
- Integrated Vehicle Health Mgmt
- Propellant Densifications
- Fiber Optics

▨ **Funded Upgrades**



Device Driver Unit (DDU)

Description

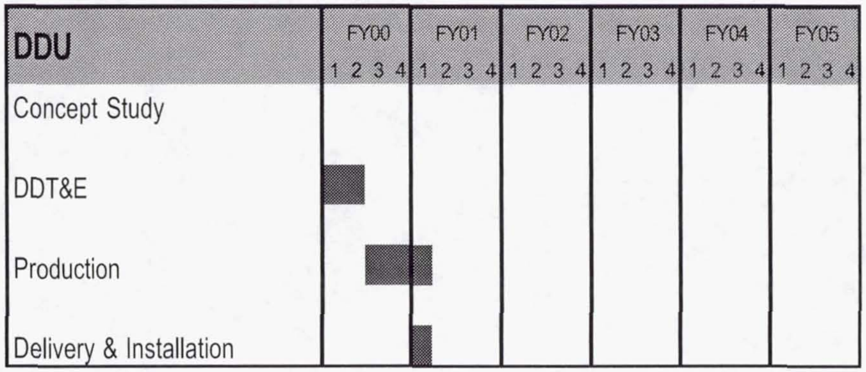
Device Driver Unit takes the place of the current Dispay Driver Unit

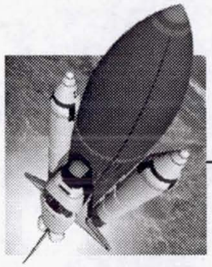
- Current DDU's integrated with MEDS
- Device control functionality removed from existing DDU's

Benefits

- Integrated display drivers with MEDS
- Separate device control from displays and MEDS
- Increased reliability

Schedule



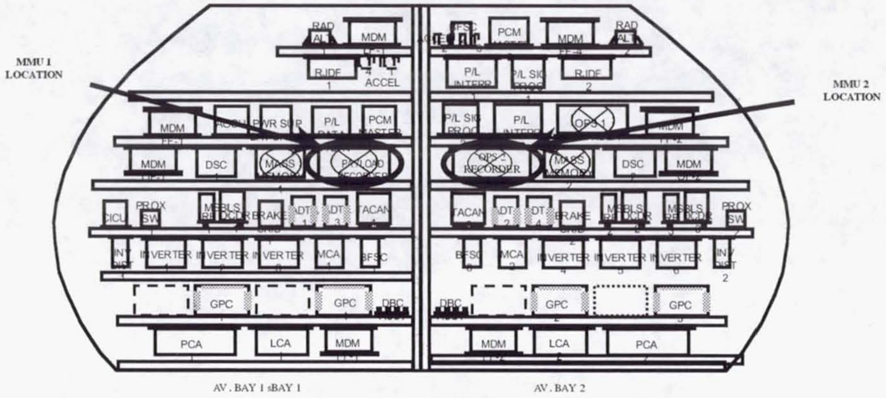


Modular Memory Unit (MMU)

Description

MMU Functions

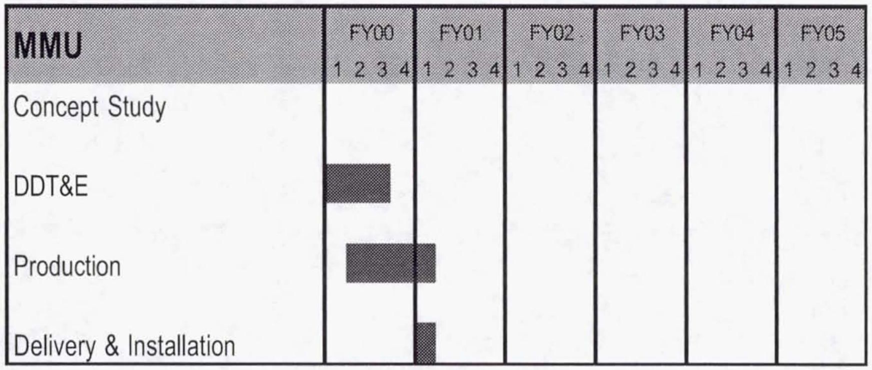
- Solid state recorder (SSR) – 425 Mbytes requirement (uses 46 Bytes card)
  - Replaces ops/payload recorder
- Solid state mass memory (SSMM) – 16 MBytes
  - Replaces Mass Memory Unit



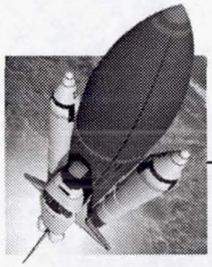
Benefits

- Replaces old tape units with solid state technology (greater storage, faster dump)
- Weight savings: 195 lbs current – 104 lbs upgraded
- Power savings (peak): 272 w current – 84 w upgraded
- 10 Spare slots in chassis and spare power capacity for future growth

Schedule



MMU	FY00				FY01				FY02				FY03				FY04				FY05			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study																								
DDT&E	▨	▨	▨																					
Production		▨	▨	▨	▨																			
Delivery & Installation					▨																			

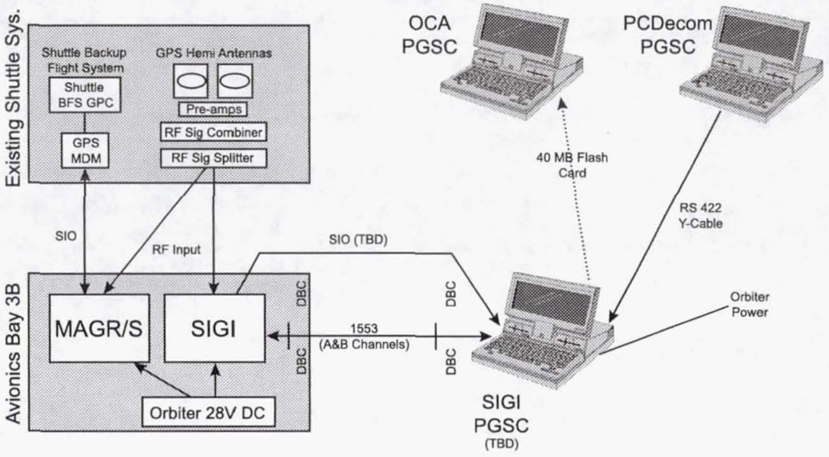


Space Integrated GPS/INS (SIGI)

Description

SIGI: Combined GPS and INS capability

- Combine functionality of global positioning and inertial navigation
- Enables replacement of TACAN and elimination of MSBLS
- Replaces HAINS

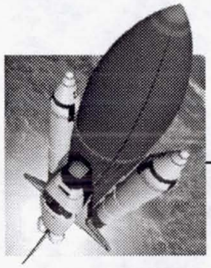


Benefits

- Provides highly reliable GPS and INS capability
- Enables elimination of high cost maintenance for MSBLS grounds systems
- Advanced technology benefit for future space vehicles

Schedule

SIGI	FY00				FY01				FY02				FY03				FY04				FY05			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study	▨	▨	▨	▨	▨	▨	▨	▨																
DDT&E																								
Production																								
Delivery & Installation																								



Orbiter Phase II Upgrades
Micrometeoroid/Orbital Debris Mitigation

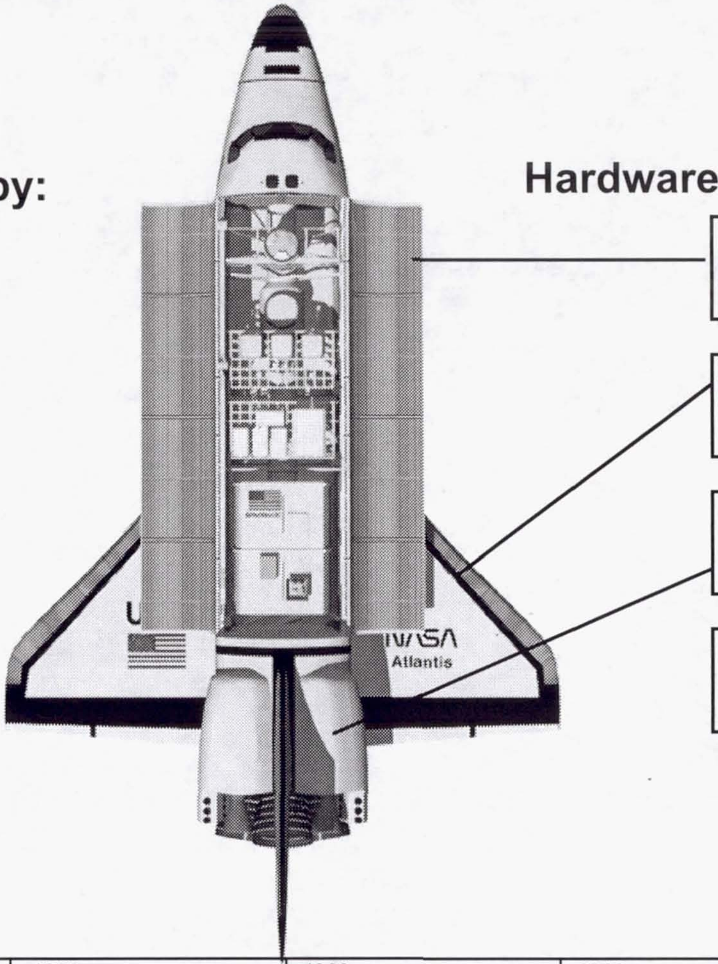
Reduce Risk of MMOD by:

- Operational Workarounds
- Attitude Timeline Modifications
- Compromises Mission Objectives
- Not always possible

MMOD Modifications will Improve:

- Safety & Mission Success
- 1/60 to 1/1190 to 1/4000
- Supportability
- Reduce Cost
- Fewer Repairs Required

Hardware Modifications

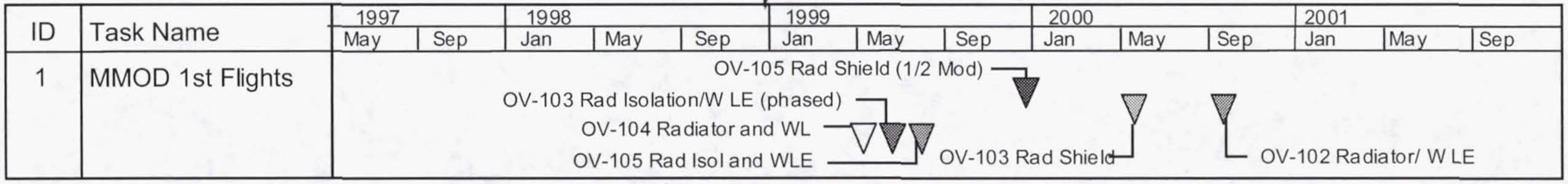


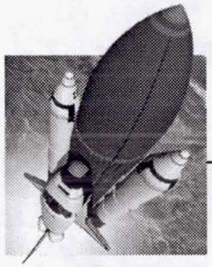
Radiator Protection Modifications

RCC Wing Leading Edge Protection

Freon Cooling Loop Isolation Valves Modification

Automatic Software Freon Loop Isolation





SRB Thrust Vector Control System Upgrades

SRB TVC System Upgrades

Auxiliary Power Unit (APU) Carbon Seal

- Current design susceptable to carbon fracture which can result in detonation from metal to metal contact - new design eliminates this

Single Mission Fuel Isolation Valve (FIV)

- Controls Hydrazine flow to the APU for the SRB TVC System
- Replaces an aging, 1970's design, reusable FIV
- Reduces leakage and improves isolation of fuel from electrical cavity
- Based on proven Orbiter FIV design

APU Gas Generator Valve Module Index Pin Modification

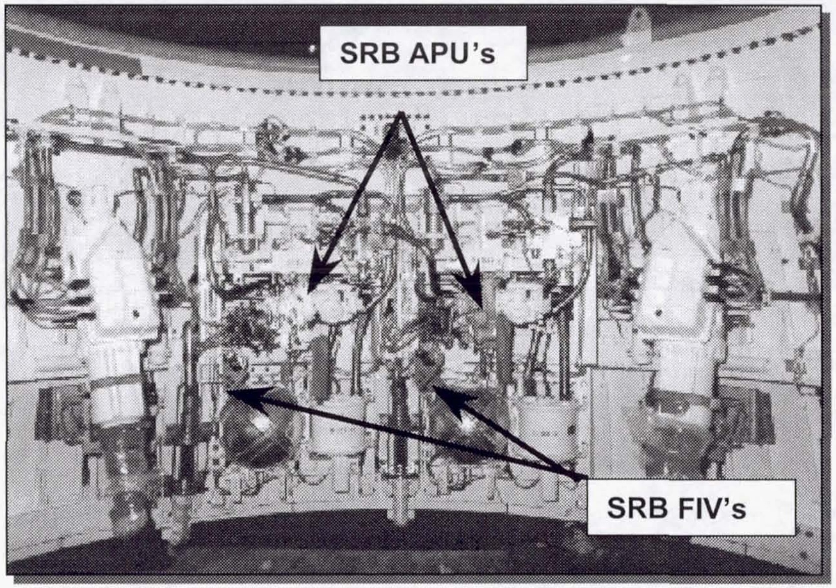
- Eliminates the possibility of index pin back-out, which can (and has in 2 cases) result in the failure of the PCV or SOV

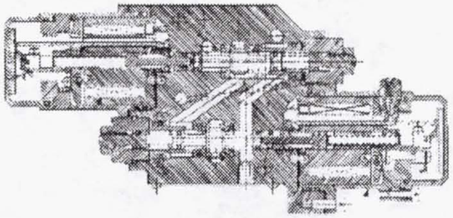
APU Turbine Wheel

- Current turbine wheel susceptible to blades cracking, new design eliminates this with a thicker blade profile
- Qualified for use on Orbiter, SRB qualification in work

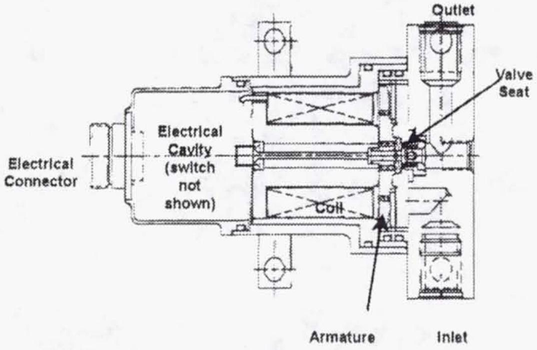
TVC In-line Filter

- Adds an in-line filter to the SRB TVC Fuel system "Flush & Purge In" line (Only unfiltered TVC Fuel system line)

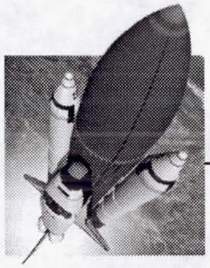




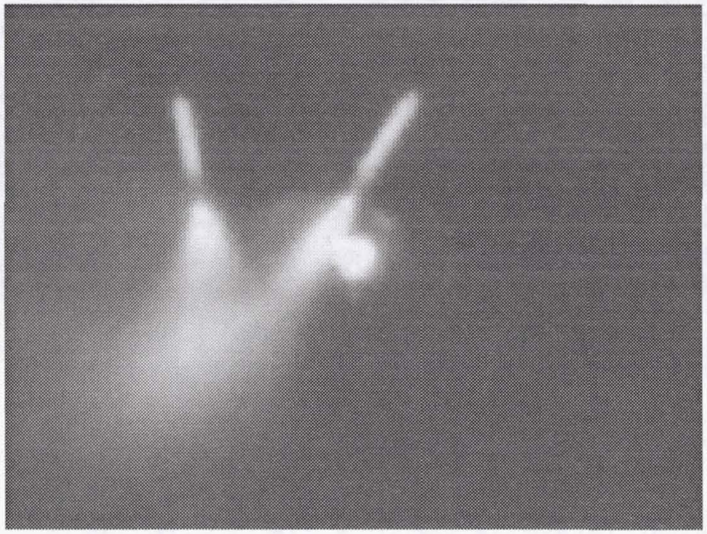
APU GGVM



FIV



Altitude Switch Assembly (ASA)



Description

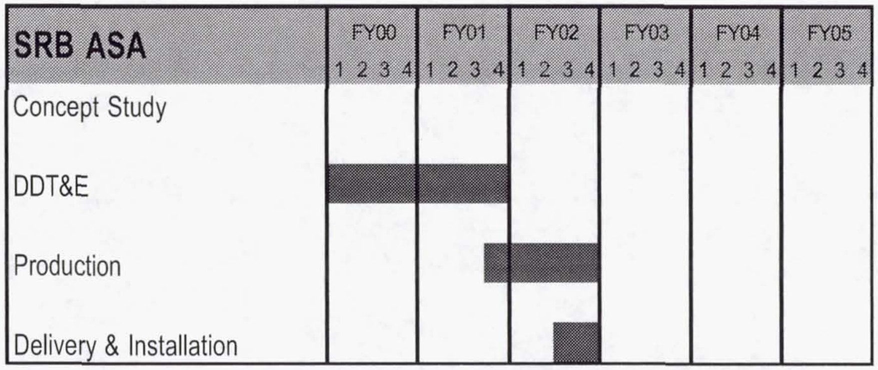
ASA: Pressure sensing device to initiate SRB recovery sequence (one unit per SRB)

- Nose cap ejection – pilot/drogue parachute deployment
- Frustrum separation – main parachute deployment

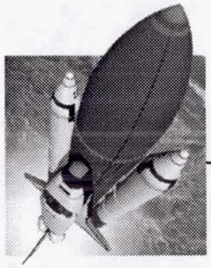
Benefits

- Improve fault tolerance and reliability
- Improve supportability
    - Eliminate welded case, enable internal repair
    - Relax limitations on flight rate and program duration
- Improve BITE and power protection
- Eliminate impact of obsolescence

Schedule



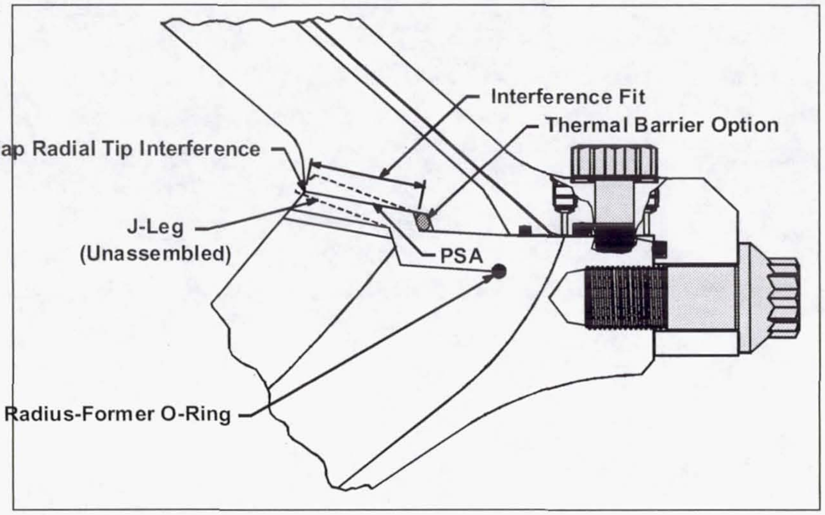
SRB ASA	FY00				FY01				FY02				FY03				FY04				FY05			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study																								
DDT&E	■	■	■	■	■	■	■	■																
Production								■	■	■	■	■												
Delivery & Installation											■	■												



RSRM Nozzle-to-Case Joint J-leg Insulation Design

Description

- The Reusable Solid Rocket Motor nozzle-to-case joint experiences gas paths through the polysulfide insulation to the wiper O-ring in approximately one out of seven motors.
  - Existing design is tolerant of this condition.
- Upgrade redesigns the nozzle-to-case joint insulation using proven technology adapted from the field joint and igniter-to-case joint J-leg designs to eliminate the potential for hot gas intrusion into the joint.
  - Uses a pressure actuated insulation joint.



Benefits

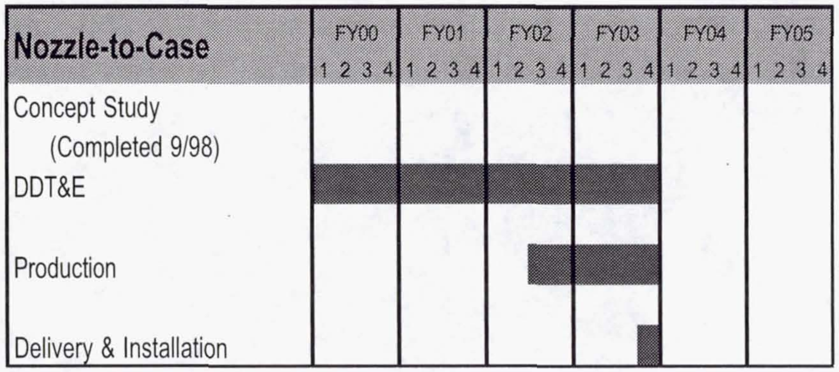
Flight Safety

- Eliminates the potential of hot gas intrusion in the nozzle-to-case joint.
  - Improves the reliability of joint.

Supportability

- Eliminates significant time and effort expended evaluating the hot gas pass throughs.

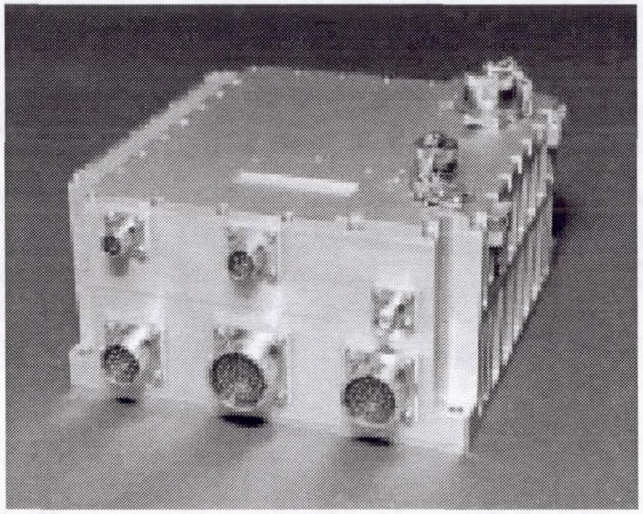
Schedule



SRB Command Receiver/Decoder (CRD)

Description

- Integrated Receiver-Decoder (IRD) and Range Safety Distributor (RSD) provide reception and command of range safety instructions
    - If needed for range safety, initiates SRB self-destruct
    - DDT&E is funded and underway and 1st engineering units are in test
- Combine IRD and RSD into one unit with new design
    - New unit is the Command Receiver Decoder (CRD)
        - Achieves full EMT compliance
        - Replace PIC with direct current firing circuit



Benefits

Flight Safety

- Eliminates a criticality 1 failure mode
- Decreased destruct reaction time

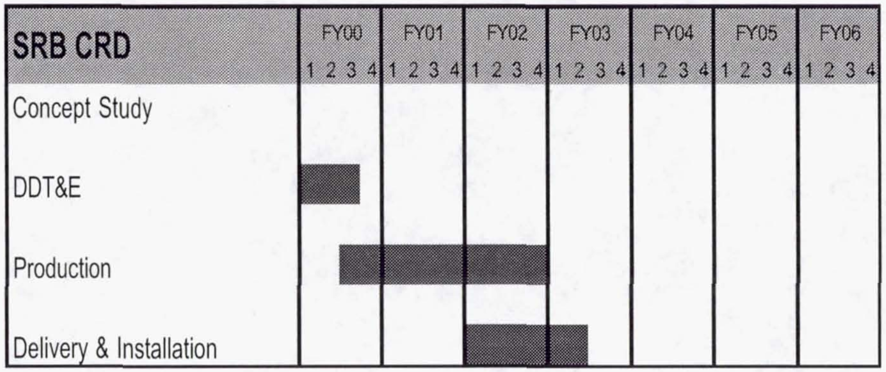
Supportability

- Mitigates obsolescence of key components
    - RSD and IRD have 39 obsolete EEE parts
    - RSD Programmable Automated Test Set requires upgrade/replacement

Improve the System

- Enhances maintainability

Schedule



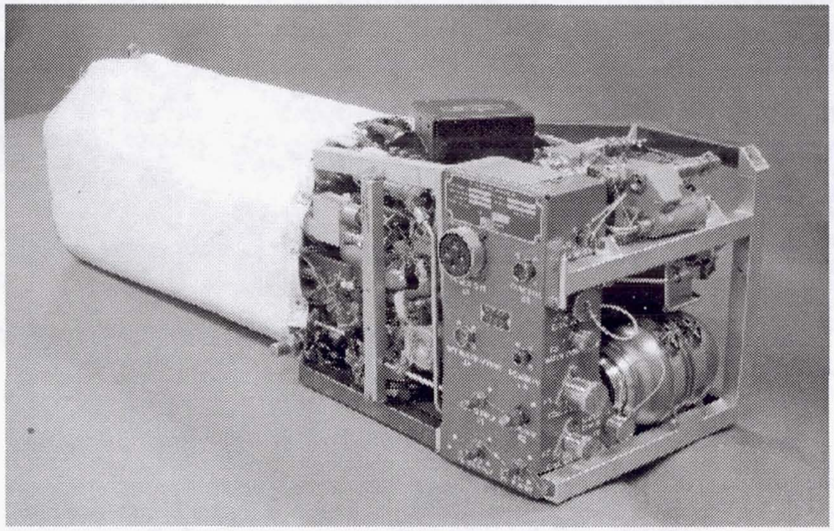
SRB CRD	FY00				FY01				FY02				FY03				FY04				FY05				FY06			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Concept Study																												
DDT&E	■	■	■																									
Production			■	■	■	■	■	■	■	■	■	■																
Delivery & Installation									■	■	■	■	■	■														

Long Life Alkaline Fuel Cell

Description

Current Alkaline Fuel Cell Modification to Long Life Alkaline

- Modify cells of existing stack to lengthen corrosion path
- Reduce reactant temperatures
- Upgrade external seals and insulator plate
- Resize reactant preheaters
- Modify regulator housing to stainless steel to eliminate aluminum corrosion
- Modification can be done during regular overhaul periods on attrition basis

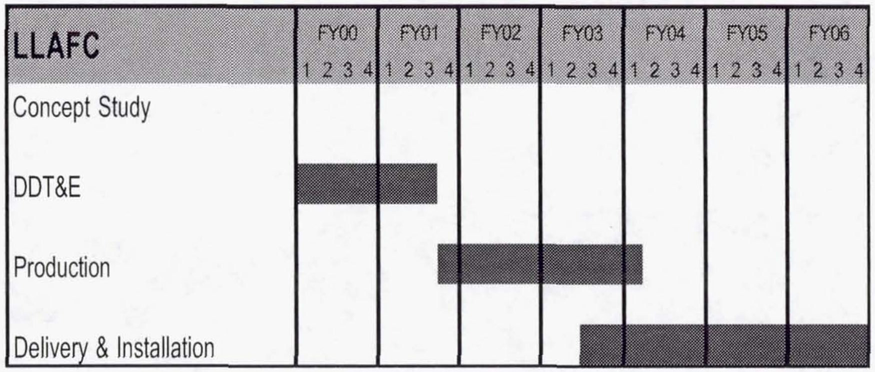


Benefits

Supportability

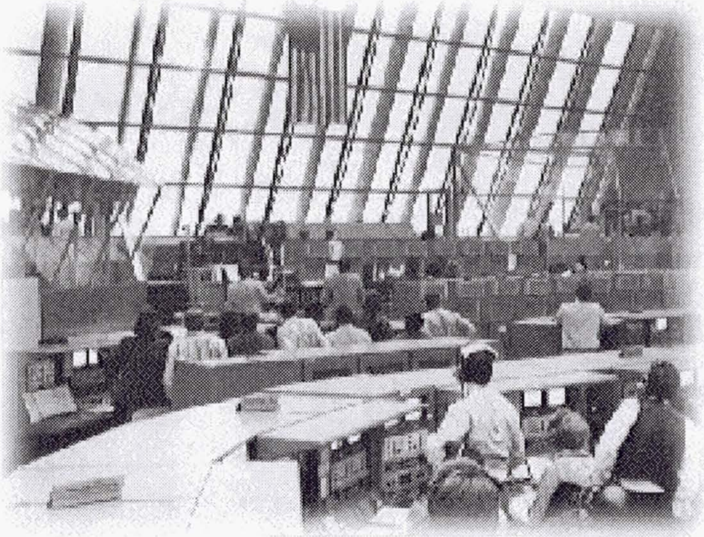
- Mitigates supportability issues of high failure and overhaul rates
  - Extended cell life
  - Reduced anode cycle voltage losses
  - Reduced operating temperatures

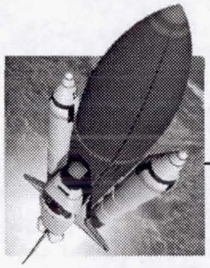
Schedule



Checkout & Launch Control System

- **The CLCS replaces the current Space Shuttle Firing Room with a state of the art control center featuring custom and commercial-of-the-shelf systems**
- **The CLCS Has Redefined the Shuttle Processing Environment in Several Key Areas Which Will Improve Checkout Efficiencies**
  - Command and Monitor Data have Been Separated
  - Multi-Discipline Testing
  - Multi-Orbiter Control
  - Consolidated Data
  - Integrated Complex/Facility Control
  - Local Commanding Operations
  - Program Compatible Data

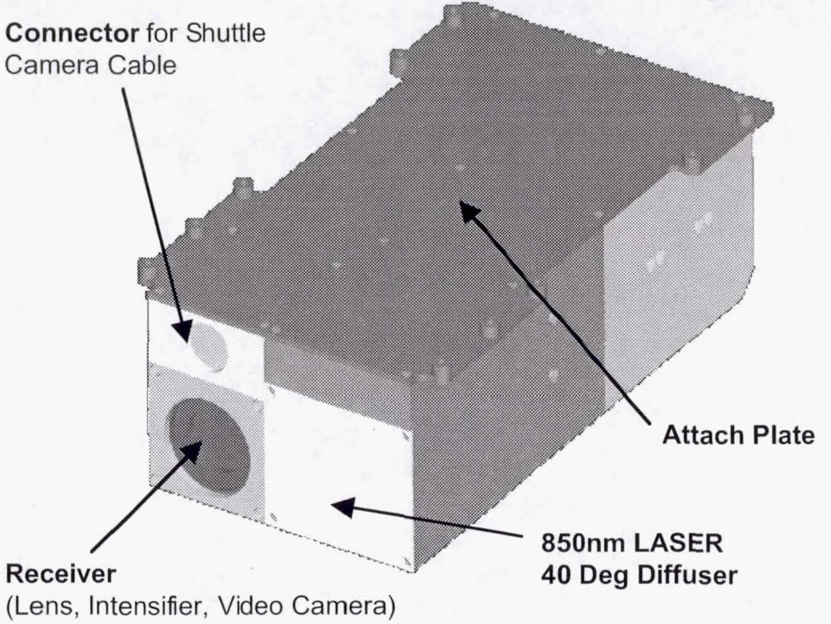




Checkout & Launch Control Systems Goals

- Reduce operations and maintenance costs by at least 50%
- Reduce the number of engineers required on console for daily power up operations by at least 50%
- Reduce the amount of paper in the control rooms by at least 50%
- Provide building blocks to support future control system requirements (e.g. Shuttle Upgrades, RLV, etc.)

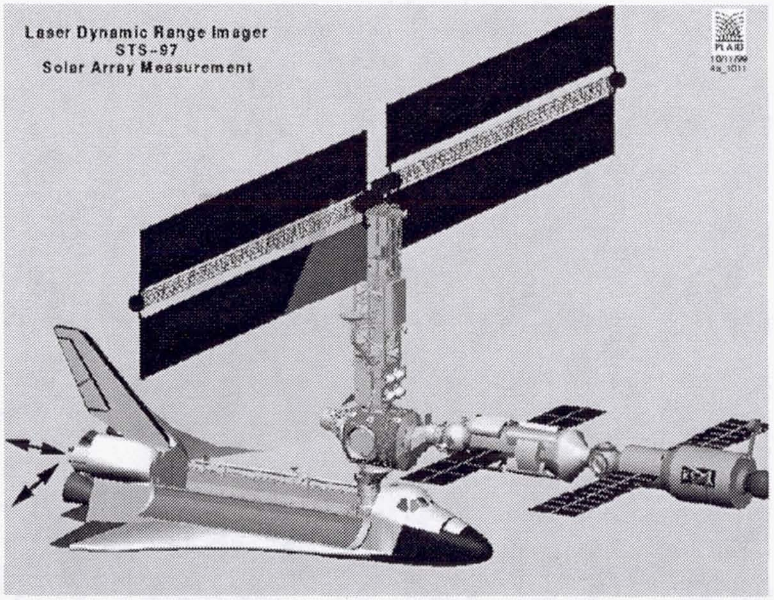
Human Exploration and Development of Space (HEDS) Technology Demonstrations

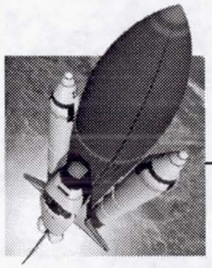


LASER Dynamic Range Imager

Description

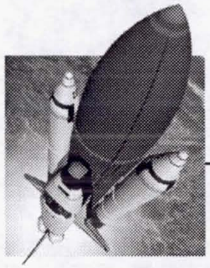
- Range for every pixel at video rates to obtain structural-dynamics
- Real-time range video for depth perception and target info (range, range-rate and orientation)
- 3-D model building for slowly moving and stationary objects
- Eye-safe LASER - no pre-positioned targets required





Flight Operations Upgrades

- **Platform Independent Downrange Abort Evaluator (PIDAE)**
  - Develop a platform independent ascent situational awareness tool for use in multiple facilities/computational environments
  - Yields enhanced flight crew/MCC situational awareness for TAL/ECAL capability assessment and range safety limit line avoidance.
- **Shuttle Upgrades Design Visualization**
- **Robotic Situational Awareness Display**
  - Provide RMS Operator tools for onboard STS Operations.
  - Improves RMS Operator situational awareness to off-set existing system limitations
    - Visual feedback
    - Position feedback
    - Unwanted manipulator positions
    - Single Joint Operations



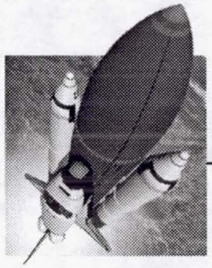
Flight Operations Upgrades (cont'd)

Human Factors/Cockpit Engineering Study

- This study provides an extensive review of the SSP cockpit and analysis of flight information to the crew.
- Rapid prototyping techniques will provide integrated solutions, information on crew situational awareness, and reductions in training. Advanced concepts of operations will be evaluated in prototypes to validate implementation. Results will be incorporated into the proposed Shuttle Cockpit Upgrades.

Expansion of MCC Landing Sites

- Provides a complete set of world-wide runway data in the MCC for utilization during emergency operations as a supplement to official landing sites and existing landing site tables.
- Expands the 42 approved sites and 150 Emergency Landing Sites to approximately 3000 sites for emergency operations.
  - Objective is to integrate with PIDAE

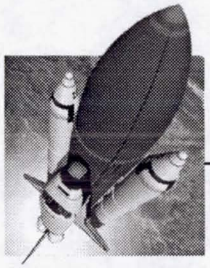


Flight Operations Upgrades (cont'd)

- **Advanced Weather Interactive Processing System (AWIPS)**
  - AWIPS is the meteorological analysis and forecasting tool that the National Weather Service (NWS) is installing in its forecast offices nationwide to replace legacy forecast systems. AWIPS will replace two obsolete NWS systems at JSC.
  - This new System will provide capabilities not currently available with older systems. AWIPS will improve safety by providing improved capability to analyze and display meteorological data at the CONUS shuttle landing facilities.
- **EECOM STS Pressure Management Tool**
  - Provide Pressure Management tools to support EECOM operations
  - Streamlines EECOM STS/ISS pressure management function by eliminating many steps performed manually by flight control personnel. This capability will greatly improve EECOM's ability to respond quickly to real-time mission impacts/re-plans and mission planning and reassessments.

Flight Operations Upgrades (cont'd)

- **Alternatives to Hardware Based Robotics Training (AHBRT)**
  - Investigates and develops technologies needed to allow software based training systems to replace hardware trainers for robotics.
  - AHBRT improves software robotics simulations, develops camera models for camera and vision system design, and develops contact models for force/torque system design.
- **DM Trajectory Operations Interface Redesign**
  - Pathfinding effort to implement findings from FDO work analysis by Ames Human Centered Computing group via a new user interface for ephemeris operations.
  - Designed to decrease unnecessary operational complexity inherent in 20 yr old architecture as well as replace several old displays/tools in the MCC.

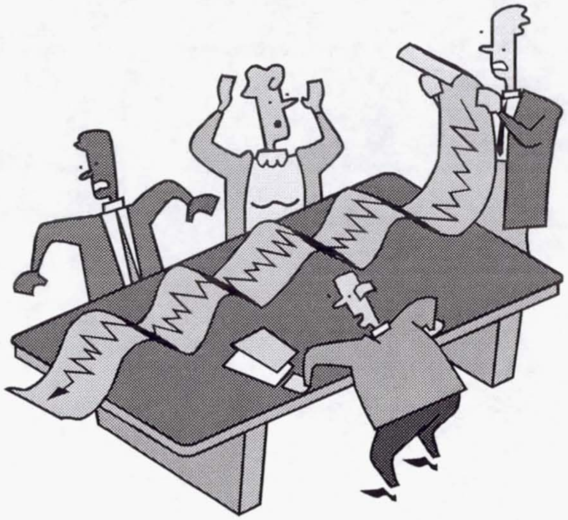


Independent Program Analysis

Description

Perform independent assessment of upgrade projects

- Assess project maturity
- Identify project risks
- Identify potential cost increases and delays
- Identify risk mitigation strategies
- Provide independent cost assessment



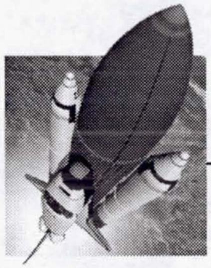
Benefits

Provide SSPDO insight to project status and activity

- Strategize upgrades budget through the end of program
- Help determine optimal solutions

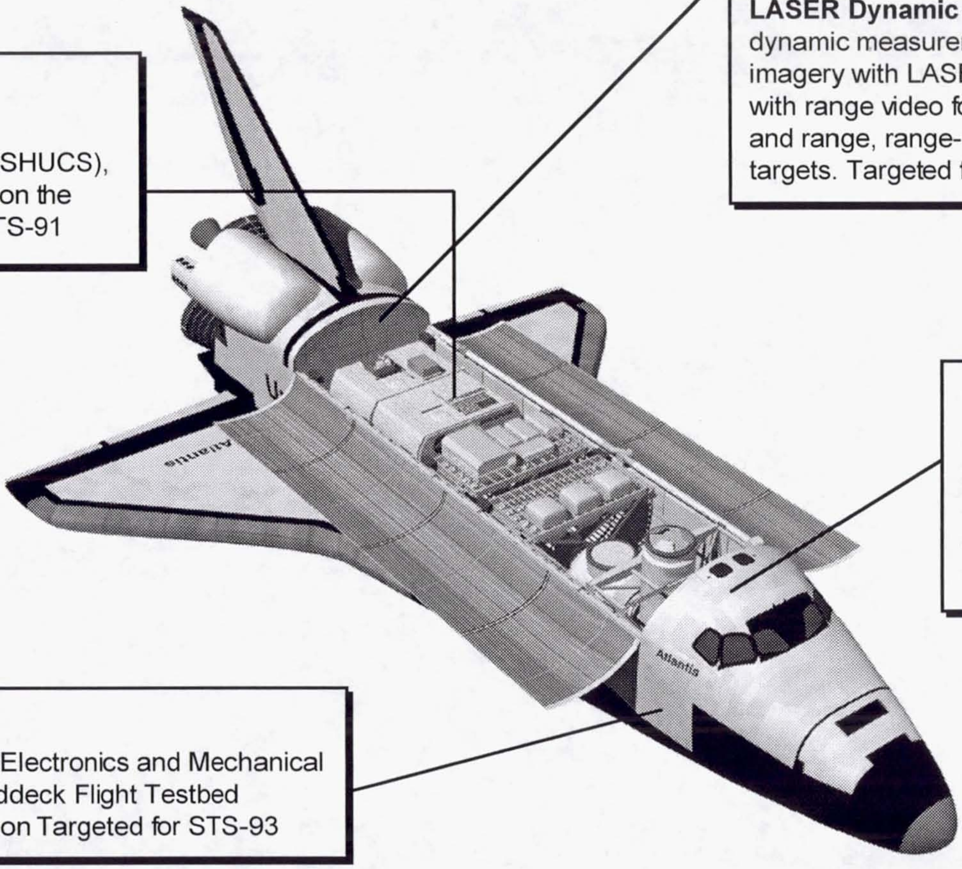
Schedule

Ongoing activity with deliveries coincident with project milestones



Human Exploration and Development of Space (HEDS) Technology Demonstrations

Approved HTDs



HTD 1401

SpaceHab Universal Communications System (SHUCS), L-Band Antenna Mounted on the SpaceHab Targeted for STS-91

HTD 1404

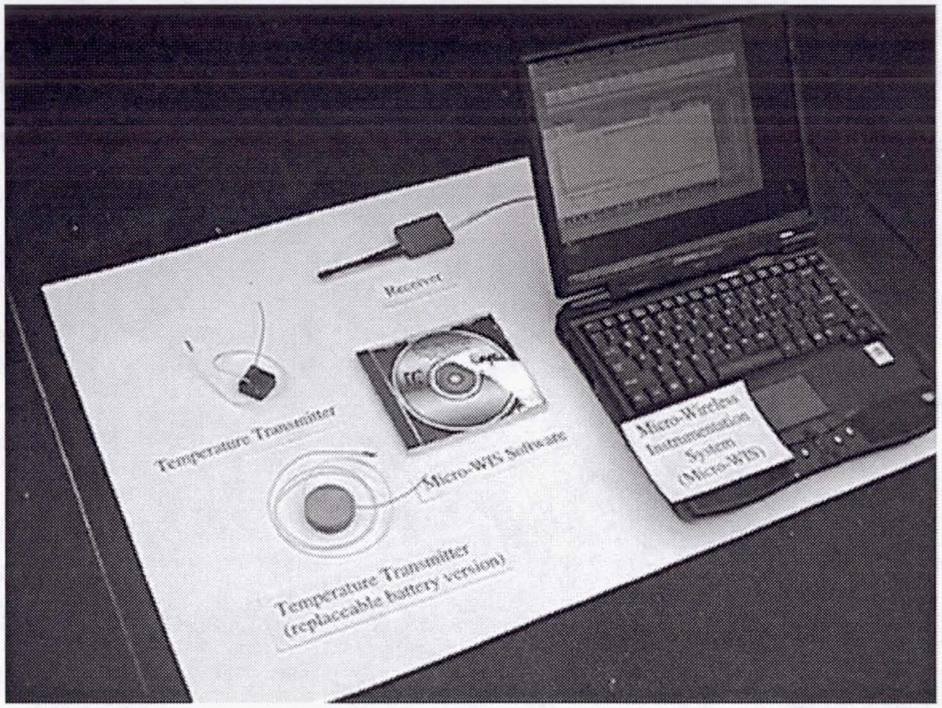
LASER Dynamic Range Imager; Structural-dynamic measurements for loads models, night imagery with LASER illumination, depth perception with range video for EVA,robotics, and fly-around, and range, range-rate and orientation for various targets. Targeted for STS-97.

HTD 1403

Micro-Wireless Instrumentation System; includes autonomous, micro-sized temperature sensor/transceivers and a data acquisition system for space and ground applications.

HTD 1404

Nano/micro Electronics and Mechanical Systems Middeck Flight Testbed Demonstration Targeted for STS-93



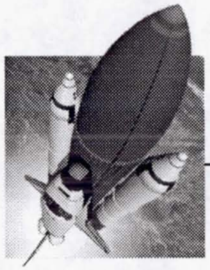
Micro-Wireless Instrumentation System

Description

The Micro-Wireless Instrumentation System (Micro-WIS) includes autonomous, micro-sized temperature sensor/transceivers and a data acquisition system for space and ground applications.

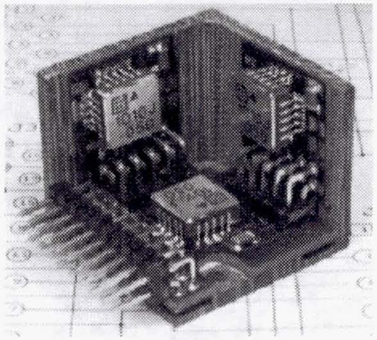
Program Supported Goals

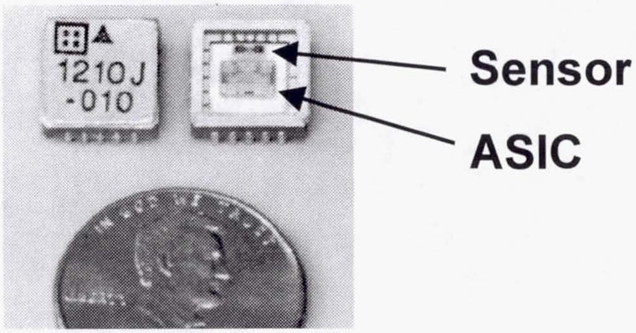
- Significant cost, weight and power savings to current operational space vehicles, ground test facilities and future spacecraft
- Revolutionary capability in systems design for future space vehicles

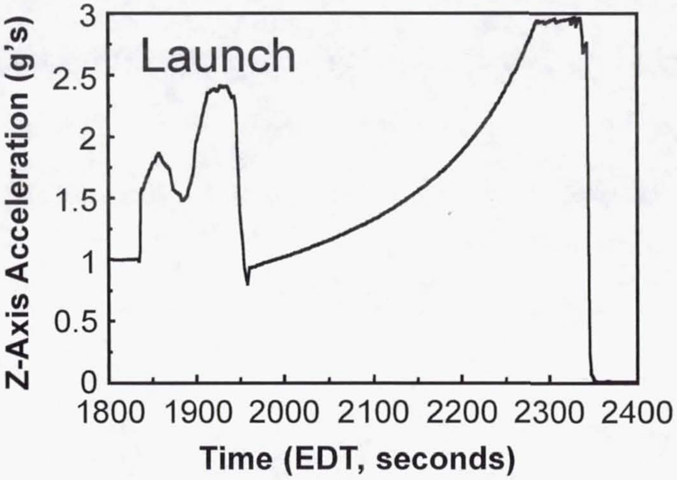


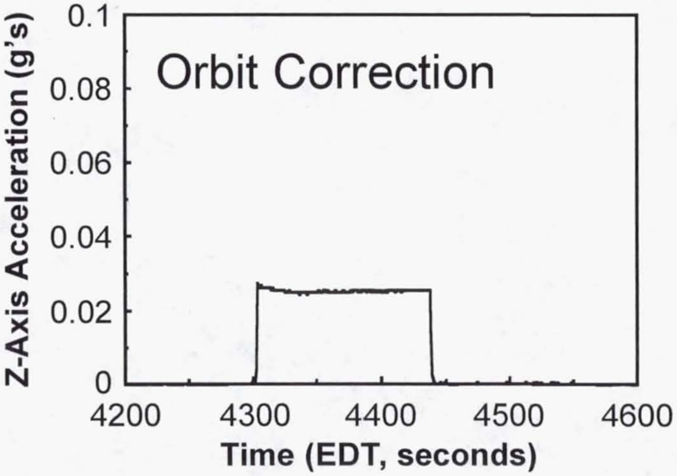
MEMS Accelerometers Monitored STS-93 Flight

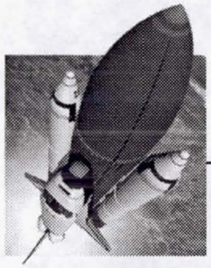
Silicon Designs 1010J & 1210J Capacitive MEMS Accelerometers





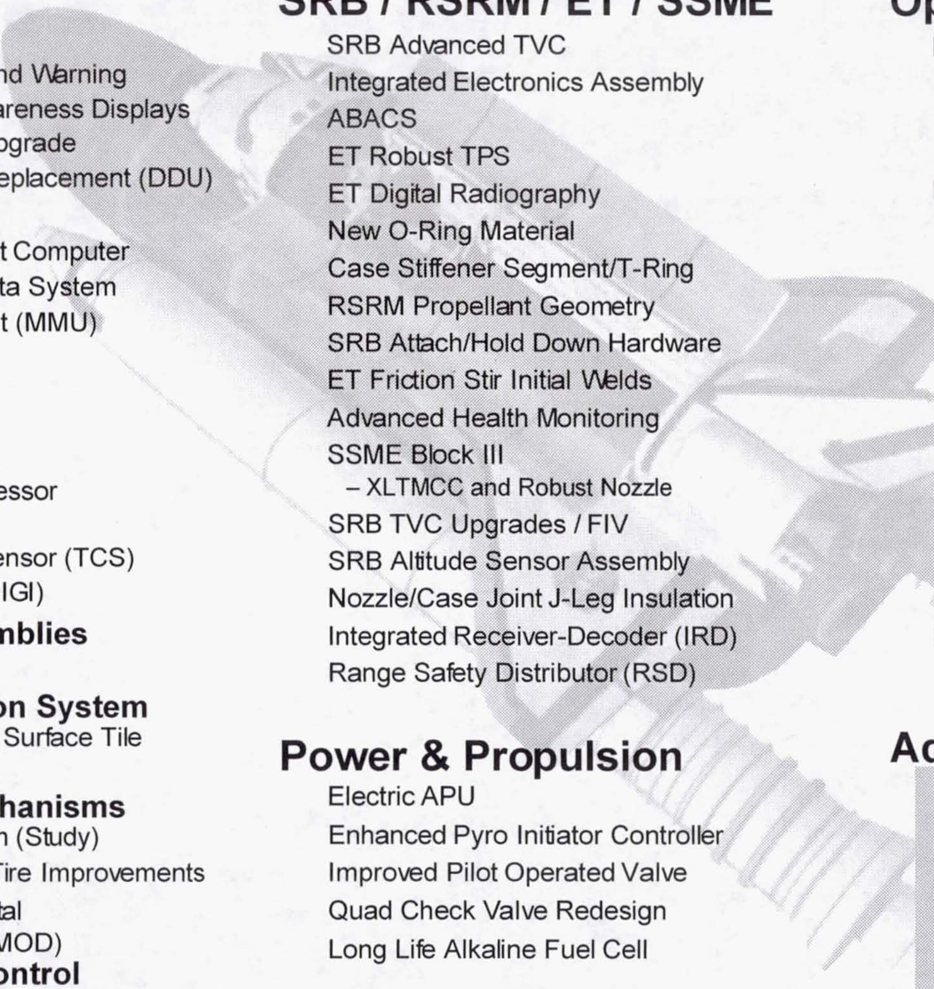






Space Shuttle Safety and Supportability
Safety Upgrade Candidates

Safety Upgrades   Supportability Upgrades   Approved Upgrades   Advanced Technology



Orbiter Avionics

- **Cockpit**
  - Enhanced Caution and Warning
  - Crew Situational Awareness Displays
  - AFD Switch Panel Upgrade
  - Device Driver Unit Replacement (DDU)
- **Data Processing**
  - Mission Management Computer
  - Modular Auxiliary Data System
  - Modular Memory Unit (MMU)
- **Communications**
  - Ku-Band DEA
  - PCMMU
  - S-Band FM
  - Network Signal Processor
- **Navigation**
  - Trajectory Control Sensor (TCS)
  - IMU Replacement (SIGI)
- **Power Sub-Assemblies**
  - Hybrid Drivers
- **Thermal Protection System**
  - More Durable Lower Surface Tile (Study)
- **Structures & Mechanisms**
  - Crew Escape System (Study)
  - Main Landing Gear Tire Improvements
  - Micrometeoroid/Orbital Debris Mitigation (MMOD)
- **Environmental Control & Life Support Systems**
  - Hydrogen Water Separator

SRB / RSRM / ET / SSME

- SRB Advanced TVC
- Integrated Electronics Assembly
- ABACS
- ET Robust TPS
- ET Digital Radiography
- New O-Ring Material
- Case Stiffener Segment/T-Ring
- RSRM Propellant Geometry
- SRB Attach/Hold Down Hardware
- ET Friction Stir Initial Welds
- Advanced Health Monitoring
- SSME Block III
  - XLTMCC and Robust Nozzle
- SRB TVC Upgrades / FIV
- SRB Altitude Sensor Assembly
- Nozzle/Case Joint J-Leg Insulation
- Integrated Receiver-Decoder (IRD)
- Range Safety Distributor (RSD)

Power & Propulsion

- Electric APU
- Enhanced Pyro Initiator Controller
- Improved Pilot Operated Valve
- Quad Check Valve Redesign
- Long Life Alkaline Fuel Cell

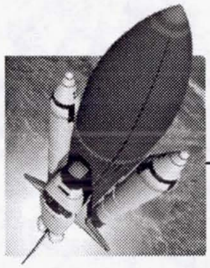
Operations

- **Ground Operations**
  - Maintainability for Safety (Study)
  - SCAPE Suit Improvements (Study)
  - CLCS
- **Flight Operations**
  - PIDAE
  - Shuttle Upgrades Design Visualization
  - Robotic Situational Awareness Display
  - Human Factors/Cockpit Engineering Study
  - Expansion of MCC Landing Sites
  - AWPS
  - EECOM STS Pressure Management Tool
  - Alternatives to Hardware Based Robotics Training
  - DM Trajectory Operations Interface Redesign
- **Flight Tests**
  - Wireless Sensor
  - Laser Dynamic Range Imager HTD

Advanced Technology

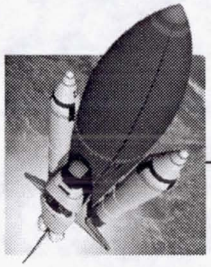
- Crew Escape
- Reusable First Stage
- Non-Tox OMS/RCS Propellants
- PEM Fuel Cell
- Electromechanical Actuators
- Water Membrane Evaporator
- Integrated Vehicle Health Mgmt
- Propellant Densifications
- Fiber Optics

Advanced Technology



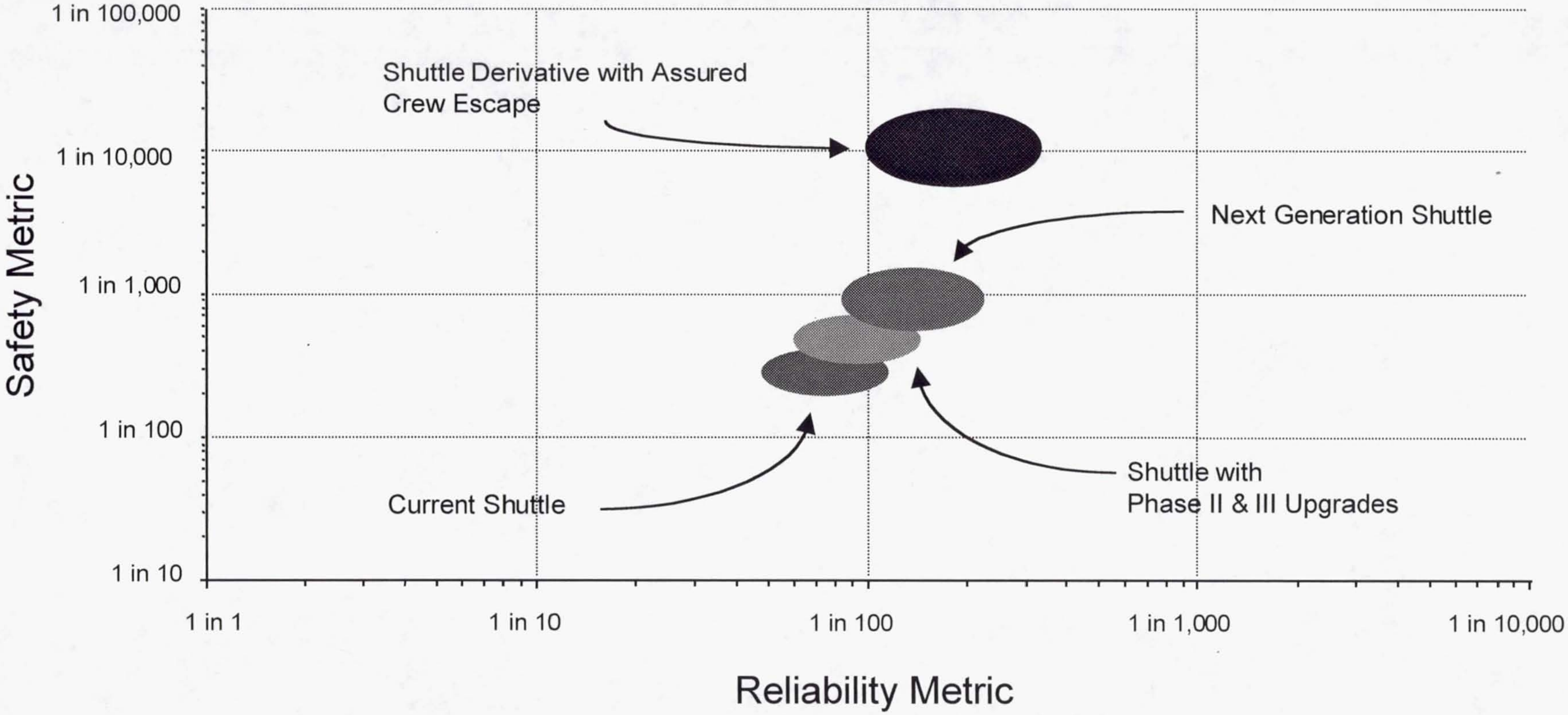
Shuttle Upgrade & Evolution Future

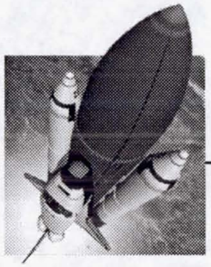
- **Near Term Shuttle Development Priorities are:**
  1. Implementing the approved safety upgrades into the fleet by 2005.
  2. Keeping the infrastructure and the flight hardware available to support the manifest until the next generation RLV is operational (no earlier than 2012).
  3. Improving the system by implementing operational efficiencies and simplifying processes will reduce preparation risks and save cost.
  4. Supporting development of the ISTP technologies applicable to next generation RLV's and to shuttle evolution.
  5. Utilizing the shuttle as a test platform to demonstrate new capabilities and technologies that could mitigate risks for a new or shuttle derived RLV while improving the shuttle.
- **Options Post-2005**
  - No “next generation” replacement... implement evolutionary Shuttle upgrades to improve safety, reliability, supportability, and ops cost
  - Shuttle-derived RLV replacement developed... operate and sustain Shuttle until replacement is ready
  - New Design replacement developed... operate and sustain Shuttle until replacement is ready



Safety/Reliability with Uncertainties

50th Percentile Probability

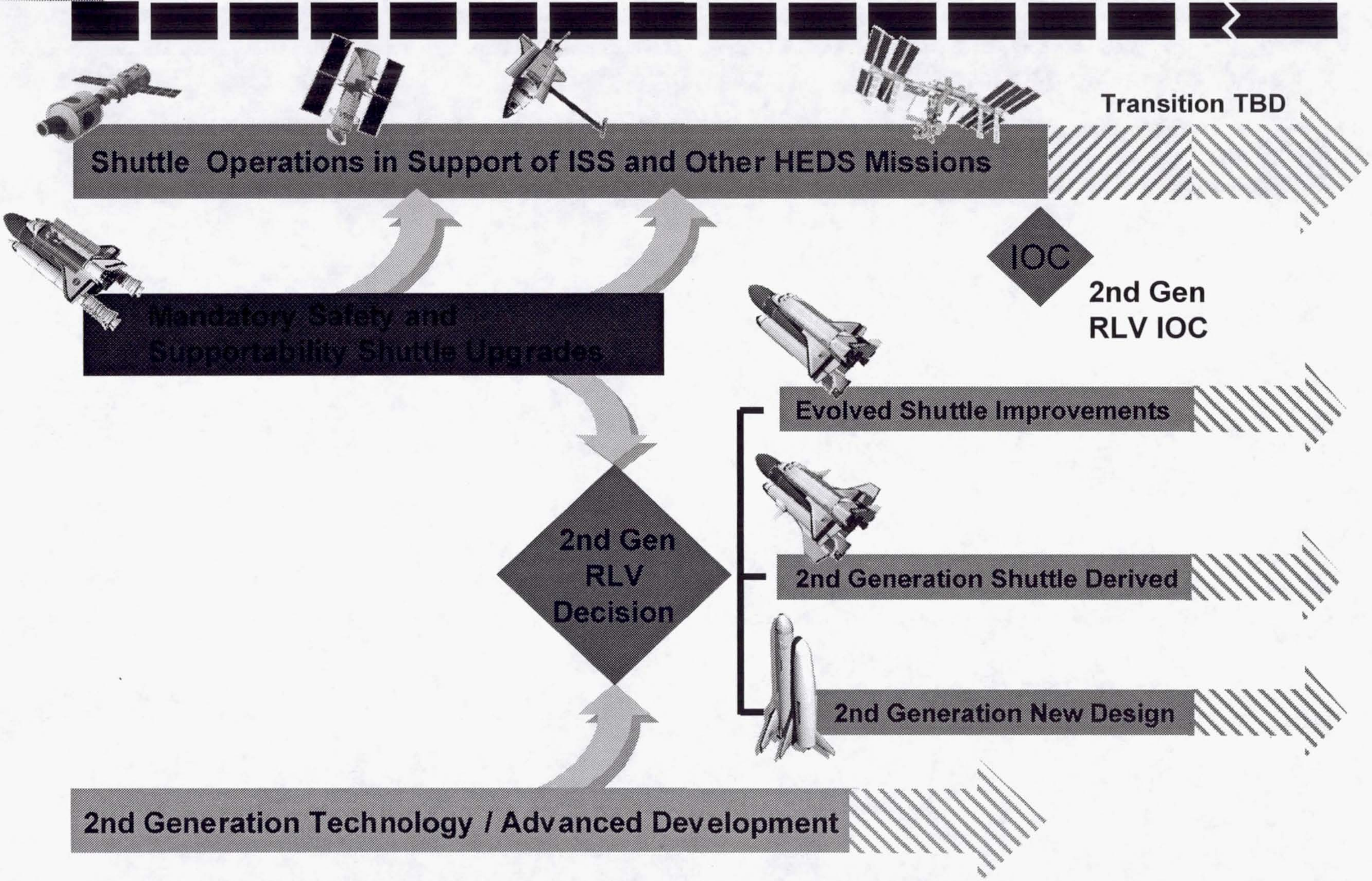




Next-Generation Shuttle Vision

- Improve safety and increase reliability by an order of magnitude
- Eliminate complex, expensive systems and drastically reduce vehicle operations cost
- Provide flexible and routine access to space
- Maintain capabilities for humans to work in space
- Enable advancing technologies for HEDS and future generation RLV's
- Increase ascent performance to provide abort-to-orbit capability and to allow next-generation vehicle enhancements

Space Shuttle Development Strategy



Transition TBD

Shuttle Operations in Support of ISS and Other HEDS Missions

IOC

2nd Gen
RLV IOC

Mandatory Safety and
Supportability Shuttle Upgrades

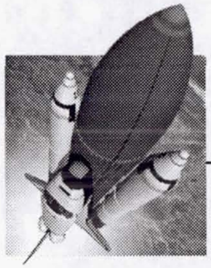
Evolved Shuttle Improvements

2nd Gen
RLV
Decision

2nd Generation Shuttle Derived

2nd Generation New Design

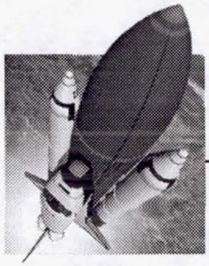
2nd Generation Technology / Advanced Development



Shuttle-Derived 2nd Generation RLV

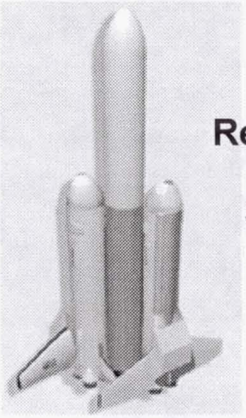
High Priority Technology / Advanced Development Needs

- Crew escape and survival technologies
- Highly reliable, long life LOx/Hydrocarbon booster engine
- Reusable first stage demonstrator
- Highly reliable, long life LOx/LH_2 main engine
- Highly reliable, inexpensive expendable LOx/LH_2 main engine (alternative)
- Inexpensive external tank (manufacturability)
- Non-toxic OMS/RCS
- Advanced, more durable and reliable TPS
- Integrated Vehicle Health Management
- Electro-mechanical actuation
- Flyback jet engines

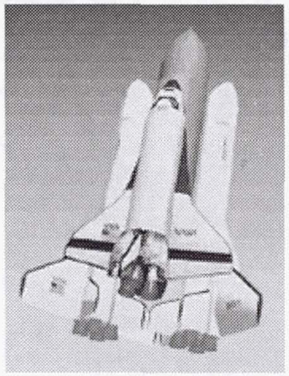


Leveraged Technologies by Partnering

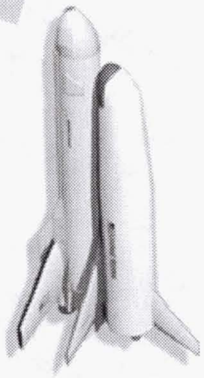
Reusable Flyback Demonstrator



Reusable First Stage



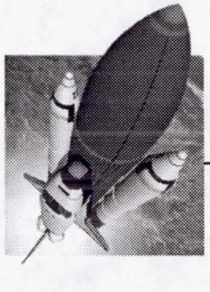
Shuttle Upgrades



Two Stage To Orbit

LFBB Enabling Technologies

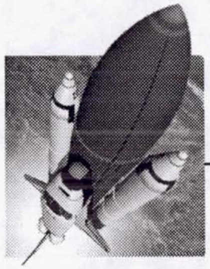
- Reusable, Reliable, Low Cost, Throttleable Booster Main Engine
- Jet Engine Integration and Exposure to LFBB Flight Environment
  - Vibro-Acoustic Environment , Air-Start, Cruise Performance
- Reusable TPS/ Cyro Insulation
  - Propellant Conditioning, High Mach No., Environmental Exposure
- Capability to Successfully Complete Mission With One Engine Out
- Integrated Vehicle Health Monitoring (IVHM)
- Serviceability and Rapid Turn Around
- Autonomous Powered Landing
- Flight Qualities
  - Aerodynamics / Aerothermodynamics
- Non-Toxic OMS/RCS
- PEM Fuel Cells



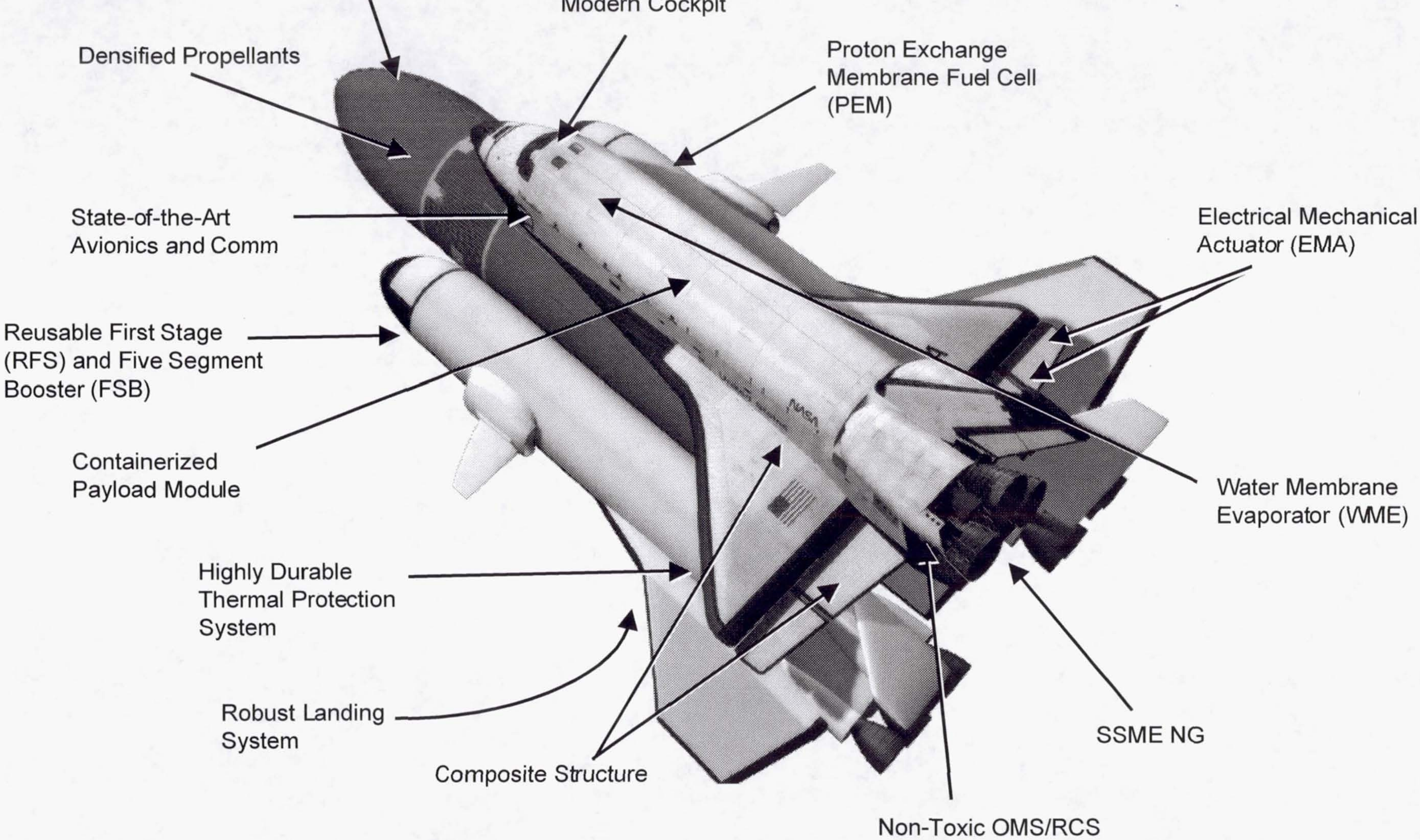
Evolved Space Shuttle Option

Potential Shuttle evolutionary improvements beyond 2005

- **Key *safety* improvement goals of evolved Shuttle**
  - Ascent "abort-to-orbit" from the pad → advanced 1st stage boosters
  - Increases main engine reliability
  - Advanced crew escape capabilities
- **Potential *advanced technology* infusion into evolved Shuttle, as demonstration *testbed* for future vehicles**
  - Phased array communication system
  - Non-toxic on-orbit propulsion & attitude control
  - More durable thermal protection system (TPS)
  - Electro-mechanical actuation
- **Advanced space transportation investments in those capabilities support *future vehicle* options as well as the evolved Shuttle option**



Evolved Space Shuttle



ET Improvements

Modern Cockpit

Densified Propellants

Proton Exchange Membrane Fuel Cell (PEM)

State-of-the-Art Avionics and Comm

Electrical Mechanical Actuator (EMA)

Reusable First Stage (RFS) and Five Segment Booster (FSB)

Containerized Payload Module

Water Membrane Evaporator (WME)

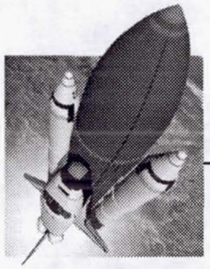
Highly Durable Thermal Protection System

Robust Landing System

Composite Structure

SSME NG

Non-Toxic OMS/RCS



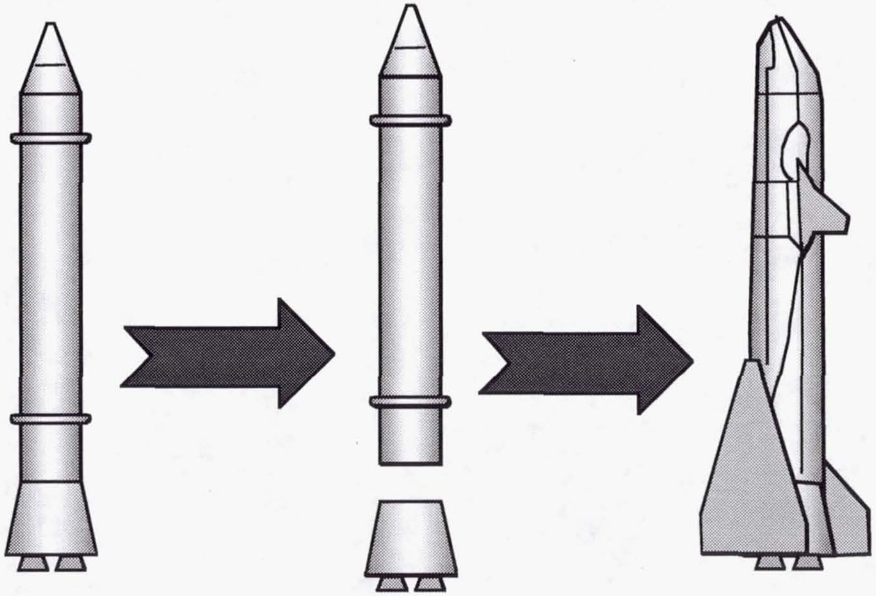
Evolvable Liquid Rocket Booster (ELRB)

Can Be Logical Building Block for Reusable First Stage

Description

- Enables most RFS safety features at less DDT&E cost
- Potentially Cuts development cost of RFS
  - Tooling for ELRB available to manufacture RFS
  - Main propulsion Test Article for ELRB is usable for RFS
  - Development test data for ELRB is applicable to RFS
  - Brings in earlier launch facility infrastructure for LOX/RP-1
- Builds experience to existing infrastructure
- Reduces impact of existing infrastructure
- Incremental Cost from ELRB to RFS is ~$TBD

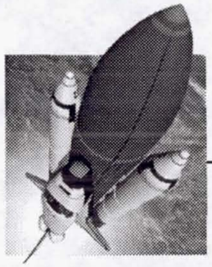
Potential ELRB Evolution Path



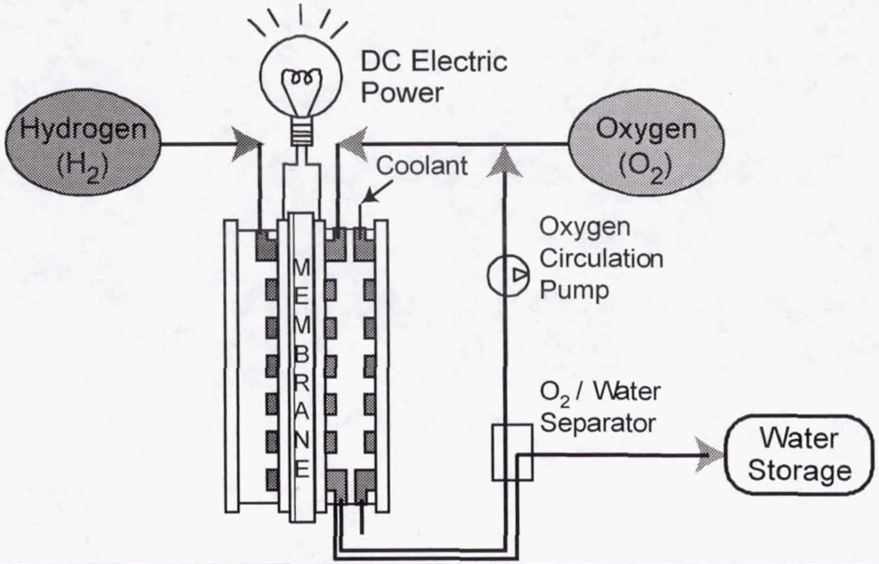
Initially
Expendable

Add Recoverable
PA Module

Add Wings and
Flyback Systems



Proton Exchange Membrane (PEM) Fuel Cell



Description

Proton Exchange Membrane (PEM) Fuel Cell produces electricity

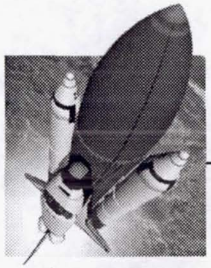
- Uses hydrogen as fuel and oxygen as oxidizer
- Split hydrogen protons pass through the thin electrolyte membrane and the hydrogen electrons produce electricity
- Byproduct is water
- Operates at relatively low temperatures
- High power density

Benefits

Replaces alkaline fuel cell currently used for producing vehicle and payload power

- Potential to supply greater power
    - Normal mission with only 2 (of 3) powerplants
    - Landing with one powerplant
- Supports and increased flight rate with fewer powerplants
- Lower maintenance costs
    - Increased time between overhauls
- KOH electrolyte and asbestos matrix are eliminated
- May eliminate a criticality 1R or 2 hazard
- Fuel cell flooding is reversible, with no hardware damage
- Leverage off of industry development

- HEDS applications include
    - Future launch vehicle power systems
    - Lunar/Mars transport and surface-based power systems
    - Fuel-cells for spacesuits
    - Recharge/backup power



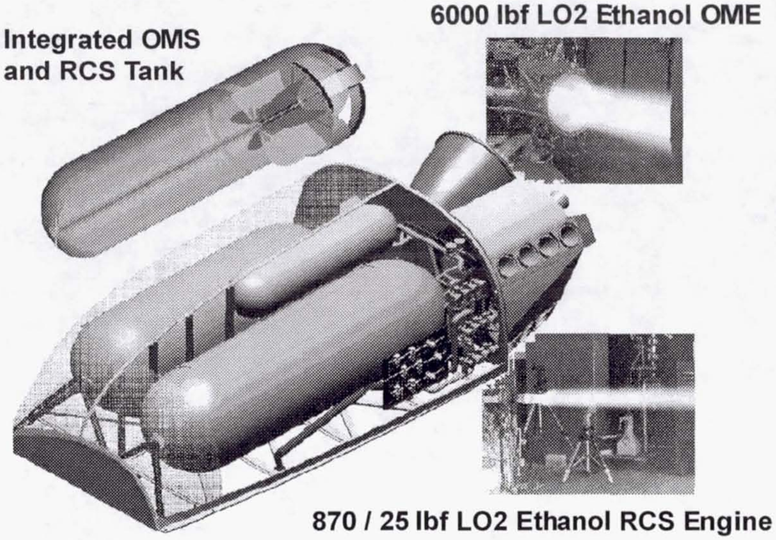
Non-Toxic OMS/RCS System

Description

Replace current toxic Hydrazine based OMS/RCS system with Liquid O_2 – Ethanol system

- Non-Toxic fuels

Implement modified pod with integrated OMS and RCS tanks



Benefits

Significant cost savings

- Eliminates SCAPE operations through the complete elimination of Hydrazine handling
- Increased ease of maintainability with ergonomically designed pod
    - All maintenance in pods within “arm’s reach”
- Reduced maintenance
- Requires EAPU upgrade

Increased system reliability

- Eliminates valve failure due to propellant ‘gumming’ or contamination of the valves

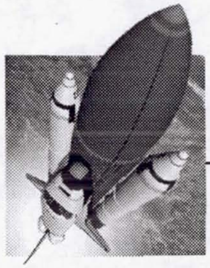
Benefits (continued)

Decreased risk of mission failure for ISS docking operations

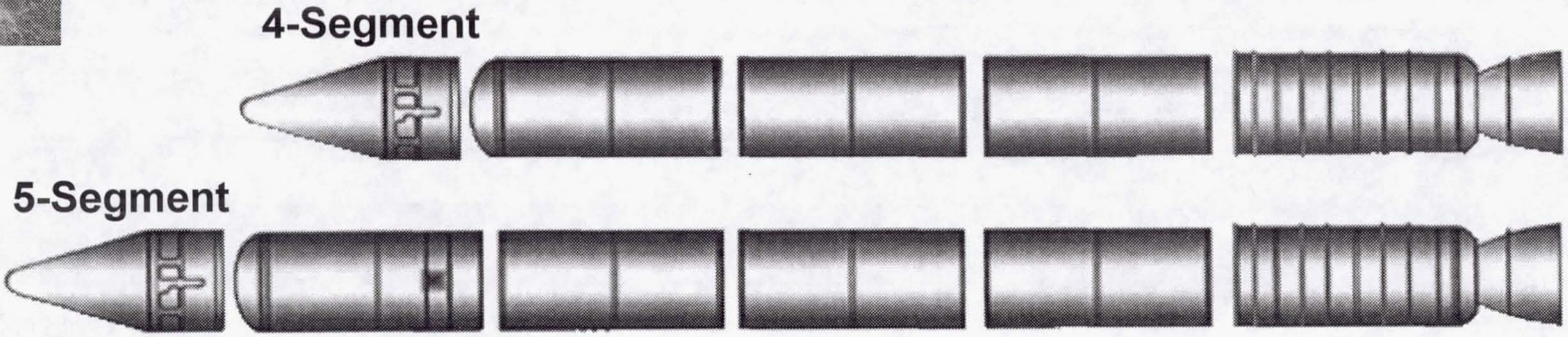
- Adds Redundant Vernier thrusters by using the Primary RCS engine torch igniter as the vernier
- Increased docking flexibility due to redundancy and improved translation capability
- Eliminates risk due to Hydrazine contamination on ISS

Improved Safety

- Eliminates auto-ignition fire hazards of hydrazine
- Eliminates risks of EVA crew exposure



5 Segment Booster



- Same forward skirt assembly and frustrum

- New attach case segments
- Grain modification
- Insulation modification

- Added center segment
- Inhibitor modification
- Insulation modification

- Standard weight stiffeners
- Added stiffener ring

- Modified nozzle
- Insulation modification

Benefits

Significant safety enhancement

- Leverages flight-proven success of existing RSRB
    - Incorporates all RSRB enhancements
- Enables engine-out from liftoff
    - Eliminates RTLS or TAL
- Demonstrated low probability of catastrophic failure

Significant cost savings

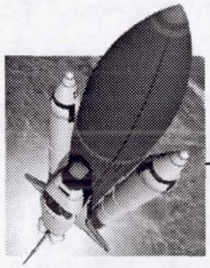
- Low life-cycle cost
    - Minimize developmental time and risk
    - Minimal facilitation
- Reduced $ / lbm to ISS

Huge increase in lift capability

- ISS payload potential increased 24 klbm
- Polar orbits from KSC

Building block for emerging programs

- Boost propulsion for HEDS missions
- Boost stage for low-cost ELV concepts



New Shuttle Ku Band PAA Communications System

Description

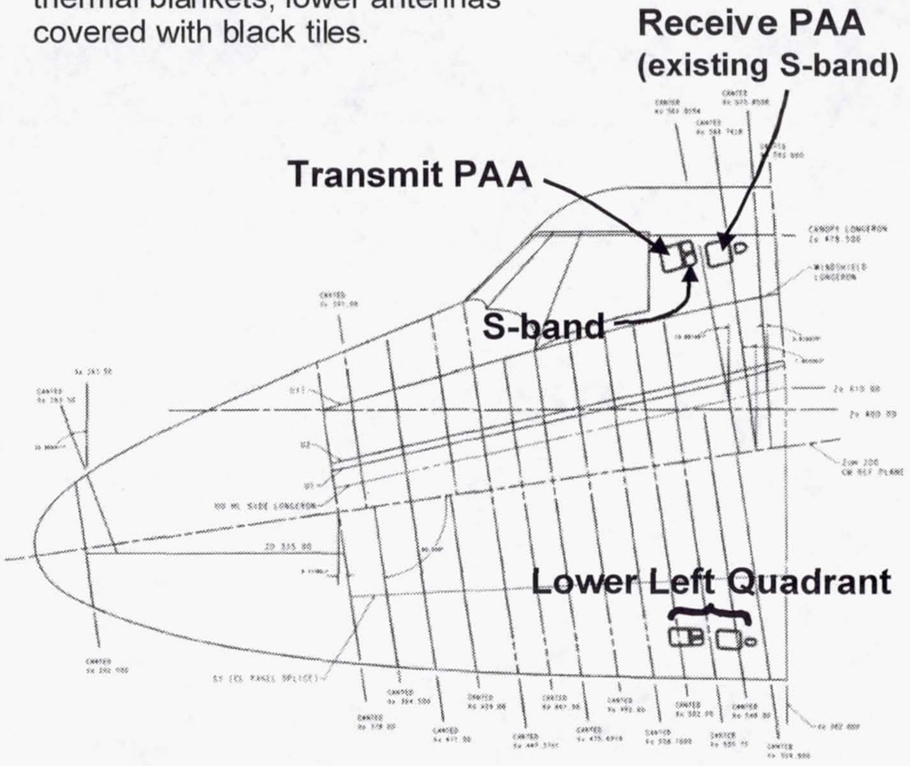
Replaces current Ku-band deployed antenna, Ku-band electronics, and the S-band FM system with four PAA transmit/receive antenna pairs and electronics

Benefits

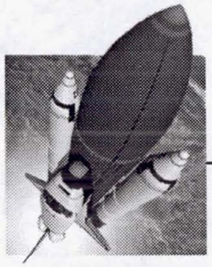
- System has potential to transmit 75 Mbps and receive 1.5 Mbps
  - Can accommodate transmission and reception of digital TV
  - Shuttle PAA elements could be used on ISS or other future space applications
  - Current Ku-band system only transmits 50 Mbps and receives 216 kbps
  - System not dependent on payload bay doors, resulting in increased system availability
- Eliminates Criticality 1 failure modes of existing deployed antenna
- New system will have increased reliability and lower maintenance

Approximate sizes
Transmit PAA - 8" X 13" X 2.5"
Receive PAA - 10" X 13" X 2.5"

Upper antennas covered with white thermal blankets, lower antennas covered with black tiles.



System electronics will be located in forward avionics bays.



ElectroMechanical Actuators (EMA)

Description

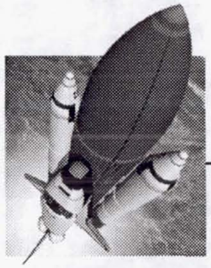
ElectroMechanical Actuators can be used as an actuator to move mechanical assemblies (landing gears, body flaps, valves, elevons etc.)

- Integrates into extend/retract control system
- Powered by AC or DC electricity
- May use a machine screw, ball screw drive, or gearbox
- Precision movement
- Broad variety of low to medium capacity applications

Benefits

- Replaces pneumatic and hydraulic technologies
  - Eliminates the need for hydraulic fluids and associated servicing
  - Greater reliability and fault tolerance
  - Lower maintenance costs
  - Longer service life
  - Built-in health monitoring
  - Runs smoothly
  - Many applications for future vehicles

- Shuttle applications include
  - Landing gear actuators
    - Nose landing gear uplock actuator
    - Nose wheel steering actuator
    - Main landing gear strut actuator
  - ET Umbilical retract actuator
  - Aerodynamic control surface actuators
  - Body Flap actuator
  - Elevon servoactuator
  - Rudder/speedbrake hydraulic motor/servo valves
  - SSME cryogenic propellant valves
  - Thrust vector control actuators
  - Various Reusable First Stage (RFS) applications

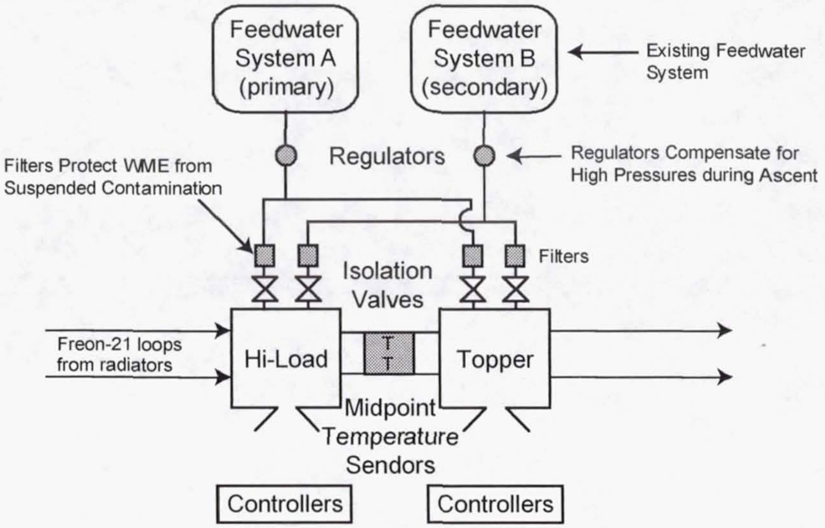


Water Membrane Evaporator (WME)

Description

Water Membrane Evaporator provides cooling

- Uses a hydrophobic micropore membrane that releases water vapor as water is heated
- Hydrophobic membrane passively controls water inventory
- Hydrophilic membrane allows cool water to replace the evaporated water
- Takes advantage of recent developments in hydrophobic micropore membrane technology



Benefits

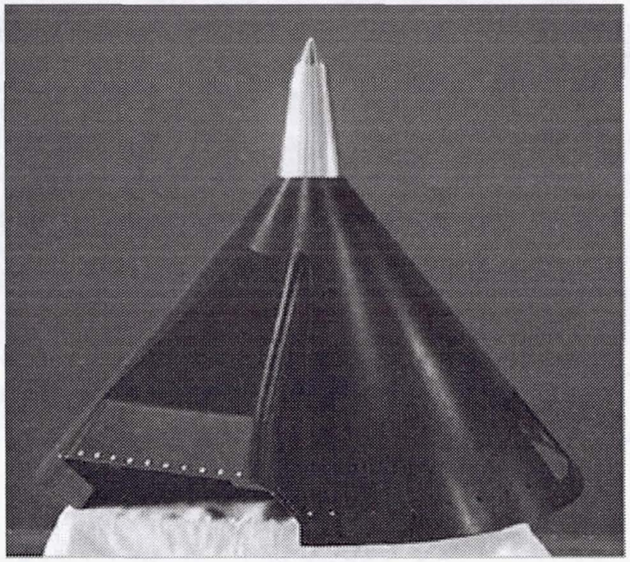
- Replaces Flash Evaporator System (FES) which provides active cooling during ascent and entry and supplemental cooling on-orbit
  - Lower maintenance costs
    - Higher reliability (less moving parts)
      - Increased time between repairs/refurbishment
      - Longer life
    - FES has problems with clogged filters and nozzle freeze-ups
  - Leverage off of industry development
  - Synergy with advanced spacesuit (EMU) cooling system development
  - Decreased sensitivity to contaminants in the feed water

Composite Structure

Description

Incorporate composite structures into evolved or next generation shuttle

- Composites are composed of continuous fibers suspended in a resin
  - Laminates provide high stiffness and strength
- Types of composites include
  - Carbon Fiber Reinforced Composites (CFRC)
  - Ceramic based
  - Carbon/Polyamide

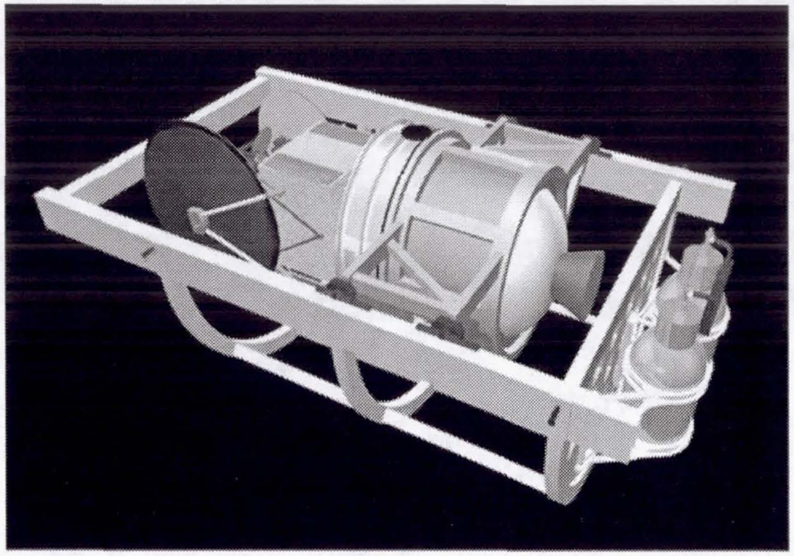


Benefits

- Lightweight
  - As much as 5 times lighter than steel
- High Stiffness
  - As much as 2.5 times the strength of steel
- Part Consolidation
  - Eliminate critical failures
- Extended life cycle
  - No fatigue, corrosion
- Vibration damping
- Can be optimized to fit design needs
- Dimensional stability under changing temperatures
- Can incorporate structures health monitoring into design

- Application include designs that need
  - Light weight, strength, and stiffness
    - Wings
    - Body flaps
    - Various weight-saving components/structure
  - Heat resistance
    - Carbon-carbon brakes
    - Leading edge applications (wing, rudder, nosecone)
      - Eliminates or reduces TPS
  - Inert chemical properties
    - Fuel tanks
  - Fatigue resistance
  - *Insulating properties*

Containerized Payload Module



Description

Design and build a containerized payload module to standardize orbiter to payload interfaces

- Install with the payload as a completed assembly
- Uses standardized interfaces

Streamline orbiter-to-payload support services and interfaces

- Orbiter and mission kit avionics, power, distribution and control hardware support upgraded to standardized support system

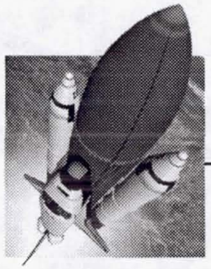
Benefits

Safety and Reliability

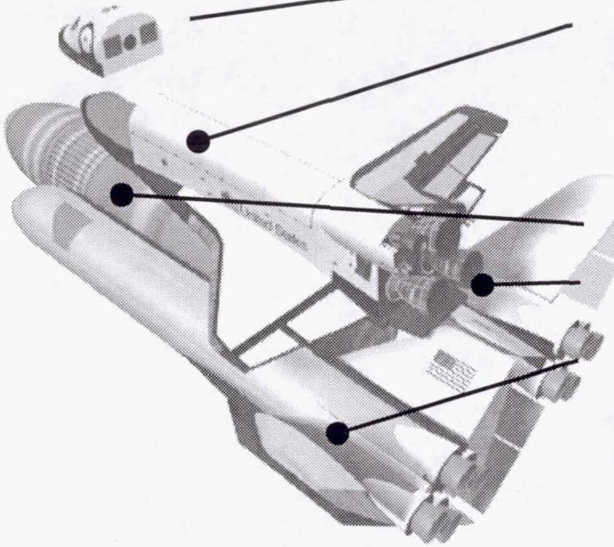
- Reduces on-orbit mission complexity

Supportability

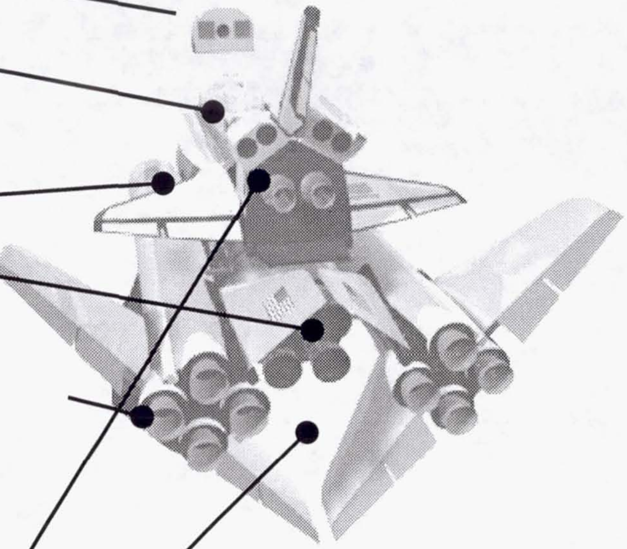
- Significant reduction in Payload Integration and KSC reconfiguration costs
  - 36% reduction in operations and maintenance costs between
    - KSC Orbiter reconfiguration
    - Payload Integration (ICD, Engineering, Mission Kit Hardware, Requirements)
  - Additional savings due to using the standardized carrier
  - Allows for payload processing at commercial facilities
  - Allows integrated testing off-line
  - Economically accommodates future payloads
- Significant reduction in templates
  - Supports flight rates of at least 15 per year
  - Reduce template by 4 to 6 months
  - Supports 30 day OPF flow
- Takes advantage of other avionics and communications upgrades
- Note – Legacy payloads would have to be recertified. Would need to be implemented after ISS assembly complete.



Representative Shuttle-Derived 2nd Generation RLV Options



Boeing / NASA In-House



Lockheed / NASA In-House

Common Features

Crew escape pod

Subsystem improvements: non-toxic OMS/RCS, electro-mechanical actuation, improved TPS, improved landing systems

Retain external tank

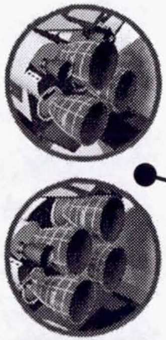
Improved highly reliable main engines

Reusable first stage (with capability to make orbit with one booster engine out)

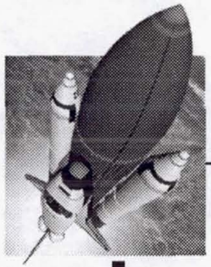
Variations

Air breathing jet engines on orbiter for range extension and landing "wave off/go around" capability

Main engines (expendable or recoverable) moved from orbiter to external tank



3 "Super" SSME or 4 SSME Engines for engine out to orbit from the pad



Shuttle Upgrades Enabling Technologies for the Future

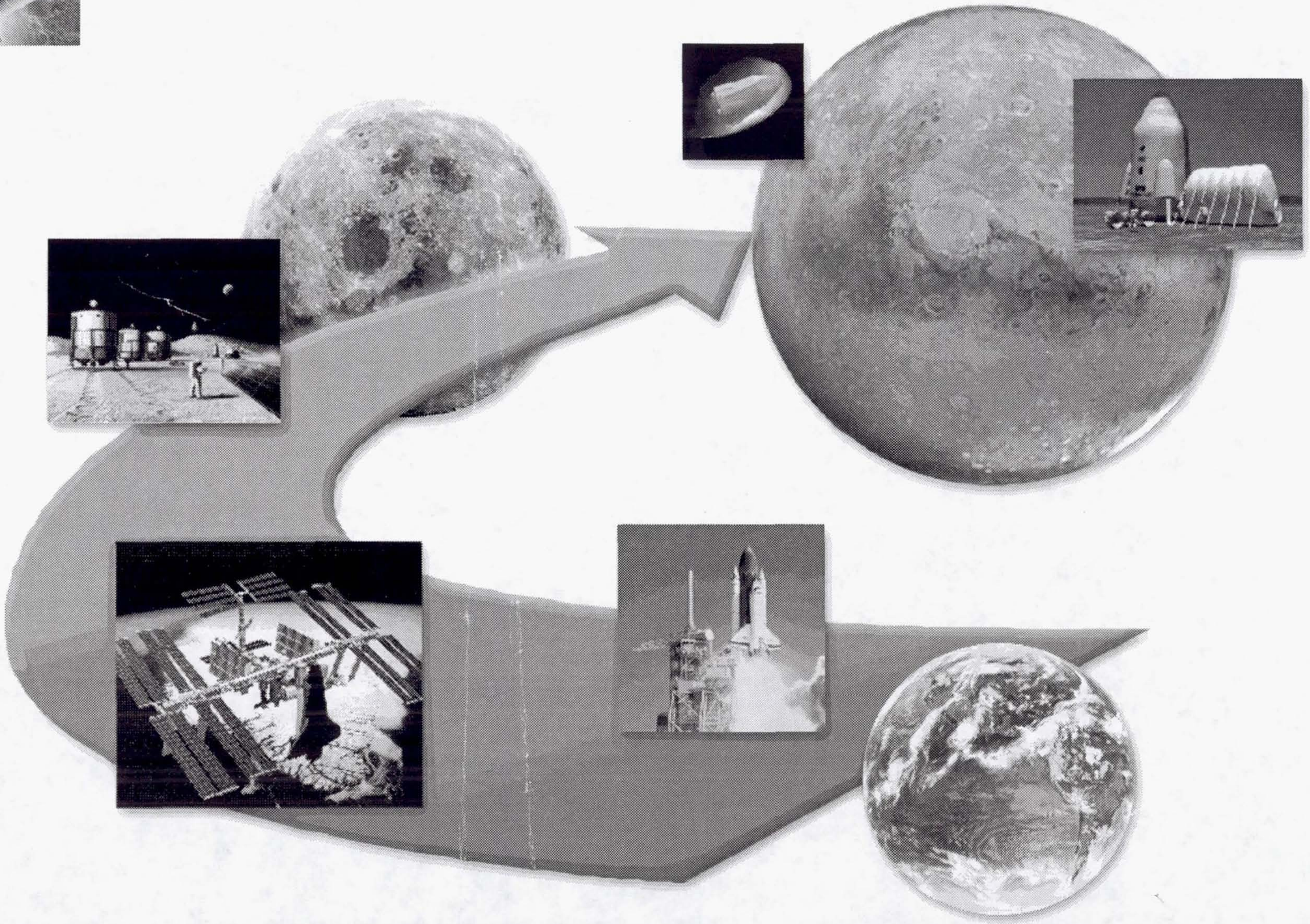
Near Term

- Long-Life Fuel Cells
- Avionics Cockpit Upgrades
- Electric APU
- MLG Tire
- AHM
- BLK III SSME

Advanced Technology

- Crew Escape
- Reusable First Stage
- Non-Tox OMS/RCS Propellants
- PEM Fuel Cell
- Electromechanical Actuators
- Water Membrane Evaporator
- Integrated Vehicle Health Mgmt
- Propellant Densifications
- Fiber Optics

The Vision . . .



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Space Transportation Information Network

Mark Ogles

Teledyne Brown Engineering

October 12, 2000

Information Network

ASTP

TELEDYNE
BROWN ENGINEERING
A Teledyne Technologies Company

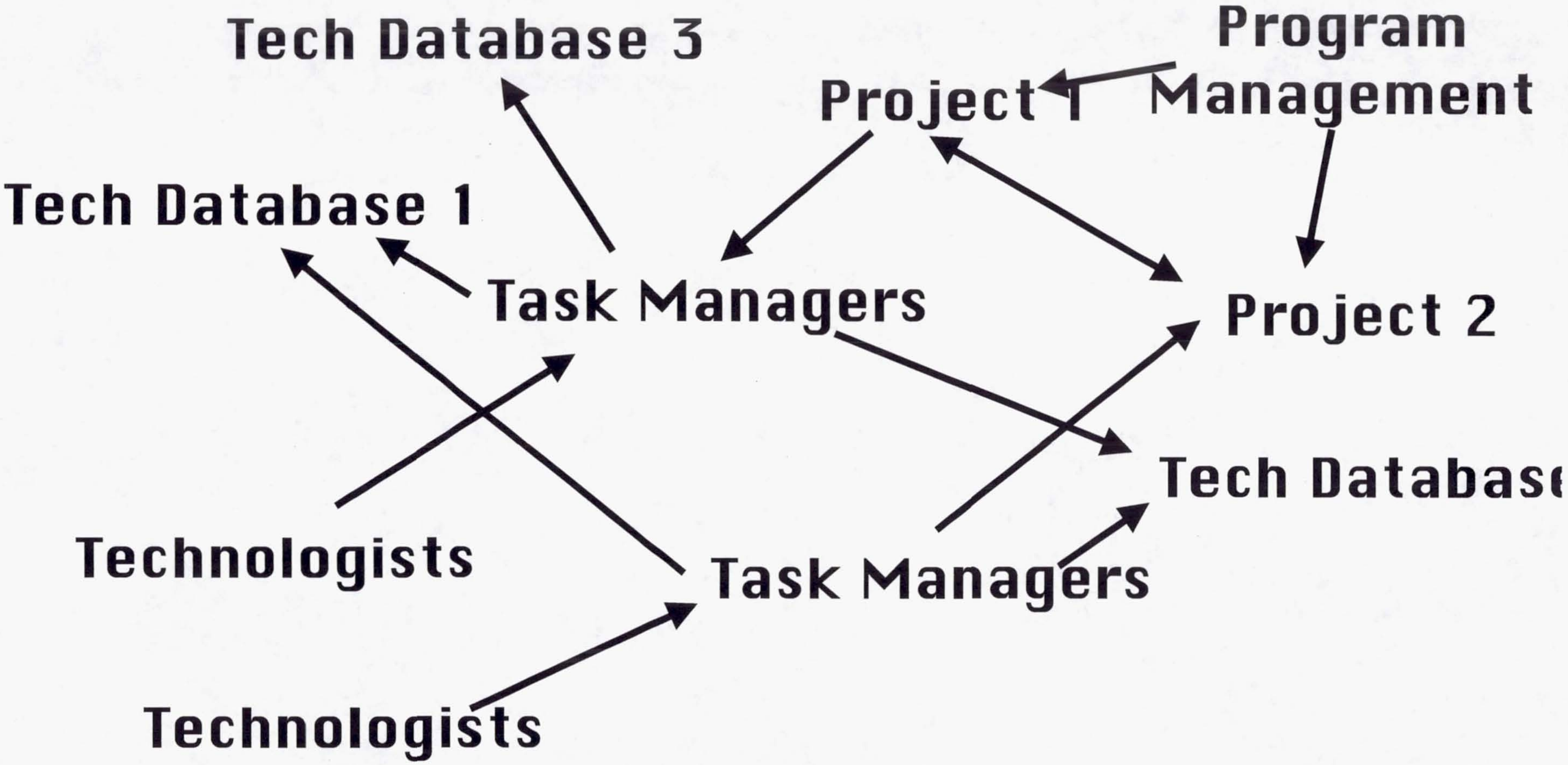
Introduction

- Teledyne Brown Engineering has supported MSFC since its establishment
- SpaceLab, Space Station Payload Integrator
- Developer of Space Station Payload Data Library (PDL)
- Supported MSFC in Requirements Definition for STIN
- Selected as Developer for STIN

The Need (Current State of ASTP)

- Significant number of technology and advanced development activities are underway at numerous NASA centers, industry partners and academia
  - With a significant increase in activity starting in FY01
- A responsive "knowledge capture and transfer" process within the space community does not exist
  - Depends on informal networks, luck, etc.
  - Often old and incomplete data
- Need exists to track progress towards technical and programmatic goals and objectives
- Diverse number of regular reviews and database inputs are required (NASA Tech Inventory, Monthly OAT reviews, etc.)
- ISAT needs the latest technology data to accurately fulfill its missions
- Too much time is spent by technologists and managers on "overhead"
  - Filling in databases, multiple status charts to various formats,

Current Interfaces


Tech Database 3

Program Management

Project 1

Tech Database 1

Task Managers

Project 2

Tech Databas

Technologists

Task Managers

Technologists

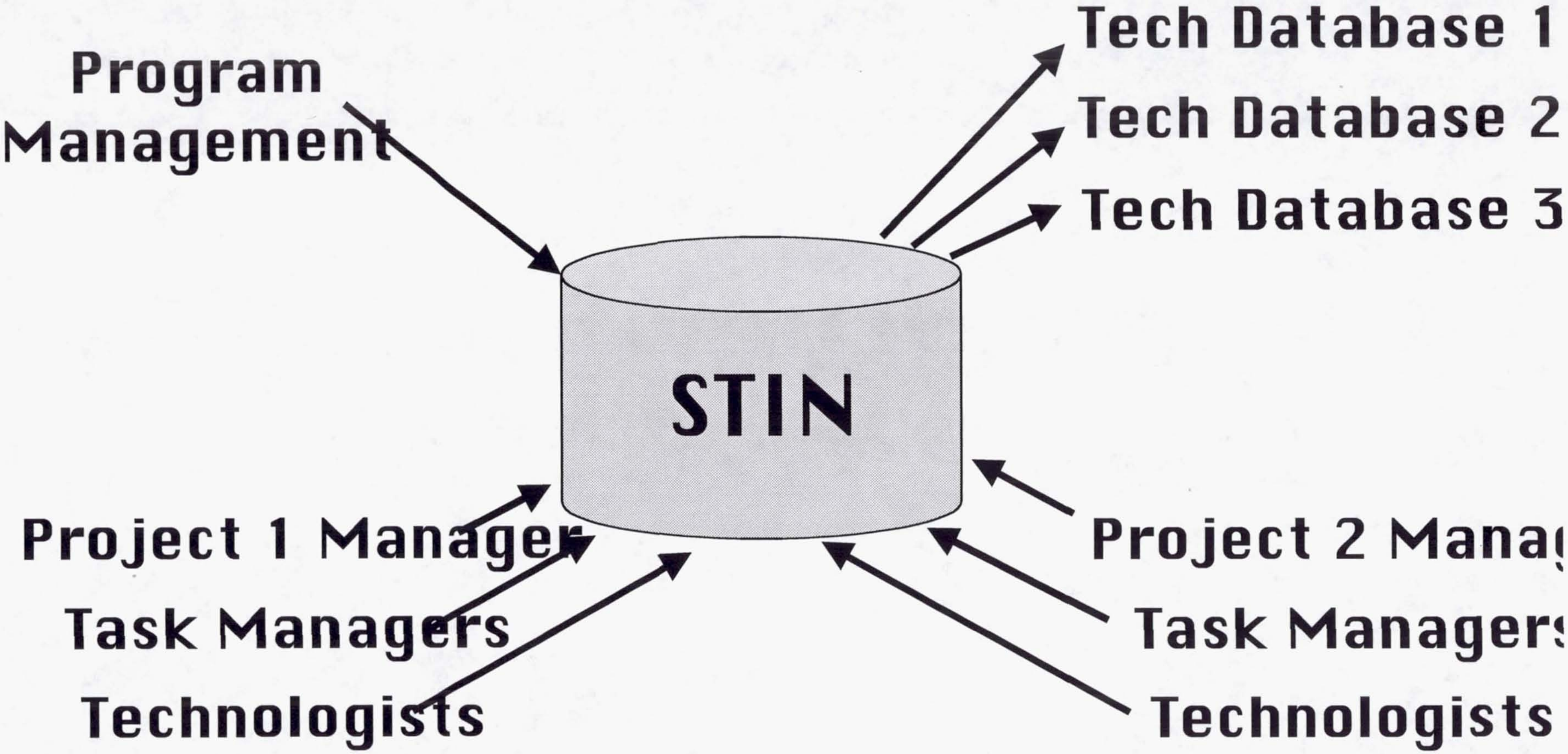
The *Integrated* Solution

To establish a centralized system for submittal, evaluation, and distribution of NASA's space transportation technology and advanced development information

STIN

Technical Programmatic

Proposed Architecture



Program Management

Tech Database 1

Tech Database 2

Tech Database 3

STIN

Project 1 Manager

Task Managers

Technologists

Project 2 Mana

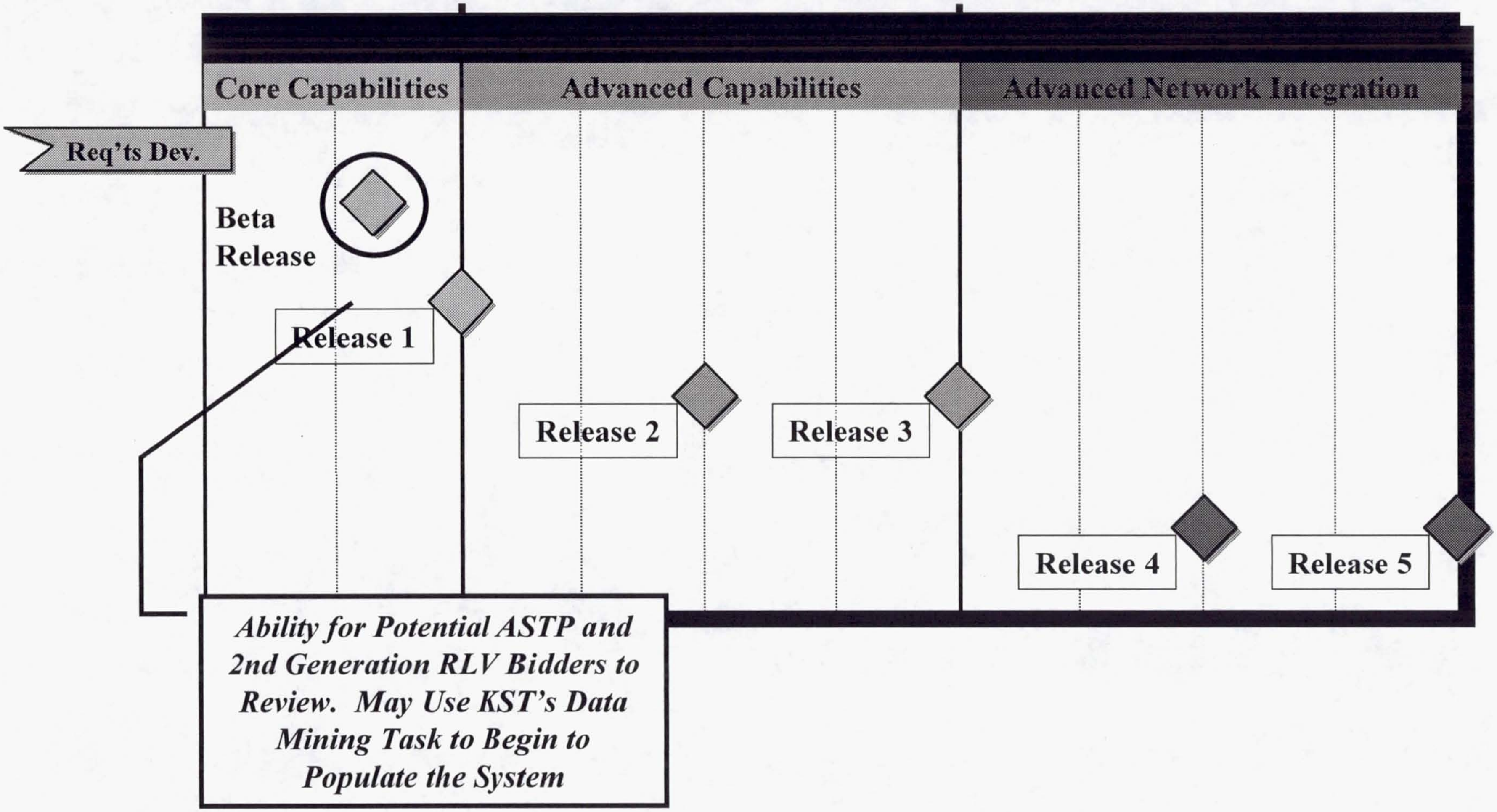
Task Manager

Technologists

STIN Applications

- Management tool for Space Transportation Technology / Advanced Development Managers to track technical, schedule, and cost information.
- Single interface between technology developers and management, ensuring better communication.
- Gives NASA's partners (industry and academia) access to the latest technology development results.
- Provides a vehicle to identify future technology needs.
- Tool to support ISAT evaluation of vehicle technologies.
- Tool to feed other required database inputs.
- Effectively facilitate research queries into

Development Schedule



Core Capabilities

Advanced Capabilities

Advanced Network Integration

Req'ts Dev.

Beta Release

Release 1

Release 2

Release 3

Release 4

Release 5

Ability for Potential ASTP and 2nd Generation RLV Bidders to Review. May Use KST's Data Mining Task to Begin to Populate the System

Hierarchical Structure

- Directorate
  - Program
    - Investment Area (Optional)
      - Project
        - Sub-Project (Optional)
          - Task

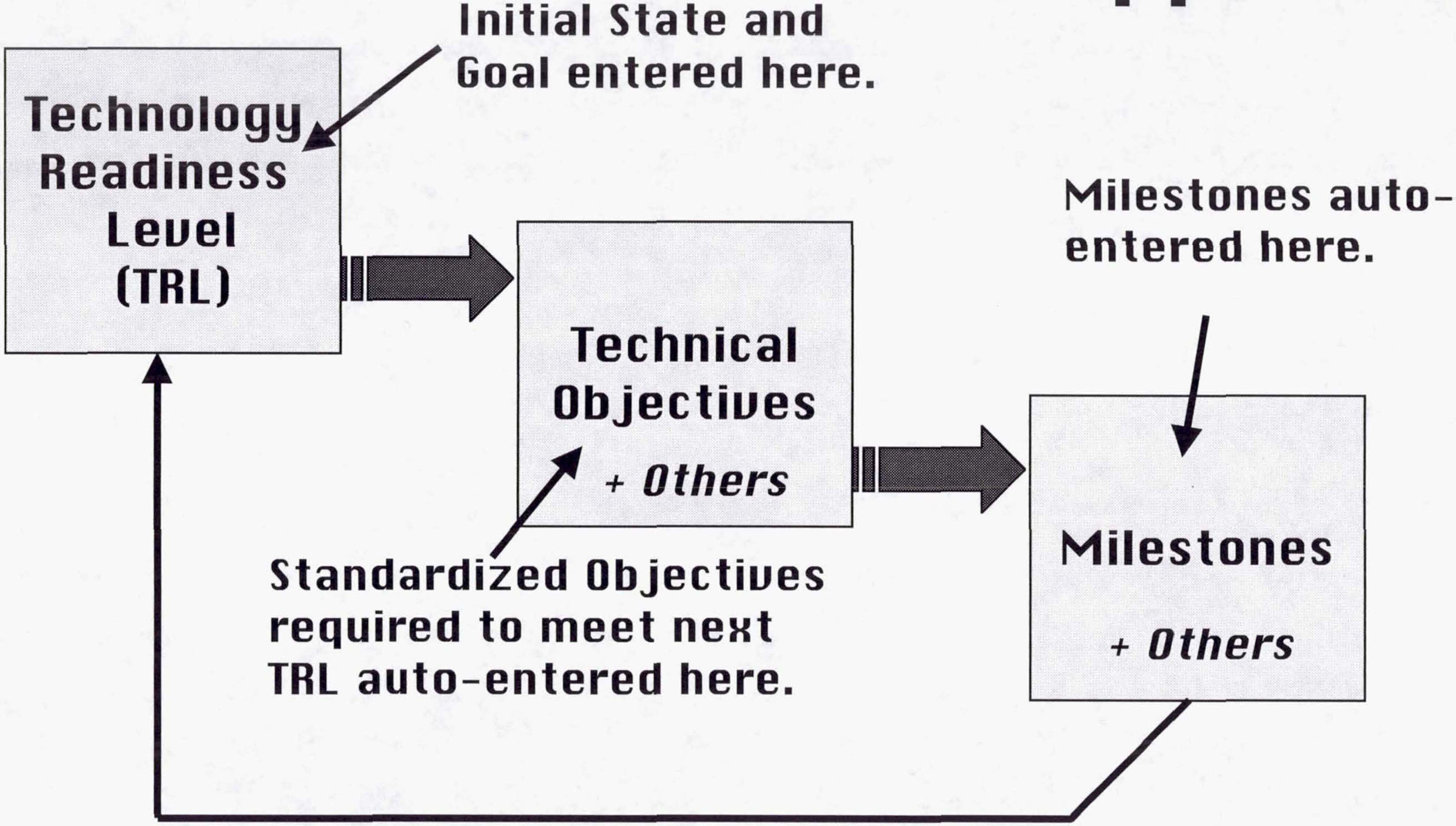
Technical Content

- Description
- Benefits
- Related Technologies
- Technology Application
- Technical Performance Metrics
- Technology Readiness Level
- System Concept and Architecture Analysis
- Objectives
- Technical Documentation
- Risk Management

Programmatic Content

- Resources
- Milestones
- Schedules
- Monthly Status
- Documentation
- Technology Transfer
- Procurement Structure
- Related Websites

Systems Engineering Approach



Initial State and Goal entered here.

Technology Readiness Level (TRL)

Technical Objectives

+ Others

Milestones auto-entered here.

Milestones

+ Others

Standardized Objectives required to meet next TRL auto-entered here.

As Milestones are completed the current TRL is Updated.

Application Features

- Web Based / GUI and Platform Independent (Mac, PC, Unix)
- Multi-level User Access
  - Technology Developers
  - Project Managers
  - ISAT Team members
  - Program Management and Staff
- Online Help information for each area of collection
- Email reminder / notification of events and required inputs

Application Features (cont)

- MPD 2810 IT Security Compliance
- Exports to other NASA systems
- Linkage/interface to analysis tools
- Keyword Search in uploaded documents
- Directorate/Program/Project Navigation
- Technology-based Navigation
- Goals-based Navigation
- Web-based report request capability
- Customized report development

Application Features (cont)

- Helpline Staffing
- Integrated (Imbedded) Training
- Automated Account Request and Approval
- Facilitates Research Queries into other systems

In Order to be successful...STIN must:

- **Be viewed as value-added by the technology development community**
  - Save time and effort in generating status reports / database entries
  - Provide a long term, searchable repository of technical information
- **Protect the data**
  - From unauthorized foreign use (ITAR, export control)
  - Maintain the integrity of company-proprietary information
- **Be comprehensive**
  - ASTP plans to require all future tasks (in-house or out-of-house) to utilize this network
  - Implementation by other Space Transportation Programs is TBD
- **Be user friendly**
  - Web-based / GUI

Summary

- NASA has a need to streamline its technology management approach.
- Efforts underway in multiple locations within NASA to combine/eliminate database input requirements.
- Most technology databases are limited in focus. (set up to meet a specific need)
- STIN is designed to meet technical, programmatic, public, and archival needs

Summary

- There is a reluctance on the part of technologists to accept “another technology database”.
- If Program/Project managers use a STIN-like system to manage tasks, then all the information needed by various other organizations will already be available online without additional collection and submittals.

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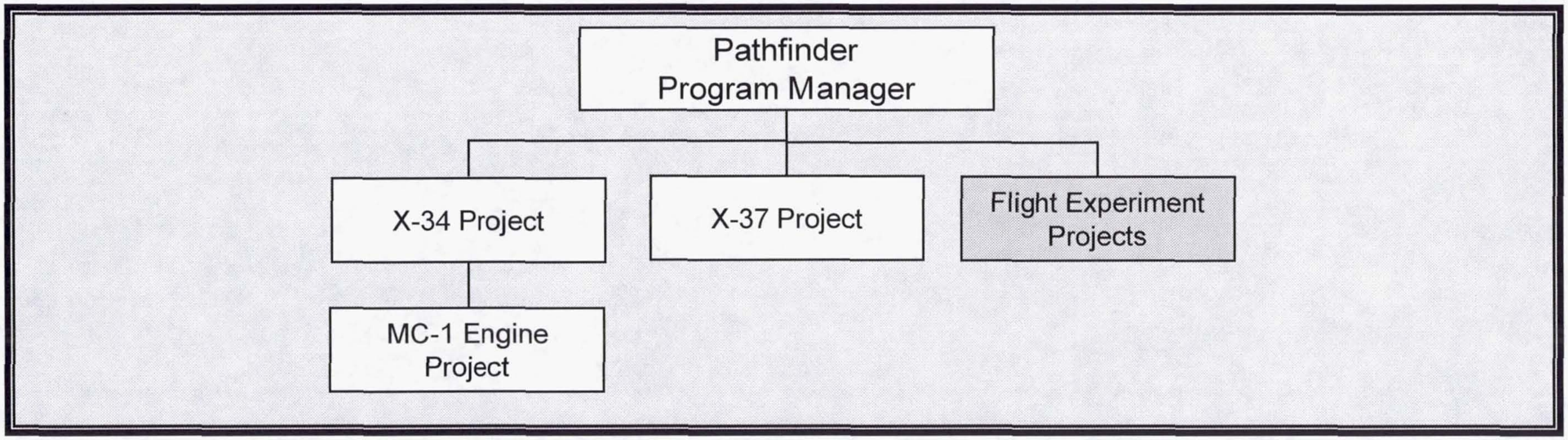
Flight Experiment Platforms/Opportunities

Michael Phipps
Experiments Project Manager
Pathfinder program Office
(256) 544-0828

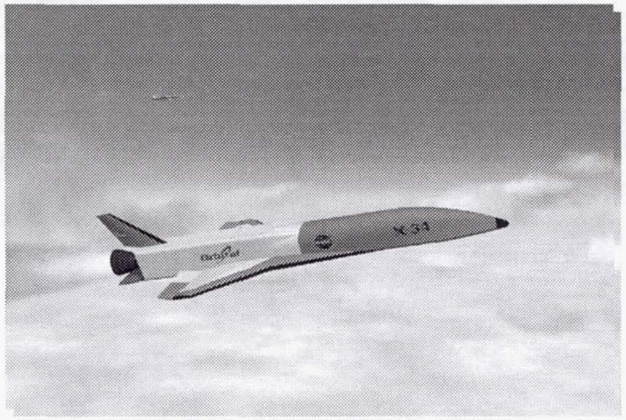
Pathfinder Experiments Project Office

- ◆ **FLY EXPERIMENTS ON ANY VEHICLE AVAILABLE**
- ◆ **GROUND TEST EXPERIMENTS AT AVAILABLE LOCATIONS EWS**



Pathfinders X-34 and X-37 Projects

- **X-34 Rocket Plane is a Suborbital/Atmospheric Technology Testbed**
  - Modular Design
  - Embedded and Hosted Technologies and Experiments
  - Low Cost Operations Testbed

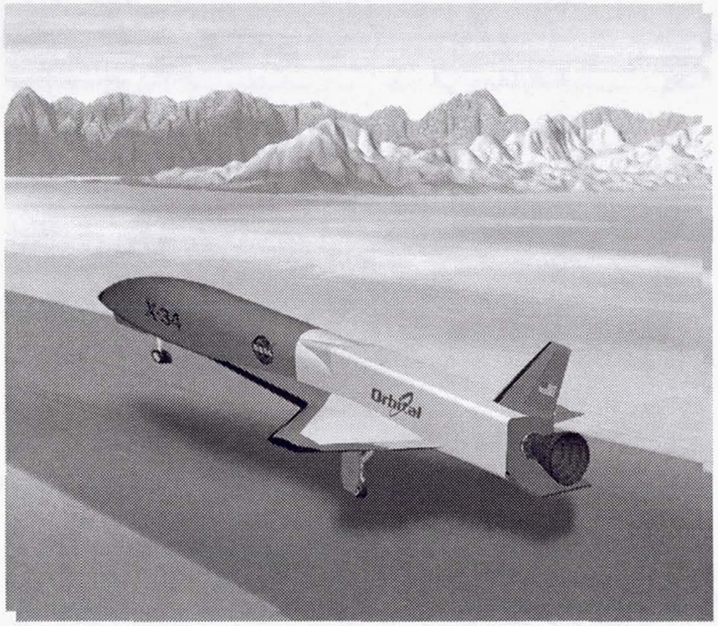


- **X-37 Space Plane is an Orbital/Reentry Technology Testbed**
  - First Orbital Test Bed X-vehicle
  - Modular Design
  - Embedded and Hosted Technologies and Experiments

X-34 Focus Area Technical Goals

New RLV Technologies Embedded in Vehicle Design

- **Demonstrate technologies throughout flight profile**
  - Subsonic and hypersonic flight
  - Capable of powered flight to at least 250k ft
  - Capable of attaining Mach 8
- **Capable of autonomous flight operations**



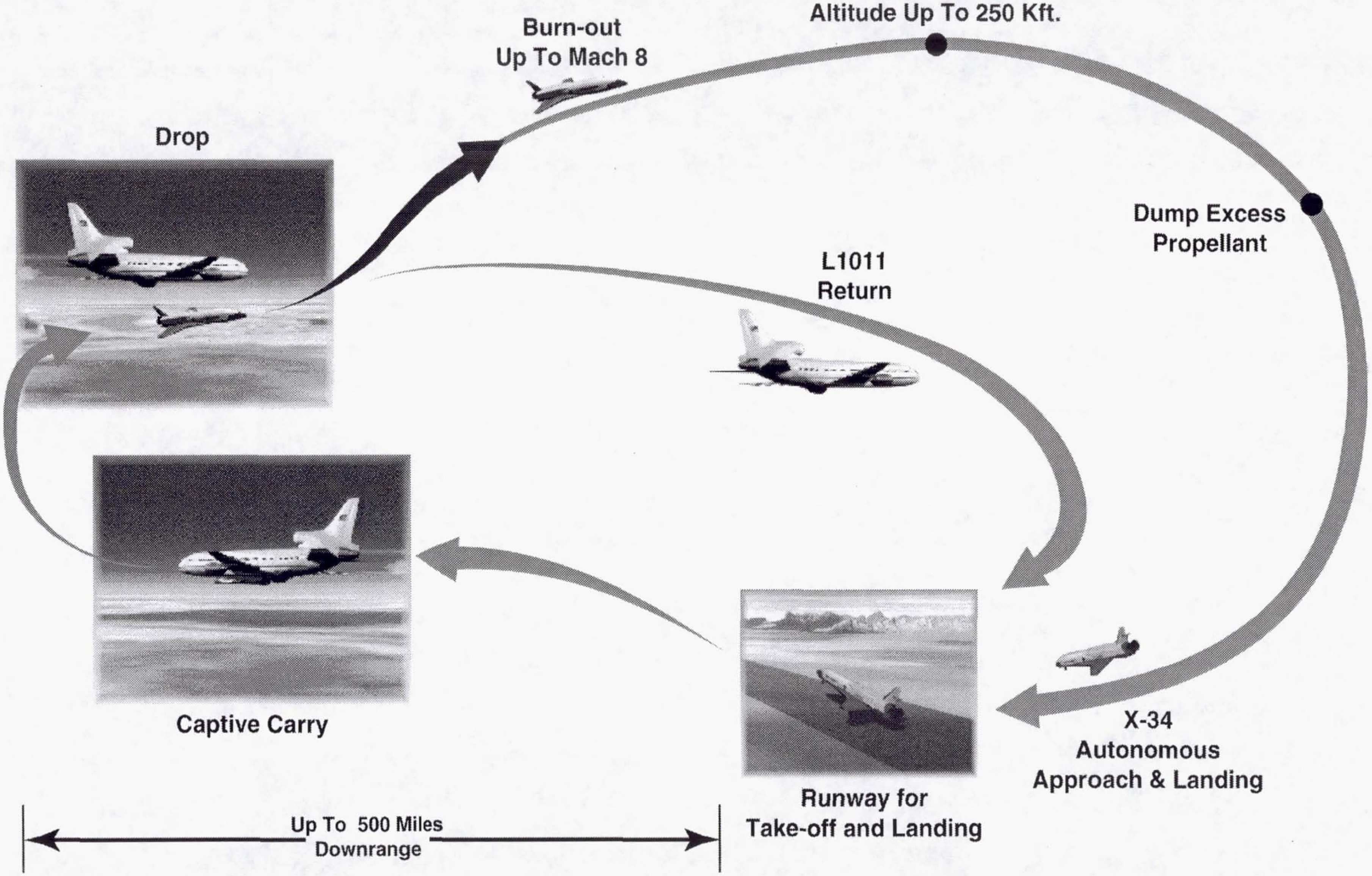
Investigation of New Methods for Low-Cost Operations

- **Low cost operations capable of demonstrating safe abort**
  - Small work force
  - Nominal 2-week turnaround
  - Surge capability of 2 flights within 24 hours
  - Capable of attaining average recurring flight cost of $500k
- **Operation in RLV-type environments**
  - Flights through rain and fog
  - Landings with cross winds of 20 knots or greater

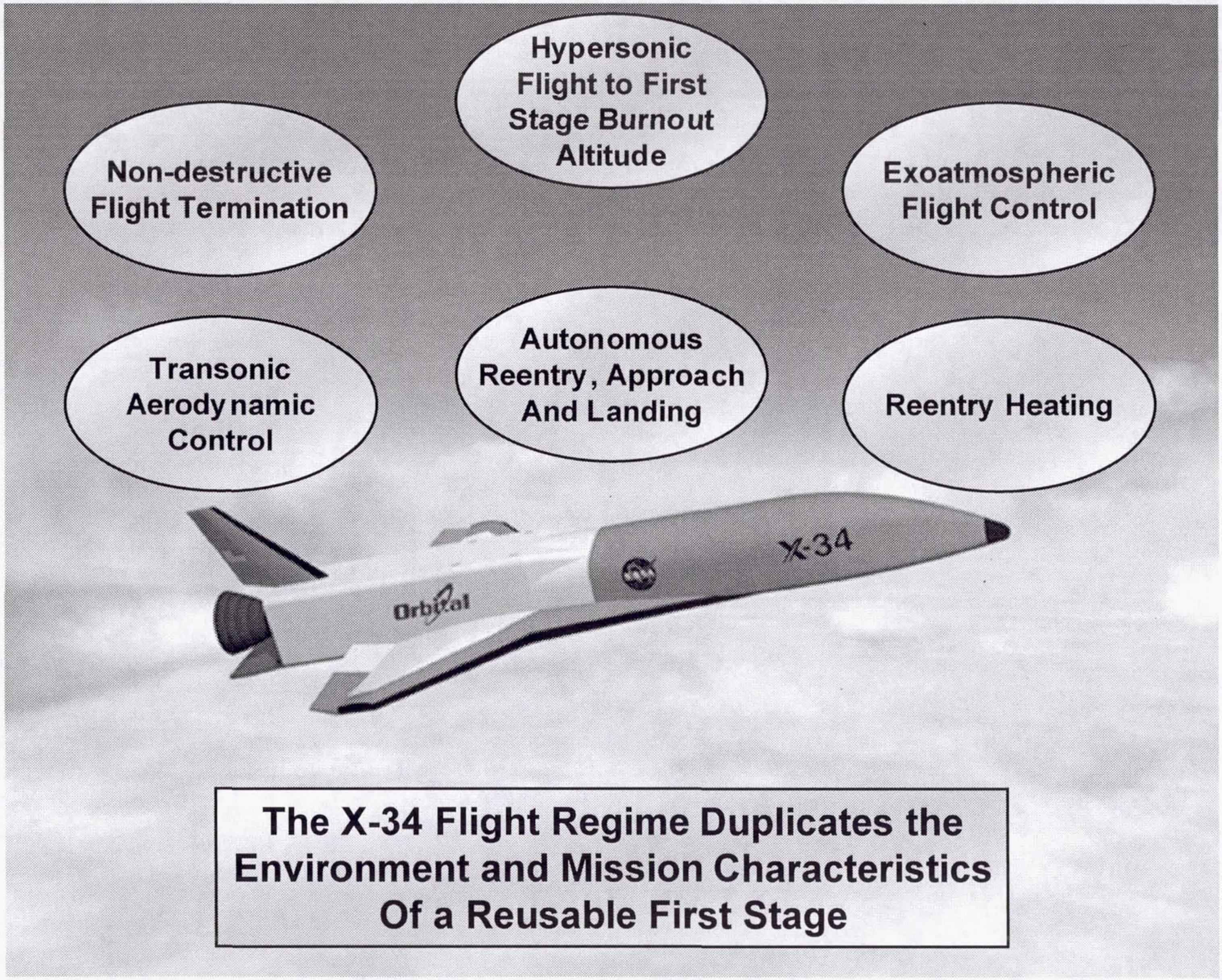
Testbed for Hosted RLV and Hypersonic Experiments

- **On-board instrumentation for testing embedded technologies**
- **Small area for "carry-on" experiments**

X-34 Typical Mission Profile

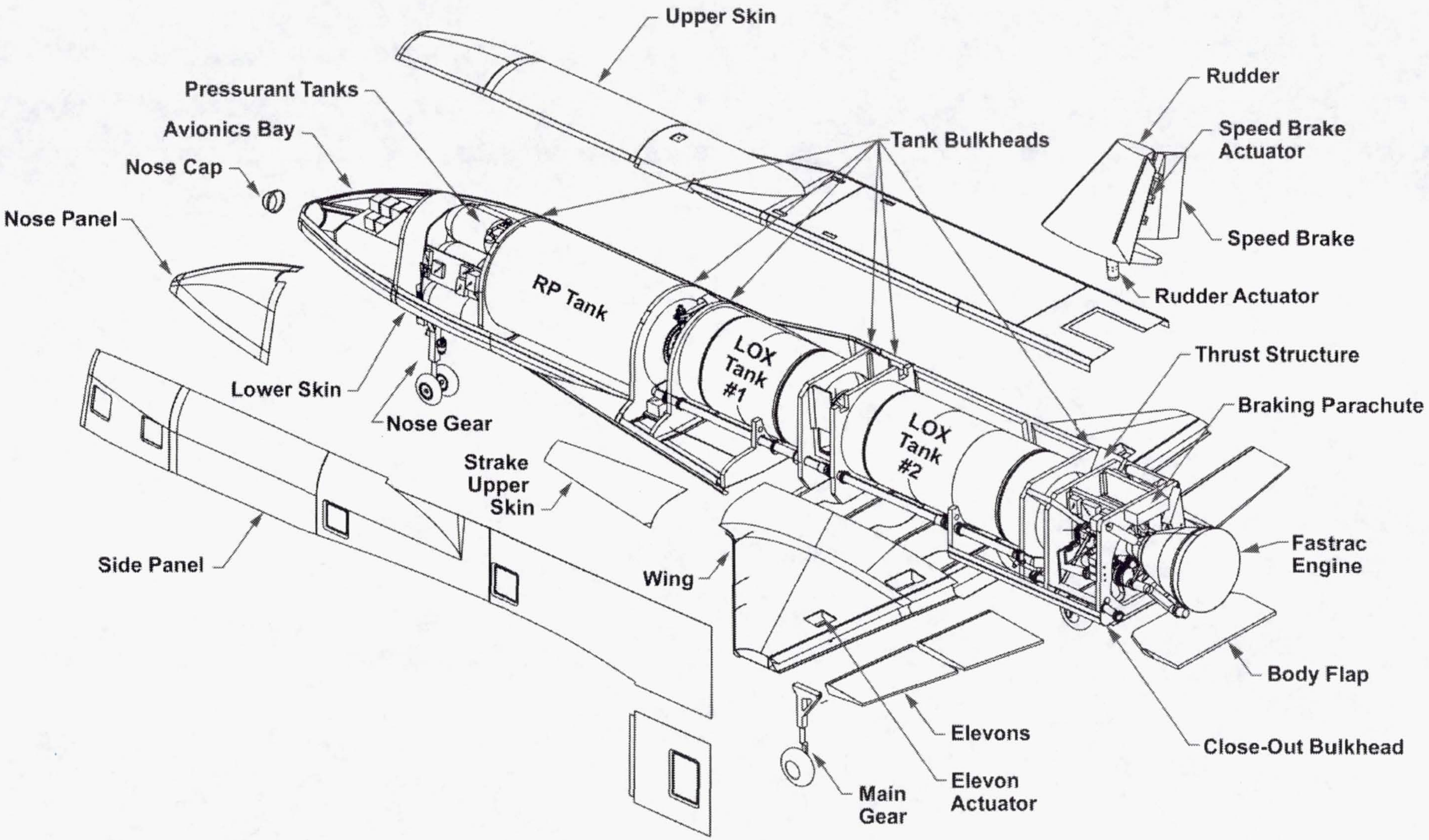


Flight Testing for a Multistage Reusable System

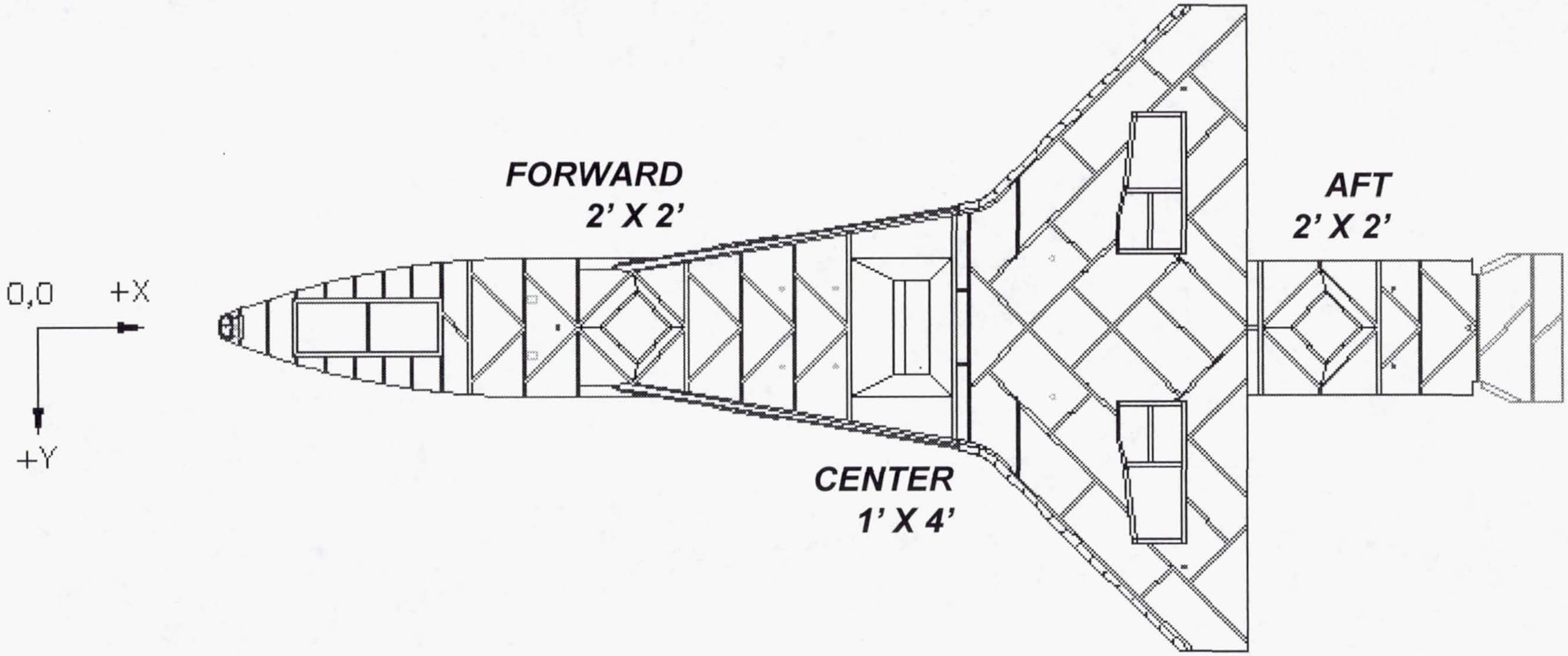


The X-34 Flight Regime Duplicates the Environment and Mission Characteristics Of a Reusable First Stage

X-34 Expanded View

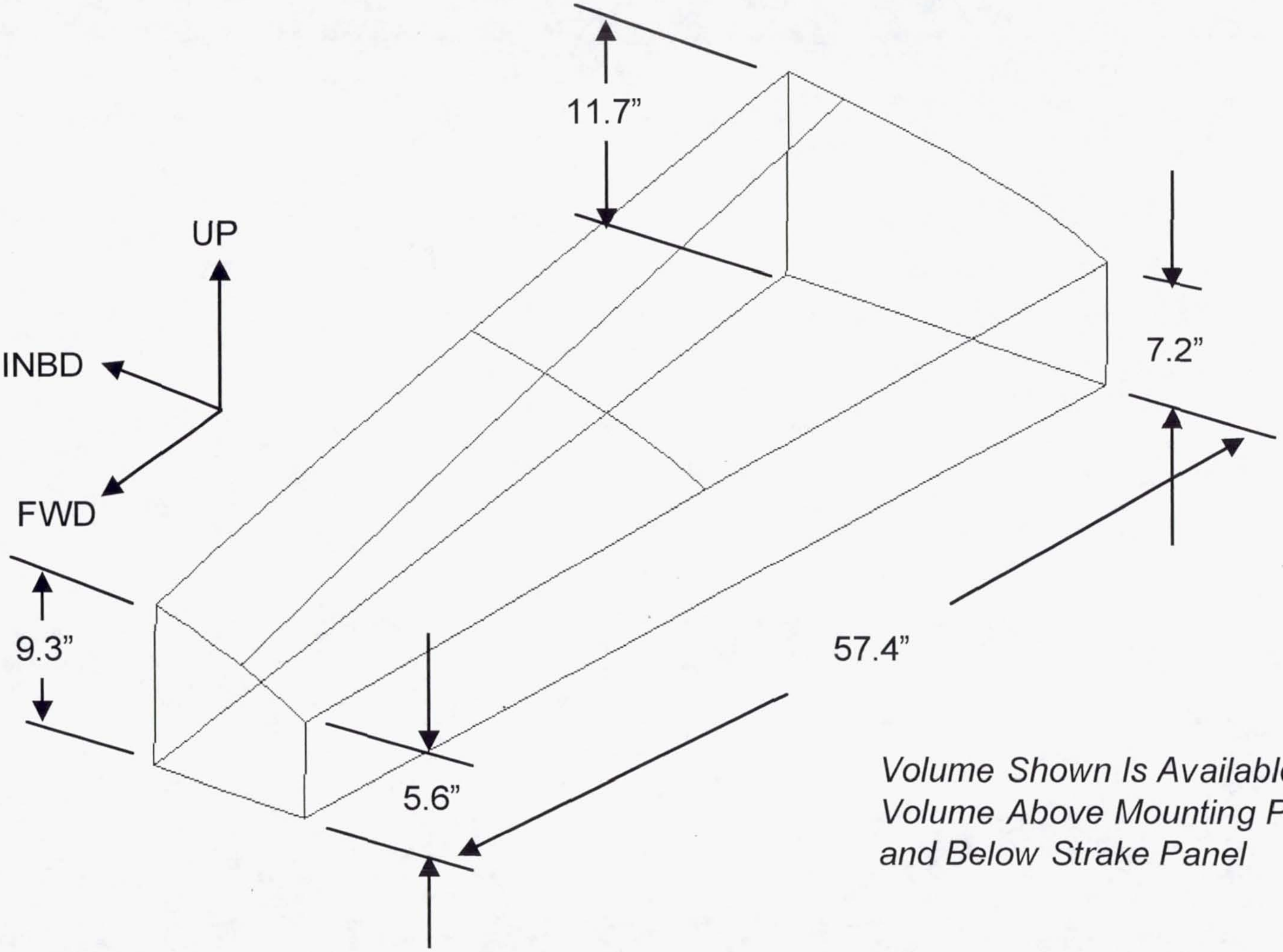


X-34 TPS Attach Points



X-34 Payload/Experimentation Volume

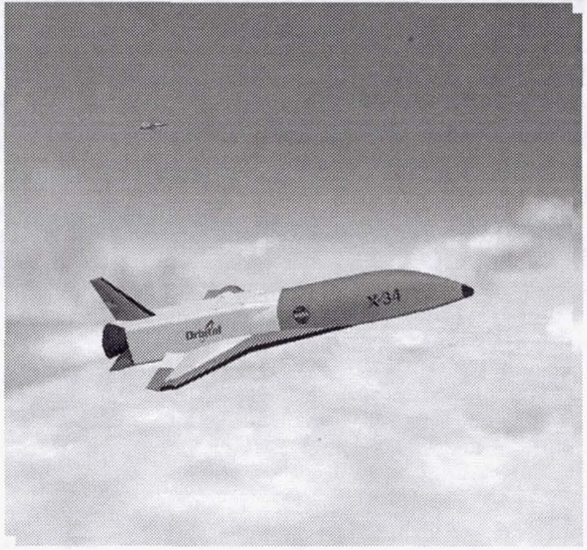
Strake Volume Available



Volume Shown Is Available Volume Above Mounting Panel and Below Strake Panel

Pathfinder Experiments on X-34

- **X-34 Rocket Plane - Atmospheric technology testbed Flight Experiments**



Base-lined X-34 Experiments

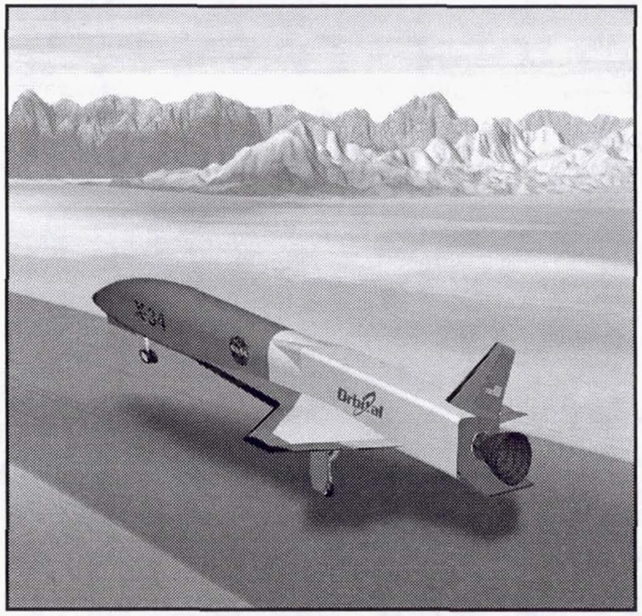
- Active Damage Interrogation Health Monitoring System
- Acoustic Emission Health Monitoring System
- Autonomous Abort Landings
- Integrated Vehicle Health Management (IVHM)
- Unlined Composite LOX Tank

Reviewing Proposals on:

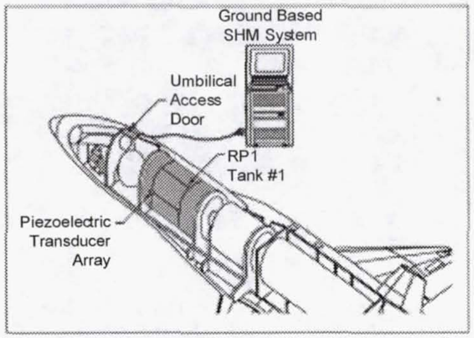
- Base Drag (DFRC)
- Range Safety (Goddard, KSC)

Efforts currently on hold:

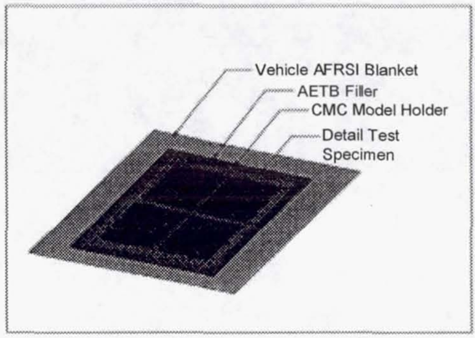
- Gamma-Titanium Aluminum-Based TPS
- Advanced C/SIC TPS
- Mechanically Attached Flexible TPS
- Encapsulated Waterproof 2500°F CMC TPS
- Flight Test Detailed Specimens In Certified Holder



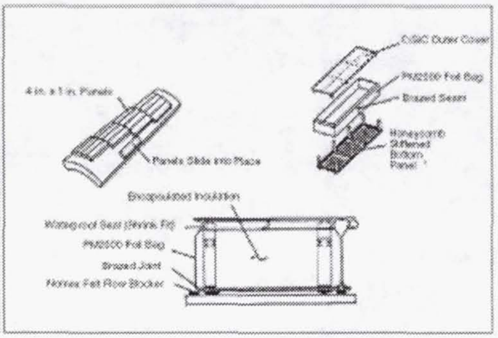
Original Baseline Experiments



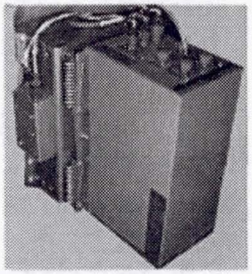
Integrated Structural Health Monitoring System for the X-34 RP1 Tank (Boeing, St. Louis).



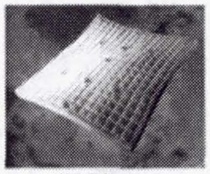
Detail Test Specimen Model Holder (Boeing, Huntington Beach).



CMC Encapsulated TPS Assembly (Boeing, Huntington Beach).

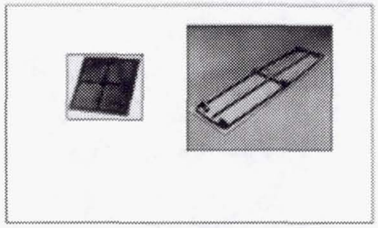


Acoustic Emission Health Monitoring System (Boeing, Seattle).

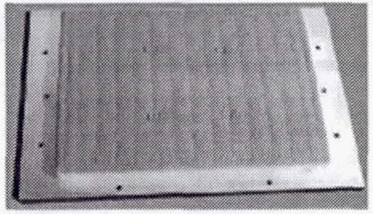


IFI Blanket

TiAl Based TPS (Alenia, Italy)



Advanced C/SiC Based TPS (Daimler Benz, Germany).



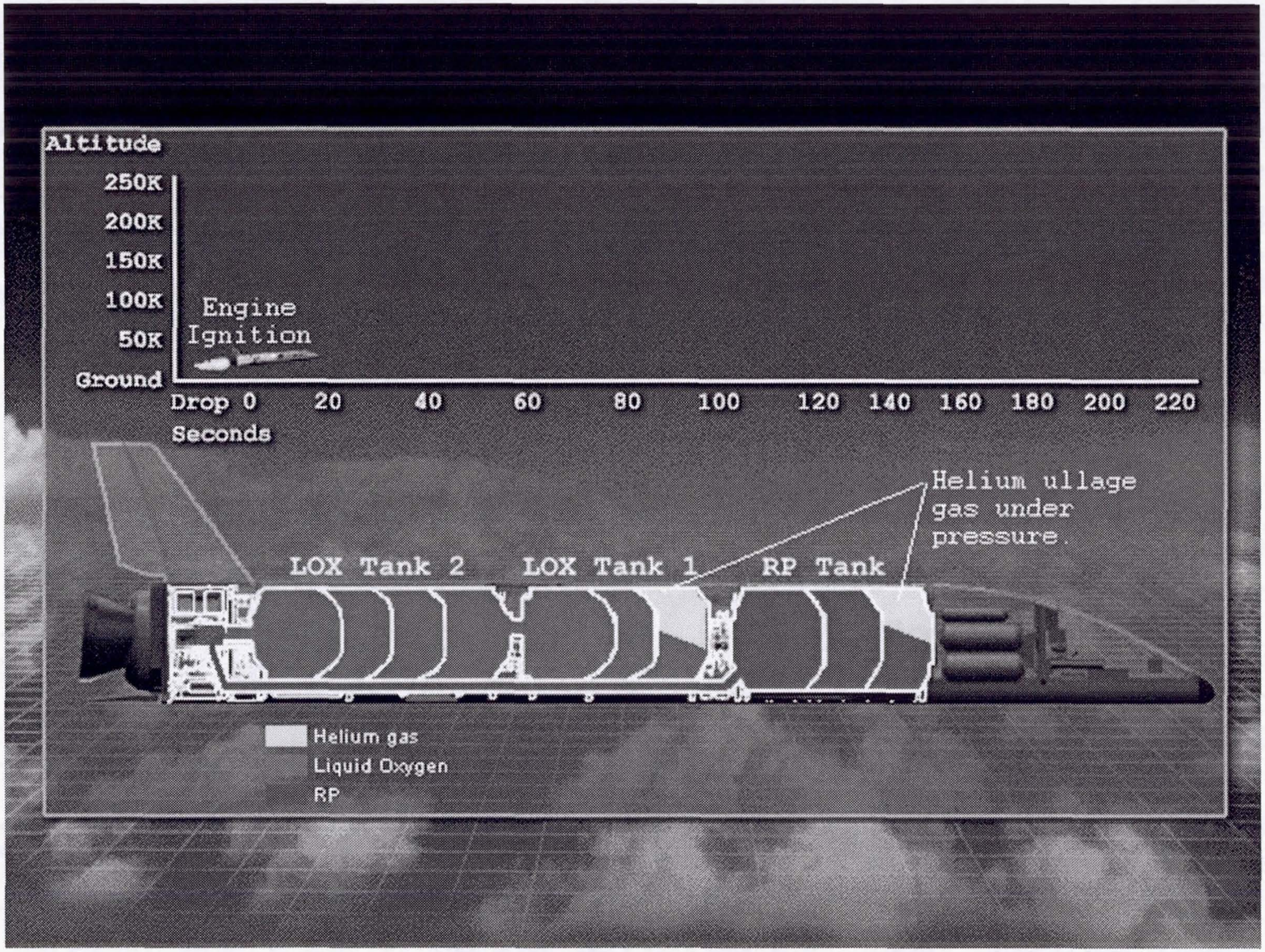
Mechanically Attached Thermal Protection System (Boeing, Seattle).

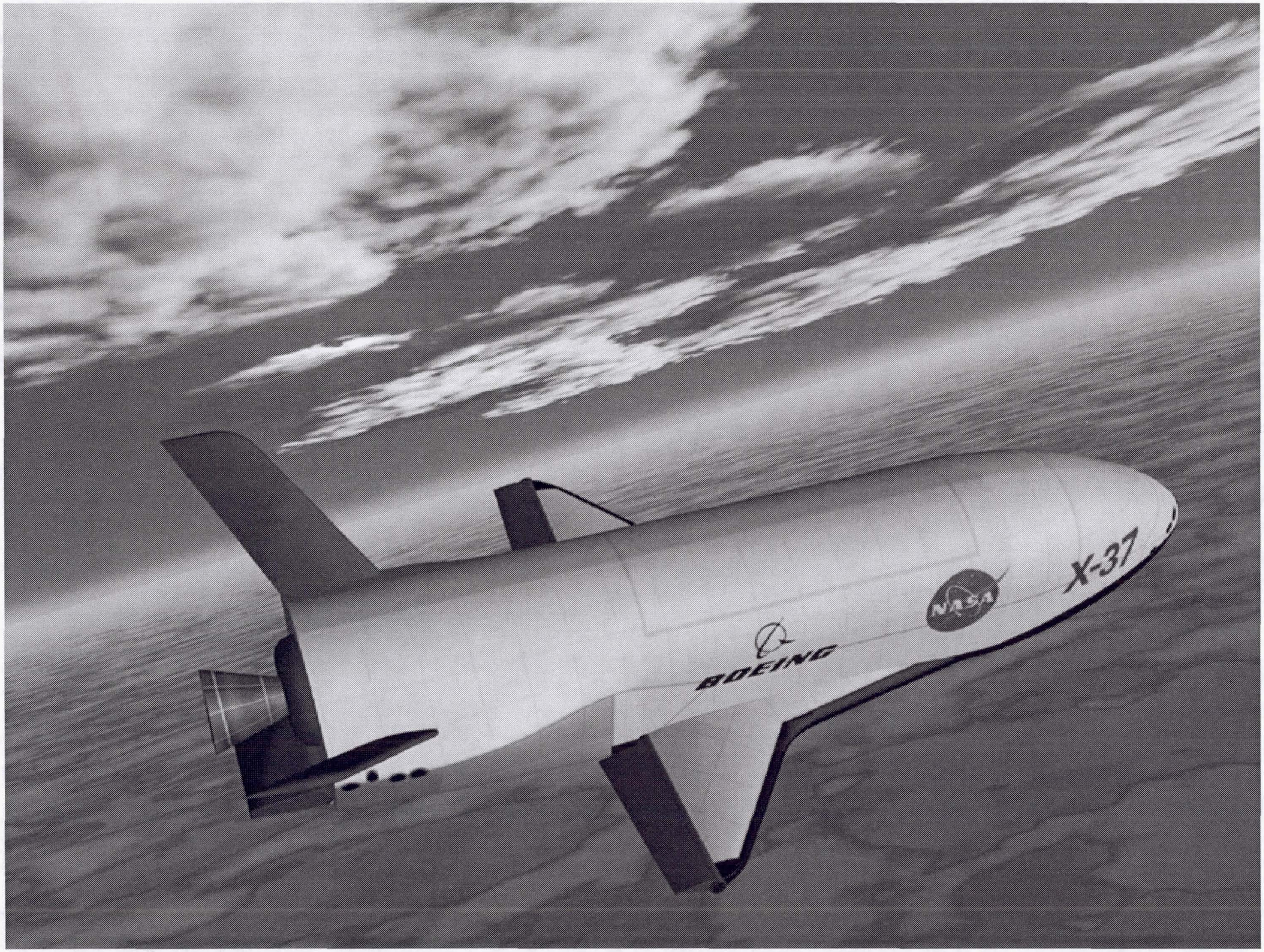
X-34 Flight Experiments

- **Autonomous Abort Landings**
  - Technology-- Development and integration of onboard Real-Time mission planning and robust guidance and control for low mach flight. Will reduce number of ground personnel for flight planning and reduce risk of vehicle loss in aborts.
  - Description -- Software package. After demo it will be permanent part of operational software. To be flown on X-34 in latter stages of the currently scheduled test flight series.
  - Team Members
    - Industry: Draper Lab
    - NASA: MSFC (Lead)
- **Integrated Vehicle Health Management (IVHM)**
  - Technology-- Experiment will integrate components that have been separately developed to build an integrated VHM capability. Will lead to reduced turnaround time and ops cost of RLV's.
  - Description -- Components include Propulsion system diagnostic/prognostic system, RLV Engine monitoring system, Condition-based monitoring, and data fusion. To be flown on X-34 Vehicle.
  - Team Members
    - Industry: Orbital Sciences Corporation
    - NASA: ARC (Lead), KSC, GRC, & MSFC

X-34 Flight Experiments (cont'd.)

- **Composite LOX Tank**
  - Technology-- Reusable composite Liquid Oxygen tank demonstrated in relevant environments.
  - Description -- A composite Liquid Oxygen tank will be developed and integrated into the X-34 technology demonstrator vehicle. The tank will be flown in relevant environments and reused a number of times.
  - Team Members
    - Industry: Lockheed-Martin (Lead), Orbital Sciences Corporation
    - NASA: MSFC, JSC White Sands Test Facility

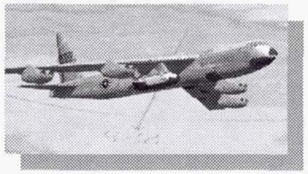

Altitude
250K
200K
150K
100K
50K
Ground
Engine Ignition
Drop 0
20
40
60
80
100
120
140
160
180
200
220
Seconds
Helium ullage gas under pressure.
LOX Tank 2
LOX Tank 1
RP Tank
Helium gas
Liquid Oxygen
RP

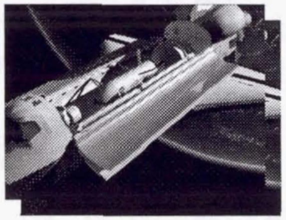

X-37
NASA
BOEING

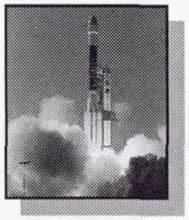
X-37 Project Overview

- **Project Objective**
  - Demonstrate technologies required to reduce the cost of access to and operations in space
- **Key Features**
  - Designed to close current X-Vehicle gap
  - Addresses both Earth-to-Orbit (TA-1) and Orbit-to-Orbit (TA-2) technologies in single testbed vehicle
  - Modularized for rapid insertion of broad range of technologies and experiments
  - Flight test program follows progressive envelope expansion -- launch options include:
    - B-52, Shuttle, ELV

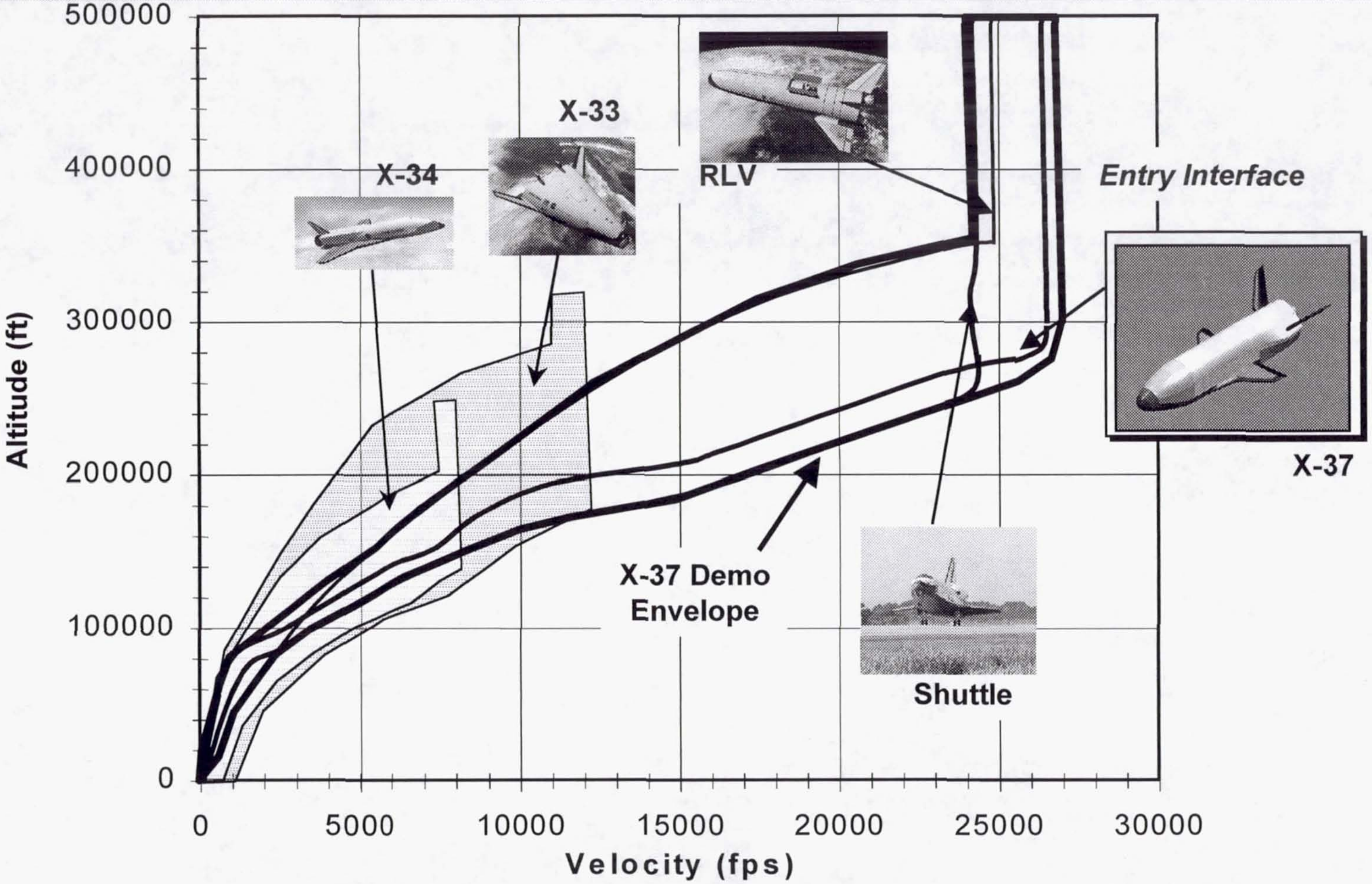
Fuselage Length (ft)	**25.7**
Wing Span (ft)	**14.4**
Baseline Payload (lb)	**500**
Entry Weight (lb)	**5,800**
GLOW (lb)	**13,090**







X-37 Extends the Testbed Envelope to Orbital Capability

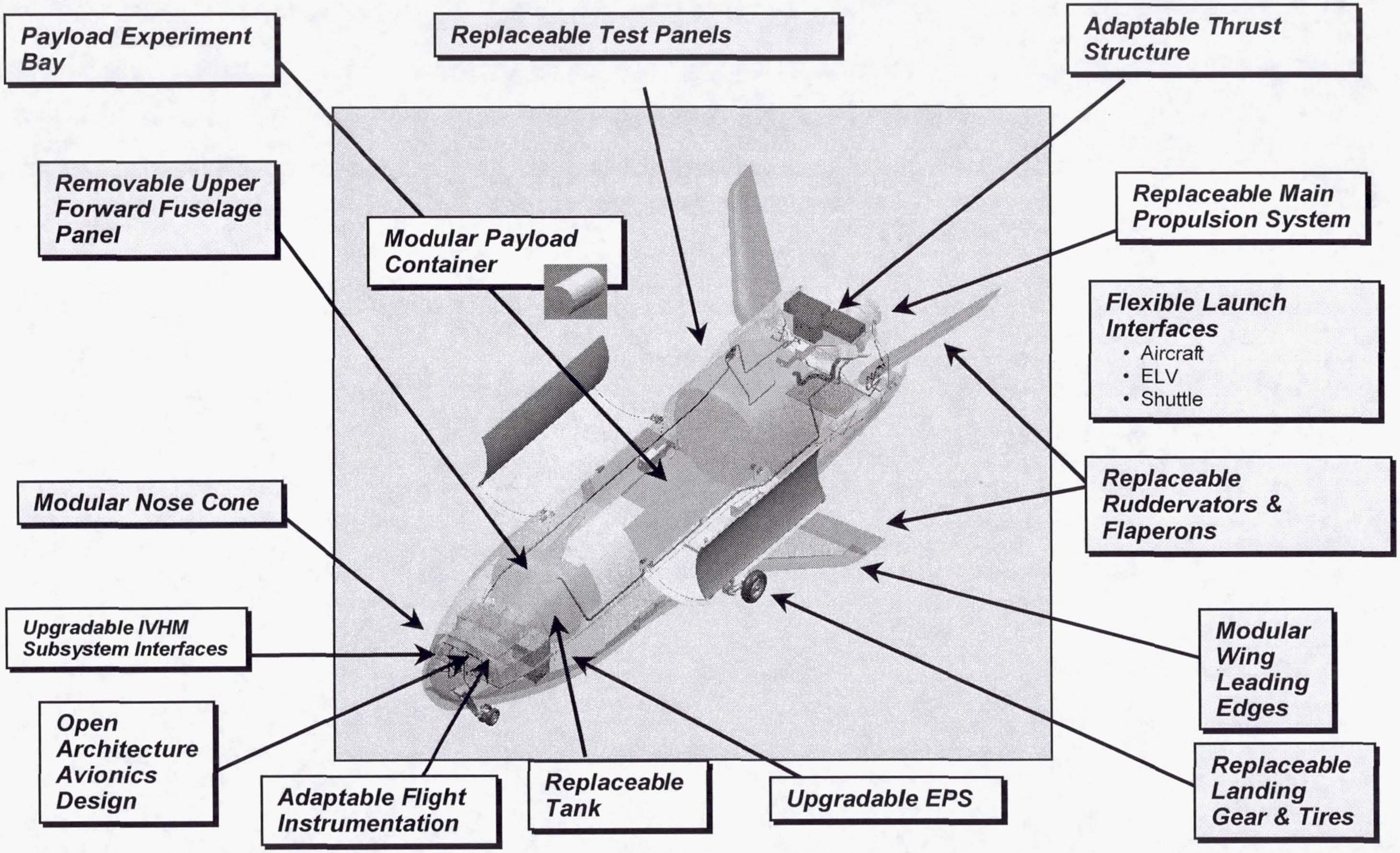


- **X-37 Provides Orbital and Re-entry Test Capability**
  - Reentry trajectory can simulate TSTO 2nd stage environment
  - Autonomous operations (maneuver and rendezvous)
  - Long-term on-orbit demonstrations (2-21 days)
  - Advanced TPS for reusable space vehicles
  - Designs/manufacturing techniques traceable to larger reusable systems

Mission Capability

- **Inclination: 28.5 to 57 degrees (per sys spec & MCR X37-99-0011)**
  - Solar Beta Angle = 0 to 80.5 degrees (derived from above & R460)
- **Orbit Altitude**
  - 100 to 470 nm (R460)
- **Duration**
  - Nominal 21 days + 5 days contingency (R459)
  - In shuttle cargo bay 2 days nominal + 5 days contingency, 10 days max (R461)
- **Pointing Accuracy**
  - 3 Axis stabilized
  - PRCS On Orbit Attitude Accuracy : ± 3.0 degrees (3 sigma) and ± 0.5 deg/sec (3 sigma), respectively, each axis. (GN&C B-spec)
  - VRCS On Orbit Attitude Accuracy ± 0.5 degrees (3 sigma) and ± 0.05 deg/sec (3 sigma), respectively, each axis. (GN&C B-spec)

X-37 Modularity Readily Supports Rapid Technology Insertion and Experiments



Payload Experiment Bay

Replaceable Test Panels

Adaptable Thrust Structure

Removable Upper Forward Fuselage Panel

Modular Payload Container

Replaceable Main Propulsion System

Flexible Launch Interfaces
- Aircraft
- ELV
- Shuttle

Modular Nose Cone

Replaceable Ruddervators & Flaperons

Upgradable IVHM Subsystem Interfaces

Modular Wing Leading Edges

Open Architecture Avionics Design

Adaptable Flight Instrumentation

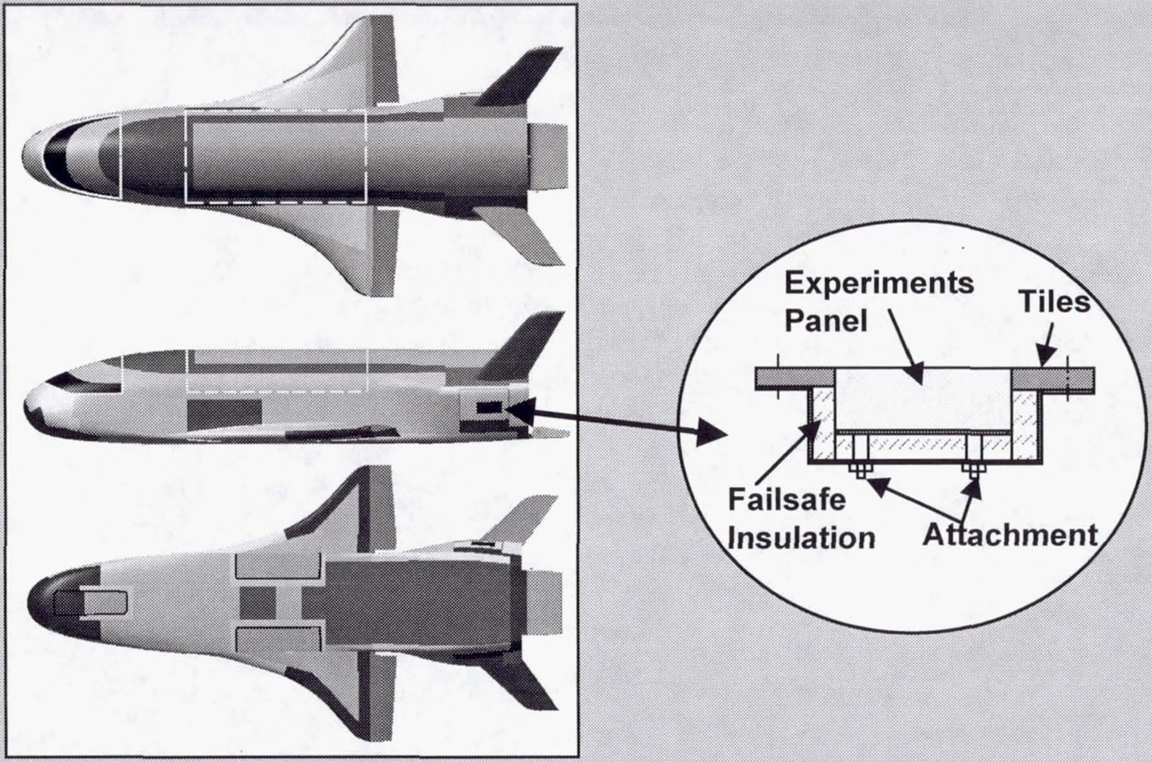
Replaceable Tank

Upgradable EPS

Replaceable Landing Gear & Tires

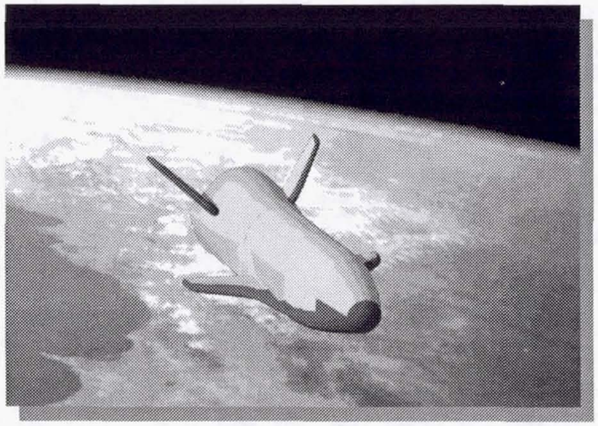
Failsafe TPS Test Panel

Objective:
The objective is to provide a fail-safe TPS screening test panel to test various potential TPS concepts (face sheets/stack-ups, structures/TPS and hot structures), in on-orbit and reentry/aeromaneuvering environments.



X-37 Overview

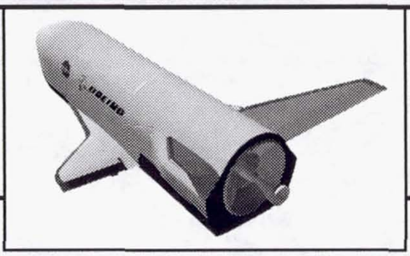
- X-37 Payload Integration Schedules
- X-37 Payload Safety
- X-37 Payload Environments
- X-37 Payload Interfaces & Services

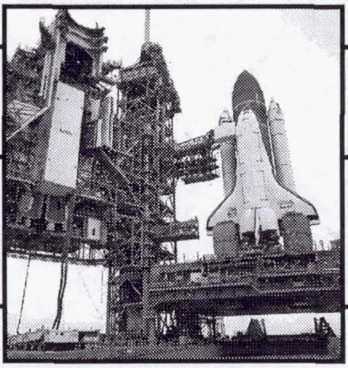


X-37 Payloads Need to Support X-37/Shuttle Orbiter Integration Milestones

X-37 Shuttle Cargo Element to Shuttle

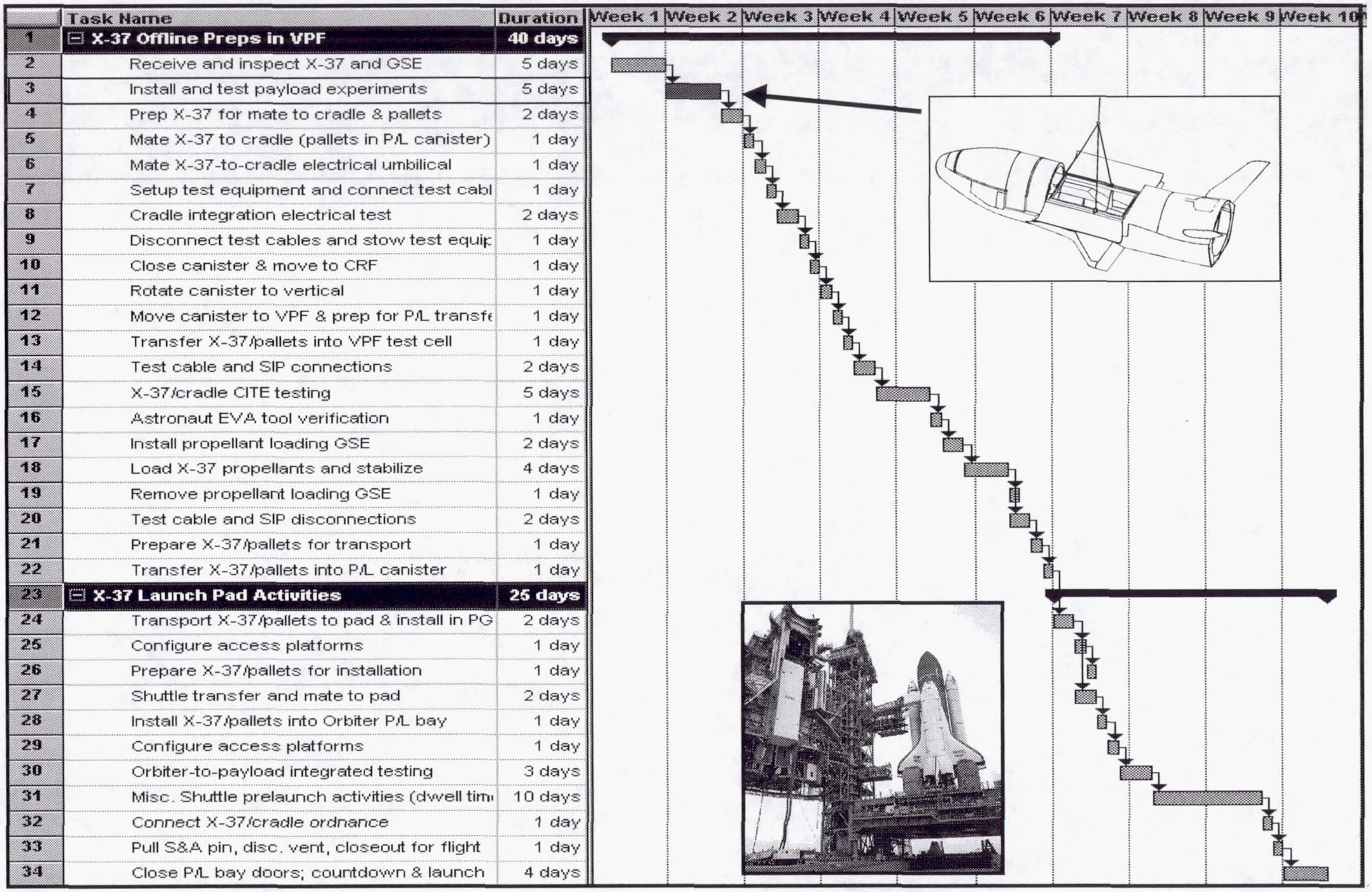
(months prior to Shuttle Launch)





	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	Launch 0
Shuttle Payload/Ground Safety Review Panels (PSRP/GSRP)	△ Phase 0/I								△ Phase II										△ Phase III				
X-37-to-Shuttle ICD Baselined (reflects unique interfaces with Shuttle Orbiter)										△													
Begin Shuttle Integration (FDRD & FRD baselined)												△											
Cargo Compatibility Review (CCR)													△										
Cargo Integration Review (CIR)															△								
Final Reconfiguration Engineering Drawings (FRED)																	△						
Launch Commit (FRR/CoFR)																					△		

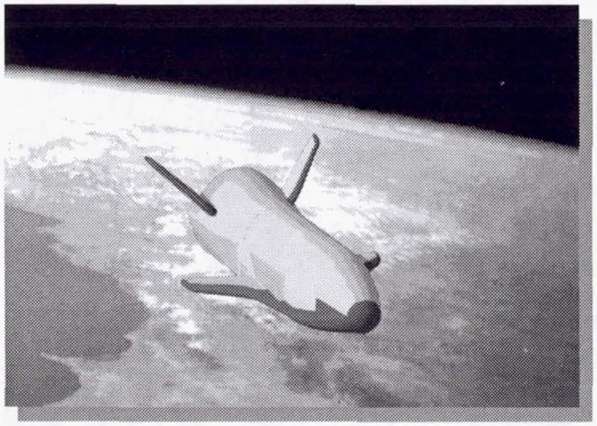
X-37 Payload Installation Occurs 9 Weeks Prior to Launch



	Task Name	Duration
1	**⊟ X-37 Offline Preps in VPF**	**40 days**
2	Receive and inspect X-37 and GSE	5 days
3	Install and test payload experiments	5 days
4	Prep X-37 for mate to cradle & pallets	2 days
5	Mate X-37 to cradle (pallets in P/L canister)	1 day
6	Mate X-37-to-cradle electrical umbilical	1 day
7	Setup test equipment and connect test cabl	1 day
8	Cradle integration electrical test	2 days
9	Disconnect test cables and stow test equi	1 day
10	Close canister & move to CRF	1 day
11	Rotate canister to vertical	1 day
12	Move canister to VPF & prep for P/L transf	1 day
13	Transfer X-37/pallets into VPF test cell	1 day
14	Test cable and SIP connections	2 days
15	X-37/cradle CITE testing	5 days
16	Astronaut EVA tool verification	1 day
17	Install propellant loading GSE	2 days
18	Load X-37 propellants and stabilize	4 days
19	Remove propellant loading GSE	1 day
20	Test cable and SIP disconnections	2 days
21	Prepare X-37/pallets for transport	1 day
22	Transfer X-37/pallets into P/L canister	1 day
23	**⊟ X-37 Launch Pad Activities**	**25 days**
24	Transport X-37/pallets to pad & install in PG	2 days
25	Configure access platforms	1 day
26	Prepare X-37/pallets for installation	1 day
27	Shuttle transfer and mate to pad	2 days
28	Install X-37/pallets into Orbiter P/L bay	1 day
29	Configure access platforms	1 day
30	Orbiter-to-payload integrated testing	3 days
31	Misc. Shuttle prelaunch activities (dwell tim	10 days
32	Connect X-37/cradle ordnance	1 day
33	Pull S&A pin, disc. vent, closeout for flight	1 day
34	Close P/L bay doors; countdown & launch	4 days

X-37 Overview

- X-37 Payload Integration Schedules
- X-37 Payload Safety
- X-37 Payload Environments
- X-37 Payload Interfaces & Services



X-37 Payload Safety Requirements

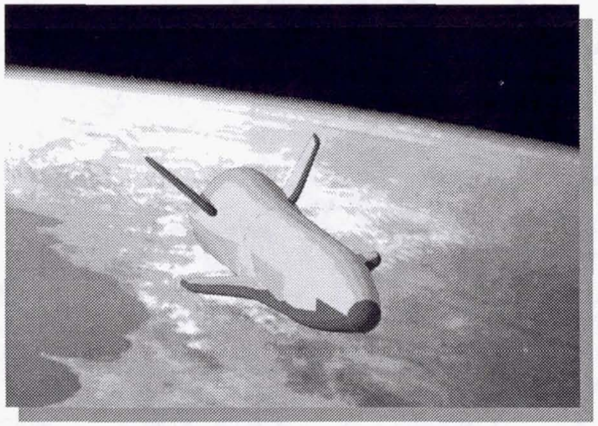
- **X-37 Payloads Must Satisfy the Following Requirements:**
  - SP877-0001, "Safety Policy for Payloads Using the X-37 Flight Demonstration Vehicle for X-37 Program Space Shuttle Flights."
  - SP877-TBD, "Ground Safety and GSE Safety Policy and Requirements for Payloads Using the X-37 Flight Demonstration Vehicle for X-37 Program Space Shuttle Flights."
- **Two Basic Safety Requirements of these Documents:**
  - Catastrophic hazards shall be controlled such that no combination of two failures or operator errors can result in the potential for a disabling or fatal personnel injury or loss of the Orbiter, ground facilities or STS equipment.
  - Critical hazards shall be controlled such that no single failure or operator error can result in damage to STS equipment, a nondisabling personnel injury, or the use of unscheduled safing procedures that affect operations of the Orbiter or another payload.

X-37 Payloads Need to Provide Supporting Safety Documentation for Safety Reviews

- **Supporting Safety Documentation from the X-37 Payload Organization Will Be Required to Support X-37 Vehicle Payload Safety Review Panel (PSRP) and Ground Safety Review Panel (GSRP) Safety Data Package (SDP) Development and Reviews.**
  - The X-37 Vehicle Organization Will Require Supporting Safety Documentation 90 Days Prior to the X-37 Vehicle PSRP and GSRP Reviews (Reference Attached X-37 Tentative Vehicle PSRP/GSRP Schedules).
    - The X-37 Vehicle organization will conduct a review with the X-37 Payload Organization of this supporting documentation prior to its incorporation into the X-37 Vehicle PSRP and GSRP SDPs.
- **Supporting Safety Documentation from the X-37 Payload Organization Will Also Be Required to Support Safety Assessment Report (SAR) Development and Appropriate Range Safety Reviews.**

X-37 Overview

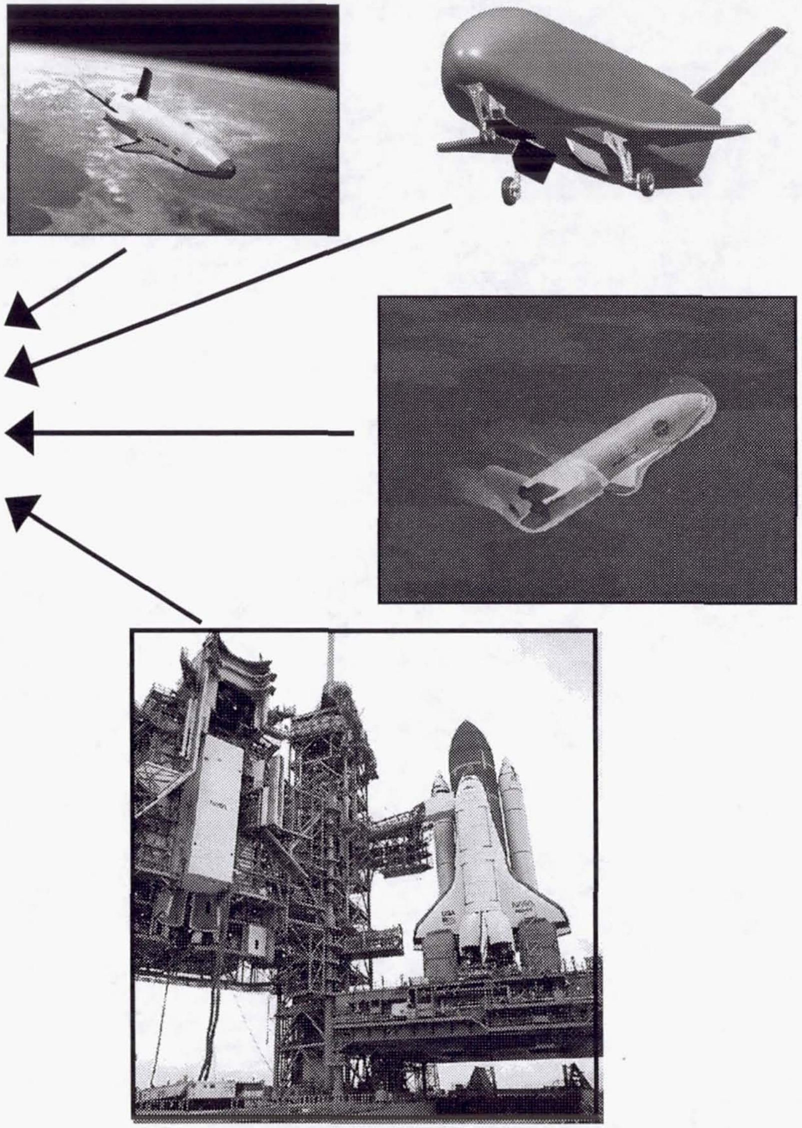
- X-37 Vehicle Summary
- X-37 Payload Integration Schedules
- X-37 Payload Safety
- X-37 Payload Environments
- X-37 Payload Interfaces & Services



Payload Environments are Under Development Based On Launch, On-Orbit and Reentry Phases

Payload Environments

- **Prelaunch Environments**
  - Air conditioning
  - Radiation & electromagnetic environments
  - Electrostatic potential
  - Contamination and cleanliness
- **Launch & Flight Environments**
  - Payload bay internal pressure
  - Thermal environment
    - Launch
    - On-orbit
    - Reentry
  - Flight Dynamic Environment
    - Steady state acceleration
    - Combined Loads
    - Acoustic Environment
    - Sinusoidal Vibration Environment
    - Shock Environment

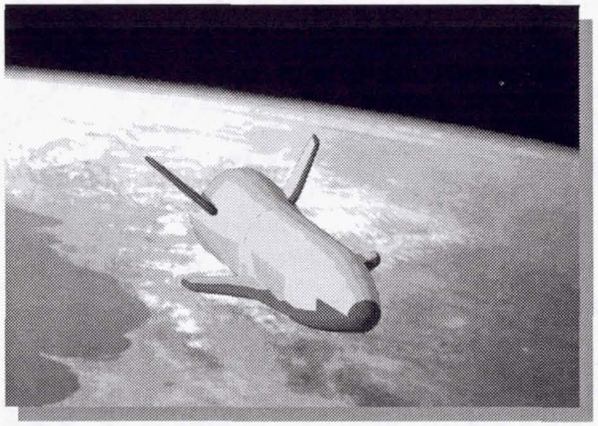


X-37 Payload Environments

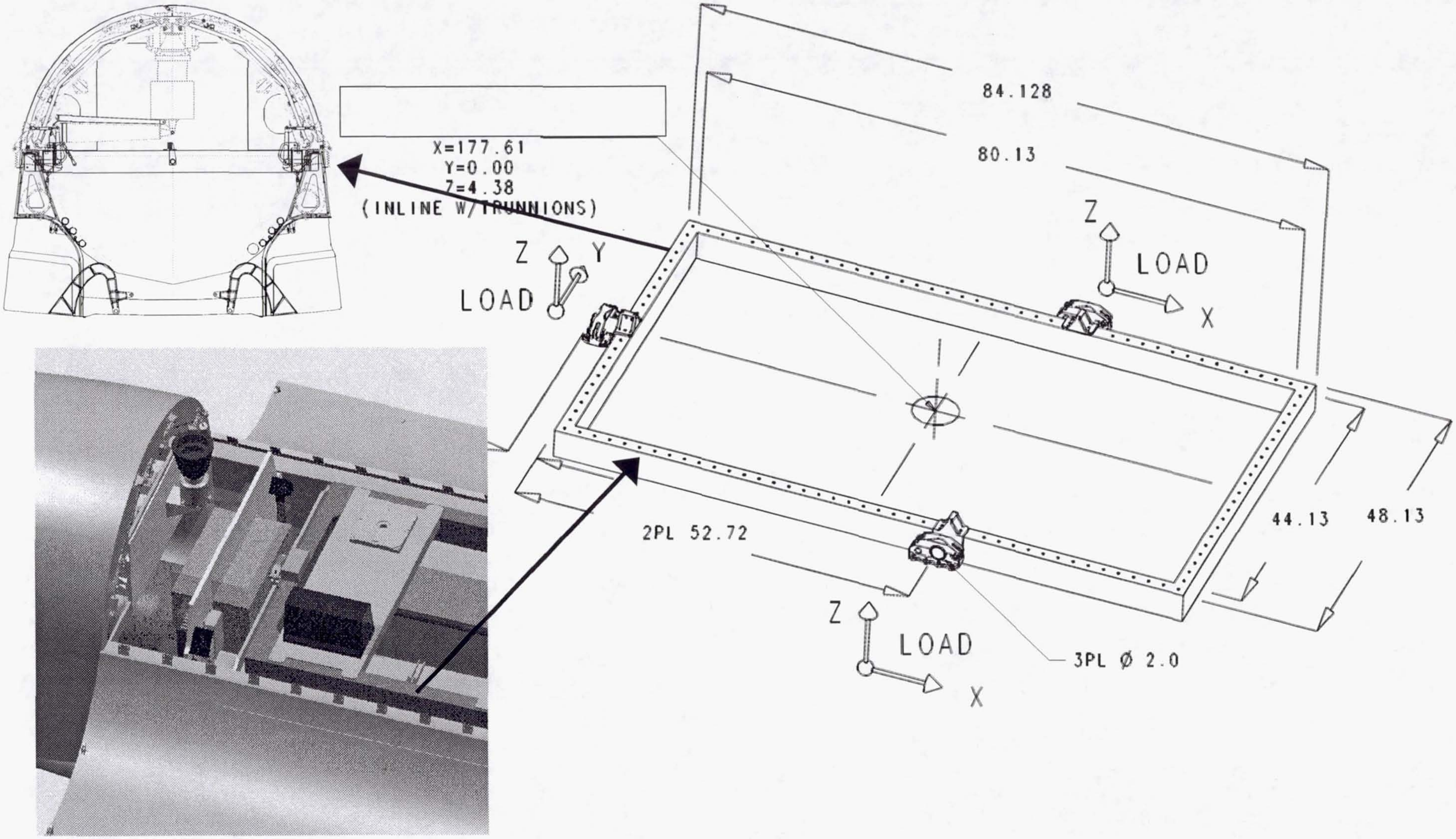
- **Radiation Environments**
  - – Compatible with inclination and altitude range specified in mission capability chart
- **Random Vibration & Acoustic Environments**
  - – Must be compatible with Shuttle ascent, Pyro separation shock loads, and entry environments
  - – Available through Boeing
- **Acceleration**
  - – Must be compatible with Shuttle ascent, on-orbit, and entry environments
  - – Available through Boeing

X-37 Mission 1 and 2 Payload Overview

- **X-37 Payload Integration Schedules**
- **X-37 Payload Safety**
- **X-37 Payload Environments**
- **X-37 Payload Interfaces & Services**



X-37 Payload Container Frame and Interface Definition



X-37 Payload Power and Avionics

- **On-orbit Power:**
  - Voltage: 28 VDC
  - Power: 100 Watts orbit average supplied from X-37
    - Payload is responsible for power requirements beyond 100 Watts average
- **Reentry Power:**
  - Voltage: 28 VDC
  - Power: payload is responsible for power requirements
- **Number of Channels: TBD**
- **Telemetry**
  - High data rate Ku band antenna: 5 Mbps (peak)
- **Data Storage**
  - Vehicle Management Computer (VMC)
- **Possible X-37 Payload Communication Interfaces Include:**
  - 1553
  - RS422
  - 1773

Integrated X-37/X-37 Payload Testing

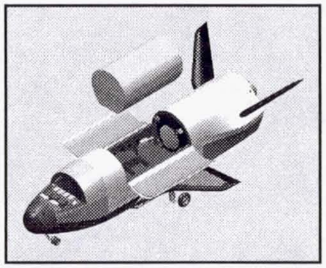
- Payloads integrated with the X-37 shall meet the requirements of NASA-STD-7002 or MIL-STD-1540C Tailored.
- Payload shall supply the necessary equipment for integrated testing and servicing.

X-40A Flight Test Vehicle Summer 00

43 Technologies and Experiments Have Been Identified for Follow-On Demonstration

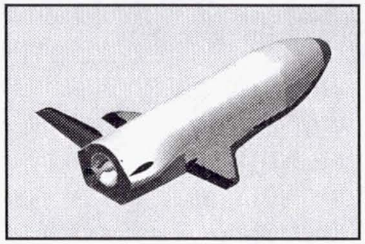
Reusable Launch/Space Vehicle Technology Testbed

- Propulsion
  - Alternate main engines and propellants
  - Improved lines/valves
  - Extended on-orbit life and operations
- Airframe
  - Interchangeable tankage
  - Alternate wings and control surfaces for concepts and materials
  - Advanced, light weight landing gear (extended on-orbit capability)
- VMS/Avionics
  - Flight diagnostics and prognostics adaptation
  - Modular insertion of advanced avionics upgrades
  - Sub-surface Ka-Band phased array antenna
  - Air data systems
- IVHM
  - Autonomous operations
  - Extended to all subsystems
- TPS
  - Lighter weight, more robust and capable materials
  - Improved installation techniques and test procedures
- EPS
  - Fuel cells
  - Turbo-alternators and supercapacitors
  - Flywheels
- Light Weight, Flexible Structures
  - C/C payload experiment bay doors integrated with radiators
  - Deployable, retractable solar arrays
  - Deployable, retractable antennas



Reusable Launch/Space Vehicle Operations Testbed

- TSTO separation systems
- Improved operations, maintenance and repair concepts/procedures to reduce turn time
- Automated rendezvous, capture and proximity operations
- Automated aeroassist and aerobraking using closed-loop data feedback
- Satellite servicing and repair
- Satellite refueling
- Debris cataloging and removal
- On-orbit payload changeout



Upper Atmosphere Testbed

- Global sampling and in-situ validation to support model development and forecasting

Expendable Spacecraft Technology Testbed

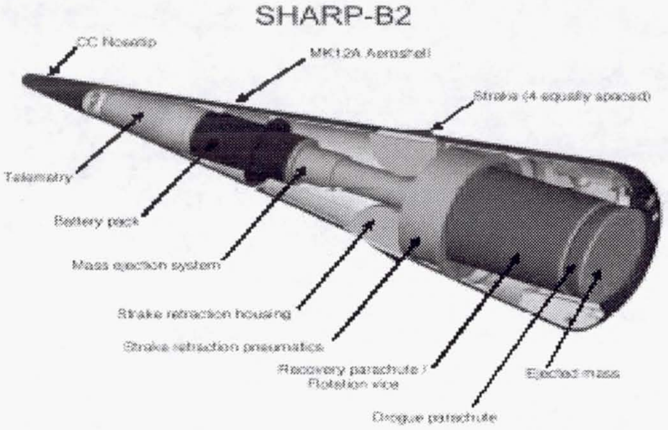
- Bus subsystems and components
- Payload/instrument elements (e.g., imagers)

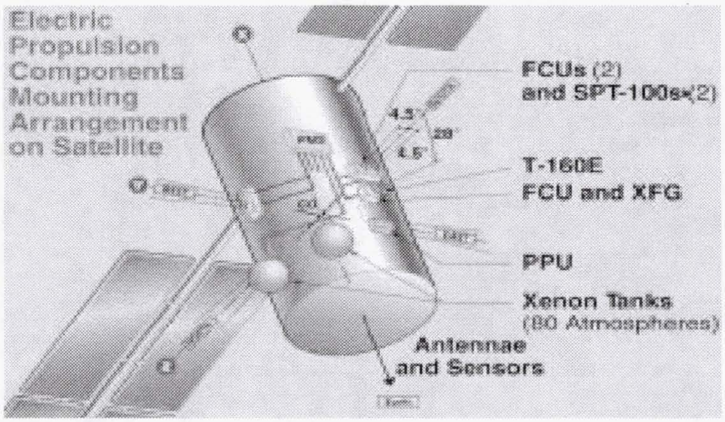
Space Exploration Technology Testbed

- Lunar exploration(including surface sample return)
- Technologies for interplanetary orbiters, landers, rovers, penetrators

Other Pathfinder Experiment

- ♦ **Flight Experiments**
  - Other Flight Experiments:
    - REDUCED COST SMALL PAYLOAD TECHNOLOGIES (AERO-ASTRO)
      - Deployed from the Space Shuttle
    - CERAMICS FOR SHARP LEADING EDGES (NASA AMES)
      - Flown on a Minuteman III
    - ProSEDS (NASA MSFC)
      - Flown as a secondary payload on a Delta II upper stage
    - HALL EFFECT THRUSTER (NASA GRC)
      - Flown on a Russian Communications Satellite
    - CRYOGENIC PROPELLANT GAUGE (NASA GRC)
      - Flown on the USAF Solar Orbit Transfer Vehicle Space Experiment





Other Flight Experiments (cont'd.)

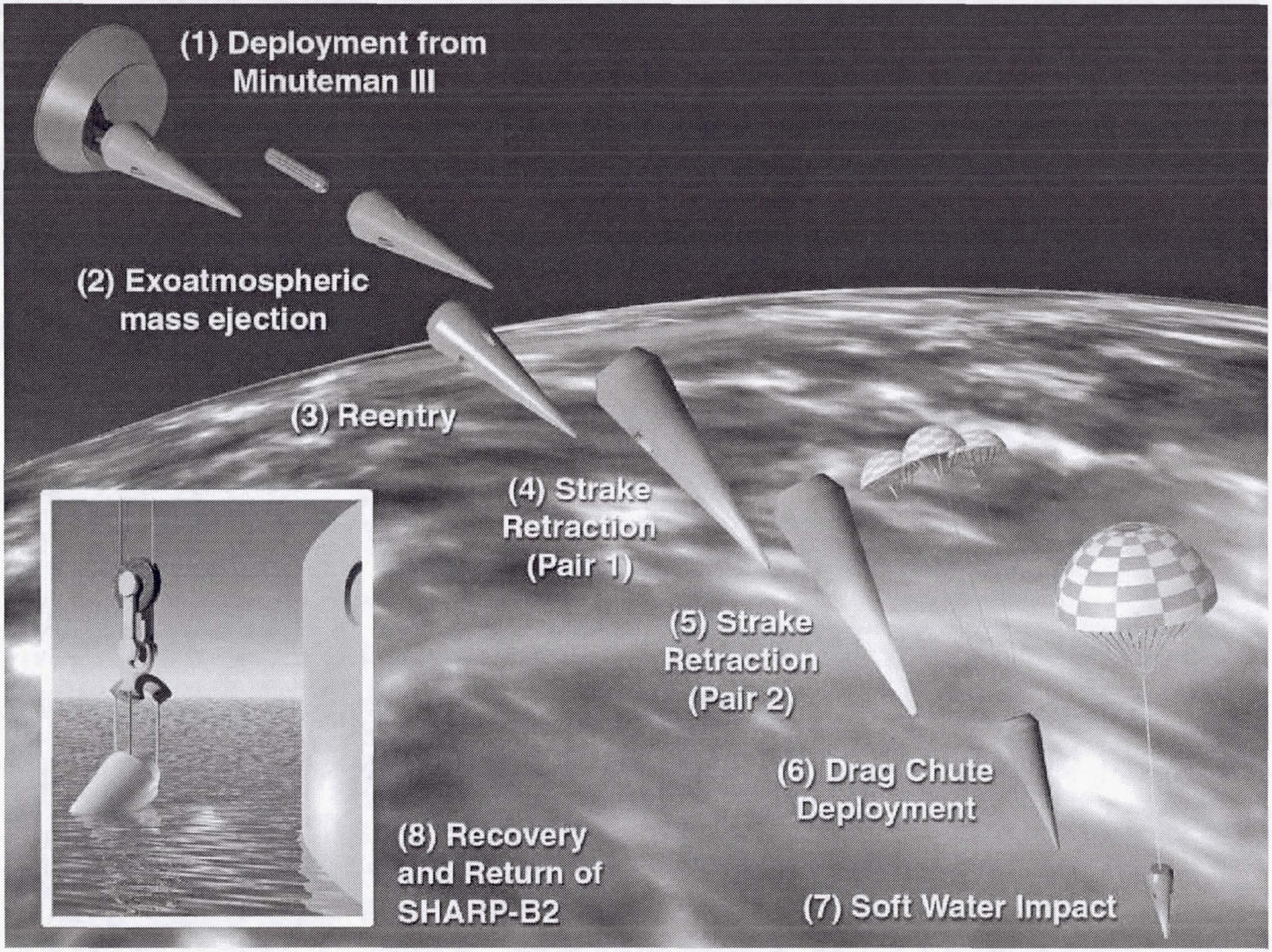
♦ Reduced Cost Small Payload Technologies

- Technology-- Technology -- Will demonstrate a small, generic, cheap, robust spacecraft kernal to manage power, attitude control, command, data handling, and communications. Eliminates need to design and build unique spacecraft components, reducing cost.
- Description -- "Bitsy" is integrated from qualified subsystems (developed under contract to USAF). Will fly as a free-flyer, Hitchhiker Payload.
- Team Members
  - Industry: AeroAstro
  - NASA: MSFC (Lead)

♦ Ceramics for Sharp Leading Edges

- Technology-- Technology -- Sharp, passive, Ultra High Temperature Ceramic (UHTC) leading edge in relevant entry environments.
- Description -- A modified MK123A re-entry vehicle with four sharp leading edges, retractable strakes (0.039" radius) made of UHTC. To be flown on Minuteman III launch vehicle and recovered (water recovery).
- Team Members
  - Industry: Sandia, U.S. Air Force
  - NASA: ARC (Lead)

Slender Hypervelocity Aerothermodynamic Research Probe 2nd Ballistic Flight (SHARP B2)



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SPACE 2000

RANSPORTATION

AY

Drag Reduction

[illegible]

In Space Investment Area Overview	Les Johnson
Hall Propulsion Technology	Robert Jankovsky
Ion Propulsion Technology	John Brophy Mike Patterson
Fission Propulsion: SAFE	Mike Houts
Cryogenic Fluid Management Technologies	David Plachta
Solar Thermal Propulsion Technologies	Steve Tucker
Momentum Transfer Tether Technology	Kirk Sorensen
Electrodynamic Tether Coatings for ProSEDS	Jason Vaughn
AeroAssist Technologies	Richard Powell
Solar Sail Technology	Humphrey Price
Mini Magnetospheric Plasma Propulsion (M2P2)	Dennis Gallagher

"ST Day 2000: Reducing Risk for the Next Generations" - ASTP

In-Space Agenda

SP CE 2000

RANSPORTATION

AY

Risk Reduction

for the Next Generation

Hall Propulsion Technology Development
NASA Glenn Research Center

50 kW Thruster Technology

EXPRESS Ground/Space Correlation

Contact Info:
Robert Jankovsky, NASA Glenn Research Center
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Robert.Jankovsky@grc.nasa.gov

Fred Elliott, NASA Glenn Research Center
216.433.2322
Fred.Elliott@grc.nasa.gov

"ST Day 2000: Reducing Risk for the Next Generations"

- Technology goals and objectives

  It is the goal of this activity to develop 50 kW class Hall thruster technology in support of cost and time critical mission applications such as orbit insertion.

- Background

  NASA MSFC is tasked to develop technologies that enable cost and travel time reduction of interorbital transportation. Therefore, a key challenge is development of moderate specific impulse (2000-3000s), high thrust-to-power electric propulsion. NASA GRC is responsible for development of a Hall propulsion system to meet these needs.

- Current Status

  First-phase, sub-scale Hall engine development completed. 10 kW engine designed, fabricated, and tested. Performance demonstrated >2400 s, >500 mN thrust over 1000 hrs of operation documented.

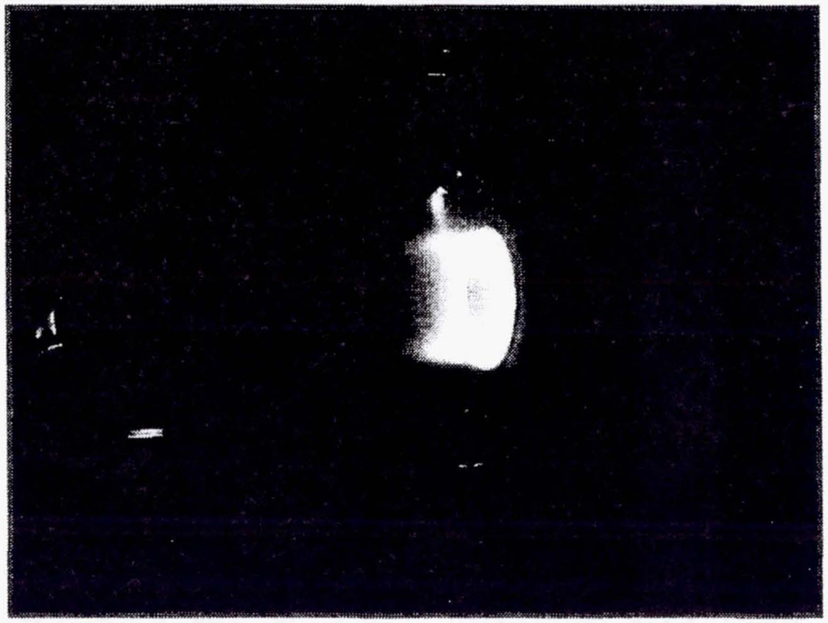
50 kW Thruster Technology

- **Major accomplishments (FY00):**

  The NASA T-220 10 kW Hall Effect Thruster demonstrated over 500 mN thrust at 2450 seconds specific impulse (Isp) and 59% total efficiency while demonstrating good erosion characteristics over 1000 hours of operation. This is the longest operation ever achieved on a high power Hall thruster (>5 kW). This test indicates the availability of 10 kW Hall thruster technology for future NASA, commercial, and military missions and confirms the technical approach for development of even higher power thrusters.

- **Near Term Plans (FY01):**

  Procure a 50 kW engine design and prepare diagnostics and test equipment.

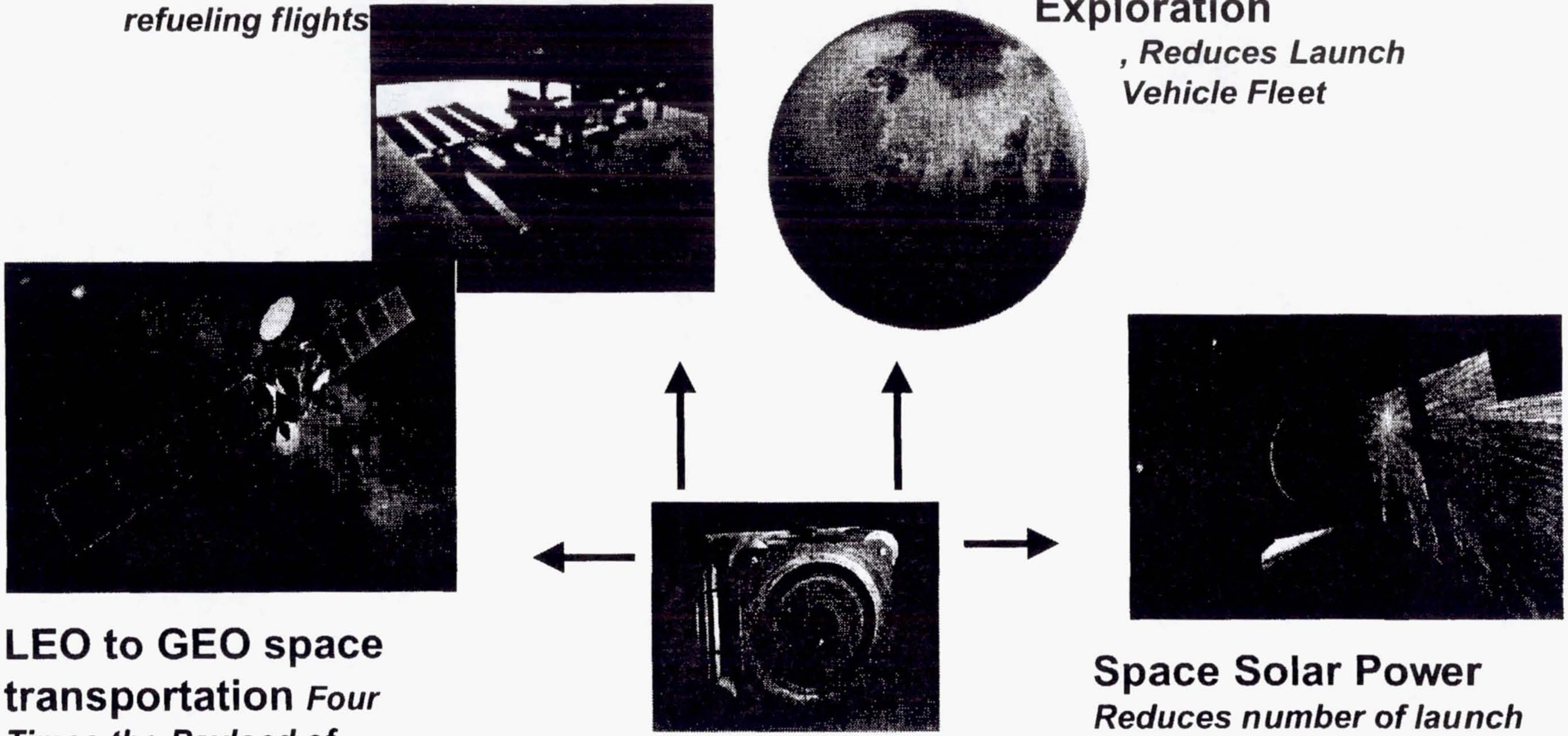


"ST Day 2000: Reducing Risk for the Next Generations" - Hall Propulsion

50 kW Thruster Technology

50 kW Thruster Applications

"ST Day 2000: Reducing Risk for the Next Generations" - Hall Propulsion



ISS Drag Makeup
Significantly reduces required refueling flights

Lunar/Mars Exploration
, Reduces Launch Vehicle Fleet

LEO to GEO space transportation *Four Times the Payload of Chemical Systems In Four Weeks using next generation Power levels*

- **Need Power Levels ~ 50 kW & Isps ~ 2000 sec**

Space Solar Power
Reduces number of launch vehicles required by a factor of 5 ! Deliveries in few weeks to less than four months.

- Technology goals and objectives

  Compare measurements of critical plasma parameters from on-orbit with ground test data. Develop fundamental understanding of the differences enabling extrapolation to other thrusters/geometries for integration assessments.

- Background/Approach
  - Several different types of sensors integrated on two Russian Geo-Comsats (Express-A #2 & EXPRESS-A #3) utilizing 1.5 kW SPT-100 Hall thrusters.
  - Ground tests validating sensors and duplicating space measurements to be taken at NASA GRC
  - Additional GRC ground tests with alternate thrusters/geometries

"ST Day 2000: Reducing Risk for the Next Generations" - Hall Propulsion

EXPRESS Ground/Space Correlation

- **Sensors integrated on to Express-A, #2 and launched**
  - Data being collected
  - Data transfer and correlation with thruster operation being addressed
- **Sensors integrated on to Express-A, #3 and launched**
  - Data being collected
  - Data requirements also being addresses
- **GRC ground testing**
  - Planning stages - test details being discussed
  - S/C representative sensors being procured

Current Status

- **Major accomplishments (FY00):**

Successful launch of sensor packages on EXPRESS-A #2, and EXPRESS-A #3

- **Near Term Plans (FY01):**

Procure a duplicate set of EXPRESS-A #2, and EXPRESS-A #3 sensors. Plan ground test program.

"ST Day 2000: Reducing Risk for the Next Generations" - Hall Propulsion

EXPRESS Ground/Space Correlation

- Sensor Types
  - **Pressure: Measure local density to understand how plume expands Simple measurement, previously conducted**
    - Measurement in back flow region very difficult on ground
    - Maybe important for assessing corona phenomena for payload
  - **Electric Field Strength: Measure how the plasma modifies E-field at S/C surface**
    - Less simple measurement , previously conducted
    - Gives insight into how the spacecraft couples to the ambient space plasma
    - Maybe important for assessing corona phenomena for payload

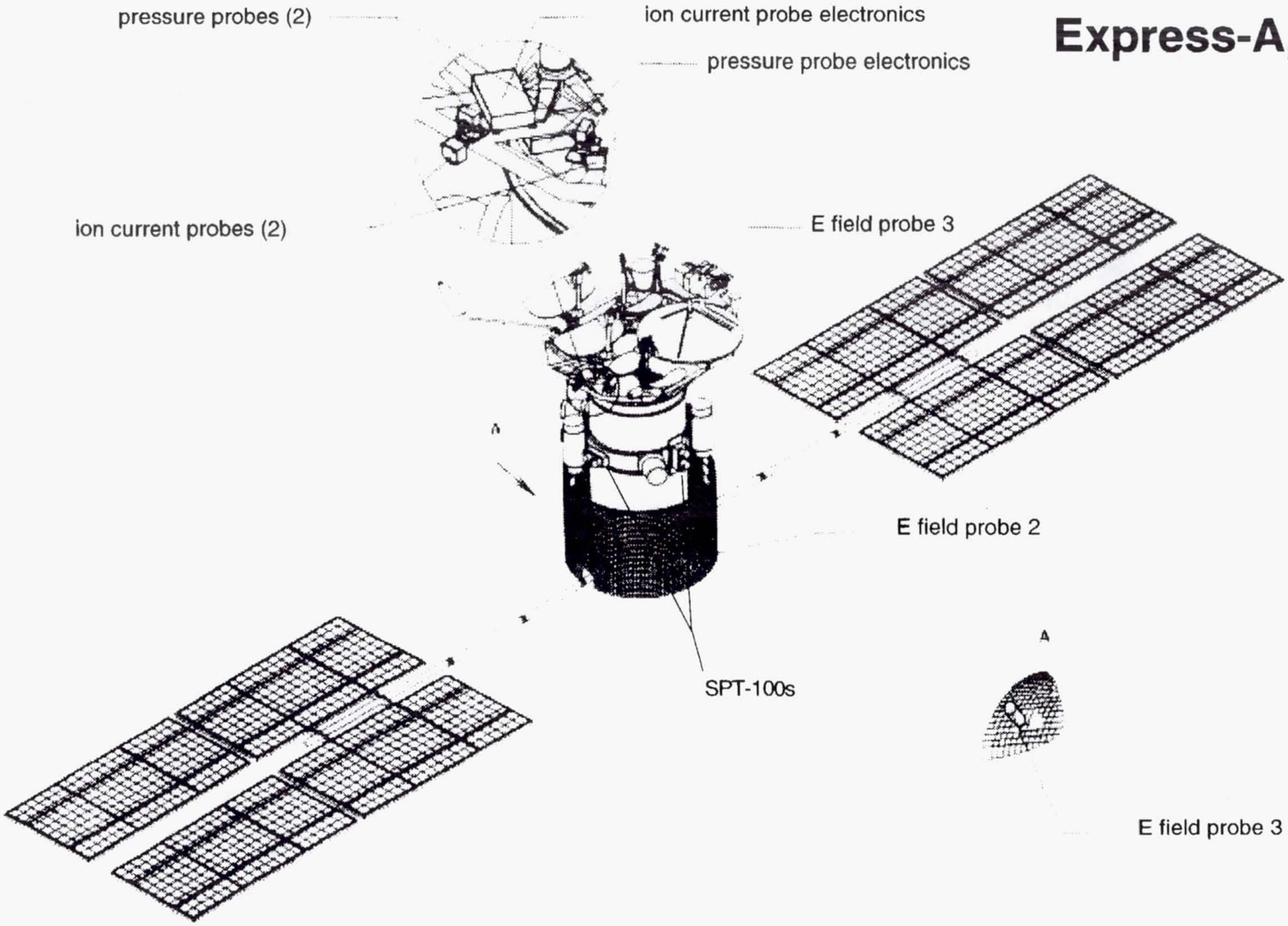
EXPRESS Ground/Space Correlation

- **Sensor Types (continued)**
  - **Ion Current: Measure the flux density of the plume ions**
    - Simple measurement, not previously conducted
    - Easily compared with ground tests data and analytic predictions
    - Flux of ions needed for estimating thermal/momentum transfer to other parts of S/C
  - **Ion Current & Energy: Measure the flux density and energy of the plume ions**
    - Difficult measurement, not previously conducted
    - Provides desired information for determination of integration impacts
    - Flux and energy ions needed for determining thermal/momentum transfer and erosion of S/C

"ST Day 2000: Reducing Risk for the Next Generations" - Hall Propulsion

EXPRESS Ground/Space Correlation

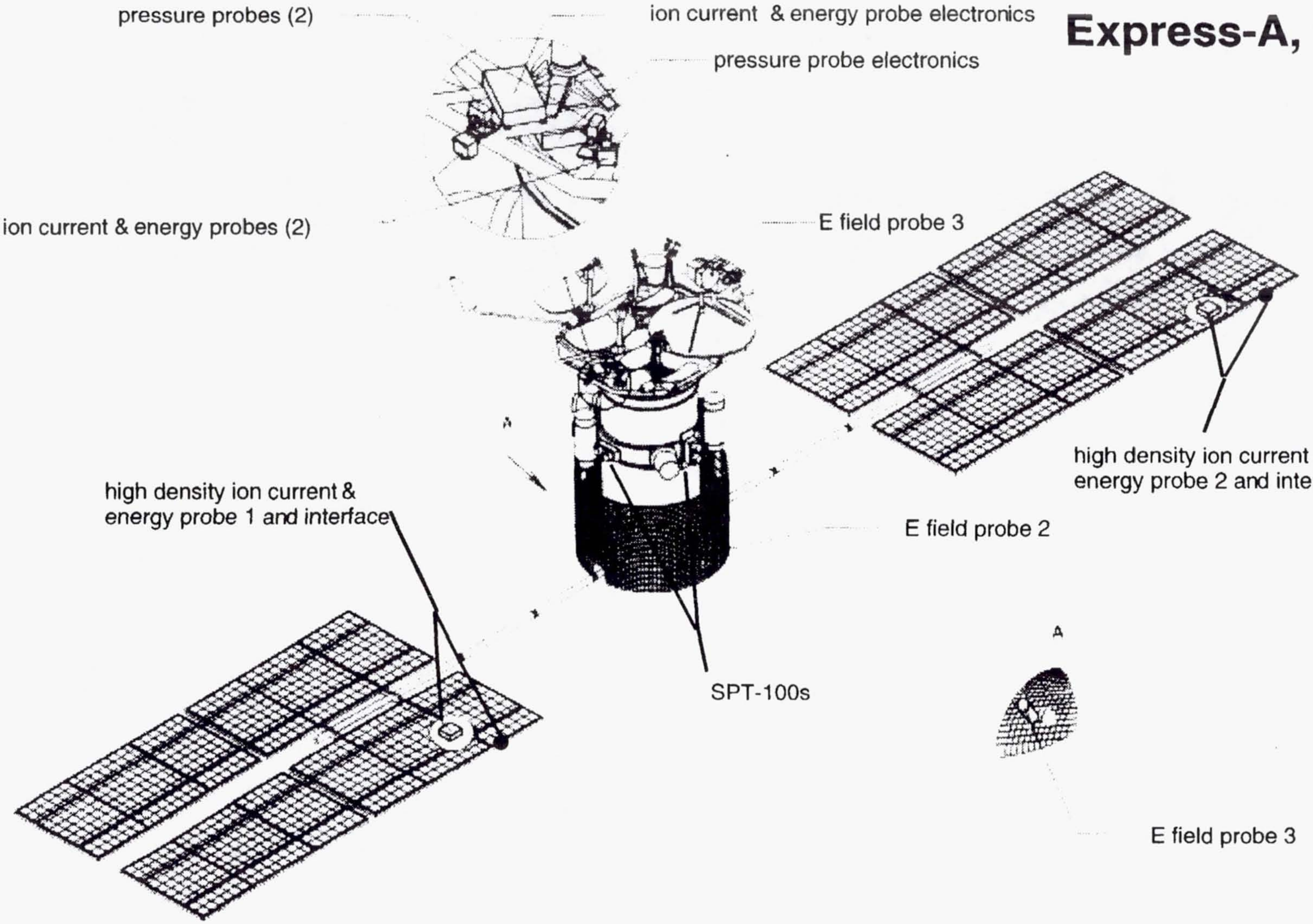
Express-A, #2



"ST Day 2000: Reducing Risk for the Next Generations" - Hall Propulsion

EXPRESS Ground/Space Correlation

Express-A, #3



"ST Day 2000: Reducing Risk for the Next Generations" - Hall Propulsion

EXPRESS Ground/Space Correlation

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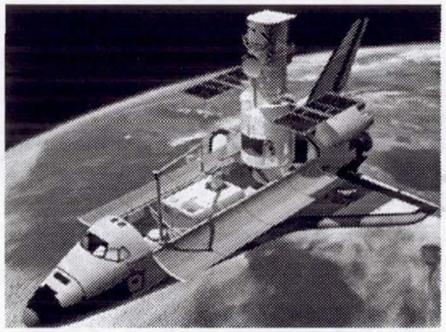
2nd Generation RLV Plans

Dan Dumbacher

Agenda

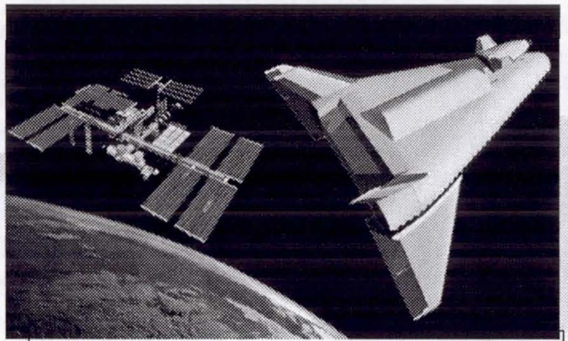
- Heritage and Background
- Goals and Schedule
- Program Requirements and Organization
- Technology Drivers and Interfaces
- Acquisition Strategy and Planning
- Status and Summary

Generations of Reusable Launch Vehicles



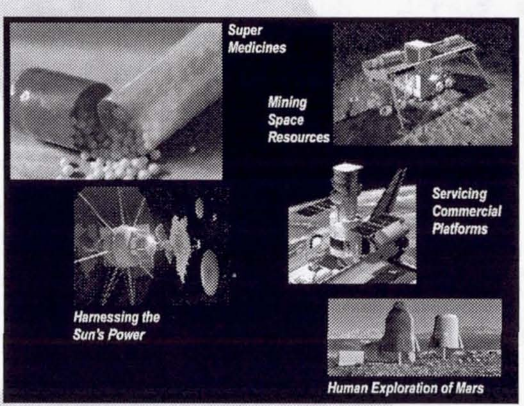
Today: Space Shuttle
1st Generation RLV

- Orbital Scientific Platform
- Satellite Retrieval and Repair
- Satellite Deployment



2010: 2nd Generation RLV

- ~~Space Transportation~~
- Rendezvous, Docking, Crew Transfer
- Other on-orbit operations
- ISS, Orbital Scientific Platform
- 10x Cheaper
- 100x Safer

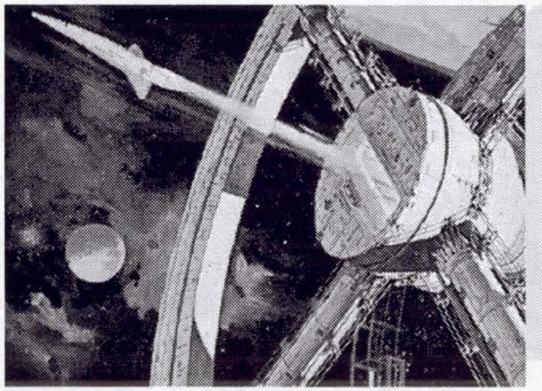


2025: 3rd Generation RLV

- New Markets Enabled
- Multiple Platforms / Destinations
- 100x Cheaper
- 10,000x Safer

2040: 4th Generation RLV

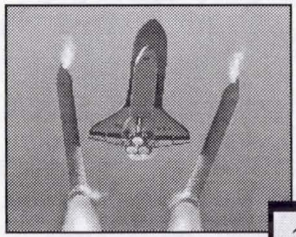
- Routine Passenger Space Travel
- 1,000x Cheaper
- 20,000x Safer



Foundation Studies and Plans

- STAS - Space Transportation Architecture Studies
  - **Focused Industry and In-House Studies of Space Transportation requirements, architecture options and preliminary risk reduction**
    - Phase I - Aug - Sept '98 - Initial requirements definition
    - Phase II - Sept '98 - Feb 99 - Initial architecture options
    - Phase III - July '99 - Dec '99 - Requirements and architecture refinement , technology prioritization
    - Phase IIIB - Dec '99 - July '00 - System engineering process definition, technical risk reduction plan
- ISTP - Integrated Space Transportation Plan
  - **Annual effort to integrate NASA plans and resource requirements for:**
    - Space Shuttle safety upgrades and on-going programs
    - Crew Transfer/Return Vehicle
    - 2nd Generation RLV and NASA Unique systems
    - Alternate Access to Space Station
    - 3rd Generation RLV and In-Space Transportation
- SLI - Space Launch Initiative → 2nd Generation RLV Program
  - **Systems Engineering and Requirements Definition**
  - **2nd Generation RLV Competition and Risk Reduction**
  - **NASA Unique systems**
  - **Alternate Access to Space Station**

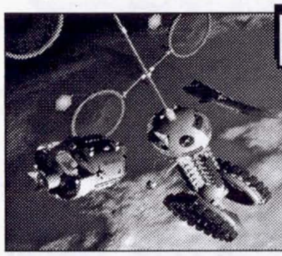
Integrated Space Transportation Plan



Ensure continued safe access to space through **Space Shuttle Safety Upgrades** until a replacement alternative has been demonstrated

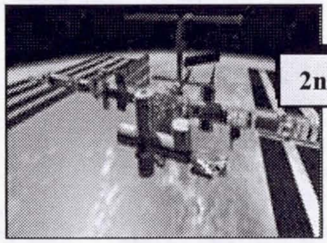
2nd GEN

Invest in technical and programmatic **Risk Reduction** activities, driven by industry needs, to enable full-scale development of commercially-competitive, privately owned and operated, Earth-to-orbit (ETO) reusable launch vehicles (RLVs) by 2005.



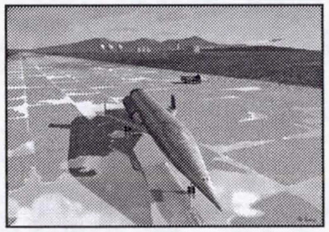
2nd GEN

Develop an integrated architecture with systems that build on commercial ETO launch vehicles to meet **NASA-Unique** requirements that cannot be economically served by commercial vehicles alone.



2nd GEN

Enable procurements of near-term, launch services for select International Space Station needs on **Existing and Emergent Commercial Launch Vehicles.**



Secure safe, reliable and cost-effective access to space in the far-term through investments in **3rd-Generation RLV Technologies** for ETO and in-space applications

Space Launch Initiative Goals

The goal of this Space Launch Initiative is for NASA to meet its future space flight needs, including human access to space, using commercial launch vehicles that will improve safety and reliability and reduce cost.

Safety Goal - *Improve safety to better than 1 in 10,000 Loss of Crew*
Cost Goal - *Reduce mission cost to $1000/lb*

Four principles exist:

Commercial Convergence – flying on privately owned and operated launch vehicles;

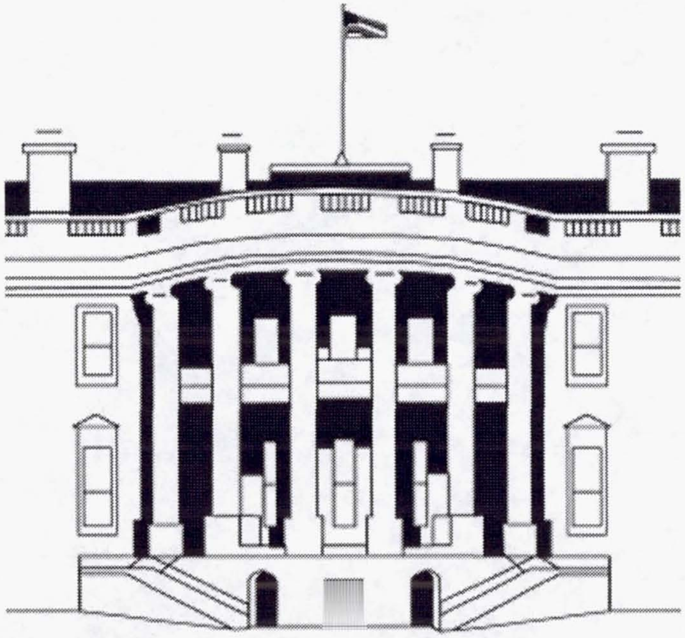
Competition – bringing innovation and new ideas to bear;

Assured Access – ensuring alternate means of getting to space despite launch mishaps;

The Ability to Evolve – adding new capabilities affordably as new mission needs emerge.

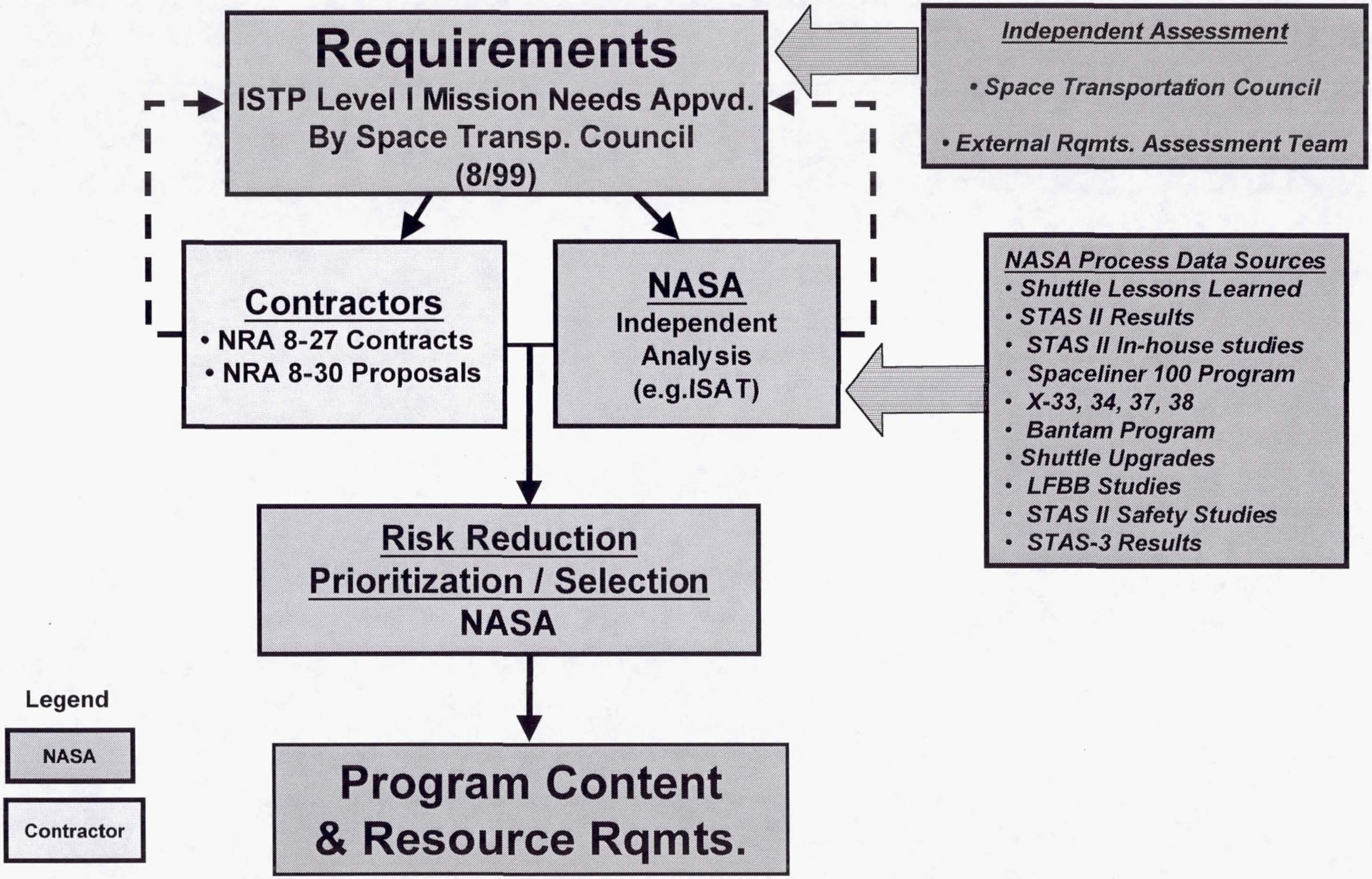
National Endeavor

"The Space Launch Initiative is an extremely ambitious undertaking. If successful – and I'm confident it will be – it will dramatically alter the economics of space launch. I believe that this Space Launch Initiative could ultimately have as profound an impact on space exploration and space commerce as anything our nation has ever attempted."



Dr. Neal Lane
Assistant to the President
for Science and Technology

2nd Gen Program Planning Process



Requirements
ISTP Level I Mission Needs Appvd.
By Space Transp. Council
(8/99)

Independent Assessment
- *Space Transportation Council*
- *External Rqmts. Assessment Team*

Contractors
- NRA 8-27 Contracts
- NRA 8-30 Proposals

NASA
Independent
Analysis
(e.g.ISAT)

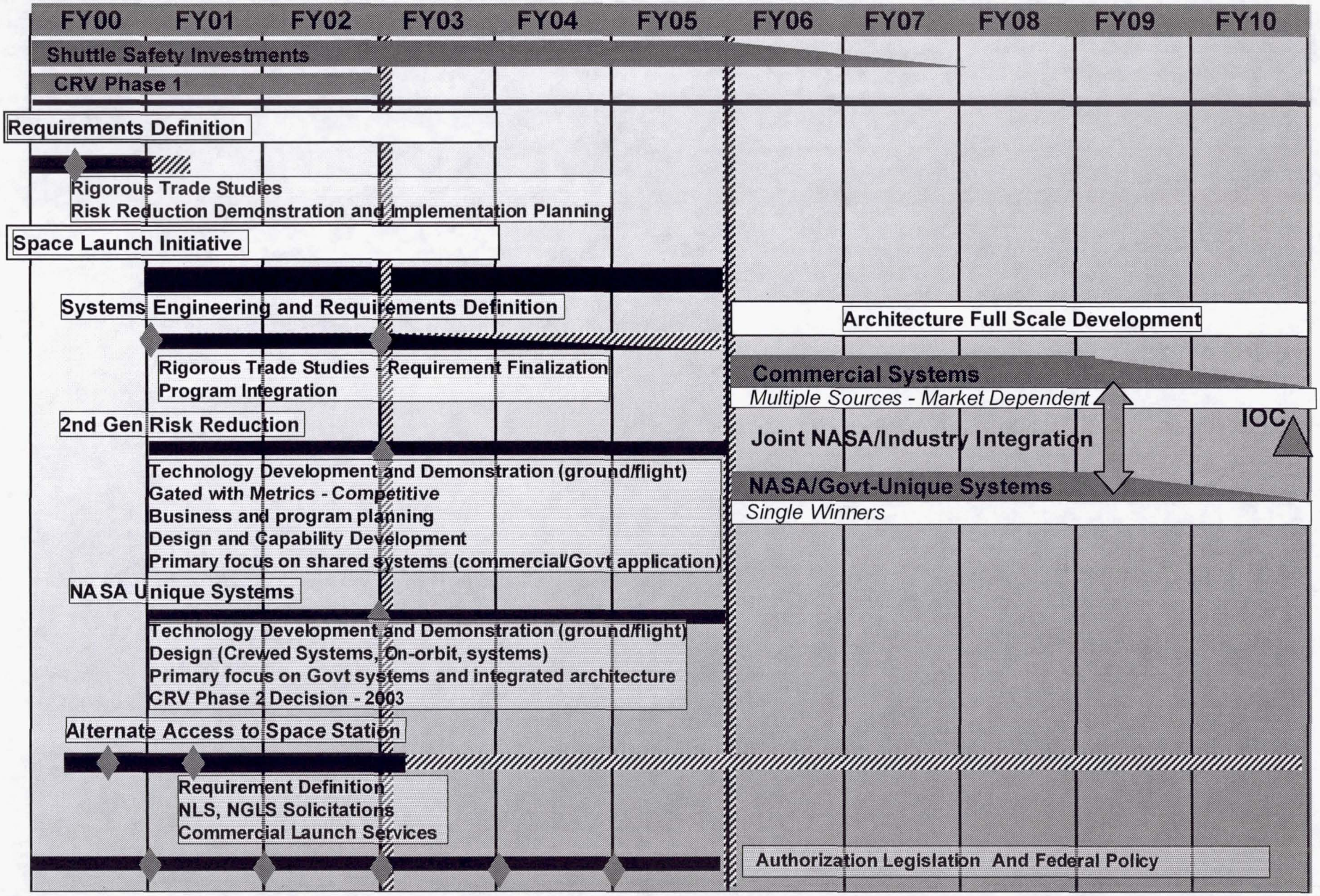
NASA Process Data Sources
- *Shuttle Lessons Learned*
- *STAS II Results*
- *STAS II In-house studies*
- *Spaceliner 100 Program*
- *X-33, 34, 37, 38*
- *Bantam Program*
- *Shuttle Upgrades*
- *LFBB Studies*
- *STAS II Safety Studies*
- *STAS-3 Results*

Risk Reduction
Prioritization / Selection
NASA

Program Content
& Resource Rqmts.

Legend
- NASA
- Contractor

2nd Generation Program Plan



FY00 FY01 FY02 FY03 FY04 FY05 FY06 FY07 FY08 FY09 FY10

Shuttle Safety Investments

CRV Phase 1

Requirements Definition

Rigorous Trade Studies
Risk Reduction Demonstration and Implementation Planning

Space Launch Initiative

Systems Engineering and Requirements Definition

Rigorous Trade Studies - Requirement Finalization
Program Integration

2nd Gen Risk Reduction

Technology Development and Demonstration (ground/flight)
Gated with Metrics - Competitive
Business and program planning
Design and Capability Development
Primary focus on shared systems (commercial/Govt application)

NASA Unique Systems

Technology Development and Demonstration (ground/flight)
Design (Crewed Systems, On-orbit, systems)
Primary focus on Govt systems and integrated architecture
CRV Phase 2 Decision - 2003

Alternate Access to Space Station

Requirement Definition
NLS, NGLS Solicitations
Commercial Launch Services

Architecture Full Scale Development

Commercial Systems

Multiple Sources - Market Dependent

Joint NASA/Industry Integration

IOC

NASA/Govt-Unique Systems

Single Winners

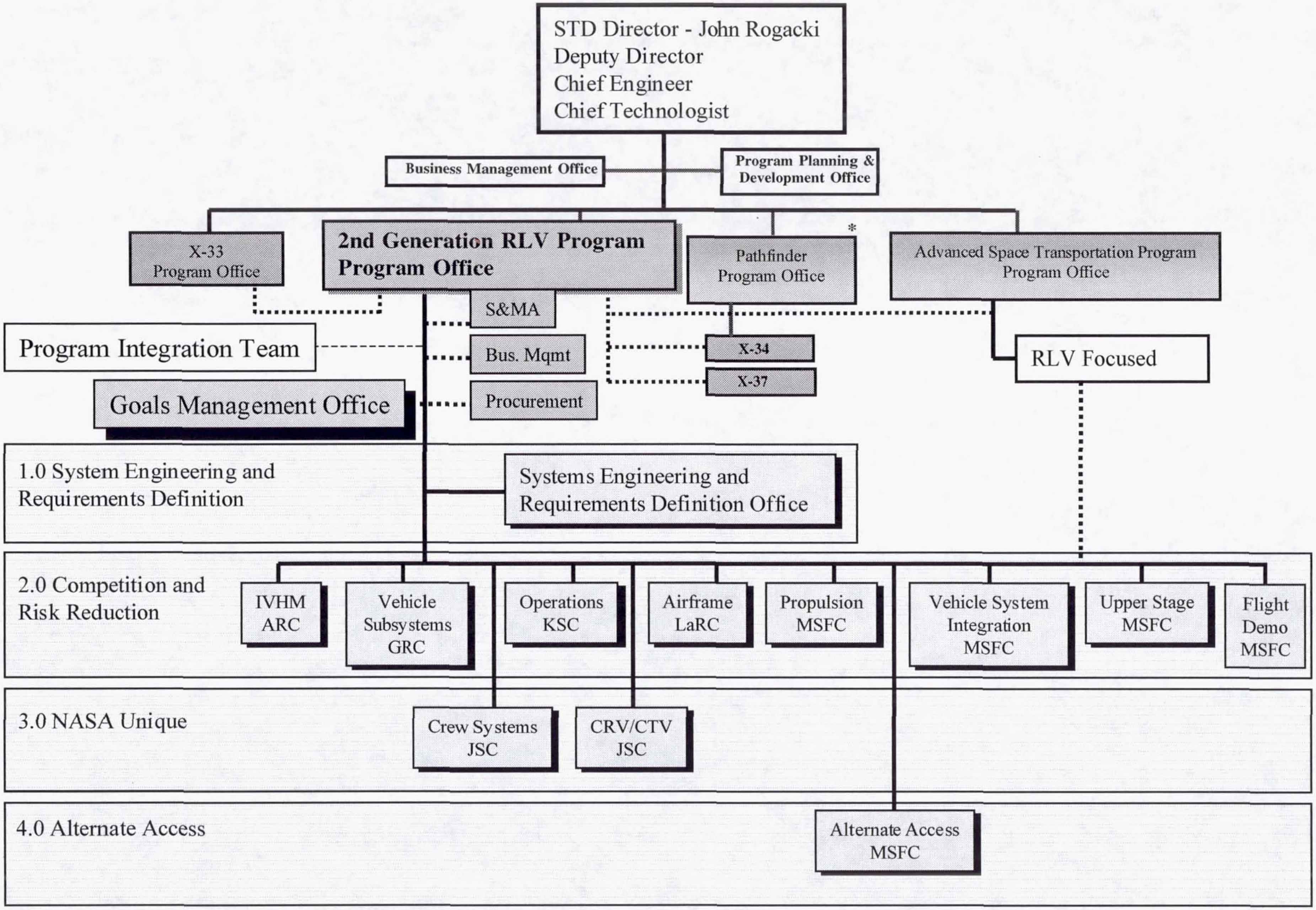
Authorization Legislation And Federal Policy

2nd Generation RLV Objectives

What 2nd Gen RLV must accomplish to meet our Goals

Objectives	Success Criteria	Date	Approach
A. Converge National Needs – Industry, NASA, and DOD	U.S. Transportation Needs Document Approved by Space Transportation Council	Baseline is August 1999 and updated annually	Initiated for ISTP with annual updates from systems engineering process
B. Provide an architecture requirement set derived from converged needs for industry competition	2nd Generation RLV System Requirements Database Approved by Space Transportation Council	Preliminary in August 2000 and updated annually	Initiated for ISTP with annual updates from systems engineering process
C. Develop systems engineering processes and tools, and connect goals to risk reduction Investments	Risk Reduction Investment Strategies documented in project plans Tools developed and validated. Knowledge base developed.	Initial - August 2000 with periodic updates 2002 2005	Implement rigorous systems engineering process (Utilizing tools developed by ISE, Design for Safety Initiative, etc) Initiated with NRA 8-27
D. Abate business and technical risks through defined risk reduction activities	Architecture definition at a minimum of a PDR level. Government / Industry full-scale development contracts initiated.	2005	In-house/ contractor led advanced development and technology demonstrations, including ground and flight, complete
E. Architectural decision made to safely meet unique NASA needs	CRV/CCTV Decision complete. NASA unique architecture elements identified and in development	2002 2005	NASA unique requiremen ts identified in Obj. A & B, risk reduction investments from Obj. D
F. Enable alternative Space Station re-supply	Launch service agreement(s) in place and enabling activities complete	2002-2005	Perform initial studies to define activities. Develop and implement activities jointly between Code M and Code R

2nd Generation RLV Program Office Structure



STD Director - John Rogacki
Deputy Director
Chief Engineer
Chief Technologist

Business Management Office

Program Planning & Development Office

X-33 Program Office

2nd Generation RLV Program Program Office

Pathfinder Program Office *

Advanced Space Transportation Program Program Office

S&MA

Bus. Mqmt

Procurement

Program Integration Team

Goals Management Office

X-34

X-37

RLV Focused

1.0 System Engineering and Requirements Definition

Systems Engineering and Requirements Definition Office

2.0 Competition and Risk Reduction

IVHM
ARC

Vehicle Subsystems
GRC

Operations
KSC

Airframe
LaRC

Propulsion
MSFC

Vehicle System Integration
MSFC

Upper Stage
MSFC

Flight Demo
MSFC

3.0 NASA Unique

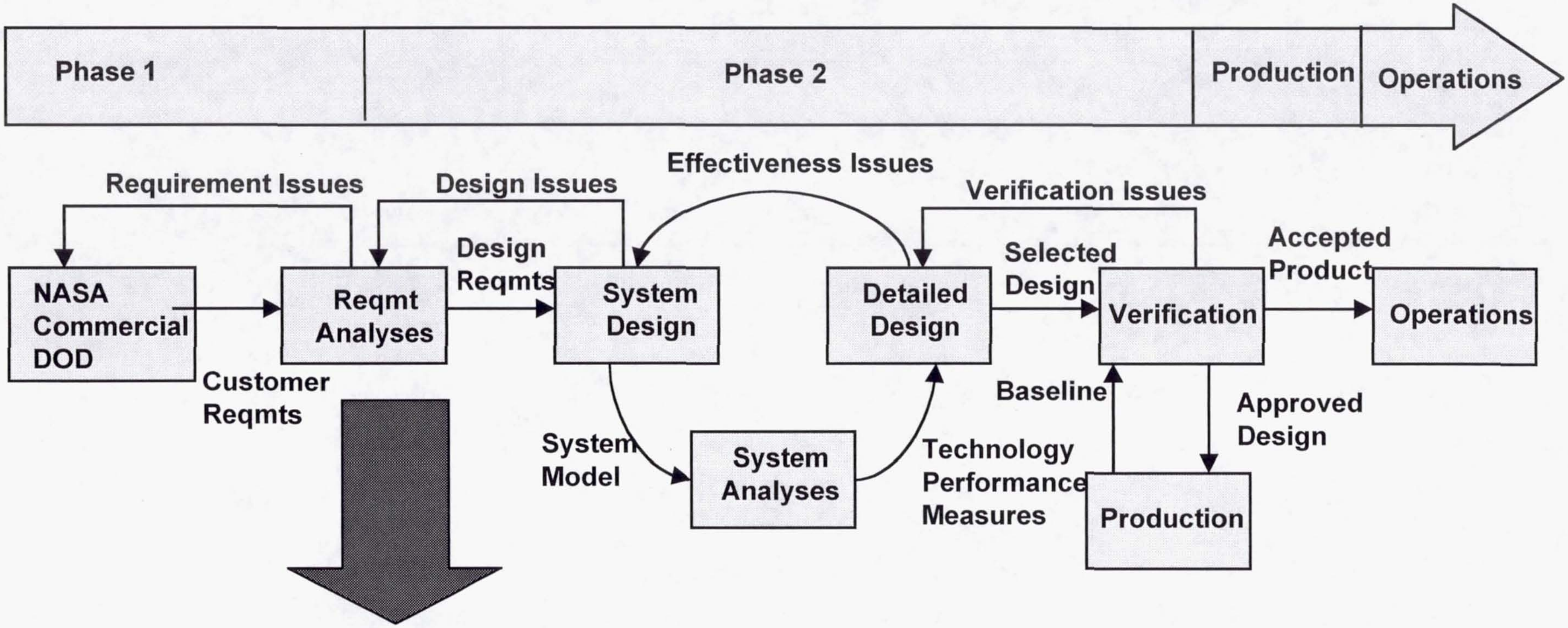
Crew Systems
JSC

CRV/CTV
JSC

4.0 Alternate Access

Alternate Access
MSFC

Requirements Drives the Process



Phase 1

Phase 2

Production

Operations

Requirement Issues

Design Issues

Effectiveness Issues

Verification Issues

NASA
Commercial
DOD

Customer
Reqmts

Reqmt
Analyses

Design
Reqmts

System
Design

System
Model

System
Analyses

Technology
Performance
Measures

Detailed
Design

Selected
Design

Verification

Baseline

Approved
Design

Production

Accepted
Product

Operations

Safety

Reliability

Affordability

Mission
Performance

Refine for
Commercial
Convergence

Define Priority
Risk
Reduction
Needs

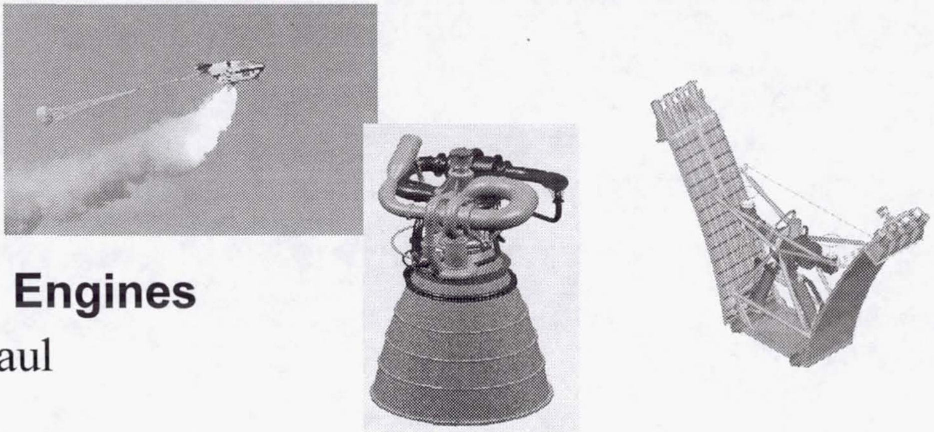
Define Scale,
Fidelity, Test
Environment
for Tech
Demos

Enable Full
Scale
Development
With 20%
Margin

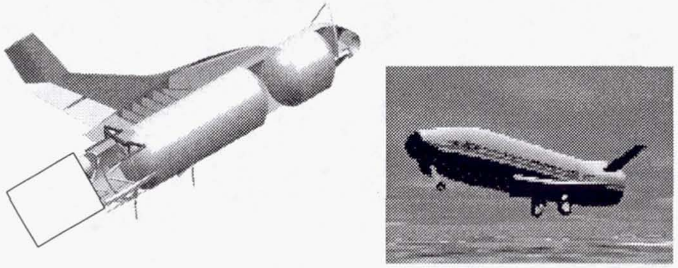
Independent Assessment / Space Transportation Council Review

Include Shuttle Lessons Learned / Business Case Closure

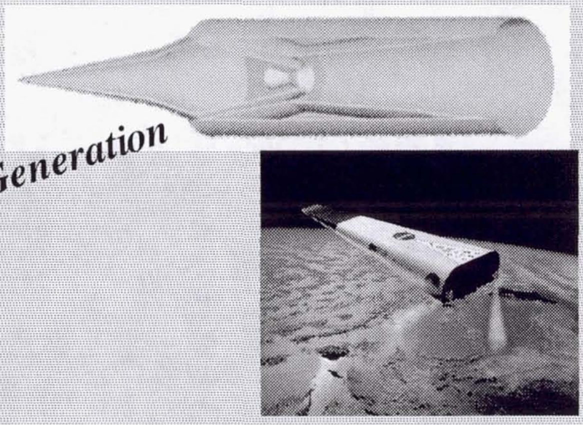
Significant 2nd Technology Drivers



- **Crew Escape and Survival**
  - Detection, separation, ascent/descent
- **Operable, Long-life H_2/O_2 and RP/O_2 Engines**
  - 100 mission life, 50 missions to overhaul



- **Long life, lightweight integrated airframe**
  - Critical integrated cycle testing (500 missions)
- **Advanced TPS, IVHM, and Operations**
  - Quick turn vehicle with intelligent data analysis



- **Ejector Ramjet**
  - Improved performance margin
- **SHARP Leading Edges**
  - Global crossrange from orbit

Cutting Edge for 2nd Generation

2nd Gen RLV Relation to Other Programs

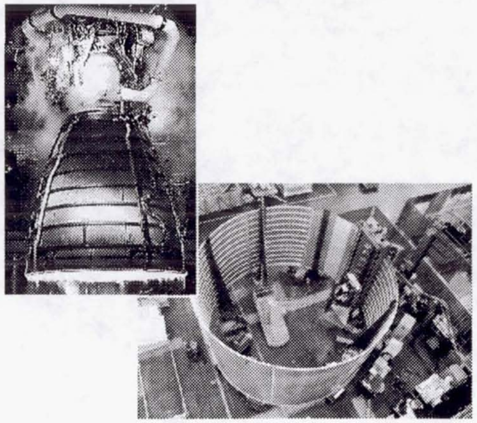
2nd Generation RLV coordinates investments with:

Shuttle

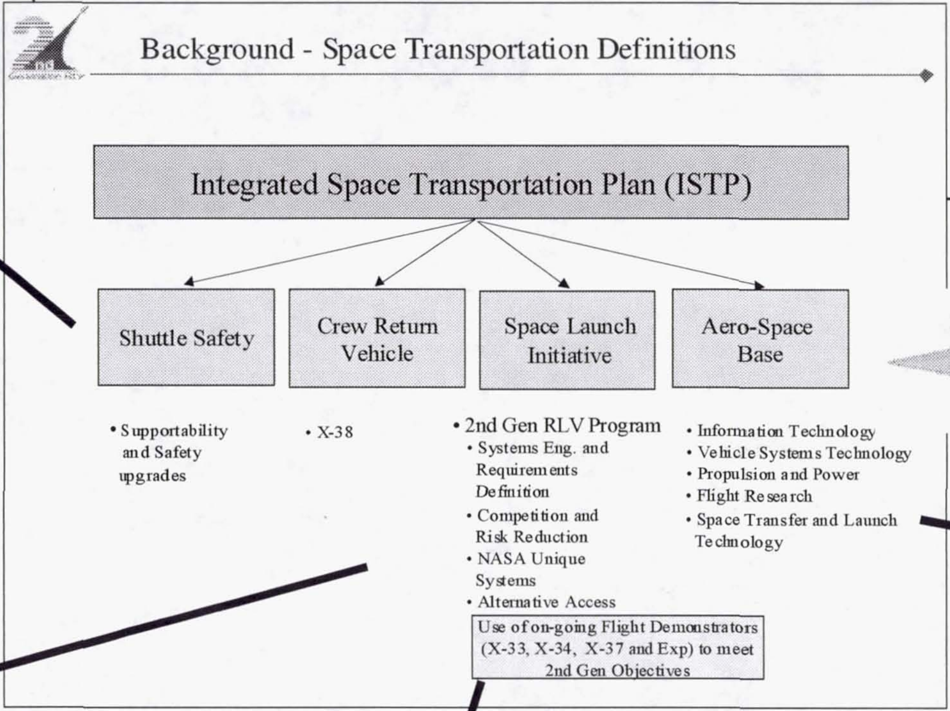
X-Vehicles

ASTP

Air Force



Shuttle Up-Grades



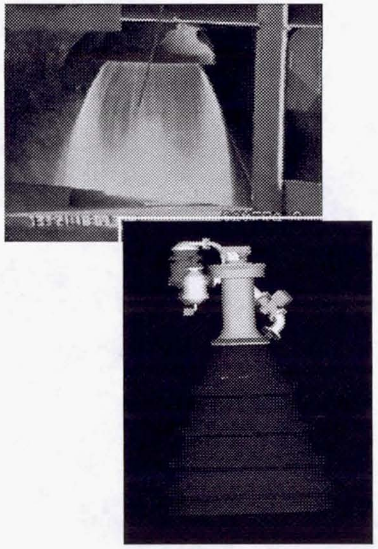
Background - Space Transportation Definitions

Integrated Space Transportation Plan (ISTP)

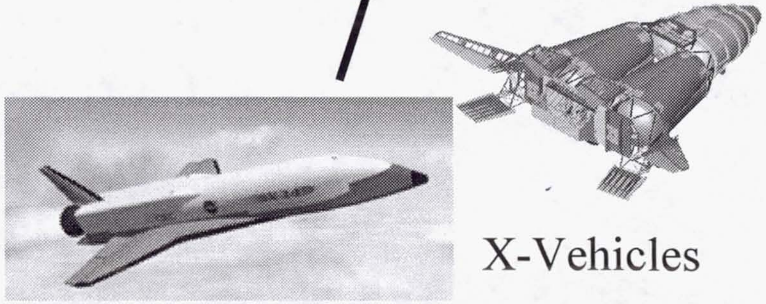
Shuttle Safety	Crew Return Vehicle	Space Launch Initiative	Aero-Space Base
- Supportability and Safety upgrades	- X-38	- 2nd Gen RLV Program - Systems Eng. and Requirements Definition - Competition and Risk Reduction - NASA Unique Systems - Alternative Access	- Information Technology - Vehicle Systems Technology - Propulsion and Power - Flight Research - Space Transfer and Launch Technology

Use of on-going Flight Demonstrators (X-33, X-34, X-37 and Exp) to meet 2nd Gen Objectives

3rd Generation Technology



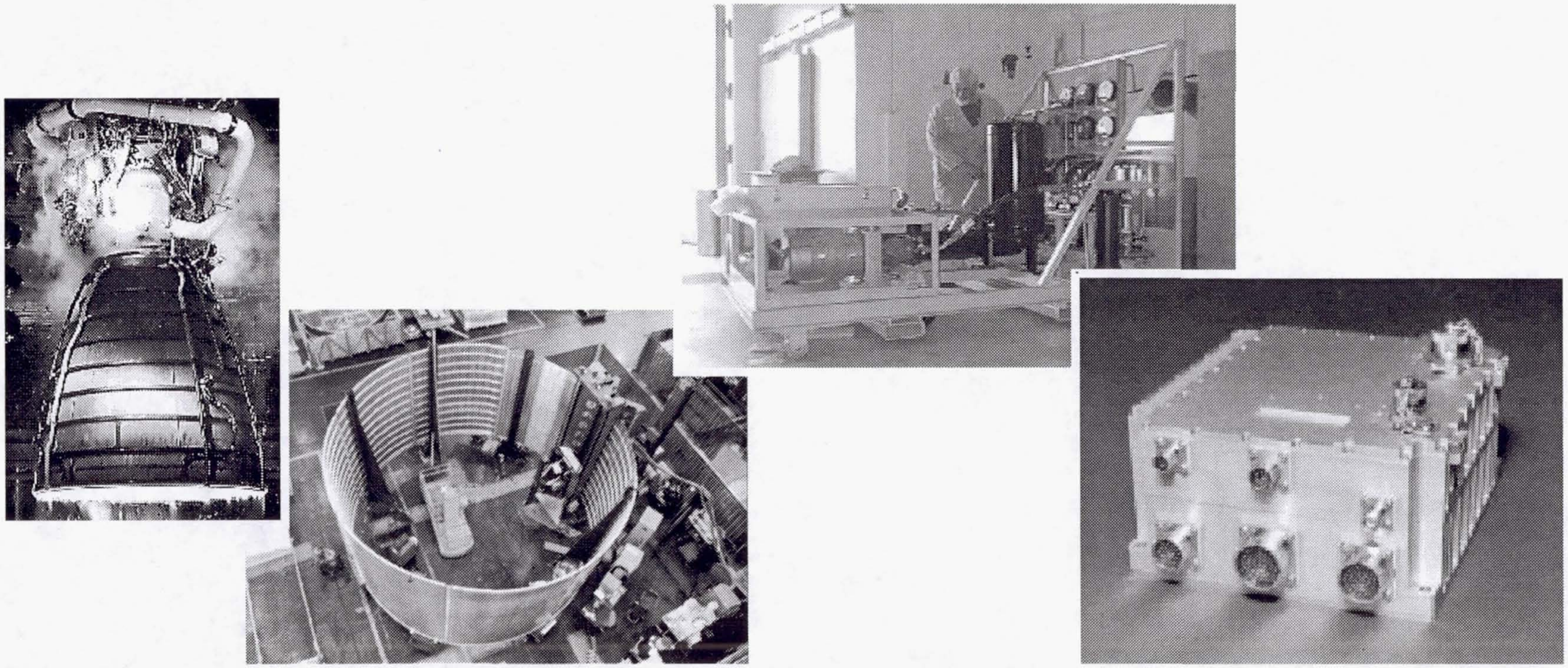
DOD Technologies



X-Vehicles

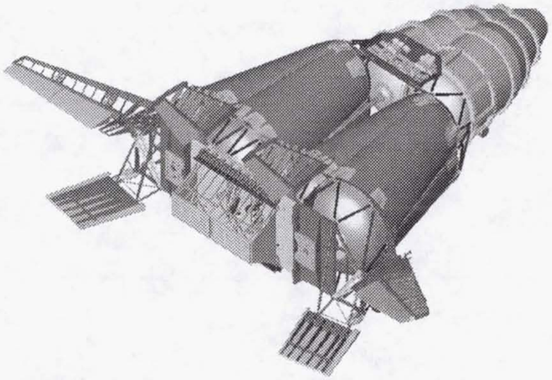
Space Shuttle Upgrades

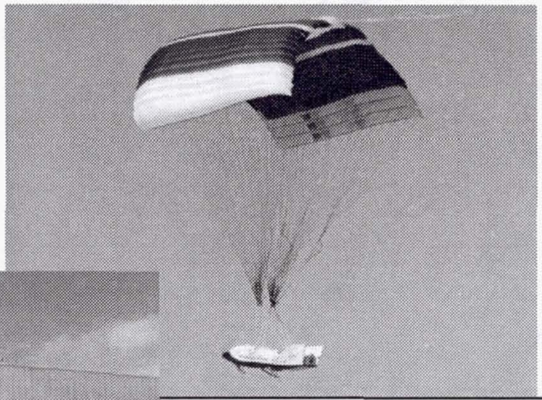
- **Cooperation with the Space Shuttle Upgrades program is required to:**
  - Coordinate technology activities
  - Avoid duplication of effort
  - Consider application of Second Generation technologies to future Space Shuttle upgrades and the evolved Space Shuttle



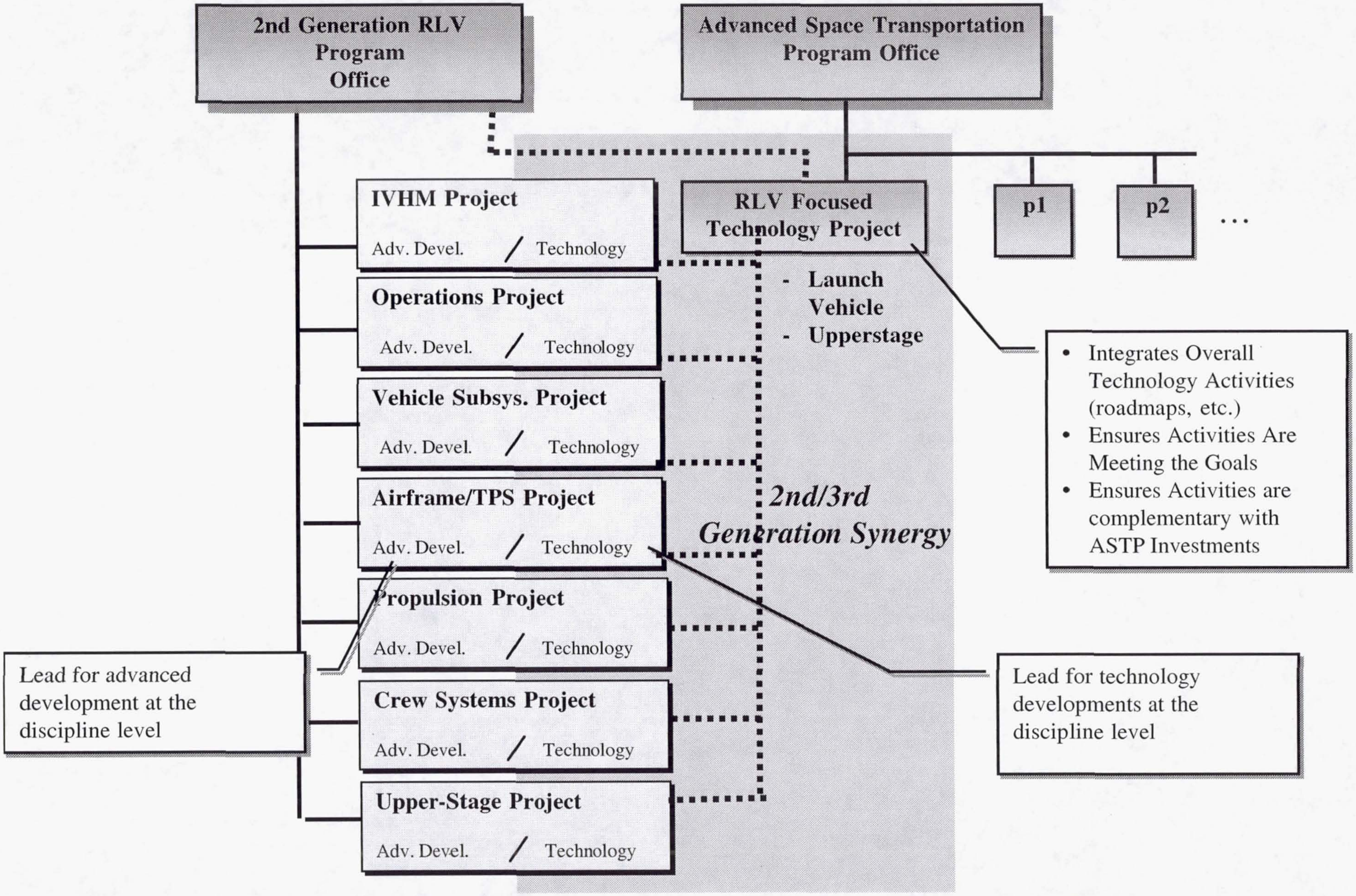
X - Vehicles

- The 2nd Generation Program is linked to the success of the current X-Vehicle programs
- The current investment in X vehicles offers a unique opportunity to reduce risk through flight test
- The future use of the current X-vehicles and other flight vehicles is dependent upon selection within the competitive process





2nd/3rd Synergy Management Structure



2nd Generation RLV Program Office

Advanced Space Transportation Program Office

IVHM Project
Adv. Devel. / Technology

Operations Project
Adv. Devel. / Technology

Vehicle Subsys. Project
Adv. Devel. / Technology

Airframe/TPS Project
Adv. Devel. / Technology

Propulsion Project
Adv. Devel. / Technology

Crew Systems Project
Adv. Devel. / Technology

Upper-Stage Project
Adv. Devel. / Technology

RLV Focused Technology Project

- Launch Vehicle
- Upperstage

p1

p2

. . .

2nd/3rd Generation Synergy

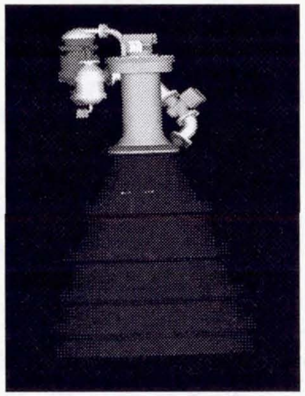
- Integrates Overall Technology Activities (roadmaps, etc.)
- Ensures Activities Are Meeting the Goals
- Ensures Activities are complementary with ASTP Investments

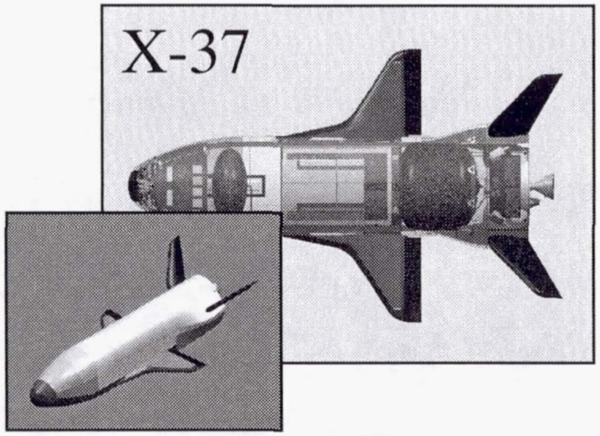
Lead for advanced development at the discipline level

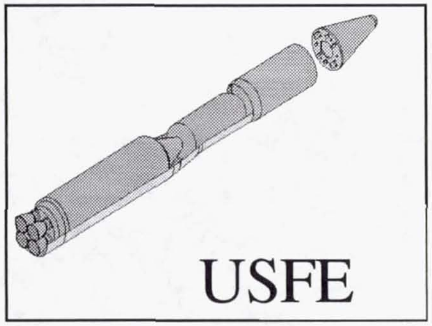
Lead for technology developments at the discipline level

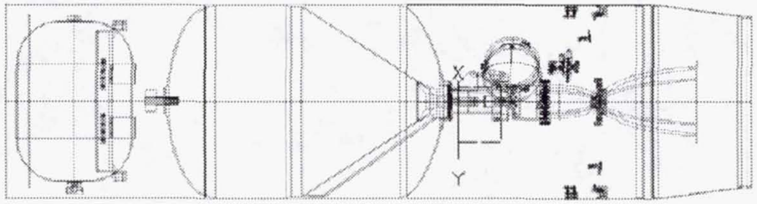
Joint Air Force/NASA Efforts

- 2nd Generation Program is coordinating its risk reduction investments with ongoing Air Force Space Transportation investments.
- 2nd Generation Program will leverage/continue already initiated joint AF/NASA efforts including IPD, X-37, USFE, Advanced Peroxide Propulsion and MWG.









Total Program Acquisition Strategy

- Overall acquisition strategy will be in 2 major competitive phases
  - **Phase I (FY00 - 02)** develops architectures through System Requirements Definition and initiates risk reduction activities.
    - NRA8-27 converges and refines top level requirements, develops process and tools and defines risk reduction priorities.
    - NRA8-30, a single NASA Research Announcement seeking competitive systems engineering and risk reduction activities conceived by the offerors, in multiple areas of program interest (e.g. propulsion, airframe)
  - **Phase II (FY03 - 05)** focuses on architecture design and advanced technology development
    - Anticipate RFP(s) for the focused architecture design and Advanced Technology development activities
  - **Phases have decision gates** for program / project updates based on systems engineering results and Agency management milestones (e.g. Space Transportation Council, Non-advocate Review)
- In-House Risk Reduction Task
  - Cross cutting risk reduction - available to all concepts with no proprietary issues
  - Develops in-house "Smart Buyers".
  - A second cycle will be implemented to fill risk reduction gaps.
- Alternate Access will be addressed separately based on study results from current contracts

Total Program Acquisition Needs

- Support a **decision for commitment to full scale development** of the RLV architecture that meets NASA's goals (target date is 2005)
  - Industry teams to define an RLV architecture life cycle implementation with emphasis on Full Scale Development (FSD) technical and business metrics.
  - Rigorous system engineering, detailed trade studies, and risk reduction activity leading to concept design with acceptable technical and investment risks.
  - Business analysis must be supported with appropriate parameter identification and metric evaluation and show closure.
- **Maintain competition** and encourage solicitation of all good ideas.
  - Established Aerospace Companies
  - Emerging Aerospace Companies
  - Stand-alone Technologies from Companies not providing a system level architecture
- Resulting awards will provide appropriate Government insight to ensure successful development of the 2nd Gen RLV.
- Resulting awards will provide appropriate options to facilitate adjustments after major program **"Decision Gates".**
  - NAR recommendations
  - Systems Requirement Review
  - Commitment to Full Scale Development (FSD)

In-House Led Activities

High Priority / Schedule Critical Activities

Activities required for 2nd Gen based on STAS 3B / ISTP

Activities best performed by NASA / Gov't (expertise, data sharing, etc.)

Activities industry may not propose & must be initiated ASAP to support 2005

- Systems Engineering and requirements
  - **Systems Analysis Tool Development**
  - **Probabilistic Risk Assessment**
  - **ORM & S/C Database Enhancements**
  - **Uncertainty Analysis and Design**
  - **Commercial Cargo System Modeling Task**
- Propulsion
  - **Full-flow staged combustion injectors**
  - **Lox / H2 Combustion devices test bed**
  - **Turbomachinery technology demonstrator**
- Airframe
  - **Integrated Aerothermal and Structural-Thermal Analysis**
  - **Stage Separation and Ascent Aerothermodynamics**
  - **Materials and Advanced Manufacturing: Permeability Resistance**
  - **Lightweight, Informed, Micrometeoroid Resistant Ceramic TPS for Leading Edge and Acreage Applications**
- Crew Systems
  - **Cockpit Architecture Roadmap Team**
- Operations
  - **Advanced mission planning / ops w/ MOD**
  - **Future Launch vehicle Umbilical Development**
  - **Satellite Telemetry Acquisition and Range Study (STARS) and Space-Based Range Safety System**
- Vehicle Subsystems
  - **Proton Exchange Membrane Fuel Cell (PEMFC) Power Plant Development**
- Integrated Vehicle Health Management
  - **IVHM Architecture Roadmap Team**
- Flight Mechanics
  - **Robust Integration Technology and test bed for RLV Navigation Systems**
  - **Natural Atmospheric Environment Technology Development**

Recent Accomplishments

- Successfully completed Program Readiness Review (May 17, 2000)
  - **First major milestone required by 7120.5A**
  - **"Program Formulation" until Non-advocate Review in June 2001**
- Systems Engineering
  - **Completed STAS 3B Final Reviews**
    - **Top level rqmts. input provided to NASA**
    - **All potential vehicle concepts are being assessed (e.g. Shuttle derived, new design) to meet NASA rqmts.**
    - **Industry top priorities remain main propulsion, airframe / cryotanks, TPS**
  - **Initiated further mission needs refinement and trade studies via NRA 8-27 contracts**
    - **Mid-term reports conducted week of Sept. 26-28, 2000**
    - **Final reports - Jan 31, 2001**
  - **CTV / CRV Planning on-going w/ JSC, LaRC, ARC, MSFC**
- Acquisition strategy developed
  - **Alternate Access study contracts in place**
  - **NASA led technology development tasks reviewed and selected, downstream selections will be based on contractor input via NRA 8-30**
  - **NRA 8-30**
    - **Pre-meeting w/ HQ Code H, G,R, & M held August 25, 2000**
    - **Acquisition strategy meeting held at HQ Sept. 11, 2000**
    - **Draft NRA released on September 21, Final to be released October 10**
- External requirements assessment team formulated
  - **Required skill areas (Shuttle / RLV experience, investment experience) identified, potential team members in work**

Summary

- Systems Engineering in work based on Space Transportation Council approved mission needs.
- Program Planning and Implementation continuing w/ broad Agency and Industry Participation
  - NRA 8-27 for requirements and tools development on-going
  - NASA In-House Development Tasks selected and set to begin
  - Draft NRA 8-30 for systems engineering and risk reduction activities on street with bidders conference planned for 10/13
- Alternate Access study contracts to develop concepts and requirements for emerging launch systems to support ISS are in place
- Looking forward to continuing to work with Industry to achieve the Nation's goal of developing the next generation Reusable Launch Vehicle

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The X-33 Program Update

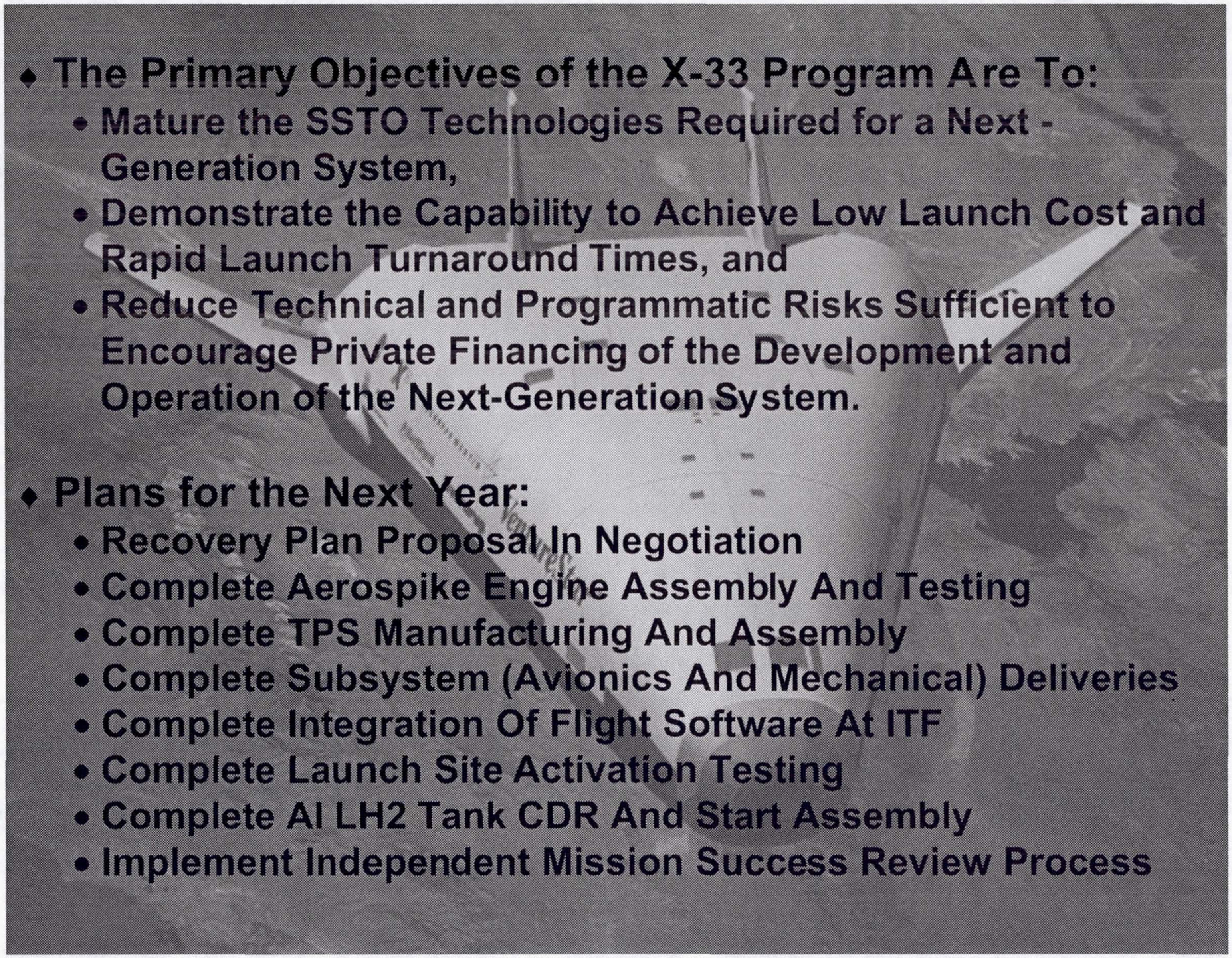
Charlie Dill, X-33 Assistant Program Manager

ST Day 2000: Risk Reduction for the Next Generations

Oct. 11 - 12, 2000

- Program Objectives and Plans
- X-33 Configuration
- Technologies
- X-33 Assembly and Test Status

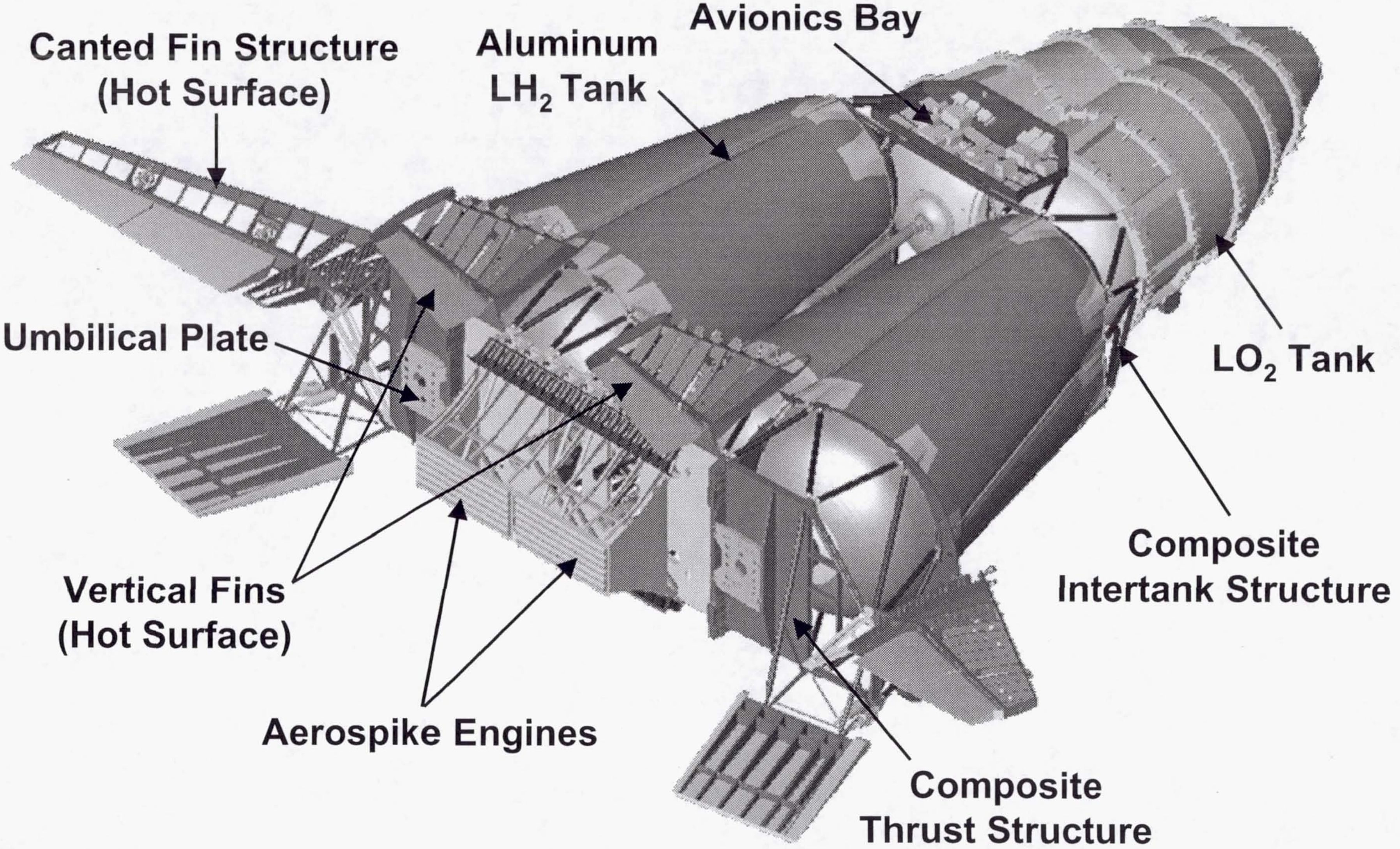
Outline



- The Primary Objectives of the X-33 Program Are To:
  - Mature the SSTO Technologies Required for a Next - Generation System,
  - Demonstrate the Capability to Achieve Low Launch Cost and Rapid Launch Turnaround Times, and
  - Reduce Technical and Programmatic Risks Sufficient to Encourage Private Financing of the Development and Operation of the Next-Generation System.

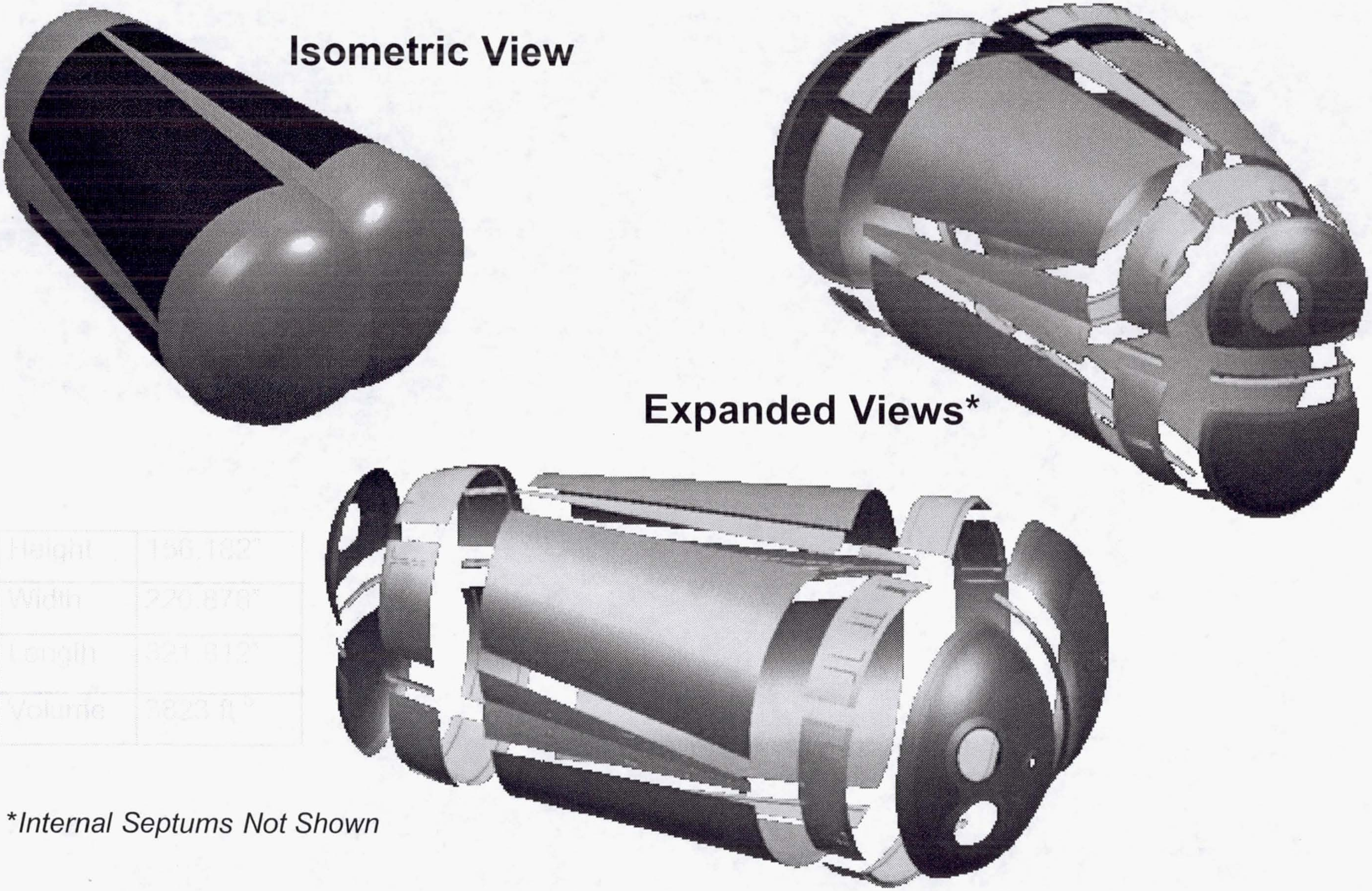
- Plans for the Next Year:
  - Recovery Plan Proposal In Negotiation
  - Complete Aerospike Engine Assembly And Testing
  - Complete TPS Manufacturing And Assembly
  - Complete Subsystem (Avionics And Mechanical) Deliveries
  - Complete Integration Of Flight Software At ITF
  - Complete Launch Site Activation Testing
  - Complete Al LH2 Tank CDR And Start Assembly
  - Implement Independent Mission Success Review Process

Program Overview



"ST Day 2000: Reducing Risk for the Next Generations" - X33 Update

X-33 Elements



Isometric View

Expanded Views*

Height	196.182"
Width	220.876"
Length	331.812"
Volume	2823 ft^3

*Internal Septums Not Shown

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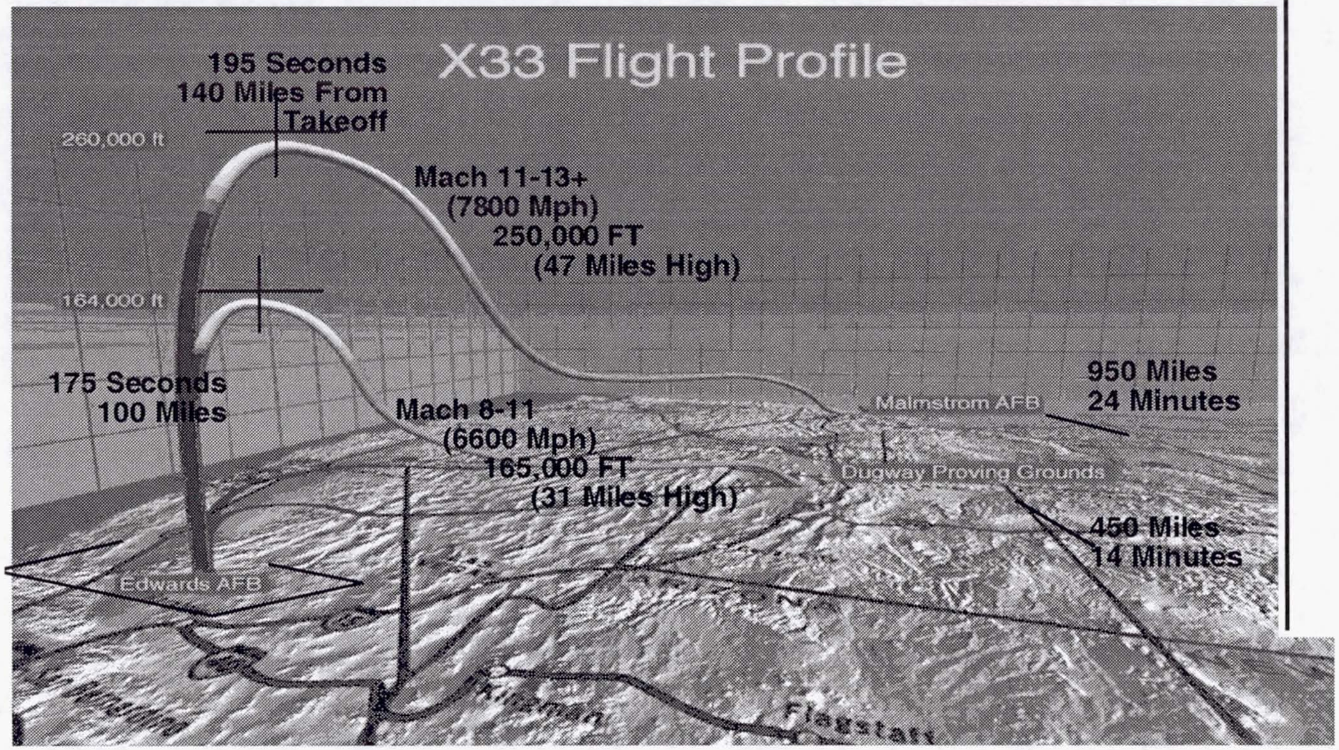
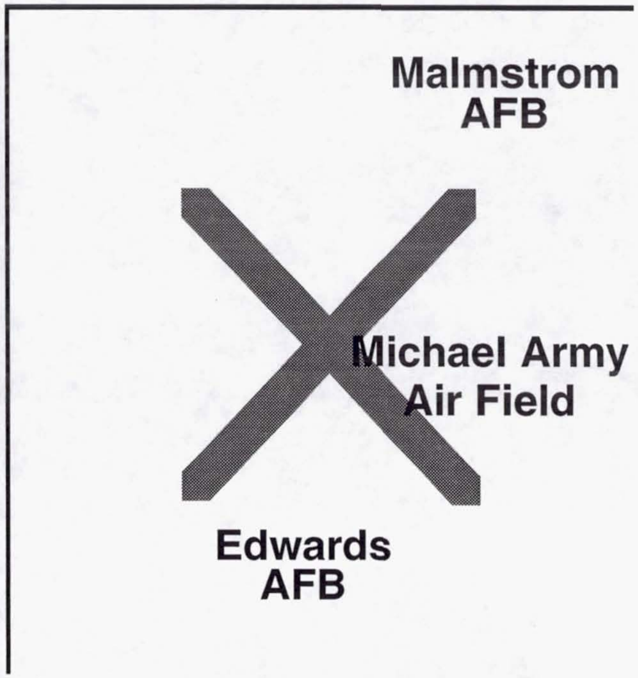
Al LH_2 Tank Design

Aircraft-like Operations: Two Seven-Day Turnarounds and One Two-Day Turnaround During Flight Test Series





2 Landing Sites

Flight 1	**Benign Thermal and Structural Loads**
Flight 2	**Intermediate**
Flight 3	**Real Gas Effects**
Flight 4	**Transition From Laminar to Turbulent Flow**
Flight 5	**Max Speed**
Flight 6	**Additional Increment of Real Gas Effects**
Flight 7	**Same Additional Increment**
Flights 8-15	**Margin to Repeat Specific Flight Profiles, Data Points**

"ST Day 2000: Reducing Risk for the Next Generations" - X33 Update

Expanding The X-33 Envelope

- **Demonstrate Aircraft-like Reusability, Maintenance and Scheduling**
  - Flying One (1) Two-day Turnaround Flight.
  - Flying Two (2) Consecutive Seven-day Turnaround Flights.
- **Robust Metallic TPS System**
  - Achieve Thermal Protection System Multi-use Operating Limits.
  - Panel Seal Designs
  - Attachment System/Replaceability
- **Composite Liquid Hydrogen Tank Mfg Processes/Assembly Techniques**
- **Linear Aerospike Engine**
  - Performance
  - Plume/Vehicle Flowfield Interaction
- **Vehicle Health Monitoring System**
  - Fiber Optic Strain & Temperature Sensors
  - Fiber Optic Hydrogen Leak Detection Sensors
- **Aerothermal Environment Prediction Verification**
  - Measure Surface Catalysis Caused by Atomic Oxygen
  - Measure Boundary Layer Transition

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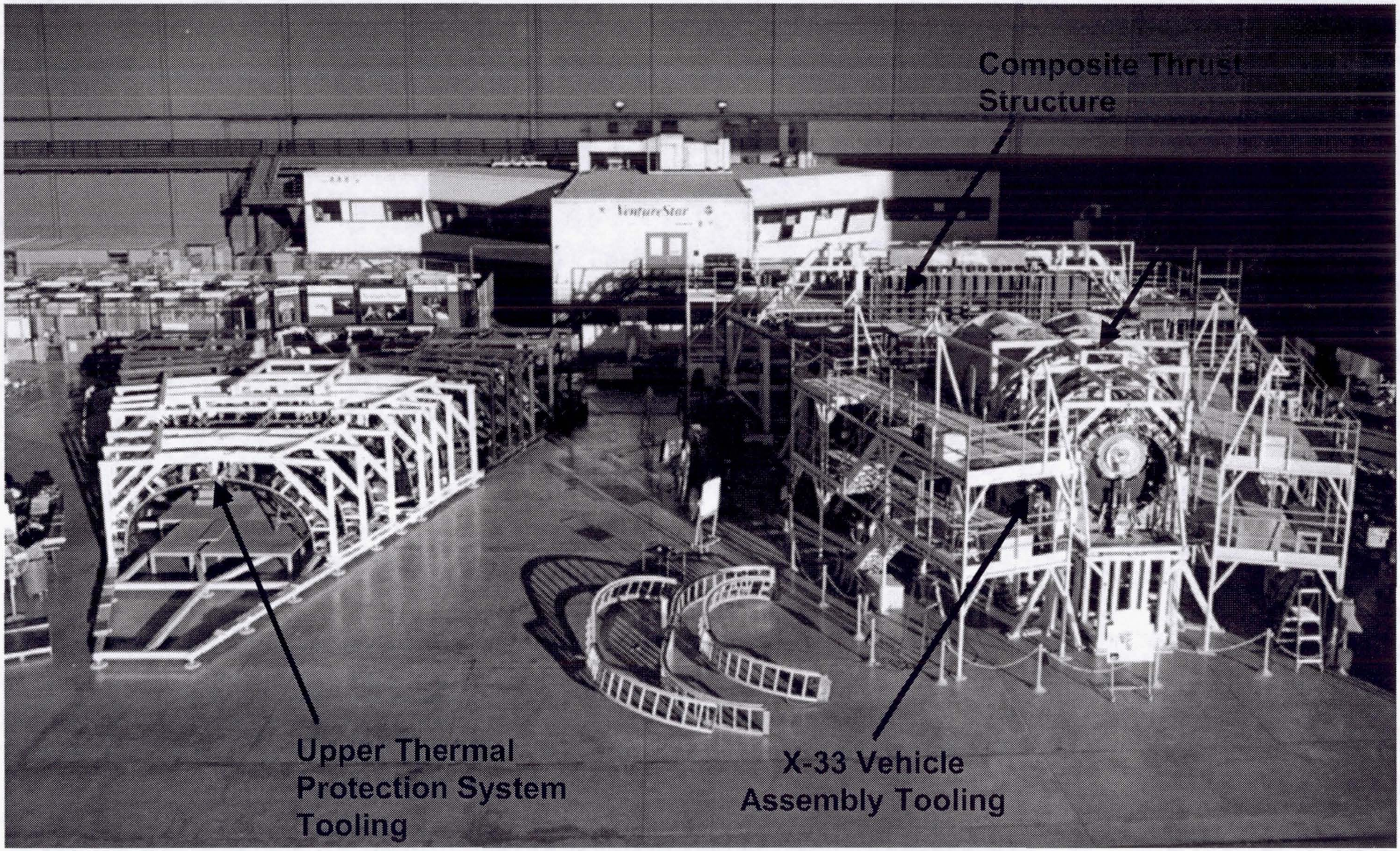
Technologies Demonstrated



Overall Assembly 75% Complete

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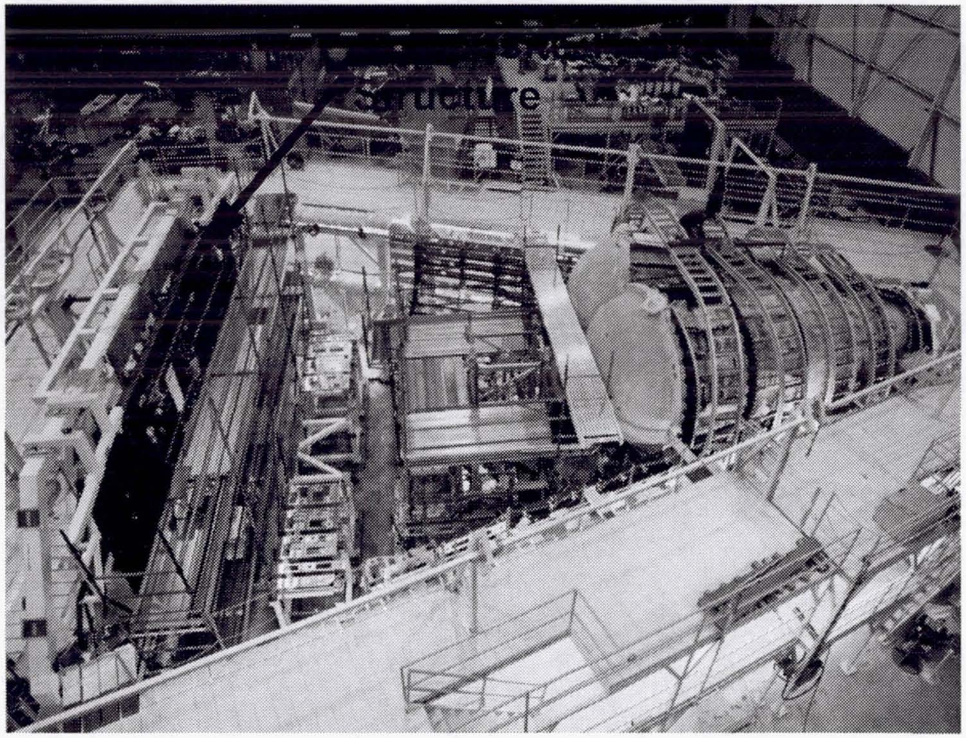
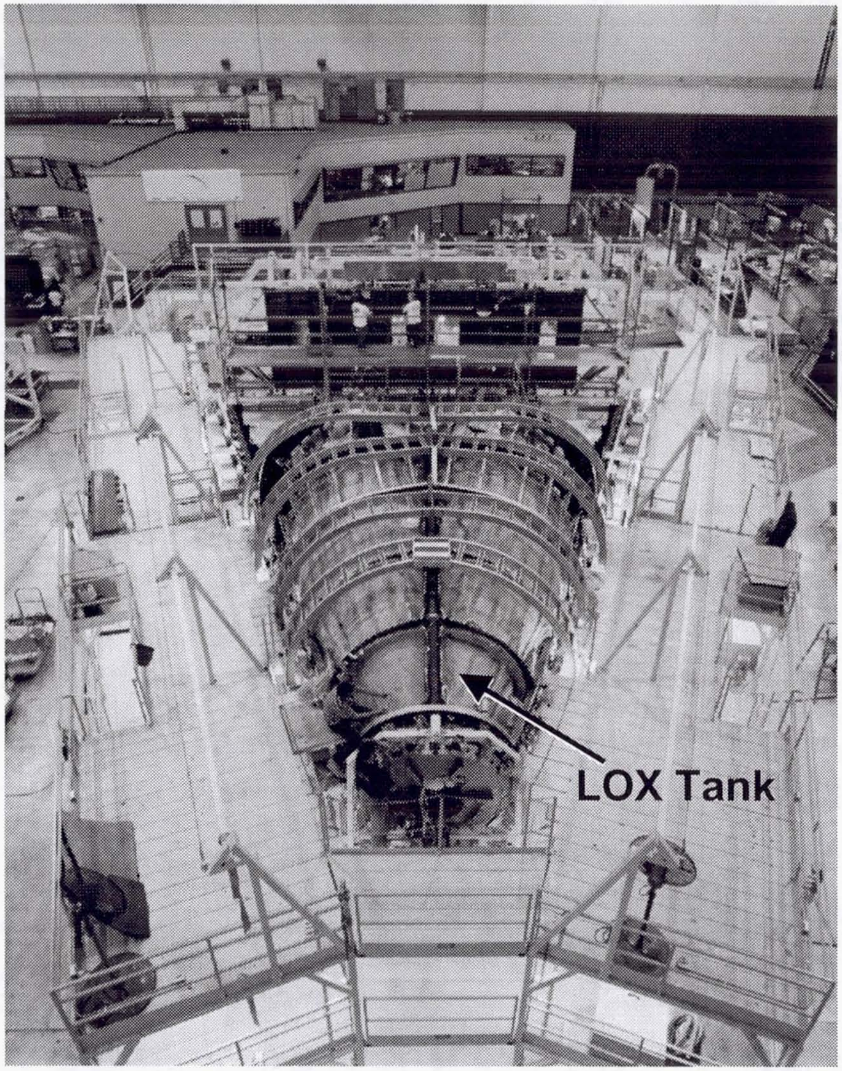
Vehicle Assembly in Palmdale

Overall Assembly 75% Complete





Websites On X-33: **www.x33.msfc.nasa.gov**
www.venturestar.com

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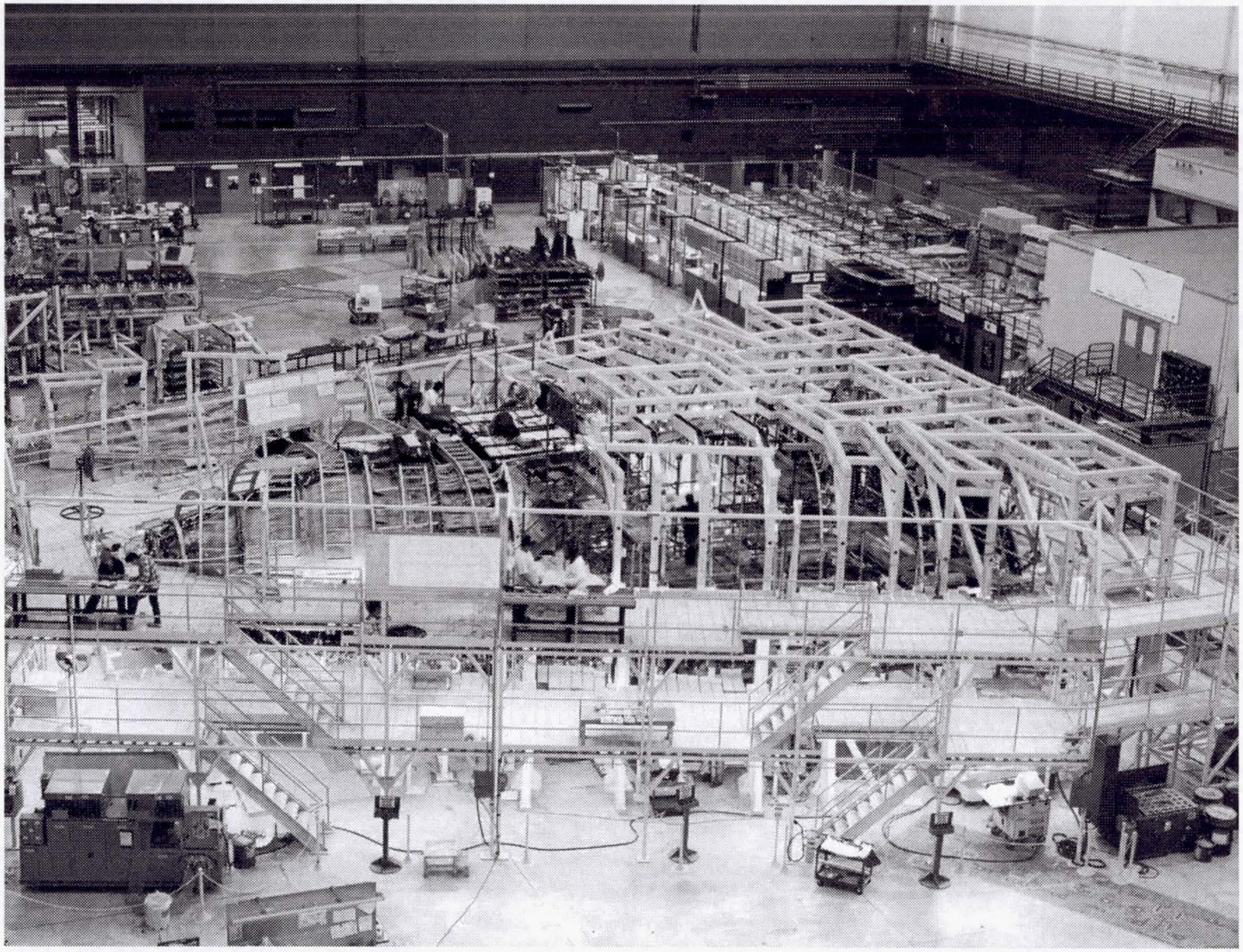
X-33 Assembly Floor

Crews Wiring X-33's Avionics Bay Within Primary Assembly Structure



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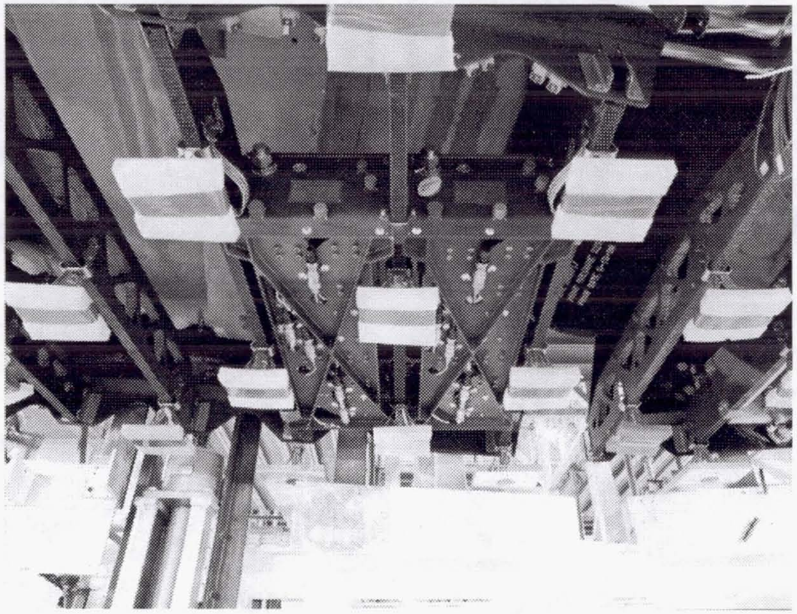
X-33 Assembly Floor

View Looking Aft

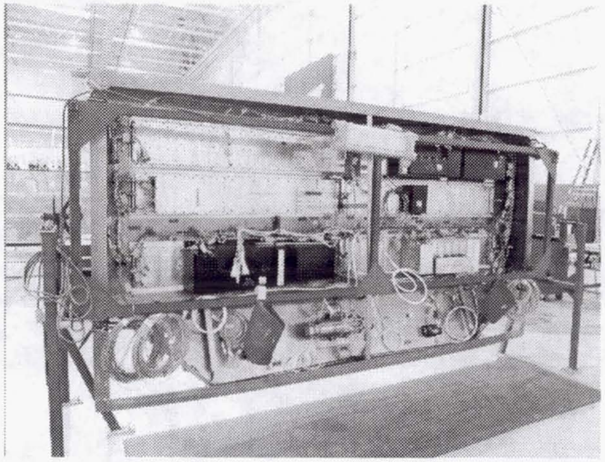
View Left to Right

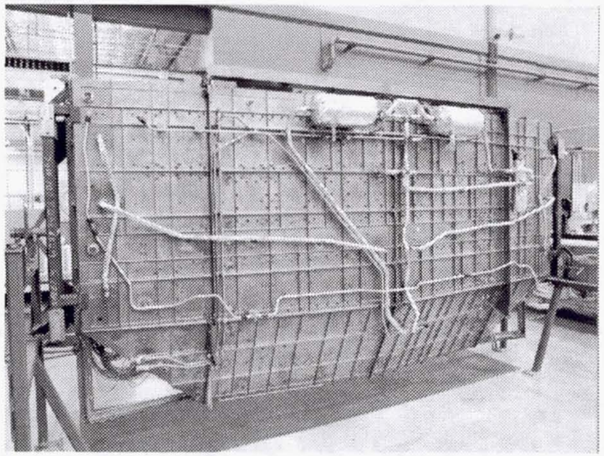
Modified F-15E Strut / F-16 Tire/Wheel

Nose Landing Gear



RCS Auxiliary Propellant Tank and Control Valve Pallets





Avionics Bay

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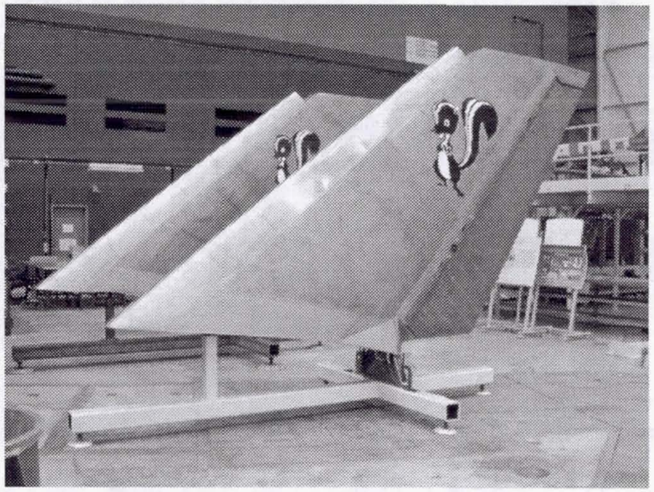
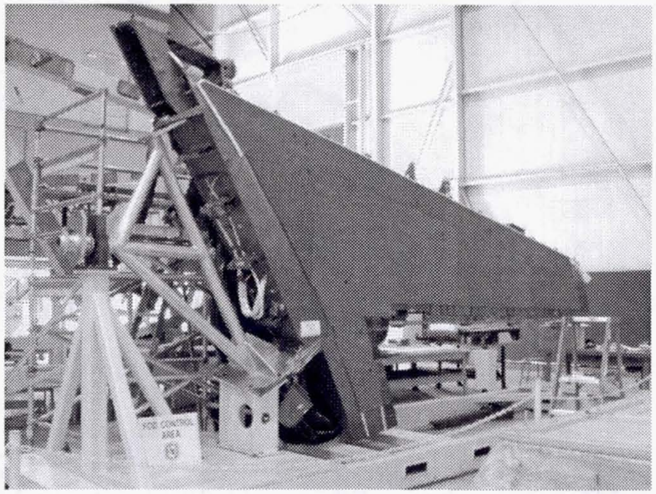
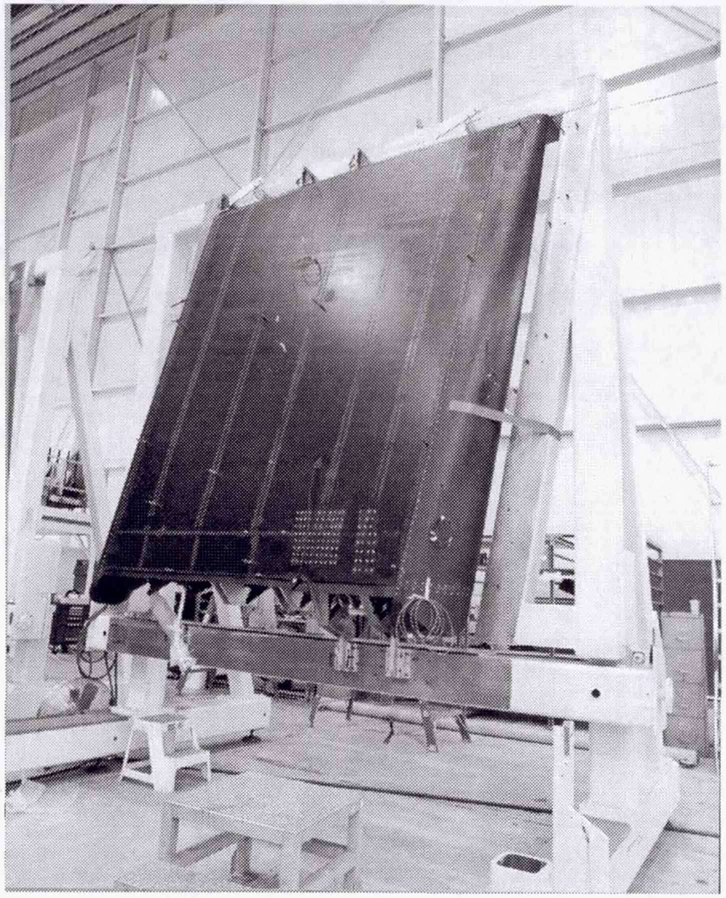
Systems Installations



Tails



Canted Fins



Body Flaps

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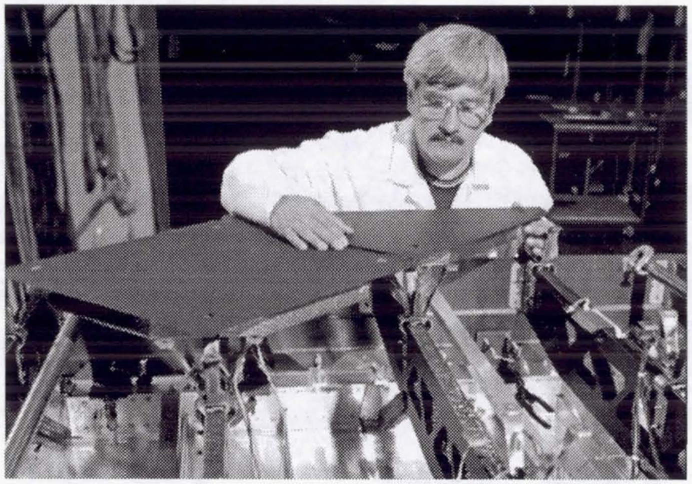
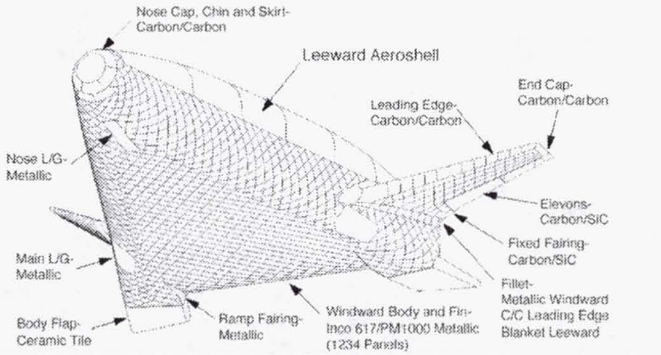
Canted Fins and Tails

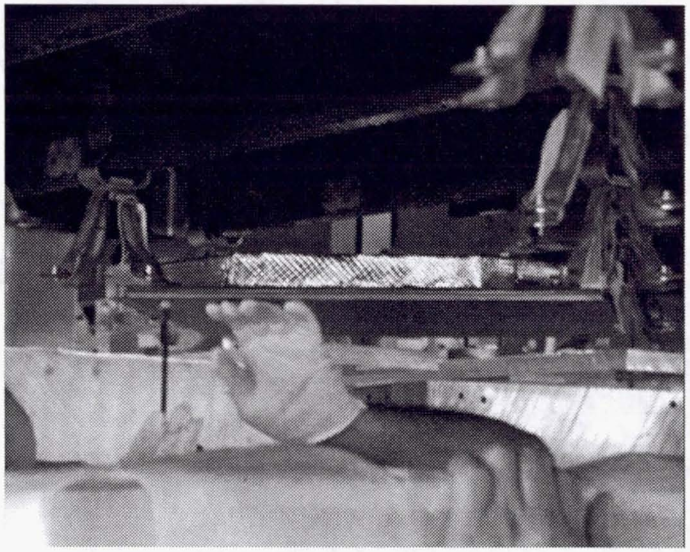
Upper Surface TPS
AFRSI/FRSI Blankets



Metallic TPS Fit Test

Metallic TPS Panel Layout





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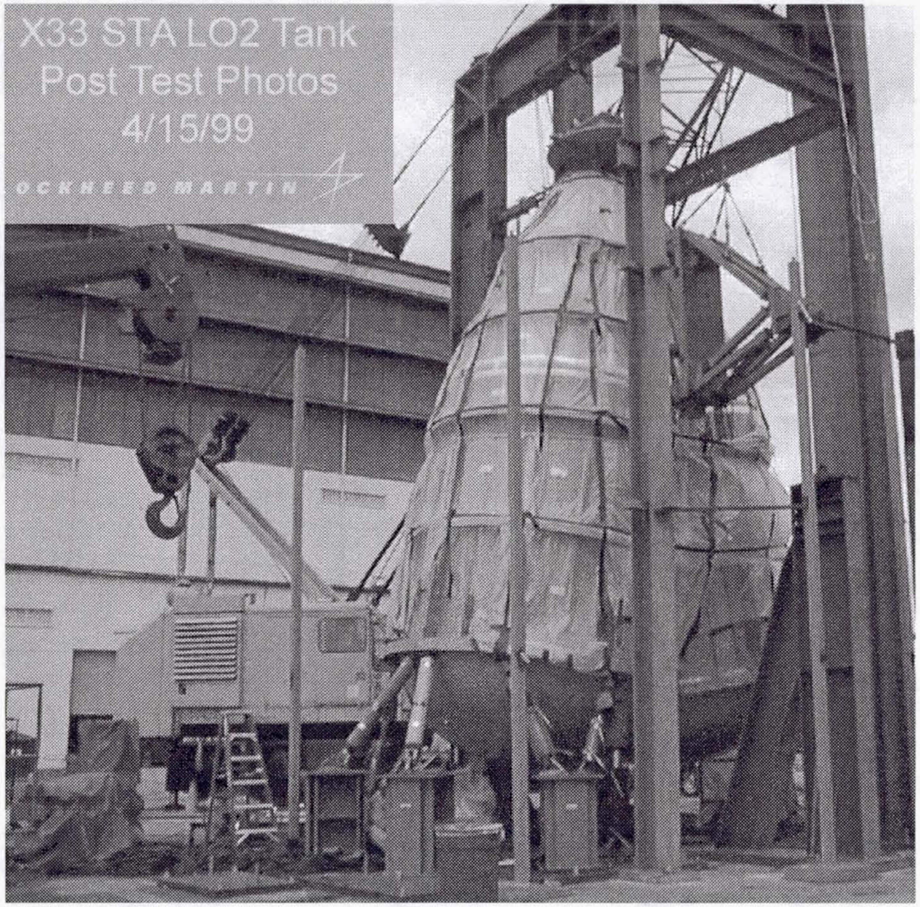
Thermal Protection System



- Test Conducted on Structural Test Article (STA) - Identical to X-33 Flight Tank
- Successfully Completed LO_2 Flight Tank Structural Verification
- STA Tank currently at Glenn Research Center for Propellant Densification Tests

"ST Day 2000: Reducing Risk for the Next Generations" - X33 Update

LO_2 Tank Testing at MSFC

- ♦ Technology
  - Graphite/epoxy Composite Material
  - Primary Load Structure
  - Complex Lifting Body Geometry
  - Unique Stand-off Structure Thermal Shield Internally Cooled
- ♦ Status
  - First Test Tank Suffered Lobe Skin Delamination Following Simulated Launch Loads With Full Load of LH_2
  - Subscale Testing Was Successful
  - Joint NASA/Lockheed Martin Team Conducted Complete Failure Investigation
  - Further Development Required for Large Scale Cryogenic Tanks Serving As Primary Structure

"ST Day 2000: Reducing Risk for the Next Generations" - X33 Update

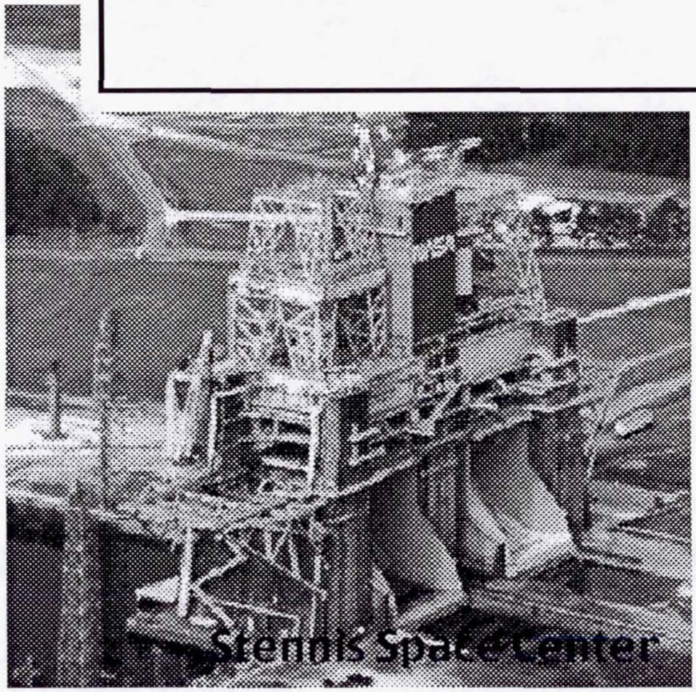
LH2 Composite Tank Test at MSFC

Aerospike Engine, XRS-2200

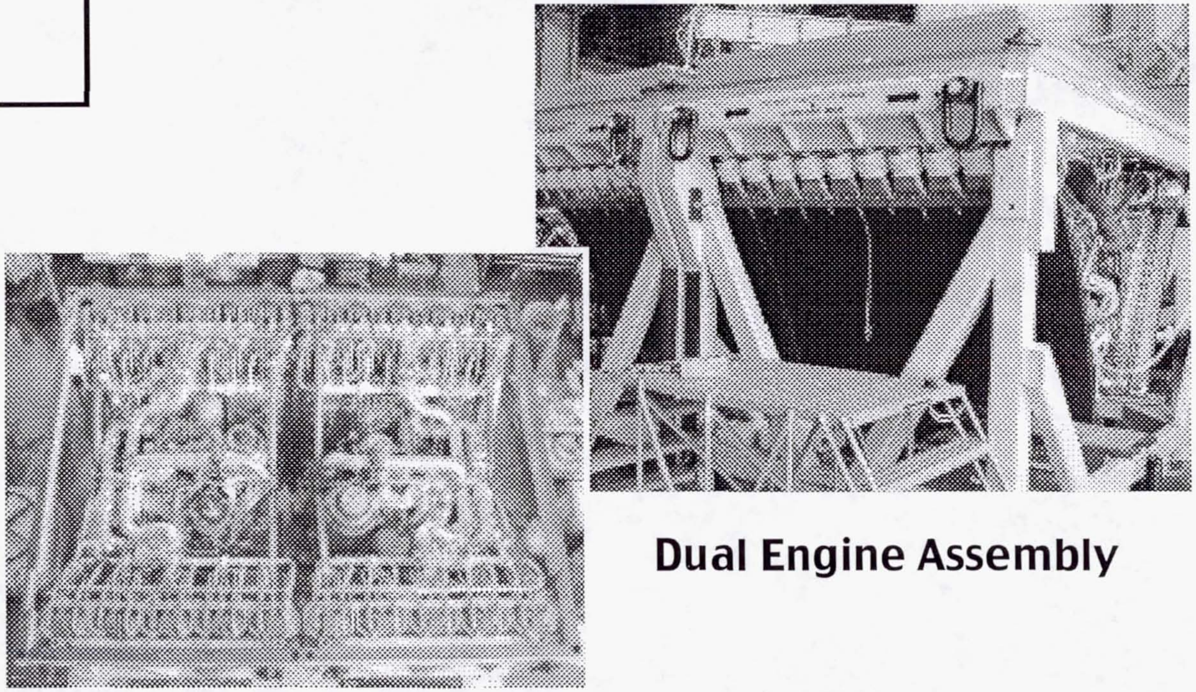
Single Engine

Replace with Quick Time Movie

- ♦ Unprecedented Success With Extensive Test Program
  - Single Thruster: 13 Tests, 985 Seconds
  - Multi Cell: 10 Tests, 49 Seconds
  - Powerpack: 17 Tests, 1506 Seconds
  - Single Engine: 14 Tests, 1563 Seconds
- ♦ No Test Cutoffs Due to Hardware Malfunction
- ♦ Achieved Full Power Level on 6th Test
- ♦ Dual Engine Testing to Begin in October(Flt. Engines)



Stennis Space Center



Dual Engine Assembly

Completed 25 - Acre, $32 Million X-33 Flight Operations Center on Edwards Air Force Base, Calif.

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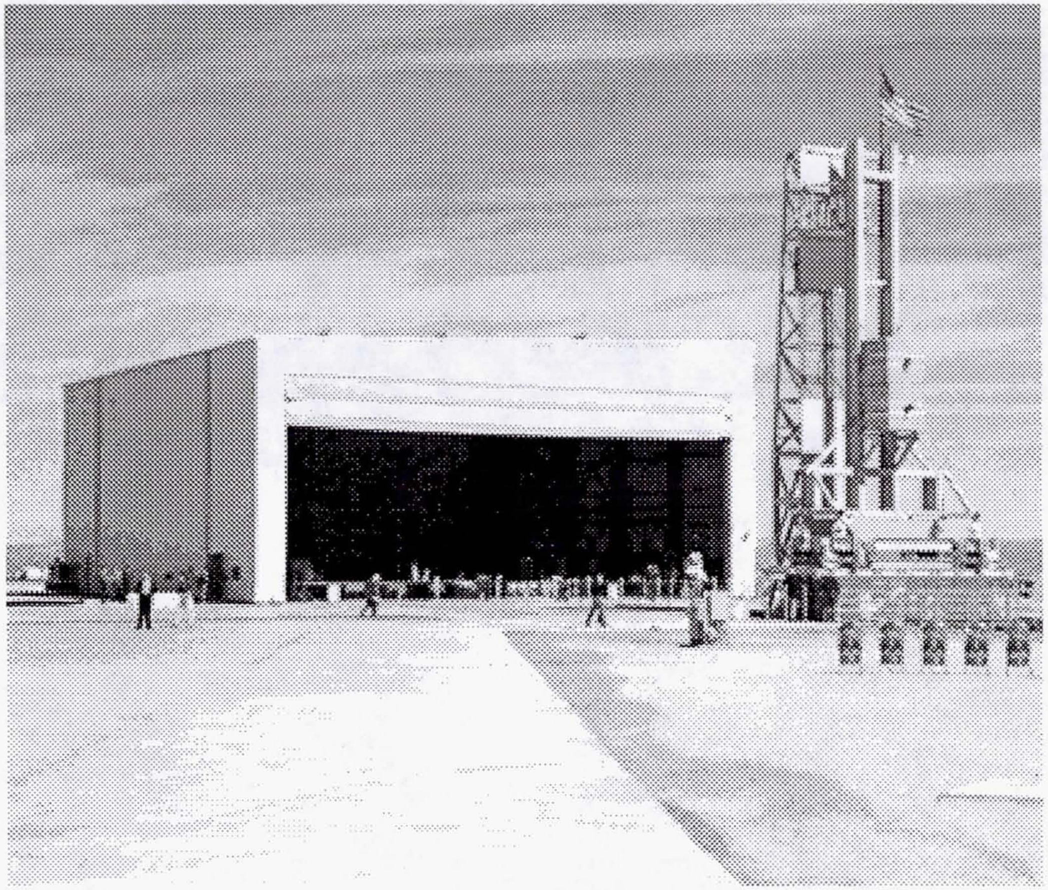
Flight Operations Center

Flight Operations Center



Translating Shelter and Strong Back with Weight Simulator

Eight-Person Control Room

Strong Back with Weight Simulator

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SPACE TRANSPORTATION TECHNOLOGY WORKSHOP
MARSHALL SPACE FLIGHT CENTER
OCTOBER 11-12, 2000

Airframe/TPS Session

- Each session chair(s) should:
  - Coordinate with their co-chair
  - Develop and show an agenda
  - Introduce each speaker
  - Lead with an overview of their area
    - Show your roadmap(s)
    - Show Working Groups and membership
  - Give contact info (name, phone, email)
  - Get your charts plus your presenters charts to Bruce Shelton (bruce.shelton@msfc.nasa.gov or 256-544-5231) by COB Sept 12
- Each speaker should address (as appropriate):
  - Technology goals and objectives
  - Background
  - Current status
  - Major accomplishments
  - Near term plans (including upcoming milestones)
  - Give contact info (name, phone, email)
- Use this as a template

◆ 12:45 - 1:00 Introduction 2nd Gen RLV Airframe	S. Welch
◆ 1:00 - 1:20 Airframe Design and Integration	S. Scotti
◆ 1:20 - 1:40 Aerothermodynamics	C. Miller
◆ 1:40 - 2:00 Structures and Materials	T. Johnson
◆ 2:00 - 2:20 Tanks	D. Smith
◆ 2:20 - 2:40 Thermal Protection Systems	M. Rezin
◆ 2:40 - 3:00 Integrated Airframe Demonstrations	D. Glass
◆ 3:00 - 3:05 BREAK	
◆ 3:05 - 3:30 Introduction 3rd Gen RLV Airframe	D. Bowles
◆ 3:30 - 3:55 Integrated Design and Analysis	T. Gates
◆ 3:55 - 4:20 Integrated Thermal Str. & Materials	B. Jensen
◆ 4:20 - 4:45 Thermal Protection Systems	S. Johnson

Airframe/TPS

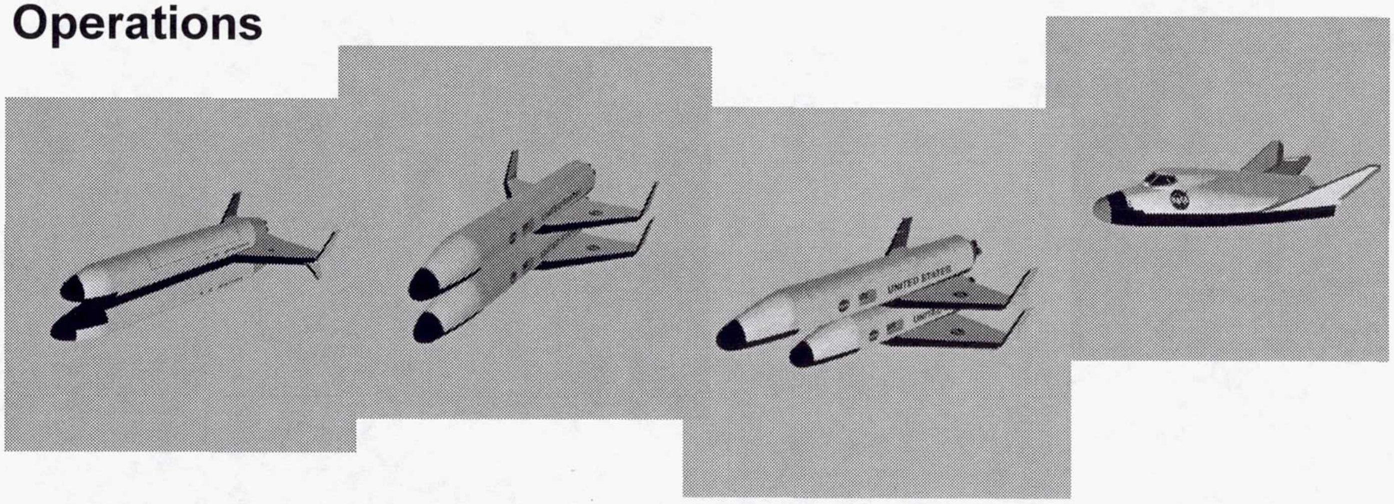
Agenda

- Identification of Airframe Issues and Critical Technology Development Requirements- STAS Reports/Internal NASA Assessments
- 2nd Gen RLV Airframe Requirements Flowdown
- Element Managers
- Project Steering Council
- 2nd Gen RLV Airframe Roadmap
- Review of Elements - Recent Accomplishments
  - Airframe Design and Integration
  - Aero/Aerothermodynamics
  - Structures and Materials
  - Tanks
  - TPS
  - Integrated Airframe/Cryotank Demonstrations

Airframe/TPS

Introduction 2nd Gen RLV Airframe

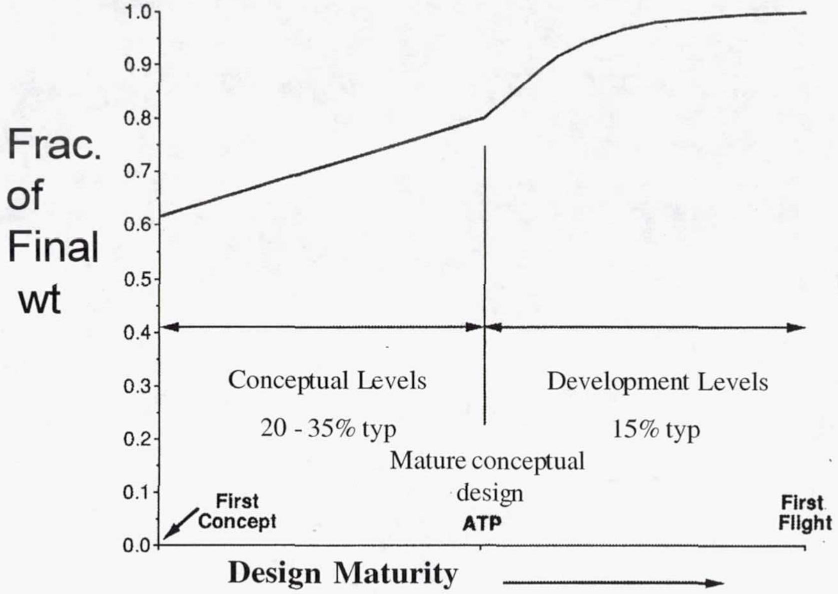
- Range of concepts considered incluude - SSTO, TSTO, HTHL, VTHL, CTV
- Airframe Technical Issues
  - Performance and Weight Margins Too Low
  - Reliability/Reusability - safety goal appears achievable, but vehicle reliability not well understood; need for crew escape identified, but airframe requirements not defined
  - Aero Controls - Separation dynamics, stability and control
  - Propulsion/Airframe Integration
  - Operations



Airframe/TPS

STAS/Internal NASA Assessments

Based on Historical data for New Space Transportation Systems



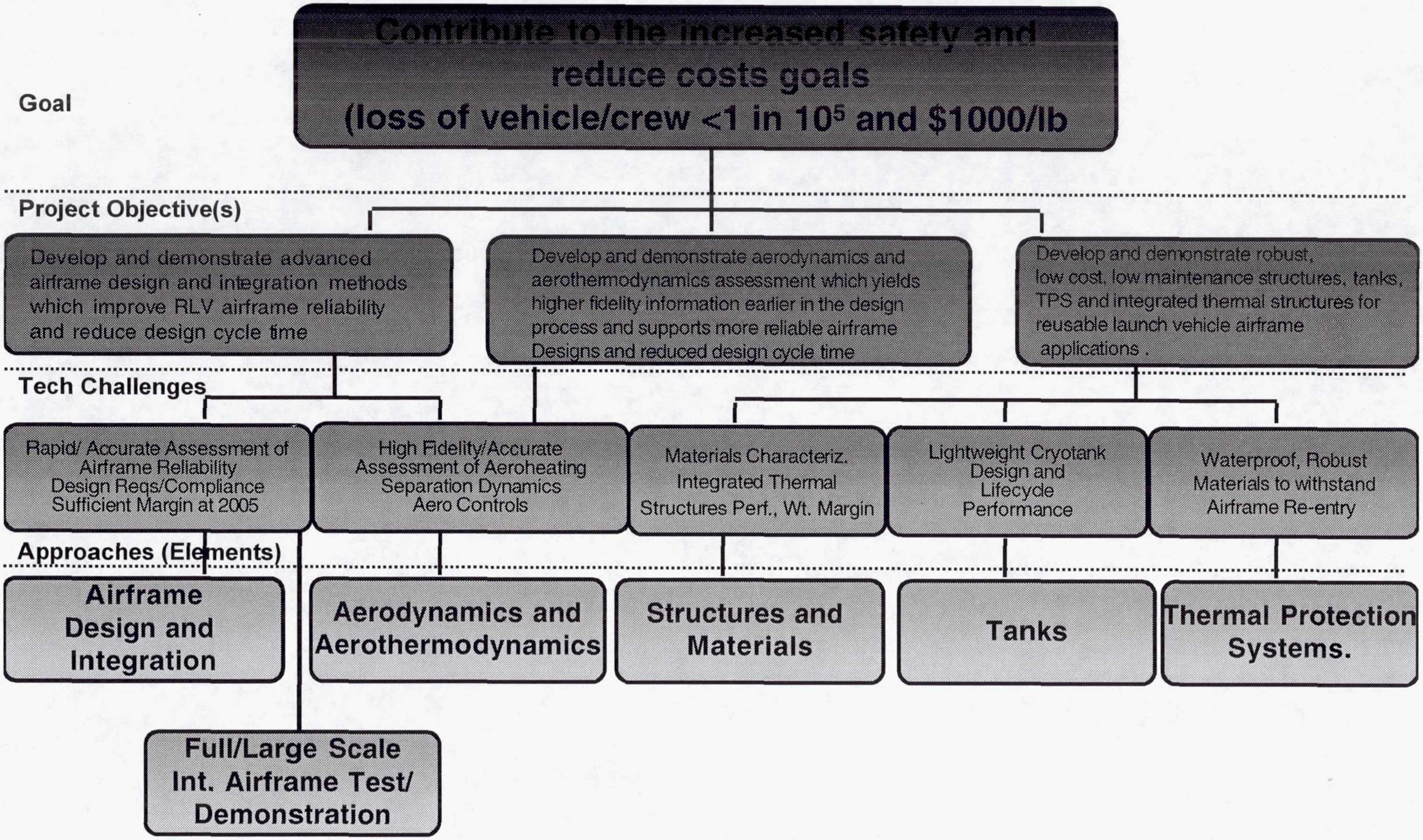
1995 Independent Assessment of X-33 Technology Development Program

"...the committee is concerned about the 15 percent maximum weight-growth margin specified by the program managers; 20 to 25 percent weight-growth margin is typical during the early stage of design development. The need to control weight growth tightly this early in the program places a premium on accurate calculation of structural performance and weight and on early verification that the structure can be built at or below the predicted weight."

-- *from National Academy of Sciences Committee on Reusable Launch Vehicle Technology and Test Program - 1995*

Airframe/TPS

Weight Growth and Weight Margin



Goal

Contribute to the increased safety and reduce costs goals (loss of vehicle/crew <1 in 10^5 and $\$1000$/lb

Project Objective(s)

Develop and demonstrate advanced airframe design and integration methods which improve RLV airframe reliability and reduce design cycle time

Develop and demonstrate aerodynamics and aerothermodynamics assessment which yields higher fidelity information earlier in the design process and supports more reliable airframe Designs and reduced design cycle time

Develop and demonstrate robust, low cost, low maintenance structures, tanks, TPS and integrated thermal structures for reusable launch vehicle airframe applications .

Tech Challenges

Rapid/ Accurate Assessment of Airframe Reliability
Design Reqs/Compliance
Sufficient Margin at 2005

High Fidelity/Accurate Assessment of Aeroheating
Separation Dynamics
Aero Controls

Materials Characteriz.
Integrated Thermal Structures Perf., Wt. Margin

Lightweight Cryotank Design and Lifecycle Performance

Waterproof, Robust Materials to withstand Airframe Re-entry

Approaches (Elements)

Airframe Design and Integration

Aerodynamics and Aerothermodynamics

Structures and Materials

Tanks

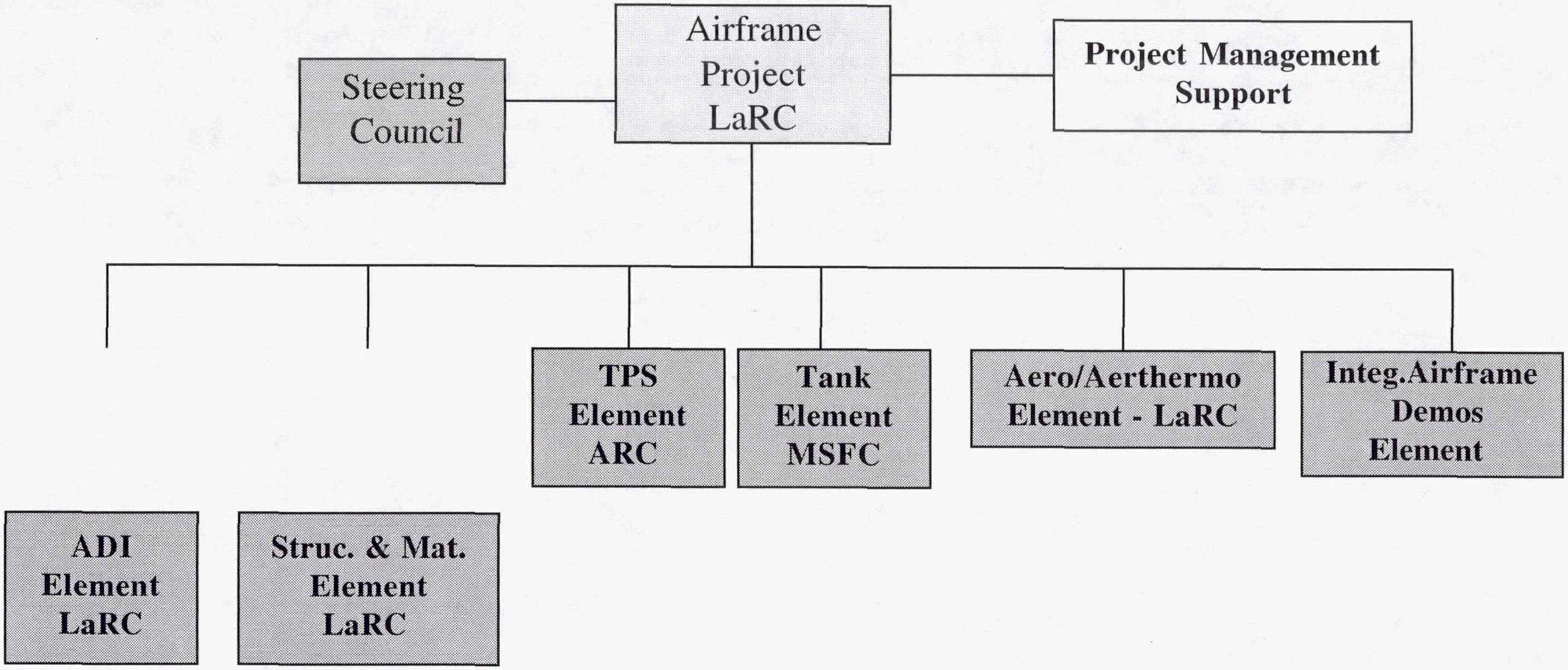
Thermal Protection Systems.

Full/Large Scale Int. Airframe Test/ Demonstration

Airframe/TPS

Airframe Requirements Flowdown

Project Management



Steering Council

Airframe Project LaRC

Project Management Support

TPS Element ARC

Tank Element MSFC

Aero/Aerthermo Element - LaRC

Integ.Airframe Demos Element

ADI Element LaRC

Struc. & Mat. Element LaRC

Airframe/TPS

2nd Gen Airframe Project

Airframe Design and Integration
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Airframe/TPS

Element Managers

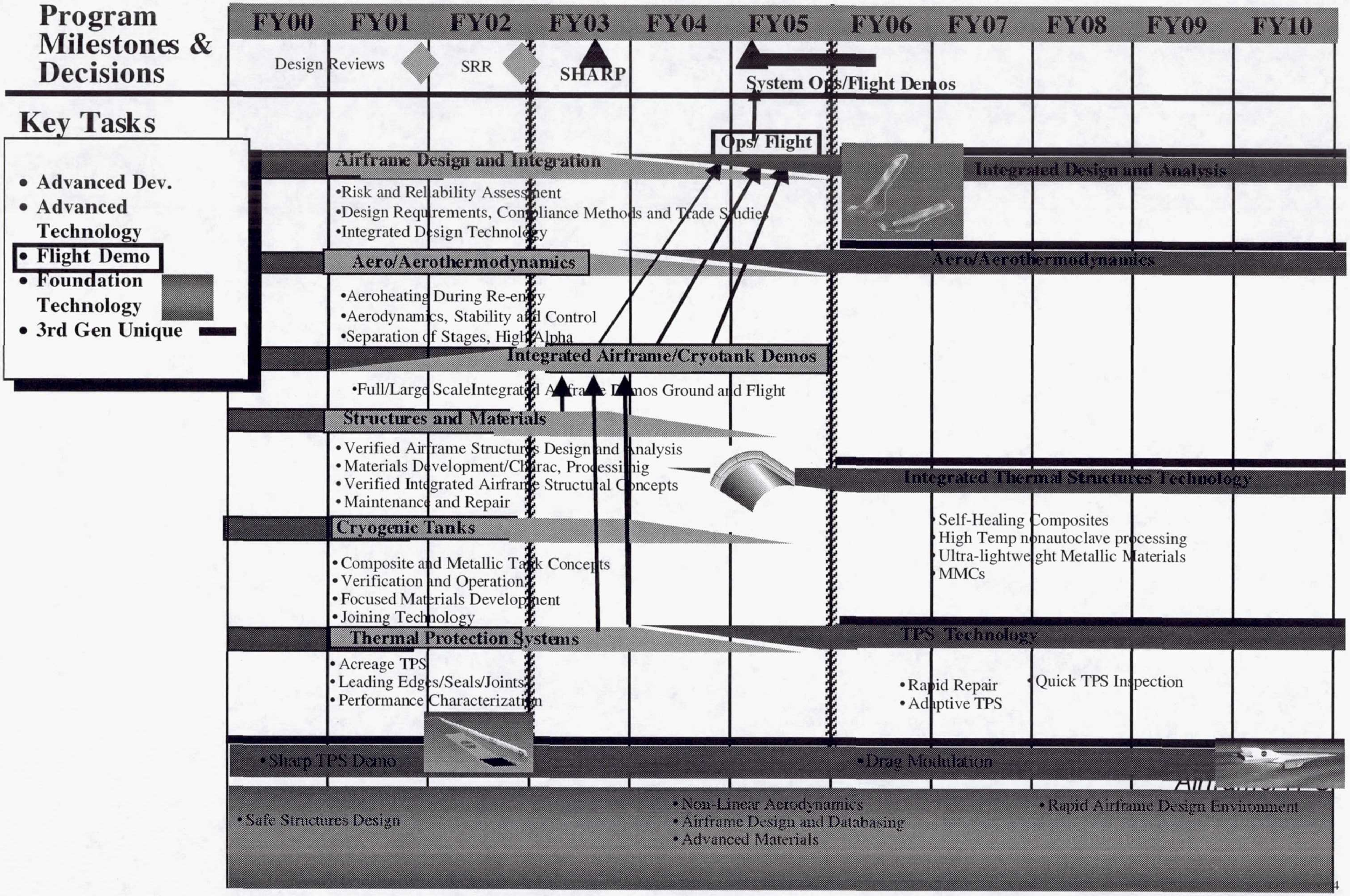
Airframe Project - Sharon Welch

Element Working Groups	Element Managers	Affiliation
Airframe Design and Integration	Kim Bey	NASA
Aero/Aerothermodynamics	Charles Miller	NASA
Structures and Materials	Jim Starnes	NASA
Tanks	Drew Smith	NASA
Thermal Protection Systems	Marc Rezin	NASA
	Consultants	
Full/Large Scale Int. Airframe/ Cryotank Demos	Industry/Element Working Groups	Industry/NASA/DoD
NASA Facilities Development	Jerry Housner	2nd Gen RLV
	James Wycoff	Systems Engineering
	John Balboni	Facilities Req. Team
NASA/DoD Req. Convergence	Michael Stropki	AFRL
	Mike Lovern	BMDO
Structures IVHM	Bob Rogowski	NASA

Airframe/TPS

Airframe Project Steering Council

Airframe/TPS Roadmap



Program Milestones & Decisions

FY00 FY01 FY02 FY03 FY04 FY05 FY06 FY07 FY08 FY09 FY10

Design Reviews

SRR

SHARP

System Ops/Flight Demos

Key Tasks

- **Advanced Dev.**
- **Advanced Technology**
- **Flight Demo**
- **Foundation Technology** ▨
- **3rd Gen Unique** ▬

Ops/ Flight

Airframe Design and Integration

- Risk and Reliability Assessment
- Design Requirements, Compliance Methods and Trade Studies
- Integrated Design Technology

Integrated Design and Analysis

Aero/Aerothermodynamics

- Aeroheating During Re-entry
- Aerodynamics, Stability and Control
- Separation of Stages, High Alpha

Aero/Aerothermodynamics

Integrated Airframe/Cryotank Demos

- Full/Large ScaleIntegrated Airframe Demos Ground and Flight

Structures and Materials

- Verified Airframe Structures Design and Analysis
- Materials Development/Charac, Processinig
- Verified Integrated Airframe Structural Concepts
- Maintenance and Repair

Integrated Thermal Structures Technology

- Self-Healing Composites
- High Temp nonautoclave processing
- Ultra-lightweight Metallic Materials
- MMCs

Cryogenic Tanks

- Composite and Metallic Tank Concepts
- Verification and Operations
- Focused Materials Development
- Joining Technology

Thermal Protection Systems

- Acreage TPS
- Leading Edges/Seals/Joints
- Performance Characterization

TPS Technology

- Rapid Repair
- Adaptive TPS
- Quick TPS Inspection

- Sharp TPS Demo
- Drag Modulation

- Safe Structures Design
- Non-Linear Aerodynamics
- Airframe Design and Databasing
- Advanced Materials
- Rapid Airframe Design Environment

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Upper Stages

(Breakout Session, Oct. 12, 10 a.m.)

Mr. Curtis McNeal, Manager, Upper Stages, MSFC

The Upper Stages Project -- a partnership between NASA, the U.S. Air Force and industry -- is developing reduced-cost technologies for potential use in 2nd Generation RLV space transportation system architectures. This session will examine peroxide-fueled liquid and liquid/hybrid propulsion systems now in development -- technologies expected to substantially lower operation costs for future transportation systems.

Briefing Objective

- **Familiarize attendees with the peroxide propulsion development currently underway**
    - **please don't propose work already underway**
- **Provide attendees with a current status of work underway**
    - **consistent with the proprietary nature of some of the work**
- **Provide contact points for teaming/partnerships**
    - Follow on work should be coordinated with initial leader of activity
    - This work may provide critical technology for a higher level system application
- **Familiarize attendees with the proposed NASA lead developments**
- **Provide a forum for answering questions**

Advanced Peroxide/RP Propulsion Roadmap

Upper Stage Technologies Project

Major Milestones & Decisions

Key Tasks

- Conceptual Design/ Vehicle Integration
- Component/ Subsystem Demo
- Integrated Demo

Objectives

◆ Demo needed propulsion technology to enable the next generation RLV

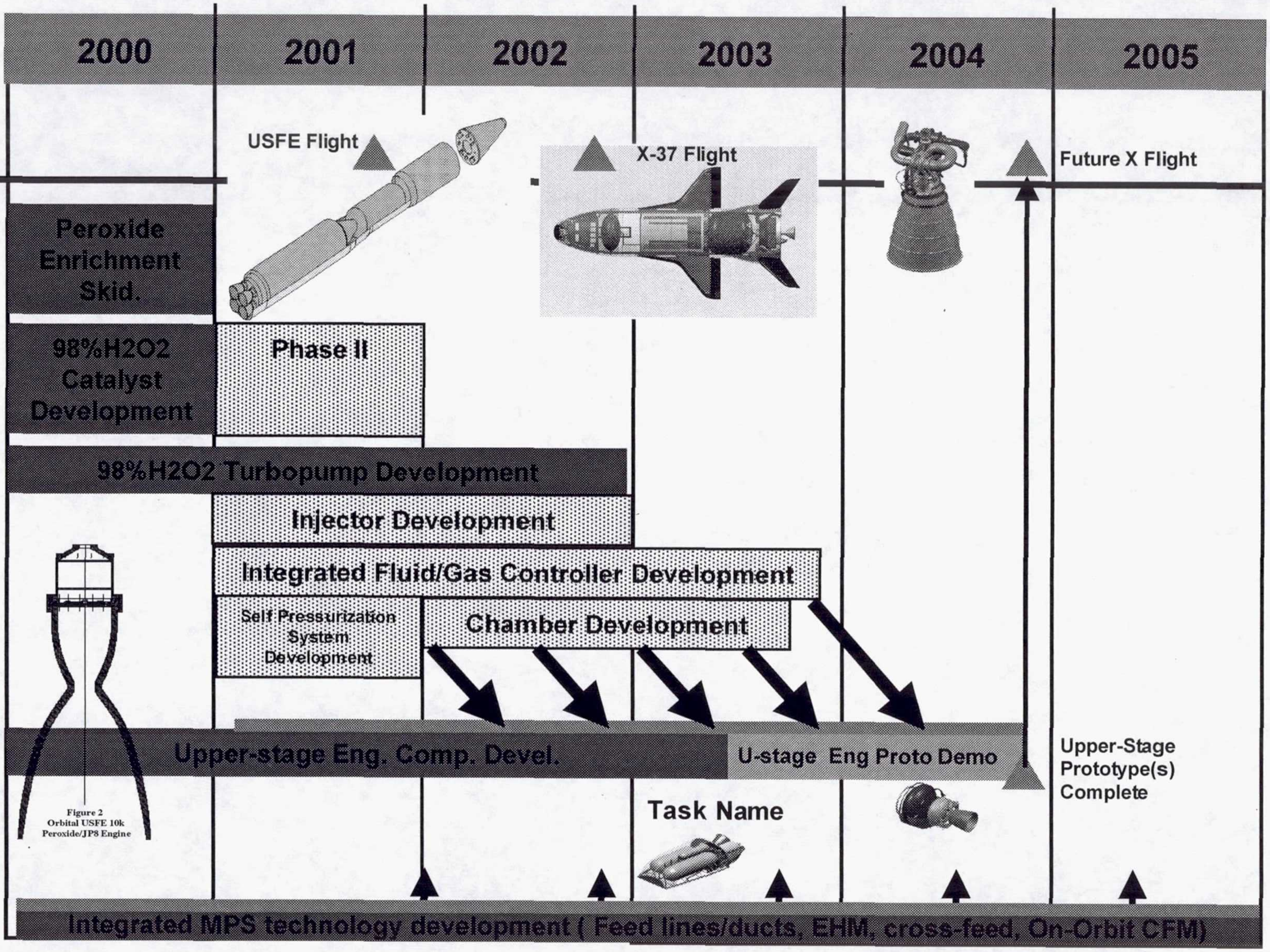


Figure 2 Orbital USFE 10k Peroxide/JP8 Engine

Peroxide Propulsion

ASTP → 2nd Generation RLV

ASTP

- Technology Development
- Subscale
- 25 year horizon
- High Risk Tolerance
- Component Demonstrations
- $115M in FY01
- Get it to work

2nd Generation RLV

- Advanced Development
- Prototyping
- 5 year horizon
- Low Risk Tolerance
- Full System Demonstrations
- $290M in FY01 Budget
- Ensure competition

Peroxide/Hybrid Propulsion Roadmap

ST Day 2000 Workshop---Upper Stages

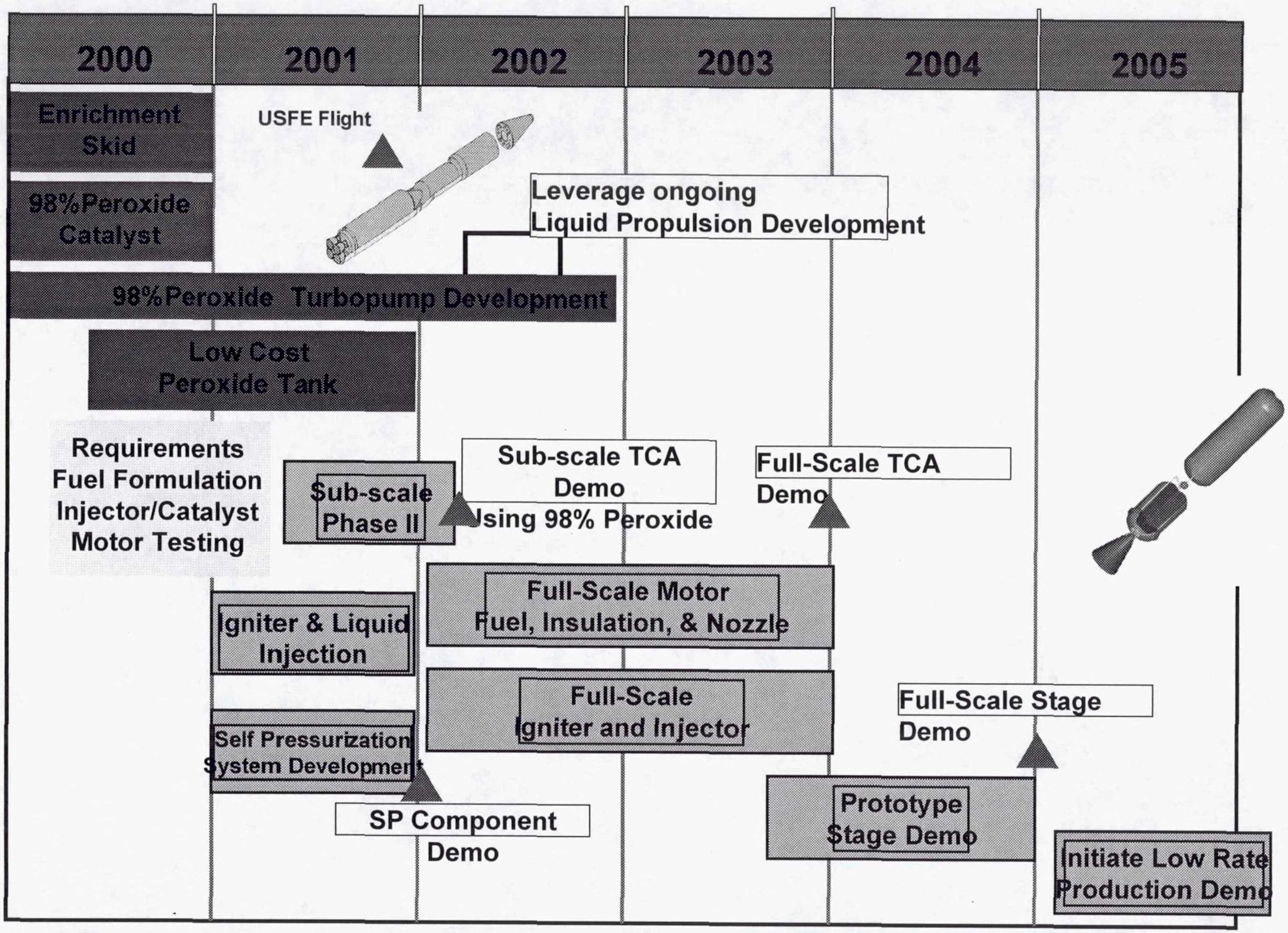
Major Milestones & Decisions

Key Tasks

- Conceptual Design/ Vehicle Integration
- Component/ Subsystem Demo
- Integrated System Demos

Objective

Mature propulsion technology to enable 2GRLV and DoD stage



2000 | 2001 | 2002 | 2003 | 2004 | 2005

Enrichment Skid

98%Peroxide Catalyst

USFE Flight

Leverage ongoing Liquid Propulsion Development

98%Peroxide Turbopump Development

Low Cost Peroxide Tank

Requirements Fuel Formulation Injector/Catalyst Motor Testing

Sub-scale Phase II

Sub-scale TCA Demo Using 98% Peroxide

Full-Scale TCA Demo

Igniter & Liquid Injection

Full-Scale Motor Fuel, Insulation, & Nozzle

Full-Scale Igniter and Injector

Self Pressurization System Development

SP Component Demo

Full-Scale Stage Demo

Prototype Stage Demo

Initiate Low Rate Production Demo

▨ Joint Efforts

░ Current Efforts

▒ Planned Efforts

Technology Working Group

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Existing NASA Peroxide Propulsion Development

Hazardous Materials Testing-FMC

Peroxide Enrichment Skid-OSC/Degussa Huls

Catalysts Development-Aerojet/P&W/TRW/Boeing/ Purdue/GK

Advanced Torch Igniter-Boeing Rocketdyne

Turbopump Development-Boeing Rocketdyne

Pressure Fed 90% Peroxide/RP Engine-OSC/GK/AAE

Integrated Peroxide Compatible Composite Common Bulkhead Structure-OSC/Aspect Engineering/AFRL

AR2-3 X-37 Engine Development Program-Boeing Rocketdyne

Peroxide Hybrid Development-LMA/Thiokol/Boeing

FMC Hazardous Materials Evaluation

Description- FMC will perform a series of industry standard tests to quantify the production, storage, and shipping hazards associated with 98% peroxide. Materials compatibility will also be determined for a limited number of samples. Work to be performed in the FMC New Jersey and Texas laboratories. FFPC.

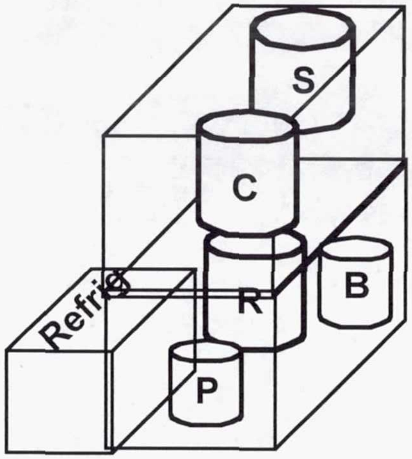
Status- Contract signed.

Contacts Mike Pinsky - 609- 951-3152

Future - This data will be used for safety analyses of advanced propulsion system designs for both Air Force and NASA missions.

Orbital/Degussa Huls Peroxide Enrichment Skid

Description-Bulk supplies of 98% concentration peroxide are needed to support NASA's research in high performance peroxide propulsion. An enrichment skid capable of concentrating commercially available product (87-90%) to 98% concentration will ensure a reliable supply until such time as a commercially viable supply becomes available. Orbital/Degussa will develop and demonstrate a safe, "turn key", portable concentrator that can produce 1000 lbs of 98% peroxide/day. The concentrator will be operated first at SSC and then at other test sites as needed to support NASA's research projects. CPIF.



Status-System Requirements established, PDR held, Hazards Analysis reviewed, CDR held, Fabrication begun, stell framework complete, tanks complete, plumbing installation underway. Checkout planned at Degussa last half of October. Installation at SSC first half of November. Operational at SSC in December.

Contacts- Dan Pauls - 334-443-2607
Stacy McMahon- 201-807-3205

Future- The skid is being installed at the Stennis Space Center where it will be operated in support of SSC conducted tests. Copies of the skid may be procured from Degussa Huls to support other requirements.

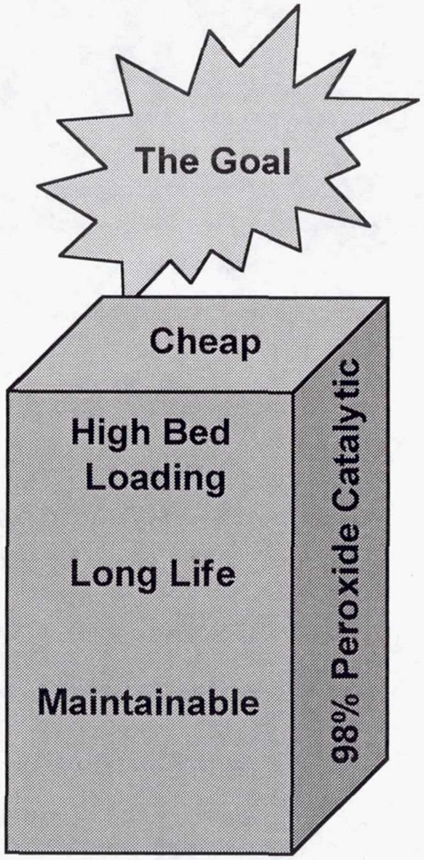
TRW Lead Advanced Catalyst Development

Description- Develop and test in a common test rig 3 potential advanced 98% peroxide catalyst. One catalyst will be wire screen based, one ceramic honeycomb based, and one pellet based. Catalyst will be tested for 1000 seconds to determine life and reuse capability. Testing to be performed at TRW facilities. FFPC

Status-All three catalysts ready for test. Test delayed by late delivery of 98% peroxide. Tests to begin week of 2 October

Contacts- TRW, William Kruse, 310-813-9268
General Kinetics, Eric Wernimont - 945-768-0166
Purdue University, John Rusek -765-494-4782

Future-Catalyst systems developed by this group will be developed into integral components in TRW engines and supplied to other industry peroxide system designers as required.



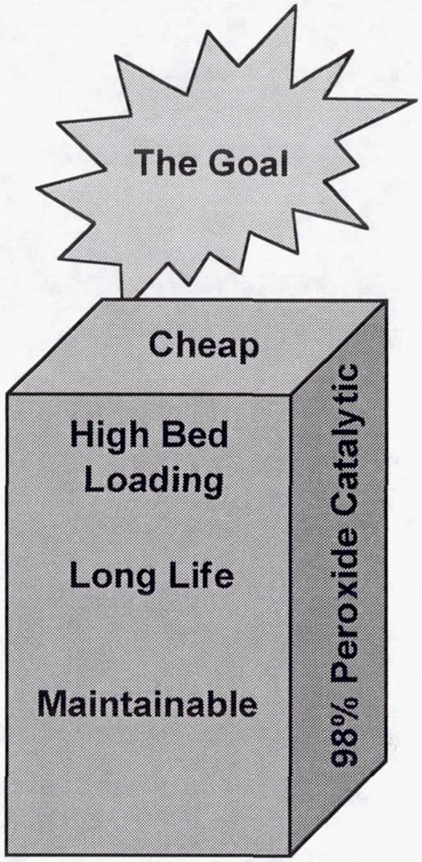
Aerojet Advanced Catalyst Development

Description- Develop and test an advanced 98%peroxide monolythic substrate catalysts. Catalyst will be tested first for its efficiency in 90% peroxide, then for long life (1000 seconds) in 90% peroxide. After successful demonstration at 90% the substrate processing will be altered for 98% peroxide catalysis and the efficiency and life determined with the 98% peroxide. Testing to be performed at Aerojet provided facilities. Cooperative agreement.

Status- in house 90% catalyst developed and tested. Life tests planned this fall.

Contact point - Adam Siebenhaar, 916-355-2535

Future-Catalyst systems developed by Aerojet will be developed into integral components in Aerojet engine systems and may be supplied to other industry peroxide system designers.



The Goal

Cheap

High Bed Loading

Long Life

Maintainable

98% Peroxide Catalytic

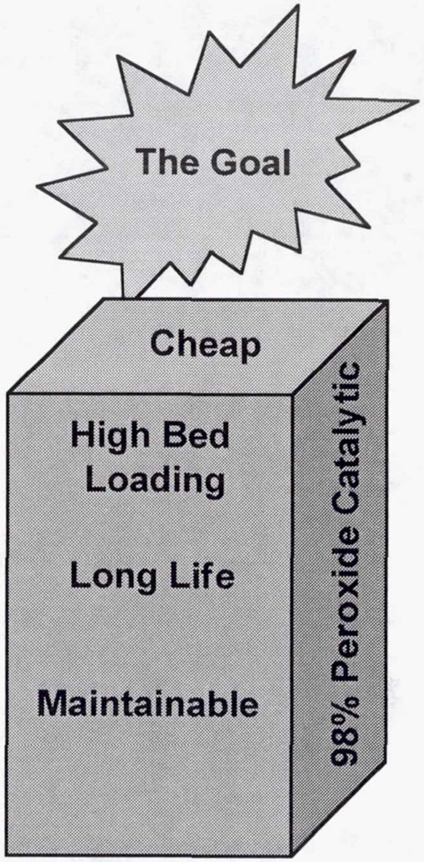
Boeing Rocketdyne Advanced Catalyst Development

Description- Develop and test an advanced 98%peroxide catalyst. Catalyst will be tested for its efficiency at Boeing facilities, and then for long life (1000 seconds min) at SSC E3 facilities. Multiple catalysts configurations are planned for test at SSC. Cooperative agreement.

Status- Catalysts development continues at Rocketdyne.

Contacts- Jeff Mays-818 586-0128

Future-Catalyst systems developed by Boeing Rocketdyne will be developed into integral components in Boeing Rocketdyne engine systems and may be supplied to other industry peroxide system designers.



Pratt & Whitney Lead Advanced Catalyst Development

Description- Test an advanced 98%peroxide catalysts on the E3 stand at SSC. Catalyst developed by P&W IRAD funds. Multiple catalysts configurations are planned for test at SSC. Space Act Agreement.

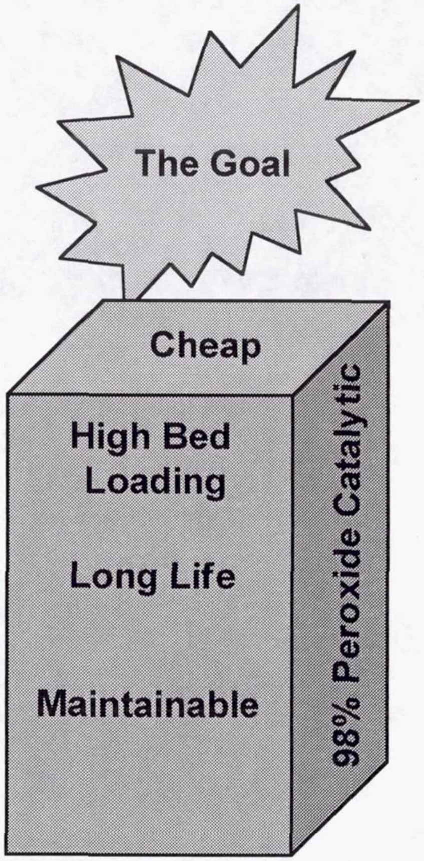
Status- Multiple catalysts tested at the Stennis Space Center. More than one catalyst system provided successful decomposition. Best catalyst tested for more than 500 seconds without degradation.

Contacts - P&W - Jeff Breen - 561-796-7407

P&W - Bill Watkins - 561-7965840

General Kinetics, Eric Wernimont - 945-768-0166

Future-Catalyst systems developed by Pratt & Whitney will be developed into integral components in Pratt & Whitney engine systems and may be supplied to other industry peroxide system designers.



Boeing Rocketdyne Advanced Torch Igniter

Description- Develop a 98% peroxide/JP8 torch igniter with the thermal capacity to initiate thermal decomposition of 98% peroxide when it it injected directly into a main combustion chamber. Testing to be performed at SSTF. Cooperative agreement. Cooperative agreement gives NASA the right to purchase 4 of these igniters to support NASA mission requirements.

Status- Design underway at Rocketdyne

Contacts- Jeff Mays-818 586-0128
Terry Lorier - 818-586-1129

Future- Igniters of this design will be incorporated into future Boeing Rocketdyne engine systems and may be provided to other industry peroxide system designers.

Boeing Rocketdyne Advanced Peroxide/JP8 Turbopump

Description- Development and demonstration of a low cost/low parts count 98% compatible peroxide/JP8 turbopump. Pump demonstration to be performed at SSTF. Cooperative agreement. Cooperative agreement gives NASA the right to purchase 4 of these igniters to support NASA mission requirements.

Status - Design requirements established. Preliminary concept design review held. PDR planned for January 2001.

Contacts - Terry Lorier - 818-586-1129
Shawn Kurizaki - 818-586-7609

Future - Pump design can be tailored to meet a number of missions as final detail mission requirements become available.

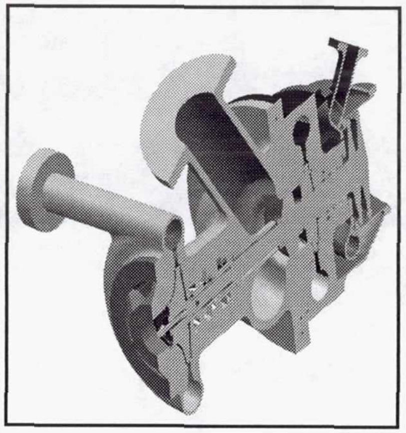


Figure 6 Peroxide Turbopump

USFE 10K Peroxide/JP8 Pressure-Fed Engine

Description- A joint AF/NASA development and demonstration of a current design practices pressure fed 90% peroxide/JP8 ablative chamber/nozzle engine. Work being performed at Orbital, GK, and SSC facilities. CPIF

Status - Catalyst bed, injector, and composite ablative chamber/nozzle all successfully developed. Two long term 140 second burns completed, Engine fluid distribution and valves, start and shutdown sequence, and purge system to be developed in 2001. Integrated engine/TVC/pressurized tank structure demonstration planned in 2002.

Contacts - Dave Crockett - 480-814-6659

Future - Engine to be used to power an upper stage flight demonstration for the Air Force in 2003.

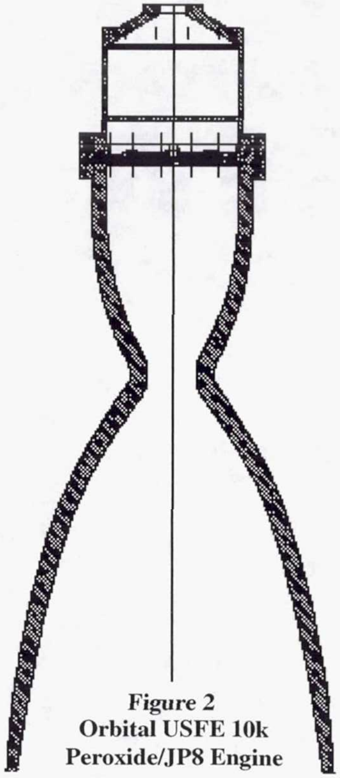
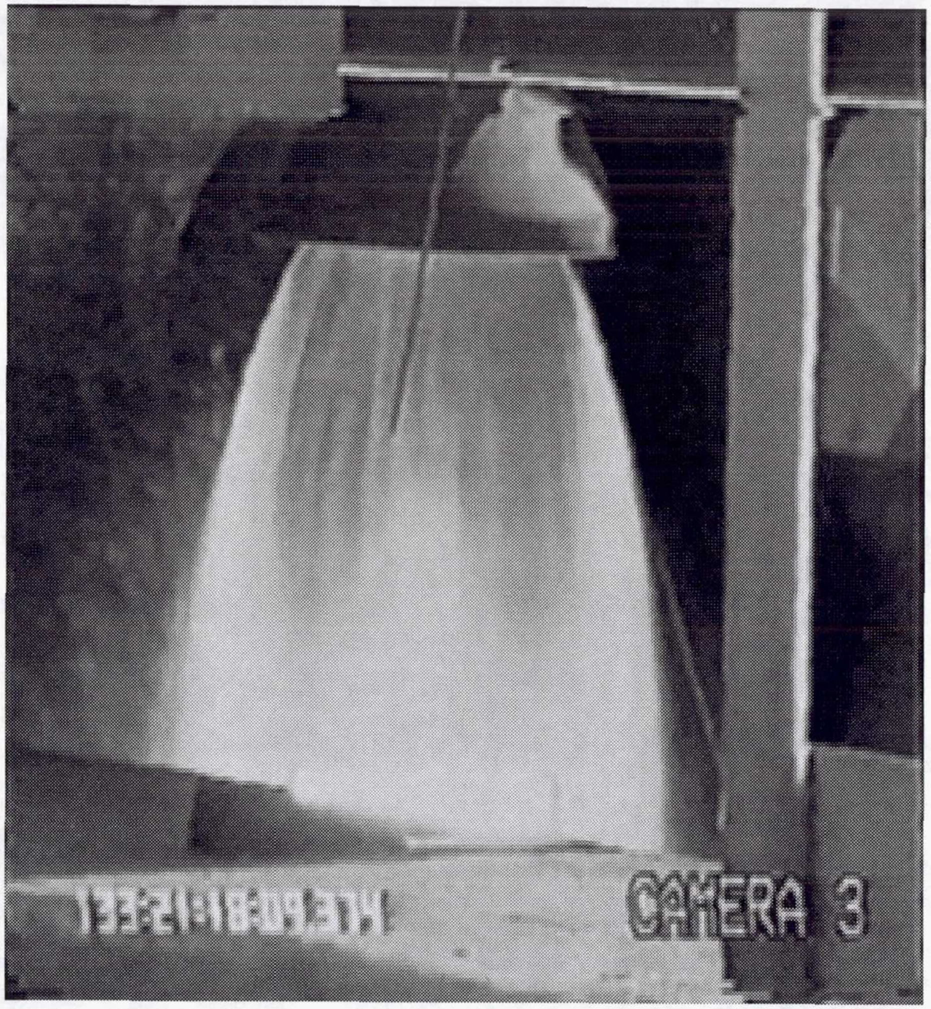


Figure 2
Orbital USFE 10k
Peroxide/JP8 Engine

The USFE 10K Peroxide/JP8 Engine

Parameter	Value
Propellants	85% HTP/JP-8
Vacuum Thrust, lbf	10,000
Chamber Pressure, psia	500
Mixture Ratio	6.0
Nozzle Expansion Ratio	40 (five for ground tests)
Chamber Contraction Ratio	7.1
Delivered Specific Impulse, s	278
Flow rate, lb/s	36.0
Burn Time, s	200
Engine Envelope	60 in. long, 40 in. diameter

Engine Component	Material	Weight Estimate
Gimbal Mount	SS304L	7
Distribution Dome	7075AL	25
Catalyst Housing	SS304L	37
Catalyst System	SS304L/Ag/Ni	39
Injector	SS304L	30
Chamber/Nozzle	F554 Fiber	103
Miscellaneous	SS304L/7075Al	17
Total		258



USFE Engine development has been successful

- conducted over 125 tests
- accumulated nearly 30 minutes of test time
- accumulated over 300 seconds of bipropellant operation using ablative chambers, including two long-duration tests of 140s and 150 s
- accumulated over 700 seconds of run time on a single cat bed without performance degradation
- demonstrated throat recession rates of less than 0.001 in/s
- demonstrated C^* efficiencies greater than 0.97 at nominal operating condition
- tested twelve different test article configurations
- tested both 85% and 90% peroxide from two different manufacturers
- demonstrated multiple restarts
- demonstrated throttling to 10% in monopropellant mode and to 20% in bipropellant mode
- maintained perfect safety record

USFE Integrated Composite Stage Structure

Description- A joint AF/NASA development and demonstration of a common bulkhead peroxide compatible all composite upper stage structure. Effort being performed at AE, AFRL, and Orbital facilities. CPIF

Status - A peroxide compatible composite material was identified in 1998, Subscale tanks were fabricated and peroxide compatibility demonstrated in 1998. A subscale composite stage structure has been designed and fabrication is nearing completion. Full scale stage structure design is planned in 2001 followed by fabrication of a full scale structure for ground test in 2002.

Contacts- Orbital Sciences- Dave Crockett - 480-814-6659
Aspect Engineering - Zack Taylor - 714-692-7779

Future - Stage demonstration provides the basis for future mission specific designs.

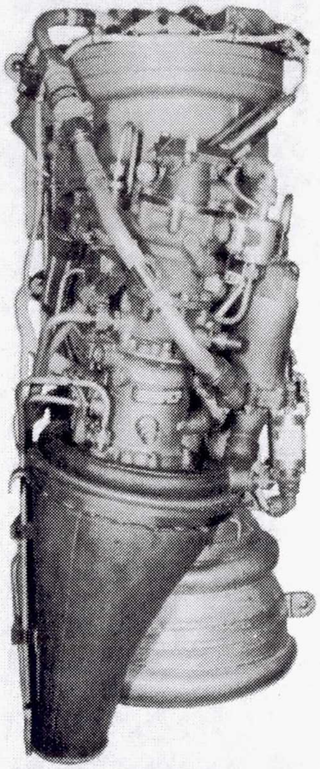
Boeing Rocketdyne AR2-3 Demonstration Program

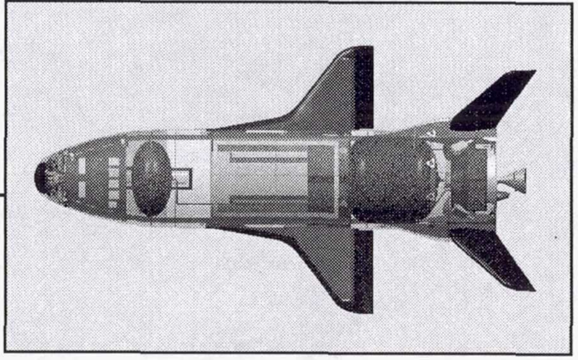
Description- A progressive development and demonstration of peroxide propulsion's application to on-orbit space transportation mission needs. The effort began with the refurbishment of an AR2-3 for initial ground test and development of control valve sequences for on-orbit operation. Two additional engines are being produced. The first engine will undergo a stringent qualification program. The second engine will undergo acceptance tests and be installed in the X-37 for flight demonstration.

Status- The initial development tests were completed in the spring of 2000. The qualification tests and the acceptance test of the flight engine are planned in early 2001.

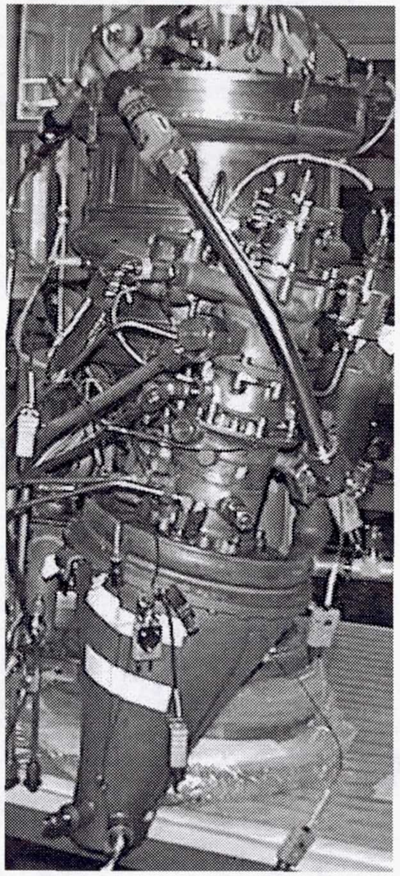
Contacts - Kathy Butler - 818-586-1158
Terry Lorier - 818-586-1129

Future - This engine will form the basis for more advanced designs which will meet future Air Force and NASA in-space propulsion needs.





AR2-3 Engine Performance.



Propellants	90%H_2O_2/JP
Thrust, vac (lbf)	6600
Isp, vac (sec)	246
Chamber pressure (psia)	560
Mixture ratio	6.5
Area ratio	12:1
Length (in)	32
Engine diameter (in)	20
Weight (lbm)	225
Gimbal angle (degrees)	0
No. or restarts	multiple
Engine life	>150 minutes

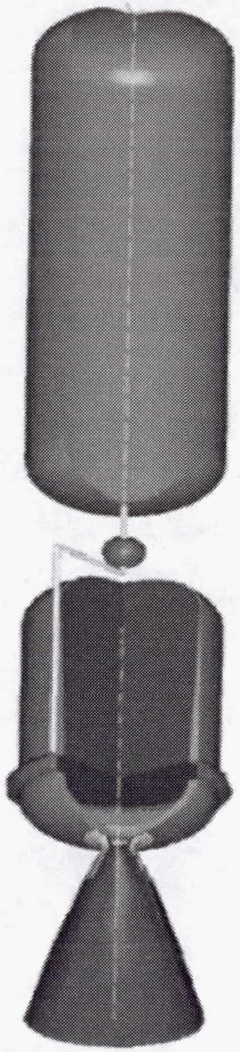
LMA Lead Peroxide/Hybrid Propulsion Development

Description- Development of design requirements, identification of technical issues, fabrication of subscale test articles, and the test and evaluation of the test articles. Work to be performed at SSC and Thiokol facilities. CPIF

Status - Basic small scale fuel formulation work complete with both Gox and decomposed peroxide. 11inch motor test articles in fab. Next test series at SSC in December 2000. Final 24inch motor test series in February 2001.

Contacts - LMA - Terry Abel -256-544-3275
Thiokol - Steve Alexander - 256-544-2582
Boeing Rocketdyne - Scott Claflin - 818-586-0329

Future - This work forms the basis for full scale design of low cost storable peroxide hybrid motors for 2nd Gen RLV expendable upper stage mission needs or Air Force and Army applications.



Proposed NASA Lead Developments

Composite Upper-Stage Tanks for 90 Percent Hydrogen Peroxide

Toroidal Upper-Stage Tank Development

Solar Thermal Propulsion: Integration and Demonstration of Critical Technologies

In-Space Propulsion Systems Analysis Tool Development Task

Composite Upper-Stage Tanks for 90 Percent Hydrogen Peroxide

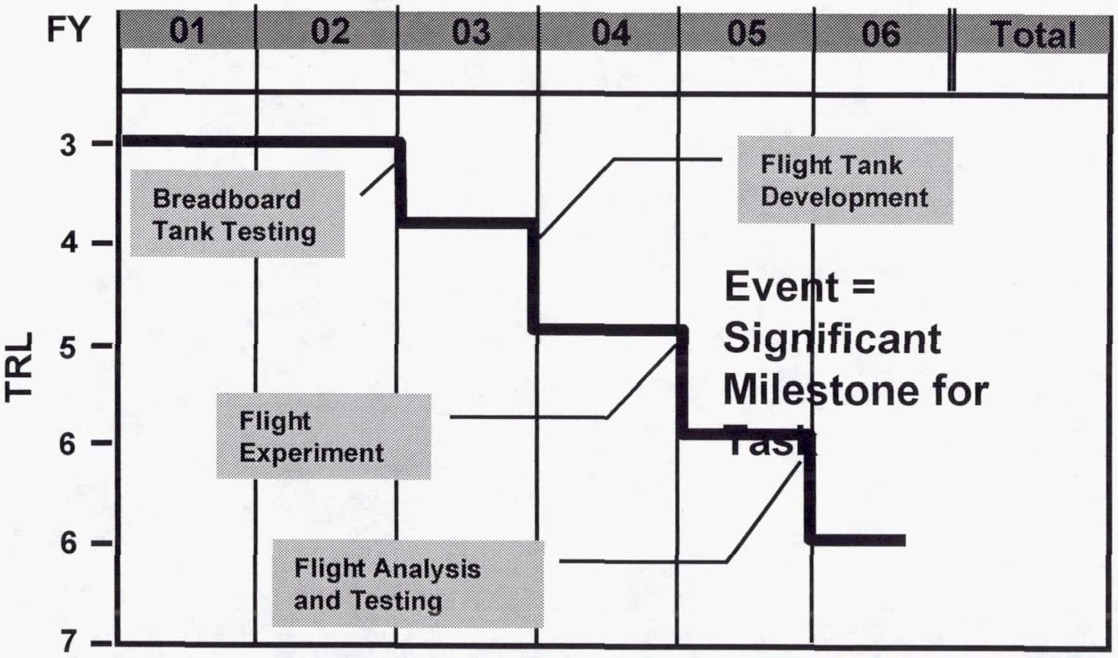
Tom Delay-MSFC

Products/Benefits

- Products
  - —Developmental tanks for long term storage of hydrogen peroxide. Flight experiment tank.
- Benefits
  - —40 percent reduction in weight compared to state-of-the-art
- Customers
  - —All four NASA enterprises
  - —DOD/NRO, Commercial(X–37, USFE etc.)
- X-cutting

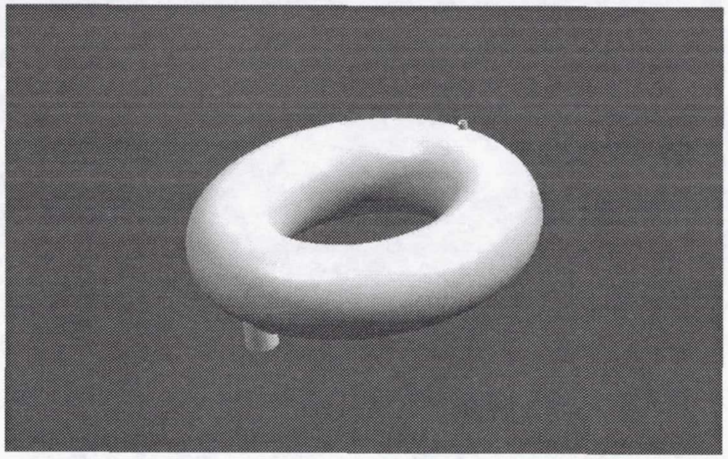
Implementation/Metrics

- Current State of the Art
  - —Aluminum tanks, stainless steel tanks with liners.
- Performance Metrics
  - —Chemical compatibility
  - —Low mass, low permeability
- Risks
  - —Testing facility availability
  - —Schedule of flight vehicle
- USG Participants
  - —MSFC lead Center
  - —AFRL



Event = Significant Milestone for Task

Toroidal Upper-Stage Tank Development
Tom Delay-MSFC

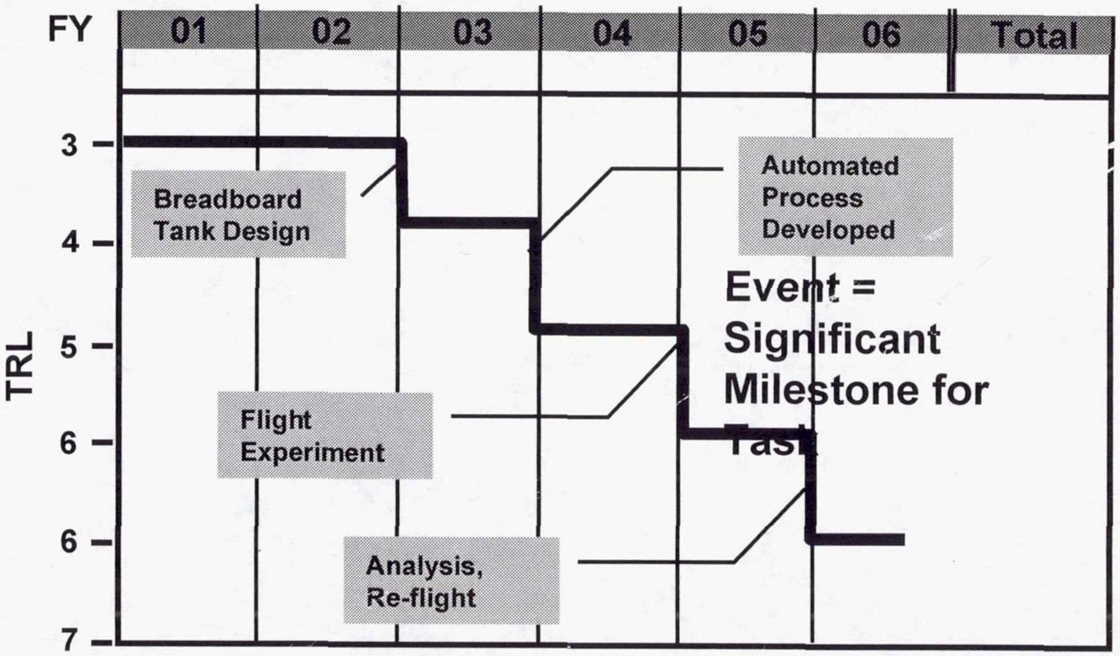


Products/Benefits

- **Products**
  - —Development and demonstration of composite toroidal tanks. Flight experiment tank.
- **Benefits**
  - —75 percent reduction in weight compared to state-of-the-art
  - —40 percent increase in storage volume
- **Customers**
  - —All four NASA enterprises. DOD/NRO
- **X-cutting**

Implementation/Metrics

- **Current State-of-the-Art**
  - —Cylindrical composite vessels
- **Performance Metrics**
  - —Low mass, packing efficiency
- **Risks**
  - —Cost effective tooling methods
  - —Schedule of flight vehicle
- **USG Participants**
  - —MSFC lead Center
  - —AFRL



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Magnetic Launch Assist

KSC-MM-5093

October 11, 2000

Jose Perez/ KSC

"ST Day 2000: Reducing Risk for the Next Generations"

- Jose Perez / Project Manager / KSC
- Dr. Robert Youngquist KSC
- Frederick Adams KSC
- William Jacobs MSFC
- John Hicks DFRC
- Kurt Kloesel DFRC

"ST Day 2000: Reducing Risk for the Next Generations" - Magnetic Launch Assist

NASA Development Team

- To develop a safe, reliable, inexpensive, and minimum operation launch assist system for sending payloads into orbit using ground powered, magnetic suspension and propulsion technologies.
- Improve safety, reliability, operability for 3rd generation Reusable Launch Vehicles (RLV).
- Reduce vehicle weight and increase payload capacity.
- Support operational testing of Rocket Based Combine Cycle (RBCC) engines.

Goals

- **BANTAM Program**
  - **MagLev Development**
    - PRT Advance MagLev Systems
    - Lawrence Livermore National Laboratory
    - Foster Miller

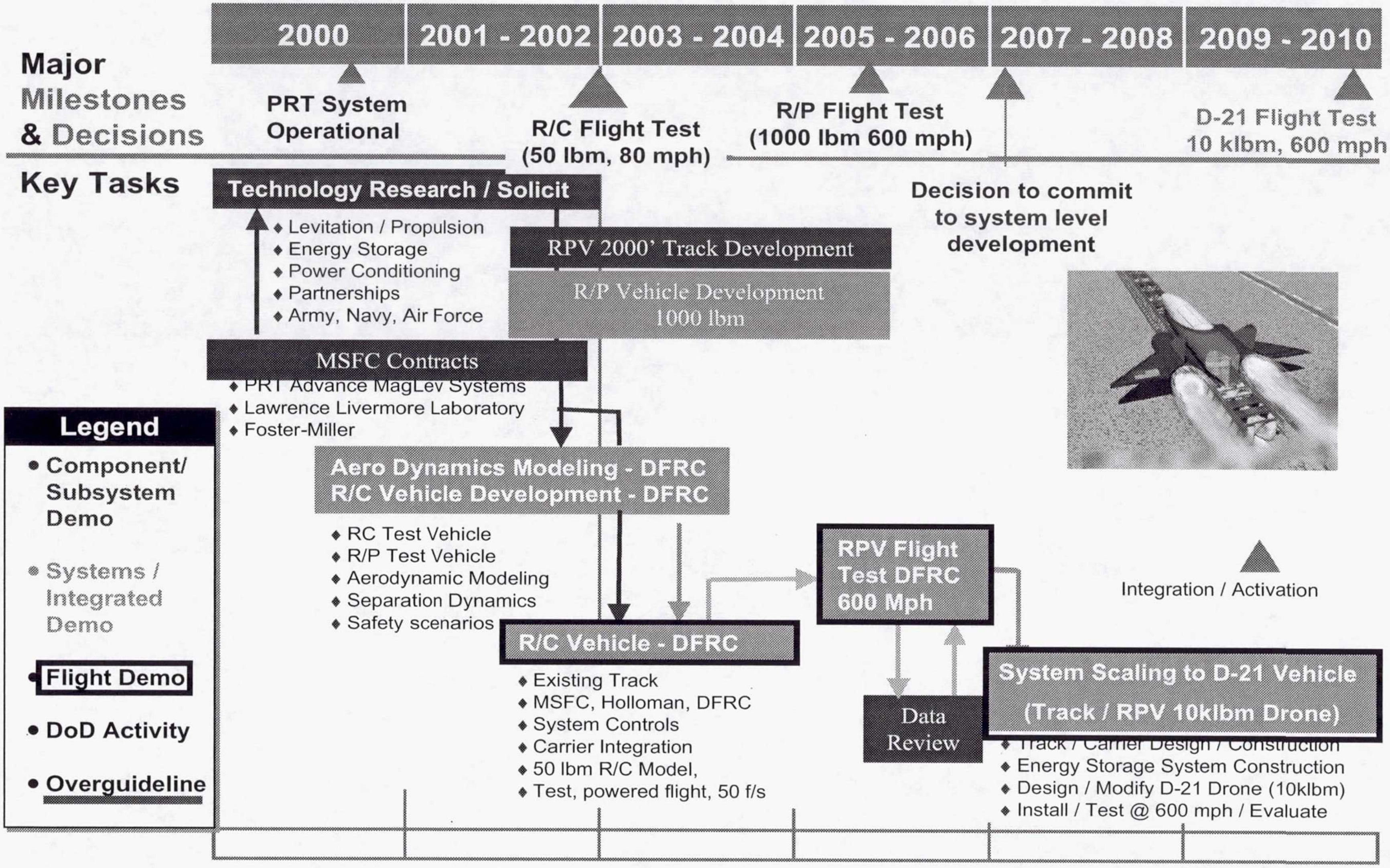
- **Advance Space Transportation Program**
  - **Spaceliner 100 Technology Development Program**
    - Launch Assist Technology Development
      - Development of MagLev Technologies

"ST Day 2000: Reducing Risk for the Next Generations" - Magnetic Launch Assist

Background

Ground Based, Electro-Magnetic Launch Assist

Ops and Range Tech



2000	2001 - 2002	2003 - 2004	2005 - 2006	2007 - 2008	2009 - 2010

Major Milestones & Decisions

- PRT System Operational
- R/C Flight Test (50 lbm, 80 mph)
- R/P Flight Test (1000 lbm 600 mph)
- Decision to commit to system level development
- D-21 Flight Test 10 klbm, 600 mph

Key Tasks

Technology Research / Solicit
- ◆ Levitation / Propulsion
- ◆ Energy Storage
- ◆ Power Conditioning
- ◆ Partnerships
- ◆ Army, Navy, Air Force

RPV 2000' Track Development

R/P Vehicle Development 1000 lbm

MSFC Contracts
- ◆ PRT Advance MagLev Systems
- ◆ Lawrence Livermore Laboratory
- ◆ Foster-Miller

Aero Dynamics Modeling - DFRC
R/C Vehicle Development - DFRC
- ◆ RC Test Vehicle
- ◆ R/P Test Vehicle
- ◆ Aerodynamic Modeling
- ◆ Separation Dynamics
- ◆ Safety scenarios

R/C Vehicle - DFRC
- ◆ Existing Track
- ◆ MSFC, Holloman, DFRC
- ◆ System Controls
- ◆ Carrier Integration
- ◆ 50 lbm R/C Model,
- ◆ Test, powered flight, 50 f/s

RPV Flight Test DFRC 600 Mph

Data Review

System Scaling to D-21 Vehicle (Track / RPV 10klbm Drone)
- ◆ Track / Carrier Design / Construction
- ◆ Energy Storage System Construction
- ◆ Design / Modify D-21 Drone (10klbm)
- ◆ Install / Test @ 600 mph / Evaluate

Integration / Activation

Legend
- **Component/ Subsystem Demo**
- Systems / Integrated Demo
- **Flight Demo**
- **DoD Activity**
- **Overguideline**

Ground □ Based, Electro-Magnetic Launch Assis

♦ Ongoing MagLev Contracts

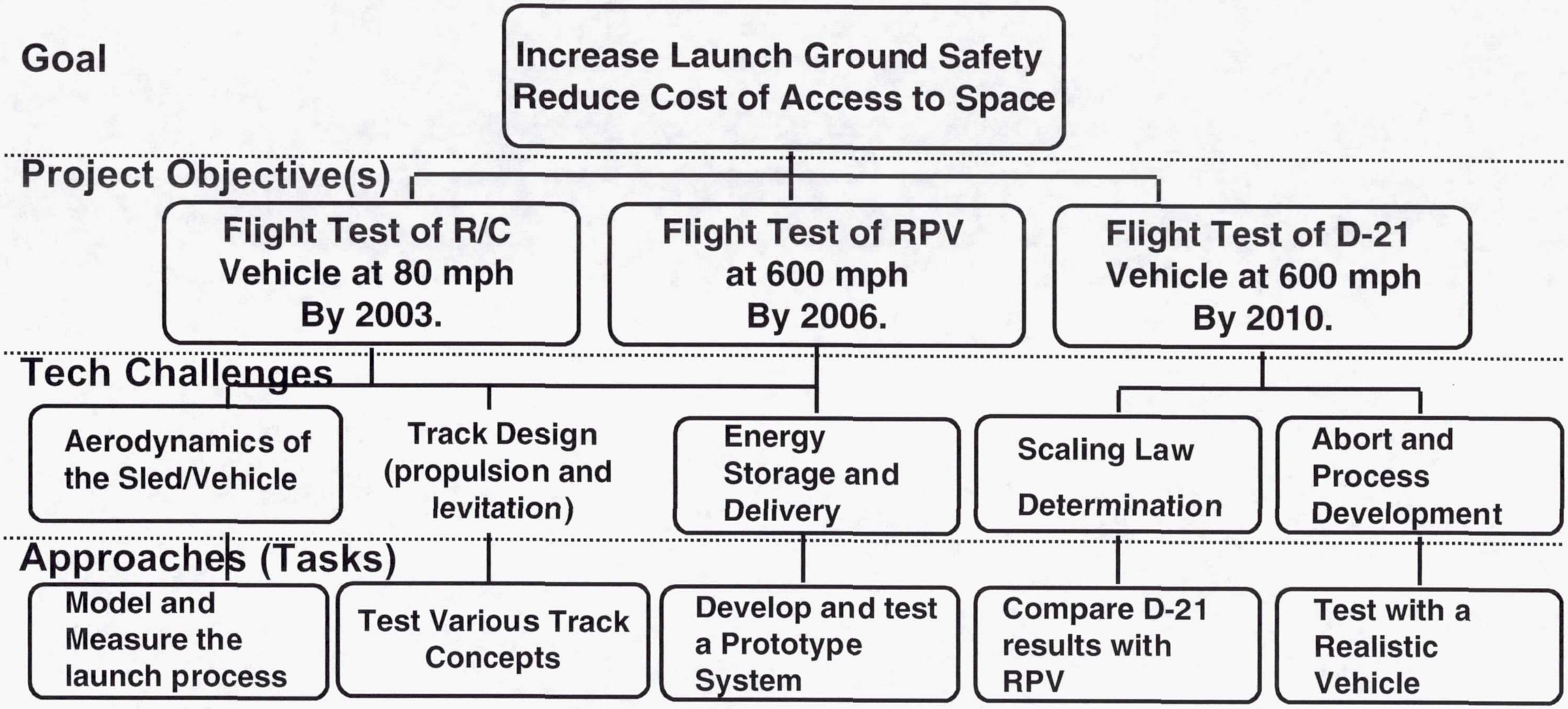
- Lawrence Livermore National Laboratory
  - Inductrack / Halbach Array – Proof of concept completed.
  - Contract extension to built a 7.8 meter (25.5 ft.) track to be tested at 30 m/s (67.2 mph) speeds.

- Foster Miller
  - Linear Synchronous Motor – 44 feet track.
  - Proof of concept completed.
  - Track is located at KSC. Research on the track will start in FY2001.
  - Contract extension for additional studies (June).

Ongoing MagLev Contracts

◆ Ongoing MagLev Contracts (continue)

- PRT Advance MagLev Systems
  - Research is being done at the Sussex University, England.
  - Linear induction motor – 50 feet track to be operational by December 2000.
  - Proof of concept completed.
  - Perform flight demonstration by the end of FY2001 using a radio control vehicle.
- Center for Electromagnetic at the University of Texas, Austin
  - Perform studies to determine the fundamental limitations of high speed linear motors.
  - Research existing motors, storage and electronic switches to guide future research.
  - Design and demonstrate a high speed linear induction and a linear synchronous motor segments.



Goal

Increase Launch Ground Safety
Reduce Cost of Access to Space

Project Objective(s)

Flight Test of R/C Vehicle at 80 mph By 2003.

Flight Test of RPV at 600 mph By 2006.

Flight Test of D-21 Vehicle at 600 mph By 2010.

Tech Challenges

Aerodynamics of the Sled/Vehicle

Track Design (propulsion and levitation)

Energy Storage and Delivery

Scaling Law Determination

Abort and Process Development

Approaches (Tasks)

Model and Measure the launch process

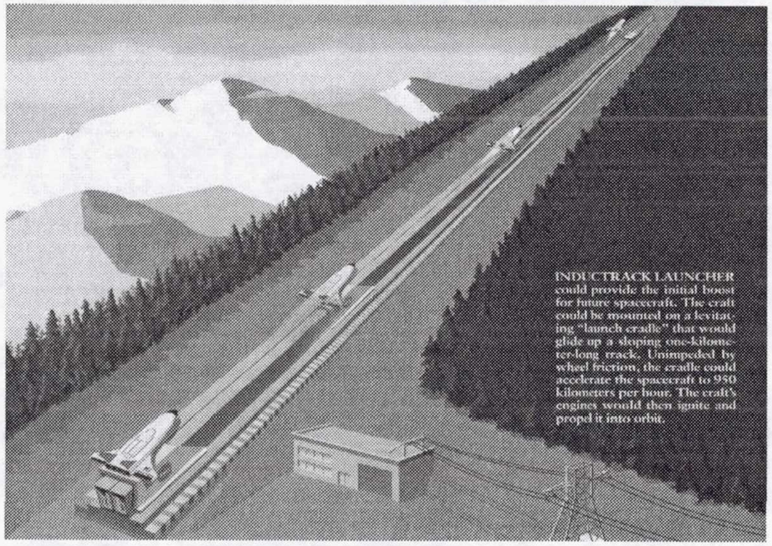
Test Various Track Concepts

Develop and test a Prototype System

Compare D-21 results with RPV

Test with a Realistic Vehicle

Requirements Flow down



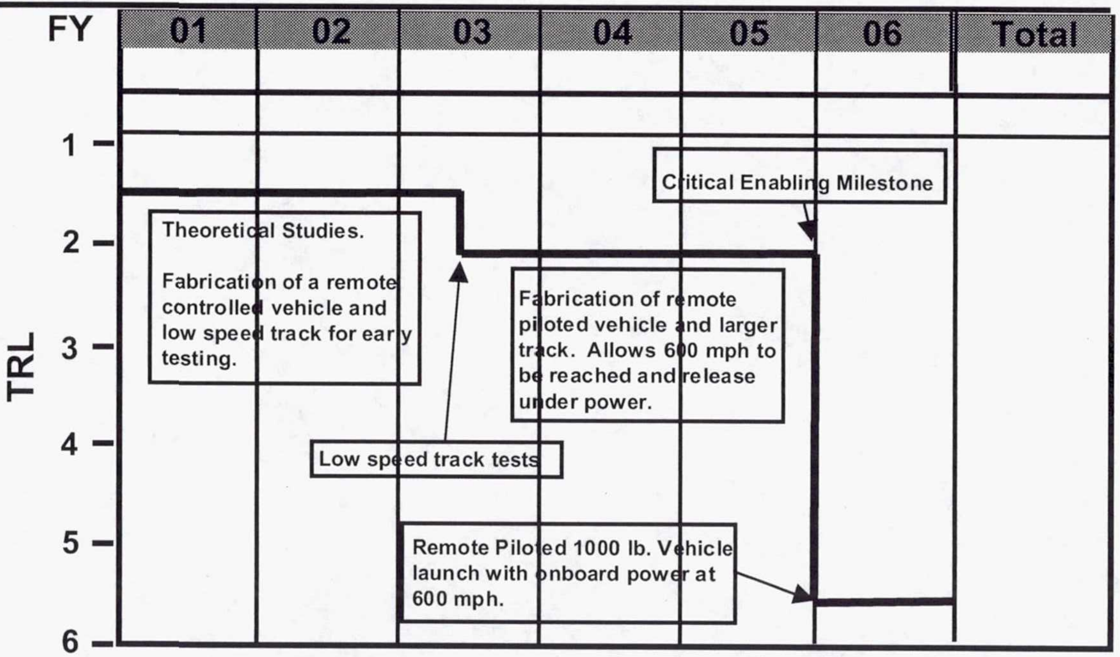
INDUCTRACK LAUNCHER could provide the initial boost for future spacecraft. The craft could be mounted on a levitating "launch cradle" that would glide up a sloping one-kilometer-long track. Unimpeded by wheel friction, the cradle could accelerate the spacecraft to 950 kilometers per hour. The craft's engines would then ignite and propel it into orbit.

Milestones / Activities

- **FY'01 Milestones**
  - Aerodynamic analysis complete by end of FY01, main issue is flutter
  - Delivery of remote controlled vehicle for test flights
  - Early flutter testing on the Foster-Miller track
- **FY'02 Milestones**
  - Low speed release of remote controlled vehicle.
  - Incorporation of flutter results into CEM effort
- **Prioritized list of Activities**
  - Aerodynamic analysis of the MagLev Sled.
  - Incorporation of these results into the long range design
  - Aerodynamic testing on the Foster-Miller Track

Implementation / Metrics

- **Current State of the Art**
  - Negligible. High speed cars and airborne release indicate the complexity and possible dangers.
- **Performance Metrics**
  - Successful and well understood demonstrations
- **Risks**
  - High cost effort which potentially does not address the issue in adequate detail.
- **Participants**
  - KSC,DFRC, MSFC, Holloman Test Track and Florida Institute of Technology



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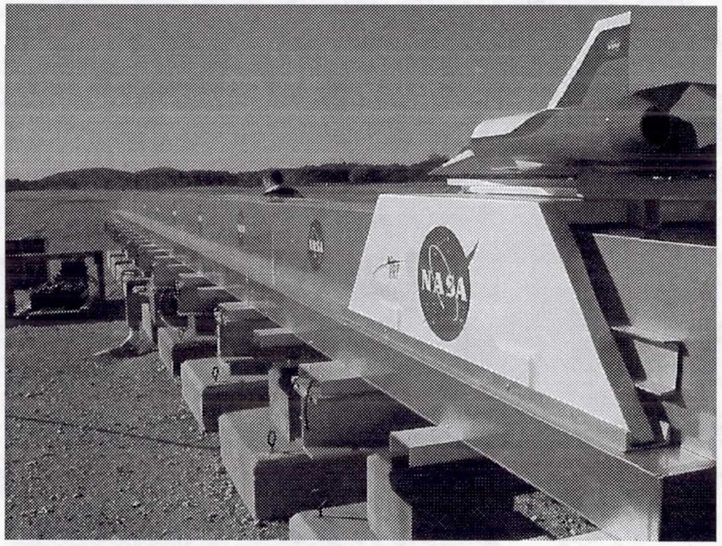
Aerodynamics and Sled/Vehicle Interaction

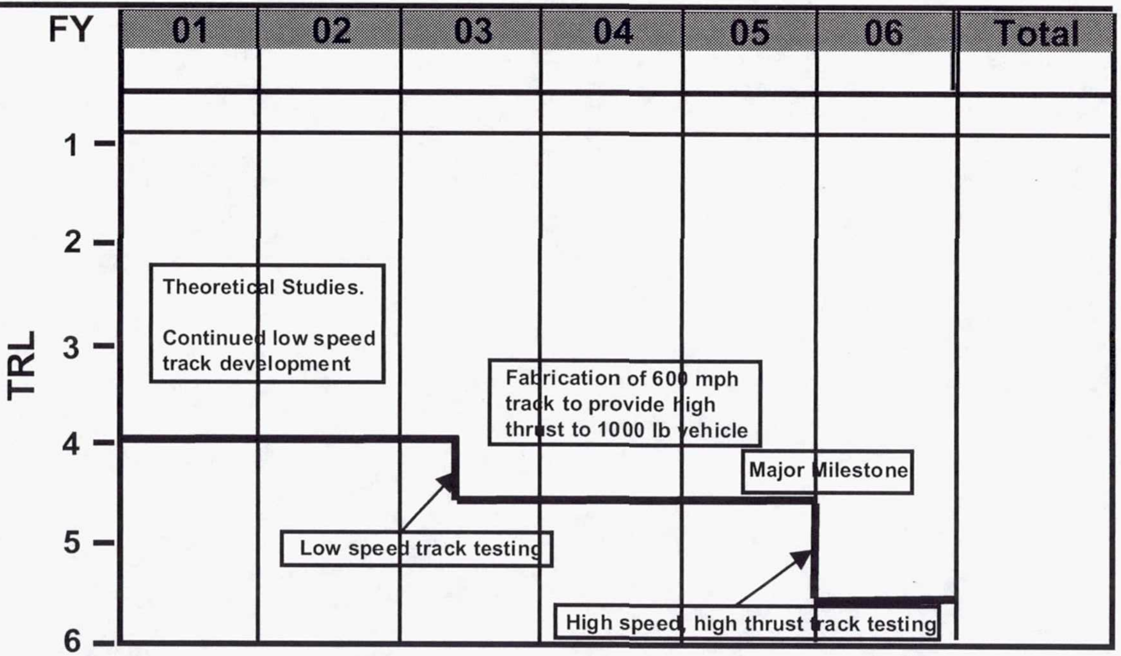


Products / Benefits

- **FY'01 Milestones**
  - Results of scaling study by Foster-Miller
  - Results from PRT waffle motor demonstrator
  - Results from CEM linear motor study
- **FY'02 Milestones**
  - CEM linear motor segment high speed demonstrator
  - Possible follow on work with either LLNL, PRT, or Foster-Miller
- **Prioritized list of Activities**
  - CEM effort on understanding the limits of high speed linear motors
  - Demonstrator studies with data acquisition to determine system performance and track operation issues.
  - Scaling and control studies and experiments.

Implementation / Metrics

- **Current State of the Art**
  - Linear Induction Motors and Linear Synchronous Motors exist, but not to the scale needed.
- **Performance Metrics**
  - Demonstration of Technology
- **Risks**
  - Minimal since computer simulation is well developed, but technology limited.
- **Participants**
  - KSC, MSFC, Center for Electromechanics, PRT, Foster-Miller, Lawrence Livermore, Navy EMALS,



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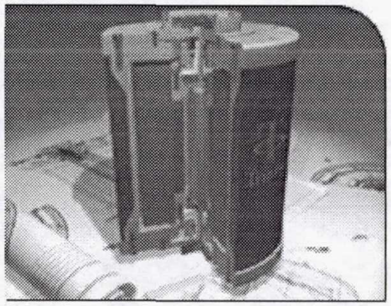
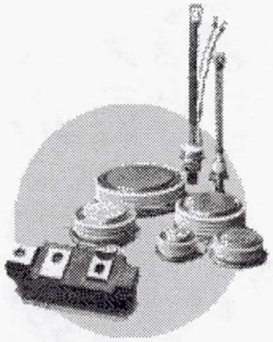
Magnetic Propulsion Technology



Composite Flywheel



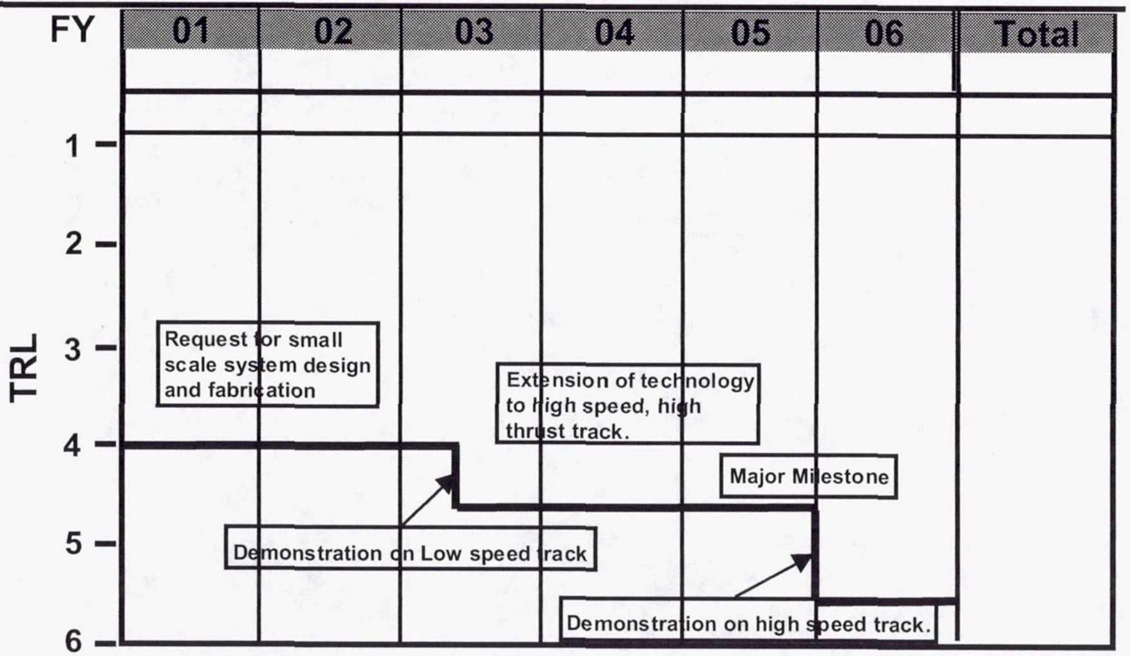
High Power Electronic Components

Products / Benefits

- **FY'01 Milestones**
  - PRT 50' track inverter installation and demonstration
  - Possible PRT 200' track Compulsator installation and demonstration
- **FY'02 Milestones**
  - CEM study results on flywheels and electronics for the high speed linear motor demonstrator
  - Internal effort on LN2 superconductrors
- **Prioritized list of Activities**
  - CEM effort – high TRL– flywheels and electronics
  - KSC effort – low TRL – superconducting energy storage and delivery
  - PRT demonstrators

Implementation / Metrics

- **Current State of the Art**
  - Flywheel technology appears adequate. Power semiconductors are nearly adequate. Cost is high.
- **Performance Metrics**
  - Demonstration of Technology
- **Risks**
  - Fairly high TRL but cost must come down.
- **Participants**
  - KSC, CEM, NAVY EMALS, PRT



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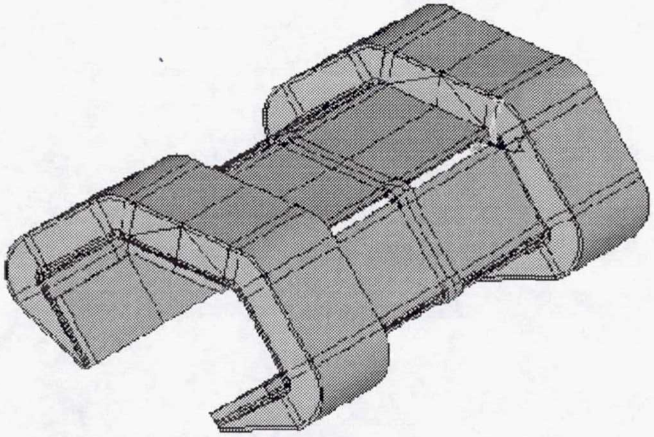
Energy Storage and Delivery



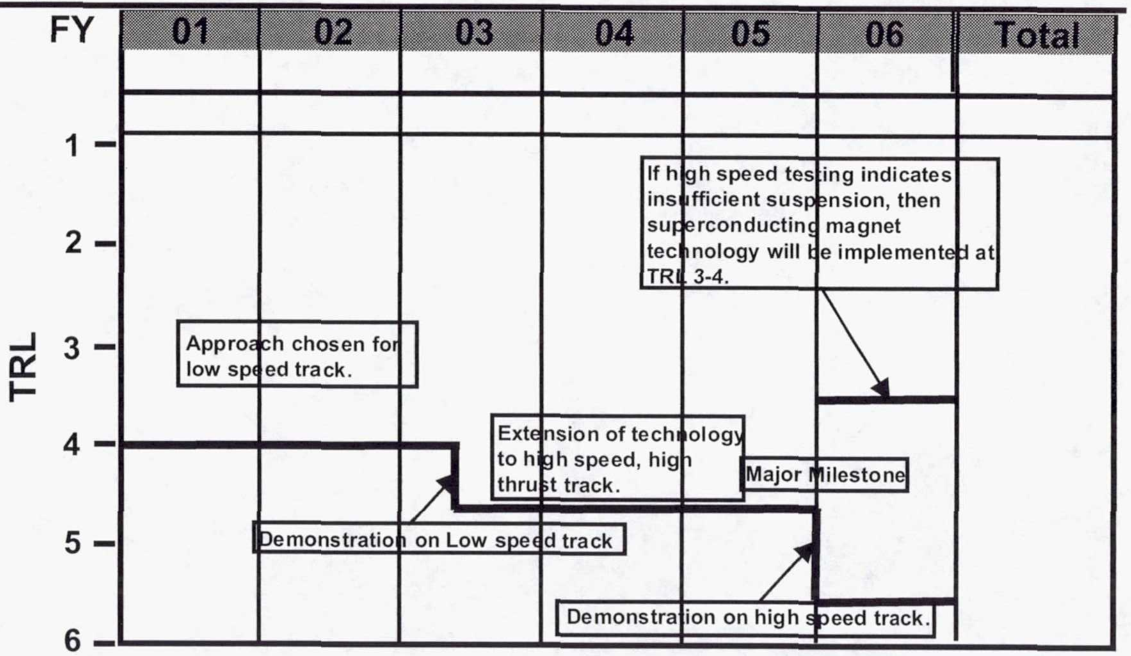
Triple Halbach Array Sled-Levitation Concept

Products / Benefits

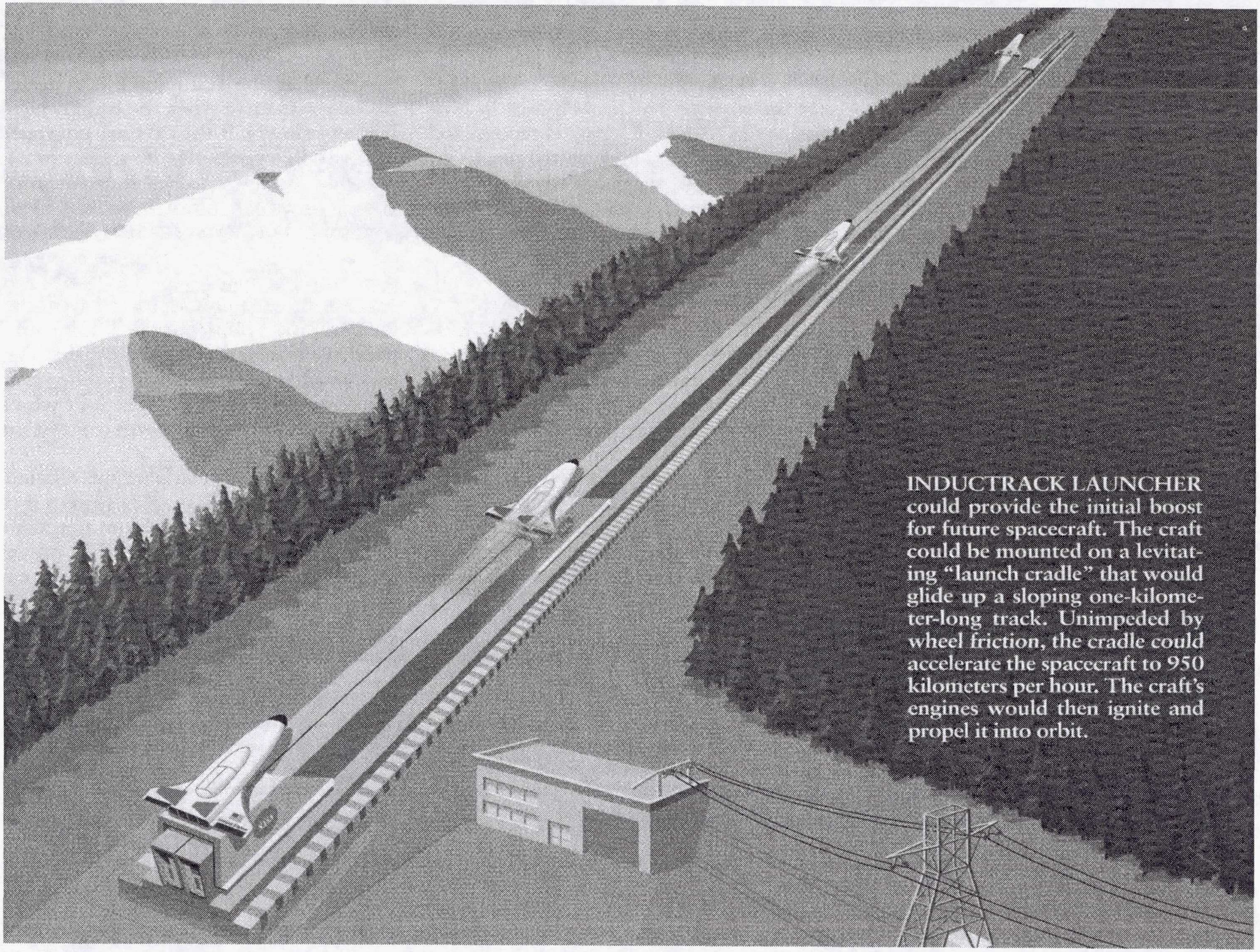
- **FY'01 Milestones**
  - Foster-Miller scaling study results
  - Lawrence Livermore Inductrack demonstrator results
  - PRT invertor controlled levitation
  - MIT STTR complete on Liquid He superconducting magnets
- **FY'02 Milestones**
  - Internal KSC concept study and demonstrator
  - Results of CEM effort
- **Prioritized list of Activities**
  - CEM study, levitation incorporation into high speed linear motor segment
  - Demonstrator Track experimentation and study, includes Foster-Miller, LLNL, and PRT
  - Continued new concept studies and experiments

Implementation / Metrics

- **Current State of the Art**
  - Small scale demonstrations at high acceleration, large scale systems at low acceleration.
- **Performance Metrics**
  - Demonstration of Technology
- **Risks**
  - Minimal, unless superconducting approach required.
- **USG Participants**
  - KSC, PRT, Lawrence Livermore, Foster-Miller, CEM



Magnetic Levitation



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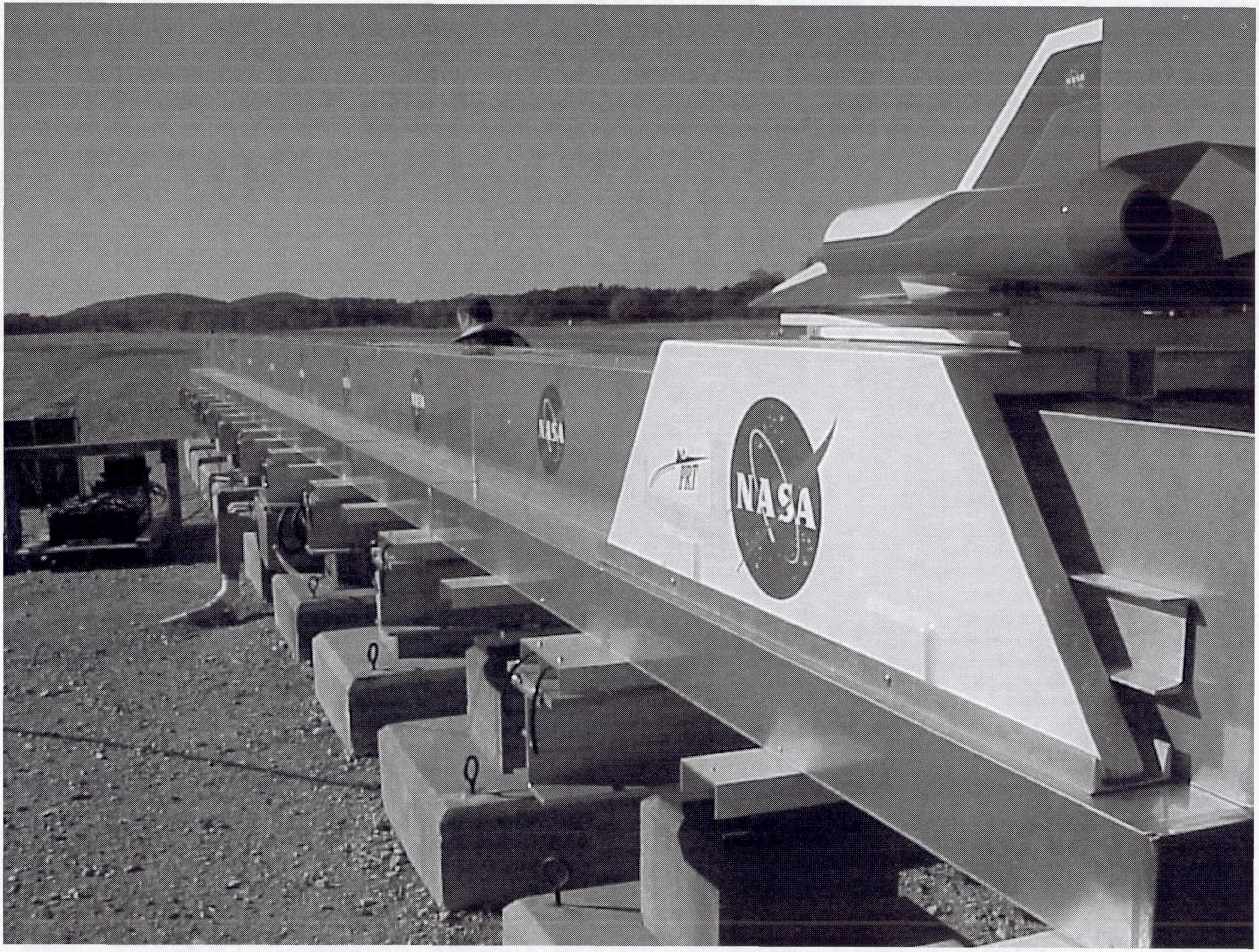
NASA
PRT
NASA
NASA

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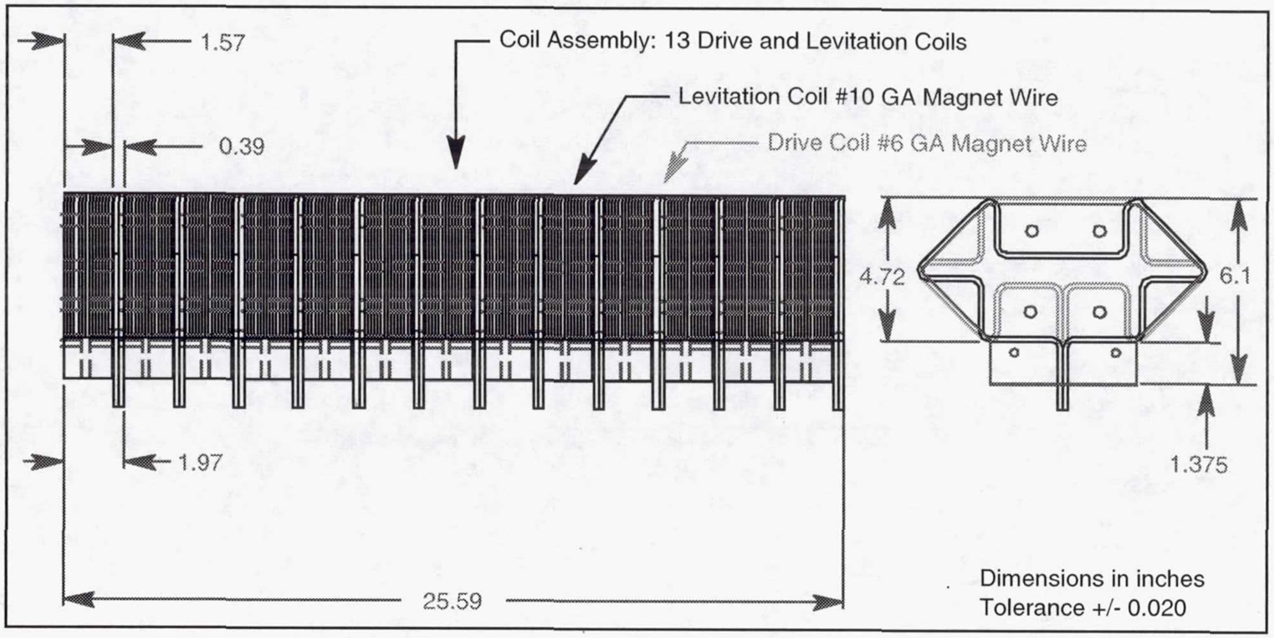
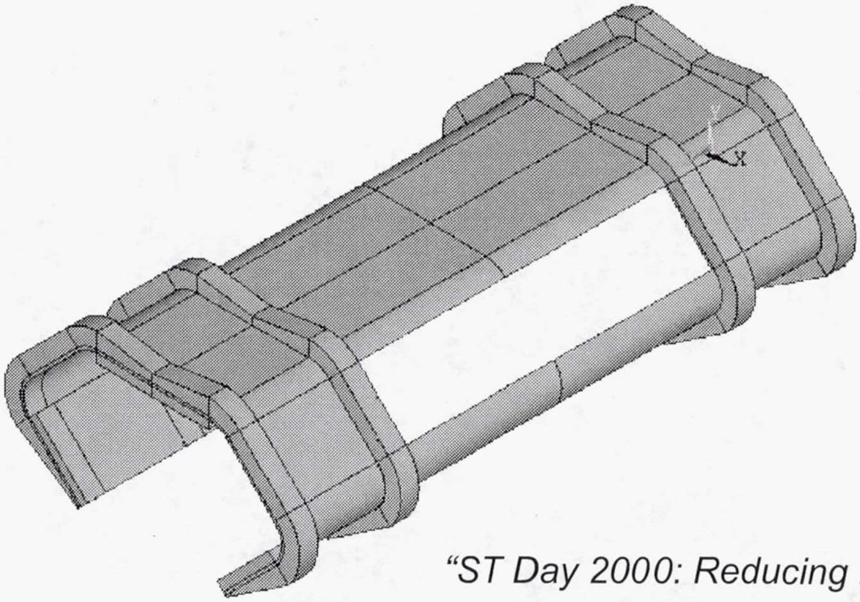
Lawrence Livermore Inductrack





Lawrence Livermore concept of
Inductrac and Carrier

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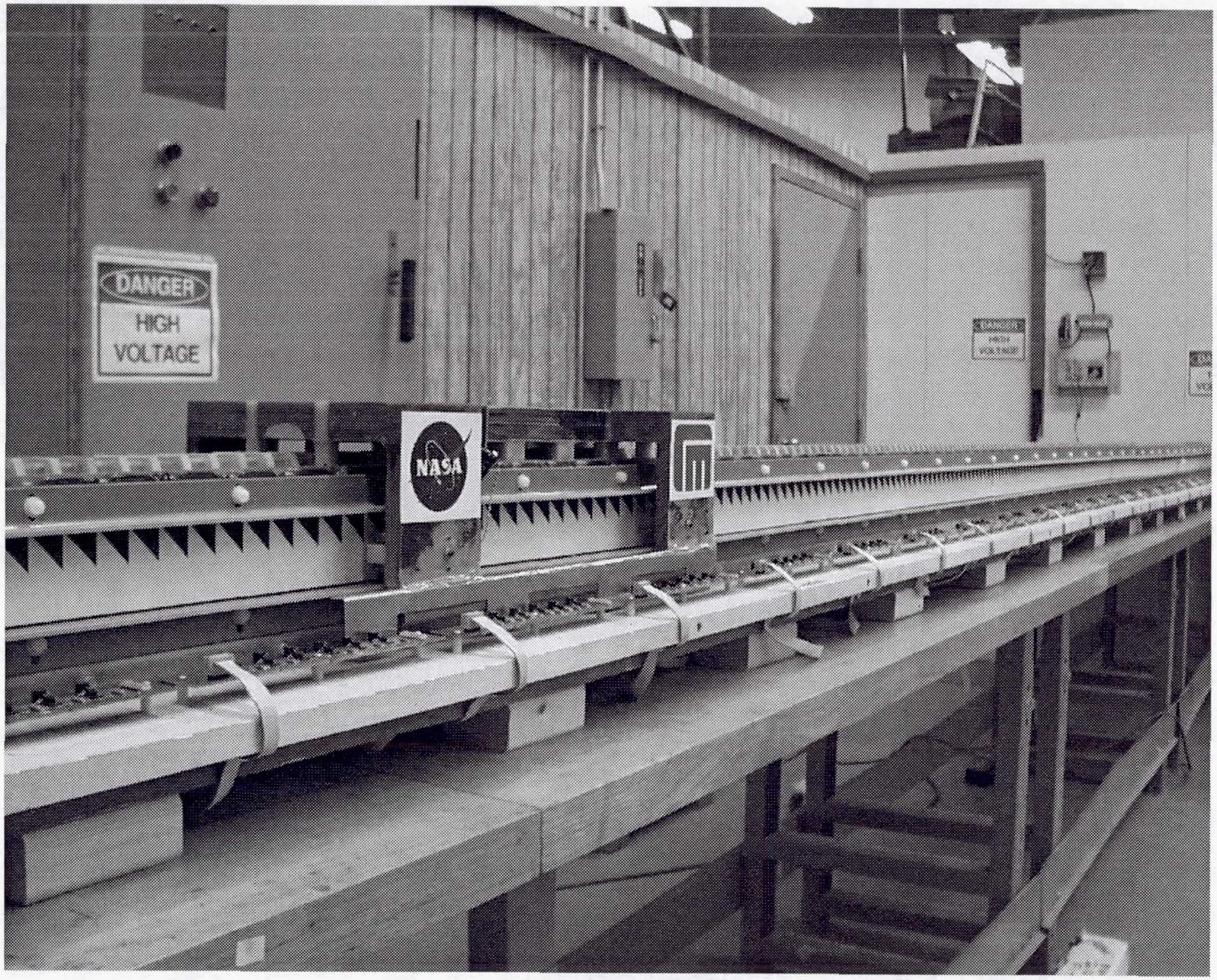
Lawrence Livermore Inductrack



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Foster Miller Track

- MSFC – PRT track testing.
- DFRC – Aerodynamics / Flight Dynamics / Flight Test.
- Ames – Computational Analysis / Wind Tunnel Testing.
- Florida Space Institute (FSI) – Foster Miller track testing.
- DoD (Navy) – EMALS and Arrestor program.
- Academia – Magnetic levitation/propulsion and energy storage system studies.
- Industry - LLNL / Foster Miller / PRT Advance Maglev Systems.
- KSC - STTR Phase I (Advance Magnet Labs and MIT) Study on superconducting systems.

Partnerships for the project

- Proposal
  - During the first year the project will research, test, and develop partnerships to understand the technical feasibility of using magnetic suspension to launch prototype vehicles to test technologies for the development of the 3rd generation RLV.

- Technical Approach
  - Research available magnetic launch systems.
  - Research available energy storage systems.
  - Research switching, power distribution, and controls.
  - Follow ongoing MSFC contracts.
  - Develop partnerships with DoD and Academia.

Proposal / Technical Approach

- **Accomplishment this year**
  - Formed a partnership with the Navy to participate in the development of the EMALS and Arrestor program.
  - Formed a partnership with DFRC to perform fly dynamics and demonstrations for the project.
  - Extended the Lawrence Livermore National Laboratory contract to built and test and Inductrack at their facilities.
  - Extended the Foster Miller contract for additional studies on the Linear Synchronous motor track they built.
  - Developed a 10 year road map for the project and got it approved by the program.
  - Formed a partnership with Florida Space Institute and relocated the Foster Miller 44 ft track to KSC. We will use graduate student under our guidance to do research.
  - Signed a grant with the Center for Electromagnetic at the University of Texas in Austin to evaluate the existing high speed motors available for the MagLev System.

Accomplishments

- Plans for next fiscal year
  - Perform flight testing from the PRT 50 ft track located at MSFC using a Radio Control powered vehicle.
  - Investigate aerodynamic problem due to wing “flutter”.
  - Participate in the development of the EMAL system with the NAVY.
  - Design and commence fabrication of a test bed to test various configurations of linear motors at the Center for Electromagnetic.
  - Modify and test different coils configuration for propulsion and levitation using the Foster Miller 44 ft track.

FY2001

◆ Risks

- Long term funding, Program survival.
- Energy storage systems.
- Aerodynamics.
- Scaling.

"ST Day 2000: Reducing Risk for the Next Generations" - Magnetic Launch Assist

Risks

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Advanced Range Technologies

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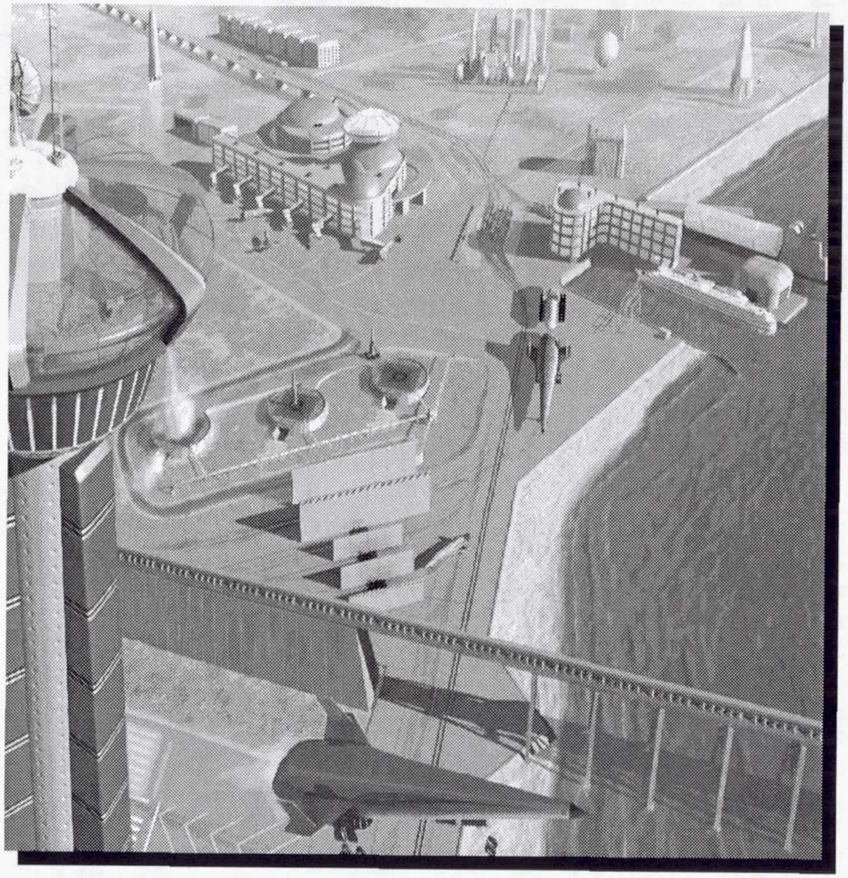
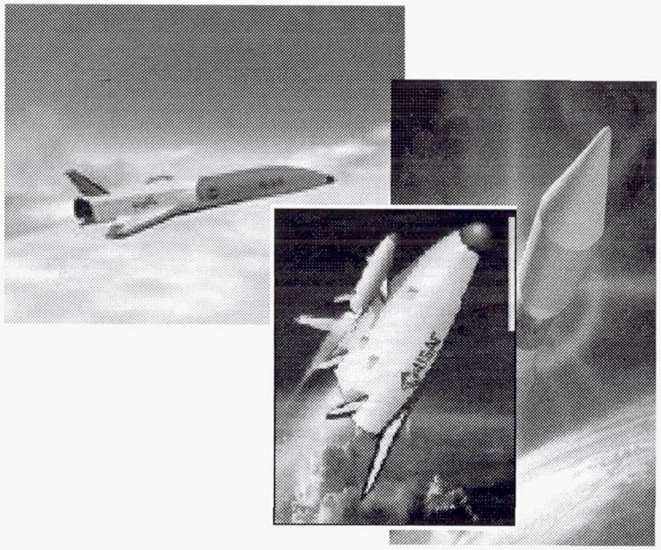
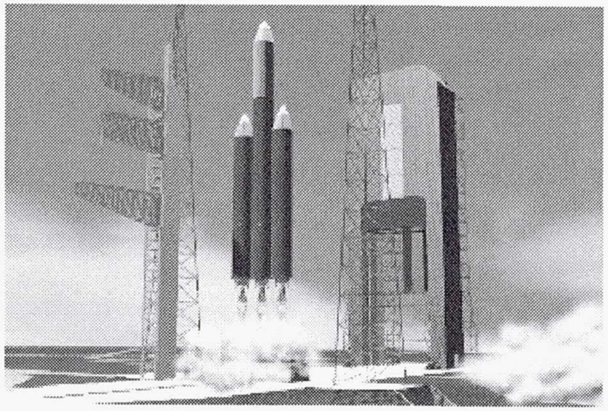
"ST Day 2000: Reducing Risk for the Next Generations"

- Historically, the majority of the total life cycle cost for any complex system is attributed to operational and support activities
- Therefore, a primary strategy for reducing life cycle costs should be to develop and infuse spaceport technologies in future space transportation systems
- Advanced technologies will benefit current and future spaceports on the earth, moon, Mars, and beyond



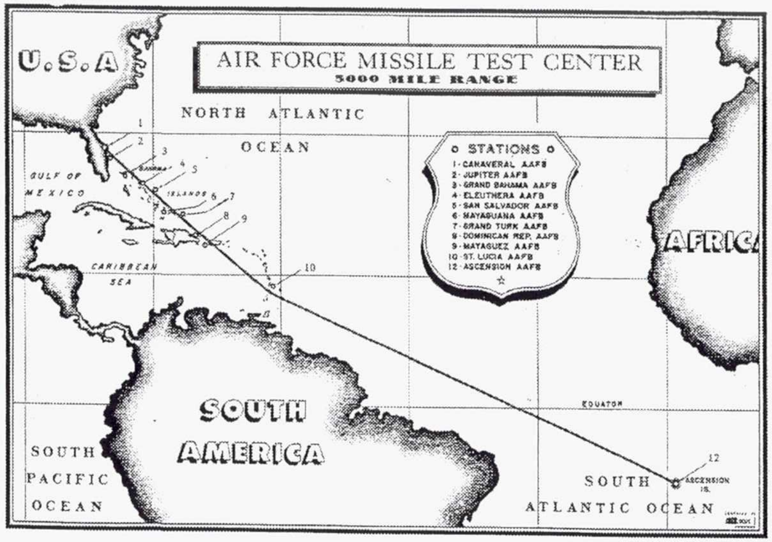
- Current Weather & Range attributable delays and scrubs will limit future space launch cost/lb. goals
- Range infrastructure is falling behind needs for future Commercial, and next generation RLV launch systems



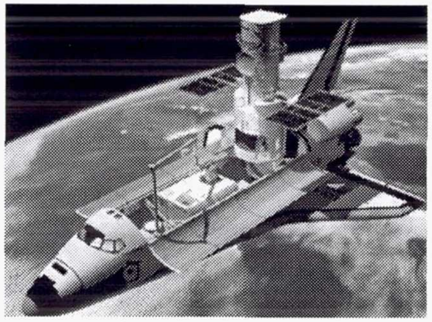


Why X-Range R&D ?

- Range Technology History
  - Air Force was responsible for developing and operating the ER and WR since 1950
  - Infrastructure was historically capitalized by DoD programs
  - Commercial users only reimburse direct costs; technology upgrades remain DoD responsibility

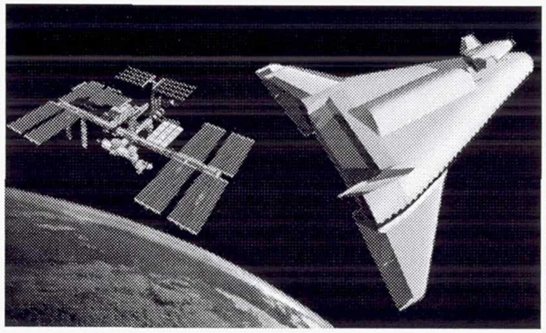


- Global and U.S. Future Range Trends forecast strong growth
  - Emerging space launches need specialized technologies to enable their business plans
  - Launch services becoming mostly commercial
  - Factor of 2-10 volume increase in five years
  - FAA involvement increasing (Spaceport Licenses)
  - National Security remains Driver
  - > 14 Global Launch Ranges



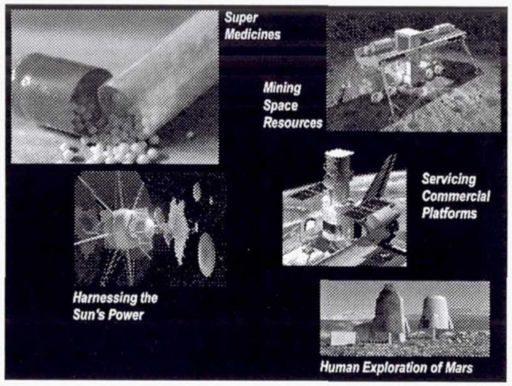
Today: Space Shuttle
1st Generation RLV

- Orbital Scientific Platform
- Satellite Retrieval and Repair
- Satellite Deployment



2010: 2nd Generation RLV

- Space Transportation
- Rendezvous, Docking, Crew Transfer
- Other on-orbit operations
- ISS, Orbital Scientific Platform
- 10x Cheaper
- 100x Safer



2025: 3rd Generation RLV

- New Markets Enabled
- Multiple Platforms / Destinations
- 100x Cheaper
- 10,000x Safer

2040: 4th Generation RLV

- Routine Passenger Space Travel
- 1,000x Cheaper
- 20,000x Safer

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Range Technologies

Generations of Reusable Launch Vehicles

- **Vision**
  - **Guiding Assumptions**
    - 2020-2025 operational transportation to / from orbit
    - Launch assist (possibly MagLev, catapult, or other)
    - Fly back booster
    - 26 launch vehicles
    - Multiple spaceports (7)
    - A minimum of 2,000 missions annually
  - **Given these assumptions each 3rd generation vehicle**
    - Minimum of 77 missions/year with a Maximum of 4 days turnaround
    - Simultaneous operation with other vehicles at a Spaceport or multiple Spaceports
      - Launch
      - Landing
      - Vehicle processing
    - 'Seamless' interface with the National Air Space
    - On-board real-time access to weather, ATC and navigational data required for ascent and landing

- Goals
  - Double U.S. Range Surge Capacity
  - Factor of three Reduction in Delays and Scrubs
  - Demonstrate Flight Plan Operations
  - Reduce fixed and variable costs to our customers and government
  - Leverage Exploration Initiative, e.g., Planetary Range

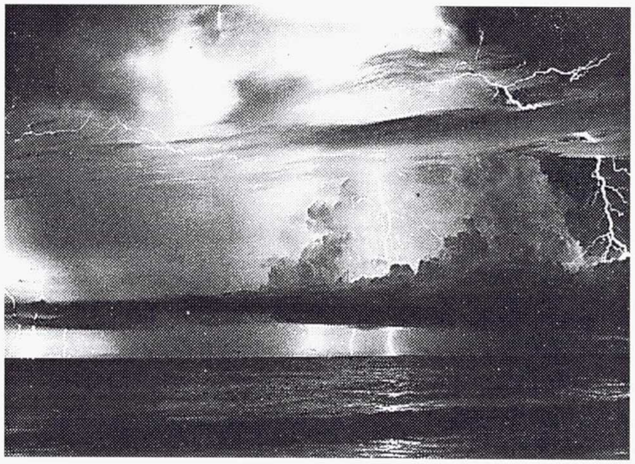
- Charter
  - Develop/mature technologies and knowledge that support the goals of the future generations of Reusable Launch Vehicles (RLV) enabling greater access to/from space
  - Technologies developed will assure Safe and Efficient operations while providing increased launch/landing opportunities and thereby decreasing the $/lb to orbit
  - Transfer knowledge of range technologies so that they are available to future spaceport(s) and existing National range(s)
- Consisting of five (5) technology focus areas:
  - Weather Instrumentation & Systems
  - Space Based Range
  - Spaceport Range Systems
  - Decision Models & Simulations
  - Spaceport Information Systems Management

Advanced Range Technologies

◆ Weather Instrumentation & Systems

- **Description**
  - – Develop and apply new technologies to weather instrumentation and systems in order to:
    - Reduce conservatism
    - Provide timely warnings for personnel and asset safety
    - Provide decision models with timely data

- **Candidate Projects**
  - – Lightning Launch Commit Criteria Instrumentation and systems
  - – Mesoscale Numerical Weather Prediction 4DDA
  - – Integrated Weather Instrumentation Systems
  - – Upper-level Wind Measurement/Forecast
  - – Short term Forecasting Tech.



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Advanced Range Technologies

Products / Benefits

Products
- Improved lightning launch commit criteria

Benefits
- Increased safety and fewer launch scrubs

Customers
- All vehicles launched from American spaceports
- 2nd Gen Project Team

Implementation / Metrics

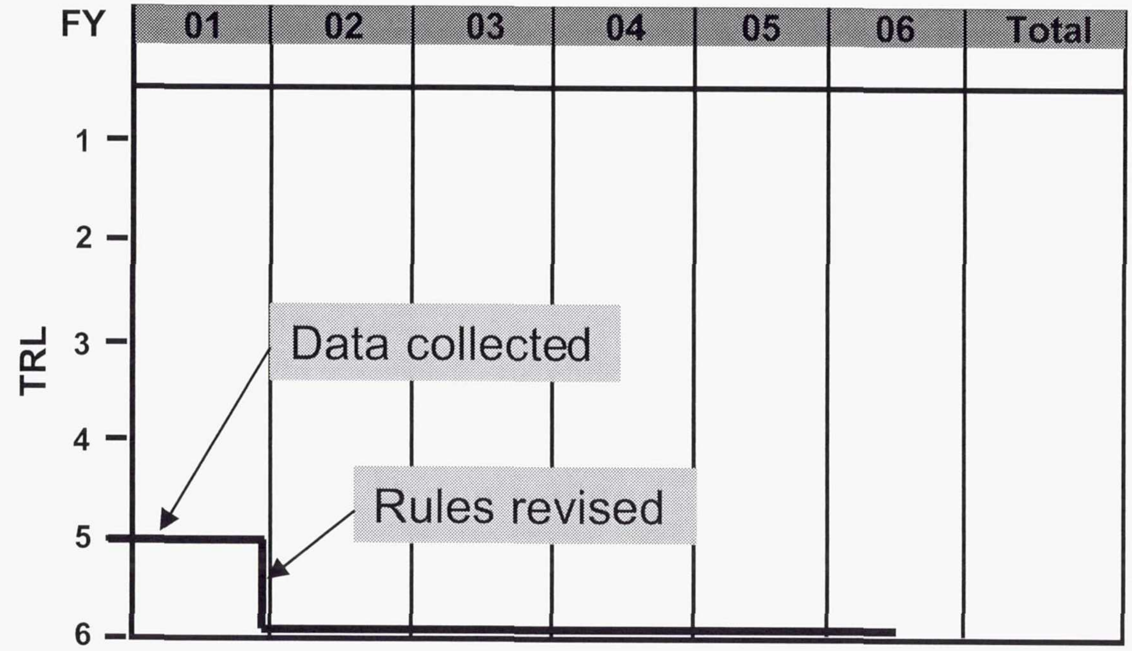
Current State of the Art
- Rules based on qualitative estimates

Performance Metrics
- Reduce standoff distances and/or time delays in rules by 20%

Risks
- Inability to obtain sufficient data

USG Participants
- KSC (lead), MSFC, USAF, NOAA,

  NCAR



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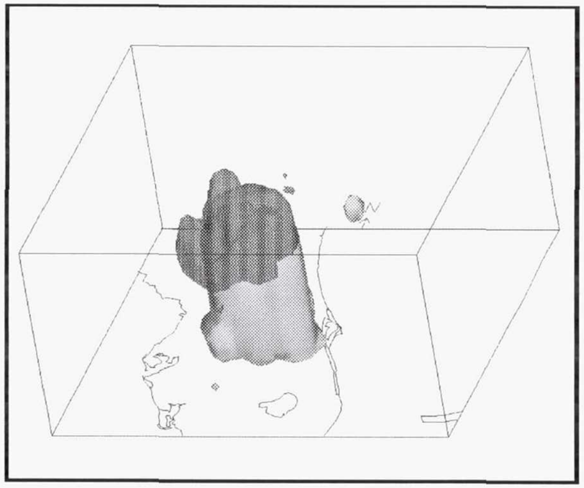
Lightning Launch Commit Criteria



Products / Benefits

Products
- Software permitting real-time (4D) data ingest into mesoscale numerical weather prediction systems

Benefits
- Improved accuracy and timeliness of forecasts of winds, precipitation, temperatures and hazardous conditions
- Improved safety due to better warnings
- Fewer false alarms and associated down time

Customers
- All users of the Eastern Range
- 2nd Gen Project Team

Implementation / Metrics

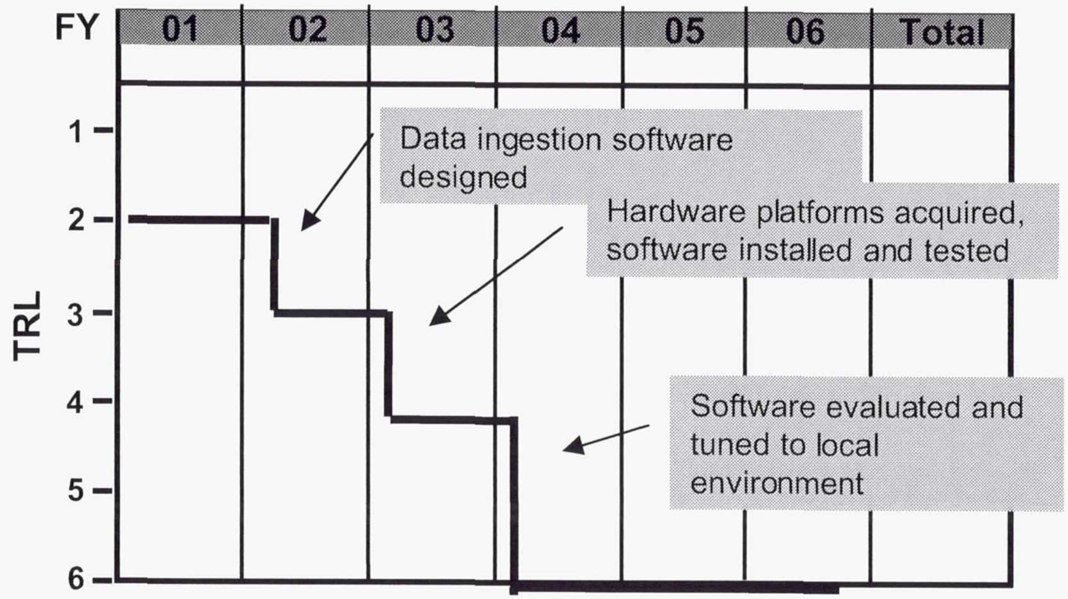
Current State of the Art
- Models initialized every 6 to 12 hours, then free run

Performance Metrics
- Models updated with observations at least hourly

Risks
- Insufficient computing power available at reasonable cost

USG Participants

- KSC



Data ingestion software designed

Hardware platforms acquired, software installed and tested

Software evaluated and tuned to local environment

Mesoscale Numerical Weather Prediction 4DDA

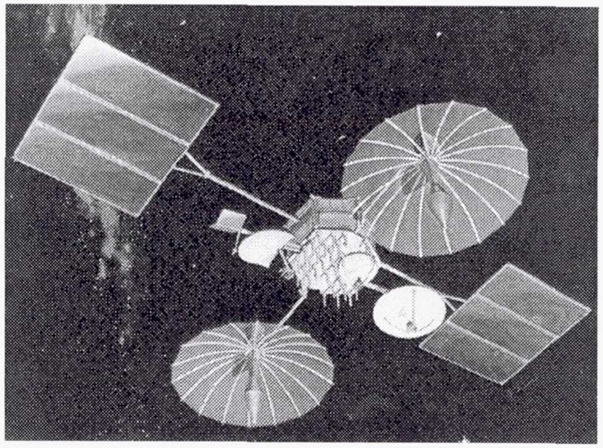
◆ Space Based Range

• Description

- Provide integrated Range/Spaceport space based weather, communications, tracking and surveillance assets that may consist of:
  - A specific satellite platform with these capabilities, or
  - A constellation of individual satellites that fulfill these capabilities
- Current tracking and telemetry data acquisition and distribution for space vehicle launch involves a geographically diverse set of assets which provide vehicle position determination from launch to orbit and return.
  - The use of these assets requires advanced scheduling, is very expensive and is only available in certain locations and for certain trajectories.

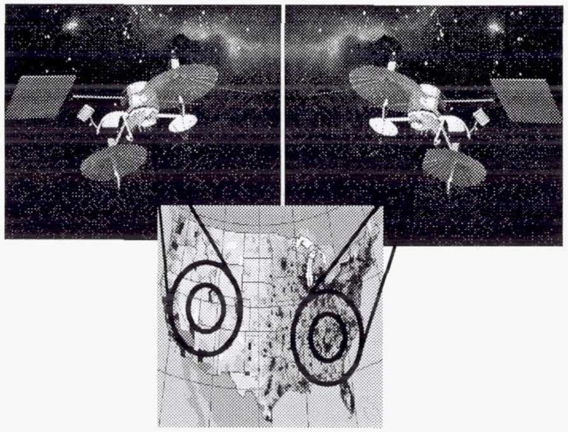
• Candidate Projects

- Digital Command Receiver Decoder Technology Range Safety commanding
- Passive Coherent Locator (Metric Tracking)
- Advanced DGPS/INS metric tracking systems
- All weather Imaging
- Air/Sea Surveillance



"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Range Technologies

Advanced Range Technologies



Products / Benefits

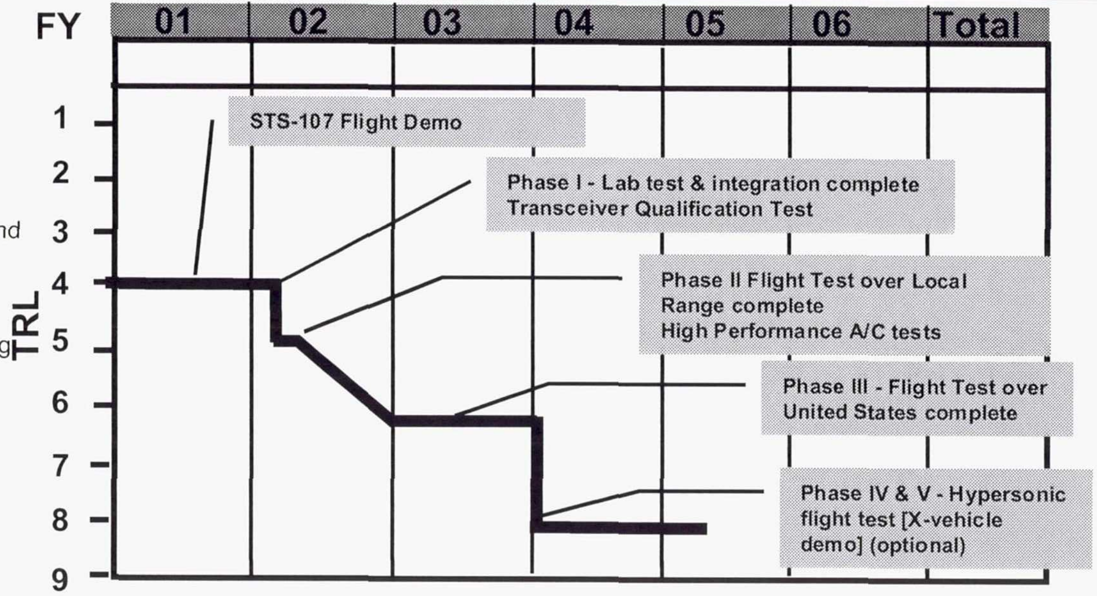
- Products

  Utilizing the TDRSS Space Network demonstrate the state-of-the-art transceivers and protocols will satisfy Range Safety Flight Termination and telemetry requirements. This will provide a reliable and alternative communications links for 2nd Generation reusable launch vehicles.
- Benefits
  - Safely reduce the cost by eliminating the need for downrange assets
  - Provides Space Based capability that will support multiple ranges/spaceports
  - Determine the feasibility and advantages of forward and return satellite links to transmit and receive telemetry data at Dryden.
  - Provide over the horizon tracking for current and future generations of hypersonic vehicles.
- Customers

  Internal AST, HEDS; external DoD, FAA, future spaceports

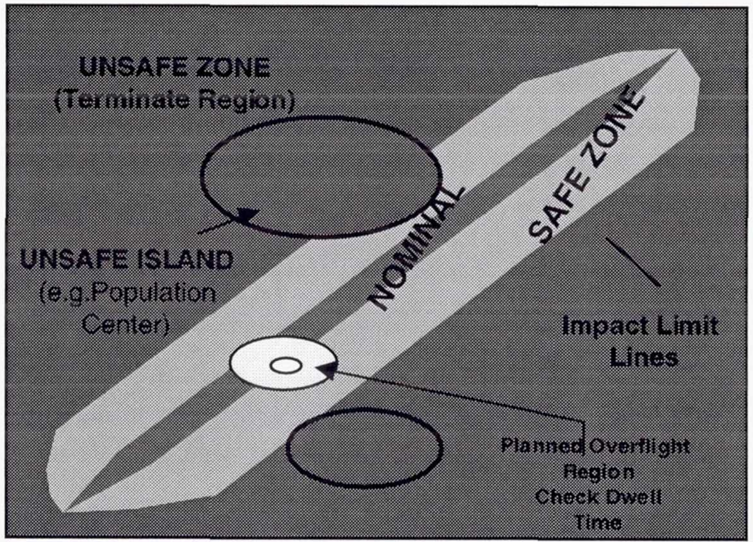
Implementation / Metrics

- Current State of the Art
  - New programmable TDRSS transceivers-Soft Radios in qualification testing
  - Lighter/low power/multi-channel/GPS
  - *Current range systems supporting hypersonic flights are ground* based and primarily support aircraft testing
- Performance Metrics
  - High integrity, continuity and availability to meet safety requirements for manned spacecraft Range Safety commanding
  - Reducing the infrastructure and systems required for missions will lower the ops costs
- Risks
  - Low. Transceiver developed. by another program
  - Programmable
  - Timely Startup Funding to initiate procurements
  - Vendor deliverables to NASA
  - Flight test vehicle for Phase II & III
- USG Participants
  - DOD, FAA, NASA KSC, GSFC, DFRC



"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Range Technologies

Space Based Telemetry and Range Safety



Products / Benefits

Product

Development of an on-board real-time processor that will make autonomous 'Flight Termination' decisions based on:

- Vehicle performance
- Unsafe zones and islands
- Potential landing sights
- Flight path considerations, such as, real-time weather and Air Traffic Control (ATC)

Note: RLV Flight Termination will result in new abort scenarios that do not result in loss of vehicle

Benefits

Safe reduction of ground infrastructure required for Range Safety

Implementation / Metrics

Current State of the Art

- Ground based infrastructure intensive
- 'Man-in-the-Loop' Range Safety Officer

Performance Metrics

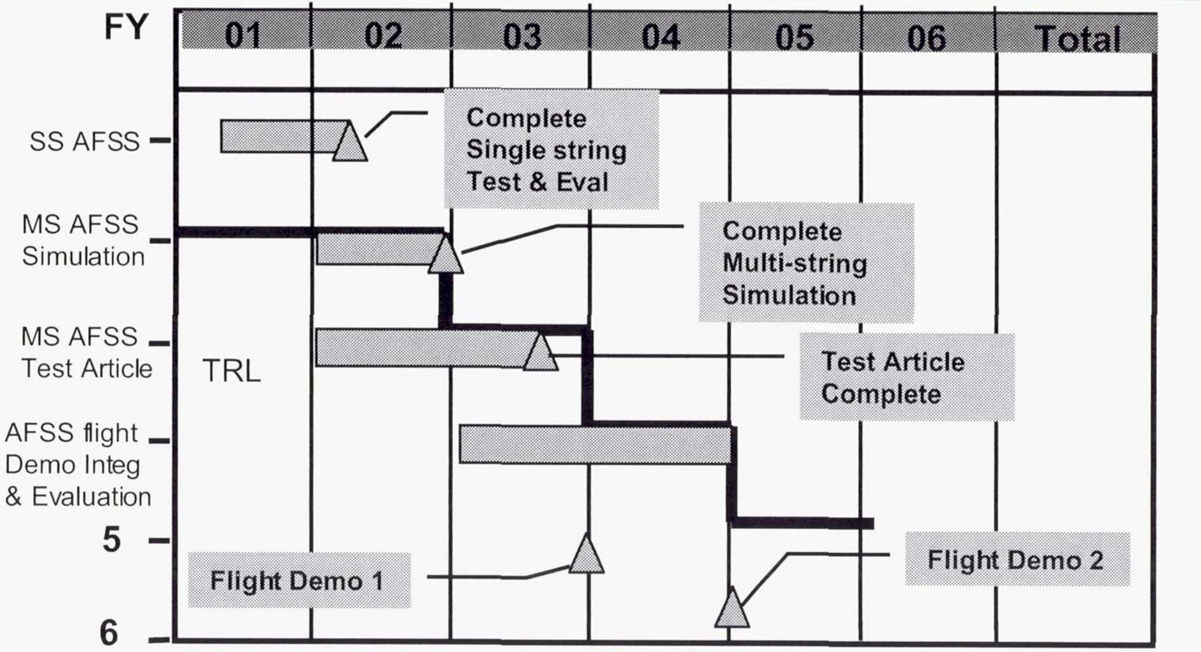
- Cost reduction as the direct result of elimination of ground infrastructure necessary to support Range Safety
- Increased Crew and Mission Safety by providing greater 'abort' capability

Risks

- Access/availability of GPS/INS unit
- Space Flight qualified processor speed

Participants/University

- MSFC, KSC, DFRC
- Lockheed Martin



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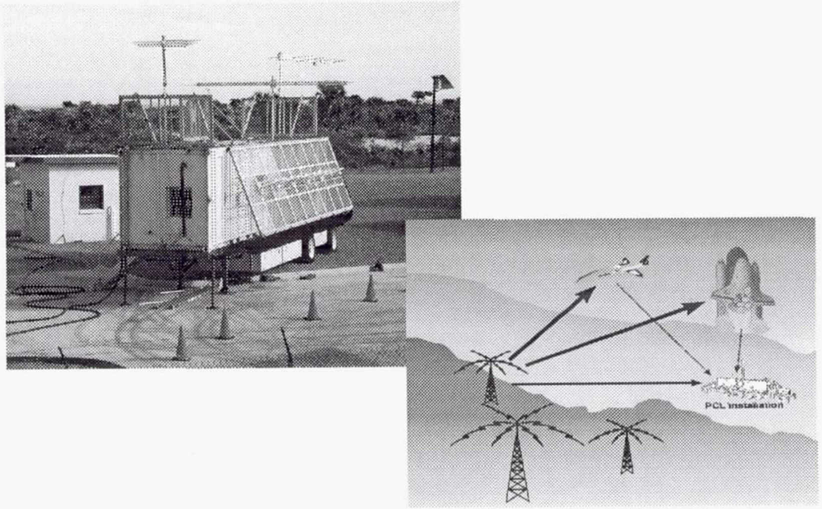
Autonomous Flight Safety System

- **Spaceport Range Systems**
  - **Description**
    - Provide Spaceport range systems architecture that would integrate all range support into a single system.
    - Provide for an integrated and automated capability that will make re-configuration of range systems for various launch vehicles, timely and efficient.
    - Provides ground based assets for Spaceport to meet requirements:
      - **that can not be met by the Space Based Range capabilities**
      - **necessary to provide communications between the Spaceports and Space Based Range**

  - **Candidate Projects**
    - Passive Coherent Locator (Metric Tracking)
    - Advanced low cost, transition DGPS Landing Systems
    - Automated Range Resource Management System
    - Mobile Launch Head Range System
    - Air/Sea Surveillance
    - Range Dispersion Monitoring System



Products / Benefits

Product

- Provides for all weather precision surveillance and tracking.
  - PCL uses existing TV and FM broadcast transmitters as the illuminators for a multistatic Continuous Wave (CW) RADAR-like system with very high performance and survivability attributes

Benefit

- Safely reduce infrastructure
- Primarily a COTS solution will reduce O&M cost
- Environmental clean
- Continuous operation

Implementation / Metrics

Current State of the Art

- Complex 30+ year old C-Band Radar(s)
- Utilize vehicle transponders

Performance Metrics

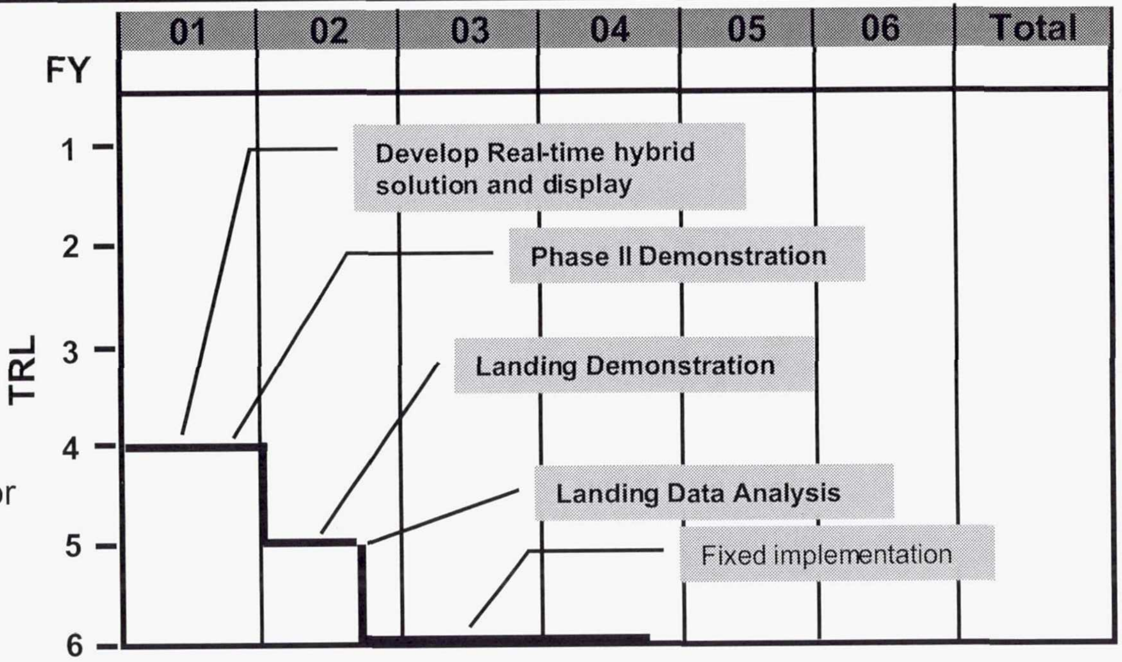
- Reduced life cycle cost as compared to existing infrastructure and capability
- Multi-role functionality

Risks

- Low. easily characterized and modified for refinement of capability

USG Participants

- NASA KSC, MSFC and Lockheed Martin



Develop Real-time hybrid solution and display

Phase II Demonstration

Landing Demonstration

Landing Data Analysis

Fixed implementation

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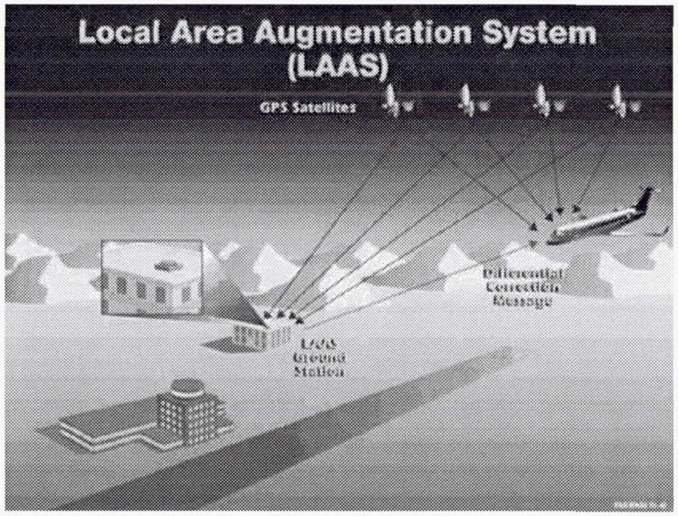
Passive Coherent Location

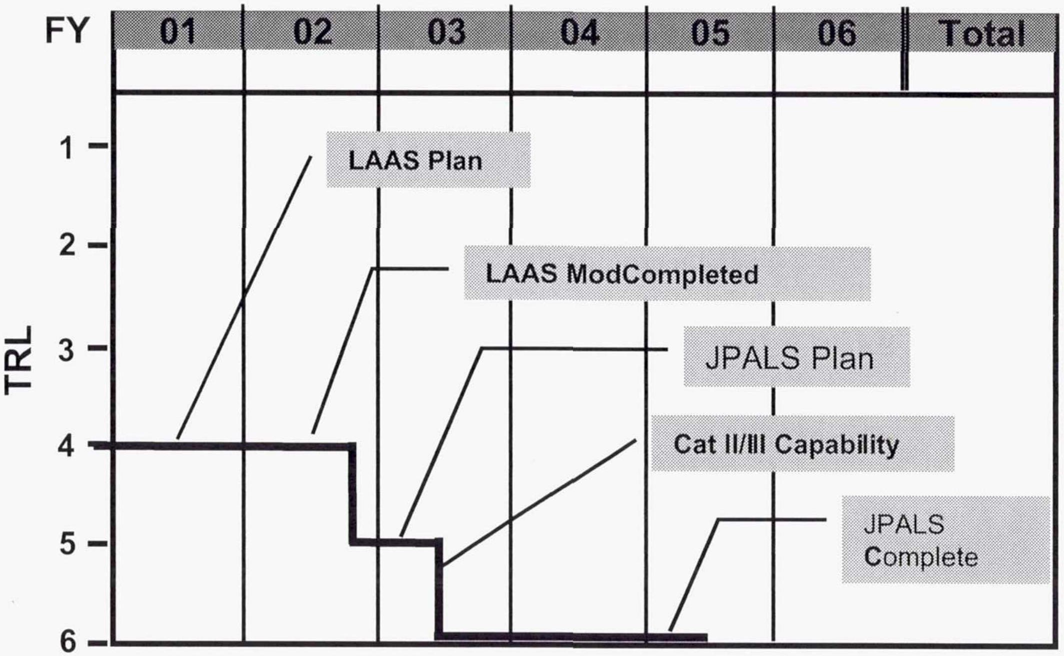


Products / Benefits

- Products
  DGPS ground stations at designated landing fields and compatible avionics
- Benefits
  Use of current standards will share development costs with other government agencies (FAA and DOD)
- Customers
  Internal AST, HEDS; external DoD, FAA, future spaceports

Implementation / Metrics

- Current State of the Art
  FAA LAAS Category I system in Test
  CAT II/III and JPALS TRL: 5/4 now.
- Performance Metrics
  High integrity, continuity, availability, and accuracy to meet safety requirements for manned spacecraft landing.
- Risks
  Low. Development done by FAA/DOD
- USG Participants
  DOD, FAA, NASA KSC

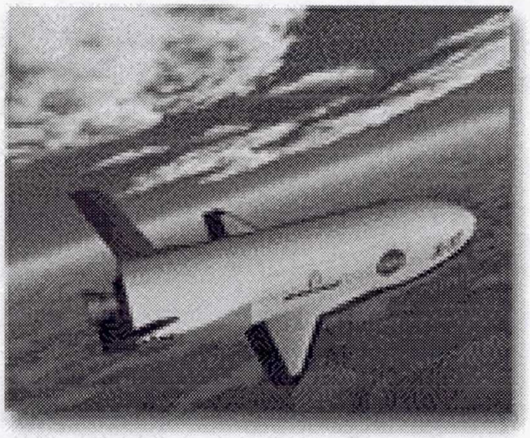


"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Range Technologies

DGPS Precision Approach & Landing System

- ♦ **Decision Models & Simulation**
  - **Description**
    - Existing models interject conservatism in order to compensate for computational and technology limitations.
    - New technologies exist that can reduce conservatism, while providing the fidelity necessary to ensure safe and cost effective models .
  - **Candidate Projects**
    - Spaceport Dispersion Three-Dimensional Model (SD3D)
    - Decision Model Optimization
    - High Fidelity Plume Conflagration Model
    - Disaster Sheltering Assessment Improvements
    - Knowledge-based Toxic Hazard Repository
    - Real-time Dispersion Monitoring System (RDMS)
    - RLV Composites Combustion and Toxicity Assessment

Spaceport Dispersion Three-Dimensional Model (SD3D)



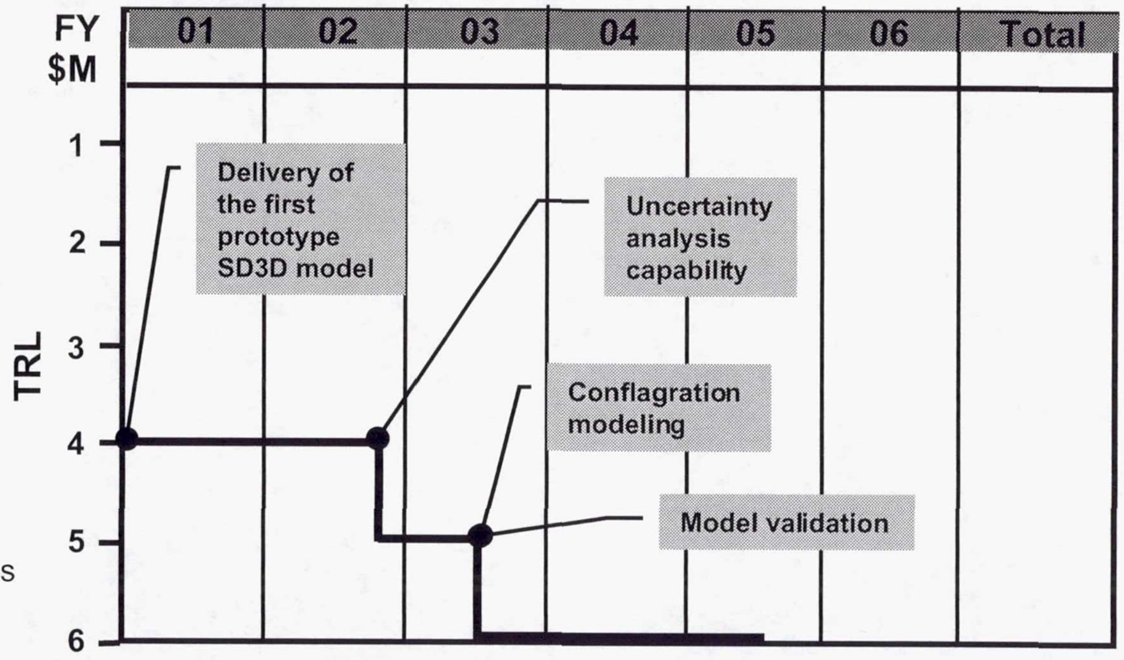
X-37 Demonstrator

Products / Benefits

- Products: SD3D model with capabilities that include, but not limited to an uncertainty analysis capability, toxic dispersion improvements and validation, and high fidelity conflagration analyses
- Benefits: Spaceport hazards shall be cost effectively controlled/mitigated with the above developed, and validated model
- Customers:
  Internal - NASA RLV Spaceports; External - DOD, FAA, and future spaceports
  Technologies will benefit 2nd Gen. by providing accurate decision assistance for operations at any spaceport
- Common / Enhancing: Products reduce uncertainty and conservatism which in turn reduces turnaround time.

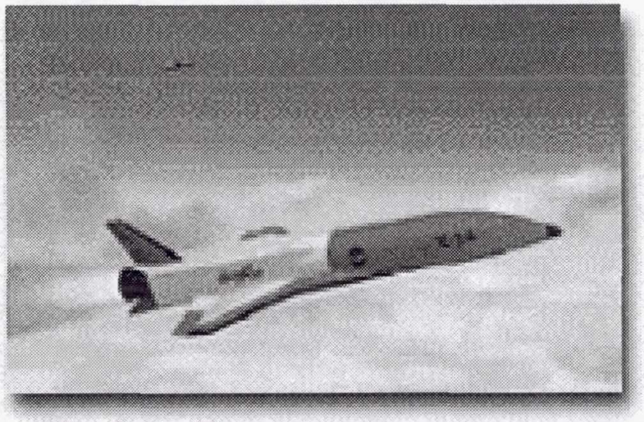
Implementation / Metrics

- Current State of the Art:
  Current capability based on a 20 year old empirical model (REEDM). The SD3D will replace this model.
- Performance Metrics
  - Product delivery dates
  - Demonstrated capability during operations
- Risks
  - Getting model "accepted" onto the spaceport
  - Compatibility of model with existing databases
- Participants
  - KSC
  - PAFB/CCAFS
  - Spaceport Florida Authority and future Spaceports



"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Range Technologies

RLV Composites Combustion and Toxicity Assessment



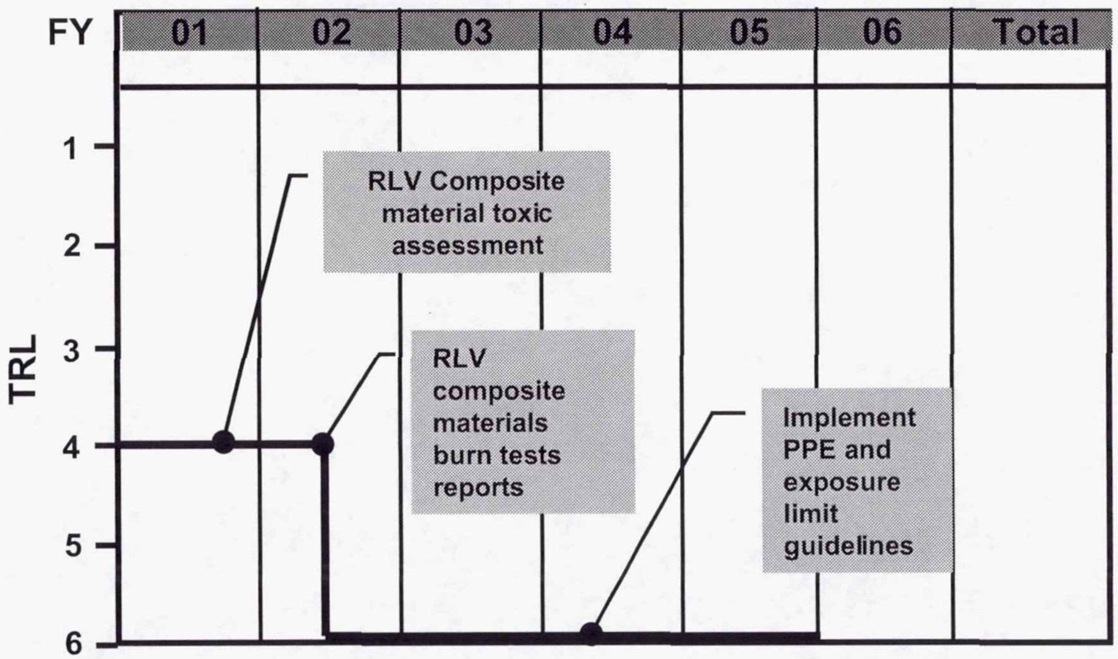
X-34 Demonstrator

Products / Benefits

- Products: Personal Protection Equipment (PPE) and exposure limit recommendations (if any) and procedures as it relates to RLV composite materials hazards
- Benefits: Spaceport composite material hazards (if any) will be cost effectively controlled/mitigated
- Customers:
  Internal- NASA Spaceports; External - DOD, FAA, and future spaceports
  Technologies will benefit 2nd Gen. by providing safety guidance for operations at any spaceport
- Common / Enhancing: Products provide safety guidance which reduces accidents and/or long term health effects

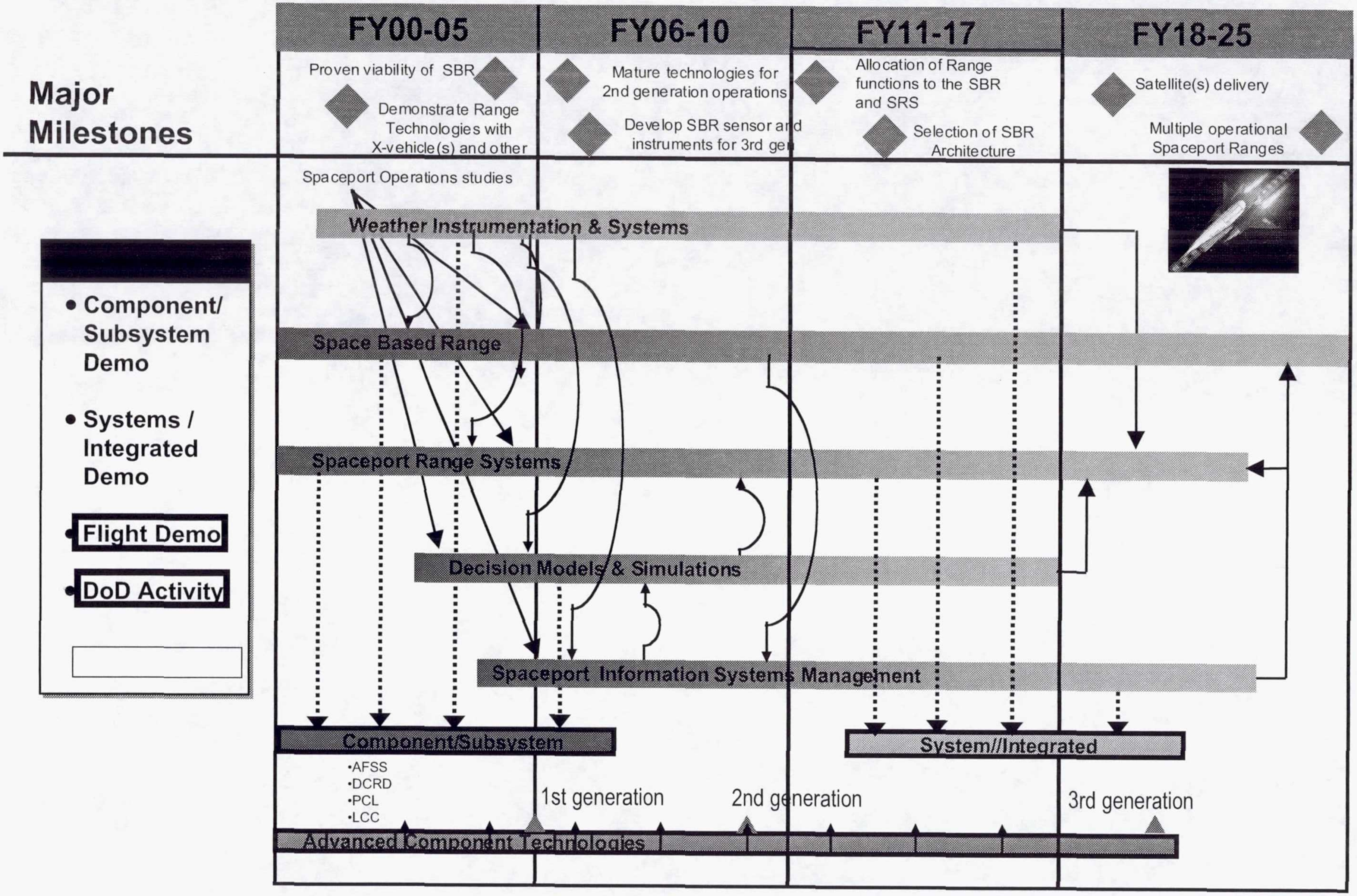
Implementation / Metrics

- Current State of the Art:
  The hazards associated with exposure to burning composite materials is a new area and not well understood
- Performance Metrics
  - Composite material burn test dates
  - Reports/recommendations on composite material hazards
- Risks
  - "Piggy-backing" on burn tests planned by other agencies
  - Availability of composite material test samples and propellant material to use in burn tests
- Participants
  - KSC, MSFC, LaRC
  - Army, PAFB/CCAFS and other AF organizations
  - Spaceport Florida Authority and future Spaceports



♦ Spaceport Information Systems Management

- **Description**
  - Advanced Space Based and Spaceport Range systems will require an architecture that:
    - provides for the sharing of range information
    - supports distributed processing
    - provides support for simultaneous ground and flight operations
      - to/from multiple Spaceports/Ranges
      - multiple vehicles
- **Candidate Technologies**
  - Space Based Internet viewing of vehicle data and vehicle access to range services
  - Networks Administration and Management systems
  - Standardization of vehicle data interfaces
  - Standardization of range systems interfaces



Major Milestones

FY00-05	FY06-10	FY11-17	FY18-25
Proven viability of SBR Demonstrate Range Technologies with X-vehicle(s) and other Spaceport Operations studies	Mature technologies for 2nd generation operations Develop SBR sensor and instruments for 3rd gen	Allocation of Range functions to the SBR and SRS Selection of SBR Architecture	Satellite(s) delivery Multiple operational Spaceport Ranges

- Component/ Subsystem Demo
- Systems / Integrated Demo
- **Flight Demo**
- **DoD Activity**

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Range Technologies

Advanced Range Technologies

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Potential Benefits

- **Lower per Launch Costs**
- **Shorter Lead-time**
- **Higher Through-put**
- **Lower number of Weather Scrubs or Delays**
- **Lower number of Range/Spaceport Scrubs or Delays**
- **Lower Infrastructure Capital & O&M requirements**
- **Converts fixed (non-reimbursable) to variable costs**
- **Outsourcing options**
- **Multi-Range/Spaceport Compatibility**

- Customers

Stakeholder	Interest
• KSC	Advanced Range Leadership, Strategic Planning & R&D
• MSFC	Space Transportation Program
• JSC	SOMO Shuttle
• FAA	License/Regulations
• Space Launch Industry	Low Cost & High Availability
• Spaceports	Site Infrastructure
– California, Florida, others	
• USAF	SMC, Space Wings, & EELV
• GSFC	TDRS Office

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Spaceport Operations Element

NASA Ames Research Center
And
NASA Kennedy Space Center

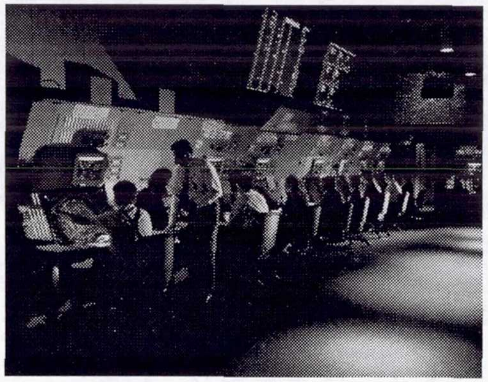
Outline

- NASA Ames Air Traffic Management Technologies
- Space Transportation of the Future
- Spaceport Flight Operations Research Topics

Air Traffic Management at Ames

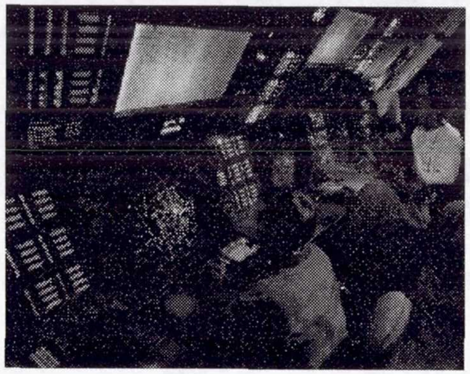
- NASA Ames Unique Air Traffic Control Software
  - Center TRACON Automation System, CTAS
  - Future ATM Concepts Evaluation Tool, FACET
- NASA Ames Unique Research Facilities
  - Future Flight Central
  - Vertical Motion Simulation
  - Pseudo Aircraft Simulator

Ames Developed Technologies



Traffic Management Advisor

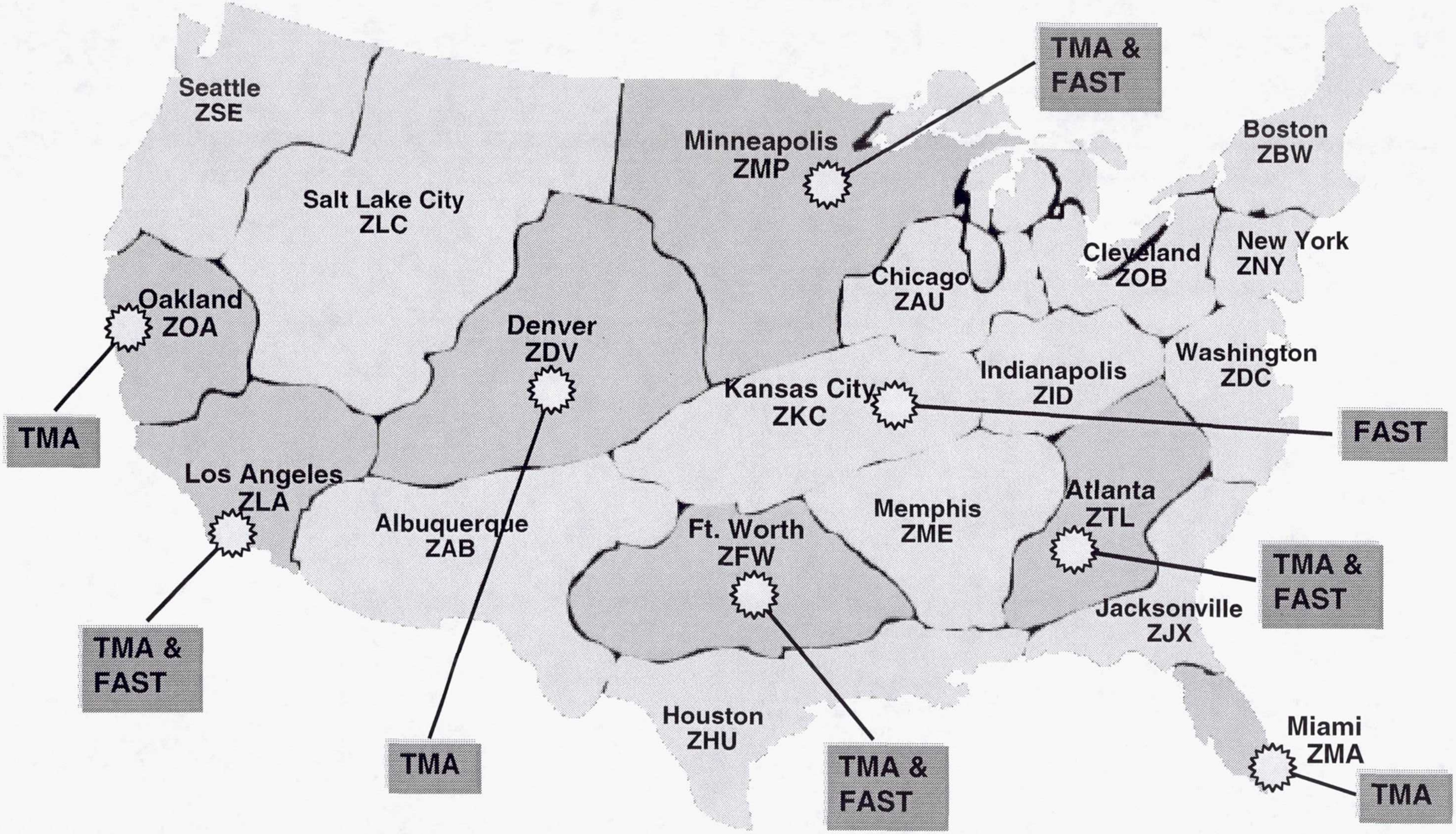
Surface Movement Advisor



Final Approach Spacing Tool Passive

- Central to FAA's NAS Modernization
- Comprise three of the five tools selected by FAA/industry in support of on-going Free-Flight Phase 1
  - 66% of the expected cost savings due to automation
  - 43% ($222M) of implementation budget for automation tools

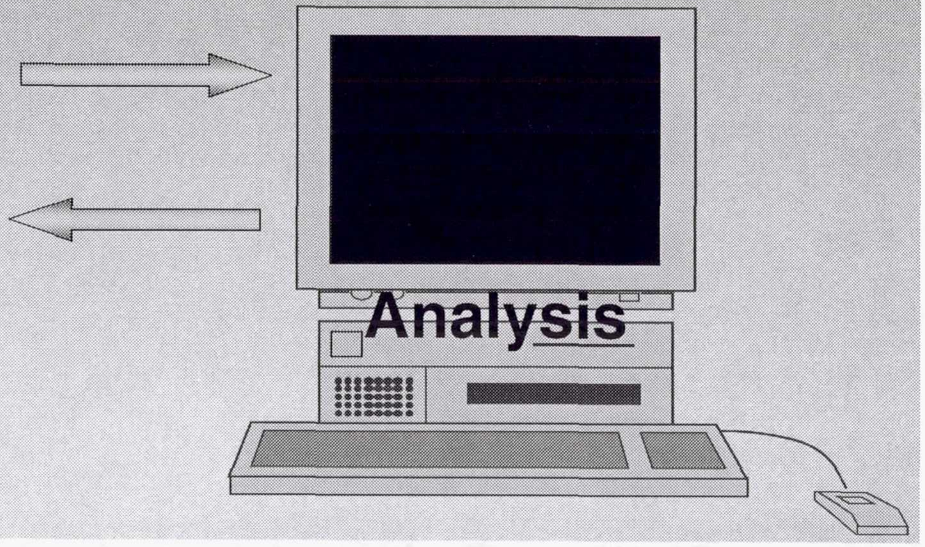
Free Flight Phase-I CTAS Sites



FACET

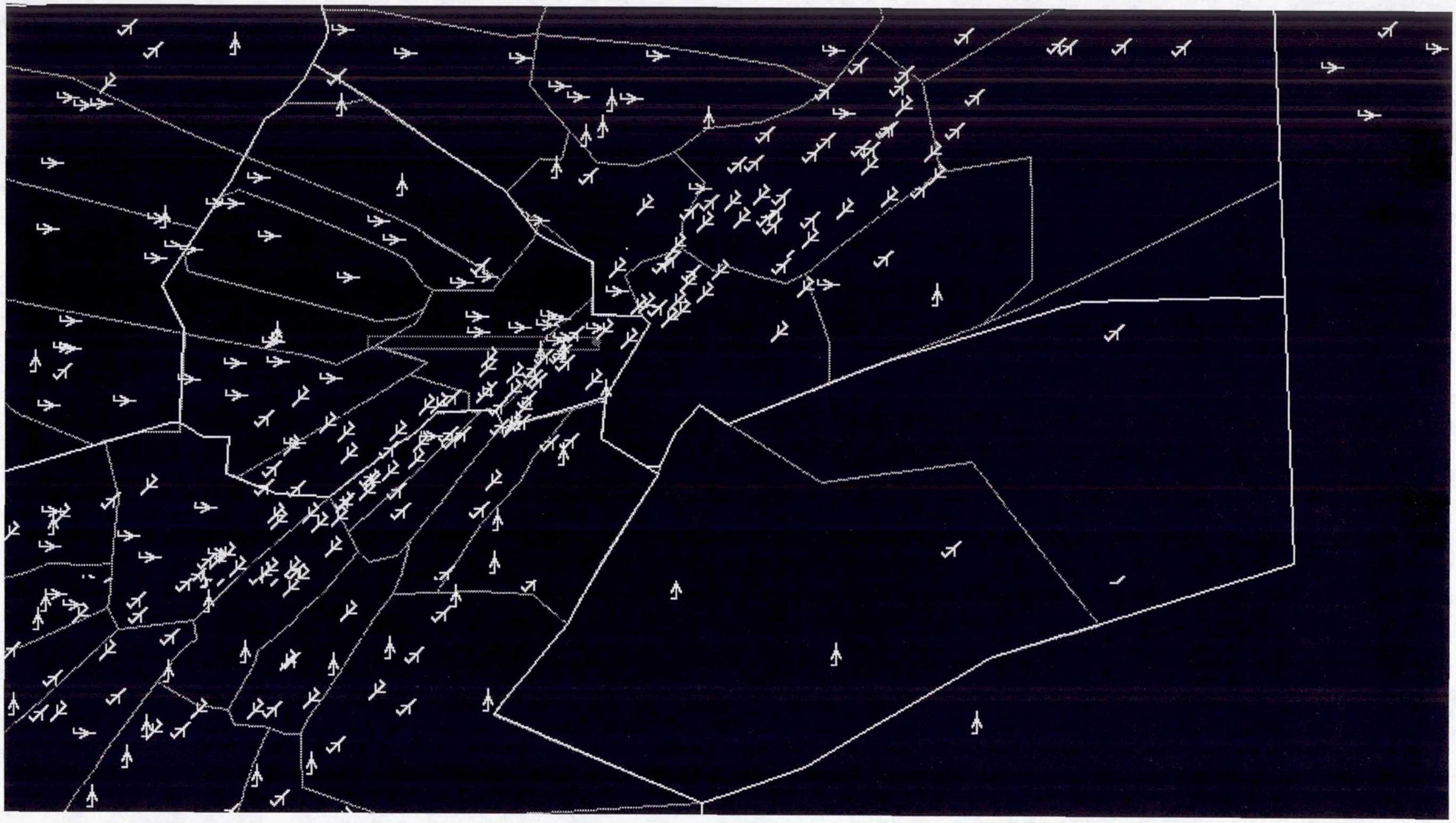
Ames Research Center

Future ATM Concepts Evaluation Tool

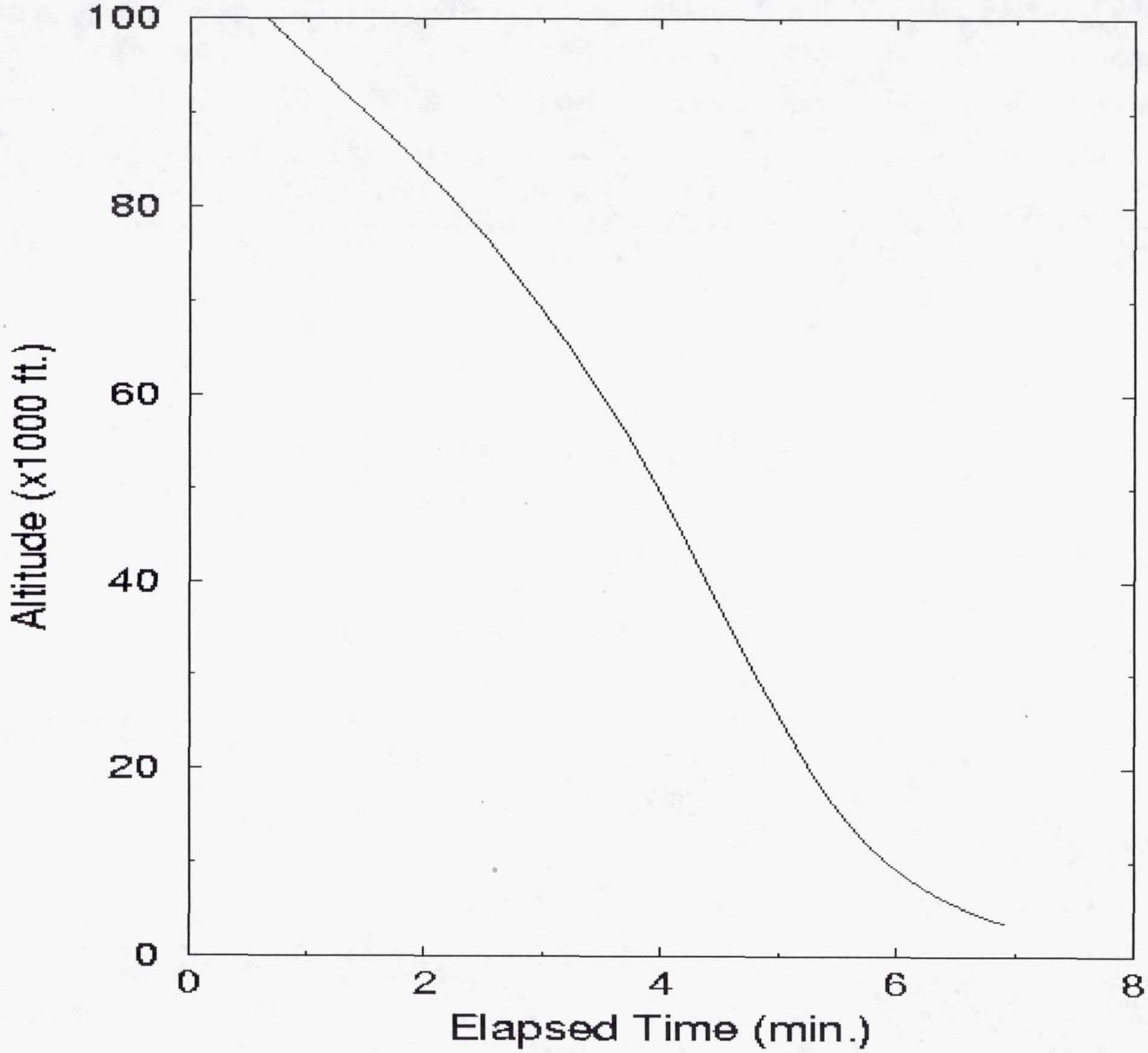


RLV Operation in the NAS

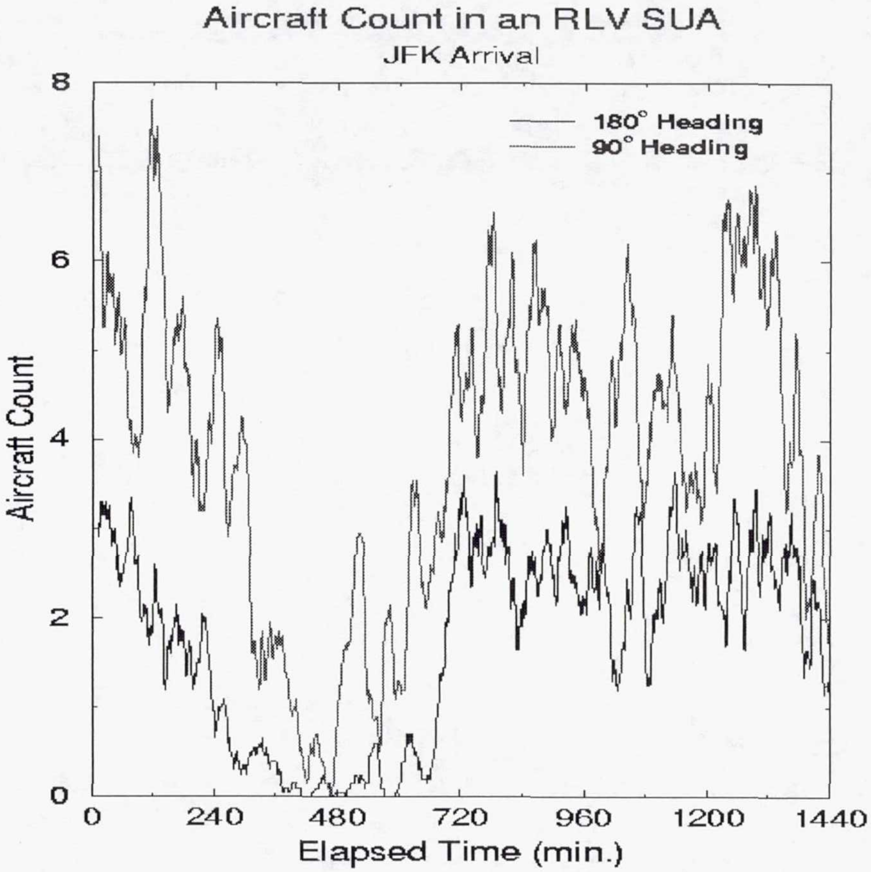
RLV Operations at JFK

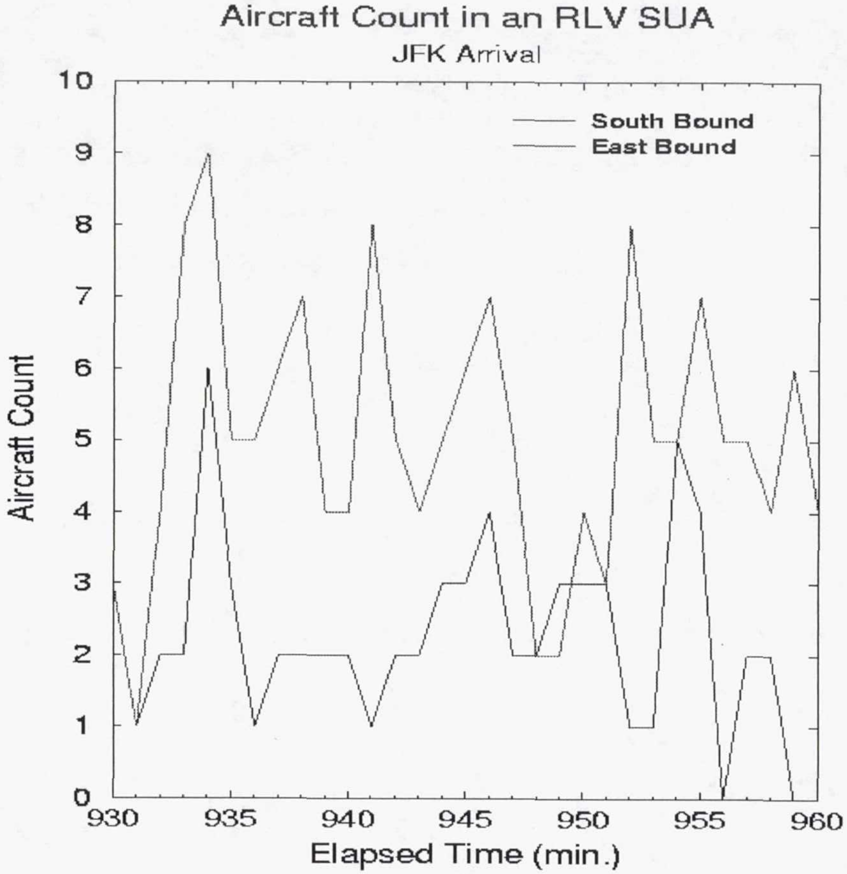


RLV Descent Trajectory



Number of Aircraft in RLV Path at JFK



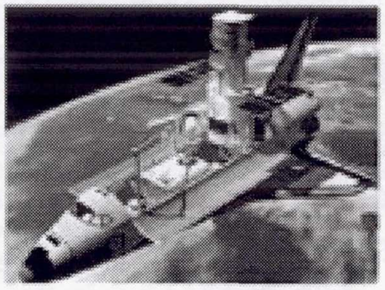


Future Flight Central

Space Transportation in the Future

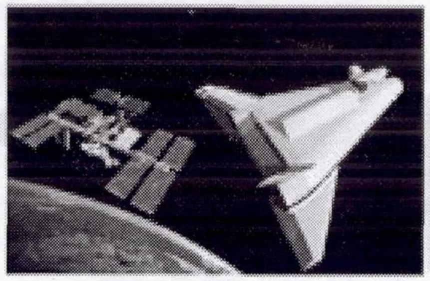
- NASA Space Transportation Goals and Roadmap
  - Increase safety
  - Reduce Cost
- United States Spaceport Locations
  - Inland locations
  - Increased number of spaceports
- Vision Spaceport
  - Spaceports that operate similar to today's airports

NASA Space Transportation Roadmap and Goals



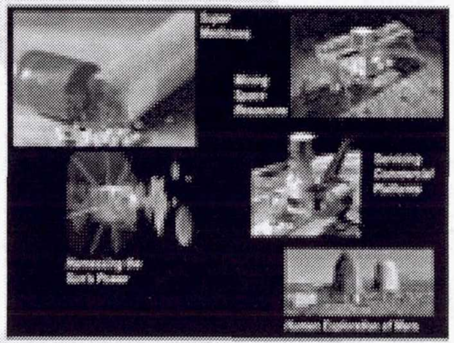
Today: Space Shuttle
1st Generation RLV

- Orbital Scientific Platform
- Satellite Retrieval and Repair
- Satellite Deployment



2010: 2nd Generation RLV

- Space Transportation
- Rendezvous, Docking, Crew Transfer
- Other on-orbit operations
- ISS Orbital Scientific Platform
- 10x Cheaper
- 100x Safer

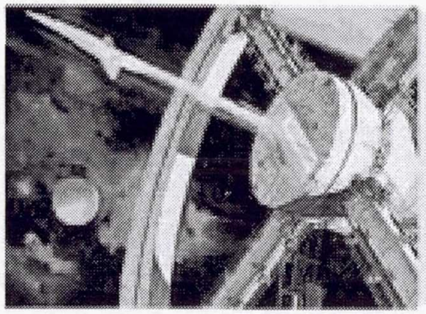


2025: 3rd Generation RLV

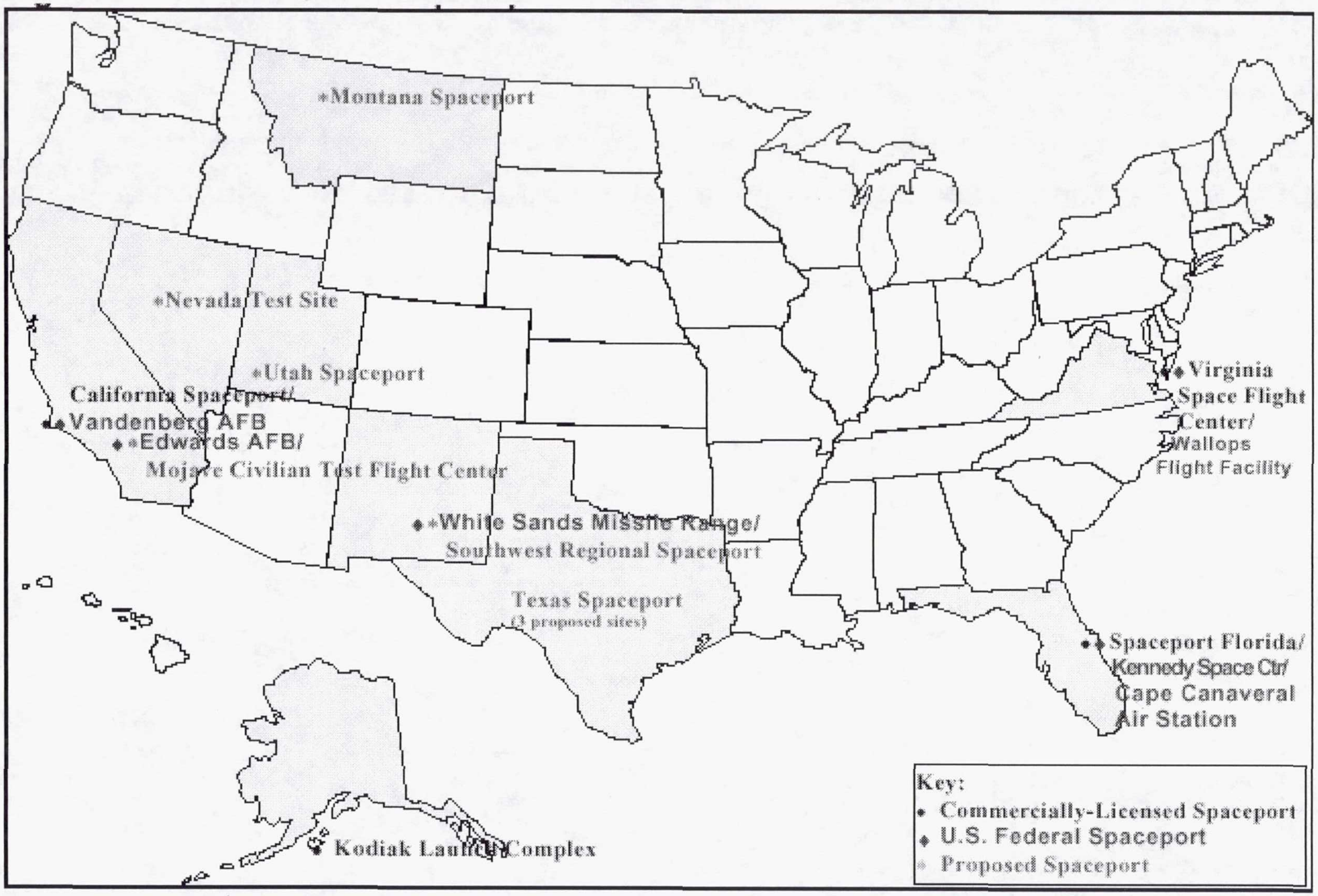
- New Markets Enabled
- Multiple Platforms / Destinations
- 100x Cheaper
- 10,000x Safer

2040: 4th Generation RLV

- Routine Passenger Space Travel
- 1,000x Cheaper
- 20,000x Safer

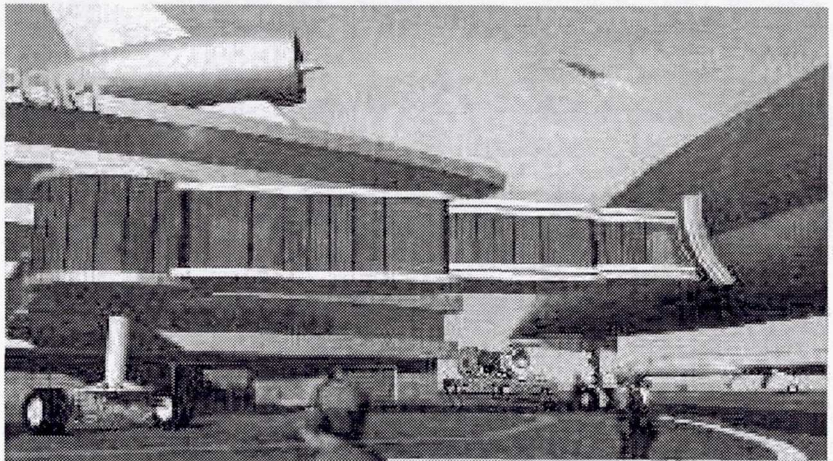


USA Spaceport Locations

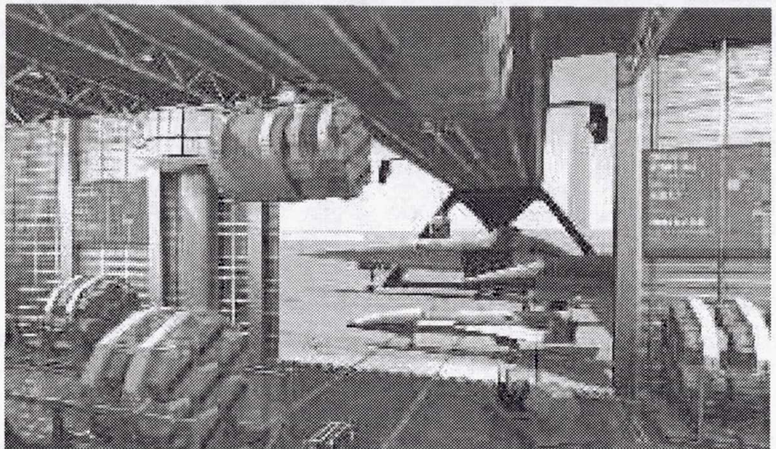


Vision Spaceport

Ultimately -Space for Anyone



High-Volume Cargo Operations



Spaceport Flight Operations Research Topics

- Flight Planning and Scheduling
  - International Space Station
  - Increased and Varied Spaceport Locations
  - Aborts
  - Emergency De-orbit
- Airspace Negotiation
  - FAA Licensing
  - Trajectory negotiation
  - Range Operations

Spaceport Flight Operations Research Topics

- RLV Performance and Flight Operations
  - SHARP Technologies
  - Commercial Ventures
- Collision Detection and Resolution
  - Aircraft
  - Space Debris

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Cryogenics Testbed Technology Focus Areas

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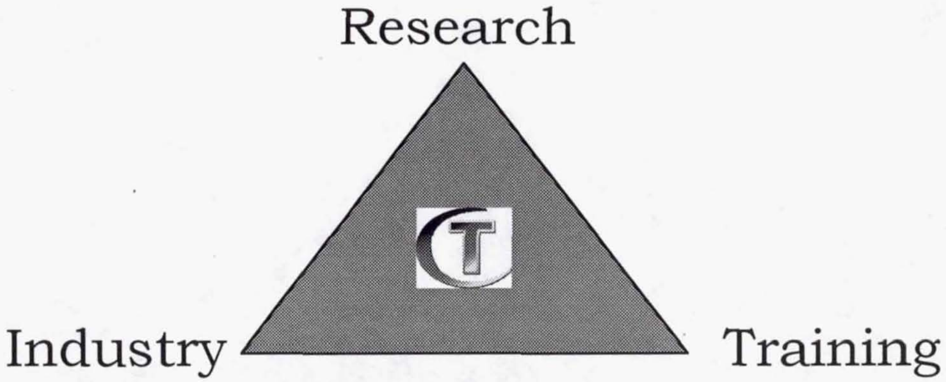
CRYOGENICS TESTBED OVERVIEW

- Our mission is to bring together the mutual elements of research, industry, and training in the field of cryogenics to advance technology development for the spaceports of the future.
- Successful technology and productive collaboration comes from the these three ingredients working together in a triangle of interaction.



Research

Industry

Training

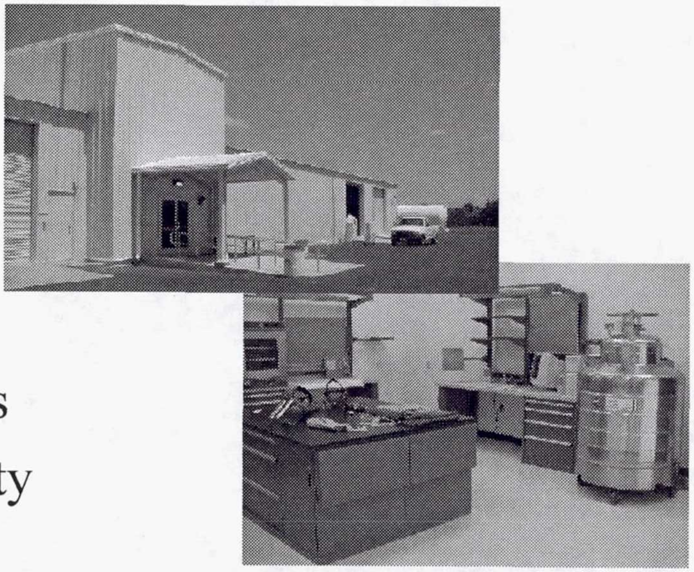
CRYOGENICS TESTBED OVERVIEW

Collaboration

- Research → *energy efficient cryogenics*
- Industry → *engineering, test, and evaluation*
- Training → *international school of excellence*

Facilities

- Cryogenics Test Laboratory
- LN2 Flow Test Area
- Launch Systems Test Area
- Materials Science Laboratories
- Launch Equipment Test Facility



CRYOGENICS TESTBED TASK AREAS

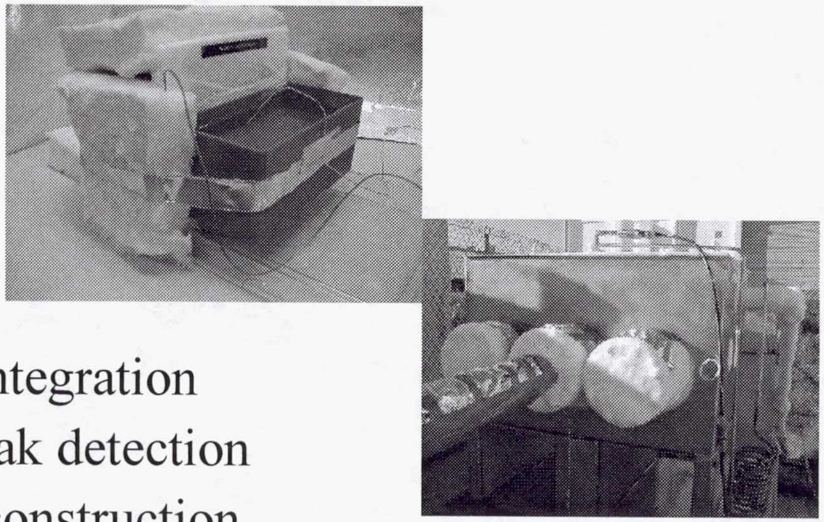
Aerospace

- Exploration initiatives
- Future launch vehicle servicing
- Space Shuttle technology upgrades
- Experiment design and setup
- Spaceport 2050 (energy integrated launch site)

Commercial

- Cryogenic and vacuum testing
- Specialized system design engineering
- Component test and evaluation
- Prototype construction
- Cryobiology, food technology, electronics, materials, and other low temperature applications

CRYOGENICS TESTBED
EXAMPLE AREAS OF WORK



- Thermal insulation testing
- Liquid nitrogen flow testing
- Engineering test and evaluation
- Equipment qualification testing
- Propellant systems planning and integration
- High vacuum measurement and leak detection
- Conceptual design and prototype construction
- Low-temperature applications such as energy transfer, superconductivity, medical, food industry
- International school of excellence in cryogenics (charter)

CRYOGENICS TESTBED TECHNOLOGY FOCUS AREAS

Thermal Insulation Systems

Cryogenic Components

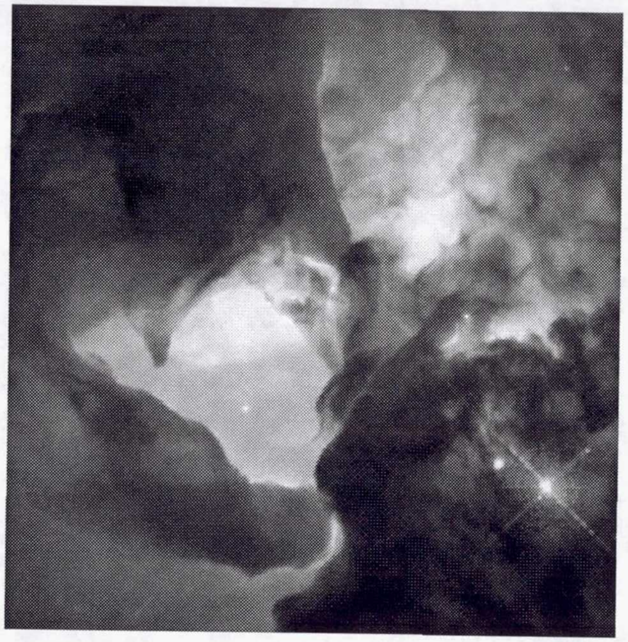
Propellant Process Systems

Low-Temperature Applications

- ➢ The focus areas comprise the core work which is the technical foundation of the testbed
- ➢ The focus areas are linked to the long range strategic goals of NASA

THERMAL INSULATION SYSTEMS TECHNOLOGY FOCUS AREA

Energy
Efficient
Cryogenics



Objective: ***Develop the materials, the testing technologies, and the engineering for the efficient storage, transfer, and use of cryogens and cryogenic propellants on Earth and in space.***

THERMAL INSULATION SYSTEMS TECHNOLOGY FOCUS AREA

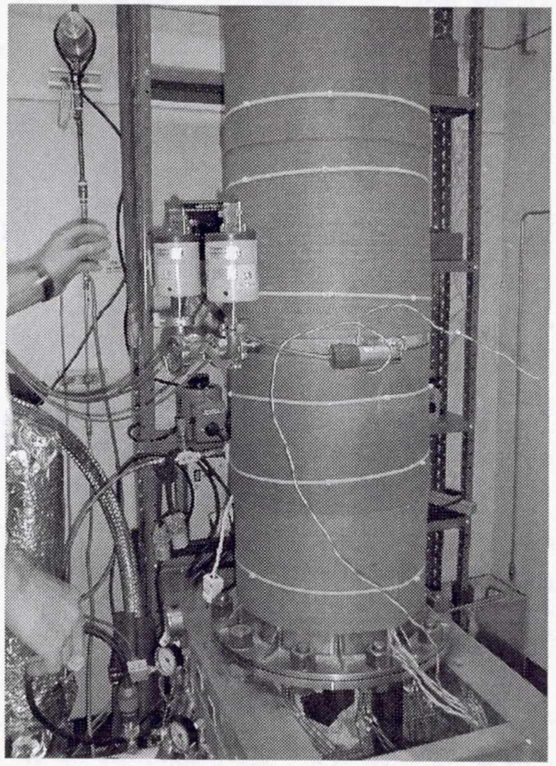
- Insulation Testing Technology
- Efficient, Robust Insulation Systems
- Applications

INSULATION TESTING TECHNOLOGY

- Cryostat-1
- Cryostat-2
- Cryostat-3
- Dewar Test Apparatus
- Pipeline Test Apparatus

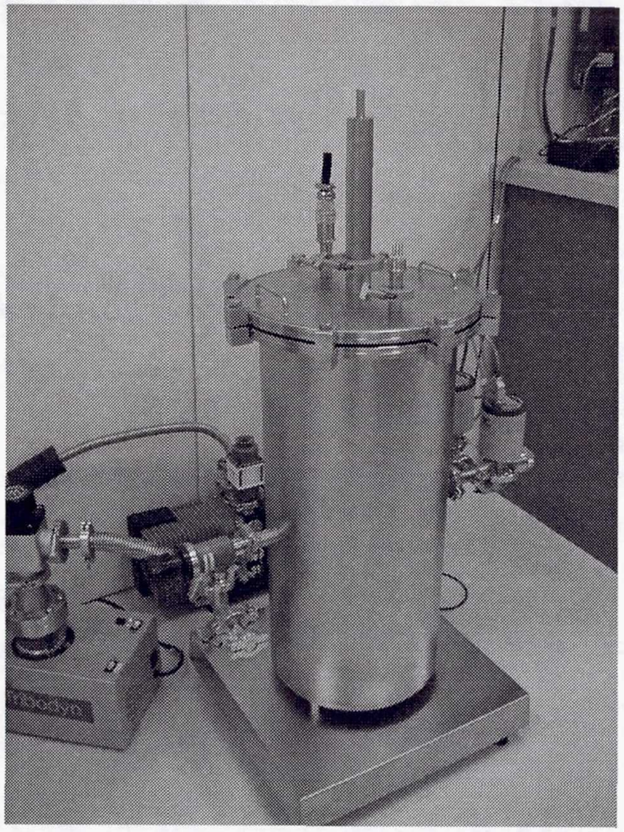
INSULATION TESTING TECHNOLOGY

Cryostat-1 is a liquid nitrogen boiloff calorimeter apparatus for direct measurement of the apparent thermal conductivity (k-value) of a material system at a fixed vacuum level. The configuration includes a 1 m long cylindrical cold mass with liquid nitrogen guard chambers. The steady-state measurement of the apparent k-value is made when the vacuum level, all temperatures, and the boiloff flow are stable.



INSULATION TESTING TECHNOLOGY

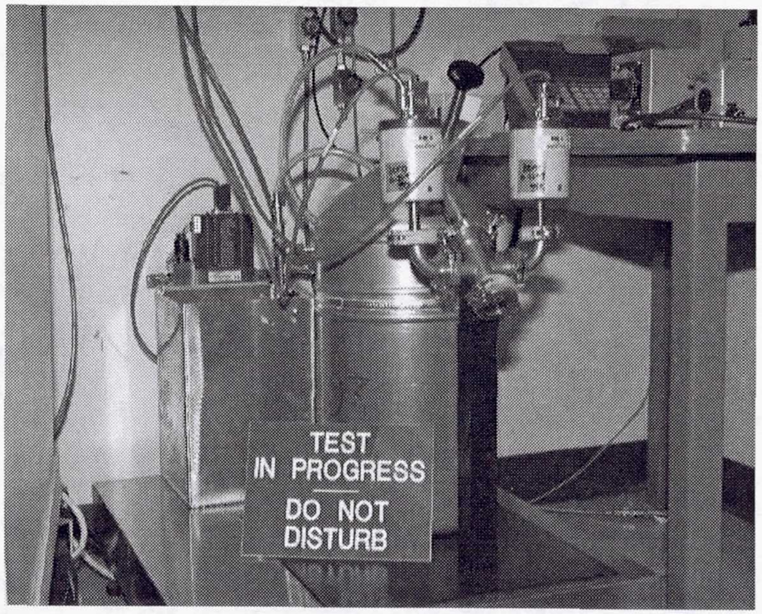
Cryostat-2 is a liquid nitrogen boiloff calorimeter apparatus for calibrated measurement of the k-value. The configuration is _ m long cylindrical with aerogel disks for thermal guards. This apparatus with its removable cold mass allows a quicker testing of different specimens, is convenient for materials screening, and can also be configured for flat plate geometries.



Cryostat-3 is a similar test apparatus used for testing insulation materials in specialty environments such as carbon dioxide.

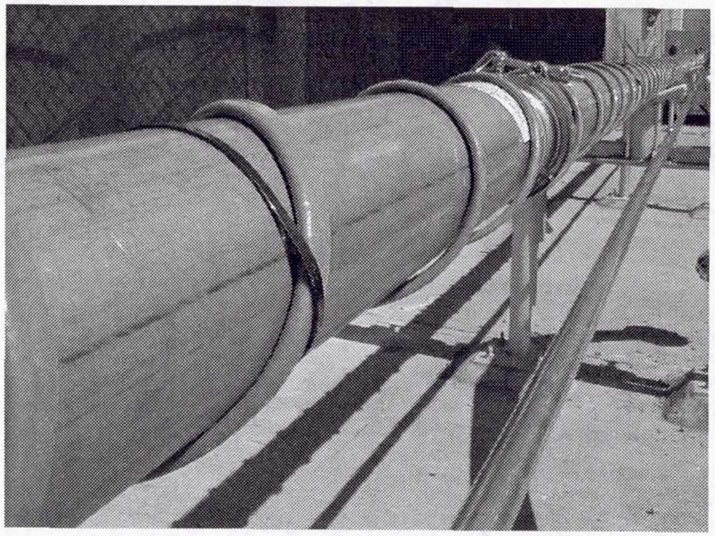
INSULATION TESTING TECHNOLOGY

The ***Dewar Test*** is an apparatus to determine the "real world" performance of an insulation system with consideration given to the fabrication, quality control, testing, and operation of the cryogenic tank. This method gives a direct measure of actual system performance as a function of cold vacuum pressure. The weight loss due to the boiloff of nitrogen gas is proportional to the total system heat leak rate.



INSULATION TESTING TECHNOLOGY

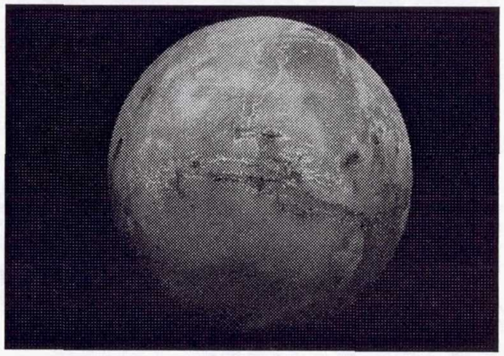
The ***Pipeline Test Apparatus*** is designed for precision thermal performance measurements of complete assemblies. The pipelines may be rigid (up to 60 feet) or flexible (any length). Three pipelines with outside diameters of up to 8 inches may be installed at one time. Both ends are thermally guarded by liquid nitrogen reservoirs with special mounting adapters. Test article surfaces are maintained at a constant warm temperature using a heater jacket. Static nitrogen boil-off flow rates are recorded after a suitable stabilization period. A field portable property measurement and data acquisition system is used. The system may be adapted for use with other process fluids under dynamic (flow through) conditions.



EFFICIENT, ROBUST INSULATION SYSTEMS

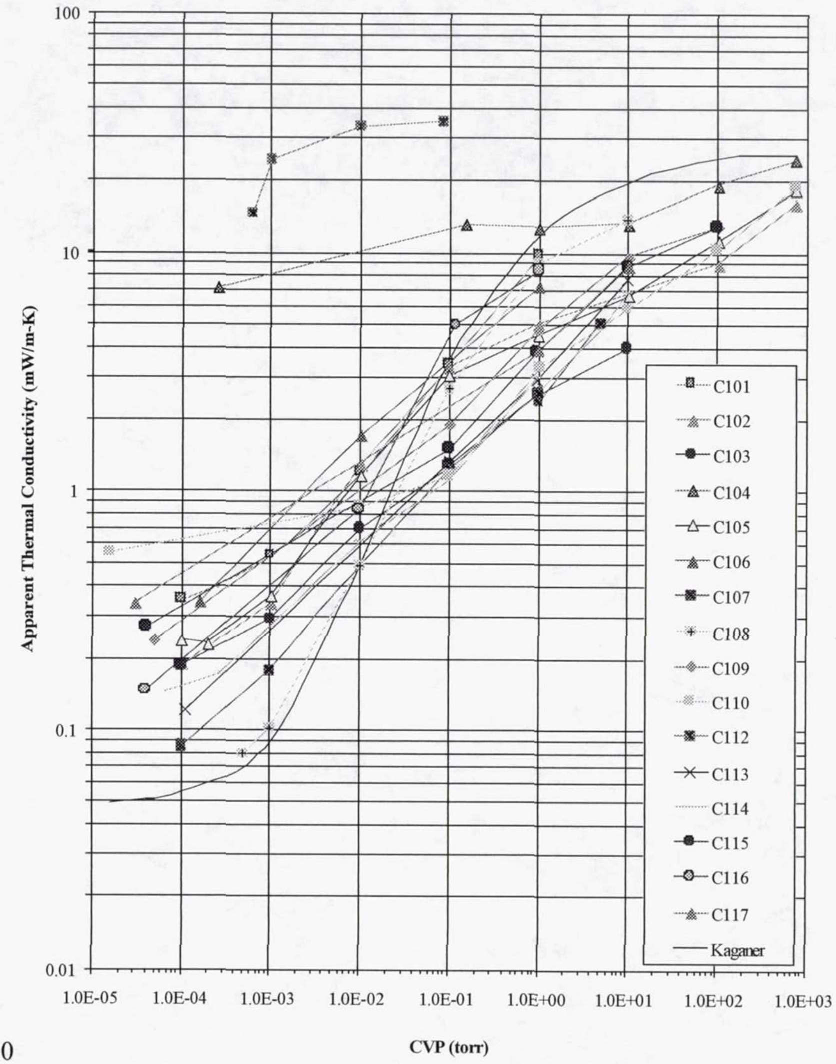
- Technological developments of the last century have led to insulation systems that have approached the ultimate limit of performance. More technologies and markets forecast for rapid expansion into the 21st century will require, in many cases, not superinsulations but more efficient systems for a wide variety of cryogenic applications. The development of **efficient, robust thermal insulation systems** is a target area of work.
- Liquid nitrogen boiloff methods are used to test both conventional and new materials in **high vacuum, soft vacuum, and no vacuum** environments. Materials include combinations of reflection shields, fiberglass papers, polyester fabrics, aerogel composite blankets, fumed silica, aerogel powders, aerogel beads, and foams.
- A new **layered composite insulation** under development should benefit industry for the storage, transfer, or handling of low temperature fluids, by lowering the manufacturing and life-cycle costs for equipment. These insulation systems should also allow for more flexibility in the overall design and implementation of cryogenic systems, a key benefit to the cryogenic equipment on Earth and in Space.

NO VACUUM



SOFT VACUUM

HIGH VACUUM


Comparative Study of Cryogenic Insulation Systems
Apparent Thermal Conductivity as a function of CVP

TEST SUMMARY CRYOSTAT-1

- Boundary temperatures were approximately 80 K and 280 K
- Typical installed thickness was 25-mm.
- Residual gas was nitrogen.
- Layered composite C107 gave superior performance of 2.4 mW/m-K (R-60) at 1 torr which is about four times better than the benchmark MLI C108.
- C107 was comparable to the benchmark MLI at high vacuum (0.09 versus 0.08 mW/m-K).

APPLICATIONS

- Low Cost High-Efficiency Pipelines for Long Distance Transfer of Cryogens
- Long Term Storage of Cryogens on Mars Using Soft Vacuum Thermal Insulation System
- Long Flexible Cryostats for High-Temperature Superconducting Cables

APPLICATIONS

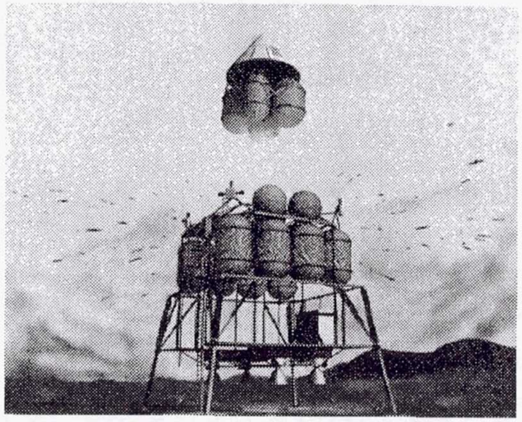
Low Cost High-Efficiency Pipelines for Long Distance Transfer of Cryogens

- Thriving spaceports of the future will rely on new approaches to supply of the requisite propellants and gases. Services built around thermally efficient, integrated launch pads supplied by centralized plants for both energy conversion and cryogenic production are envisioned. A key part of these services will be the transfer pipelines to deliver the cryogenic fluids (helium, hydrogen, nitrogen, and oxygen) across long distances. Achieving the goal of an "energy integrated" launch site can be done if all elements are given due economic consideration at the start of the design concept.
- Current work includes the development of low-cost high-efficiency pipelines for the long distance transfer of cryogens. Two commercial off-the-shelf products are being tested: a vacuum-jacketed pipeline with multilayer insulation and two standard bayonet joints and a foam insulated pipeline (both are 60 foot length). The heat leak of this pipeline, which will be determined through a series of liquid nitrogen boil-off tests, will also serve as a benchmark for thermal performance comparison. New pipelines, both rigid and flexible, using experimental insulation materials, will be fabricated and tested.

APPLICATIONS

Long Term Storage of Cryogens on Mars Using Soft Vacuum Thermal Insulation System

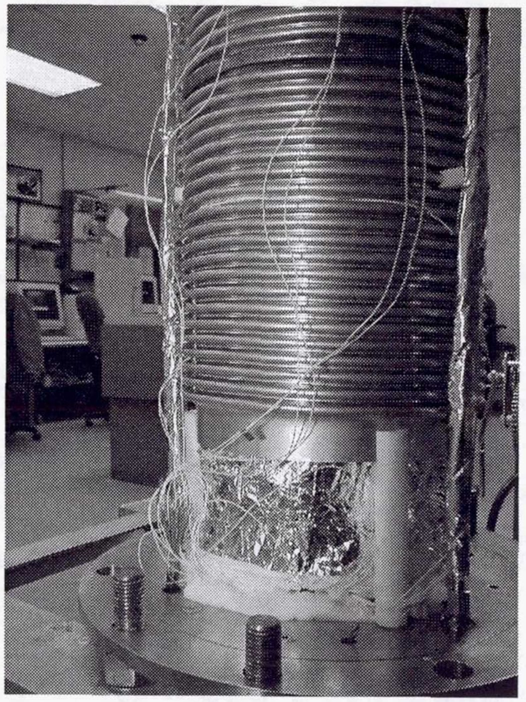
- Missions to explore Mars will require complex, autonomous systems that are highly energy efficient, integrated across all subsystems, and rugged. The long term storage of cryogens, in particular liquid oxygen and liquid methane, is an important challenge for the planned step by step success of these missions. Liquid oxygen supplies for life support and for return trips to Earth will be produced well in advance of the human missions and must remain ready to use for a variety of contingency scenarios. The atmosphere on Mars is a "soft vacuum" (about 5 torr) composed primarily of carbon dioxide.
- Current work is focused on the test and evaluate the thermal performance of experimental materials in the approximate Martian environment. This region is very dynamic because radiation, gas conduction, and convection (as well as solid conduction) are all significant contributors to the total heat leak rate. Tests are typically conducted in nitrogen (for comparison), in carbon dioxide, and in high vacuum as well. Materials tested to 77 K include aerogels in loose fill, blanket, and layered composite forms.



APPLICATIONS

Long Flexible Cryostats for High-Temperature Superconducting Cables

- High temperature superconducting (HTS) materials for power transmission applications are now being demonstrated in prototype situations. Future space applications for HTS materials, in addition to power transmission, include areas such as microwave communications, quantum devices, propulsion by plasma beams, and electromechanical actuators. Global proliferation of long length power cable systems, from the refrigeration point-of-view, will depend on an energy efficient cryogenic system that is economical to manufacture and operate. An inherent element of these supporting cryogenic systems is the thermal insulation system.
- Current work is focused on thermal management of HTS power transmission equipment for future energy needs. Insulation performance levels of materials versus those of typical systems in operation have been described through extensive cryostat tests in the 77 K temperature range. A simulated section (1 meter) of a flexible cryo power cable has been constructed. Measurement of the overall thermal performance under varied conditions of vacuum level and mechanical loading is being performed. This research study being done in cooperation with Oak Ridge National Laboratory through the Department of Energy's Superconducting Partnership Initiative.



CRYOGENICS TESTBED TECHNOLOGY FOCUS AREAS

SUMMARY

Thermal Insulation Systems

- Energy efficient cryogenics

Cryogenic Components

- Valves, pumps, and sensors

Propellant Process Systems

- Liquid hydrogen, liquid oxygen densification

Low-Temperature Applications

- High temperature superconductivity

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Ground Operations

Space Transportation Technology Workshop
October 11, 2000

Randy Eastman/KSC

"ST Day 2000: Reducing Risk for the Next Generations"

- **Integrated Space Transportation Program (ISTP)**
  - **Shuttle Upgrades (1st Generation)**
  - **Space Launch Initiative (2nd Generation)**
  - **Advanced Space Transportation Program (3rd Generation)**
    - Support 2nd Generation RLV
    - Spaceliner 100 Investment Area
      - Propulsion
      - Airframe
      - Launch Technologies
      - IVHM
      - Operations and Range Technology Project
        - Range
        - Launch Assist
        - Ground Operations Element
        - Spaceport Operations
    - In-Space
    - Space Transportation Research
  - **4th Generation RLV Research**

- **Ground Operations**
  - **Technologies that could reduce ground operations costs**
  - **What are the systems issues driving ground ops costs as we know them today?**
    - Example: Labor intensive manual mating of umbilicals
  - **What new technologies could reduce ground ops costs?**
    - Example: Automated umbilical mating
  - **Other benefits**
    - Reduced processing time
    - Increased safety and reliability

- **Ground Ops Technologies**
  - **Sensors**
  - **Umbilicals**
  - **Payload handling & checkout**
  - **Propellant production, handling & storage**
  - **Cryogenic systems**
  - **Weight & CG measurement**
  - **Hold down posts & vehicle positioning**
  - **Etc.**

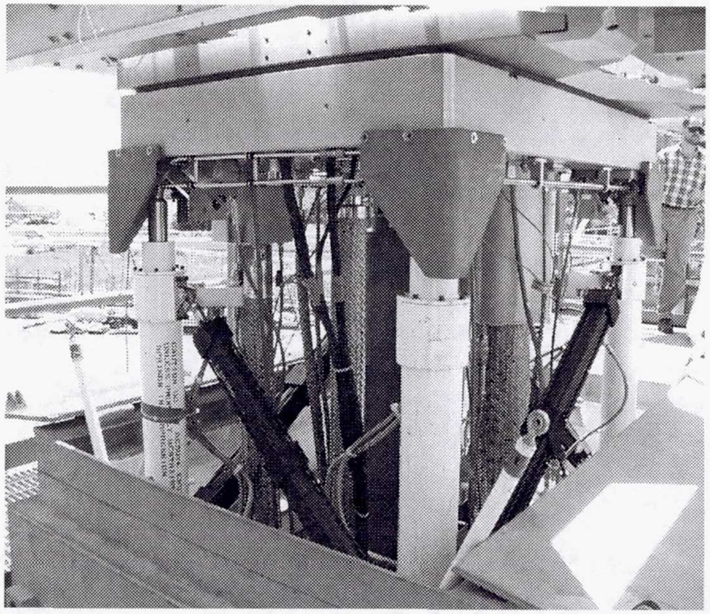
- **Sensors**
  - **Smart Instrumentation and Electronics development**
    - Near-term objectives
      - Multi-array Pressure Transducer demo and begin work on Miniature Universal Signal-Conditioning Amplifier
      - Demo robust MEMS miniature sensor work in H2, O2, P and T
      - Begin Non-Invasive Sensor work
      - Begin Self-Healing Electronics, Advanced Power Management, Advanced Software work
      - Advanced Software Algorithms
    - Long-term objectives
      - Testing of candidate instruments for miniaturized robust mass spectrometer
      - Continue Non-Invasive Sensor work
      - Continue Self-Healing Electronics, Advanced Power Management, Advanced Software work at simulation level

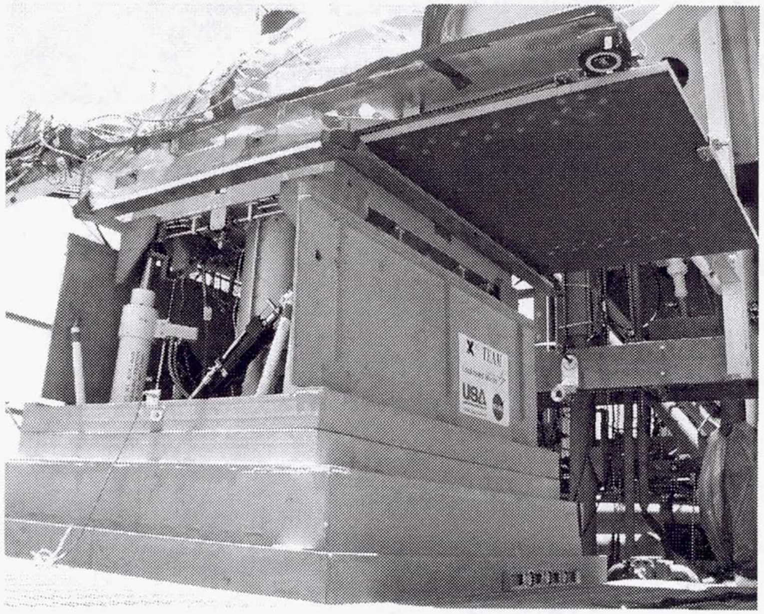
- **Umbilicals**
  - **Provide fuel fill, drain, & vent capabilties as well as power, communications, and data to vehicle prior to "T-0"**
  - **Overall goal: "Smart" umbilicals**
    - Develop enabling technologies
      - Q.D.'s
        - Fluids & fiber optics
        - Self-checking (leaks, cleanliness, etc.)
        - Self-correcting (ultimate goal)
        - - Smart seals, shape-changing alloys
        - Develop with industry partners
        - - Developed spec, currently reviewing proposals
      - Automated mating
        - Vision systems
        - Advanced actuators
        - Latching systems
        - Control systems
        - Ice/frost prevention/removal systems
      - Integrate advanced sensors
        - Acoustic leak detection

"ST Day 2000: Reducing Risk for the Next Generations" - Ground Operations

Umbilicals

- **30+ years experience in umbilical design, testing & operation At KSC**
  - **Apollo**
  - **Shuttle**
  - **X-33**
    - Rise-off umbilical
      - Joint NASA/USA design
      - Ground and flight side plates
      - Tested at LETF





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Umbilicals

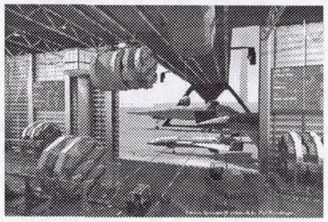
2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2015-22

Pathfinder

2x Cost Reduction

10x Cost Reduction

100x Cost Reduction



▢ Focus Technology
▨ Core Technology
░ Research

Focused Technology

Remote Servicing Automated Servicing On-Demand Servicing

Fiber Optics Connector

De-Icing System

Latching Sys
EMA
Magnetic
Vacuum

Location System

Self Checking Fluid Connector (Leak, Cleaning)

Wireless Data & Power System

Next Generation Fluid Connector

Core Technology

Connector, Insulation, Sensor, Seal Development and EMA, Magnetic, Vacuum Technology

Materials, Electro-Magnetic, Advanced Sensors

Insulation Testing

Sensor Testing
+ Vision + Infra Red
+ Laser + Ultrasonic

Connector Reliability

Rapid Verifiable Connectors

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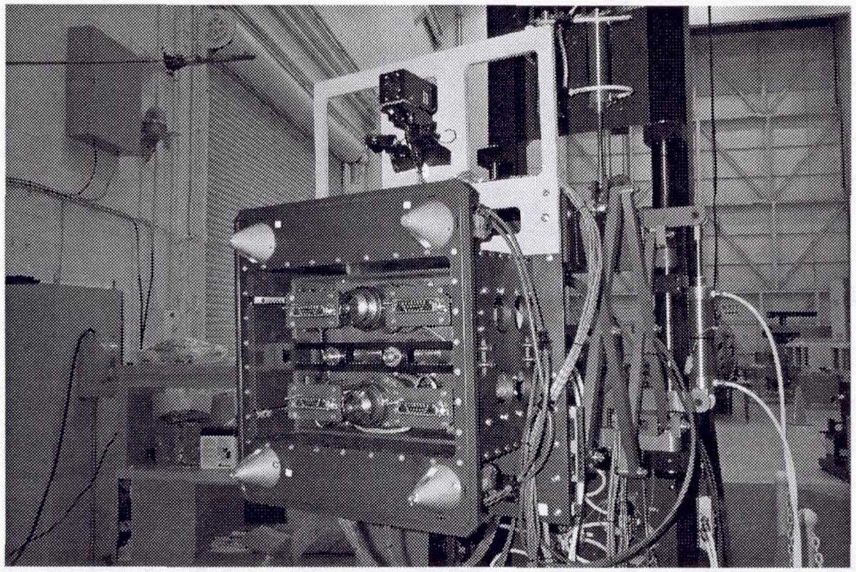
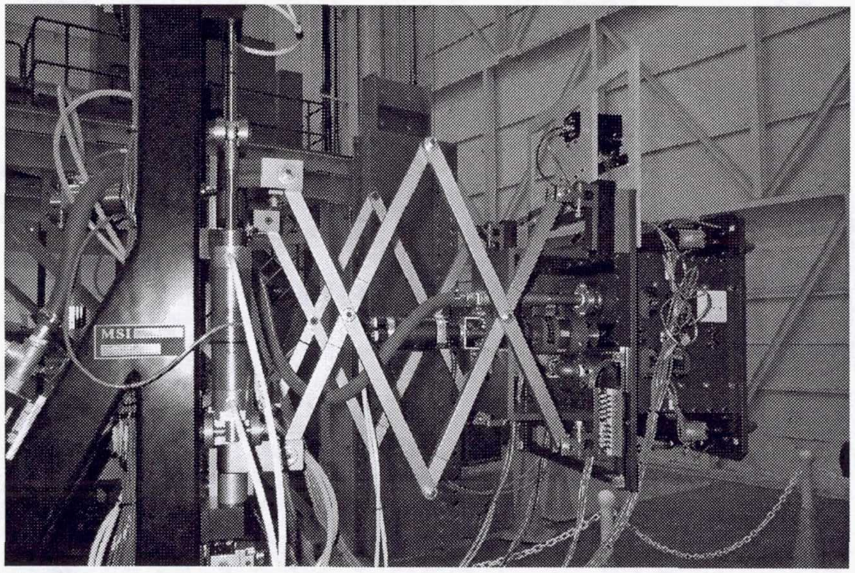
Umbilical Roadmap

- ♦ **Automated Umbilical Mating Technology**
  - **Project began as SBIR Phase I**
    - Merritt Systems Inc. of Oviedo, FL
  - **Further developed under SBIR Phase II**
    - Scissors-type mechanism
    - Pneumatic actuators
    - Vision system





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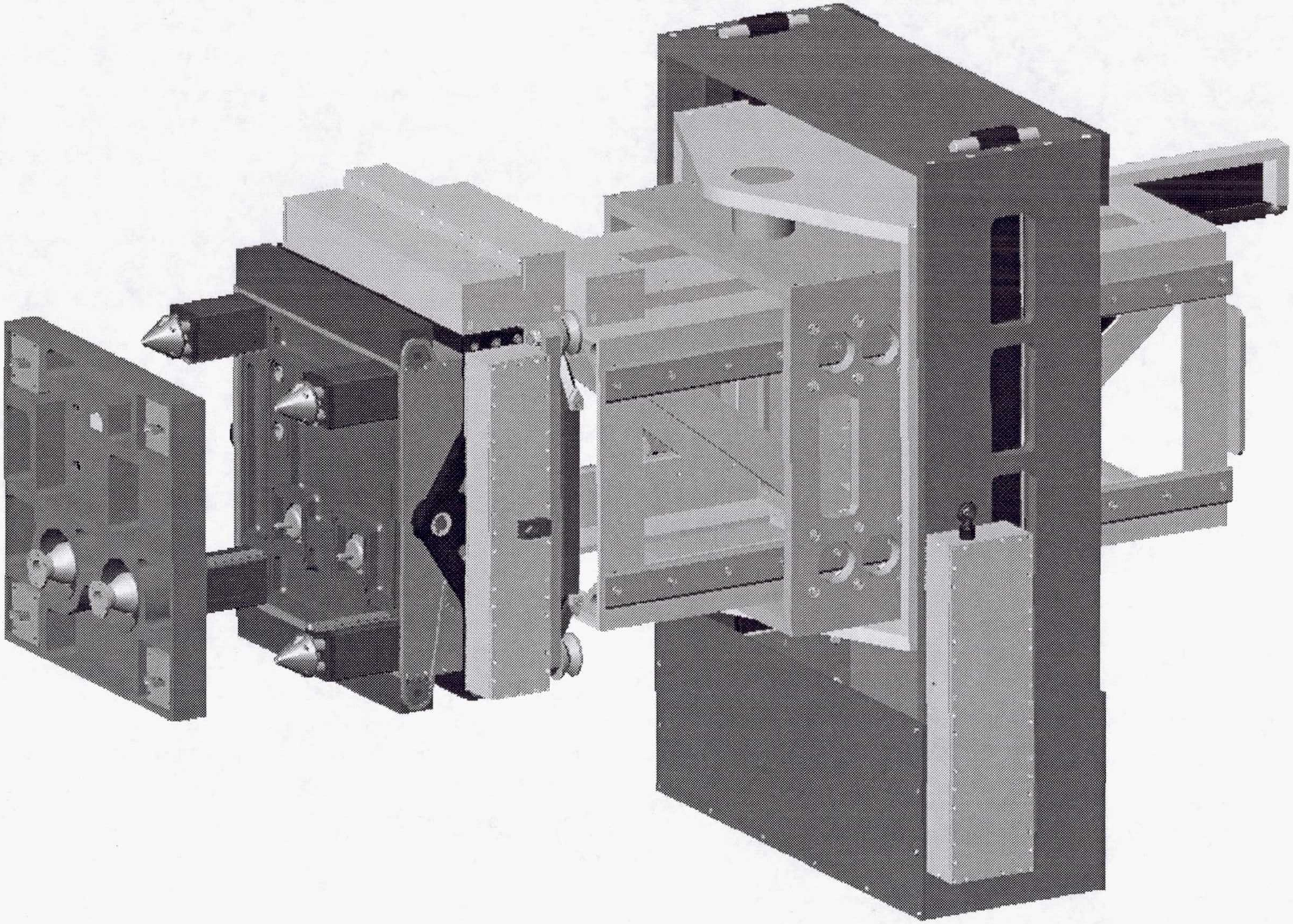
Automated Umbilicals

- Phase III
  - Initially funded under Bantam X program
  - No specific umbilical requirements for Bantam were developed
  - Focus shifted to development of enabling core technologies required for an automated umbilical system
    - Location/tracking (vision system)
    - Positioning (actuators)
    - Control system (hardware/software)
    - De-icing (required for re-mate capability)
  - Looked at existing and future launch vehicle configurations to determine requirements common across all systems
  - Developed a generic, scalable, adaptable, "worst-case" design concept
    - End of swing arm, active control of 6 DOF, harsh environment, re-mate capability, fail-operational, etc.
  - Basic technology can then be tailored to fit specific vehicle requirements
    - Possible on-orbit or planetary surface applications
    - Commercial aircraft and automotive refueling

Automated Umbilicals



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Automated Umbilicals

- **Operational concept**
  - **Independent system required to position automated umbilical into its operational envelope**
    - Swing arm, TSM, rail, etc.
  - **Initial approach to vehicle using vision system**
  - **Actuators based on linear induction motors provide precise control of movement in X, Y, Z, yaw, pitch, and roll**
  - **After alignment cones enter receptacles on flight side, force-feedback control is employed**
  - **Linear motors allow adjustment of "compliance" of system to ensure excessive loads are not imparted to vehicle**
  - **Mate is 2-stage process**
    - Alignment cones provide hard mate to vehicle
    - Secondary carrier plate is then driven forward to gang-mate all fluid and electrical connections
  - **Once successful mate is achieved, system becomes "passive"**

Automated Umbilicals

- **Operational Concept**
  - **At predetermined commit point in countdown, system de-mates from vehicle and withdraws to a safe position**
  - **If launch is aborted after de-mating, umbilical will re-mate to vehicle to allow fuel drain**
    - System must be fail-operational to ensure re-mate can be accomplished
      - Redundant actuators
      - Fault-tolerant control system
    - Any build-up of ice/frost from mating surfaces must be removed prior to re-mate
      - Infrared lamps
      - Warm fluid loops

- **Status**
  - **Design currently being finalized**
  - **Fabrication and delivery of prototype/demonstrator in FY01 pending funding**

Automated Umbilicals

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Supporting the NASA RLV Program

Kathryn E. Caggiano
Peter L. Jackson
John A. Muckstadt

Cornell University
Operations Research and Industrial Engineering

"ST Day 2000: Reducing Risk for the Next Generations"

Develop analysis tools for determining and evaluating spare parts stocking policies for components of Reusable Launch Vehicles

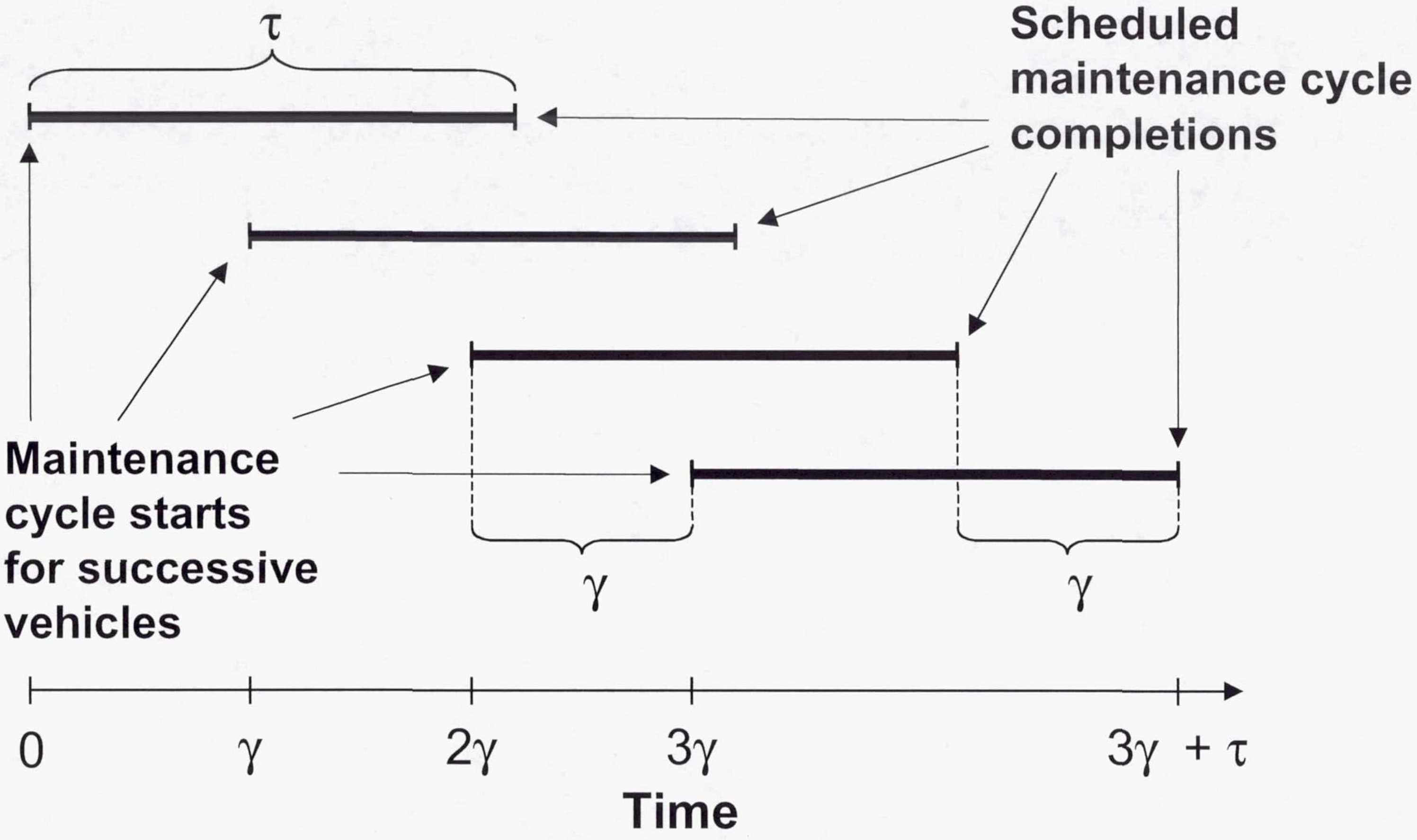
Cornell Project Objective

- System Framework
- Analysis Tools
- Analysis Process (GEM)

Overview

- RLV Ground Maintenance Process
- Line Replaceable Unit (LRU) Repair Process
- Shop Replaceable Unit (SRU) Repair Process

System Framework



Scheduled maintenance cycle completions

Maintenance cycle starts for successive vehicles

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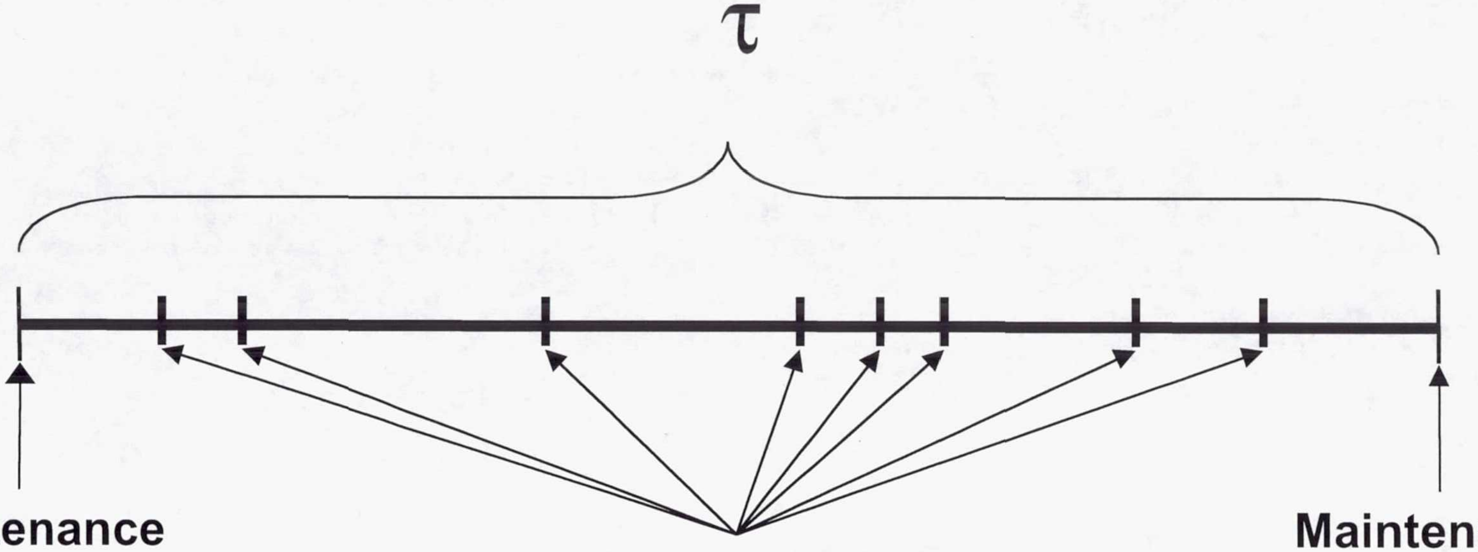
RLV Maintenance Cycles



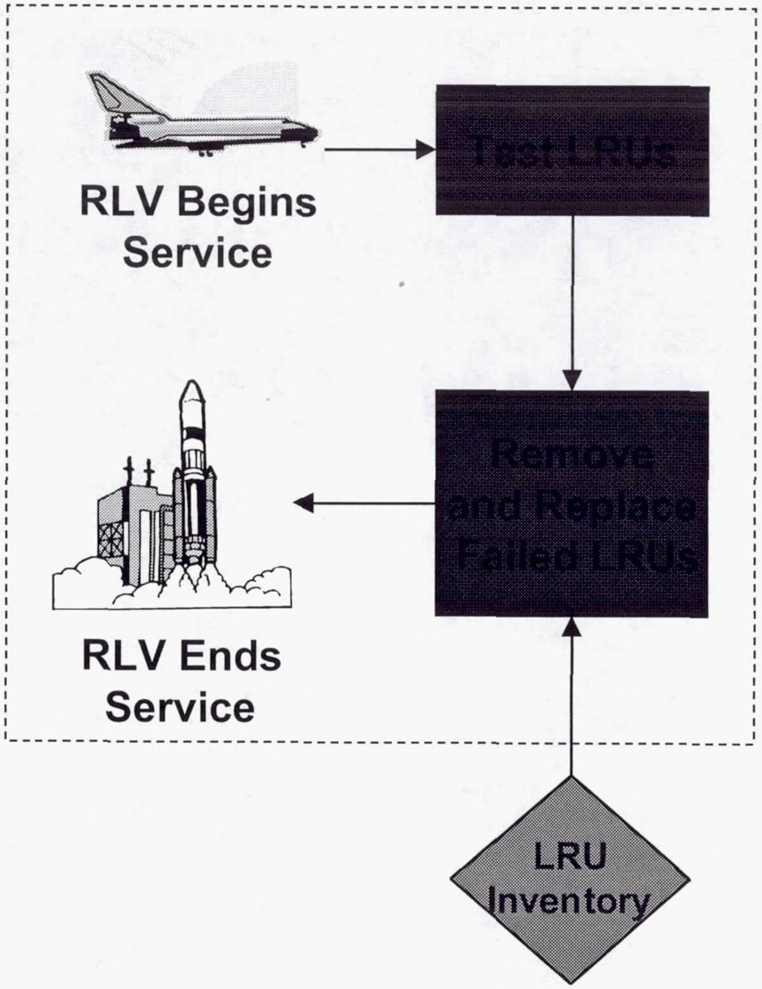
Maintenance Cycle Begins

LRUs tested for soundness

Maintenance Cycle Scheduled to End

Failed LRUs must be replaced by the scheduled end date in order to avoid a delay.

One Maintenance Cycle



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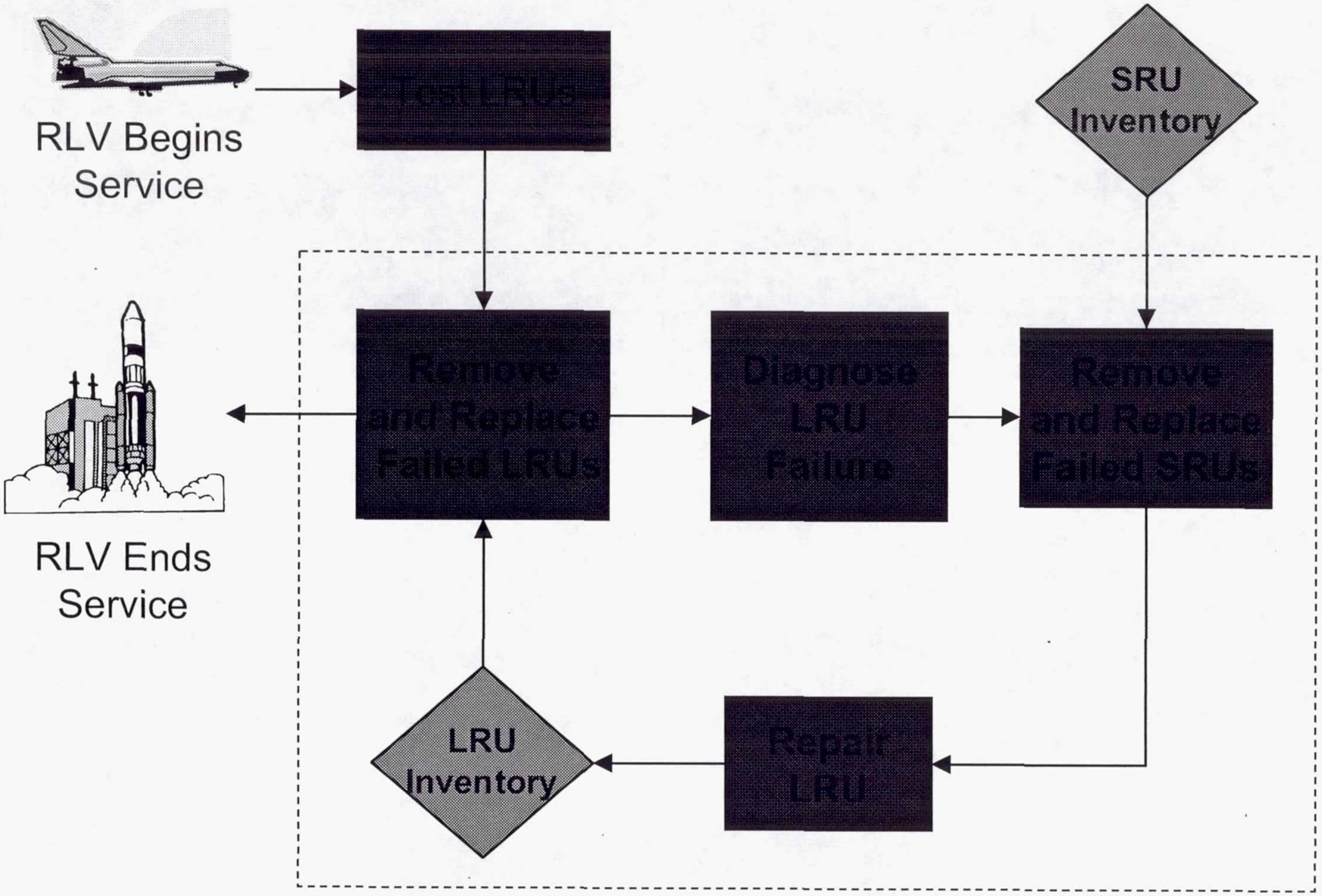
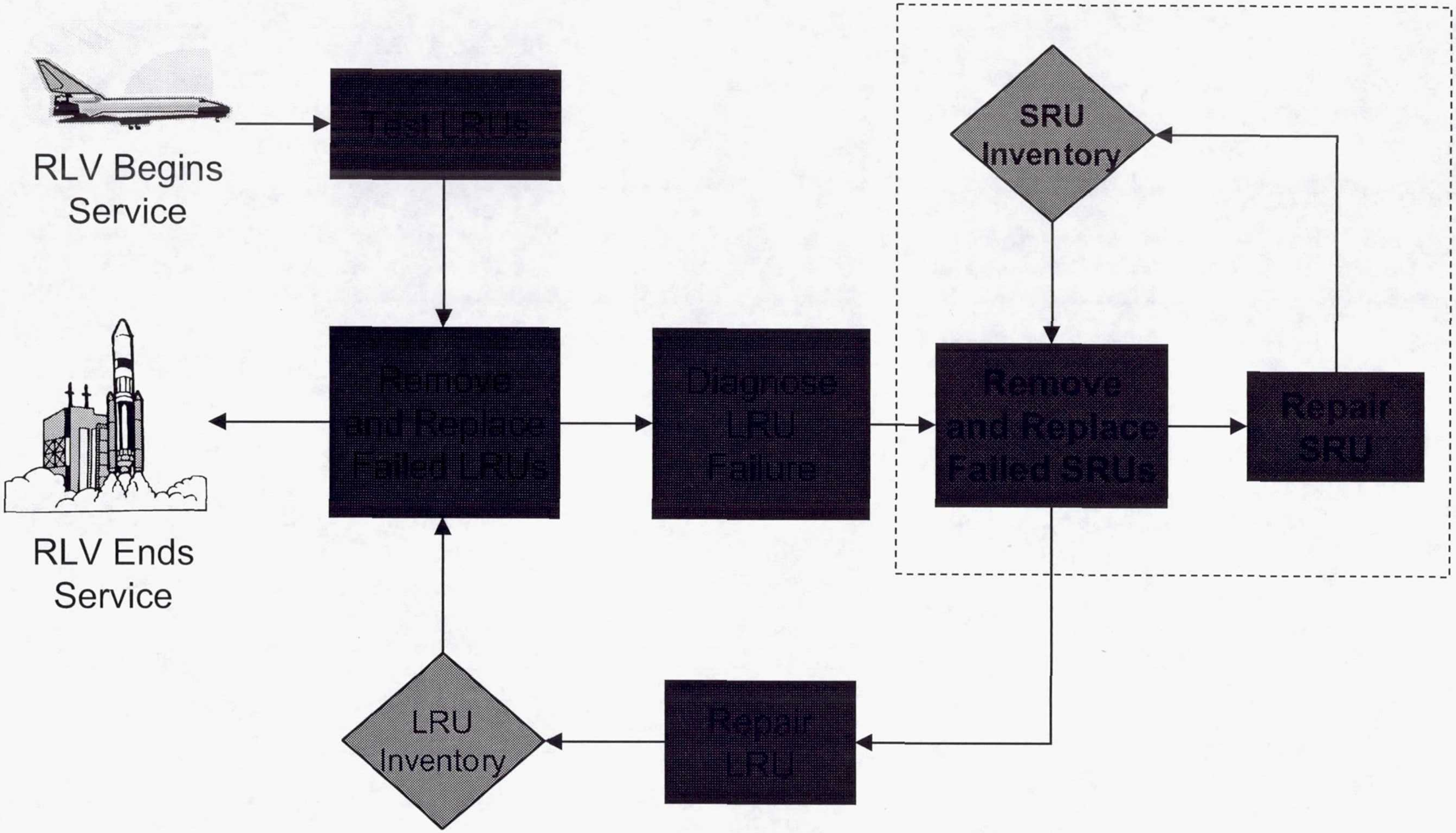
RLV Ground Maintenance



LRU Repair Process



RLV Begins Service

Test LRUs

Remove and Replace Failed LRUs

RLV Ends Service

Diagnose LRU Failure

SRU Inventory

Remove and Replace Failed SRUs

Repair SRU

Repair LRU

LRU Inventory

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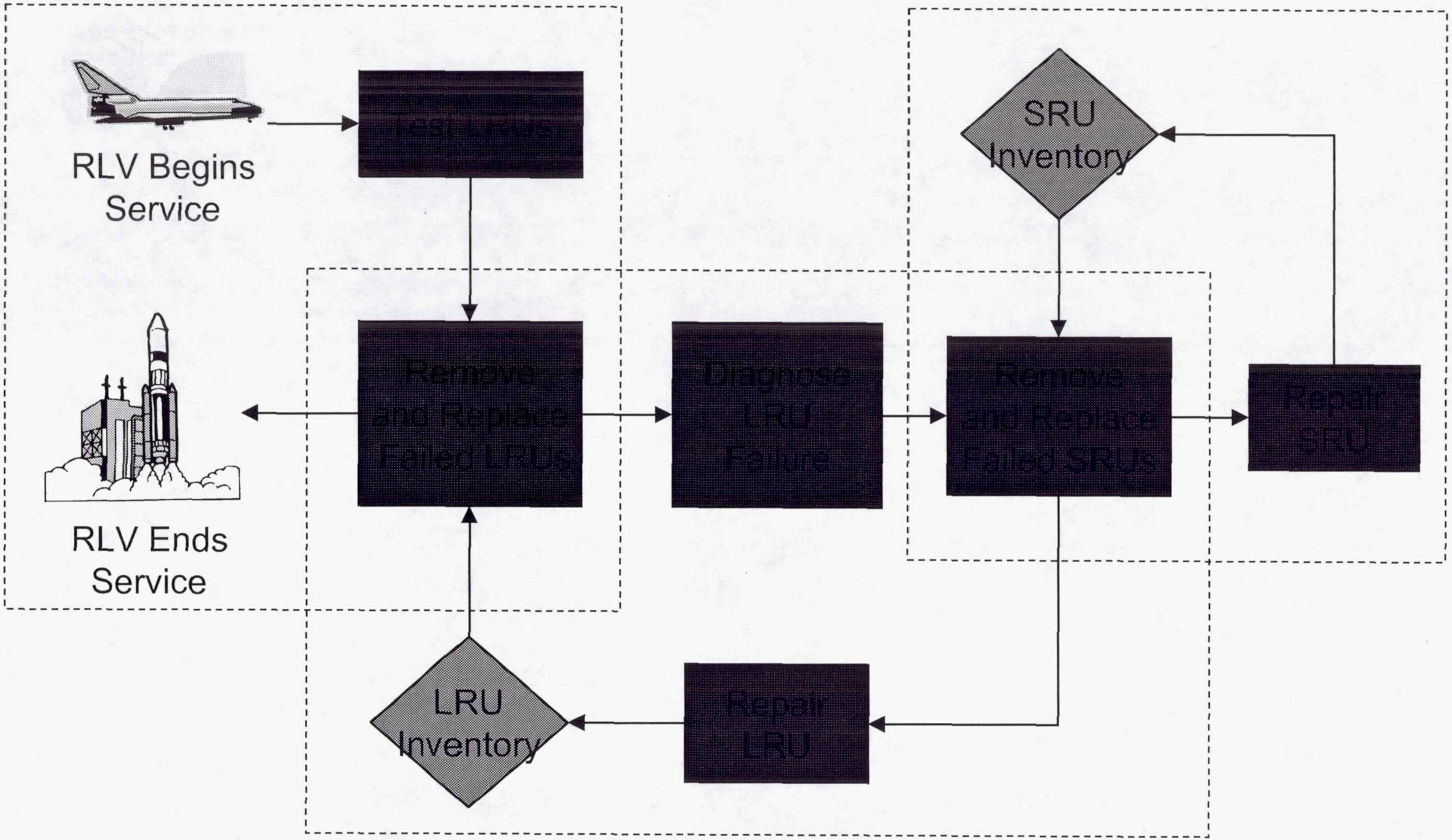
SRU Repair Process



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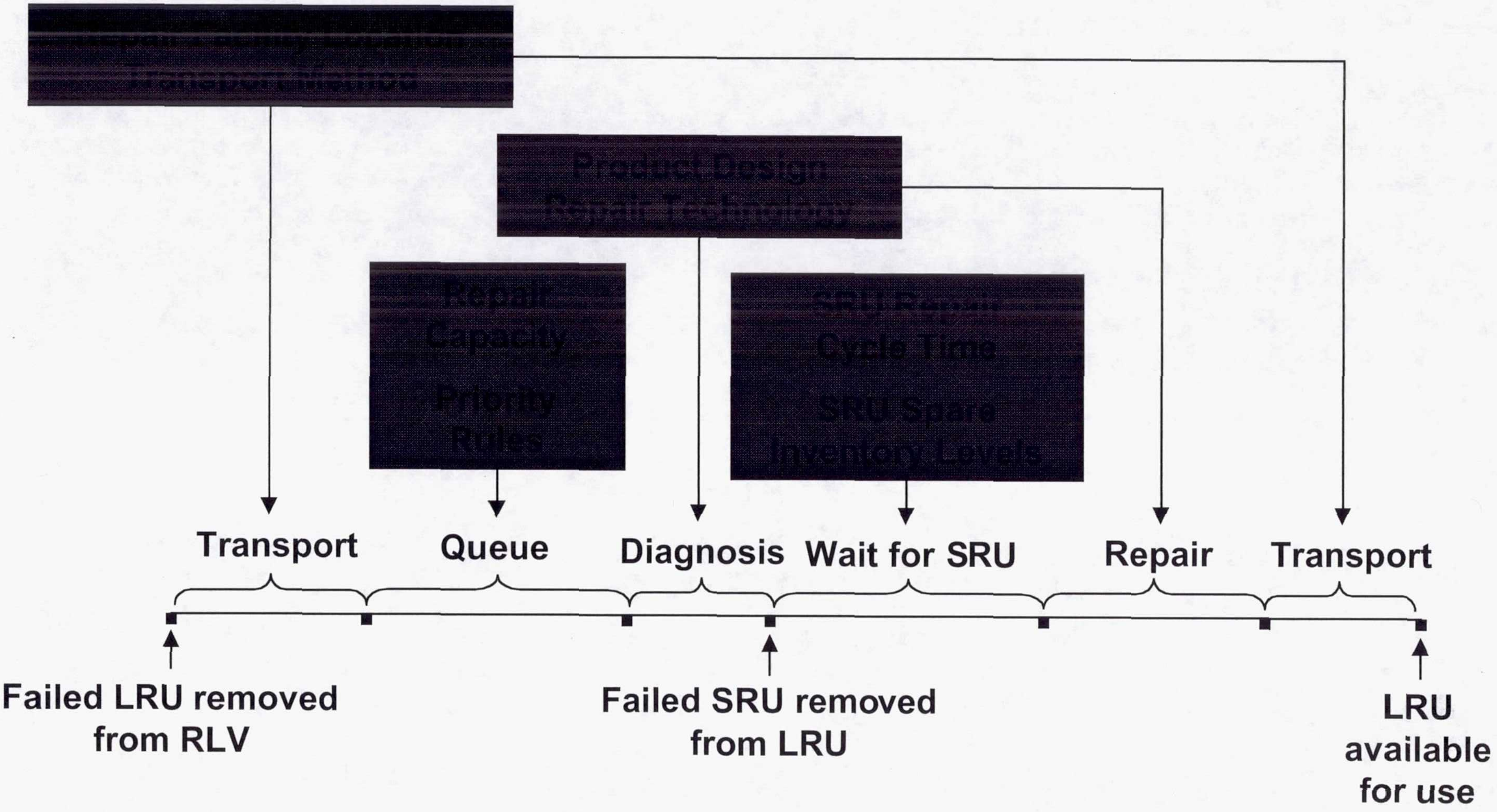
System Framework



Repair Facility Location
Transport Method

Product Design
Repair Technology

Repair Capacity
Priority Rules

SRU Repair Cycle Time
SRU Spare Inventory Levels

Transport
Queue
Diagnosis
Wait for SRU
Repair
Transport

Failed LRU removed from RLV

Failed SRU removed from LRU

LRU available for use

LRU Repair Cycle Time

- System Framework
- Analysis Tools
- Analysis Process (GEM)

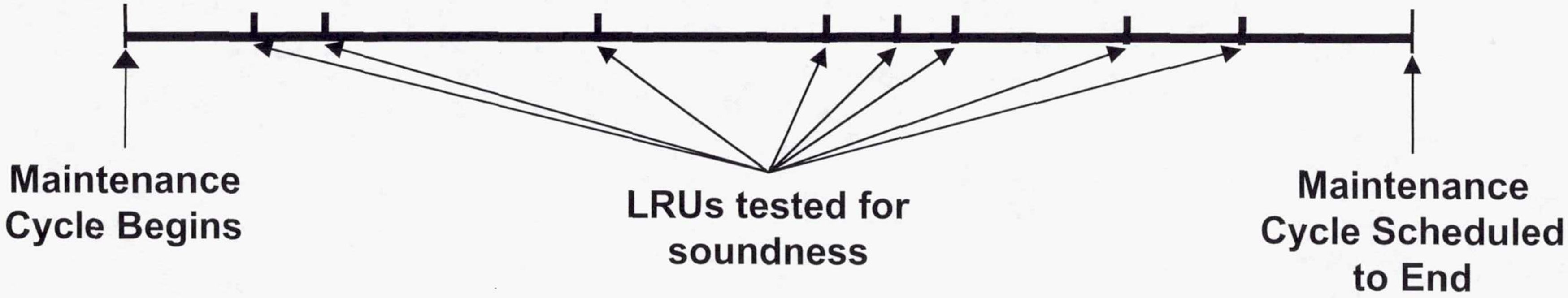
Overview

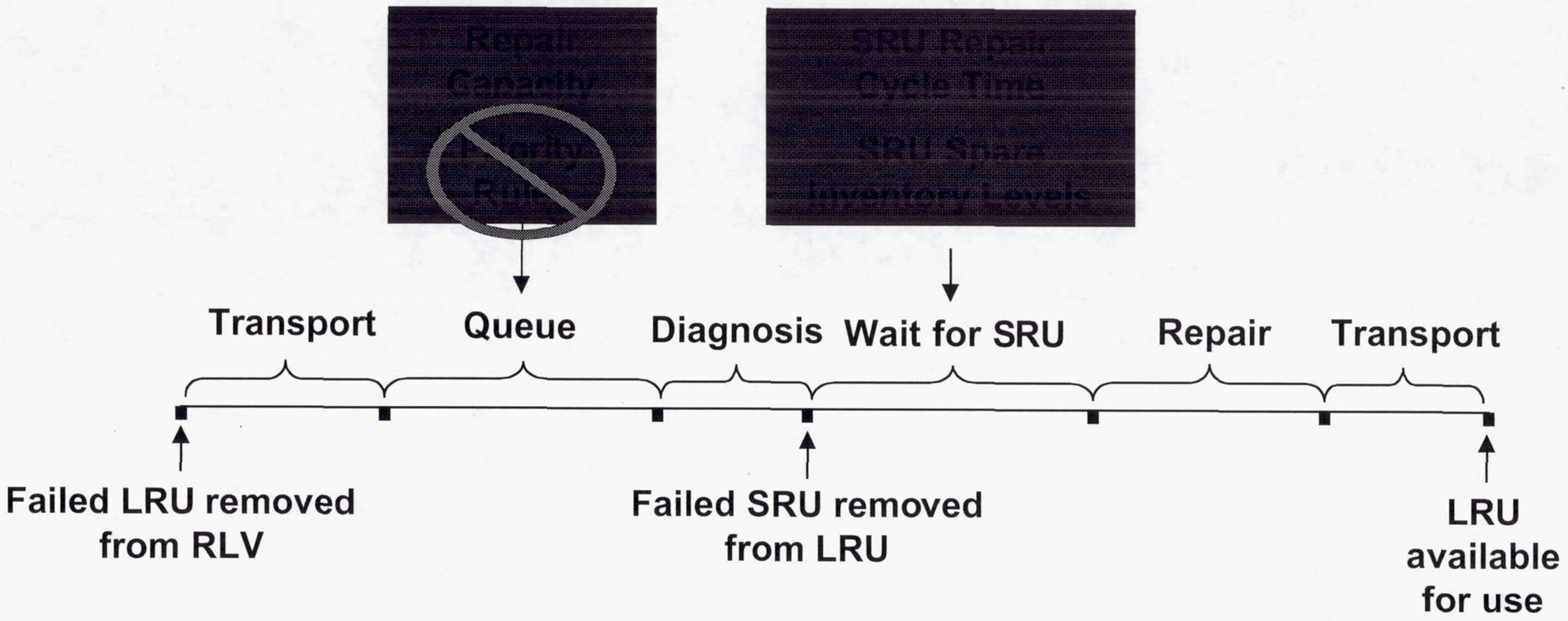
- Mathematical Model
- Simulation Model

Analysis Tools

Goal:

Given a target investment level, determine LRU and SRU spare inventory levels that minimize the expected number of "holes" in an RLV at the end of its scheduled maintenance cycle.





Repair Capacity

Priority Rules

SRU Repair Cycle Time

SRU Spare Inventory Levels

Transport

Queue

Diagnosis

Wait for SRU

Repair

Transport

Failed LRU removed from RLV

Failed SRU removed from LRU

LRU available for use

LRU Repair Cycle Time

Considerations:

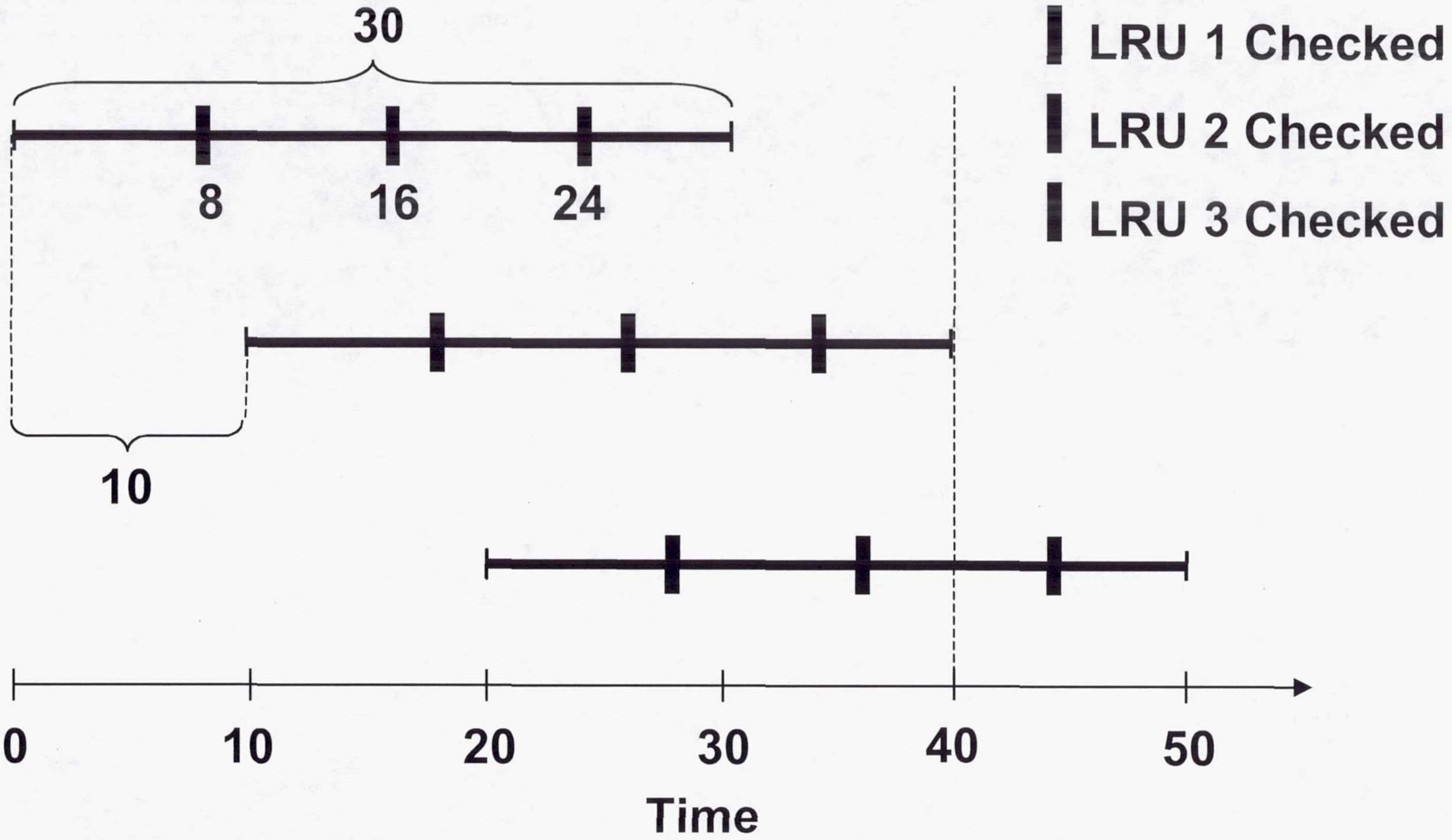
- RLV maintenance schedule parameters (τ, γ, etc.)
- Times at which LRUs are tested (relative to τ)
- Part failure characteristics
- Bill of material relationships
- For LRUs repaired in-house, repair cycle time components (other than queue time and wait time)
- For LRUs with outsourced repair, the repair cycle time distribution
- SRU repair cycle time components (other than queue time)
- Repair capacity
- Target budget level and part costs

Does not capture:

- Variability of transport, queue, and service times
- Work prioritization

Mathematical Model

Example

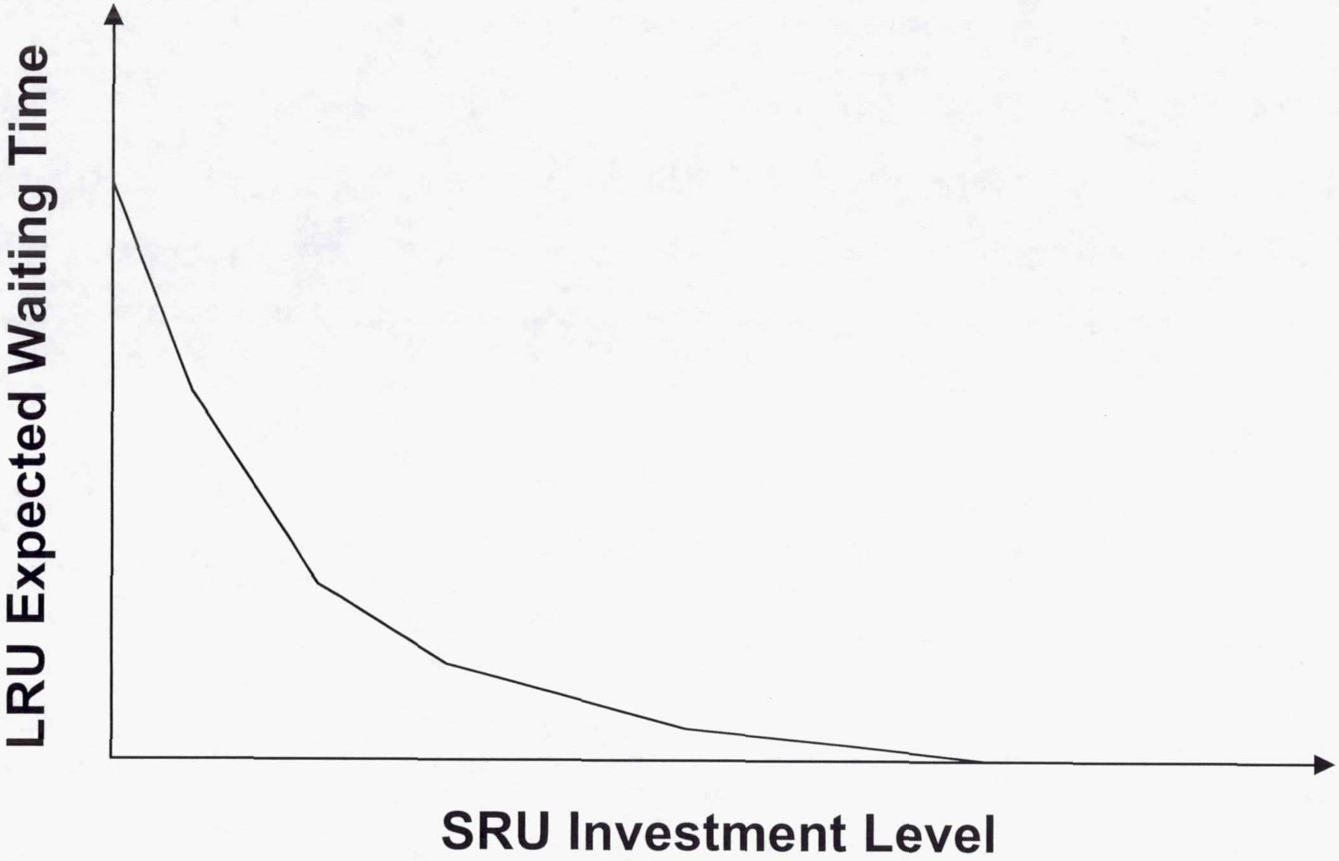


LRU Repair Cycle Time = 11
if no wait for SRUs

SRU Repair Cycle Time = 7

Outline of Method:

- For each LRU type, build the SRU tradeoff curve.
- For each LRU type, build the family tradeoff curve by evaluating LRU/SRU budget allocation strategies, keeping points on the convex minorant of the curve.
- Build the overall tradeoff curve using marginal analysis on the family tradeoff curve points.
- Find the point on the overall tradeoff curve that requires a total investment closest to (but not exceeding) the target investment level.



SRU Tradeoff Curve

Outline of Method:

- For each LRU type, build the SRU tradeoff curve.
- For each LRU type, build the family tradeoff curve by evaluating LRU/SRU budget allocation strategies, keeping points on the convex minorant of the curve.
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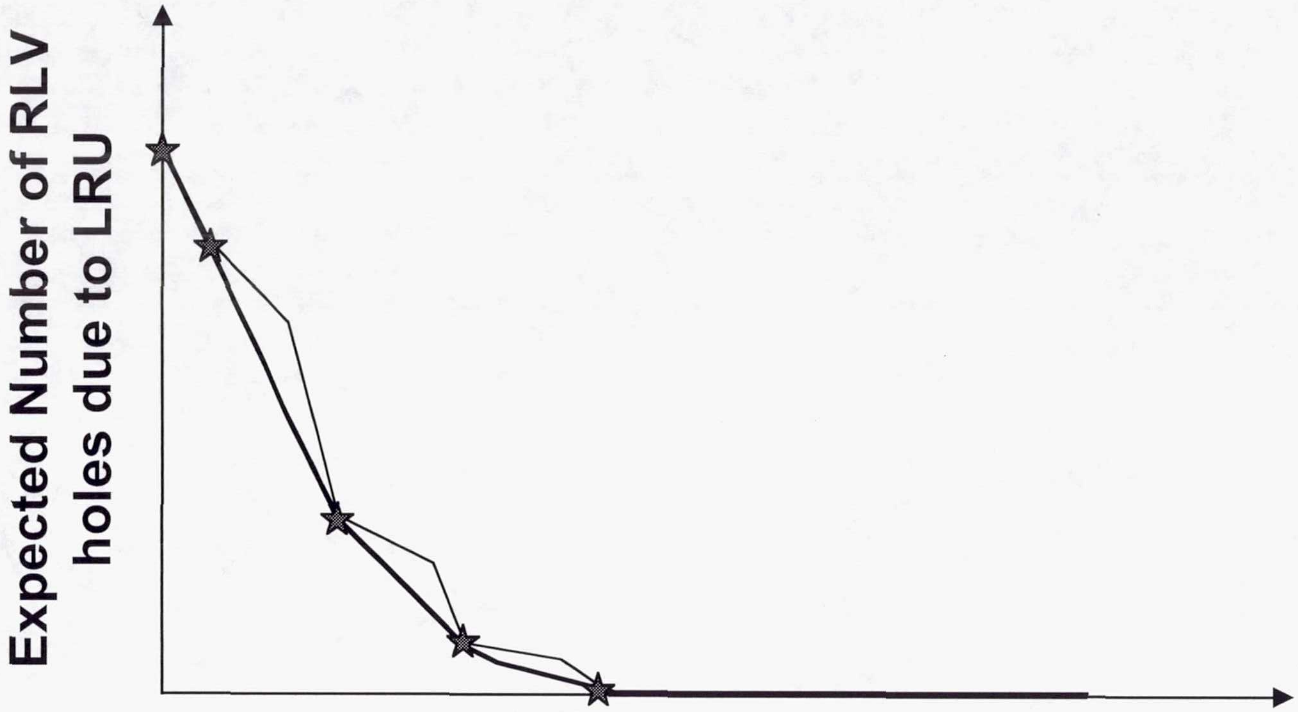


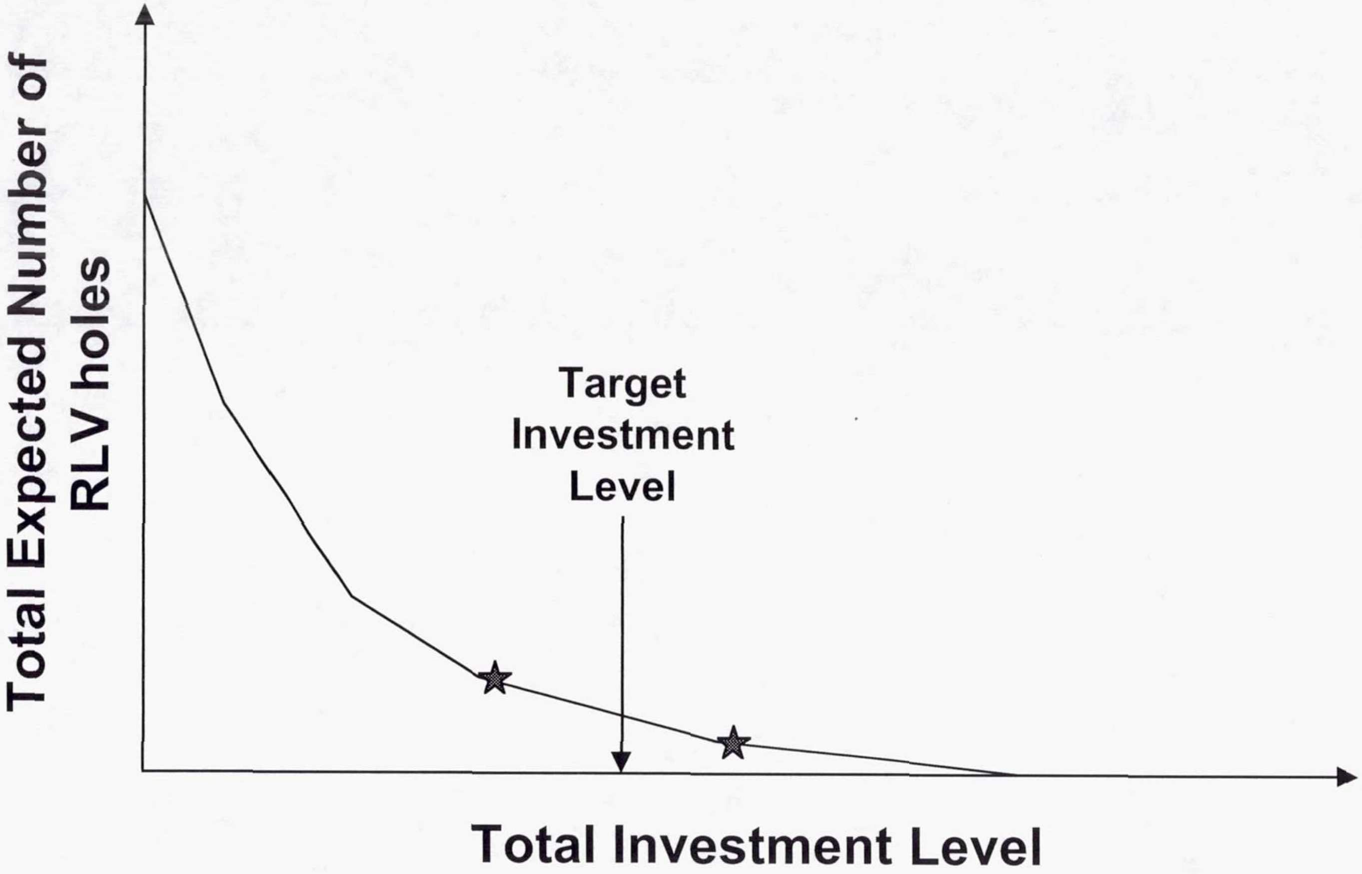
LRU Family Investment Level

LRU Family Tradeoff Curve

Outline of Method:

- For each LRU type, build the SRU tradeoff curve.
- For each LRU type, build the family tradeoff curve by evaluating LRU/SRU budget allocation strategies, keeping points on the convex minorant of the curve.
- Build the overall tradeoff curve using marginal analysis on the family tradeoff curve points.
- Find the point on the overall tradeoff curve that requires a total investment closest to (but not exceeding) the target investment level.

Determining Spare Levels



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Overall Tradeoff Curve

Goal:

Evaluate maintenance resource strategies, including LRU and SRU spare inventory levels, in the dynamic RLV environment.

Considerations:

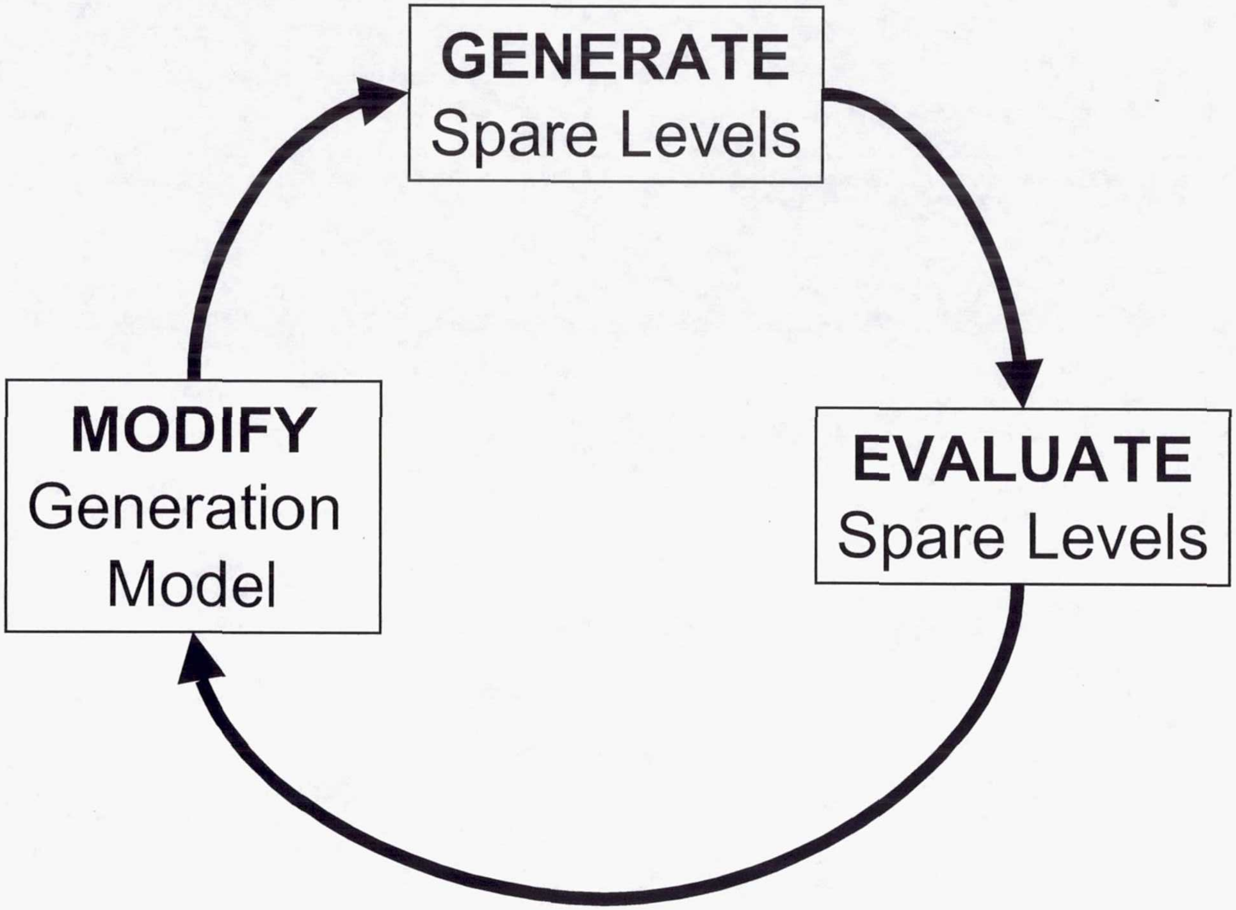
- Outsourcing of repair
- Condemnation
- Limited capacity for in-house diagnosis and repair
- Probabilistic transport and service times
- Limited inventories
- Dynamic work prioritization at repair centers

Simulation Model Features

- Identify Events
- Model Delays Between Events
- Manage Priorities
- Track Inventories
- Select Inputs
- Capture Outputs

- System Framework
- Analysis Tools
- Analysis Process (GEM)

Overview



GENERATE
Spare Levels

EVALUATE
Spare Levels

MODIFY
Generation
Model

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Analysis Process

- Validate models with realistic data

- Use analytic tools to evaluate alternative maintenance resource strategies

- Enhance the current mathematical model
  - Repair queue time variability
  - Repair capacity decisions
  - Repair facility location decisions
  - Repair facility assignment decisions

Next Steps

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Space Shuttle Processing Simulation Model

Macro Level Simulation Model
Of
Space Shuttle Processing

Developed under a NASA Space Act Agreement
between the Kennedy Space Center and the University of Central Florida

NASA UCF

"ST Day 2000: Reducing Risk for the Next Generations"

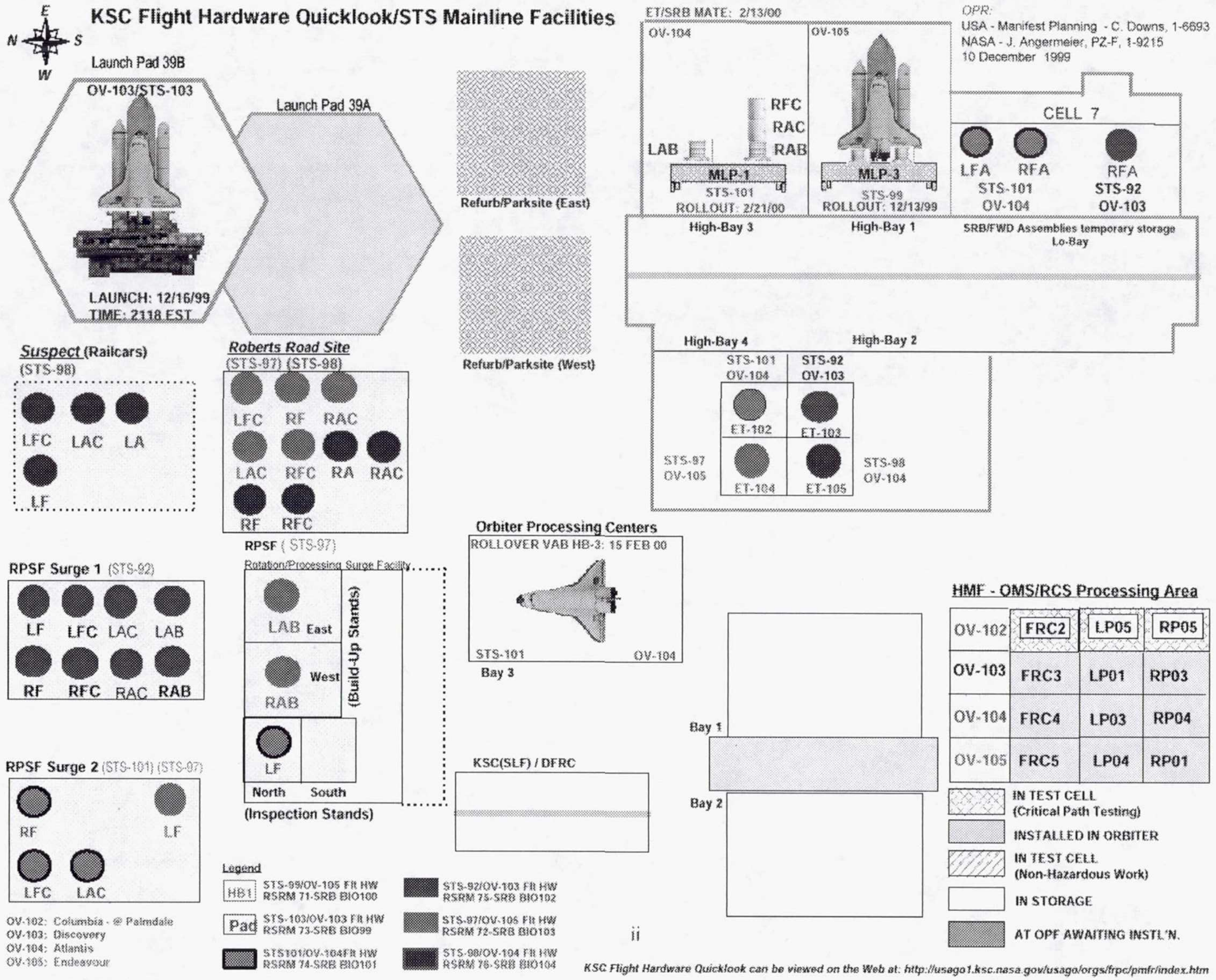
◆ **The simulation model encompasses the existing space shuttle ground processing Facilities, Ground-Support Equipment (GSE) infrastructure and Flight-Hardware elements to the level of detail that NASA retains management responsibility for; such as...**

Flight Hardware	Facilities	GSE
Orbiters	OPF	Orbiter Transporter
SSMEs	Engine Shop	Engine Hyster
External Tanks	VAB	ET Transporter
SRM/SRB	MLPs	Crawler/Transporter

◆ **The simulation model logic is consistent with current Space Shuttle program ground rules and constraints such as...**

- After 8 flights, the shuttle orbiter undergoes depot level maintenance (OMDP/OMMP) in California.
- only one shuttle on orbit at any given time.

Space Shuttle Processing Simulation Model



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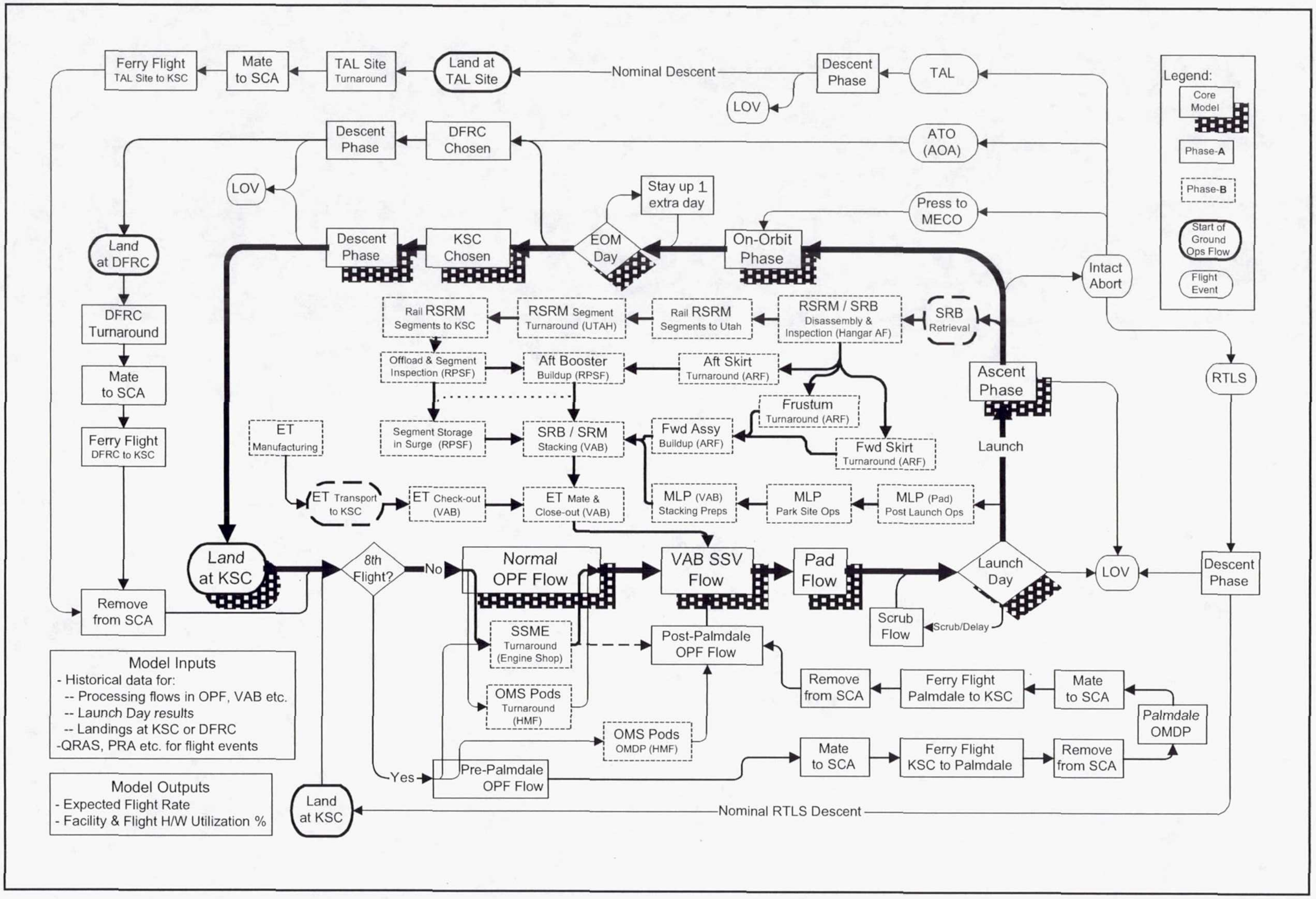
Space Shuttle Processing Simulation Model



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Space Shuttle Processing Simulation Model

Flow Diagram

Utilized commercial off-the-shelf Software

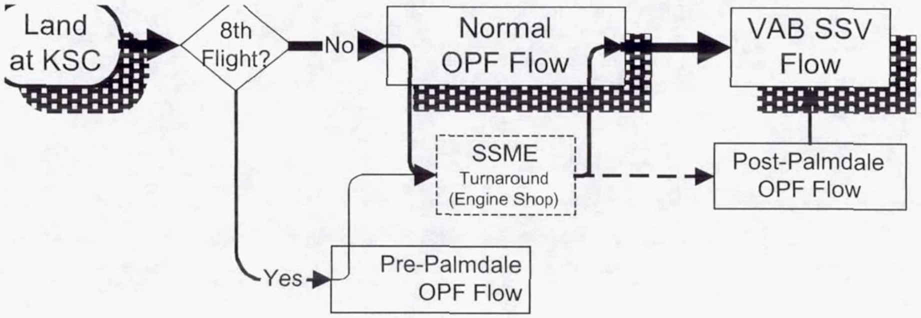
Rockwell Software* Arena _*Systems Modeling_	Simulation Software
Microsoft Project	Project Schedule
Microsoft Excel	Data Files
Microsoft PowerPoint	Knowledge Files & Presentations
Microsoft Visio	Flow Diagrams
Averill M. Law & Associates, Inc. ExpertFit	Distribution Fitting

Process Title	Process Location	File
"Normal" OPF Flow	OPF	OPF Flow.ppt OPF UCF TA Days.xls
VAB SSV Flow	VAB Integration Cell	VAB SSV Flow.ppt VAB SSV TA Days.xls
Pad Flow	Launch Pad	Pad Flow.ppt Pad Flow UCF.xls
Launch Day	Launch Pad	Launch Day.ppt Launch Data.xls
Scrub Flow	Launch Pad	Scrub Flow.ppt Launch Data.xls
Ascent Phase / Intact Abort Scenario's		Ascent.ppt SAIC Midterm Abort.ppt Risk PRA.xls
On-Orbit Phase	LEO	On-Orbit.ppt On Orbit UCF.xls
End of Mission (EOM) Day	LEO	On-Orbit.ppt Landings.xls
Land at KSC	SLF	KSC Landing.ppt Landings.xls
Land at DFRC	Edwards Air Force Base, CA	DFRC Landing.ppt Landings.xls
Land at TAL Site	Spain or Africa	TAL Landing.ppt
Mobile Launcher Platform (MLP) Life	Launch Pad, MLP Park Site, VAB	MLP UCF Phase- MLP TA Days.xls

Process Title	Process Location	File
SRB Retrieval	Atlantic Ocean	SRB Retrieval.ppt
SRM / SRB Disassembly & Inspection	Hangar AF	SRB Safng Disassy.ppt
RSRM Off-Site Turnaround Cycle	Utah Rail Roads	RSRM.ppt RSRM Transit Time.xls
Rail RSRM Segments to Utah	Rail Roads	RSRM KSC Time.xls
SRB Subassembly Turnaround Cycle	ARF	SRB ARF.ppt SRB ARF Data.xls
RPSF Operations	RPSF	RPSF.ppt SRB Aft Booster Bld Up.xls
SRB/SRM Stacking	VAB Integration Cell	SRB Stacking.ppt
ET Manufacturing	Michoud, LA	ET Manufacturing.ppt
ET Transport to KSC	LA to FL	ET Manufacturing.ppt
ET Checkout	Checkout Cell	ET Check Mate.ppt ET Ck-Out TA Days.xls
ET Mate & Closeouts	VAB Integration Cell	ET Check Mate.ppt ET TA Days.xls
SSME Turnaround	OPF, VAB, Pad, Engine Shop	SSME UCF Phase B.ppt SSME Data.xls
OMS Pods & FRCS Contingency Turnaround	HMF	OMS Pods & FRCS.ppt HMF History.xls
OMS Pods & FRCS OMDP Flows	HMF	OMS Pods & FRCS OMDP.ppt HMF History.xls
Orbiter OMDP	OPF, Palmdale	Orbiter OMDP.ppt Omdpflows UCFrev A.xls

"ST Day 2000: Reducing Risk for the Next Generations" - Space Shuttle Processing

Space Shuttle Processing Simulation Model Knowledge Acquisition



Land at KSC

8th Flight?

No

Yes

Normal OPF Flow

VAB SSV Flow

SSME Turnaround (Engine Shop)

Post-Palmdale OPF Flow

Pre-Palmdale OPF Flow

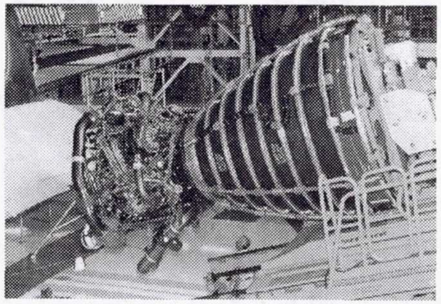
Diagram at left is the SSME related portions of the model.

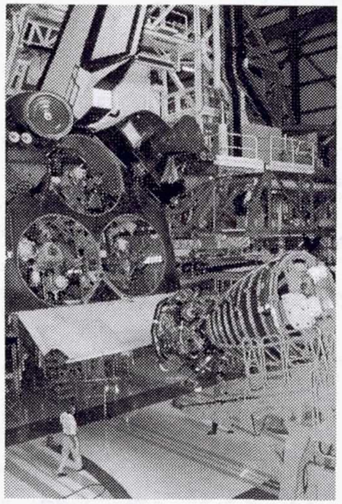
Of interest from a modeling standpoint is:

- •How long from OPF roll-in to SSME removal.
- •Travel time between OPF and Engine Shop.
- •Duration of Engine Shop activity.
- •Minimum time between engines-out and engines-in.
- •Duration between SSME installation and OPF roll-out.

Initial modeling assumptions and subsequent changes :

- •The engine set (3 engines) stays together. (Changed to allow engines to be separated in the engine shop
- •There are 13 engines and thus four sets of engines plus one ready spare engine. (Changed to 21 engines or 7 sets to more closely reflect 1992-1997 time-frame)
- •The engine shop can process one set of engines at a time. (Changed to any number of engines at a time)
- •Any engine set can go in any orbiter on a first need, first served basis.
- •Engine removal during a Pre-Palmdale OPF Flow is modeled the same as Normal OPF Flow.





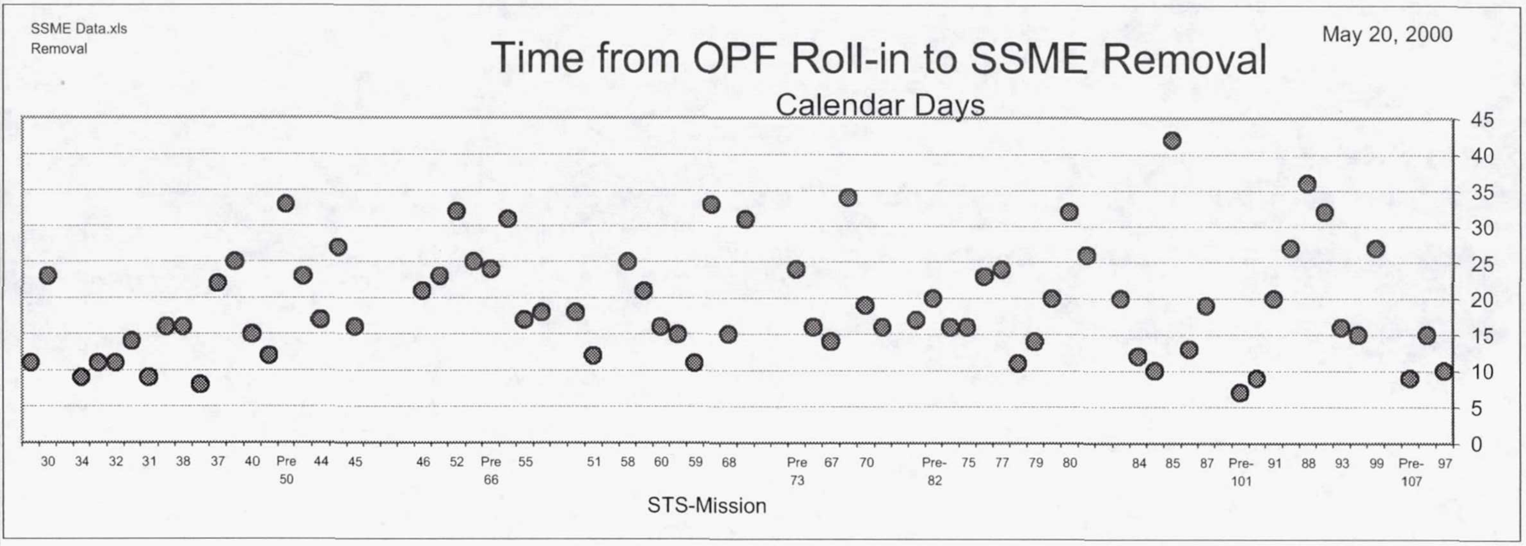
"ST Day 2000: Reducing Risk for the Next Generations" - Space Shuttle Processing

Space Shuttle Processing Simulation Model Knowledge Acquisition Excerpts from Introductory Briefings

Example of historical data

Mean	19.26
Median	17.00
Mode	16
Min	7
Max	42
Std Dev	7.795
Count	72

Bin	*Freq*
8	2
10	6
12	8
14	4
16	14
18	5
20	6
22	3
24	7
26	4
28	3
30	0
32	5
34	3
36	1
38	0
40	0
42	1

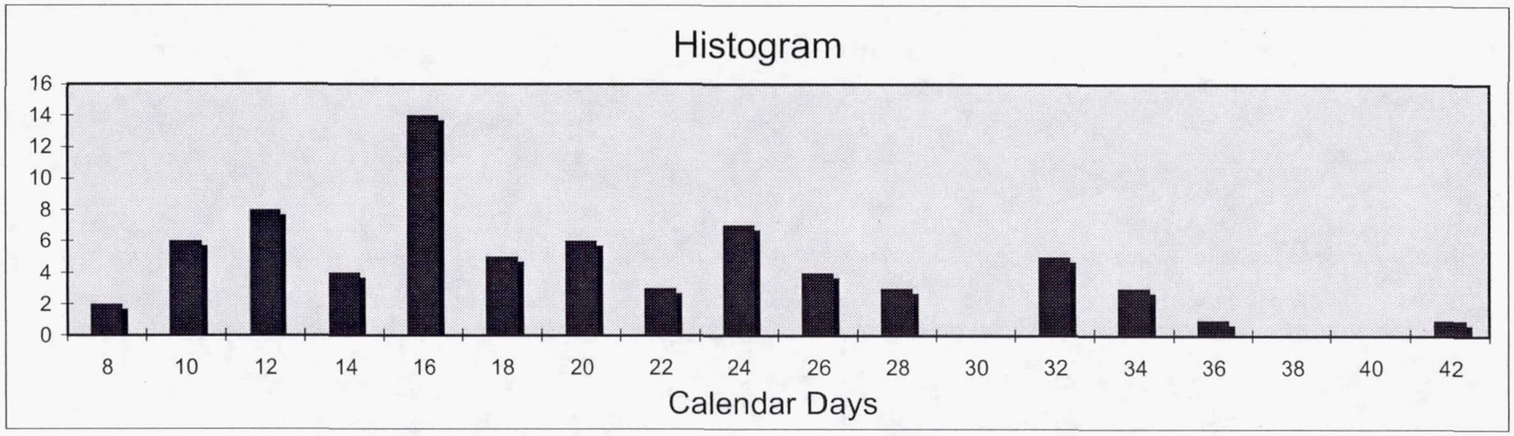


Time from OPF Roll-in to SSME Removal

Calendar Days

SSME Data.xls
Removal

May 20, 2000

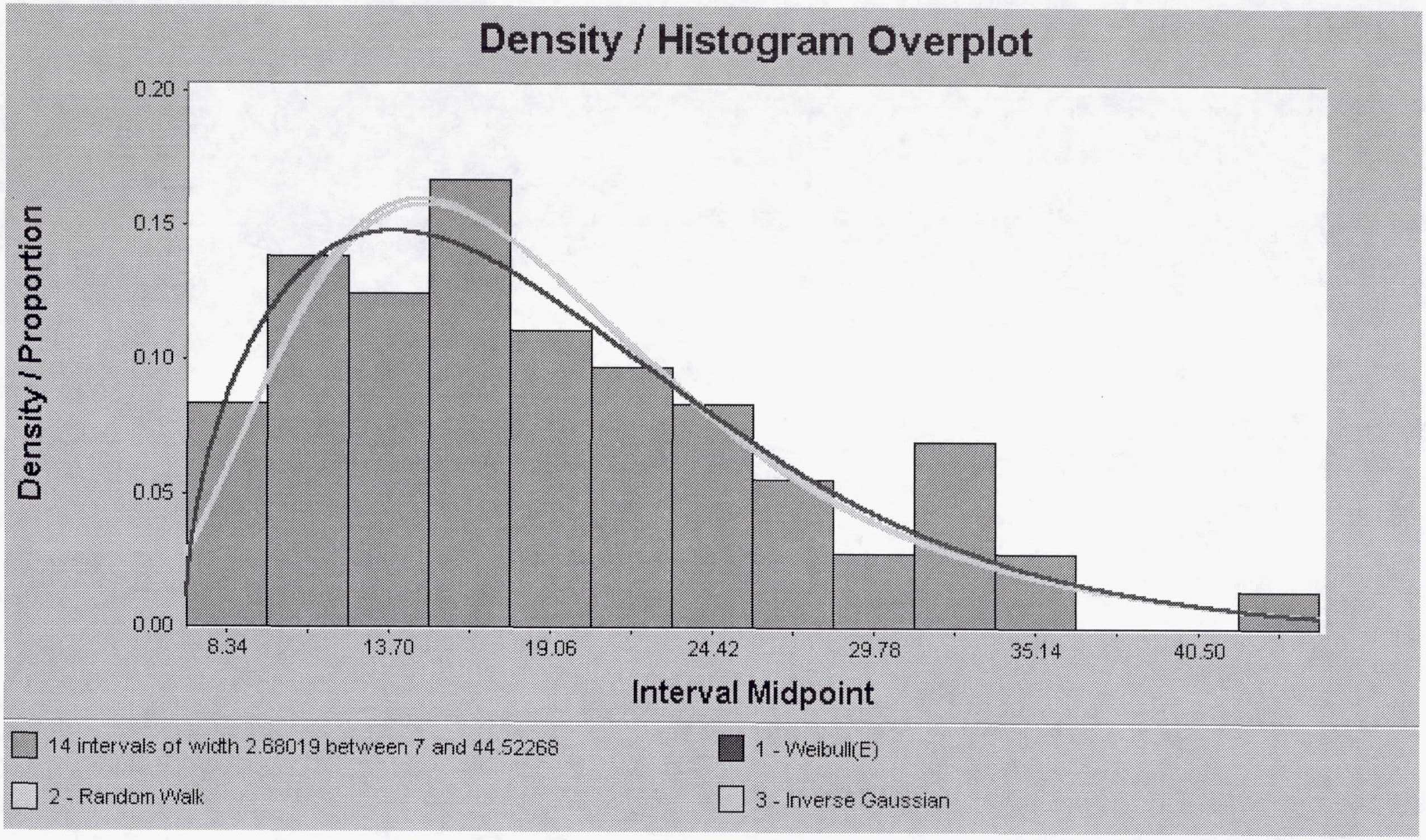


Histogram

"ST Day 2000: Reducing Risk for the Next Generations" - Space Shuttle Processing

Space Shuttle Processing Simulation Model Knowledge Acquisition

Example of Probability Distribution Selection using ExpertFit: OPF Roll-in to SSME Removal



"ST Day 2000: Reducing Risk for the Next Generations" - Space Shuttle Processing

Space Shuttle Processing Simulation Model

Simulation Input Analysis

A functional probabilistic based simulation of space shuttle operations now exists and can be used for several applications:

- ♦ **Analysis of present Space Shuttle System**
  - Identify Facility & Flight Hardware Utilization percentages
  - Identify potential bottlenecks
- ♦ **Flight Rate Experiments**
  - Manipulate process-duration probability distributions to achieve 10 (or more) flights per year and analyze model outputs.
- ♦ **What-if questions can be analyzed such as:**
  - What is the expected impact on flight rate given the loss of a launch pad?
  - What is the expected impact on flight rate given the loss of one VAB Integration Cell?
- ♦ **The current model offers an architecture that allows lower level detail to be modeled for system specific operational processes or events.**

Space Shuttle Processing Simulation Model

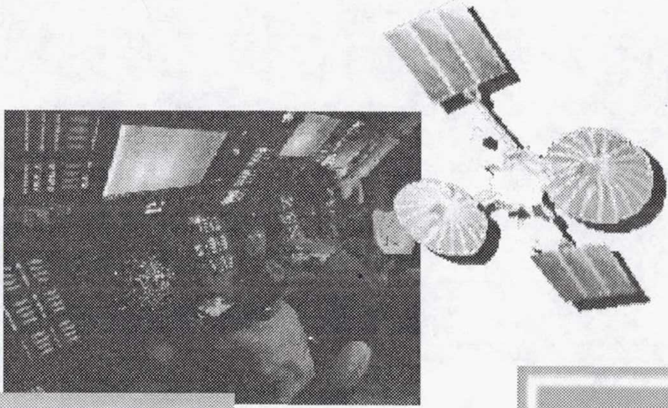
Model Applications in current Shuttle Environment

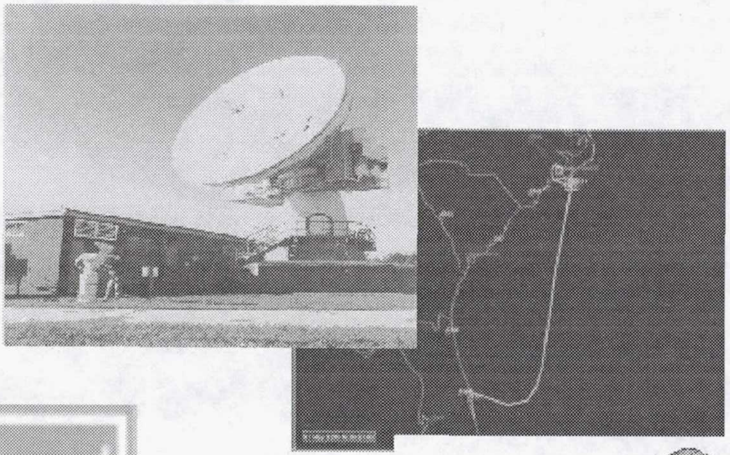
- **The existing model can serve as a First Generation RLV baseline for comparison**
  - Aid in understanding and serve as a point of departure for new reusable Space Launch Initiatives
- **New RLV specific models can be used to increase insight into reusable launch vehicle turnaround, operational processes and business case closure risk.**
  - Demonstrate Flight Rate dependence on such factors as the RLV architecture, probabilistic processing times, launch scrubs, and ascent outcomes.
- **Provide the government with a tool for analyzing and comparing competing architectures**
  - Requires that each architecture be modeled using similar methodology.

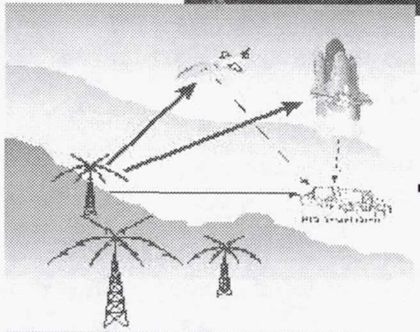
Space Shuttle Processing Simulation Model

Model applications for future RLV's

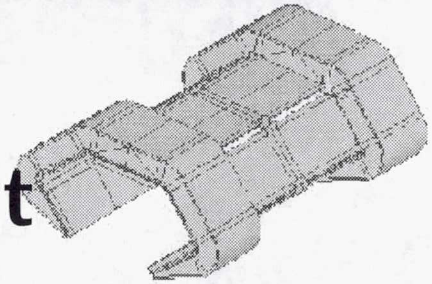
Conf. Paper/IN/16   2000159476   490895
S16   14P



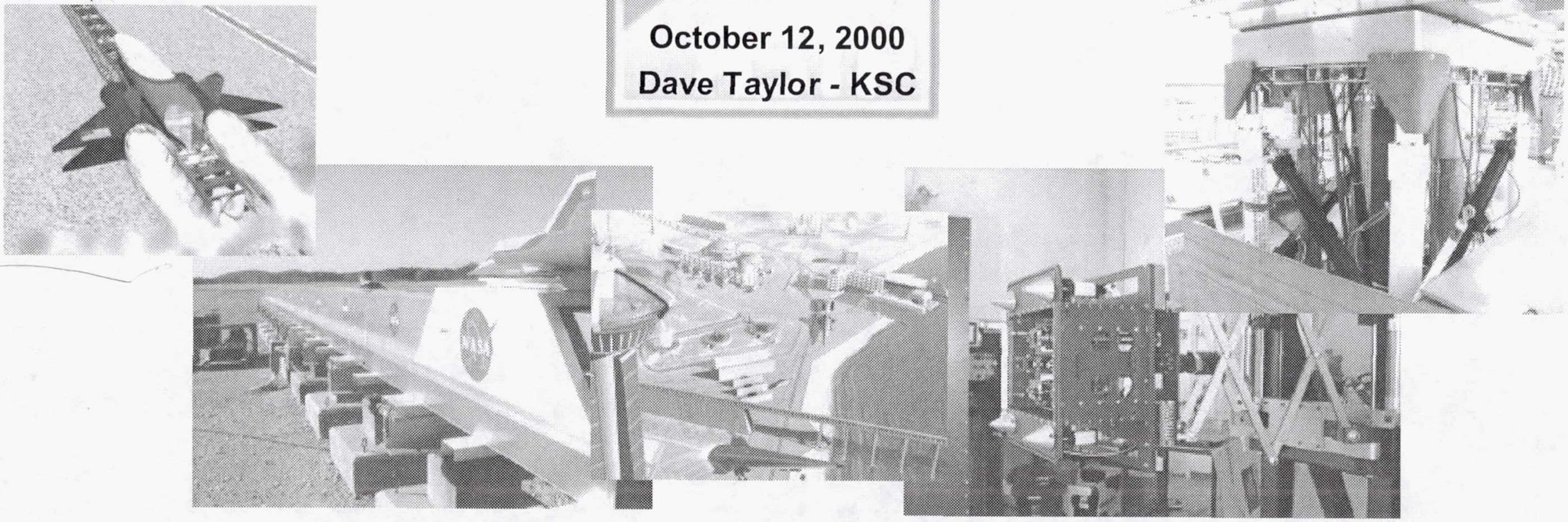


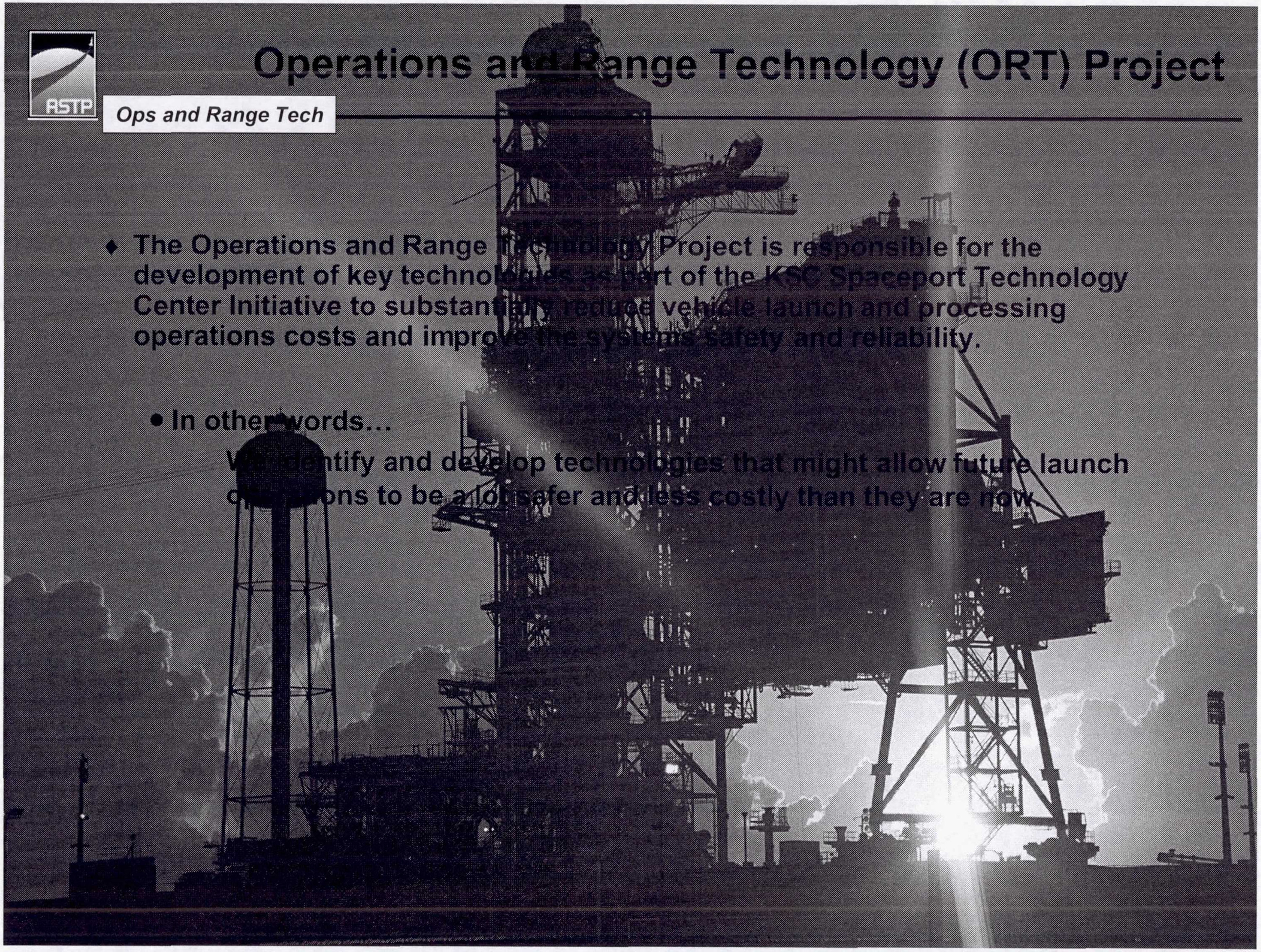


Operations and Range Technology Development



October 12, 2000
Dave Taylor - KSC





Operations and Range Technology (ORT) Project

Ops and Range Tech

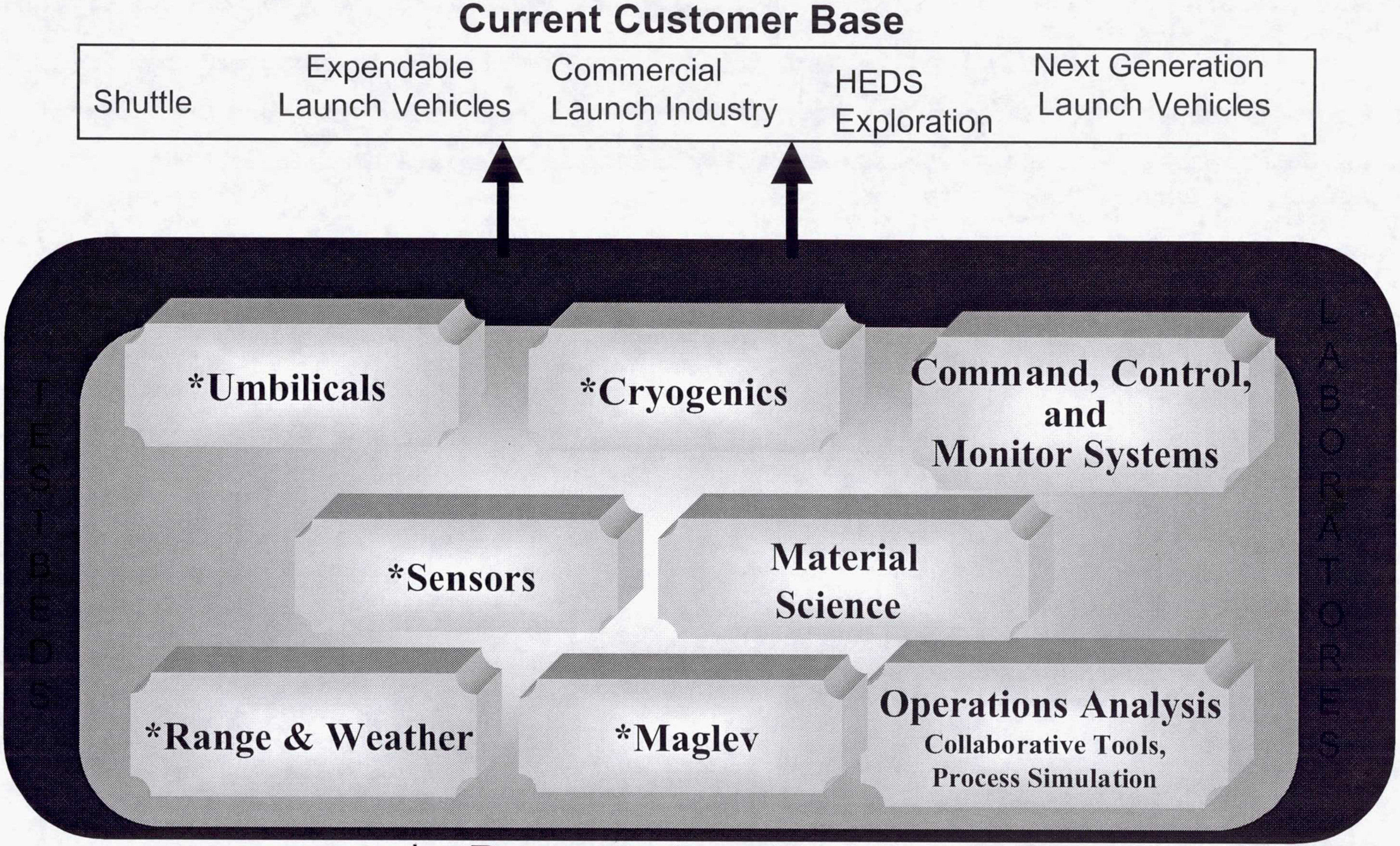
- The Operations and Range Technology Project is responsible for the development of key technologies as part of the KSC Spaceport Technology Center Initiative to substantially reduce vehicle launch and processing operations costs and improve the systems safety and reliability.
  - In other words…

    We identify and develop technologies that might allow future launch operations to be a lot safer and less costly than they are now

Operations and Range Technology Development

- **Operations and Range technologies are being developed by both the 3rd Generation RLV Program (ASTP) and the 2nd Generation RLV Program**
  - Space Transportation Architecture Studies (STAS) and the Integrated Space Transportation Plan (ISTP) defined requirements and prioritized technologies that needed further development to accomplish the goals of the 2nd and 3rd Gen. Programs.
  - Both the 2nd and 3rd Gen. operations technology development efforts are currently managed for the Programs by the Kennedy Space Center
    - KSC has been involved in a wide range of activities aimed at developing “spaceport” technologies

Spaceport Technology Areas



Current Customer Base

- Shuttle
- Expendable Launch Vehicles
- Commercial Launch Industry
- HEDS Exploration
- Next Generation Launch Vehicles

TESTBEDS

***Umbilicals**

***Cryogenics**

Command, Control, and Monitor Systems

***Sensors**

Material Science

***Range & Weather**

***Maglev**

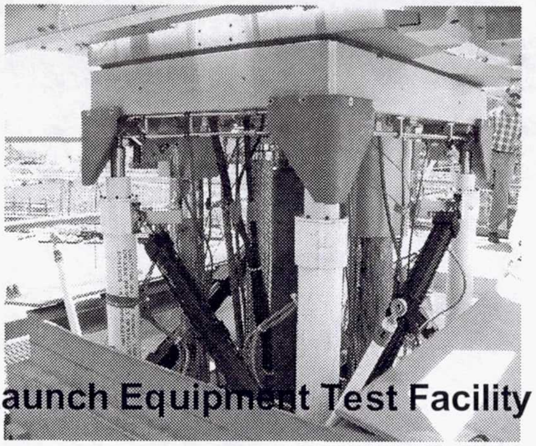
Operations Analysis
Collaborative Tools, Process Simulation

LABORATORES

* - Presentations Today

Umbilical Systems Development

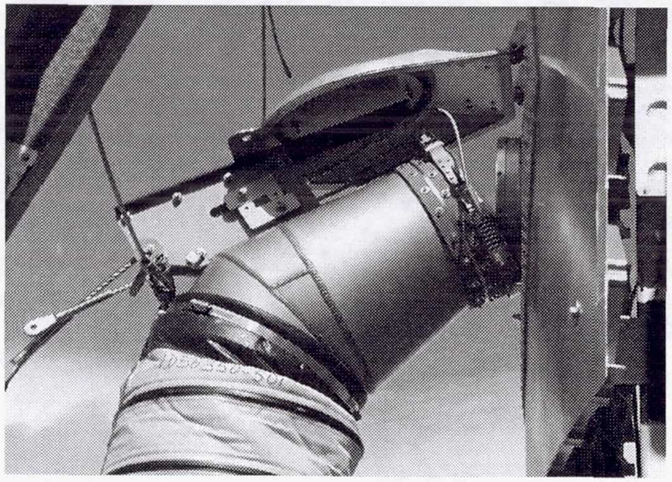
Ops and Range Tech



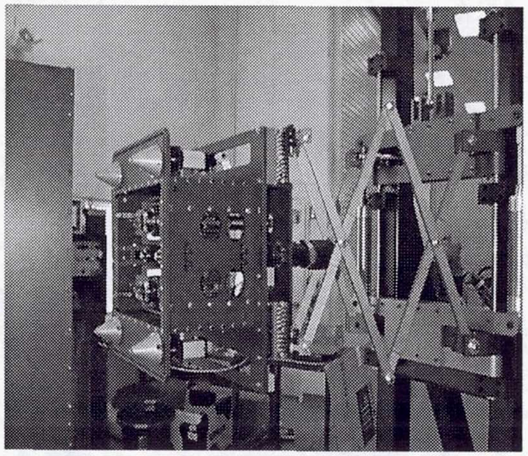
Launch Equipment Test Facility

- Design & Test of X-33 Rise off Umbilicals
- *Partnership with Lockheed Martin*

Pad Testing

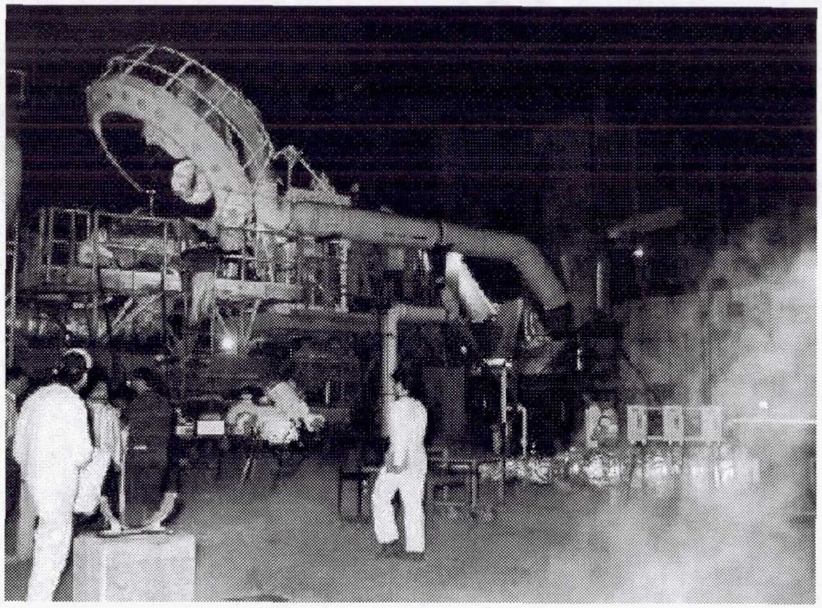


- Delta IV EELV ECS Duct Design, Fab and testing
- *Partnership with Boeing*



- Fluid & Electrical Automated Umbilical Mate & Checkout
- *SBIR Partnership*

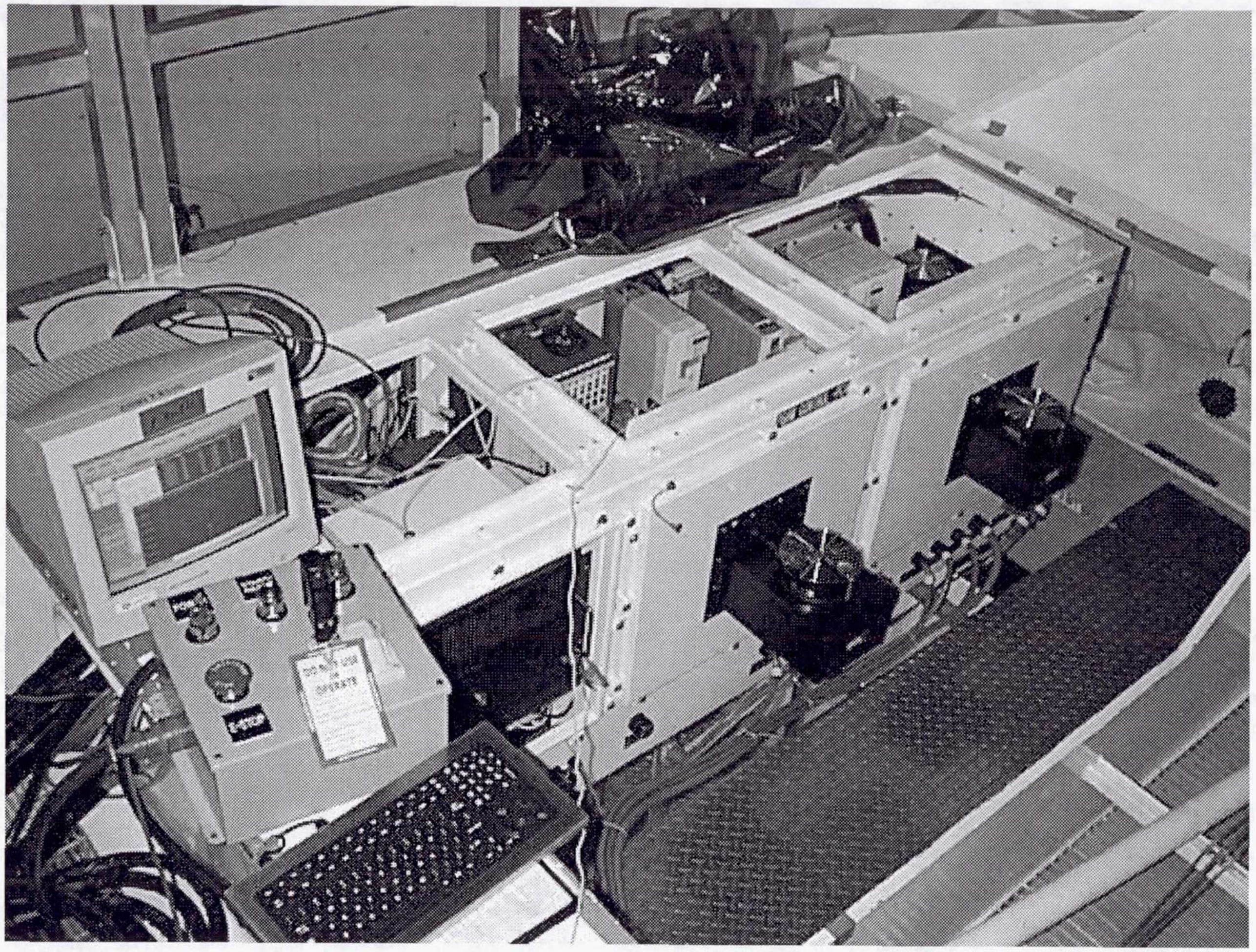
Ops and Range Tech



- •Gox Vent/Composite Nose Cone testing setup to test the New composite nose cone for Shuttle
- •*Partnership with KSC, MSFC, & Lockheed Martin Michoud*

Automated Payload Handling Systems

Ops and Range Tech

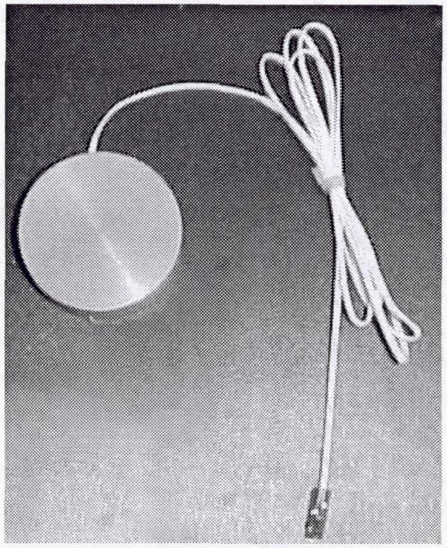


- Design and Development of an automated control System for the Payload Ground Handling Mechanism At LC-39
- *USA Patnership*

Ops and Range Tech

Command, Control & Monitor Systems

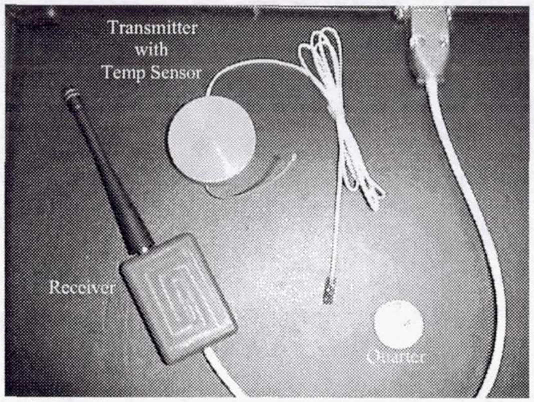
- HEDS Technology Demo - Shuttle Flight Experiment to demonstrate new instrumentation technologies (fiber optic, micro-electro mechanical sensor)
- **Flight Experiment on STS-96**
- *Multi-Center, Industry & Academia Partnership: KSC, JSC, MSFC, LaRC, GRC, Boeing North American, USA, Sanders Division of Lockheed Martin, Rockwell Science Center, Oklahoma State University, University of Maryland, Dynacs Engineering Company*



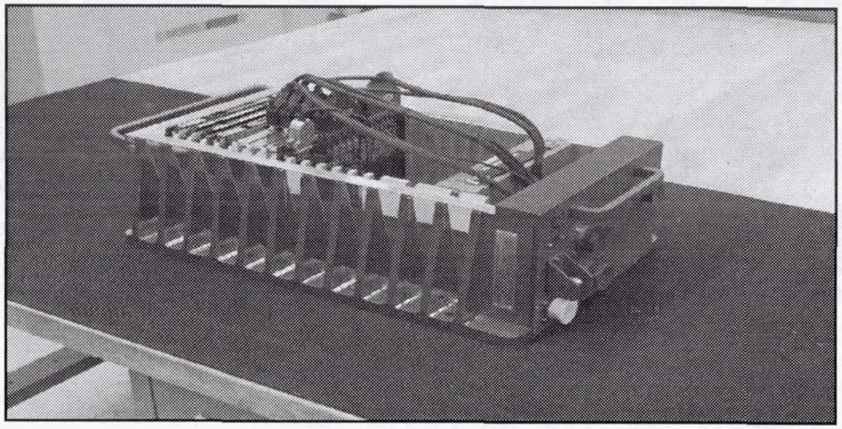
- Autonomous Micro-Temperature Recorder was part of the SpaceHab Oceaneering Space Systems Payload (SHOSS) used to characterize on-orbit temperature environment. Each unit can be programmed to “wake up” at a user defined time at which it begins sampling temperature.
- *Partnership with Invocon Inc., KSC and JSC*
- **Experiment flew on STS-101**

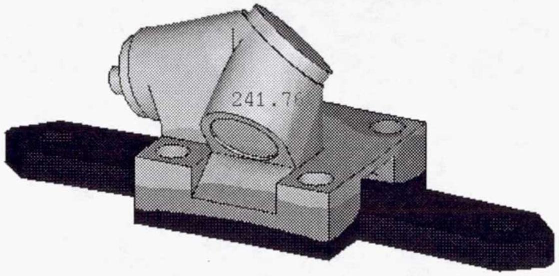
- ***Partnership with Ivacon Inc., KSC and JSC***

Command, Control & Monitor Systems



- Micro Wireless Instrumentation System is a smal Battery operated temperature sensor system Comprised of transmitter and receiver units. The Transmitter units measure temperature at various Locations in the crew module and send data to Receiver via RF.
- **Experiment flew on STS-101**
- *Partnership with Ivocon, Inc., KSC and JSC*



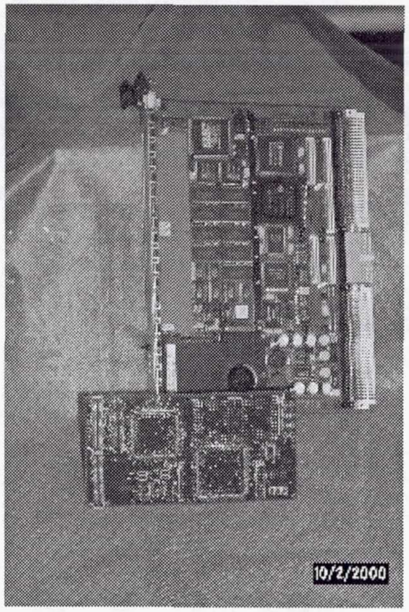


- Optical Plume Anomaly Detection OPAD - Shuttle Flight Experiment to demonstrate technology to monitor ultraviolet and visible light spectrum in rocket engine plume, detect metallic presence in the parts per billion range, and provide indication of hardware mass loss
- Partnership with *MSFC*
- **Scheduled to Fly on STS-113**

Command, Control & Monitor Systems

10/2/2000

Portable Ground Station for Monitoring Experiment



10/2/2000

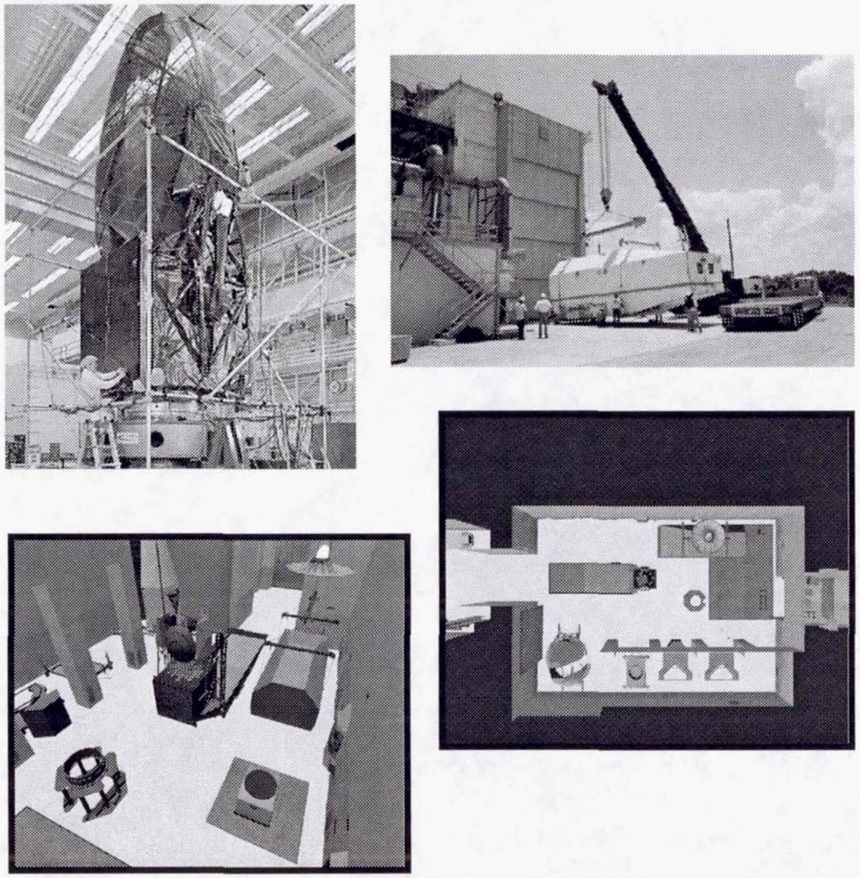
Electronic Components For the Experiment

•NASA IVHM Technology Experiment - X-34 Flight experiment to demonstrate software techniques for modeling & monitoring main propulsion system, reaction control system, and fast track engine system

•*Partnership with ARC, GRC, and MSFC, Orbital Sciences Corporation*

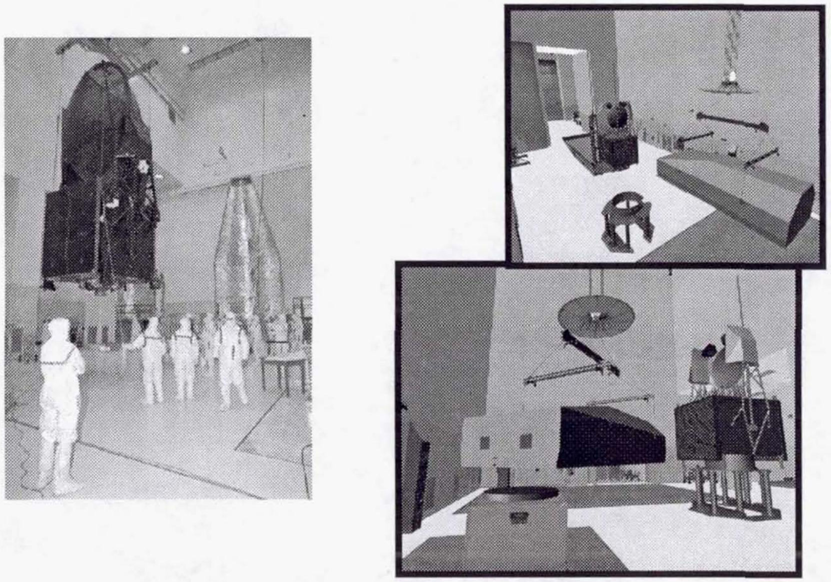
Intelligent Synthesis Environment

TDRSS Processing Simulation

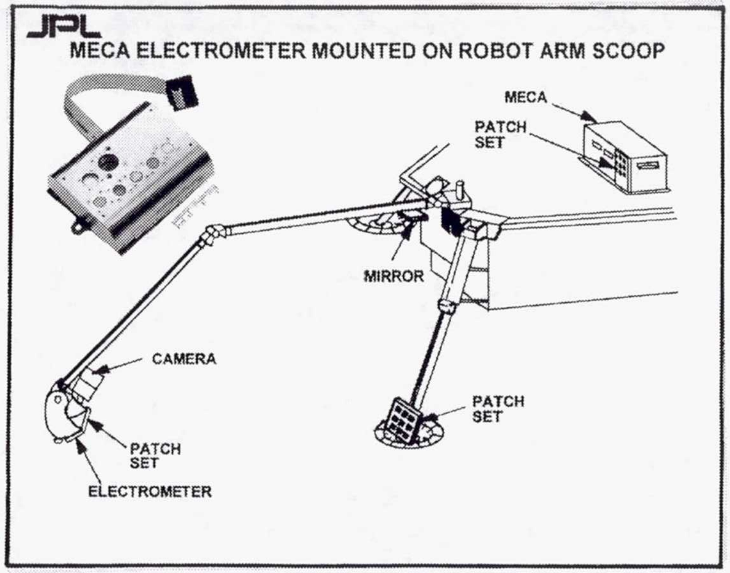


Future Plans

- Integrate engineering and operations analysis codes into this ISE tool.
- Finish modeling complete representation of ground processing environment
- Use tools to design and develop new launch and payload processing systems and to assess their operational approach



Low TRL Development



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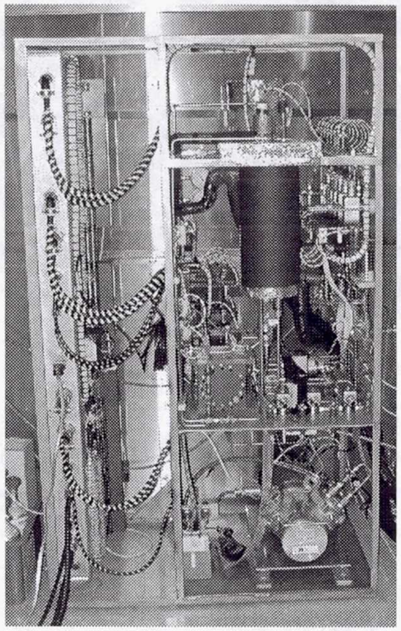
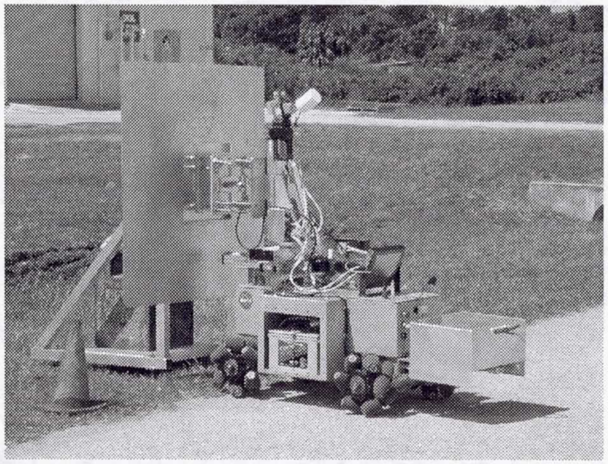
The ***Mars environmental compatibility assessment*** project's electrometer was jointly developed at JPL & KSC to facilitate the characterization of the electrostatic properties of different types of insulating materials that are likely to be used on future unmanned and manned explorations of Mars.

Reverse water Gas Shift -
A cyclic process
Technology for
Oxygen Production



Mars Umbilical Technology Demonstrator
Robotic Mate of Electrical Power



2nd Gen. Project Organization

- **The 2nd Generation RLV operations and range technology efforts include the following areas:**
  - Automated Umbilicals
  - Modular Payload Systems
  - Spaceport Range Technologies
  - Propellant production, handling, and storage
  - Standardized interfaces
  - Advanced checkout and control systems
  - Intelligent Instrumentation
  - Optimization and Analysis tools

ASTP Project Organization

- **ASTP (3^{rd} Gen.) Ops and Range Technology Project is divided into four Elements:**
  - Range
    - Decision Models, Weather Instrumentation & systems, Ground-based Range systems, Space-based Range systems
  - Ground Ops
    - What are the systems issues driving ground-ops costs as we know then today? What new technologies could reduce ground ops costs?
  - Spaceport Ops
    - Based on an airport analogy, what would a spaceport of the future look like … what are the issues to get there?
  - Launch Assist
    - Maglev and others?

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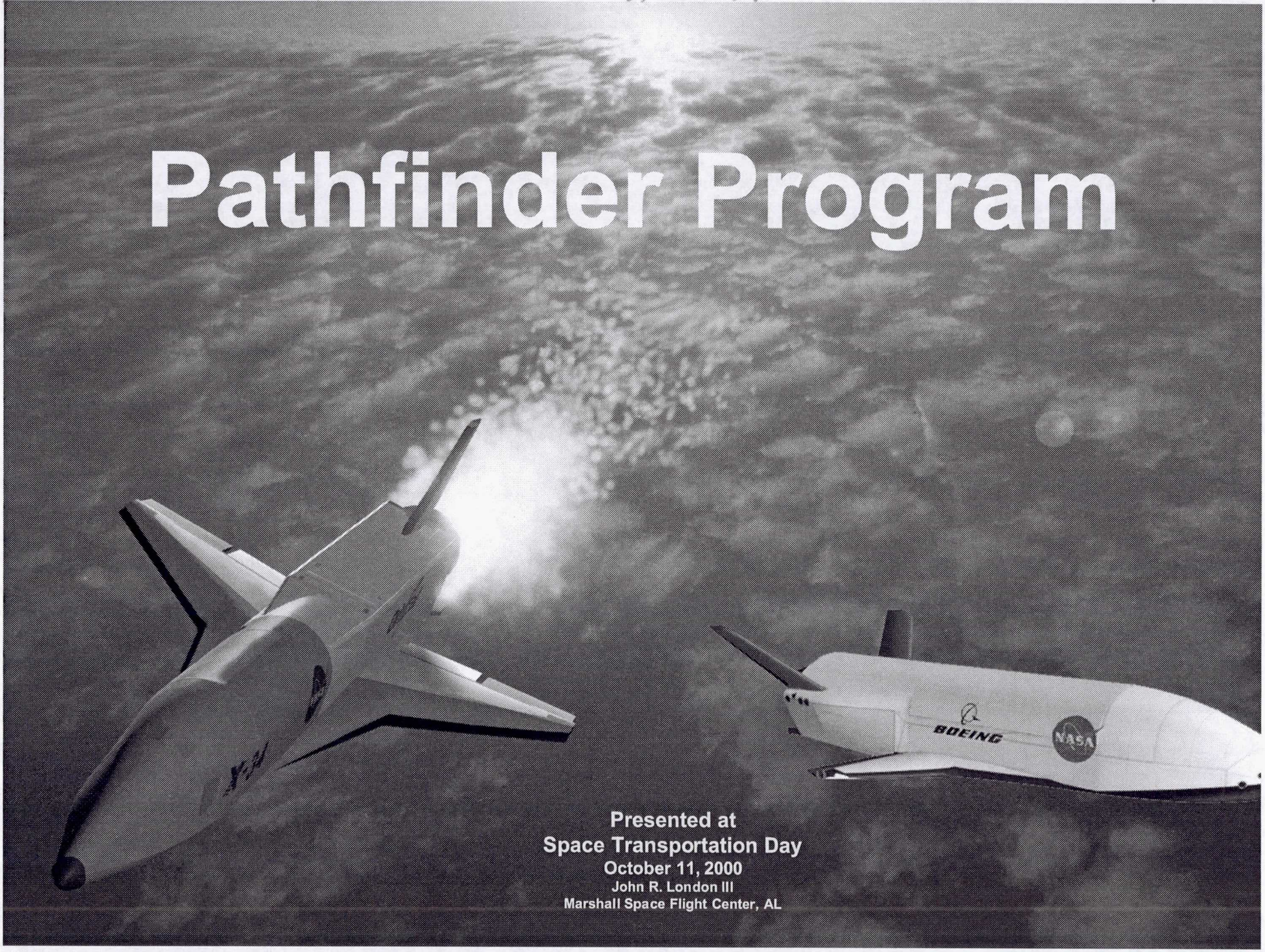


Pathfinder Program

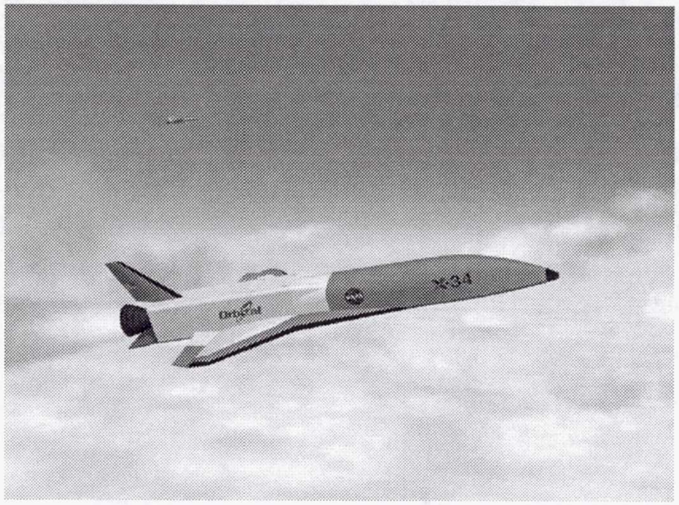
Presented at
Space Transportation Day
October 11, 2000
John R. London III
Marshall Space Flight Center, AL

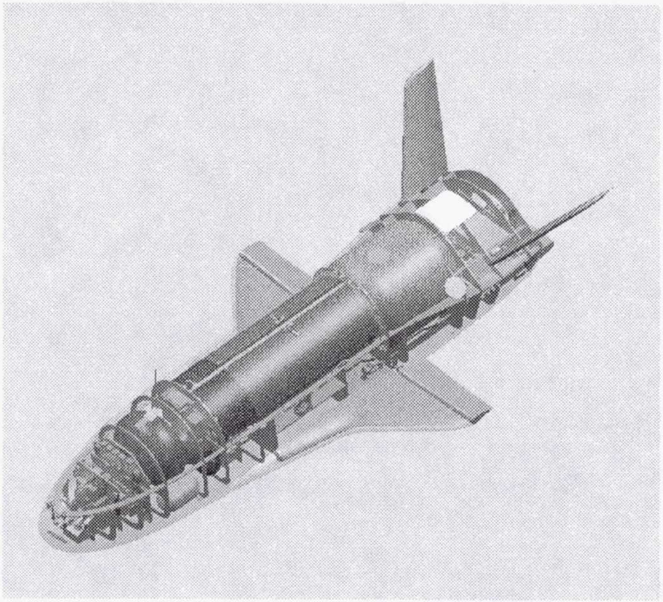
Program Overview

- **RLV Goal: to Significantly Reduce the Cost of Access to Space**

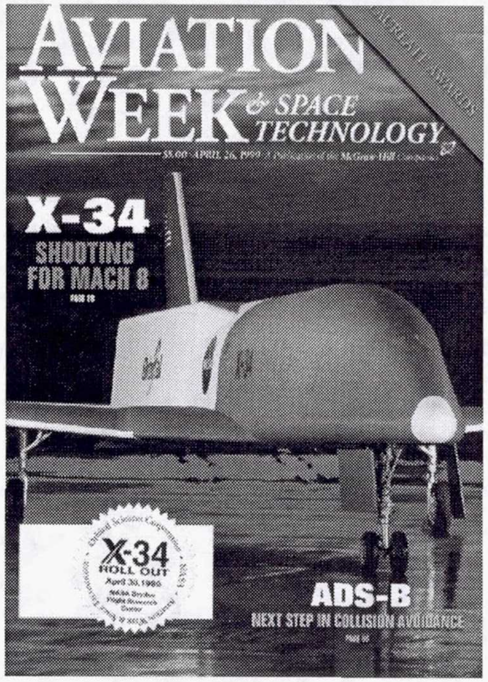
- **X-34 Project Objectives**
  - Test Bed Vehicle for Demonstrating Key Reusable Launch Vehicle (RLV) Operations and Technologies
  - Focus Areas
    - ◆ **Investigation of New Methods for Low-Cost Operations**
    - ◆ **New RLV Technologies Embedded in Vehicle Design**
    - ◆ **Demonstration of Hosted RLV and Hypersonic Experiments**

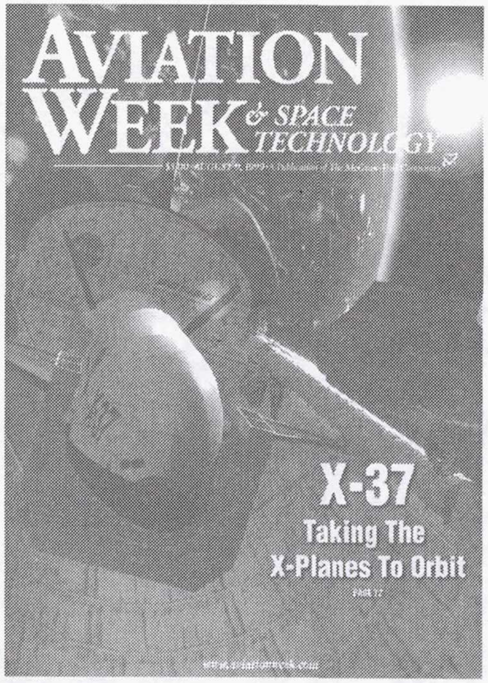
- **X-37 Project Objectives**
  - Test Bed Vehicle for Demonstrating RLV In-Space and Re-Entry Technologies and Flight Experiments
  - Focus Areas
    - ◆ **Investigation of New Methods for Design and Manufacturing**
    - ◆ **New RLV Technologies Embedded in Vehicle Design**
    - ◆ **Demonstration of Hosted RLV and Re-Entry Experiments**





High Visibility Flight Projects





Significant Events / Accomplishments

X-34:

- Completed the build of A-1A at Dryden utilizing government technicians
- Issued a NTE contract change to OSC to include operations at White Sands & Dryden for unpowered and powered flights respectively
- Completed the report on the Risk Assessment in support of the Environmental work
- Vehicle system level testing on A-1A 90% complete
- First powered flight vehicle essentially complete (A-2)
    - Delivered the 2nd flight wing
- Participated in Fastrac/MPS and avionics/flight controls independent reviews January-March 2000
- Completion of A-2 Static Loads Testing

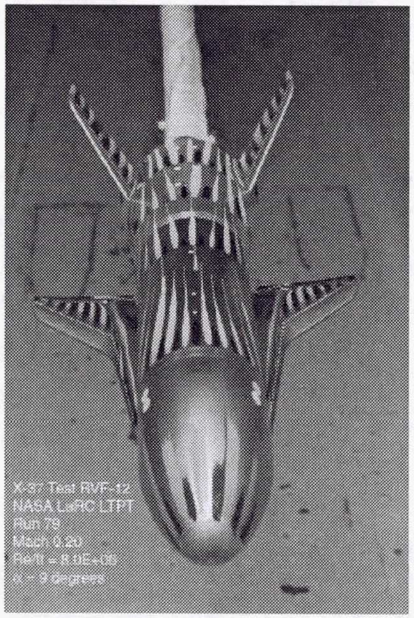
X-37:

- Independent Annual Review (IAR) conducted Jan. 25-26, 2000
- Flight S/W SRS Release 1.0, Jan, 2000
- X-40A Risk Assessment conducted Feb. 10-11, 2000
- Initial Design Review (IDR) conducted Mar. 7-8, 2000
- Fuselage Master Tooling Fabrication Complete April, 2000

Other Flight Experiments:

- Composite LOX Tank nearing fabrication completion
- SHARP -B2 successfully launched on Sept. 28, 2000

X-34 Vehicle (A-1A) at Dryden

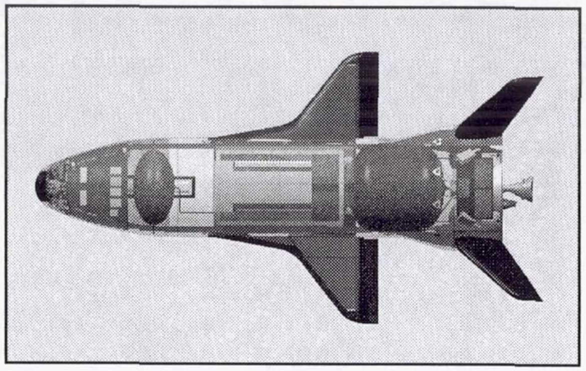


X-37 WTT at LaRC

Pathfinder Flight Experiments

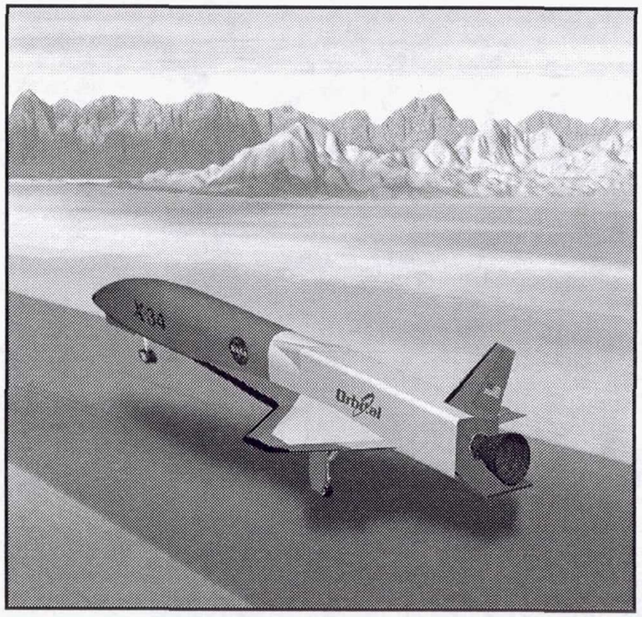
Flight Demonstrator Vehicles

- X-34 Rocket Plane - Mach 8 technology testbed
- X-37 Space Plane - Orbital technology testbed



Flight Experiments

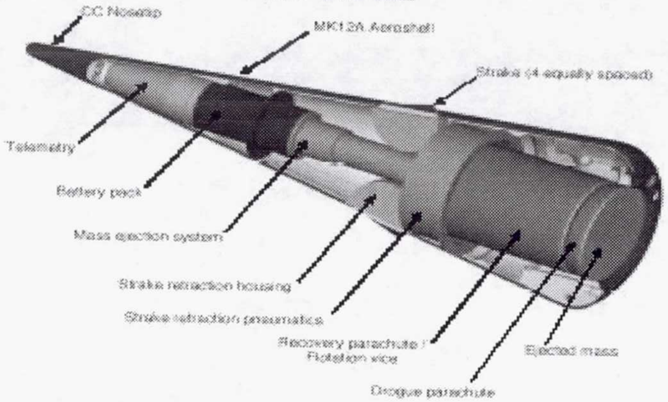
- Flown on X-34:
    - ◆GAMMA-TITANIUM ALUMINUM-BASED TPS (ALENIA AEROSPACE)
    - ◆ADVANCED C/SIC TPS (ESA-DAIMLER-BENZ)
    - ◆MECHANICALLY ATTACHED FLEXIBLE TPS (BOEING)
    - ◆ENCAPSULATED WATERPROOF 2500F CMC TPS (MDA [Now BOEING])
    - ◆FLIGHT TEST DETAILED SPECIMENS IN CERTIFIED HOLDER (MDA [Now BOEING])
    - ◆ACTIVE DAMAGE INTERROGATION HEALTH MONITORING SYSTEM (MDA [Now BOEING])
    - ◆ACOUSTIC EMISSION HEALTH MONITORING SYSTEM (BOEING)
    - ◆AUTONOMOUS ABORT LANDINGS (DRAPER LAB)
    - ◆INTEGRATED VEHICLE HEALTH MANAGEMENT (IVHM) (NASA AMES)
    - ◆COMPOSITE LOX TANK (LOCKHEED-MARTIN)
- 40 Embedded or Carry-On Experiments Baselined for X-37

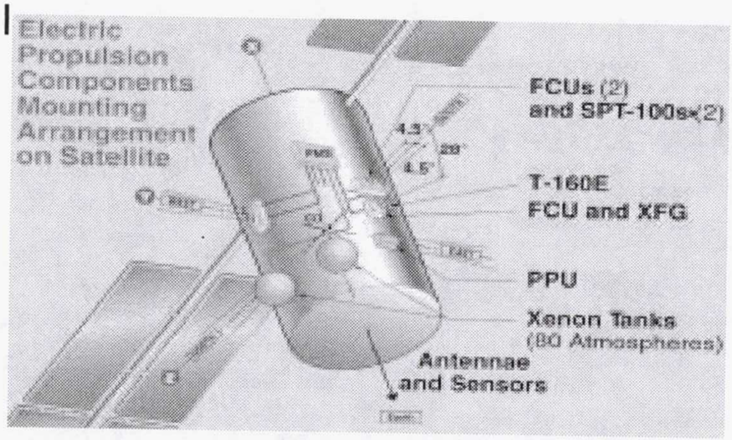


Pathfinder Flight Experiments (cont'd.)

- **Flight Experiments**
  - Other Flight Experiments:
    - ◆ **REDUCED COST SMALL PAYLOAD TECHNOLOGIES (AERO-ASTRO)**
      - Deployed from the Space Shuttle
    - ◆ **CERAMICS FOR SHARP LEADING EDGES (NASA AMES)**
      - Flown on a Minuteman III
      - Successfully launched on Sept. 28, 2000
    - ◆ **ProSEDS (NASA MSFC)**
      - Flown as a secondary payload on a Delta II upper stage
    - ◆ **HALL EFFECT THRUSTER (NASA GRC)**
      - Instrumentation flown on a Russian communications satellite
    - ◆ **CRYOGENIC PROPELLANT GAUGE (NASA GRC)**
      - Flown on the USAF Solar Orbit Transfer Vehicle Space Experiment

SHARP-B2

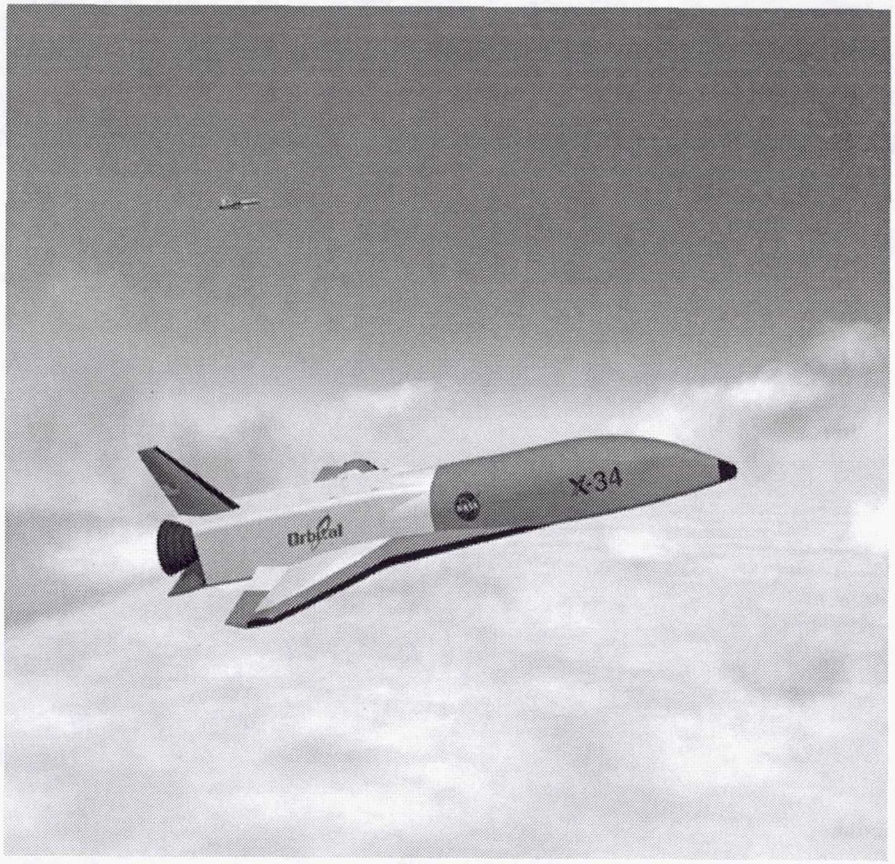





X-34
34

Top Level Goals

- **RLV Goal: to Significantly Reduce the Cost of Access to Space**
- **X-34 Program Objectives**
  - Test Bed Vehicle for Demonstrating Key Reusable Launch Vehicle (RLV) Operations and Technologies
  - Focus Areas
    - ◆**Investigation of new Methods for Low-Cost Operations**
    - ◆**New RLV Technologies Embedded in Vehicle Design**
    - ◆**Demonstration of Hosted RLV and Hypersonic Experiments**



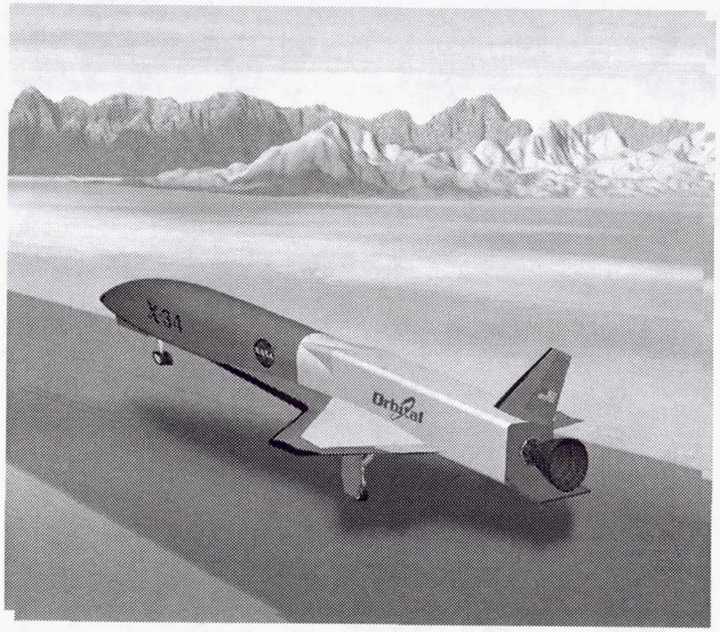
Focus Area Technical Goals

New RLV Technologies Embedded in Vehicle Design

- **Demonstrate technologies throughout flight profile**
  - Subsonic and hypersonic flight
  - Capable of powered flight to at least 250 K ft
  - Capable of attaining Mach 8
- **Capable of autonomous flight operations**

Investigation of New Methods for Low-Cost Operations

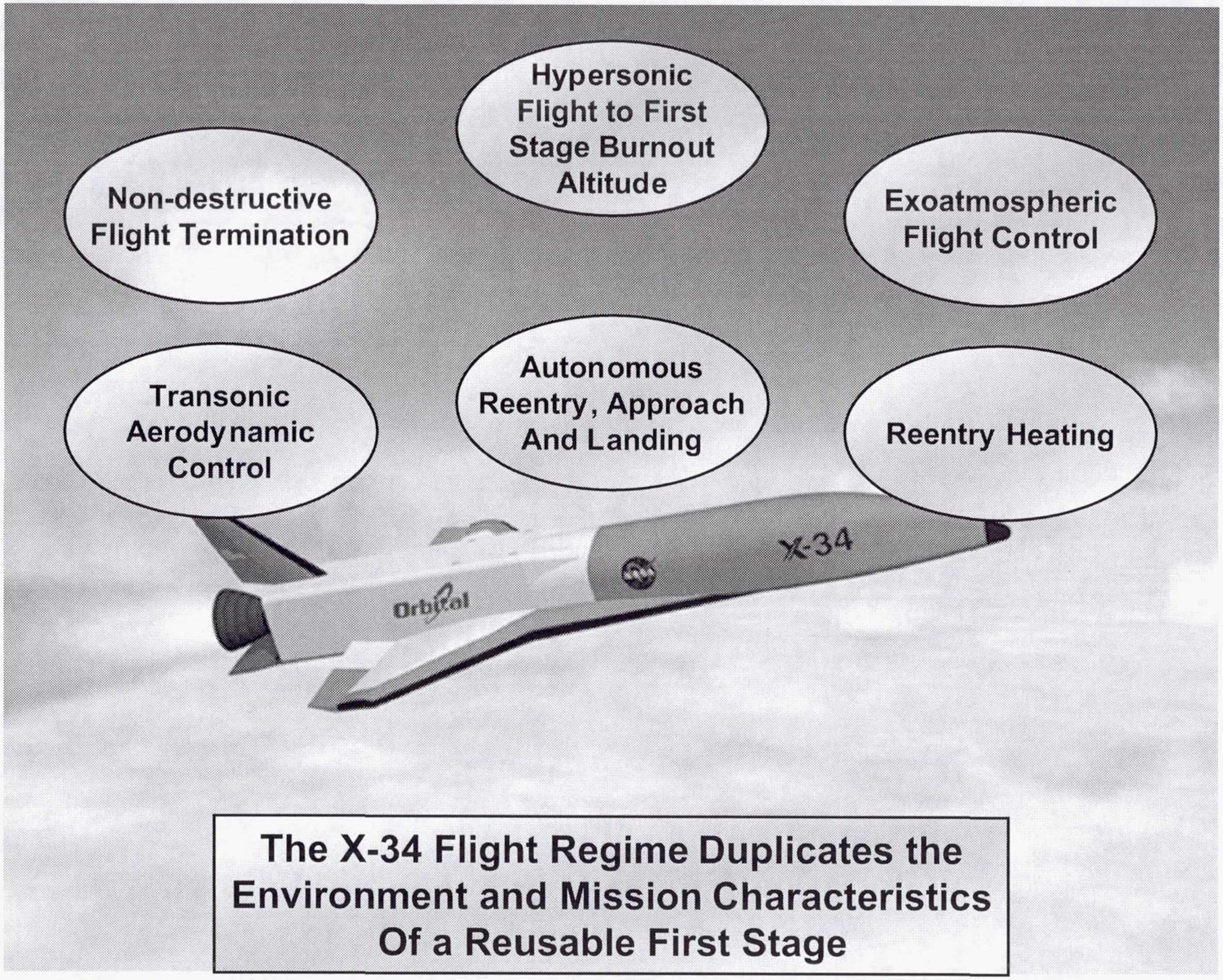
- **Capable of demonstrating safe abort**
- **Capable of 25 test flights over a period of one year (OMB metric)**
- **Low cost operations**
  - Small work force
  - Nominal 2-week turn-around
  - Surge capability of 2 flights within 24 hours
  - Capable of attaining average recurring flight cost of $500K
- **Operation in RLV-type environments**
  - Flights through inclement weather
  - Landings with cross winds of 20 knots or greater



Testbed for Hosted RLV and Hypersonic Experiments

- **On-board instrumentation for testing embedded technologies**
- **Small area for "carry-on" experiments**

Flight Testing for a Multistage Reusable System



Hypersonic Flight to First Stage Burnout Altitude

Non-destructive Flight Termination

Exoatmospheric Flight Control

Transonic Aerodynamic Control

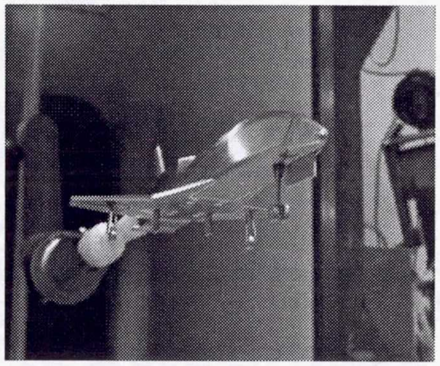
Autonomous Reentry, Approach And Landing

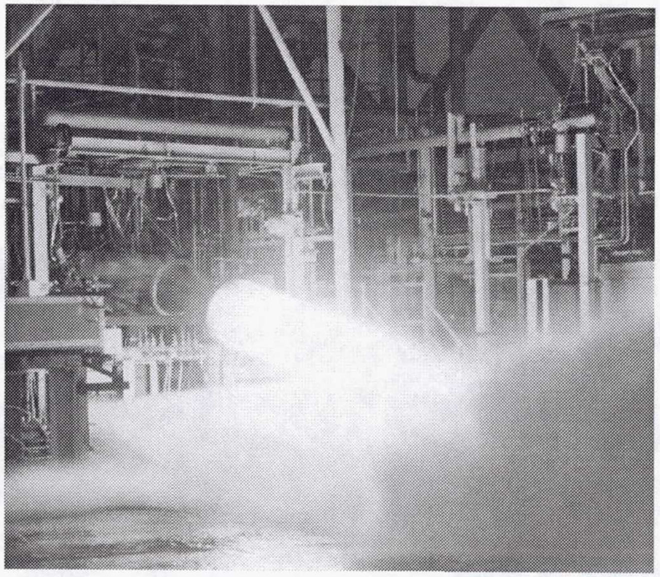
Reentry Heating

The X-34 Flight Regime Duplicates the Environment and Mission Characteristics Of a Reusable First Stage

Key Embedded Technologies

- Composite Primary and Secondary Airframe Structures
- Composite Reusable Propellant Tanks
- Integrated Vehicle Health Monitoring System
- Advanced Operable TPS Including Leading Edge Materials
- Low-Cost Avionics Including Integrated (GPS/INS) and Differential (DGPS) GPS
- New Low-Cost Rocket Engine (Government Developed)
- Integral Closed Loop Flush Air Data System





X-34 Vehicle Description

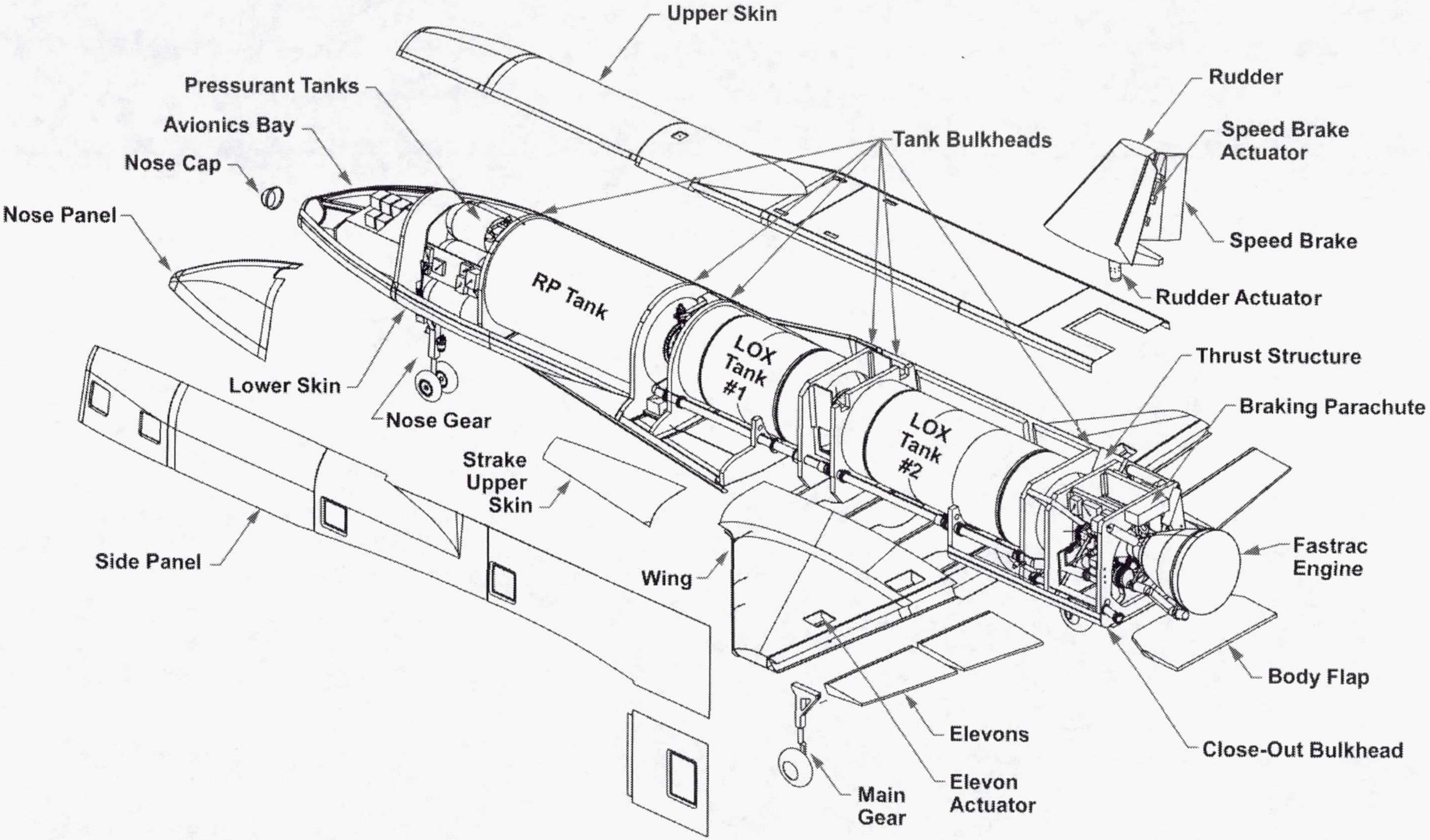
- **Single Stage, Sub-Orbital, Fully Reusable, Unmanned Testbed Aerospace Plane**
- **Three airframes: A-1A, A-2, A-3**
  - A-1A is unpowered, A-2 and A-3 are powered
- **Vehicle Characteristics**

Length	58.3ft
Wing Span	27.7 ft
Gross Weight	*45,488 lbs.
Propellant	*30,350 lbs.
Payload	450 lbs.
Operating Weight Empty*	15,138 lbs.

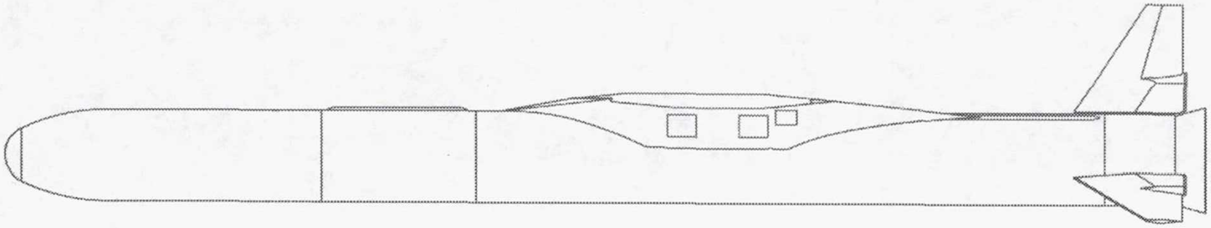
*Target Weight

- **Airframe**
  - Composite structure and skin
  - One piece wing with center carry through structure
  - Elevon control surfaces
  - All-flying vertical tail
  - Body flap for pitch axis trim
- **Avionics**
  - Single string with exception of dual string flight termination system

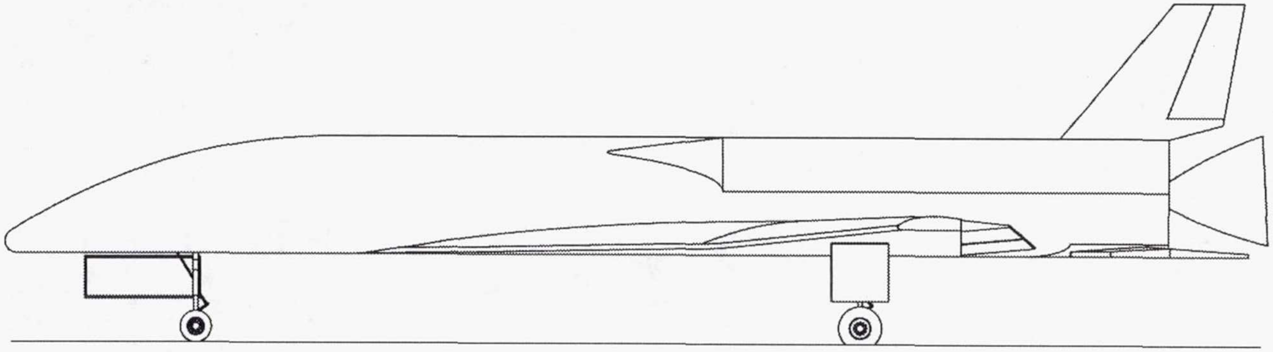
X-34 Expanded View



Vehicle Size Comparison

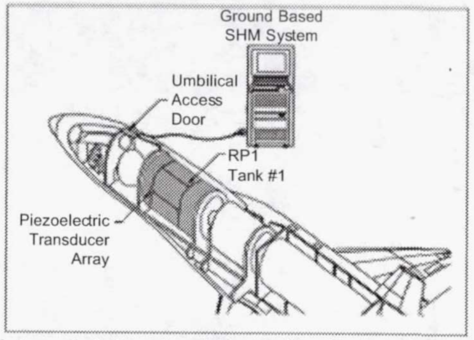


Pegasus XL

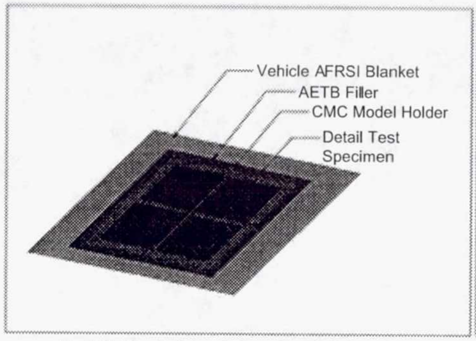


X-34 Technology Testbed Vehicle

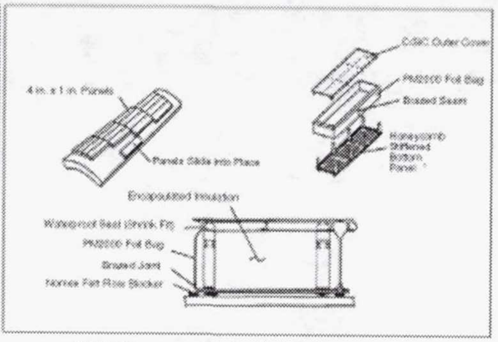
X-34 Experiment Examples



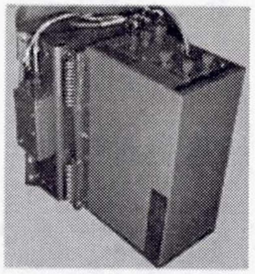
Integrated Structural Health Monitoring System for the X-34 RP1 Tank (Boeing, St. Louis).



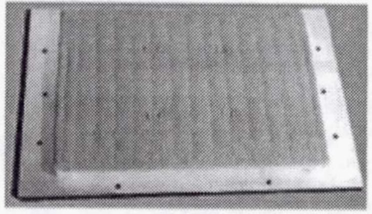
Detail Test Specimen Model Holder (Boeing, Huntington Beach).



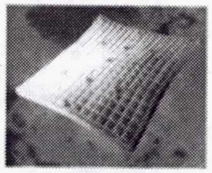
CMC Encapsulated TPS Assembly (Boeing, Huntington Beach).



Acoustic Emission Health Monitoring System (Boeing, Seattle).

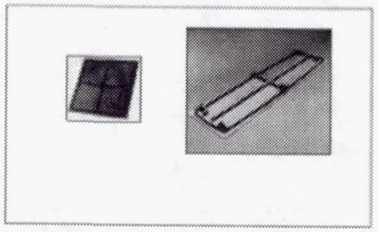


Mechanically Attached Thermal Protection System (Boeing, Seattle).



IFI Blanket

TiAl Based TPS (Alenia, Italy)



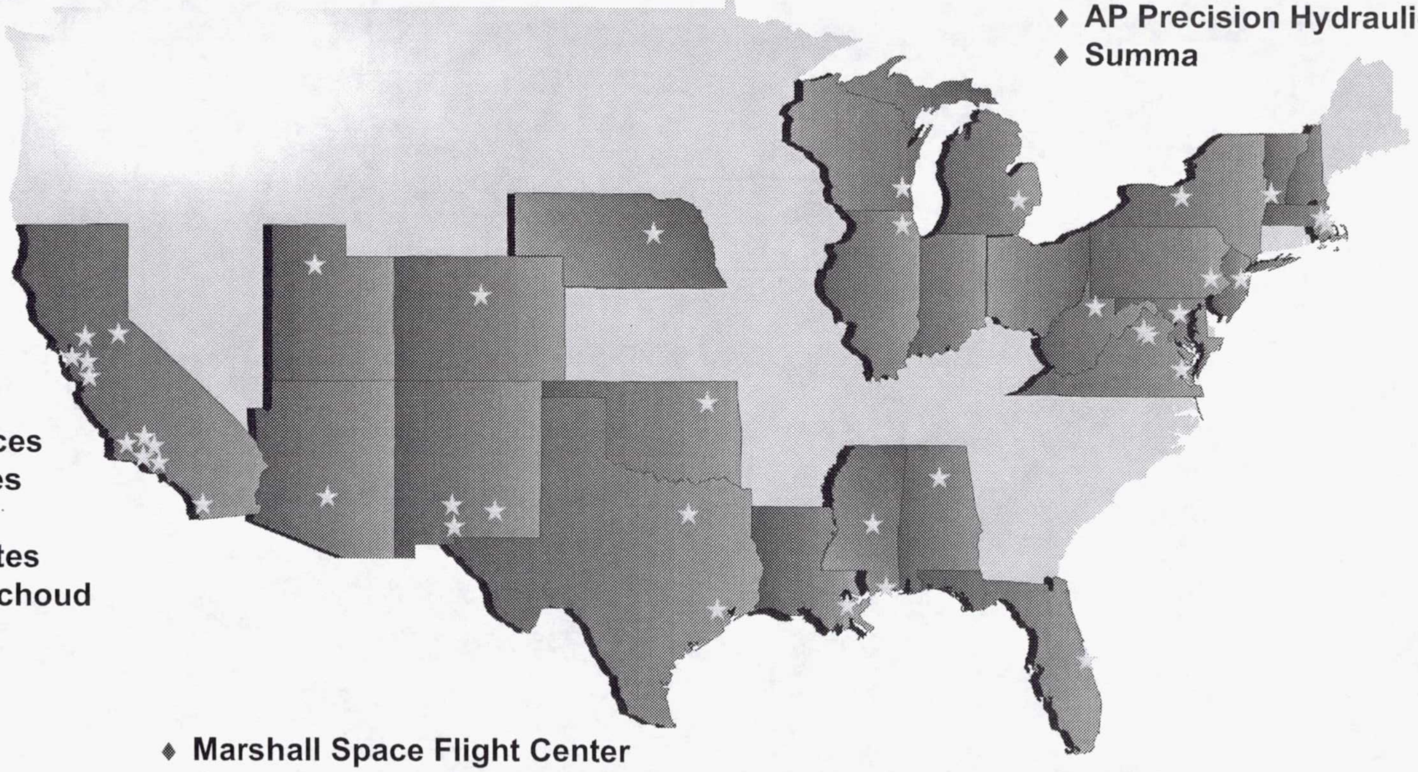
Advanced C/SiC Based TPS (Daimler Benz, Germany).

Government Participation

Government and Industry Participants

- AlliedSignal Aerospace
- The C. S. Draper Labs
- Oceaneering Space Systems
- Vermont Composites

- Litton
- OR Computers
- AP Precision Hydraulics
- Summa



- Aurora Flight Sciences
- R-Cubed Composites
- Spincraft
- Advanced Composites
- Lockheed Martin-Michoud

- Marshall Space Flight Center
- Ames Research Center
- Langley Research Center
- Dryden Flight Research Center
- Johnson Space Center
- Holloman Air Force Base

- White Sands Test Facility
- Edwards AFB
- White Sands Missile Range
- Kennedy Space Center
- Stennis Space Center

X-34 Restructure Status

- **A-1A complete at DFRC, A-2 complete at Orbital, A-3 fuselage structure complete at Orbital**
- **A-1A tow testing to begin at Edwards AFB week of May 15th**
- **Two reviews completed; others planned for the near term**
  - Sackheim propulsion system review
  - McConnaughey avionics and flight controls review
- **A-1A has been judged ok for unpowered drop tests at White Sands Space Harbor, starting in early '01**
  - Consensus of MSFC, DFRC, Orbital, and the McConnaughey review team
  - Assumes addition of increased hardware-in-the-loop testing, surrogate aircraft flights, and minor hardware fixes
- **Significant work required before A-2 is ready for first powered flight in '02**
  - Will add integrated vehicle/engine testing (e.g., MPTA), a key Sackheim team finding
  - RPV link will be added to allow some level of human control of the vehicle during contingencies
  - Avionics will be upgraded with the goal of "no single failure results in loss of vehicle"
- **Program is working closely with Second Generation Program to ensure synergy, including use of A-3**
- **A new contract arrangement will be established with Orbital**
- **New program leadership at MSFC and Orbital**
- **DFRC role in X-34 will be significantly increased; e.g., DFRC will provide Deputy Program Manager**

Significant Events/Accomplishments

- Shipment of A-1 Vehicle to DFRC
- SVR (System Verification Review) at OSC
- Roll Out of A-1 Vehicle at DFRC
- Installation of LOX & RP Tank into A-2 Vehicle
- Completed a project sparing study and received a proposal for long lead spares
- GVT (Ground Vibration Test) of A-1 Vehicle with L-1011
- Initiated Captive Carry Flight Testing with the X-34 and L-1011
- Received final direction on range operations: [unpowered flights at WSMR, powered flights at Dryden & KSC]
  - Proposal received from OSC and is in review
- Incorporated additional risk mitigation activities such as IV&V of software, Tow Testing, and conversion of A-1 to unpowered flight status
- Delivered 2nd flight wing to OSC
- Completion and Integration of Wing #2 with the A-2 Fuselage
- Conducted Independent Code Q Review
- Defined requirements for the 3rd party indemnification of X-34 by NASA
- Defined and initiated environmental work to support flights as defined within the project
- Defined and negotiated three new experiments to fly on X-34 (Robust abort, Composite Lox Tank, & IVHM)
- Put in place new contract with Summa to provide engines and support for the 25 flight option
- Completed the retrofit of A-1 to A-1A with the combination of DFRC, KSC, MSFC, and OSC manpower (system testing underway)

X-34 Project Status

- **Restructuring effort underway**
  - Possible increase in ground testing for engine and vehicle, avionics mods, and new propulsion test article
  - Focused to support 2nd Gen Program
- **A-1A unpowered vehicle complete and on the runway at Edwards AFB**
  - Series of captive-carry flights and high-speed tow tests underway
- **A-2 powered vehicle complete and undergoing tests at Orbital's Dulles facility**
- **A-3 airframe essentially complete at Orbital's Dulles facility**
- **MC-1 (formally Fastrac) engine testing continuing at Rocketdyne's SSFL in Calif.**
  - 45 hot-fire tests already completed at SSC

Project Status

Last Month's Accomplisments

- **Significant Progress achieved on updating the X-34 Contract**
  - Majority of Task Directives closed or suspended
    - **Tow test TD open until September 1st**
    - **Mission Success Support TD and IV&V TD will remain open**
    - **All other TDs terminated or suspended**
  - Paid Orbital $4.4M in provisional Milestone Payments for partial completion of Milestones
  - 1 open Request for Equitable Adjustment (REA) value $1.1M
  - 1 Open Contract Mod (Mod 32)
    - **Plan to negotiate by September 31**
    - **NTE Period of Performance extended to allow work to continue**
- **Conducted tow tests of A-1A vehicle on DFRC lakebed**
  - 4 tests successfully conducted, including a 30 mph release test
  - Test anomaly occurred on 1st & 6th test
    - **Only damage to vehicle was Nose gear tire**
    - **NG tires have been replaced.**
- **Worked with TD management on restructure trades/options**
- **Supported Internal ISO 9000 Audit**
- **Continued the build of the first powered flight vehicle (A-2)**

Project Status

Last Month's Accomplishments (continued)

- **Supported Osh Kosh Airshow with flight engine display**
- **Proof load tested Engine Installer**
  - Problems identified with anti rotation mechanism
  - Retest next month
- **Conducted turbopump water flow tests**
- **Supported range safety requirements review and assessment**
  - Current design of Engine MOV & GGOV will not likely be able to comply with rqmnts
- **Conducted engine tests at Santa Susana facility in CA**

Date	**Planned Dur (sec)**	**Actual Dur (sec)**	**Objective**
18-Jul	5	5	Start Sequence
29-Jul	24	24	Calibration Baseline
8-Aug	24	24	LOX inlet Ramp-up
17-Aug	24	24	Calibration Verification

Project Status

Next Month's Plan

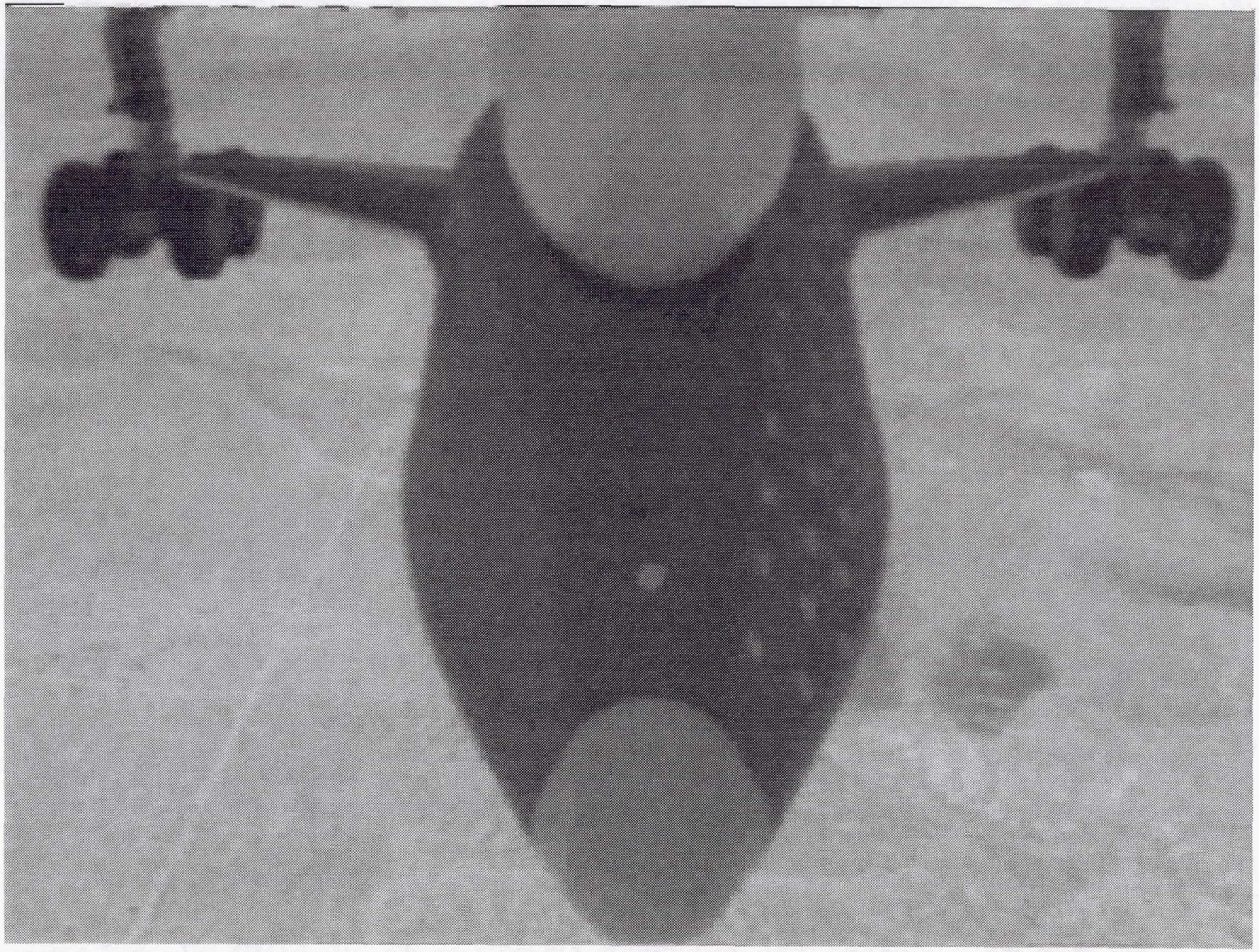
- **MSFC/DFRC site visit to WSMR, WSTF and Holloman AFB - Aug 28-25**
- **Conduct Audit of Orbital actual costs on X-34 - Aug 28-31**
- **Support GAO Review as required**
- **Support IG Audit**
- **Closeout Tow Test Task Directive (9-1-00)**
- **Captive Carry Flight Test Planning**
- **Reconfigure A-1A Vehicle for resumption of FAA Captive Carry tests**
  - Dependent upon L1011 availability
- **Increase Project and project support staffing**
- **Develop X-34 Systems Requirements Document**
- **Baseline X-34 Configuration Management Plan**
- **Develop FY01 CWCs**
- **Develop Detailed schedule and cost plan for unpowered flights & A-2 integrated propulsion testing**
  - Powered flight portion of the project dependent upon funding and Management decisions

Project Status

Next Month's Plan (continued)

- **Continue discussions with Range safety at DFRC on FTS requirements**
- **Continue working partnership agreements with DFRC**
- **Finalize Tip to tail Review SOW and negotiate change with Orbital**
- **Continue to work with TD Management on restructure planning & trades**
- **Complete the integration of flight vehicle A-2**
  - Main propulsion system
  - Avionics system
- **Begin IV&V stress testing of flight software**
- **Continue Engine Testing at SSFL**
  - Engine #3 full duration test (159 sec)
  - Engine #5 calibration test(s)
- **Retest engine installer (proof load test)**
- **Conduct engine #4 installation and fit check in A-2 vehicle at Dulles**

X-34 Captive Carry Flight




X-37
X-37
NASA
BOEING

X-37 Project Objectives

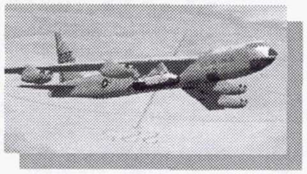
- Mature the technologies for reusable space vehicles by performing flight demonstrations.
    - Lower the cost for routine access to space and operations in space.
    - Make next-generation space transportation system commercially viable.
    - Enhance planning for future reusable launch vehicle space operations.
- Enable investor confidence in reusable space vehicle systems.
- Achieve a technology readiness level of 8 (flight proven) for critical technologies.
- Design and operate with an emphasis on safety.

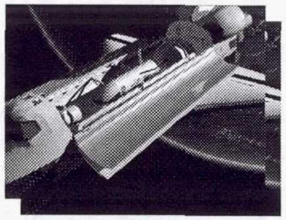
Successfully Achieve Orbit and Return to Earth Safely

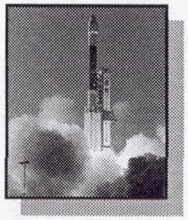
X-37 Project Specifics

- **Project Objective**
  - Demonstrate technologies required to reduce the cost of access to, in, and from space
- **Key Features**
  - Designed to close current X-Vehicle capabilities gap
  - Addresses both Earth-to-Orbit, Orbit-to-Orbit, and Reentry technologies in single testbed vehicle
  - Modularized for rapid insertion of broad range of technologies and experiments
  - Flight test program follows progressive envelope expansion -- potential launch platforms include:
    - B-52, Shuttle, ELV
- **Program**
  - First Flight: Mid 2003 on Shuttle
  - Two orbital flights planned

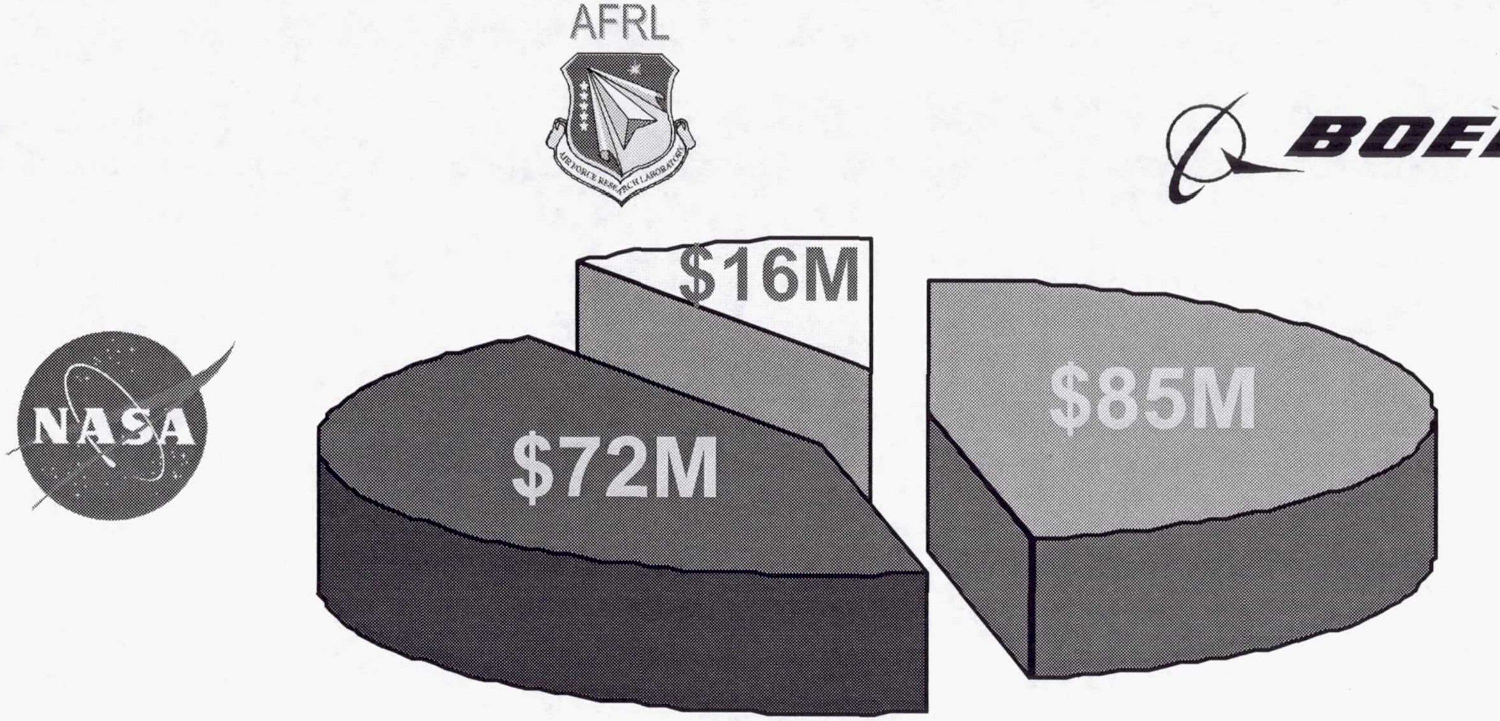
Fuselage Length (ft)	25.7
Wing Span (ft)	14.4
Payload (lb)	500
Entry Weight (lb)	5,800
GLOW (lb)	13,090







X-37 Funding



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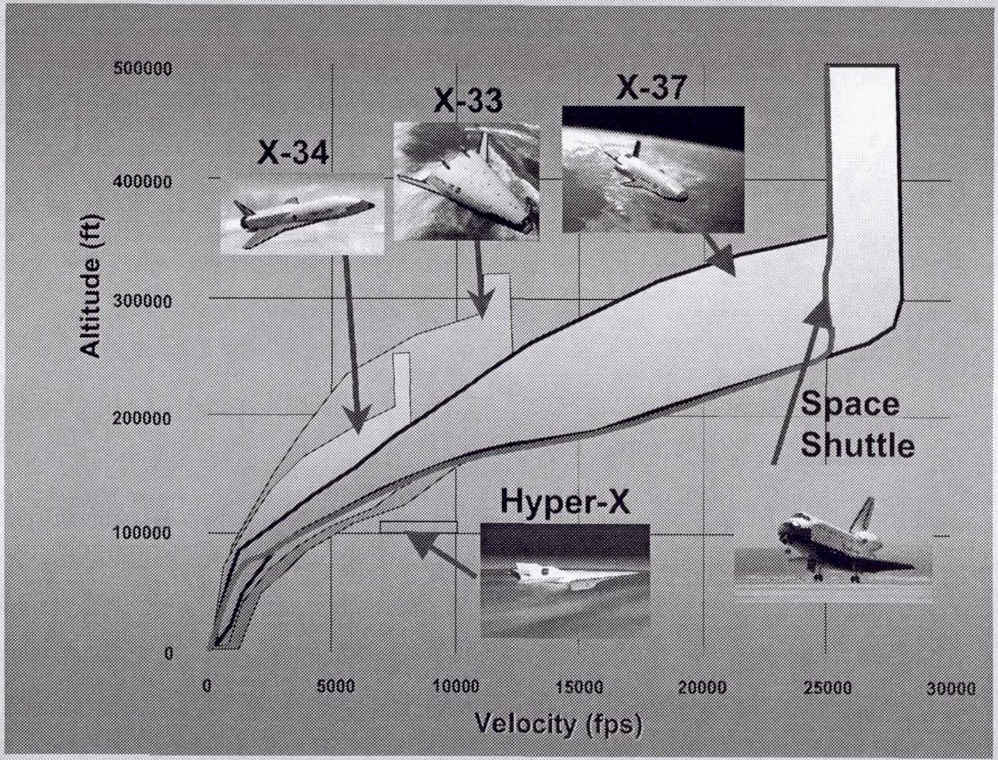
X-37 Tests RLV Flight Envelope



- **X-34** atmospheric flights up to Mach 8.
- **Hyper-X** atmospheric flights up to Mach 10.
- **X-33** atmospheric flights up to Mach 12.
- **X-37** orbital flights up to Mach 25.

Successfully Achieve Orbit and Return to Earth Safely

X-37 Industry - Government Team

Boeing

- Seal Beach Phantom Works
  Design Integra
- Huntington Beach
  System Test
- St. Louis
  Airframe
- Long Beach
  Body Flap & SB
- Rocketdyne
  Engine
- Seattle
  Solar Panels
  IRU
  PAA
- Palmdale HDAIT

NASA

- MSFC
  Program Management & Insight
  H_2O_2 Research
- ARC
  TPS Testing & Exp
  Aero optimization
  IVHM
- LaRC
  Hot & Warm Structure
  Analysis and test
- GSFC
  Avionics Support

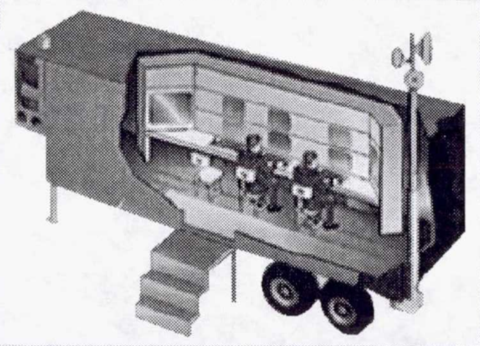
Suppliers

- Swales Aerospace
- General Dynamics Info Sys
- Honeywell
- MPC
- ABSC

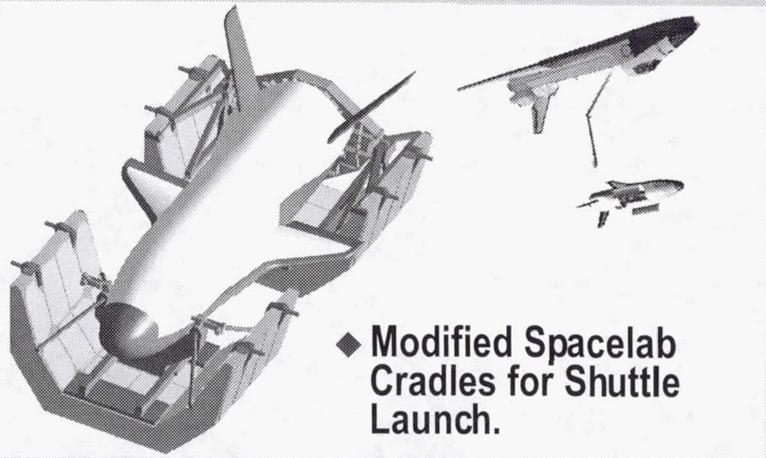
X-37 Program Products

- ◆ Prior USAF Contract: Successful automated approach and landing flight in October 1998.
- ◆ Modified for early atmospheric flights to support X-37 design.

- ◆ Advanced Technology Flight Demonstration Vehicle.
- ◆ Linked to Space Maneuver Vehicle design.



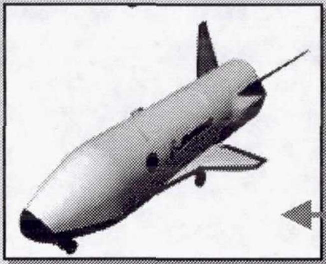
- ◆ Flight Operations Control Center (FOCC).
- ◆ Three person operation for atmospheric and orbital flights.



- ◆ Modified Spacelab Cradles for Shuttle Launch.

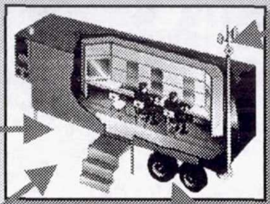
Successfully Achieve Orbit and Return to Earth Safely

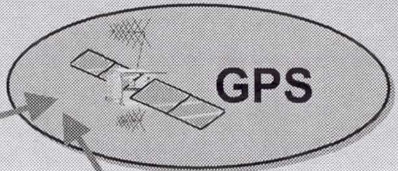
Overview of X-37 Flight Test Program

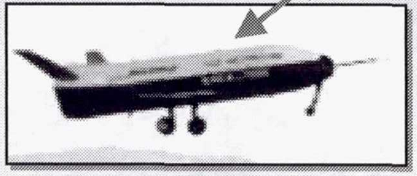


Ground Test/Simulation &
Preflight Checkout

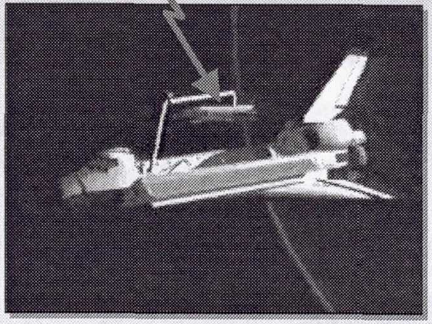
Flight Operations
Control Center (FOCC)





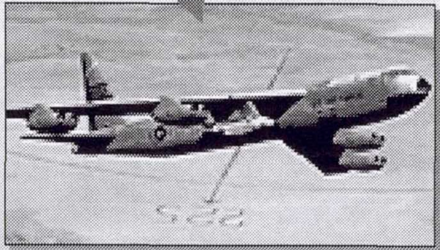


X-40A



X-37/Space Shuttle

Test Category	X-40A	X-37
Tow/Taxi	5	5
Captive Carry	3	3
Approach and Landing	7	5
On-Orbit, Reentry, Landing		2

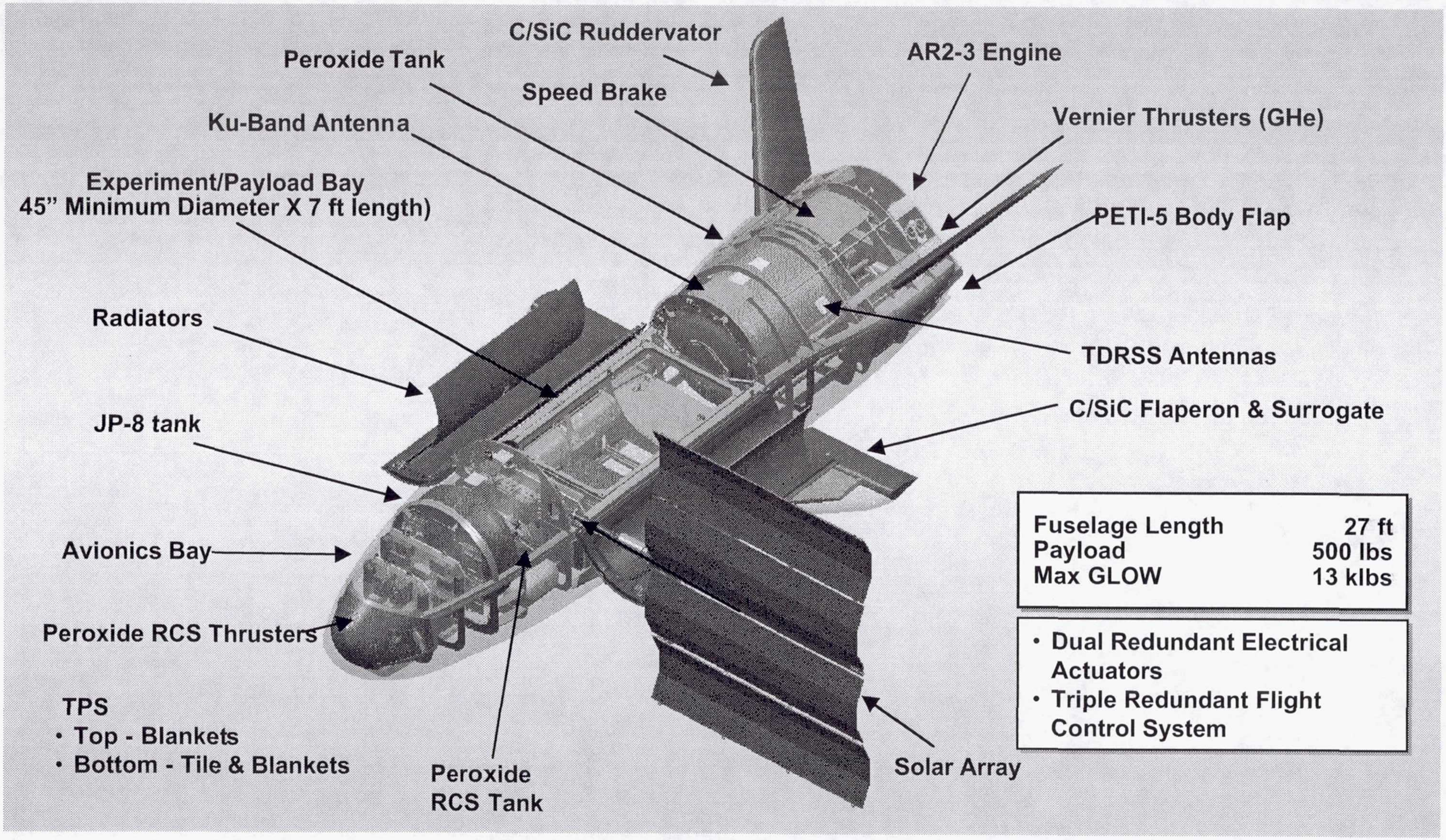


X-37/B-52

Progressive Ground and Flight Testing In Multiple Environments

Successfully Achieve Orbit and Return to Earth Safely

X-37 Vehicle Characteristics

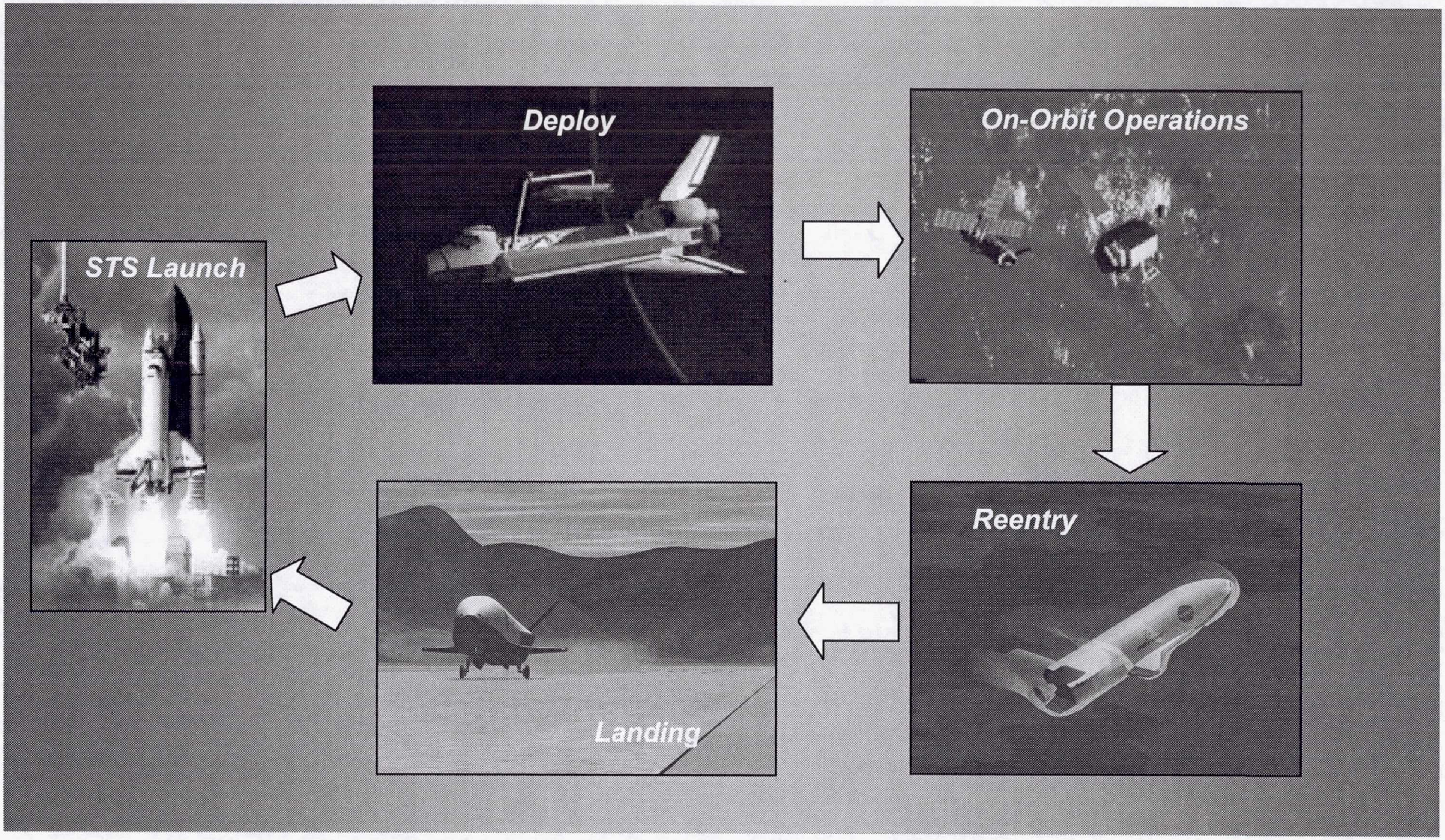


TPS
- Top - Blankets
- Bottom - Tile & Blankets

Fuselage Length	27 ft
Payload	500 lbs
Max GLOW	13 klbs

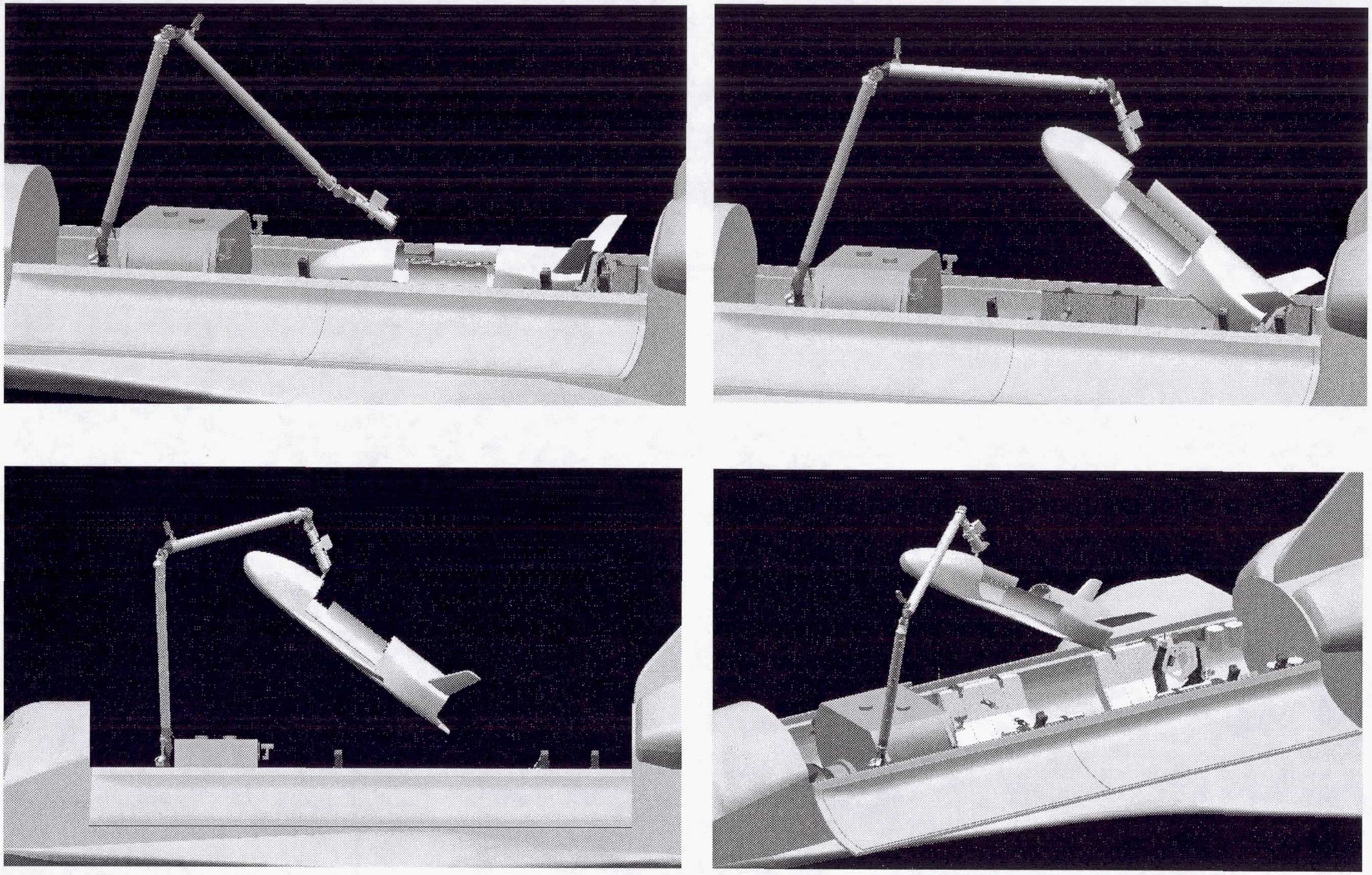
- Dual Redundant Electrical Actuators
- Triple Redundant Flight Control System

Successfully Achieve Orbit and Return to Earth Safely



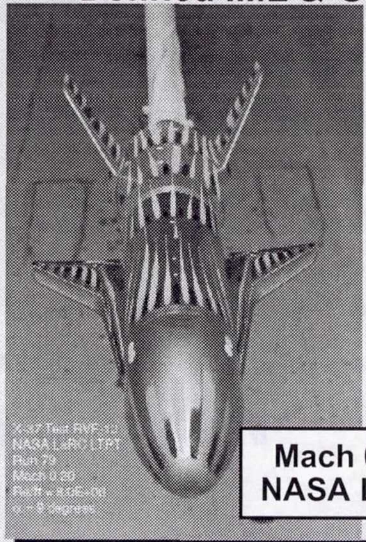
Successfully Achieve Orbit and Return to Earth Safely

X-37 Vehicle Deployment Process

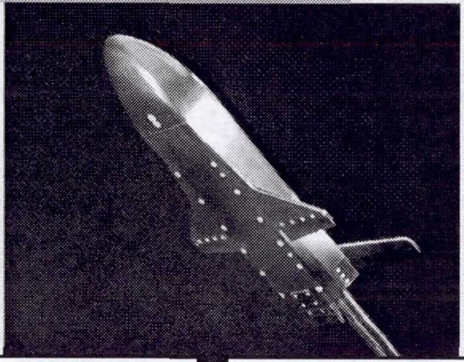


Vehicle Design and Tooling are On Track

Wind Tunnel Testing Has Defined IML & OML



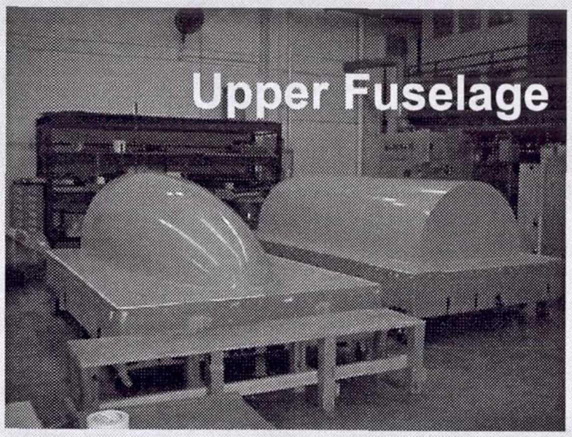
Mach 0.20
NASA LTPT

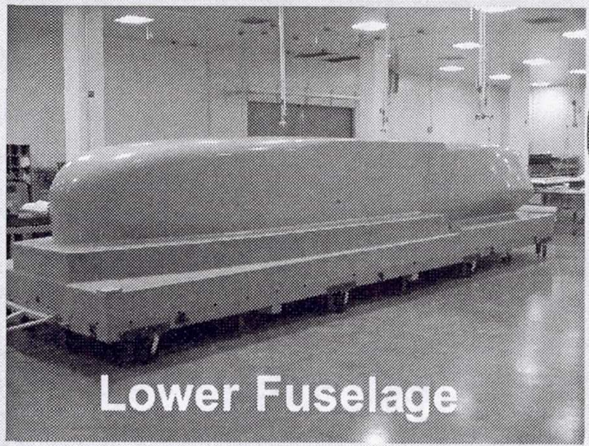


Mach 0.9 - 5.5
Boeing PSWT

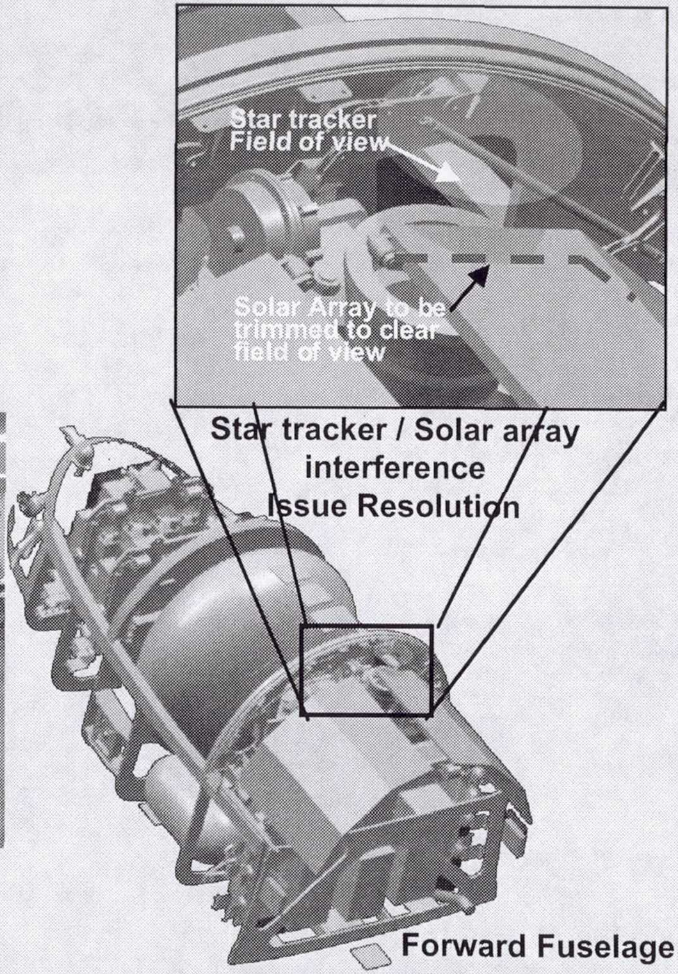
Mach 13
AEDC Tunnel 9

Fuselage Master Tools Complete





Interior Arrangement is Defined



Star tracker / Solar array interference Issue Resolution

Forward Fuselage

Use/disclosure of data contained on this sheet is subject to **Category B** restriction contained in NASA/Boeing Cooperative Agreement NCC8-190, Appendix C to Part 1274, Exhibit B. Date is fully releasable without restriction three (3) years from the date of this document.

Like Prior X-Vehicles, X-37 Will 1st Develop, Fly, Measure and Discover In Many Important Aerospace Areas

◆ 1st autonomous orbital X-plane

◆ 1st development of a re-deployable solar array for a reusable vehicle

◆ 1st use of phase change brakes

◆ 1st extensive re-use of Li-Ion Batteries in aerospace

◆ 1st flight of five TPS types at high enthalpy

◆ Discoveries in high hypersonic flight environment at lower than Space Shuttle Reynolds numbers

Forty Technologies and Experiments are Being Demonstrated on the X-37

Avionics/Software
T-12 Open Architecture Avionics
T-14 Fiber-Optic Data Bus
T-15 Ku-Band Phased Array Antenna
T-16 COTS Hardware and Software*
T-19 Fault Tolerant Autonomous Ops
T-28 Small Crew FOCC*
AFT-1 Solar Arrays
E-1 High-Temp Electronics
E-2 High-Energy Density Batteries
E-3 NASA IVHM Integrated System

GN&C
T-13 Calculated Air Data System (CADS)*
T-17 All Weather Windward Adaptive Guidance
T-26 Rapid Mission Data Loading*
T-29 Crosswind Landing for Small RSVs*

Ground/Flight Operations
T-18 Rapid-Global TPS Damage Detection
T-21 Rapid TPS Waterproofing

Flight Sciences
T-22 High Enthalpy Flight Profile

- ◆Thirty embedded technologies
  - ◆ Seventeen advanced vehicle technologies
  - ◆ Thirteen advanced operations technologies
- ◆Eight NASA flight experiments
- ◆Two Air Force flight experiments

Vehicle
T-23 Standard Payload Interfaces
T-24 Access Doors for Operability

Mechanical Systems
T-10 Lightweight Landing Gear
T-31 Phase Change Brakes

Propulsion
T-2 Peroxide RCS Thrusters
T-27 Low Cost Propulsion System
AFT-2 Enhanced Attitude Control

Structures
T-6 High-Temp Gr/BMI Sandwich Structure
T-8 Thin, Hot Aerosurfaces for SRSV
T-11 Modular Airframe - Rapid Change-Out
T-20 Lt. Wt. Std Payload Container
T-23 Standard Payload Interfaces
T-32 High-Temp Gr/PETI-5 Structures
T-XX Composite Propellant Tanks

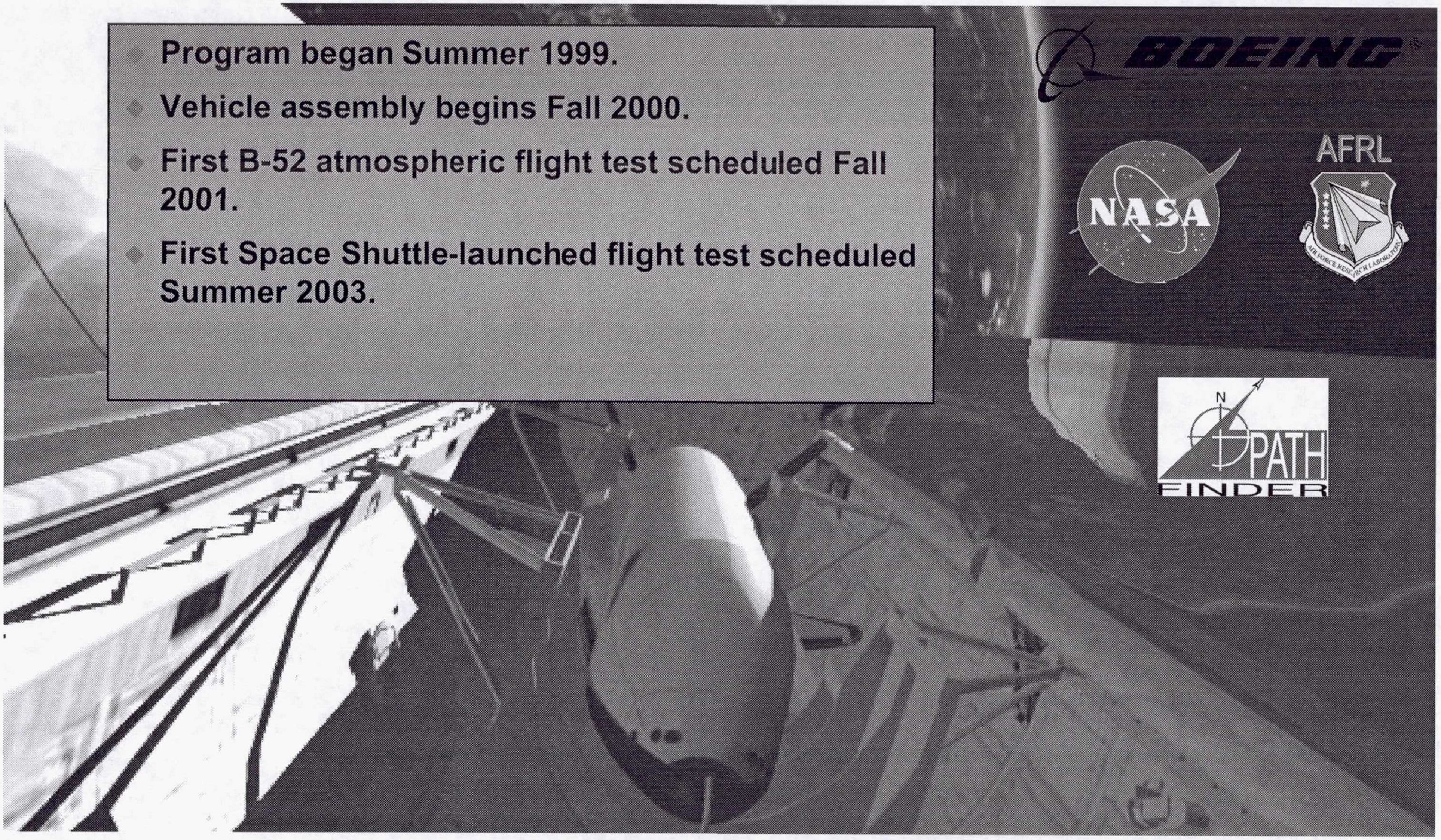
Thermal Systems
T-3 High-Temp Windward TPS
T-4 High-Temp Upper/Side TPS
T-5 Durable Leading Edge Tiles
T-7 High-Temp, Low Cost Joints/Seals
T-9 Loop Heat Pipe TCS
E-4 Failsafe Screening Surface TPS Test Panels
E-5 Durable, Low Conductivity/Density Tile
E-6 Weatherized Metal Covered Blankets
E-7 Highly Operable Metallic TPS

Successfully Achieve Orbit and Return to Earth Safely

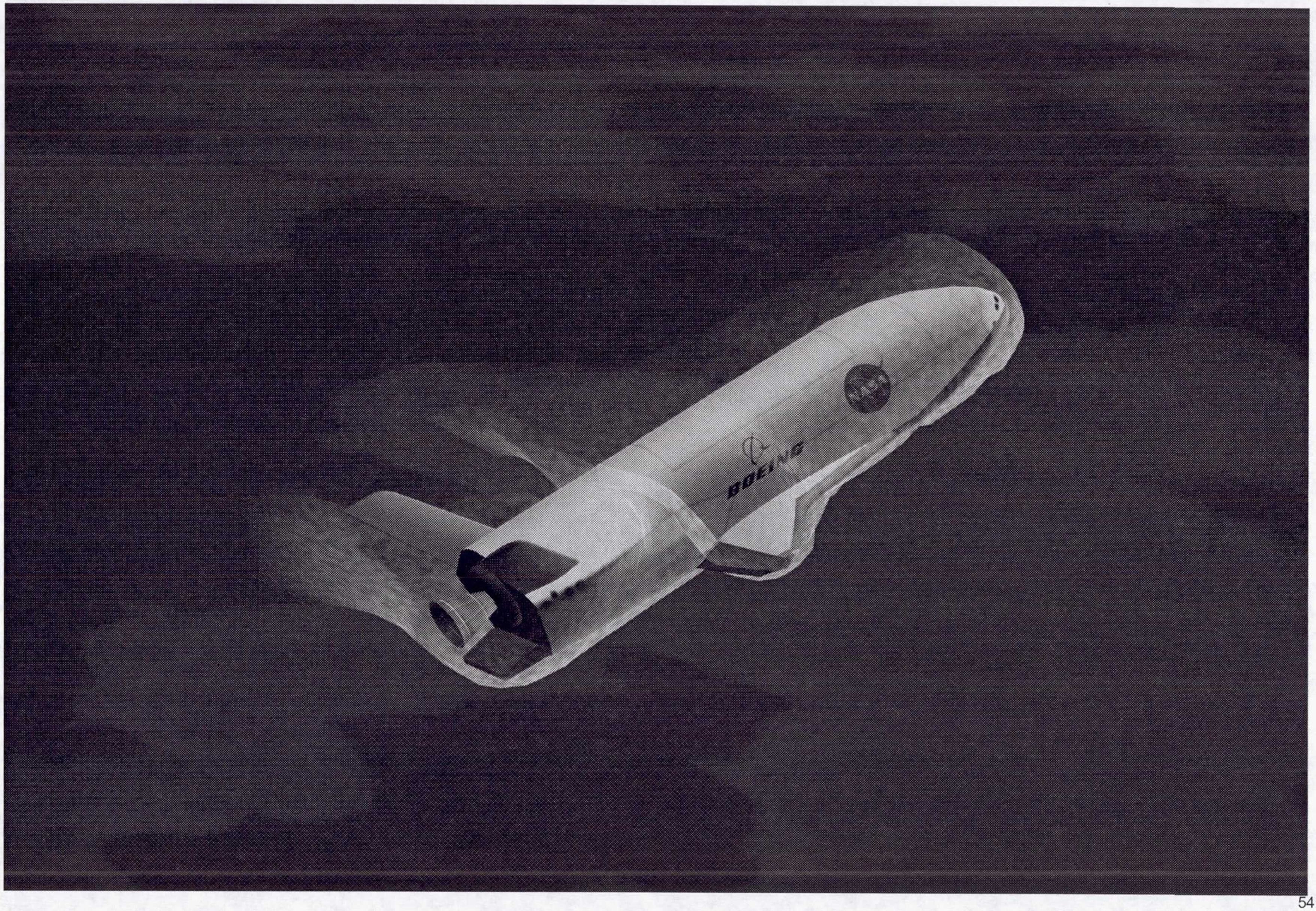
X-40A Flight Test Vehicle Summer 00

Boeing X-37

- Program began Summer 1999.
- Vehicle assembly begins Fall 2000.
- First B-52 atmospheric flight test scheduled Fall 2001.
- First Space Shuttle-launched flight test scheduled Summer 2003.

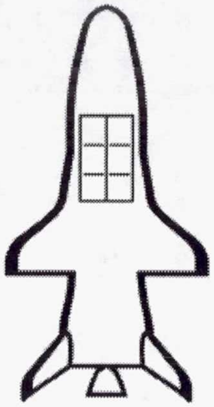


Blazing the Highway To and From Space

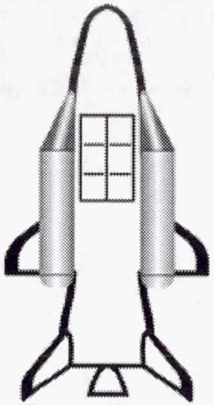


X-37 Configuration Modification Options

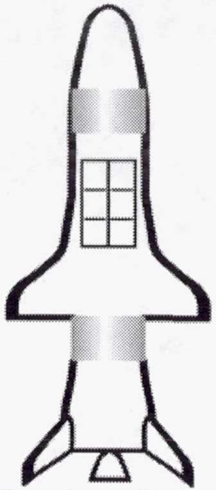
Baseline



Increased Propellant

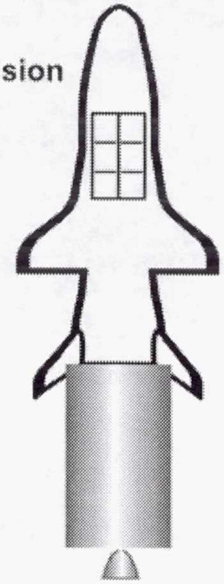


Drop Tanks

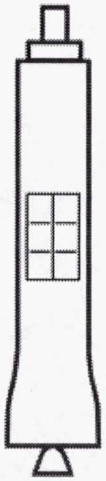


Fuselage Plugs

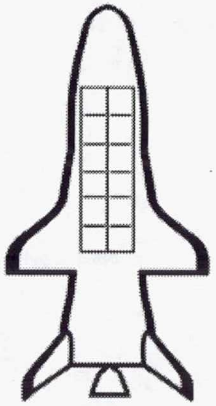
Auxiliary Propulsion



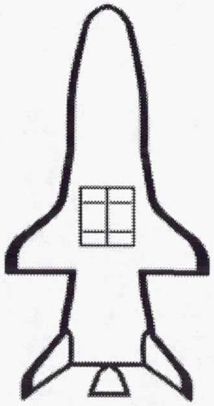
On-Orbit Only



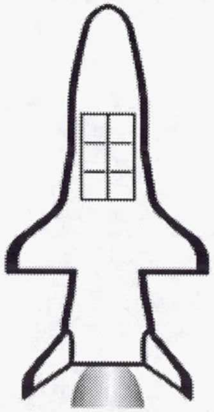
Large Payload Bay



Small Payload Bay



Main Engine Upgrades



Expansion-Deflection Nozzle

5469.43

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12P

Structures IVHM for 3rd Generation RLVs

Robert S. Rogowski

NASA Langley Research Center

Structures IVHM for 3rd Generation RLV's

POC: Dr. William Prosser, NASA Langley Research Center, 757-864-4960, w.h.prosser@larc.nasa.gov

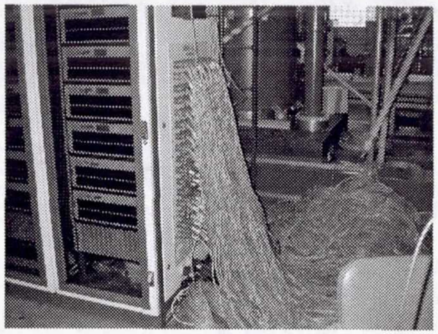
Objective

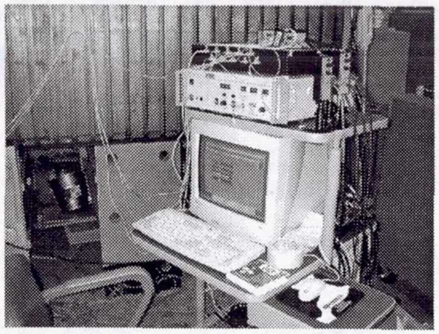
The primary goal of a Structures IVHM system for 3rd generation RLV's is to provide near 100% structural sensing coverage and thus eliminate both routine, and especially unplanned, inspections which are costly and time consuming . To meet this goal, significant advances in sensing and measurement system technology, data systems architectures, and structures based analysis methodology will be required to enable the needed large numbers of sensors with little weight penalty. This program will leverage X-33, 2nd Gen RLV, Shuttle, and Aviation Safety SIVHM system development experience to address this goal.

FY01 Activities

- Sensor Development - Investigate fiber-optic (F/O) geometry variations for improved sensors (FY00 follow-on), continue development of structures based model for acoustic emission damage detection (FY 00 follow-on)
- Structural Modeling - Start development of material and structural property databases to guide placement of sensors
- Data Systems Architecture - Investigate enabling micro-instrumentation technologies including COTS micro-sensor and micro computer technologies (FY 00 follow-on)
- Ground/Flight Testing - Evaluate ruggedized COTS tunable laser sources for F/O sensors (FY 00 follow-on) and initiate development of a SIVHM dedicated ground test bed.

High Density Fiber-Optic Strain Sensing


Wiring for 400 foil gages

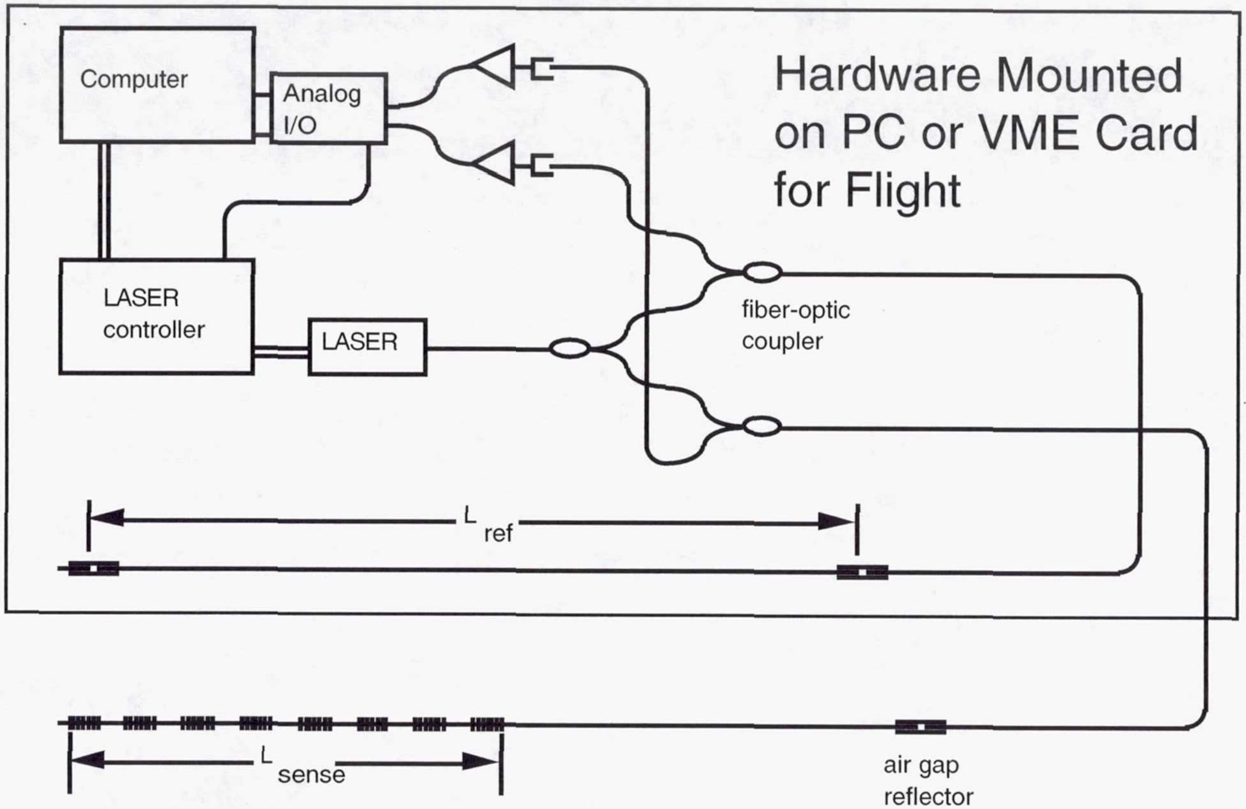

Optical Fibers for ~3000 gages


Strain Sensing on Full Scale Composite Wing

SIVHM Impact on 3rd Generation RLV Goals

- Safety
  - Structural failure detection and prediction for improved inherent system safety
  - Early warning for improved abort capability
  - Reduction of critical failures for improved crew survivability
- Cost
  - Increased system development and production costs
  - Offset by decreased operation and maintenance costs
    - ARINC Study - D&P costs could be offset in as little as 2 years for aircraft [4]
    - 50% reduction in inspection time for aircraft [1]
    - "Maintenance for cause" rather than scheduled component replacement
- System Responsiveness and Dependability
  - Improved vehicle processing time for increased system flexibility, capacity, and operability
    - 50% reduction in inspection time for aircraft [1]
  - Improved system reliability and maintainability

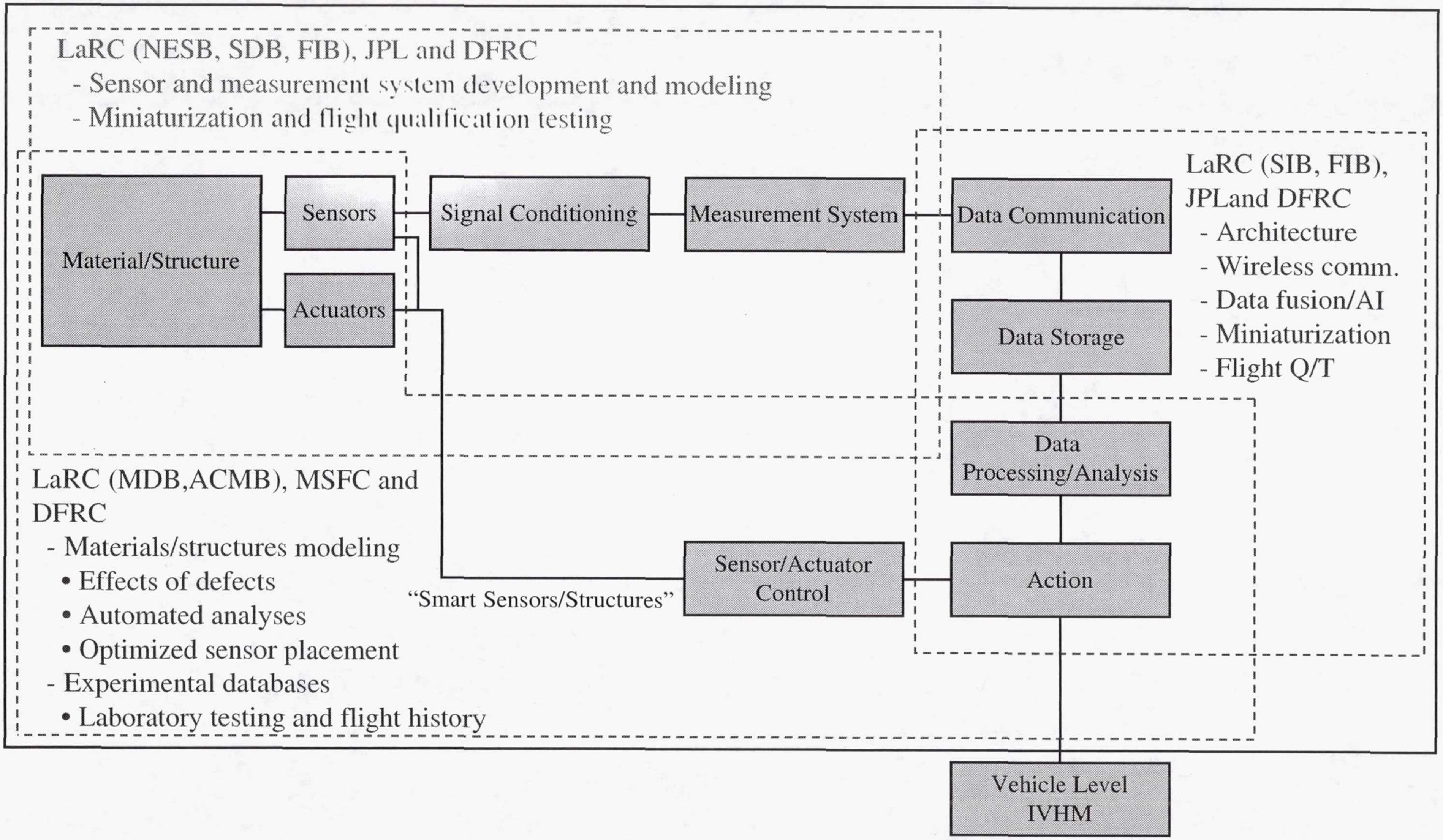
Bragg Grating Demodulation System



20’ strain sensing length

SIVHM Components, Technologies, and NASA Participants

POC: Dr. William Prosser, NASA Langley Research Center, 757-864-4960, w.h.prosser@larc.nasa.gov



LaRC (NESB, SDB, FIB), JPL and DFRC
- Sensor and measurement system development and modeling
- Miniaturization and flight qualification testing

LaRC (SIB, FIB), JPLand DFRC
- Architecture
- Wireless comm.
- Data fusion/AI
- Miniaturization
- Flight Q/T

LaRC (MDB,ACMB), MSFC and DFRC
- Materials/structures modeling
  - Effects of defects
  - Automated analyses
  - Optimized sensor placement
- Experimental databases
  - Laboratory testing and flight history

Proposed SIVHM Technologies

- Sensor and measurement systems
- Materials and structures based models for SIVHM optimization and automated data analysis
- Architectures, micro-instrumentation, and data fusion
- SIVHM ground test beds
- SIVHM flight qualification and aero-flight testing

SIVHM Sensor Systems

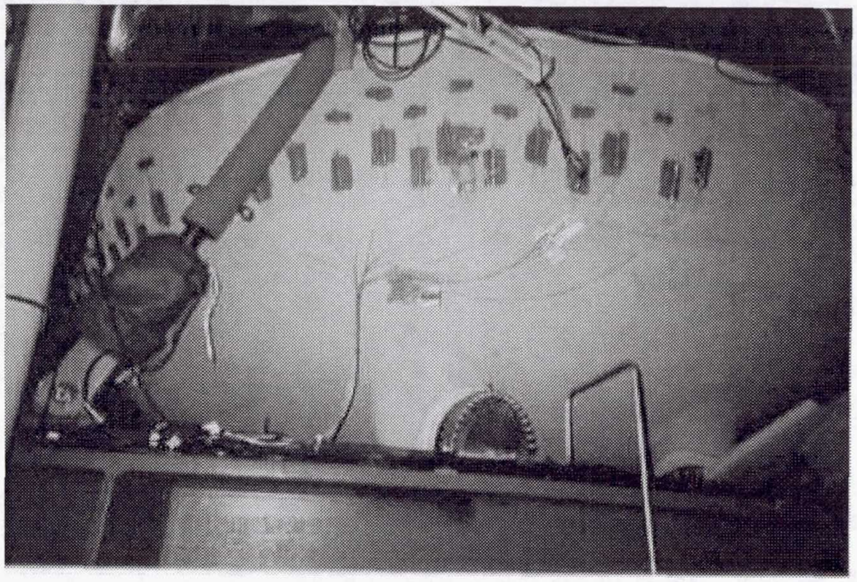
POC: Dr. William Prosser, NASA Langley Research Center, 757-864-4960, w.h.prosser@larc.nasa.gov

Goals

- Development of advanced, high density, light weight sensor technologies to enable 100% structural sensing coverage
- Development of miniaturized, rugged, flight capable measurement systems
- Development of physics based sensor response models for enhanced sensor performance, optimization of sensor placement, and improved, automated data analysis methodologies

Products

- Investigate fiber-optic (F/O) sensor measurement alternatives such as in-fiber spectroscopic methods to provide multi-variable chemical sensing capabilities.
- Investigate specialty optical materials (e.g., saphire) along with fiber geometry variations to achieve improved F/O sensor performance capable of extreme environments while providing multi-variable (e.g. strain, temperature, vibration, etc.) measurements.
- Investigate capabilities of wireless micro-transmitters in conjunction with piezoelectric and MEM's sensors to provide impact and vibration sensing.
- Develop physics based sensing models to integrate with structural models for SIVHM system optimization and automation of analyses. Initial effort to model acoustic emission damage and impact sensors.



X-33 LH2 Tank IVHM Sensor Instrumentation

Materials and Structures Knowledge Based Models for SIVHM

POC: Carlos Davila, Tom Gates, Mechanics and Durability Branch, NASA LaRC, 757-864-9130, c.g.davila@larc.nasa.gov

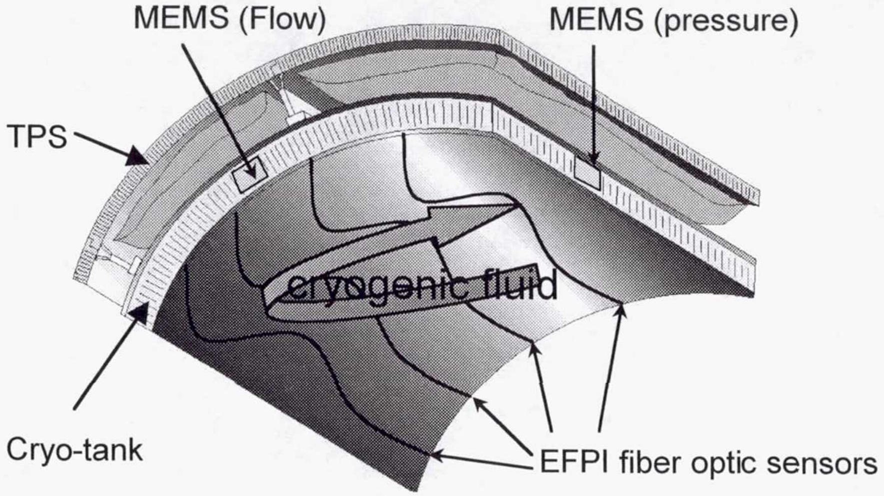
Goals

Development of tools for analysis of SIVHM sensor data to assess structural health of advanced aerospace vehicles using:

- mechanics based analysis methods
- sensor-structure integrity
- data analysis methods
- property databases
- material behavior
- structural response
- knowledge base and knowledge management

Products

- Provide descriptions of critical failure locations to guide acquisition of data and placement of sensors.
- Integration of sensor data and materials/structure response to establish relationships between sensor resolution and damage size, location, mode.
- Establish sensor-structure integration schemes to account for synergistic effects.
- Data analysis methods that utilize the knowledge base to assess residual life, strength, stiffness.
- Updated prediction of remaining life taking into account rate of change of properties and loads.



Structural/material integrity integrated with IVHM

SIVHM Data Fusion and Architectures

POC: Eric Cooper, NASA Langley Research Center, 757-864-6674, e.g.cooper@larc.nasa.gov

Goals

Develop miniaturization technologies along with data fusion and architectures that enable densely distributed sensor suites for managing the health of aerospace vehicle structures. Technology considerations will focus on reducing the weight, power, and volume requirements for sensor data acquisition, storage and processing. The effectiveness of micro-instrumentation sensor suites comprised of advanced sensing technologies such as fiber optic, MEMS, and acoustic emission, as well as computing miniaturization technologies such as multi-chip modules, chips-on-board, die-on-flex, and three-dimensional silicon die stacking, will be investigated.

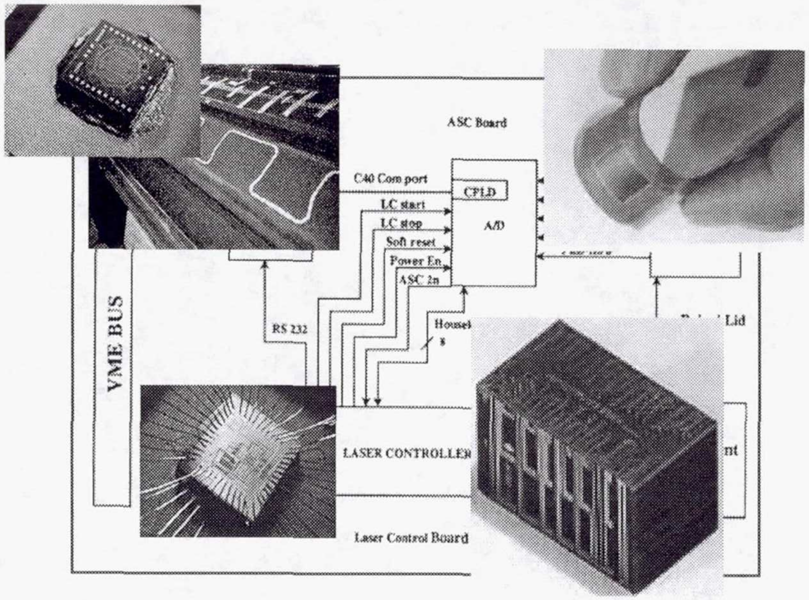
Products

- Suitability assessment of current and emerging miniaturized sensing and computing technologies for use in aerospace structures health management

- Acceleration of lab-emergent miniaturization technologies

- Distributed "smart sensor" concept that forwards pertinent structural health information to higher-level IVHM reasoning processes

- Demonstrated distributed remote sensing modules and communications architecture



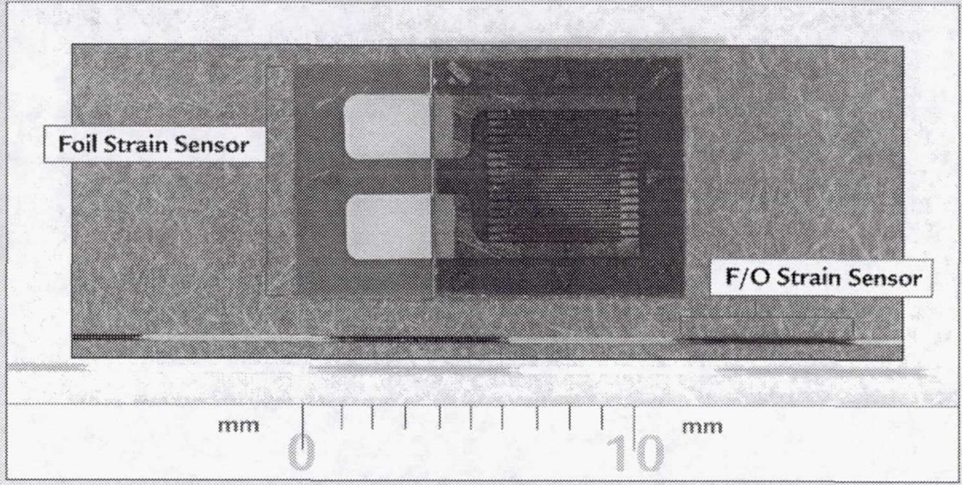
Synergies and Dependencies

- Success dependent on sizable 2nd Gen. SIVHM effort
  - Address more near term technologies
    - Miniaturize and flight harden high speed, tunable fiber laser
    - Multiplexing architectures for high bandwidth sensors
    - Etc.
- Must coordinate with TPS, propulsion, etc. IVHM elements
- Leverage previous and ongoing SIVHM programs
  - X-33, X-34, X-37, Shuttle
  - Bantam
  - Aviation Safety
  - Etc.
- Need to identify and fund future space flight opportunities
  - X-33B, Shuttle, Pathfinder, etc.
  - Not funded within current limited scope of Spaceliner

Other Potential High Payoff Long Term SIVHM Technologies

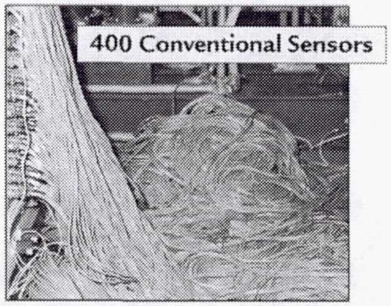
- Self-healing materials and structures
- Smart (adaptive) materials and structures
- Large area, remote NDE for SIVHM follow-up inspections
- Autonomous NDE/IVHM micro-robots for monitoring/inspections
- Nanomaterials and sensors
- Etc.

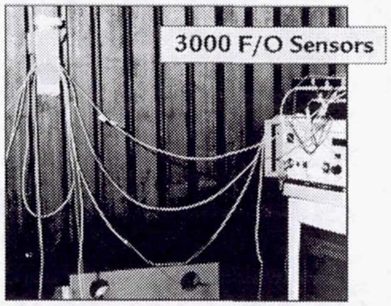
Distributed Fiber-Optic (F/O) Sensing for Structures IVHM



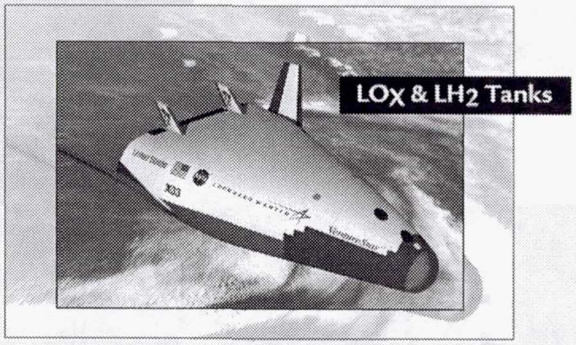
High Density Structural Sensors

- 10,000 Sensors < 1 pound
- Strain, Temperature, & Hydrogen (Propellant Leaks)
- Future Research - Vibration, Shape, Acoustic Emission, Chemistry (Corrosion)
- < $10/Sensor


400 Conventional Sensors


3000 F/O Sensors


STS-96 Hydrogen Leak Monitoring


LOx & LH2 Tanks


Composite Wing Structural Test Article

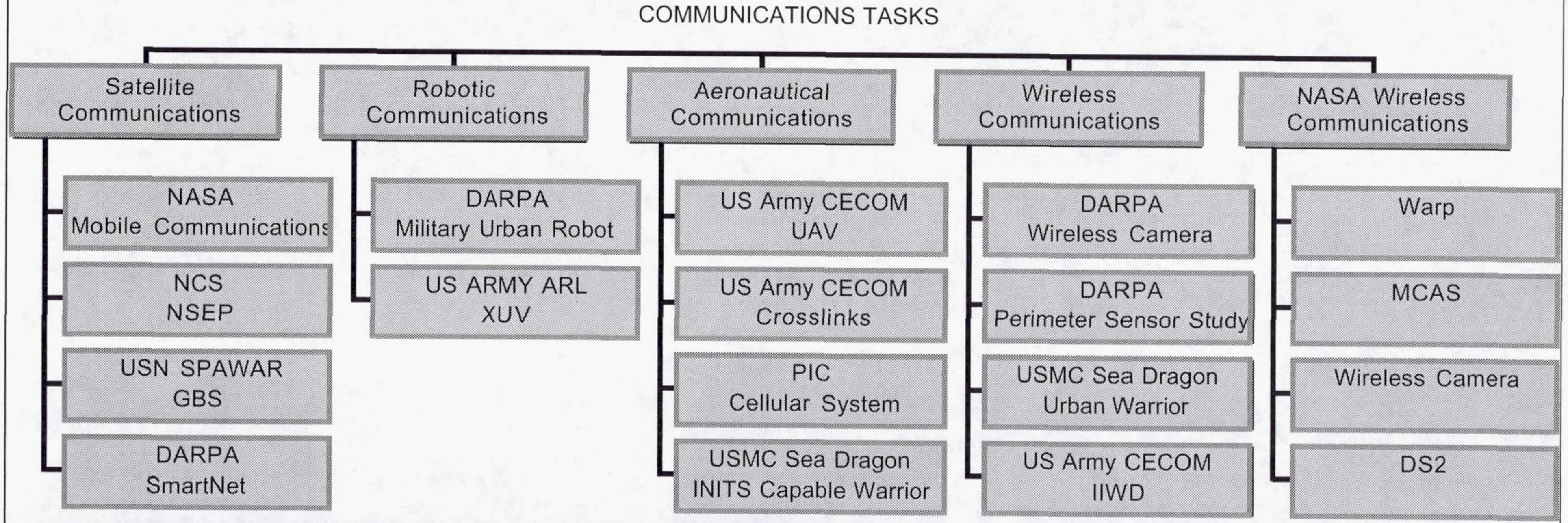
Ed Baroth, Ph.D.
Task Manager, Advanced Sensors
Jet Propulsion Laboratory
(818) 354-8339
ebaroth@jpl.nasa.gov

- **Wireless Sensors**
- **System on a Chip**
- **Advanced Analysis**

Integrated Vehicle Health Management

IVHM Technologies at JPL

- Tasks Cover Large Spectrum (UHF,L,S,K,Ka-BANDS)
- Technology Development
    - Modulation, Coding and Equalization
    - Transceivers, Antennas
    - Systems, Experiments and Deployments



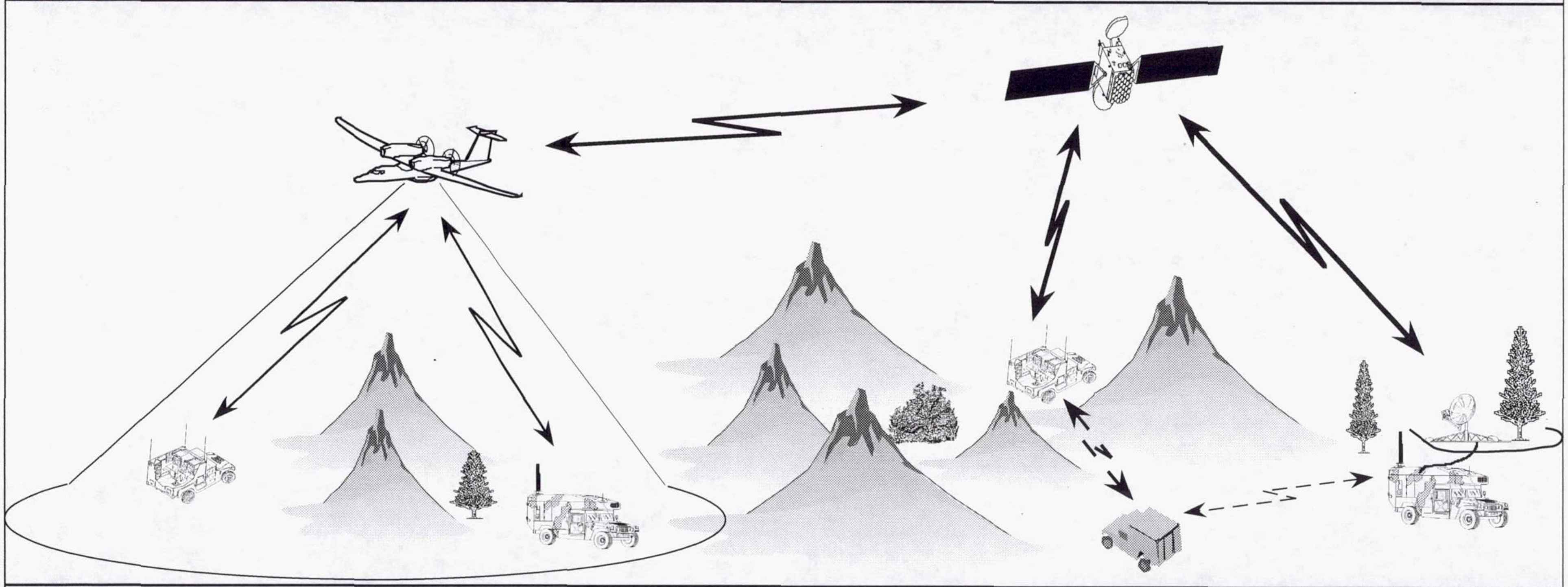
COMMUNICATIONS TASKS

- Satellite Communications
    - NASA Mobile Communications
    - NCS NSEP
    - USN SPAWAR GBS
    - DARPA SmartNet
- Robotic Communications
    - DARPA Military Urban Robot
    - US ARMY ARL XUV
- Aeronautical Communications
    - US Army CECOM UAV
    - US Army CECOM Crosslinks
    - PIC Cellular System
    - USMC Sea Dragon INITS Capable Warrior
- Wireless Communications
    - DARPA Wireless Camera
    - DARPA Perimeter Sensor Study
    - USMC Sea Dragon Urban Warrior
    - US Army CECOM IIWD
- NASA Wireless Communications
    - Warp
    - MCAS
    - Wireless Camera
    - DS2

Integrated Vehicle Health Management

WIRELESS OVERVIEW

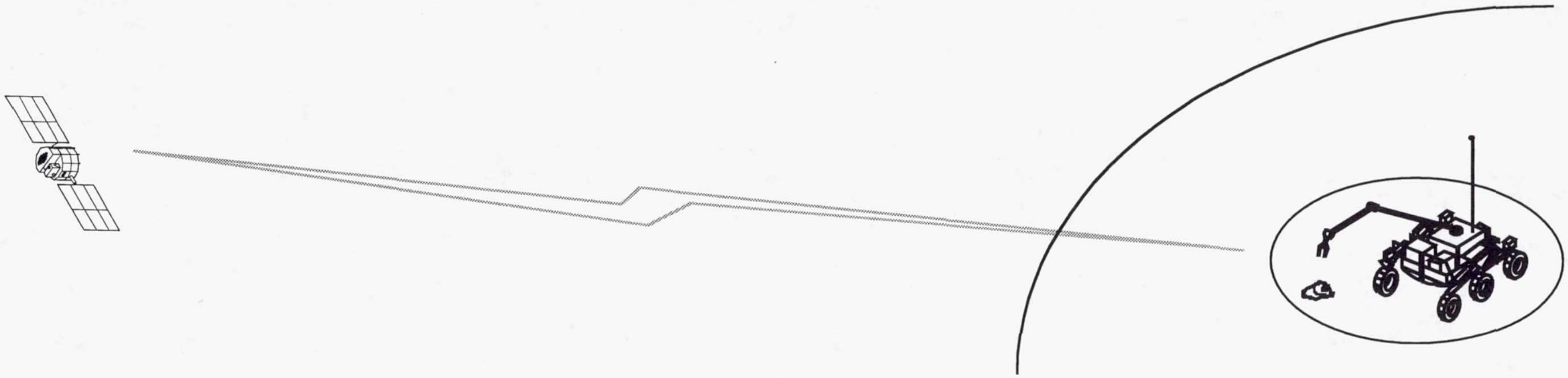
- Hybrid System - Multiband Terrestrial and Satellite Communications
- Adaptive Network Architecture, Multi-Vehicle Control

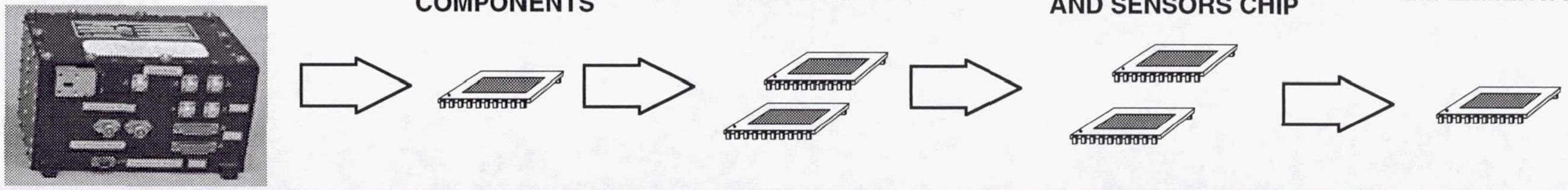


Integrated Vehicle Health Management

XUV ARL ROBOTICS FUTURE COMM ARCH.

- Objective
  - Develop Chip-Level Telecom Systems for NASA's Small Platform Missions
- Results
  - Lower Power, Reduced Mass
  - High Levels of Integration, Multi-Mission
- Currently in Phase I





CURRENT TRANSCEIVER

TELECOM CHIP W/OFF-CHIP ANALOG COMPONENTS

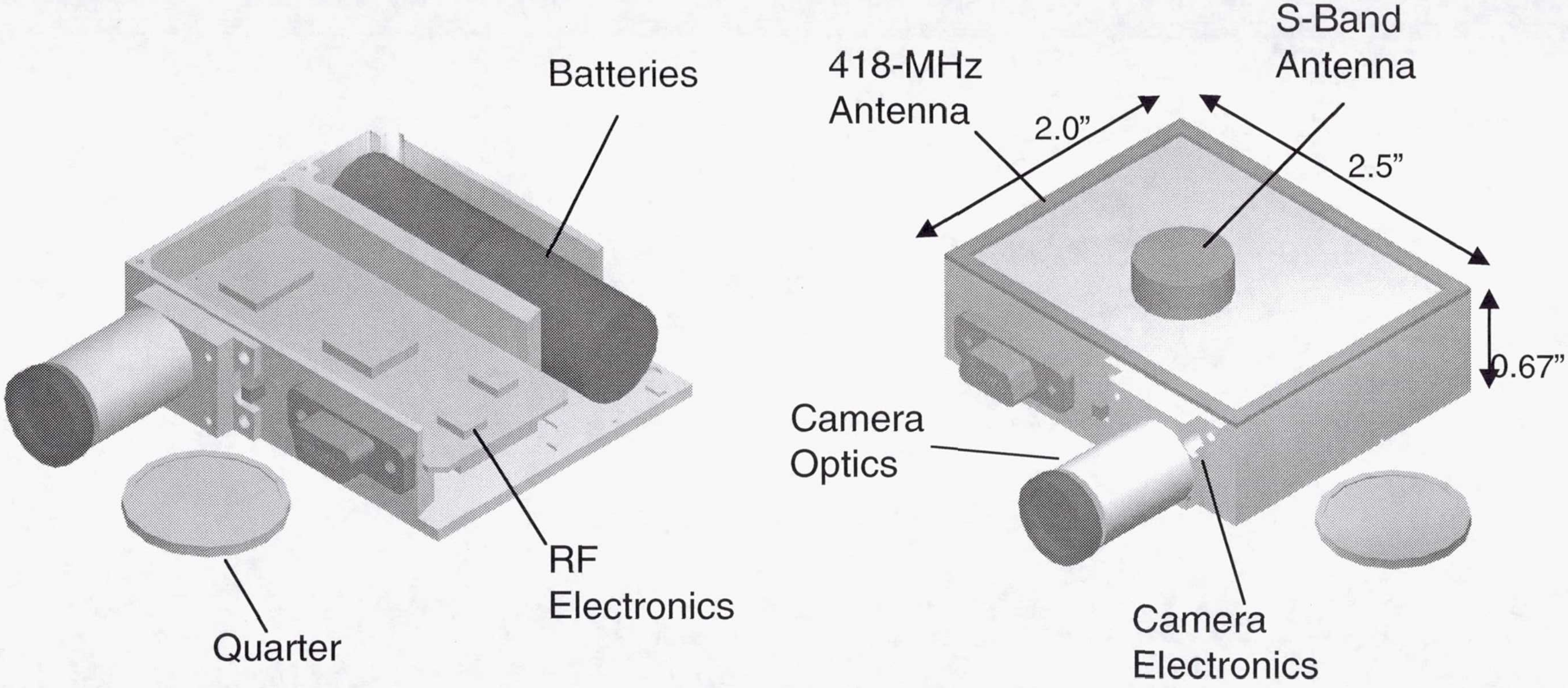
TELECOM CHIP AND MEMS OSC CHIP

TELECOM CHIP AND MEMS OSC, RF COMPONENTS AND SENSORS CHIP

SINGLE CHIP IMPLEMENTATION

MICRO COMM & AVIONICS SYSTEMS (MCAS)

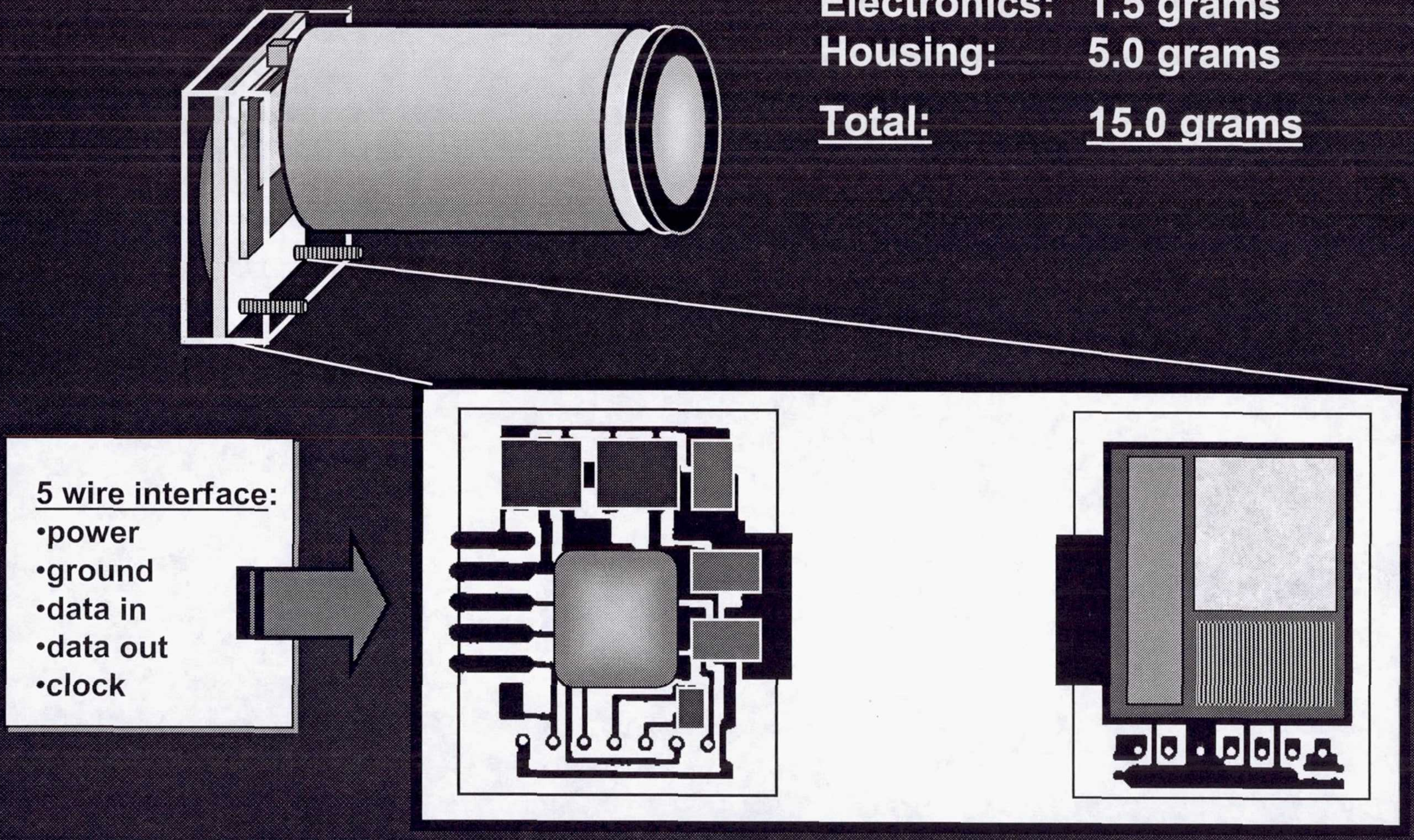
- Wireless Camera in ~1" Cube, APS Camera Chip
- 2.4 GHz (2.5 MBPS) Transmitter
- 418 MHz (1.2 KBPS) Control Link



Integrated Vehicle Health Management

NASA/DARPA WIRELESS CAMERA

Lens:	8.5 grams
Electronics:	1.5 grams
Housing:	5.0 grams
<u>Total:</u>	<u>15.0 grams</u>

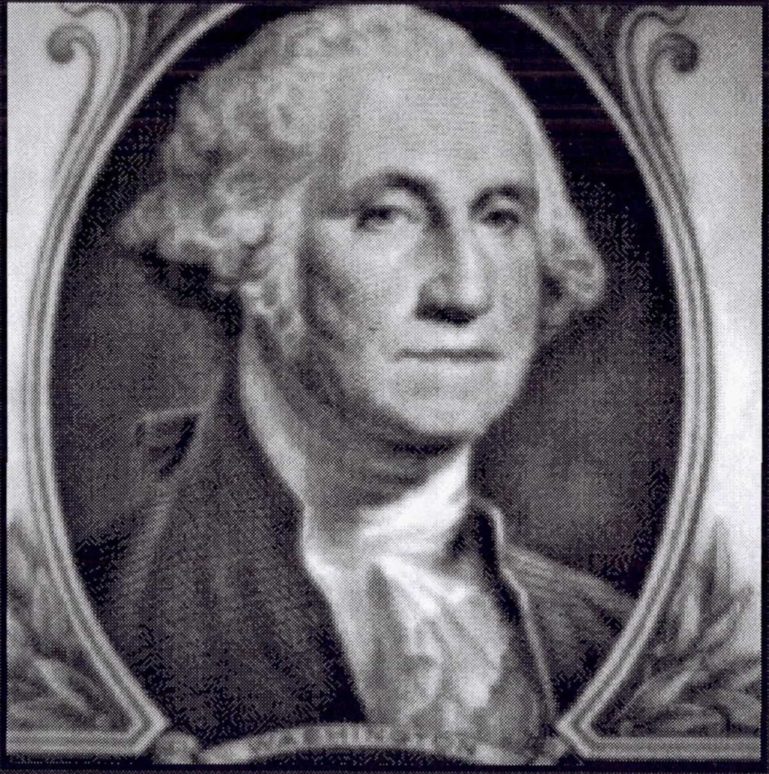


<u>5 wire interface</u>:
- power
- ground
- data in
- data out
- clock

Integrated Vehicle Health Management

WIRELESS CAMERA ASSEMBLY

- On-chip Timing and Control
- On-Chip 10-bit column parallel ADCs
- 13 10-bit programmable registers
- 256 x 256; 20.4 mm pixel pitch imager
- Initially 256^2; designed for 1024^2
- 1.2 mm, 5 V. HP n-well CMOS Process
- 9.3mm x 11.2mm Chip
- Requires 5 wires for operation
- Programmable: resolution, windowing, exposure, etc.
- Low power: 20 mW; 40 uW (standby)



8 BIT, 256 x 256, APS IMAGE

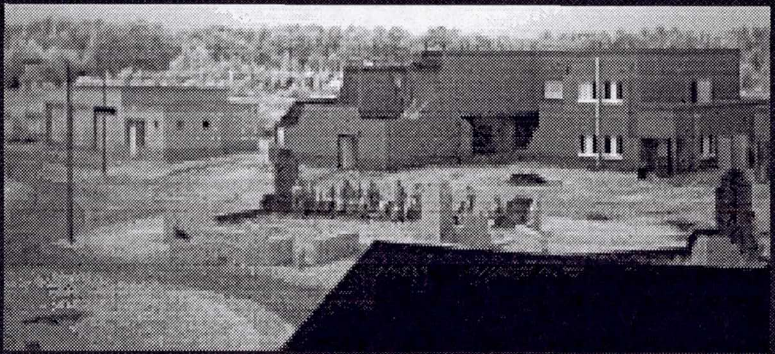
Integrated Vehicle Health Management

WIRELESS CAMER APS FEATURES

ORIGINAL IMAGE 1

ORIGINAL IMAGE 2

SHARPENED IMAGE 1



SHARPENED IMAGE 2

Integrated Vehicle Health Management

IMAGE EXAMPLES FROM CAMP LEJEUNE

WIRELESS CAMERA BATTERY

- Uses Commercially Available Lithium CR-2 Camera
- Batteries (2) Provide 3V Each with Capacity of 800mA-H

BATTERY LIFETIME ESTIMATES

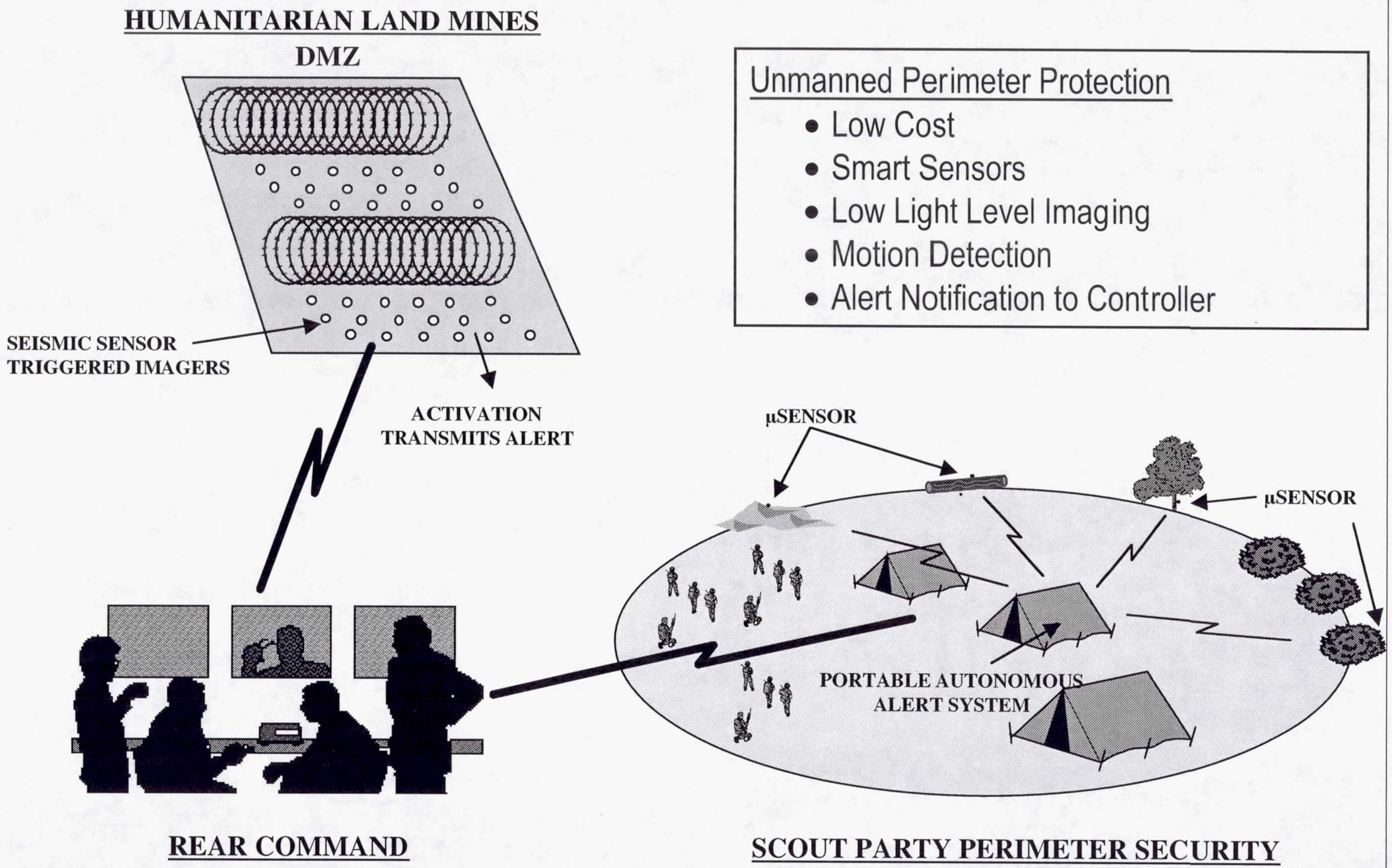
SLEEP TIME (s)	RECEIVE TIME (s)	TRANSMIT TIME (s)	PICTURES RETURNED	BATTERY LIFE (DAYS)
64	2	0.937	16009	12.4
64	2	0.937	10661	82.6
64	2	0.937	2456	190.3
512	2	0.937	12649	75.4
512	2	0.560	18076	107.7
0	0.25	0.937	16927	0.233
0	0.25	3	5296	0.199

Integrated Vehicle Health Management

DARPA PERIMETER PROTECTION

Unmanned Perimeter Protection

- Low Cost
- Smart Sensors
- Low Light Level Imaging
- Motion Detection
- Alert Notification to Controller



HUMANITARIAN LAND MINES

DMZ

SEISMIC SENSOR TRIGGERED IMAGERS

ACTIVATION TRANSMITS ALERT

μSENSOR

μSENSOR

PORTABLE AUTONOMOUS ALERT SYSTEM

REAR COMMAND

SCOUT PARTY PERIMETER SECURITY

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Integrated Vehicle Health Management (IVHM) Activities at Kennedy Space Center

Jack Fox

October 11, 2000

Integrated Vehicle Health Management

IVHM

- Technology Goals & Objectives
- Background
- Current Status
- Major Accomplishments
- Near Term Plans
- Contact Info

Integrated Vehicle Health Management

Discussion Topics

Integrated Vehicle Health Management

Technology Goals & Objectives

- **Overall Program Goals**
  - Substantially reduce the technical, programmatic and business risk associated with development of a safe, reliable and affordable 2nd Generation Reusable Launch Vehicle (RLV)

- **IVHM Goals**
  - Develop and integrate the technologies which can provide a continuous, intelligent, and adaptive health state of a vehicle and use this information to improve safety and reduce costs of operations

Now	Near Term	Future
Maintain	Monitor	Management
Human Control	Distributed Control	Autonomous Vehicle
Reporting	Processing	Reacting
Analyze	Diagnosis	Prognosis
Sensors	Intelligent Sensing	Integrated Sensor Suites
Component	Subsystems/Vehicles	System

- **KSC IVHM Goals**
  - **Reduce ground and flight operations costs for vehicles and payloads**
    - Automated in-situ vehicle checkout
    - Ground maintenance on exception-only basis
    - On-board failure isolation = reduced ground troubleshooting efforts
    - Automated servicing and checkout
    - Reduced size of flight and ground controller teams
    - Standardized payload interfaces
    - Containerized payloads with off-line testing

  - **Improve Safety & Reliability**
    - Faster identification of failures
    - Prediction of failures
    - Reduced human error through pre-programmed responses
    - Increased redundancies
    - Use of modern non-intrusive sensors in high criticality systems

Integrated Vehicle Health Management

Technology Goals & Objectives

- **KSC IVHM Focus Areas**
  - **Flight and Ground-based Test Beds**
  - **Advanced Sensors (Hazardous Gas Detection, Wireless)**
  - **Evolved Control Room Technologies with Advanced Applications**
  - **Informed Maintenance (IM)**
    - Diagnostics / Prognostics
    - Automated Maintenance Scheduling
    - Automated Logistics Coordination (People/Parts/Paper)
    - Paperless Documentation
    - Data Mining

Integrated Vehicle Health Management

Technology Goals & Objectives

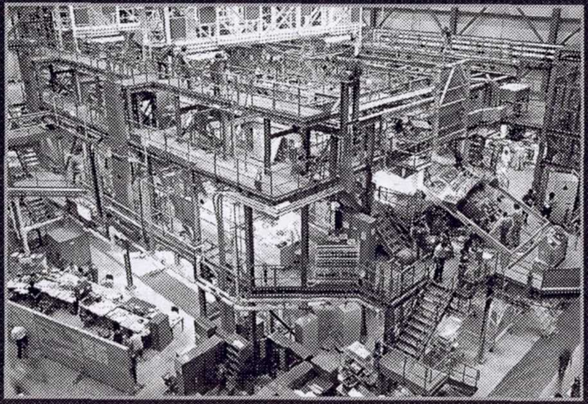
- 1st Generation Ground Operations Reality
- 2nd Generation Ground Operations Vision
- 3rd Generation Ground Operations Vision

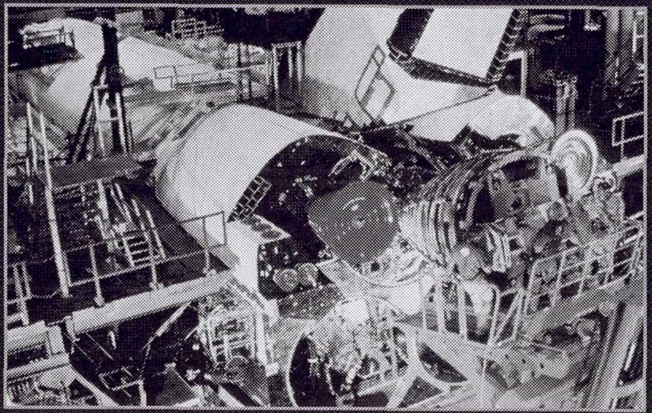
Integrated Vehicle Health Management

Background

1st Generation Ground Operations Reality

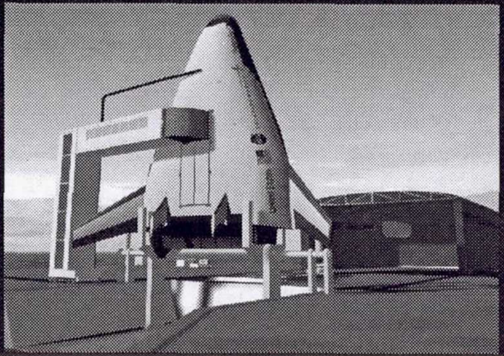
- Best described as manual integration of planned and unplanned operations
- Planned - checkout based on FMEA, R&R of limited life components, servicing
- Unplanned - IFAs and other failures - involves removals for access, troubleshooting, failures and copper path retest
- Paper intensive
- Logistics coordination (people/parts/papers) attempts to use statistics of 4 vehicle fleet, but largely manual
- Conflicts identified by representatives of subsystem engineering, shop, quality, other at scheduling meetings
- Schedules adjusted manually every shift - move magnet bars on wall!





2nd Generation Ground Operations Vision

- Described as semi-automated
- Ground systems highly integrated with flight systems from day one of design phase
- Extensive use of highly automated test and checkout equipment
- Paperless work environment
- Informed Maintenance implemented
  - Maintenance schedules automatically generated and updated taking into account planned and unplanned operations
  - Flight and ground based diagnostic/prognostic health algorithms integrated and use multi-mission data mining
  - Extensive use of intelligent applications for engineering advisories for near real-time launch and ground operations decisions
  - Ground receives periodic health summary data from flight vehicles
  - Logistics coordination and test requirement determination statistically oriented



3rd Generation Ground Operations Vision

- Described as fully automated
- Informed Maintenance implemented with the following considerations
  - Use scaled up elements of 2nd Generation IM system
  - Very large fleet and very high launch rate - large number of component health tracking down to serial number level
  - Maintenance "at the gate" in terms of hours by very small team - rapid routing and staging of proper skilled personnel and equipment as well as procedures
  - "3rd Gen" diagnostic/prognostic health algorithms and applications for engineering advisories for near real-time launch and ground ops decisions

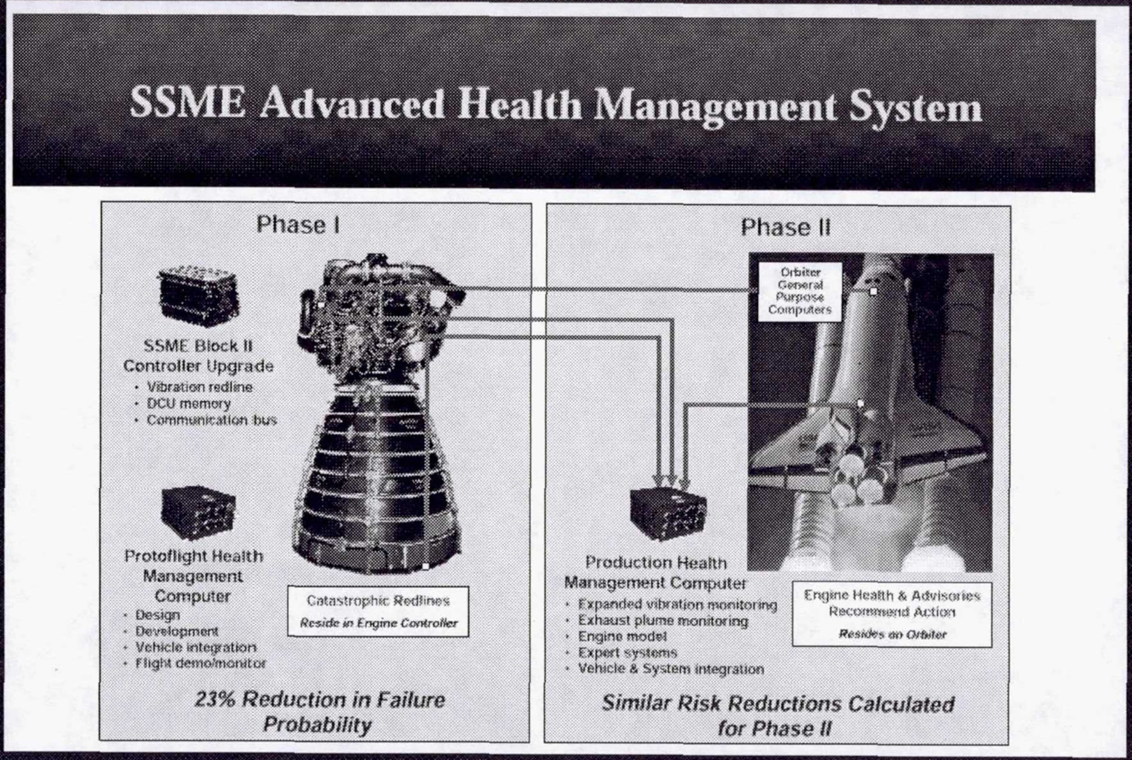
- SSME HMS/OPADS
- X-34 NITEX
- X-37 IVHM and IM
- X-38 DARTH
- CLCS
- iTPS
- PHARM
- REMA

Integrated Vehicle Health Management

Current Status

♦ Space Shuttle Main Engine Health Monitoring System (SSME HMS)

- **Optical Plume Anomaly Detection System (OPADS) Flight Experiment**
  - Planned for three flights, first mid-2002



SSME Advanced Health Management System

Phase I

SSME Block II Controller Upgrade
- Vibration redline
- DCU memory
- Communication bus

Protoflight Health Management Computer
- Design
- Development
- Vehicle integration
- Flight demo/monitor

Catastrophic Redlines
Reside in Engine Controller

23% Reduction in Failure Probability

Phase II

Orbiter General Purpose Computers

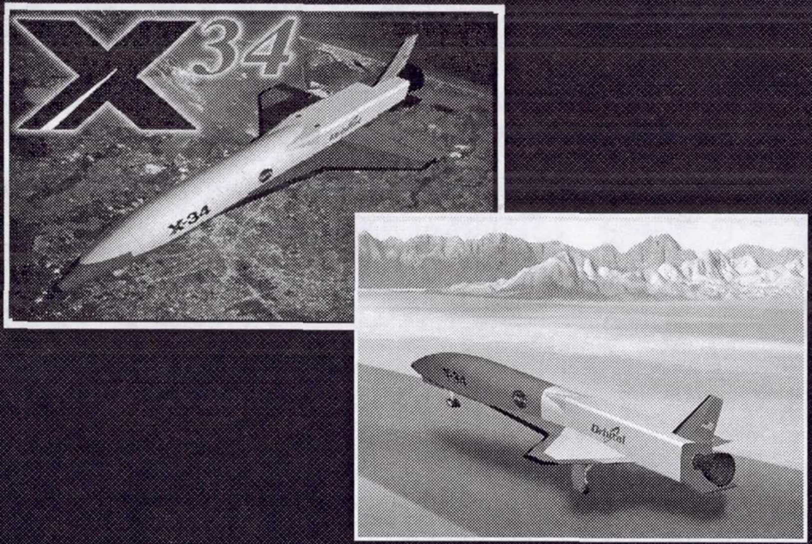
Production Health Management Computer
- Expanded vibration monitoring
- Exhaust plume monitoring
- Engine model
- Expert systems
- Vehicle & System integration

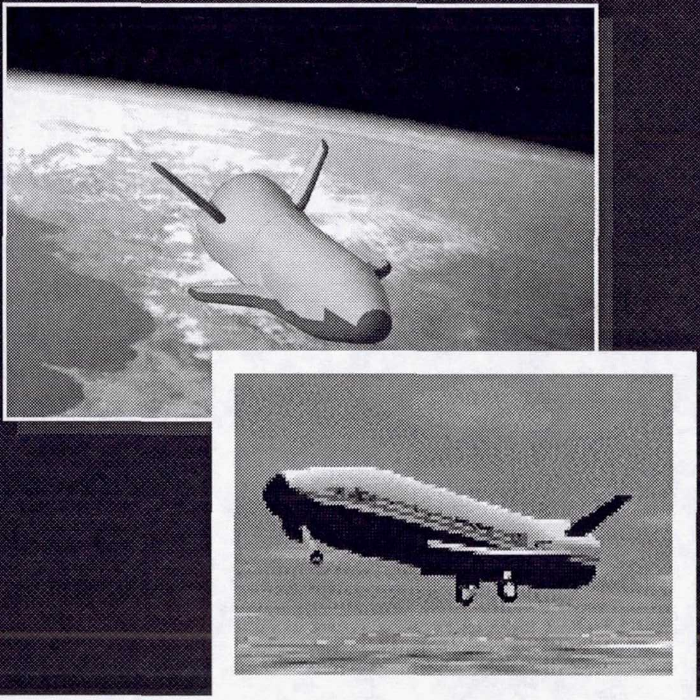
Engine Health & Advisories Recommend Action
Resides on Orbiter

Similar Risk Reductions Calculated for Phase II

★X-34 NASA IVHM Technology Experiment for X-vehicles (NITEX)

- Propulsion system health monitoring experiment
- Fly as payload on X-34
- Multiple flights (first late 2001)
- Develop prognostication





★X-37 IVHM and IM

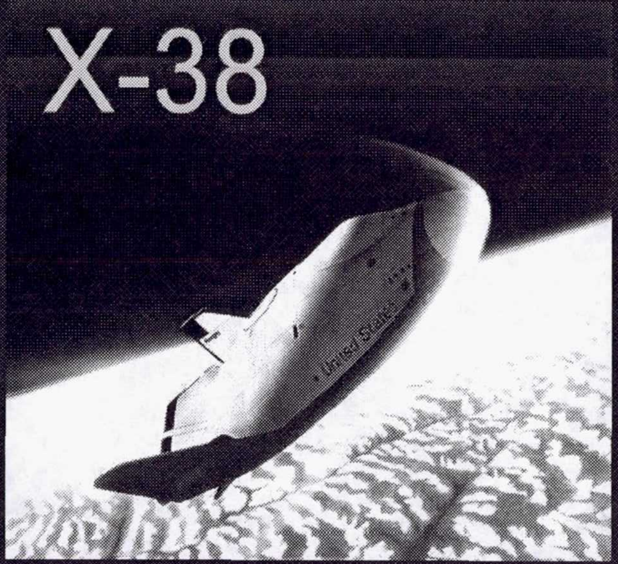
- Electro Mechanical Actuator & Power Systems Health Monitoring Experiment
- Embedded in vehicle avionics
- Operate during B-52 drop tests (1/2002) and Shuttle/ELV payload (11/2002)
- Informed Maintenance

Integrated Vehicle Health Management

Current Status

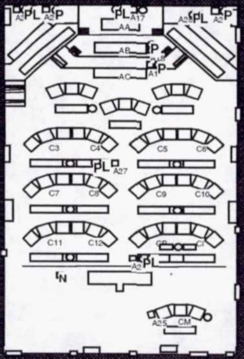
★X-38 Crew Return Vehicle (CRV)

- Provide interface between X-38 vehicle and Orbiter
    - X-38 has Device to Allow Return Telemetry Handling (DARTH)
    - Orbiter has Vehicle Analysis And Data Recording (VADAR)
- Fly as Space Shuttle payload on STS-113 (2/2002)

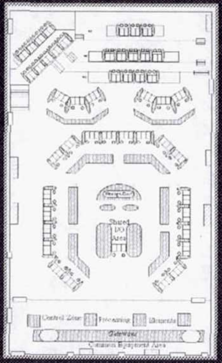


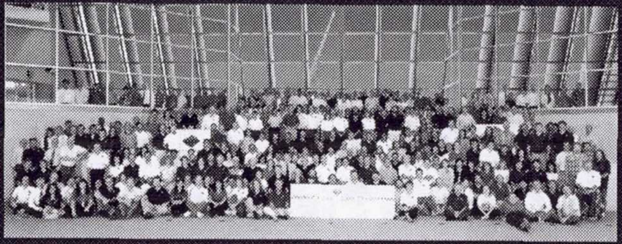
- **Checkout and Launch Control System (CLCS)**
  - Complete replacement of 1970s era Launch Processing System in work, first launch late 2002

OLD (LCC) Single Workstations



NEW (OCR) CLCS Work Groups





- intelligent Thermal Protection System (iTPS)
  - ARC-led effort, KSC role is to develop Space Shuttle flight experiments
- Informed Maintenance - Predictive Health And Reliability Management (PHARM)
  - Boeing KSC and NASA KSC
  - Develop an end-to-end Informed Maintenance system, planned completion 12/2000
  - Plan to integrate into X-34, X-37 and Spaceport Technology Test Complex
- Reconfigurable Electro-Mechanical Actuator (REMA)
  - Oklahoma State University and NASA KSC
  - Develop parallel neural network control systems for EMA operated aerosurface
  - Previous work was neural network for solenoid valve signature recognition

Integrated Vehicle Health Management

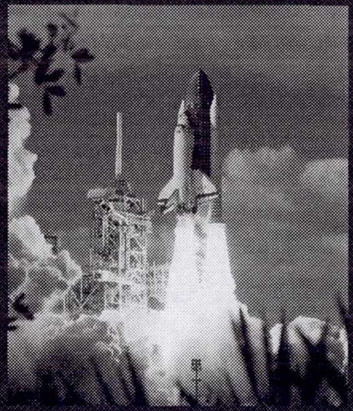
Current Status

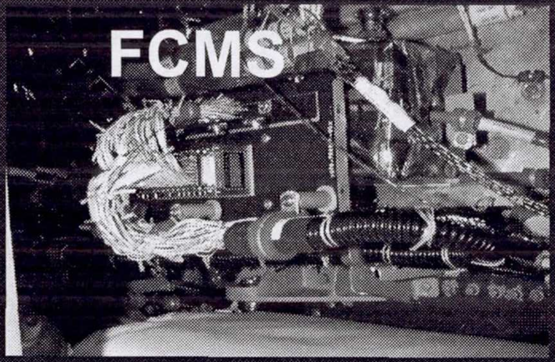
- IVHM HTDs
- FCMS
- OMS/RCS IVHM Test Bed
- u WIS
- Wireless VJ Sensor System
- SOCC

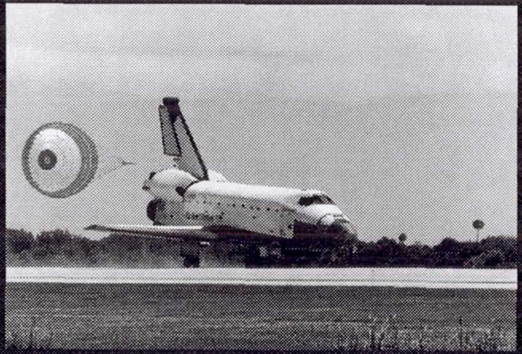
Integrated Vehicle Health Management

Major Accomplishments

Space Shuttle IVHM HEDS Technology Demonstrations







Example Problems

- Fuel Cell single cell volt test
- Aft & PLB haz gas detection
- Crit 1 GOX temp probes
- MPS LH2 FCV testing
- SSME inspections
- Radiator inspections
- MPS pneumatic system testing
- ET/Orbiter plate gap testing

Solutions

✓Fuel Cell Monitoring System

➢Smart H2 & O2 sensors + FBG FO

➢Use non-intrusive sensors, wireless

➢Hall Effect sensors w/ NN

➢SSME HMS, FFT accels, OPADS

★ Acoustic emission sensors

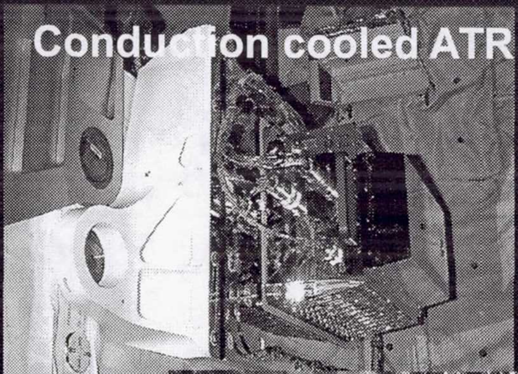
➢Helium leak detection sensors

➢Delta Press sensors

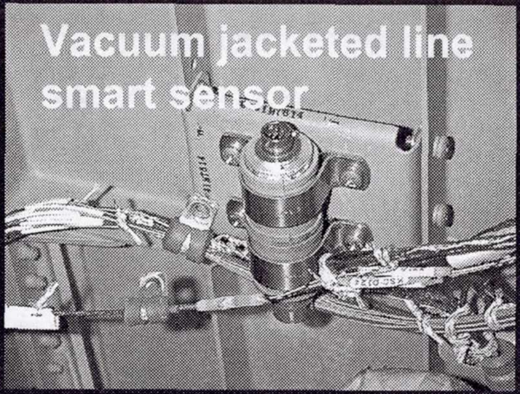
✓= implemented **➢= demo on HTD** **★ = needs development**

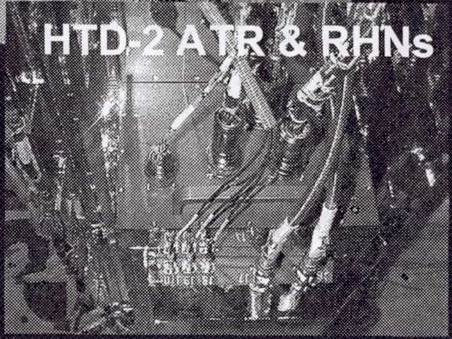
Space Shuttle IVHM HEDS Technology Demonstrations (cont'd)

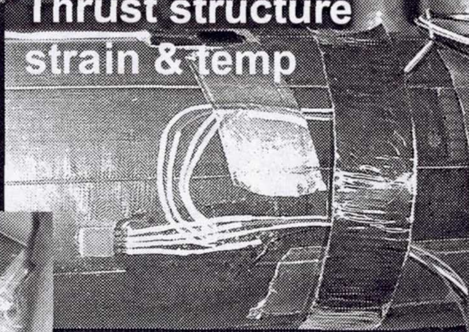
Integrated Vehicle Health Management
HTD
IVHM

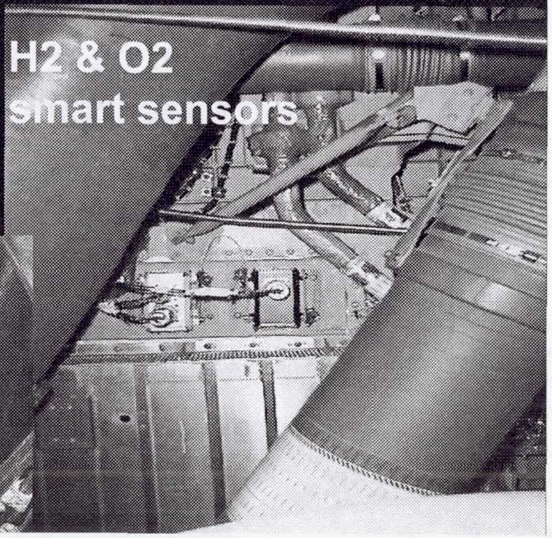

Conduction cooled ATR

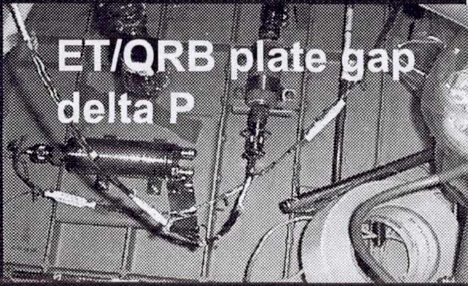

John Glenn with custom CB


Vacuum jacketed line smart sensor


HTD-2 ATR & RHNs

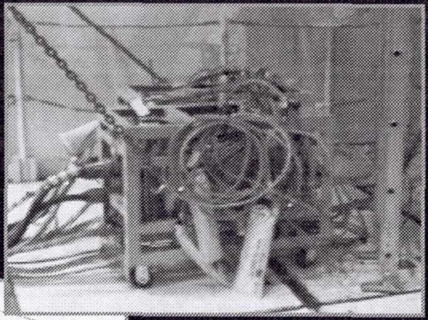

Thrust structure strain & temp


H2 & O2 smart sensors

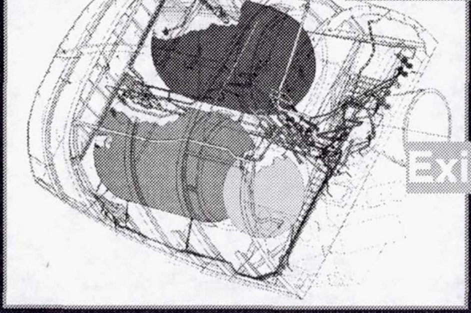

ET/ORB plate gap delta P


GOX skin temps

- ◆ **Space Shuttle OMS/RCS Helium System IVHM Test Bed**
  - Service and test 8 systems in parallel

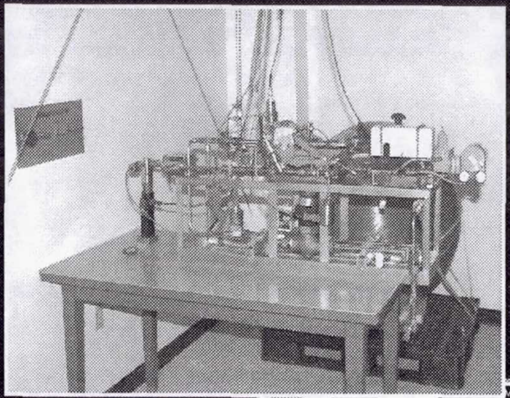


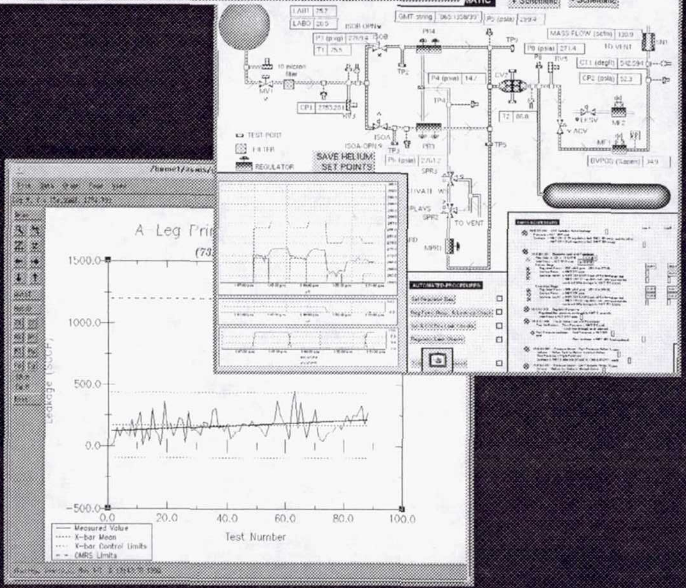
Existing GSE



Shuttle OMS/RCS

Pneumatic System IVHM Test Bed with Automated GSE





Integrated Vehicle Health Management

Major Accomplishments

- Micro Wireless Instrumentation System (u WIS)
  - NASA JSC and KSC effort
  - Two configurations: Micro-sensor/recorder packages and wireless sensors/laptop package
  - Flew STS-96, STS-101, STS-106, International Space Station

- Wireless Vacuum Jacketed Line Sensor System
  - Spin-off of IVHM HTD technology
  - University of Florida, Boeing KSC and NASA KSC
  - For use at Space Shuttle Launch Complex 39

- Florida Spaceport Authority Space Operations Control Center (SOCC)
  - Boeing KSC effort
  - Funded by state of Florida
  - Can support commercial payloads and launchers

Integrated Vehicle Health Management

Major Accomplishments

- STTC
- MMS
- IHGDS
- APHARM
- ICS

Integrated Vehicle Health Management

Near Term Plans

- **Spaceport Technology Test Complex (STTC)**
  - Develop rapid servicing and checkout technologies for "Iron Rocket" (non-flight RLV) – target 24 hour turnarounds
  - Partnership with industry, academia, other NASA Centers
  - Serve as test bed for maturing RLV technologies through rigorous multiple cycle testing in operational environment – even to the point of failure
  - Also develop new LC-39 LOX pumps, replacement Space Shuttle Orbiter LH2 Recirculation Pumps and other large-scale industrial cryogenic components
  - In addition, provide hands-on training for Space Shuttle technicians, quality control specialists, engineers as well as industry and academia

- **Miniature Mass Spectrometer (MMS)**
  - Jet Propulsion Laboratory, NASA JSC and NASA KSC effort
  - Develop hand-held device for post-EVA toxic vapor detection and clean-up while still in airlock prior to entering Space Shuttle or International Space Station

Integrated Vehicle Health Management

Near Term Plans

- Intelligent Hazardous Gas Detection System (IHGDS)
  - University of Florida, Boeing KSC and NASA KSC effort
  - Develop on-board leak localization system using mini-mass spectrometers (leveraged from JPL and others' work) and/or smart sensors (leveraged from Bantam/GRC/MSFC/KSC work)
  - Develop complex flow circulation models for algorithms and optimal sensor placements
  - Develop 1/5 scale Orbiter aft compartment for model validation
  - Space Shuttle flight experiments planned

- Informed Maintenance – Advanced Predictive Health And Reliability Management (APHARM)
  - Scale-up PHARM efforts into 2nd and 3rd Generation IM system
  - Leverage Phase II SBIR - Intelligent Automation, Inc. for 3 dimensional neural network visualization technology

- Intelligent Checkout Systems
  - Automated video, communication and telemetry switching and retest
  - Virtual control rooms for remote commanding and monitoring

Integrated Vehicle Health Management

Near Term Plans

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Integrated Vehicle Health Management

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Propulsion IVHM

Extreme Environment Instrumentation

Power IVHM

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Space Transportation Technology Workshop /IVHM:

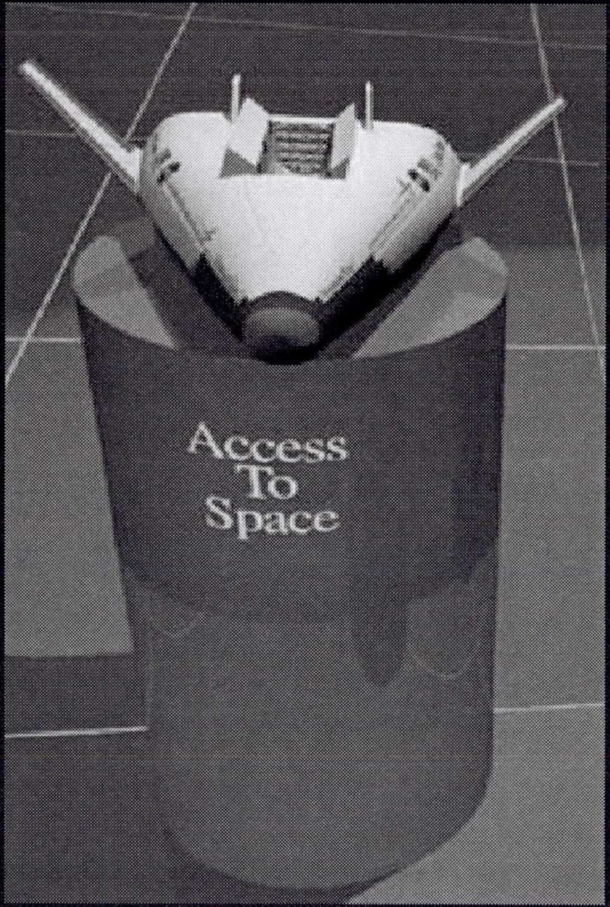
Propulsion & Power IVHM Technologies

AGENDA

- Why
- What
- Propulsion IVHM
  - Vision
  - Capabilities/Research
  - Selected Projects
    - X33
    - X34
    - AHMS
    - Smart Self Healing Propulsion Systems
    - Extreme Environment Sensors
- Power IVHM
  - Vision
  - Capabilities/Research
  - Selected Projects
    - EMAs
- Summary

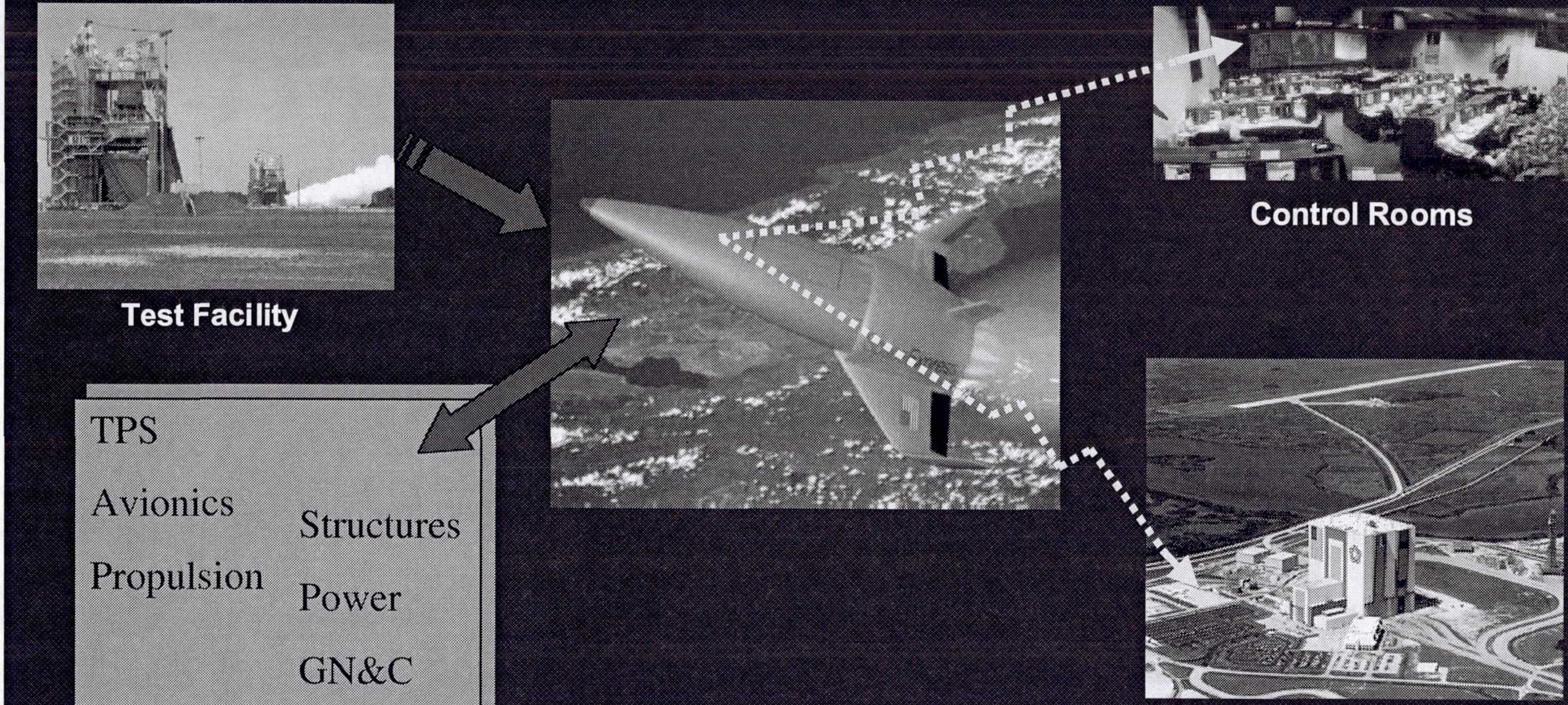
WHY?

Goal Driven Space Transportation



- Goal 9: Low-Cost Space Access
  - Reduce the payload cost to low-Earth orbit by an order of magnitude, from $10,000 to $1,000 per pound, within 10 years and by an additional order of magnitude within 25 years.
  - Increase the mission safety by two orders of magnitude within 10 years and four orders of magnitude within 25 years

WHAT?
IVHM Vision



Test Facility

Control Rooms

Ground Processing Facility

TPS
Avionics
Propulsion
Structures
Power
GN&C

WHAT?
Paradigm Shift

IVHM Paradigm Revolution

- Fully integrated throughout system with costs/benefits justification
- Fully integrated into vehicle design phase, vehicle systems, including payload, and system interactions
- Extensively ground and flight tested to develop and verify IVHM - Birth to grave knowledge and tracking

Projected IVHM Impacts

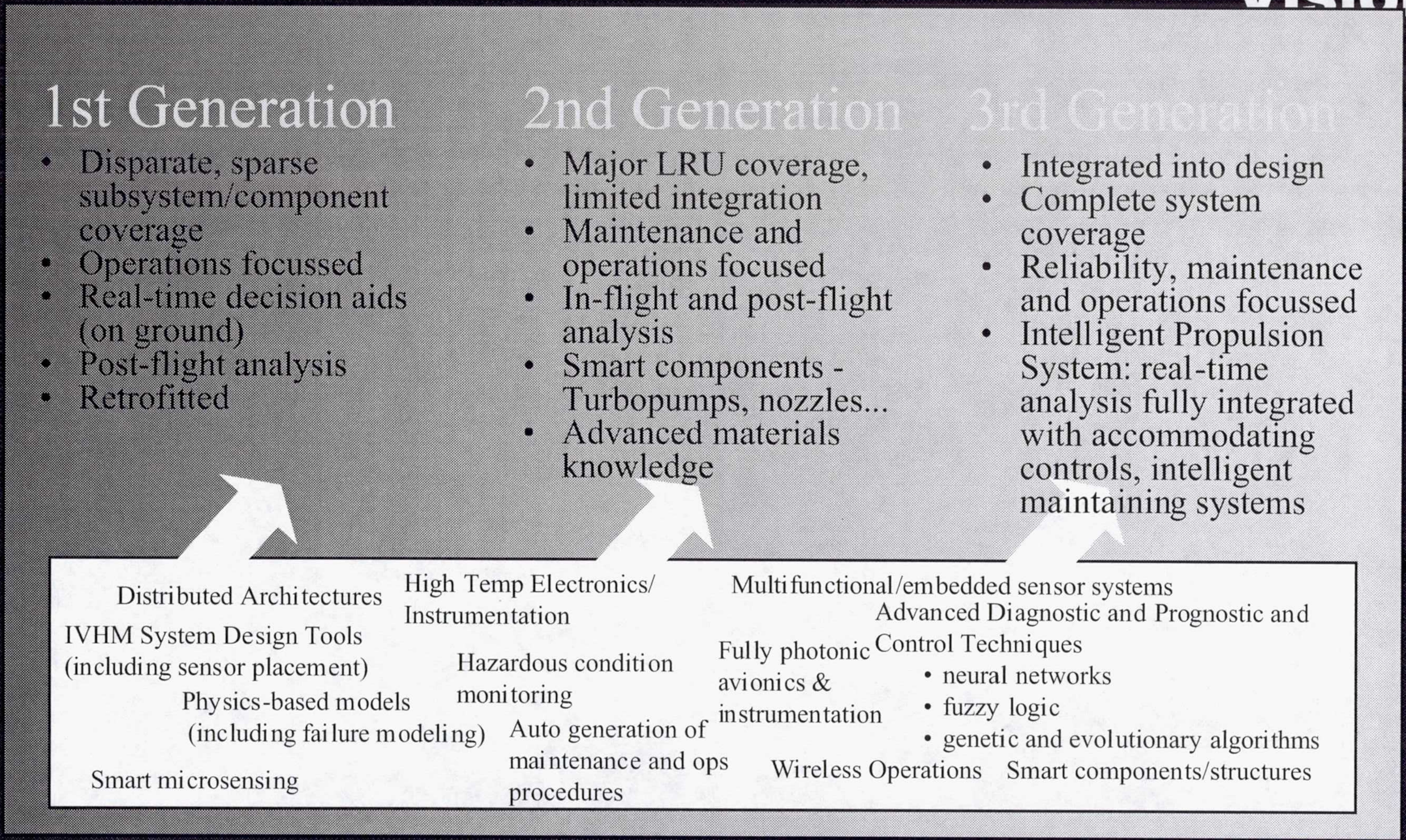
- **20x Ops and Maintenance Reductions**
  - Condition Based Maintenance
  - 100% Vehicle IVHM Coverage Integrated With Autonomous Control
  - Automated Ground Processing and Mission Control Systems

- **Reduced Development Time and Costs**
  - Integrated Tools that Facilitate Rapid Analysis and Design of Highly Reliable, Cost-Effective Vehicles

- **10x Reliability Improvements**
  - Improved real-time fault management and fault modeling
  - Increase sensor redundancy throughout system (10 to 100x)

- **15% Weight Reductions**
  - Wireless and Nano Electronics
  - Real-Time Margin Management

PROPULSION IVHM
Vision



1st Generation

- Disparate, sparse subsystem/component coverage
- Operations focussed
- Real-time decision aids (on ground)
- Post-flight analysis
- Retrofitted

2nd Generation

- Major LRU coverage, limited integration
- Maintenance and operations focused
- In-flight and post-flight analysis
- Smart components - Turbopumps, nozzles...
- Advanced materials knowledge

3rd Generation

- Integrated into design
- Complete system coverage
- Reliability, maintenance and operations focussed
- Intelligent Propulsion System: real-time analysis fully integrated with accommodating controls, intelligent maintaining systems

Distributed Architectures

IVHM System Design Tools (including sensor placement)

Physics-based models (including failure modeling)

Smart microsensing

High Temp Electronics/ Instrumentation

Hazardous condition monitoring

Auto generation of maintenance and ops procedures

Multifunctional/embedded sensor systems

Fully photonic avionics & instrumentation

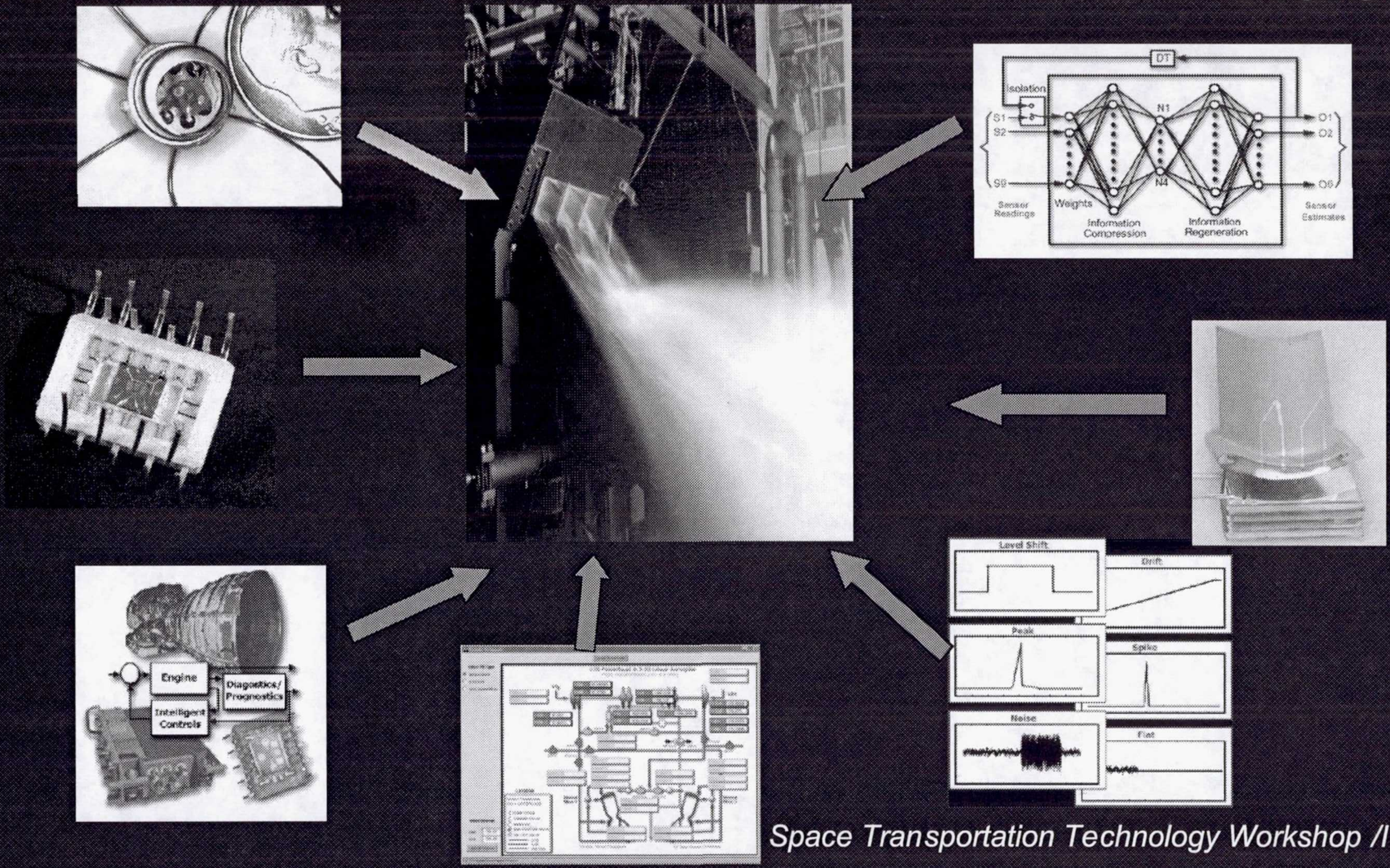
Advanced Diagnostic and Prognostic and Control Techniques
- neural networks
- fuzzy logic
- genetic and evolutionary algorithms

Wireless Operations

Smart components/structures

PROPULSION IVHM

Vision



Space Transportation Technology Workshop /IVHM:

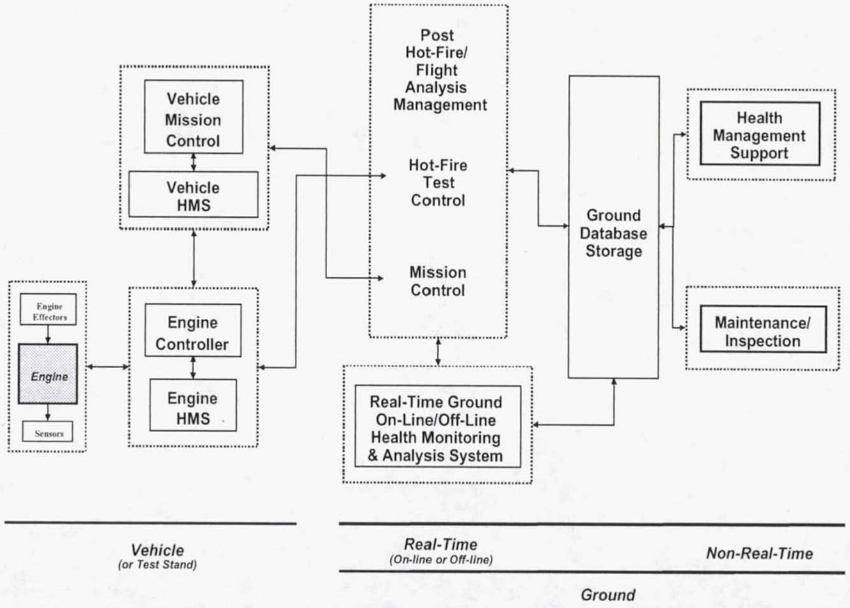
Propulsion & Power IVHM Technologies

PROPULSION IVHM

Capabilities/Research

- Propulsion IVHM works within a distributed vehicle IVHM architecture
- Propulsion IVHM life cycle approach extends inherent engine reliability and reduces costs
- Propulsion IVHM is embedded
- Flight –
  - Instrumentation
  - Avionics
  - Controls
  - Intelligent components
- Ground Elements
  - Advanced ground processing
  - Maintenance reduced
  - Paperless Systems
  - Smart Software
  - Smart GSE

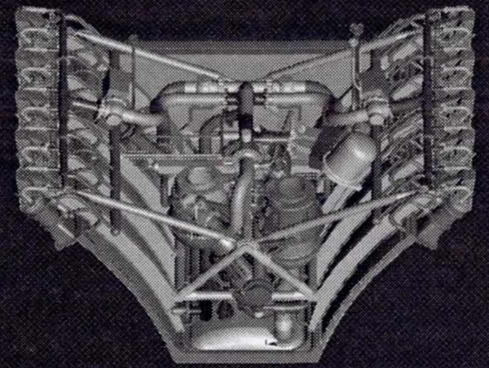
Generic AHMS Block Diagram - Top-Level View



PROPULSION IVHM

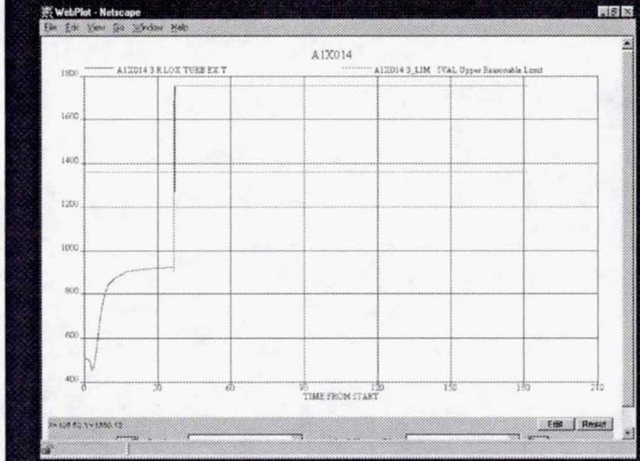
Projects: X-33 Post-Test Diagnostic System

PTDS analysis and viewing system infra-structures are in place and validated; user training conducted at Rocketdyne



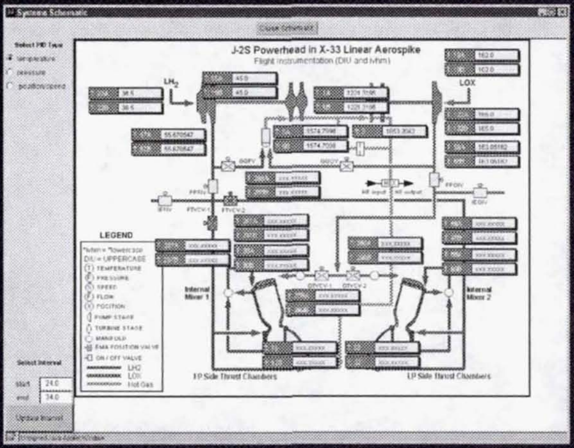
Highlights

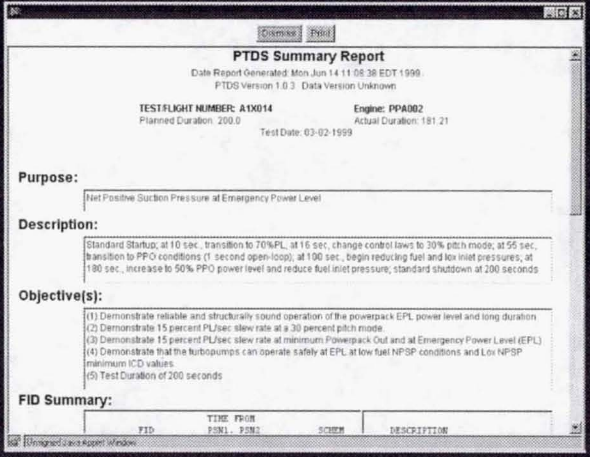
- **Has successfully analyzed all powerpack and engine firings**
- **Rocketdyne estimates order of magnitude reduction in flight turnaround time**



Comprehensive Plotting and Interactive Statistics

Interactive Schematics





PTDS Summary Report

Date Report Generated: Mon Jun 14 11:08:38 EDT 1999

PTDS Version 1.0.3 Data Version Unknown

TEST/FLIGHT NUMBER: A1X014 **Engine: PPA002**

Planned Duration: 200.0 Actual Duration: 181.21

Test Date: 03-02-1999

Purpose:

Net Positive Suction Pressure at Emergency Power Level

Description:

Standard Startup; at 10 sec., transition to 70%PL; at 16 sec, change control laws to 30% pitch mode; at 55 sec., transition to PPO conditions (1 second open-loop); at 100 sec., begin reducing fuel and lox inlet pressures; at 180 sec., increase to 50% PPO power level and reduce fuel inlet pressure; standard shutdown at 200 seconds

Objective(s):

(1) Demonstrate reliable and structurally sound operation of the powerpack EPL power level and long duration
(2) Demonstrate 15 percent PL/sec slew rate at a 30 percent pitch mode.
(3) Demonstrate 15 percent PL/sec slew rate at minimum Powerpack Out and at Emergency Power Level (EPL)
(4) Demonstrate that the turbopumps can operate safely at EPL at low fuel NPSP conditions and Lox NPSP minimum ICD values
(5) Test Duration of 200 seconds

FID Summary:

FID	TIME FROM PSN1, PSN2	SCHEM	DESCRIPTION

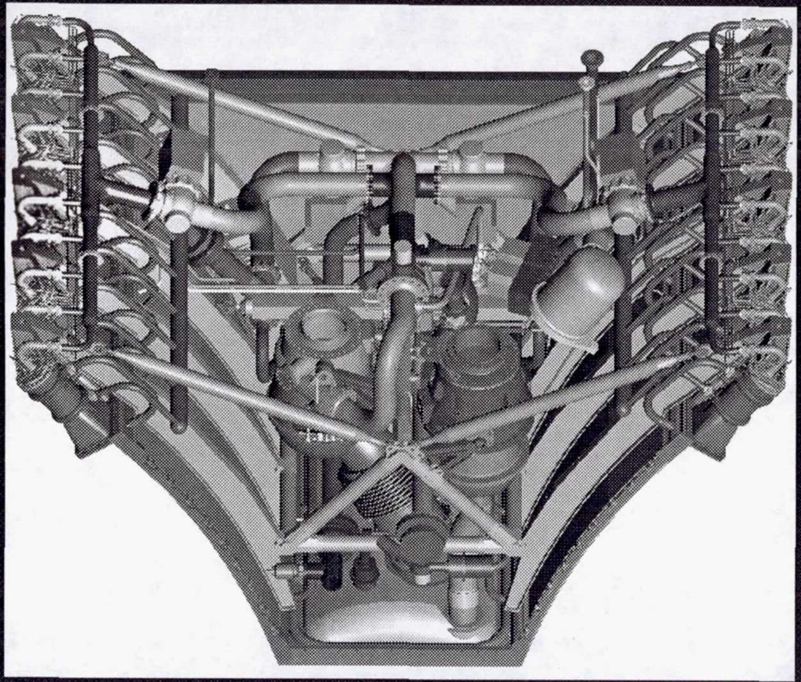
Data Review Ready Reports

Space Transportation Technology Workshop /IVHM:

Propulsion & Power IVHM Technologies

PROPULSION IVHM

Projects: X-33 Post-Test Diagnostic System



All Components Covered
- Sensors
- Gas Generator
- LOX turbopump
- Fuel Turbopump
- Valves, Actuators, Ducts
- Nozzles, Thrust Chambers

Analyses Performed
- Component Performance Predictions
- Statistical Characterization
- Life Tracking
- ICD Exceptions/Margin Analysis
- Model-Based Fault Detection

Web-Based GUI
- View Reports
- View Interactive Schematics
- View Predefined Plot Packages
- Generate/Annotate Plots on Request
- Perform Complex Statistical Analyses

Available Reports
- Summary Report
- Systems Report
- Margin Report
- Life Tracking Report
- Events Report
- Component Reports

Supports Turn-Around of Engine Tests and Flights

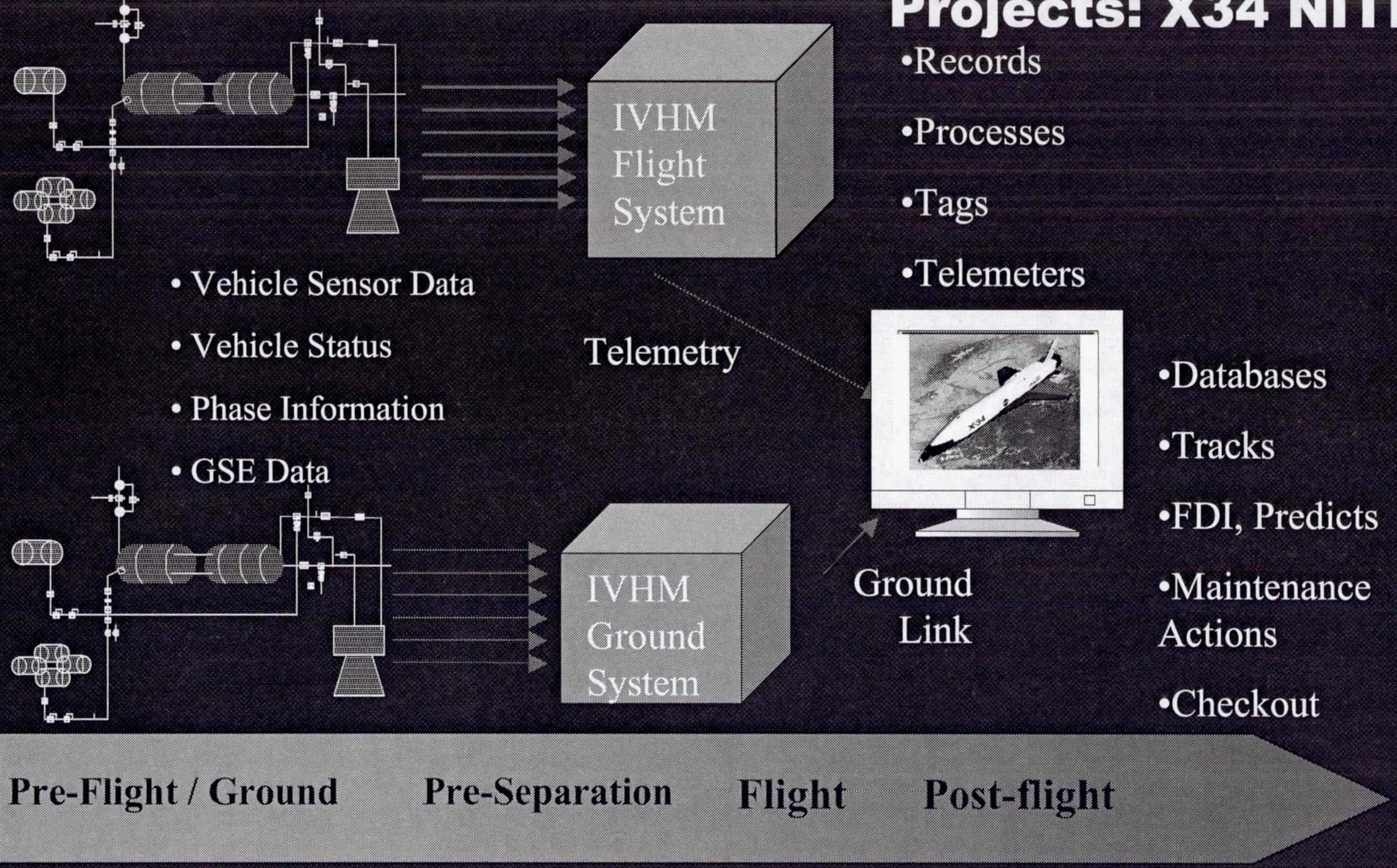
Foundation for Automated Maintenance and Reduced Operations

Space Transportation Technology Workshop /IVHM:

Propulsion & Power IVHM Technologies

PROPULSION IVHM

Projects: X34 NITEX



- Records
- Processes
- Tags
- Telemeters

IVHM Flight System

- Vehicle Sensor Data
- Vehicle Status
- Phase Information
- GSE Data

Telemetry

IVHM Ground System

Ground Link

- Databases
- Tracks
- FDI, Predicts
- Maintenance Actions
- Checkout

Pre-Flight / Ground **Pre-Separation** **Flight** **Post-flight**

PROPULSION IVHM

Projects: X34 NITEX

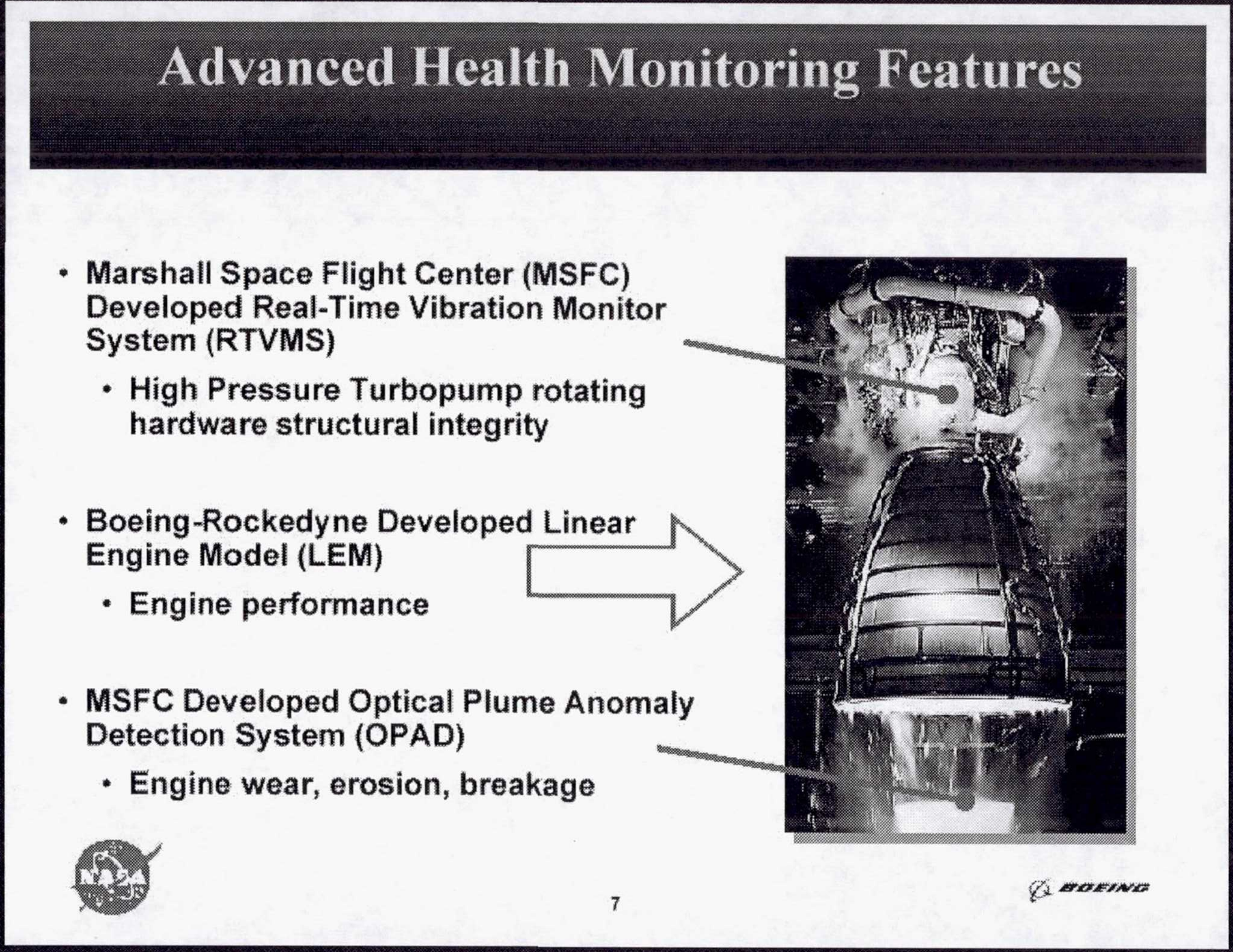
The IVHM Vision and How NITEX Relates

Blue = NITEX ***Green = Potential***

- IVHM Vision / Long Term Objectives
  - **Enhanced vehicle safety and reliability**
    - Modern sensing systems
    - **Failure detection, isolation**, *prediction*
    - Reliable, accurate health diagnosis and prognosis
  - **Reduced ground processing of reusable vehicles**
    - In flight system checks
    - Automated ground servicing and checkout
    - **Automated data analysis, information generation and presentation/explanation**
    - Informed maintenance scheduling system
  - **Autonomous operation in flight and on the ground**
    - Reduced workload for ground controller team
    - **Health summary information**
    - *Predicting and adapting to sub-system degradation and failure real-time in flight and on the ground*

PROPULSION IVHM

Projects: AHMS

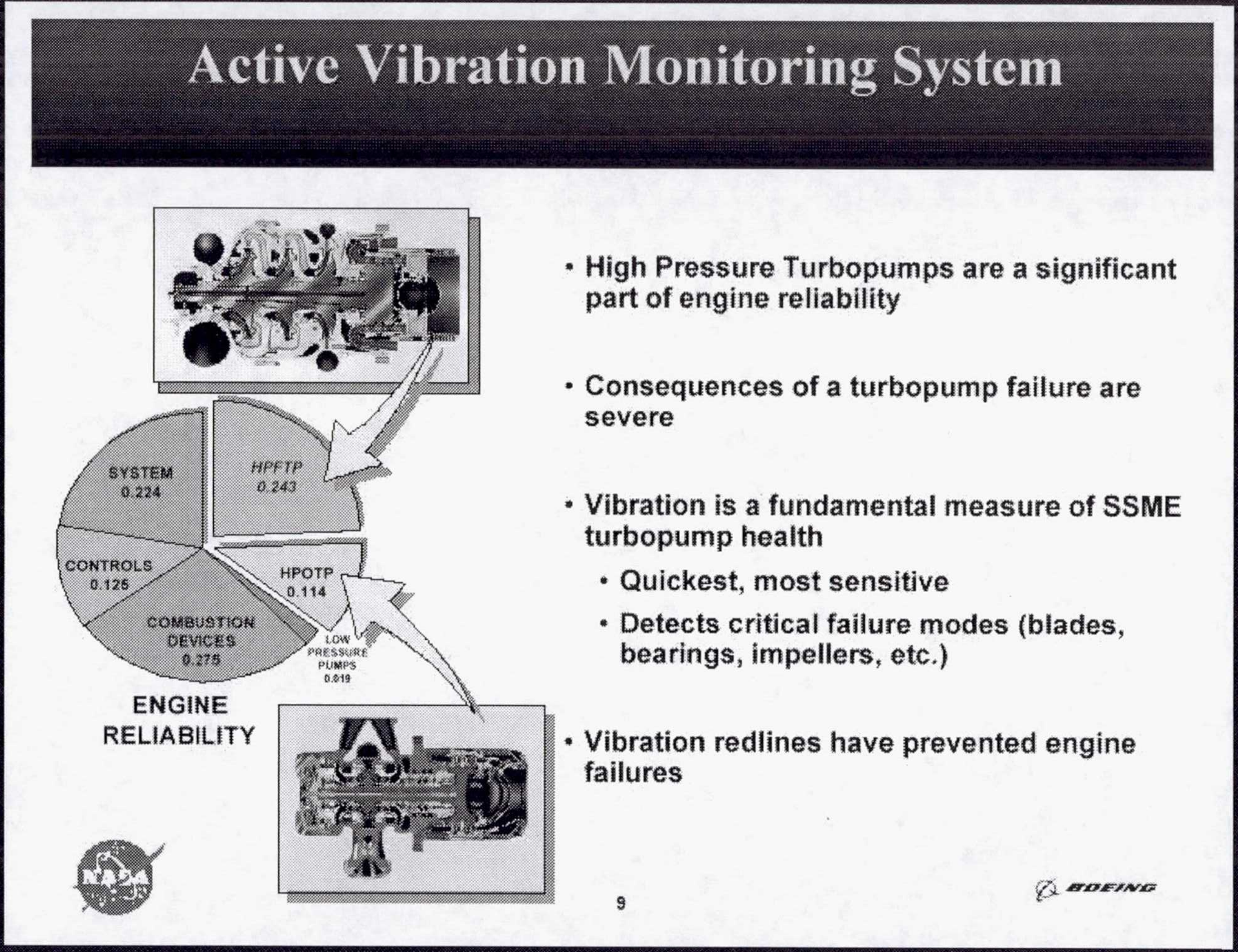


Advanced Health Monitoring Features

- Marshall Space Flight Center (MSFC) Developed Real-Time Vibration Monitor System (RTVMS)
  - High Pressure Turbopump rotating hardware structural integrity
- Boeing-Rockedyne Developed Linear Engine Model (LEM)
  - Engine performance
- MSFC Developed Optical Plume Anomaly Detection System (OPAD)
  - Engine wear, erosion, breakage

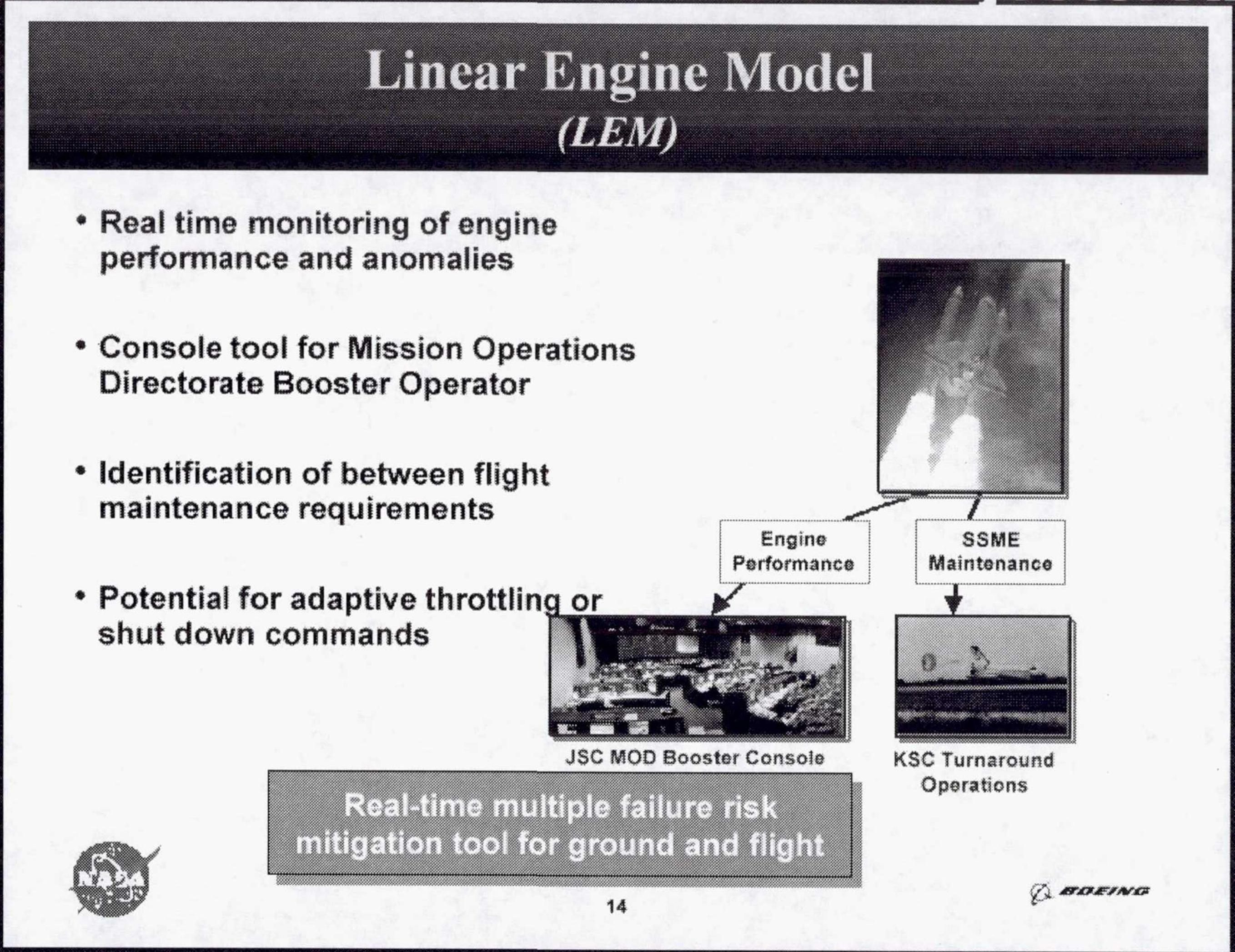
PROPULSION IVHM

Projects: AHMS



Active Vibration Monitoring System

- High Pressure Turbopumps are a significant part of engine reliability
- Consequences of a turbopump failure are severe
- Vibration is a fundamental measure of SSME turbopump health
  - Quickest, most sensitive
  - Detects critical failure modes (blades, bearings, impellers, etc.)
- Vibration redlines have prevented engine failures



Linear Engine Model
(LEM)

- Real time monitoring of engine performance and anomalies
- Console tool for Mission Operations Directorate Booster Operator
- Identification of between flight maintenance requirements
- Potential for adaptive throttling or shut down commands

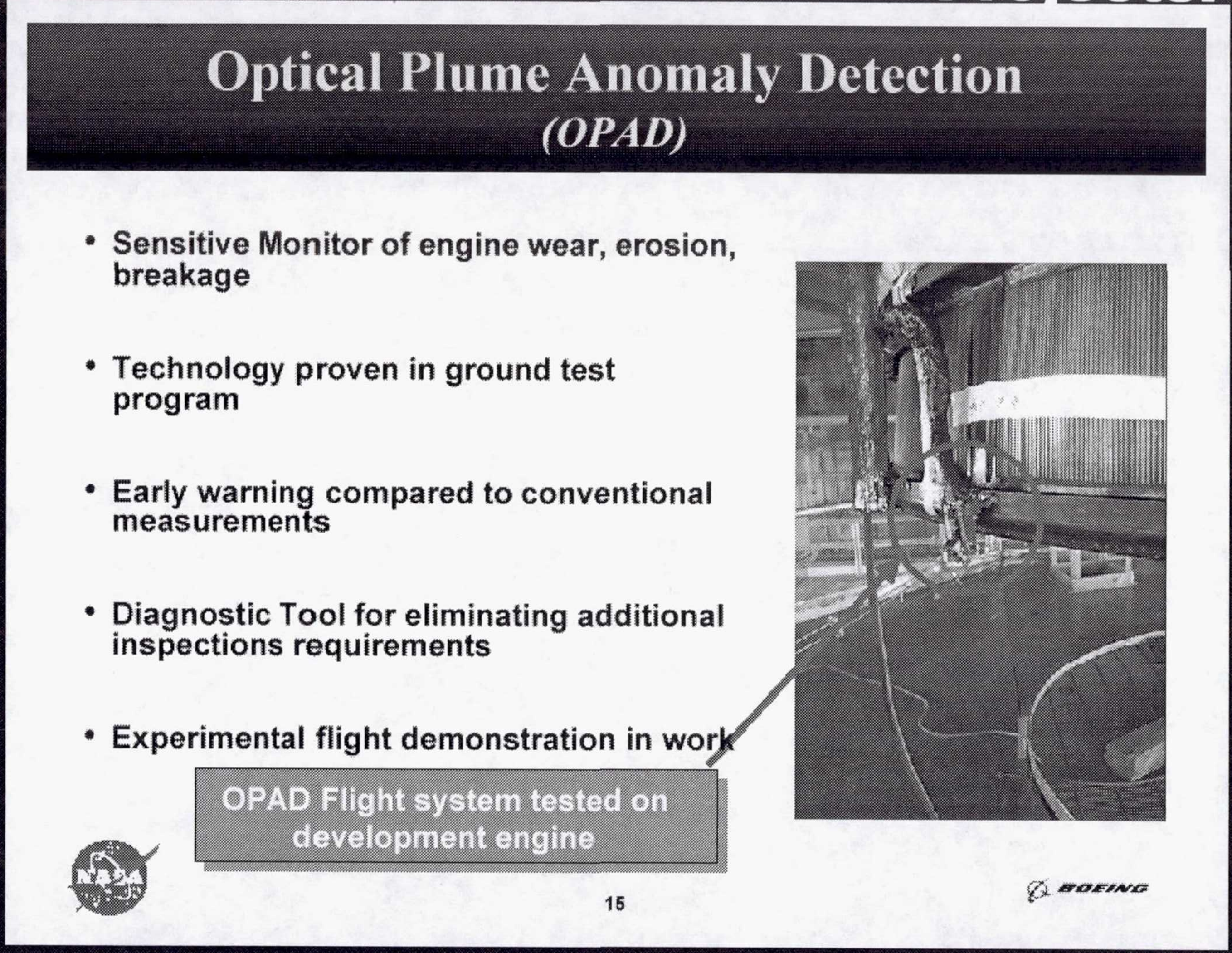
JSC MOD Booster Console

KSC Turnaround Operations

Real-time multiple failure risk mitigation tool for ground and flight

PROPULSION IVHM

Projects: AHMS



Optical Plume Anomaly Detection
(OPAD)

- Sensitive Monitor of engine wear, erosion, breakage
- Technology proven in ground test program
- Early warning compared to conventional measurements
- Diagnostic Tool for eliminating additional inspections requirements
- Experimental flight demonstration in work

OPAD Flight system tested on development engine

PROPULSION IVHM

Projects: Smart Self Healing Propulsion Systems

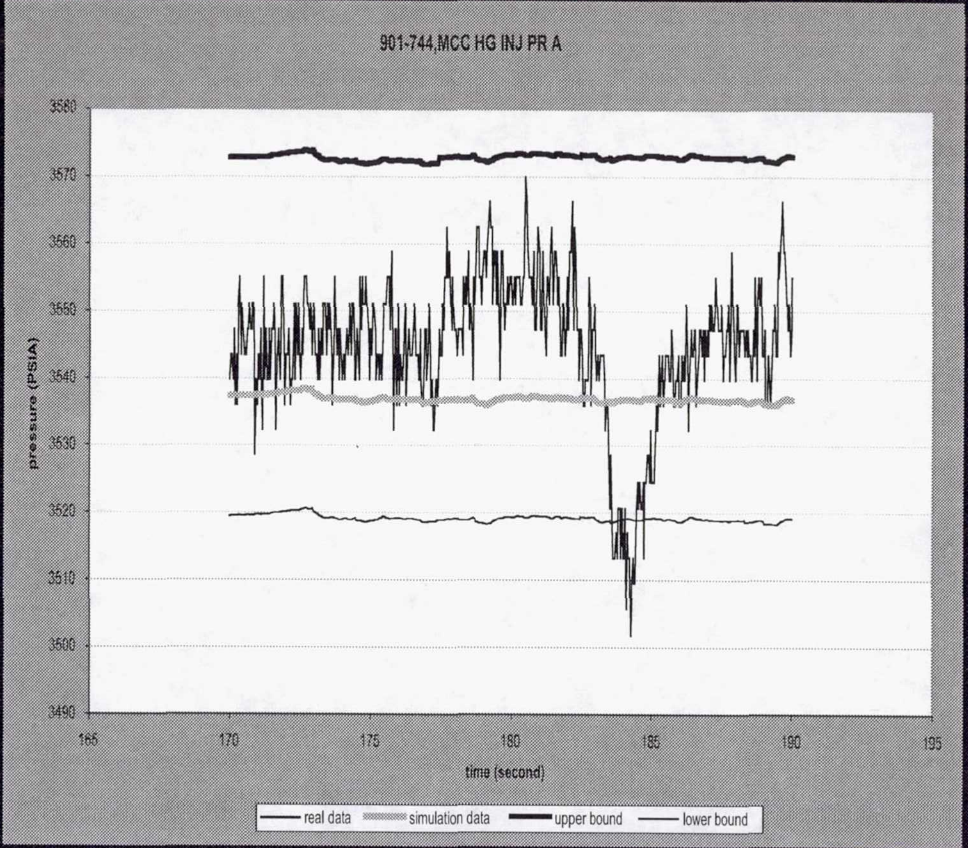
Advanced Diagnostic Algorithms

Objective: Diagnostic Solutions that

- Do not require exhaustive enumeration of faults
- Cover steady-state and transient operation
- Address test-to-test variability
- Explicitly handle model and measurement uncertainties
- Provide Confidence in Diagnostic System Output
- Provide Instrumentation Selection Guidance

Model-based monitoring algorithm

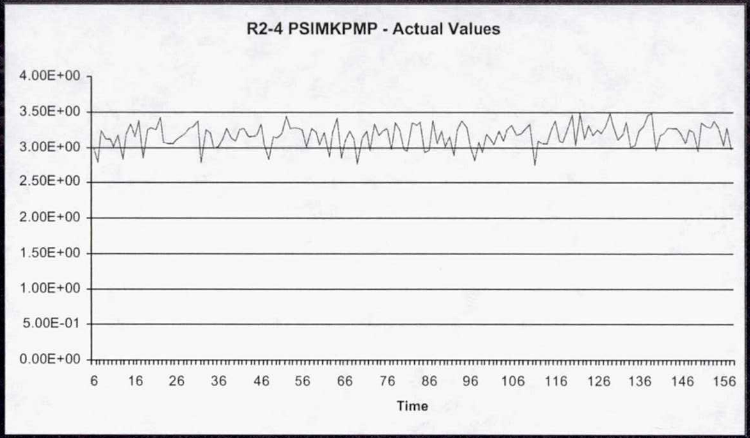
- Uses dynamic simulation of the SSME
- no false alarms on 8 nominal SSME data sets
- 10 successful isolations on 13 off-nominal SSME data sets



PROPULSION IVHM

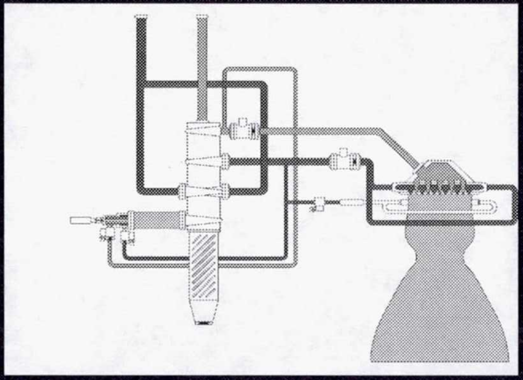
Projects: Smart Self Healing Propulsion Systems

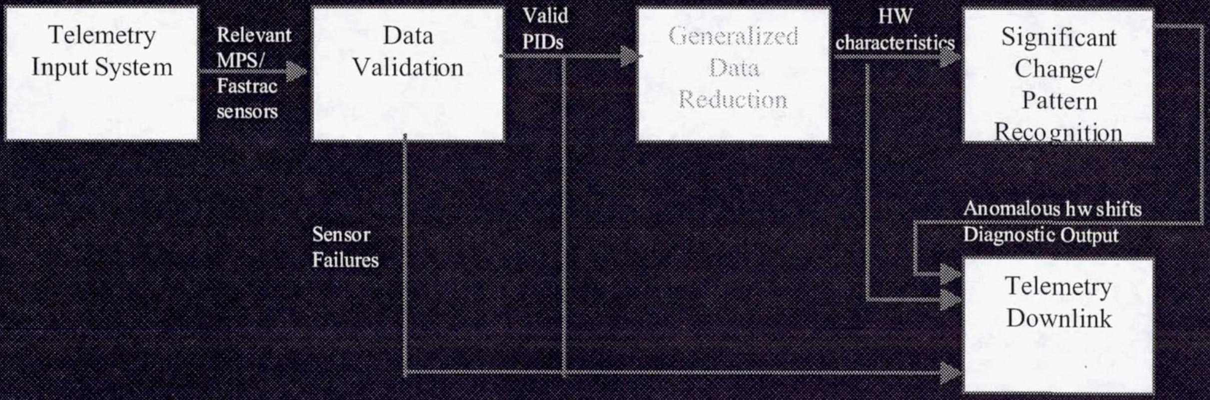
Advanced Diagnostic Algorithms



Engine Diagnostics via Data Reduction

- **Comprehensive linearity analysis has been completed for Fastrac Engine**
- **Various versions of algorithm (incorporating 1st and 2nd order effects) have been successfully demonstrated on historical data**





Telemetry Input System

Relevant MPS/ Fastrac sensors

Data Validation

Valid PIDs

Generalized Data Reduction

HW characteristics

Significant Change/ Pattern Recognition

Anomalous hw shifts Diagnostic Output

Sensor Failures

Telemetry Downlink

Will Fly as Part of X-34 NITEX

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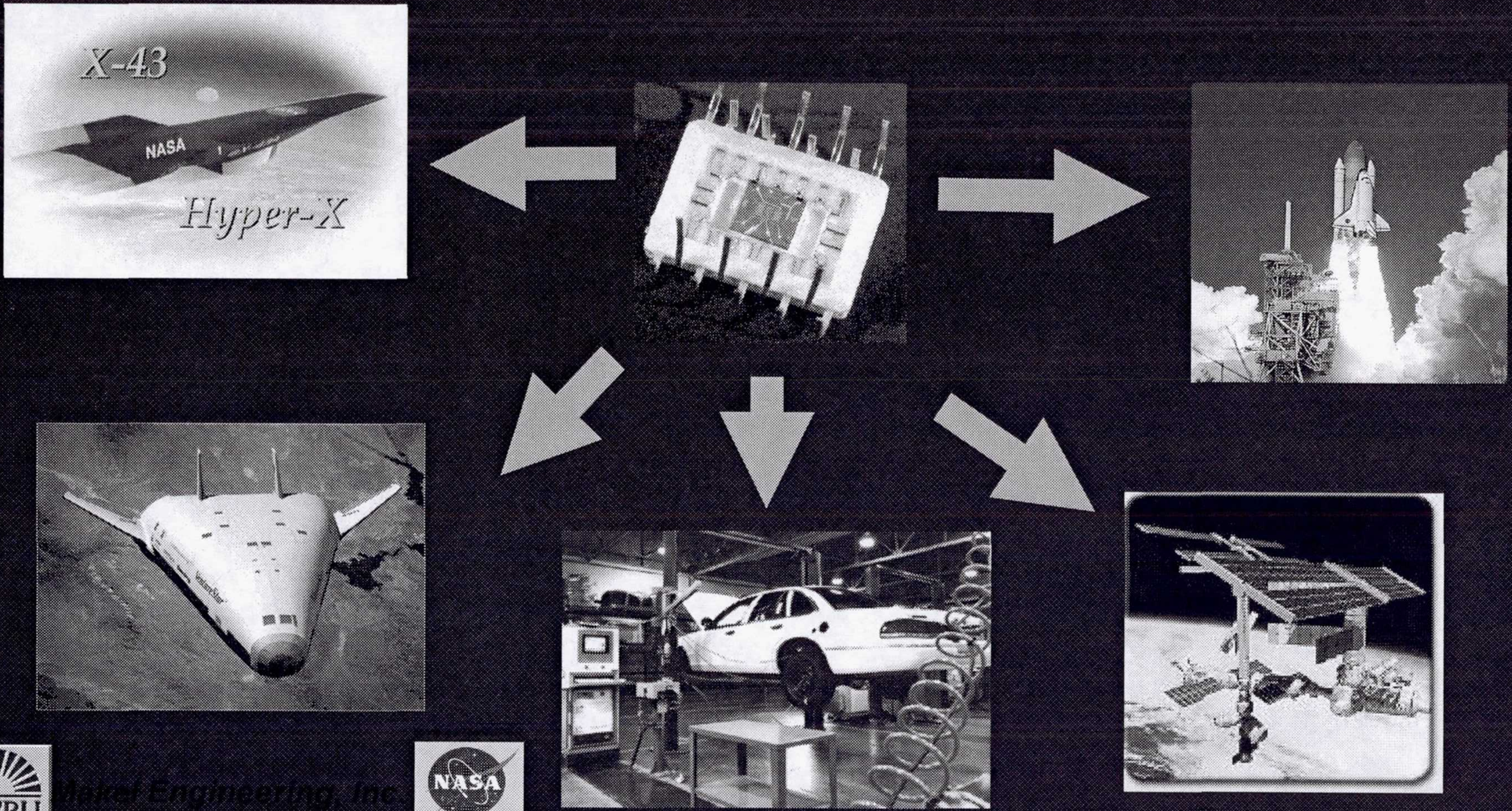
Propulsion & Power IVHM Technologies

PROPULSION IVHM

Projects: Extreme Environment Sensors

HYDROGEN LEAK SENSOR TECHNOLOGY



CWRU Makel Engineering, Inc

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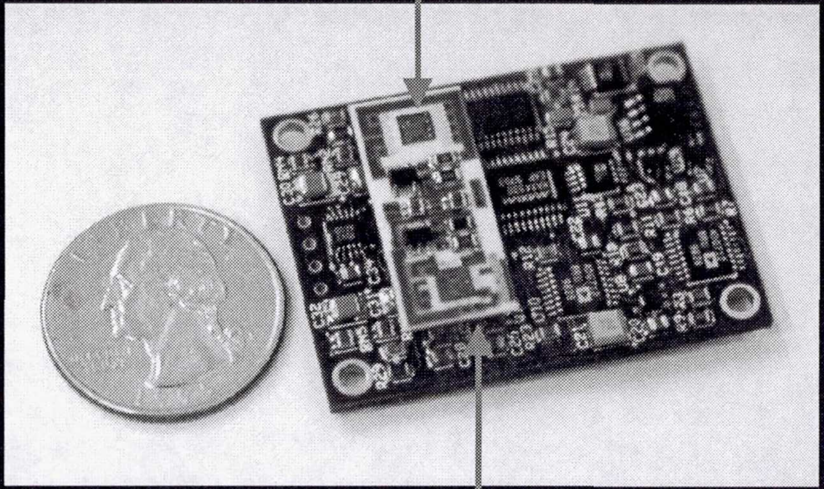
PROPULSION IVHM

Projects: Extreme Environment Sensors

Advanced Sensors and MEMS Technology Development

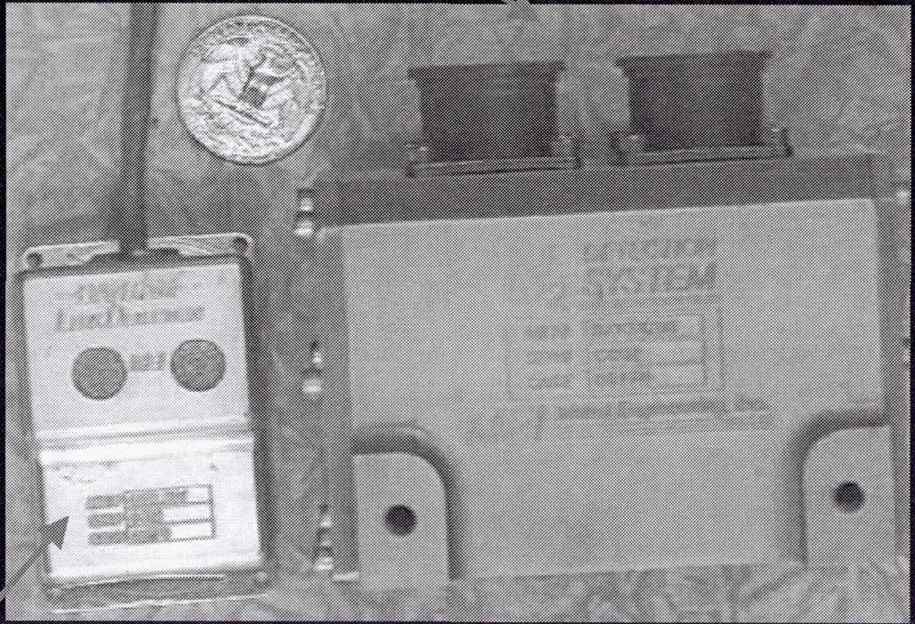
Shuttle system hardware (H2 Sensor with Electronics)

H2 SENSOR



O2 SENSOR

10 TIMES REDUCTION
IN SIZE OF
HARDWARE



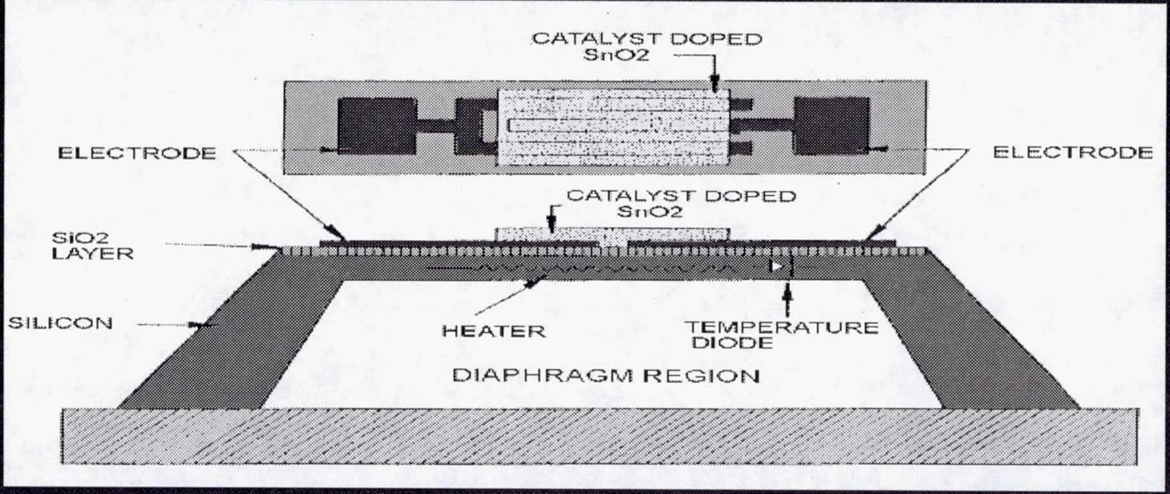
H2 and O2 Sensor with Electronics

PROPULSION IVHM

Projects: Extreme Environment Sensors

MICROFABRICATED TIN OXIDE BASED NOx AND CO SENSOR TECHNOLOGY

- Microfabricated for minimal size, weight and power consumption
- Micromachined to minimize power consumption and improved response time
- Temperature detector and heater incorporated into sensor structure
- Nanofabrication of Tin-Oxide to increase sensor stability



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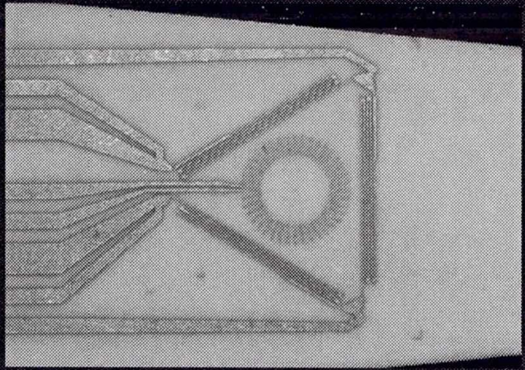
PROPULSION IVHM

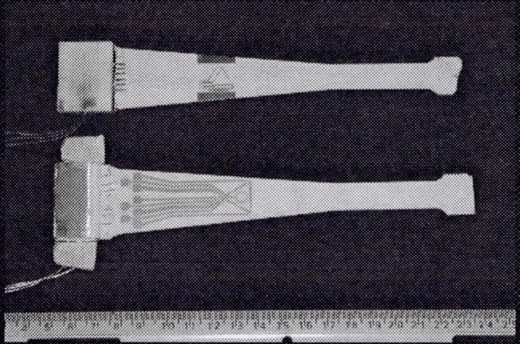
Projects: Extreme Environment Sensors

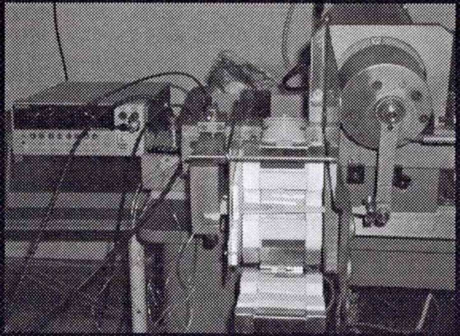
Thin Film Multifunction Integrated Sensor

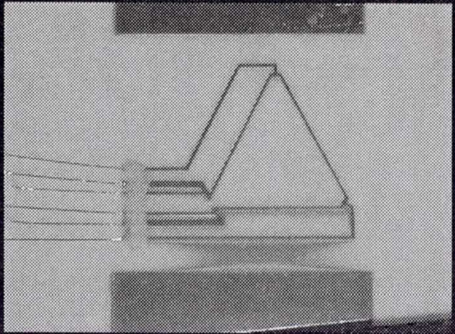


Multiple Measurements

- •Strain Magnitude & Direction
- •Heat Flux
- •Surface Temperature
- •Flow Velocity Magnitude and Direction







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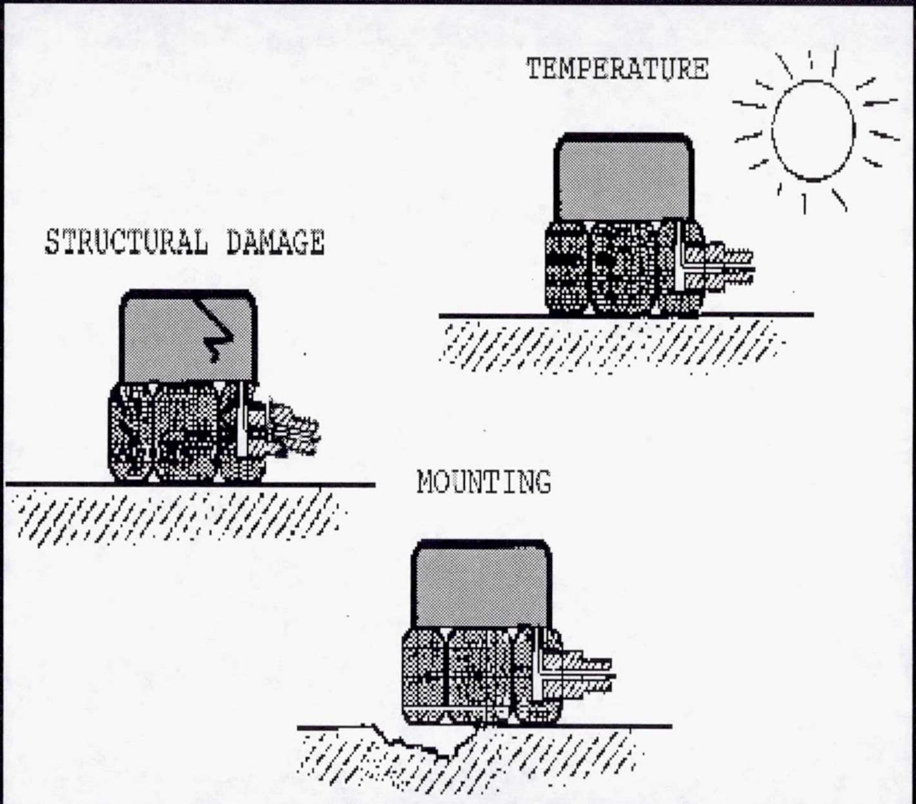
PROPULSION IVHM

Projects: Extreme Environment Sensors

Self Diagnostic / Self Compensating Accelerometers



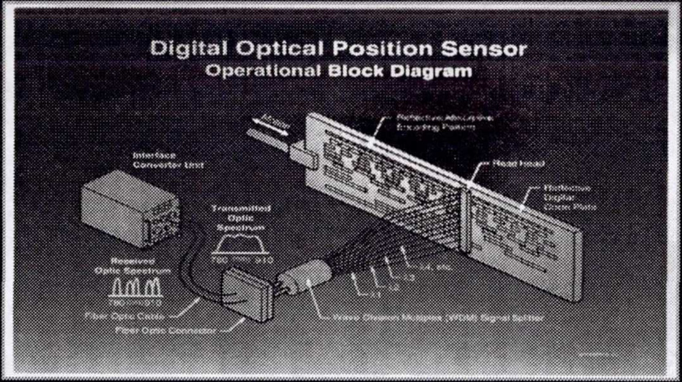
- Detects accelerometer mounting problems (i.e. torque) and structural damage
- Collects diagnostic information and acceleration data concurrently
- Increases accuracy of accelerometer data by 10X during temperature fluctuations
- No additional hardware required, accomplished by using active sensing methods
- Research to be conducted on in-situ calibration

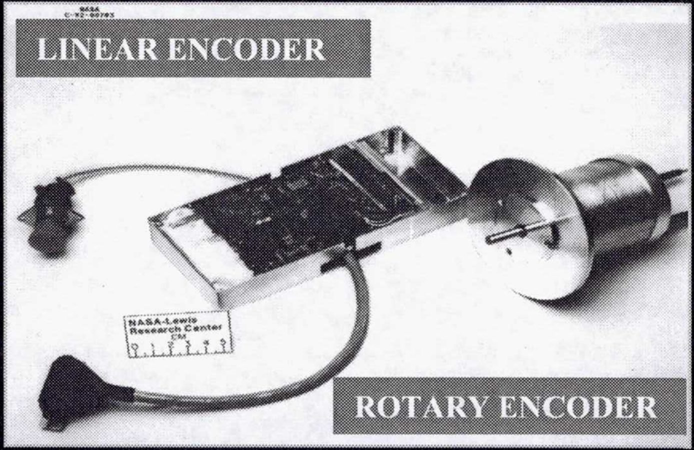
PROPULSION IVHM

Projects: Extreme Environment Sensors

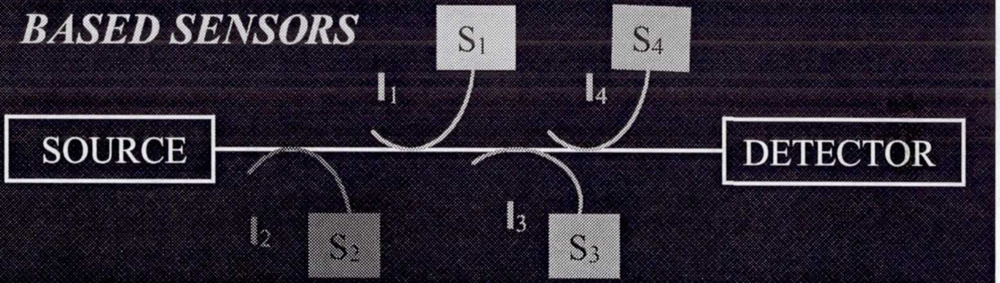
SPECTRAL DOMAIN SENSORS

DIGITAL SPECTRAL ENCODERS



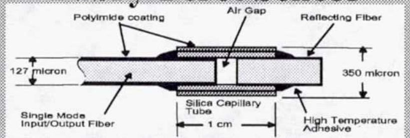


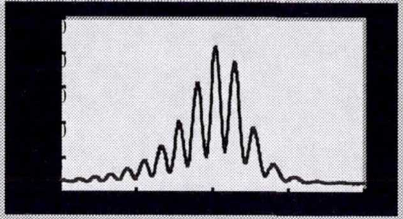
ANALOG SPECTRAL BASED SENSORS



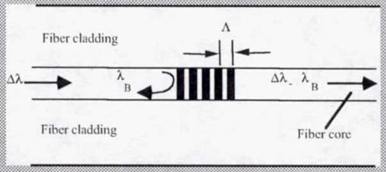
OPTICAL WAVELENGTH BASED SENSORS

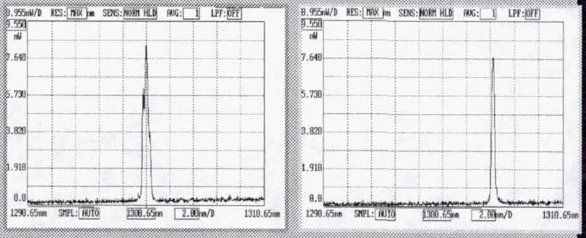
Fabry-Perot Sensor





Bragg Grating Sensor





Room Temperature

300°C

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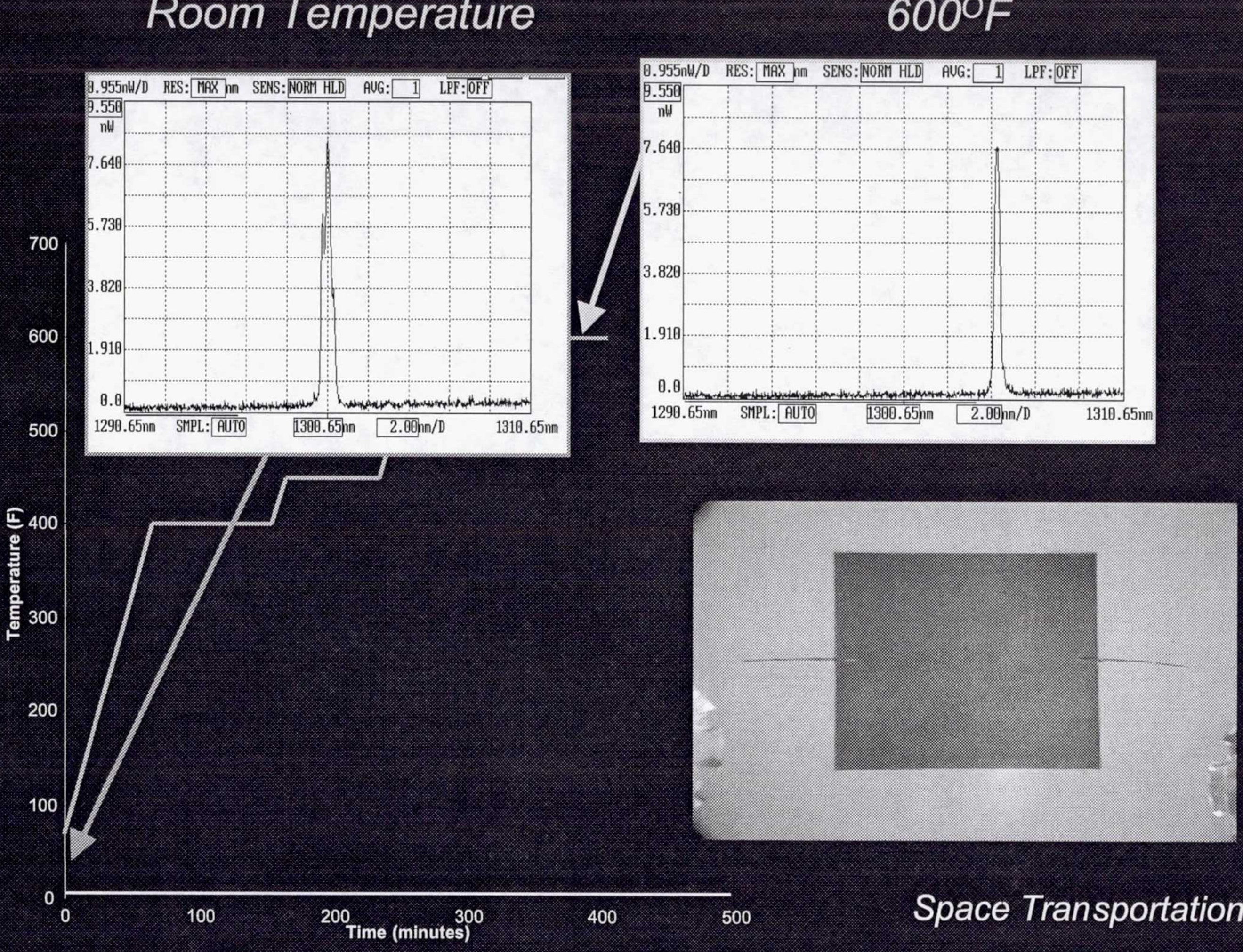
PROPULSION IVHM

Projects: Extreme Environment Sensors

HIGH TEMP. FBG EMBEDDED IN POLYMER MATRIX COMPOSITES



```
0.955nW/D  RES: MAX nm  SENS: NORM HLD  AVG: 1  LPF: OFF
9.550 nW
7.640
5.730
3.820
1.910
0.0
1290.65nm  SMPL: AUTO  1300.65nm  2.00nm/D  1310.65nm
```

```
0.955nW/D  RES: MAX nm  SENS: NORM HLD  AVG: 1  LPF: OFF
9.550 nW
7.640
5.730
3.820
1.910
0.0
1290.65nm  SMPL: AUTO  1300.65nm  2.00nm/D  1310.65nm
```

Embedded Fiber Optic Sensors

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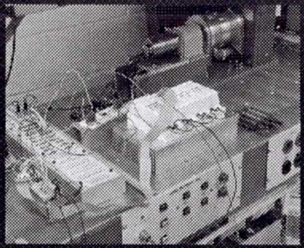
POWER IVHM
Vision

Autonomous EPS Operation

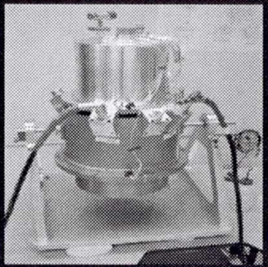
Objectives

- Maximize safety
- Minimize costs
- Maximize dispatch reliability



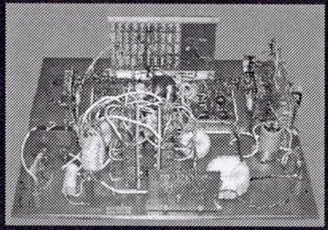
Approach

- Minimize human involvement in power system operations
- Monitor component health
- Manage redundancy



Automate

- Incipient failure detection
- Time-to-failure estimation
- Optimal load management



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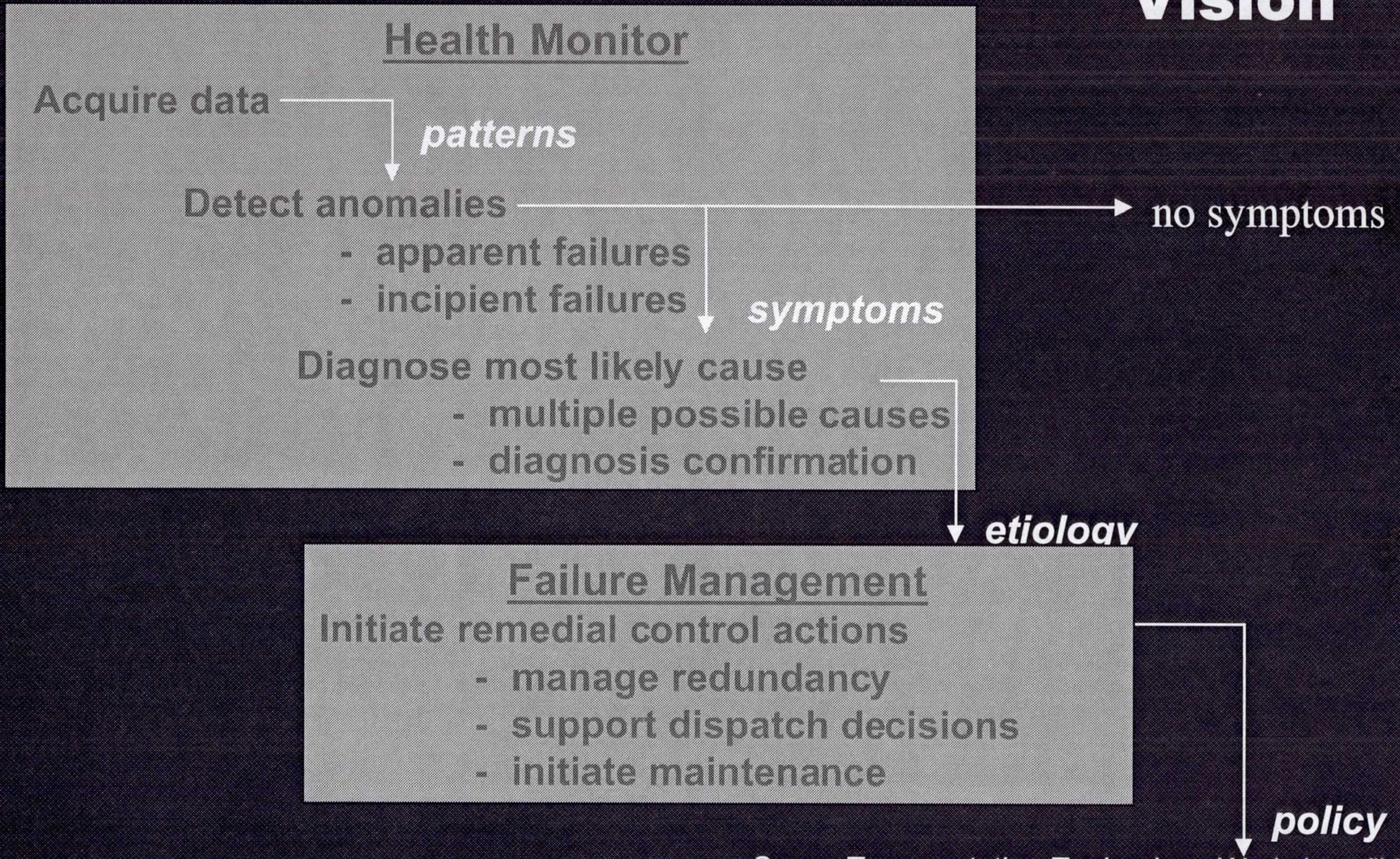
Propulsion & Power IVHM Technologies

POWER IVHM
Vision

- Responsiveness & Dependability
  - **System Flexibility & Operability**
    - Autonomous optimal load management accomplishes in-flight redundancy
  - **System Reliability**
    - Optimal load allocation during partial failures in generation or distribution provides the most functional redundancy for equipment still operating.
  - **Maintainability**
    - Automated failure cause diagnosis eliminates costly manual diagnosis when identifying faulty electrical equipment.

POWER IVHM
Vision



Health Monitor

Acquire data

patterns

Detect anomalies
- apparent failures
- incipient failures

no symptoms

symptoms

Diagnose most likely cause
- multiple possible causes
- diagnosis confirmation

etiology

Failure Management

Initiate remedial control actions
- manage redundancy
- support dispatch decisions
- initiate maintenance

policy

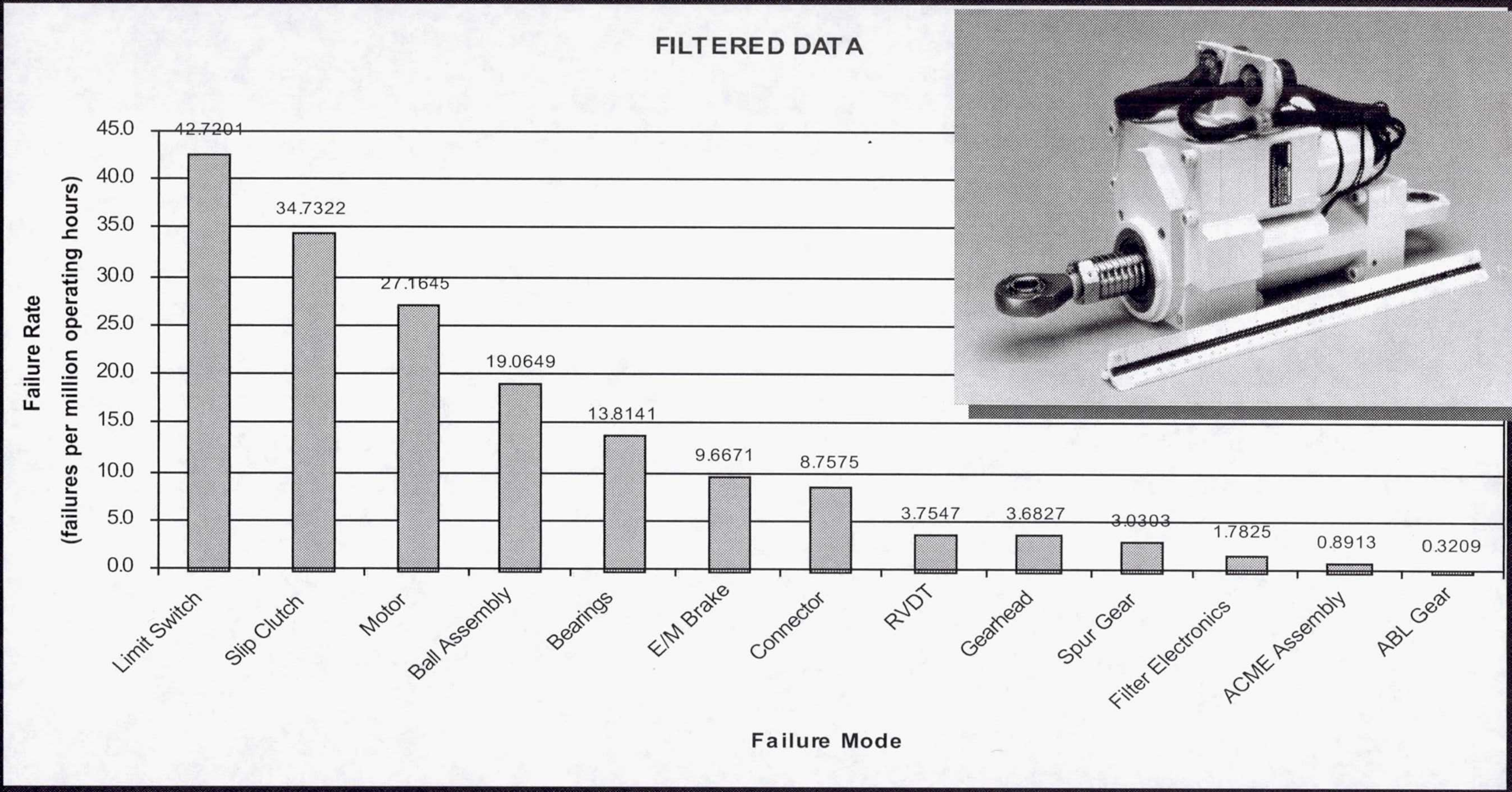
POWER IVHM

Capabilities/Research

- Develop advanced architecture
- Develop expert automated agents continued
  - Flywheel energy storage systems
  - Power distribution control centers
  - Power converters
  - Distribution network wiring
  - Generators
- Develop expert automated agents that are competent in:
  - Planning
  - Scheduling
  - Optimal load management
- Demonstrate using a RLV power system test-bed.

POWER IVHM

Projects: Smart EMA Agent



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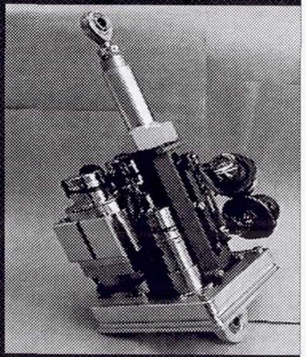
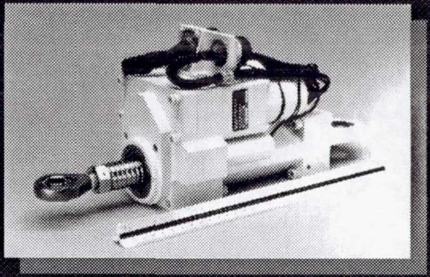
POWER IVHM

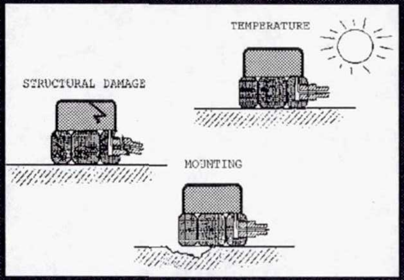
Projects: Smart EMA Agent

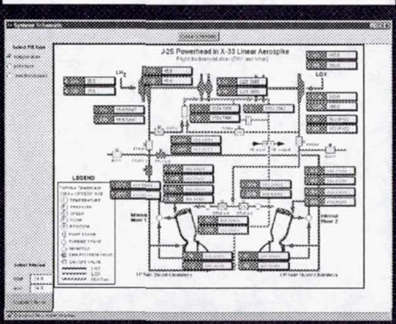
Item / Measurement	Windings	Bearings	Friction Surfaces
Differential Torque	Low	Medium	High
Vibration	Low	High	Medium
Temperature	Medium/High	Medium	Medium/Low
Voltage/ Current	High	Medium/Low	Medium/Low

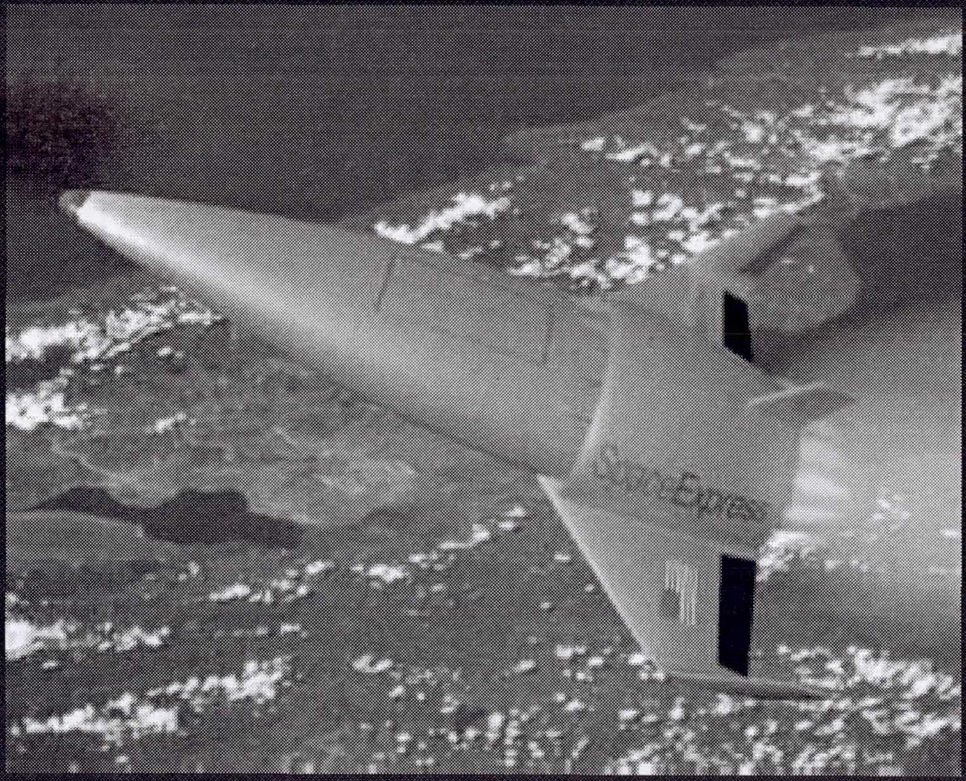


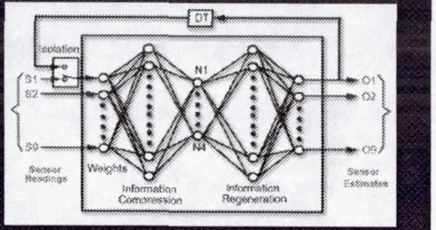
Summary

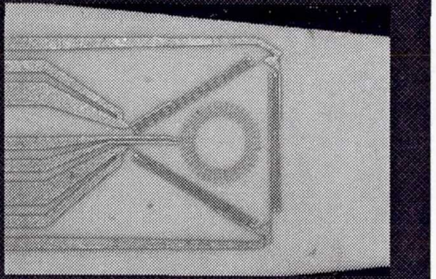


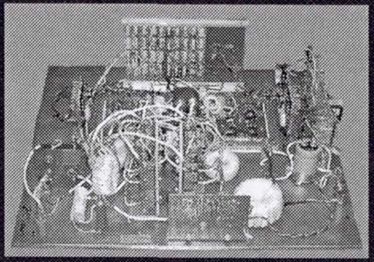












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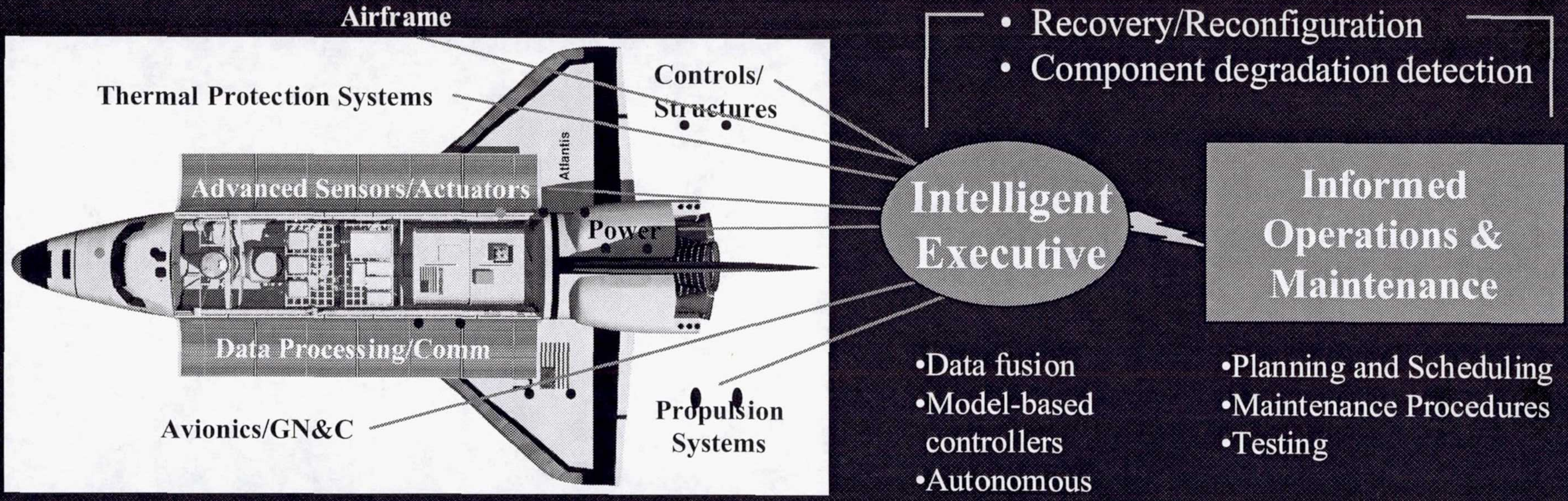
490195 19p

IVHM Systems Engineering & Integration Office

NASA Ames Research Center
POC: Kevin Flynn
650-604-4062
kflynn@mail.arc.nasa.gov

Collect, process, and integrate information about the health of a launch system including the vehicle, subsystems, components, sensors, and ground support systems to make informed decisions and take appropriate actions to ensure the success of a mission

- Anomaly detection and isolation
- Recovery/Reconfiguration
- Component degradation detection

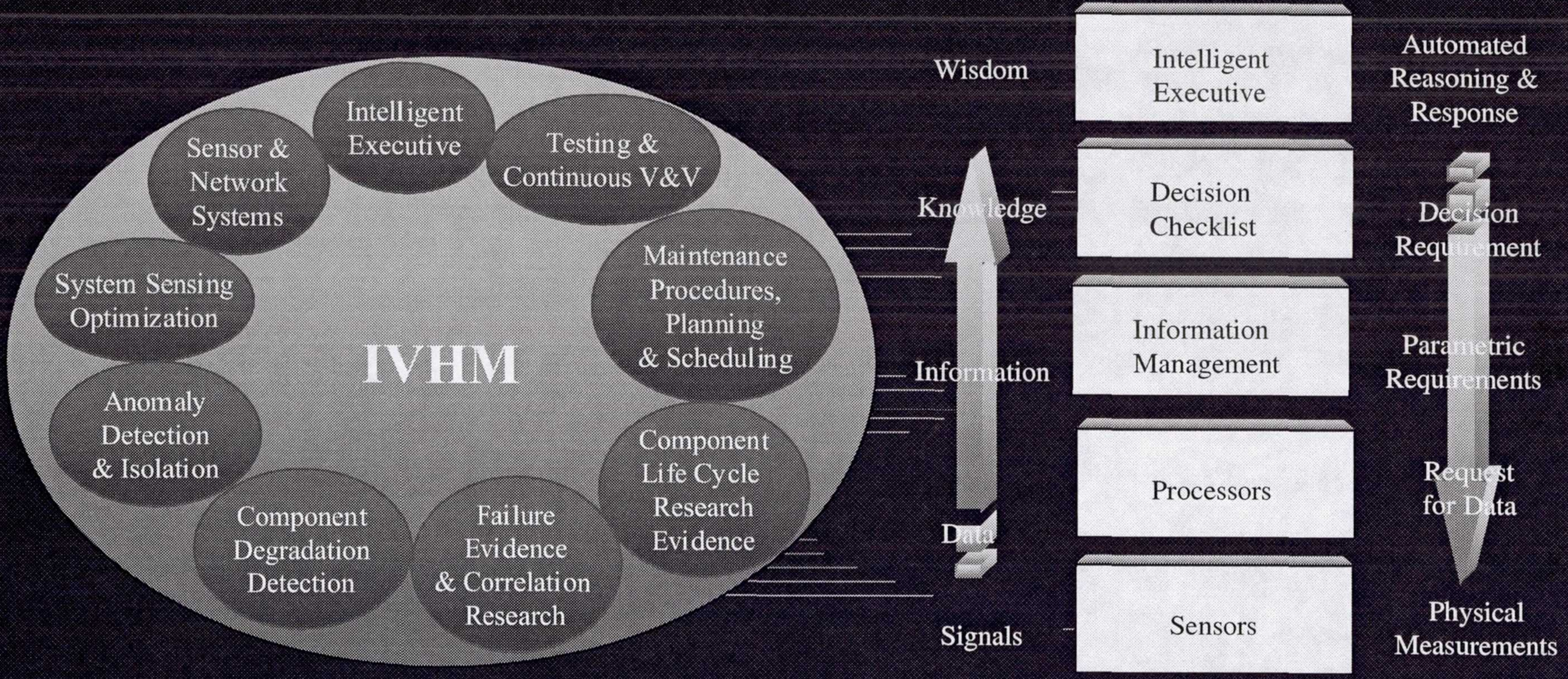


- Data fusion
- Model-based controllers
- Autonomous Software Agents

- Planning and Scheduling
- Maintenance Procedures
- Testing

The Union of Advanced Hardware and Software -
Providing higher reliability, with greater robustness, at lower costs

Integrated Vehicle Health Management:
IVHM



IVHM

Sensor & Network Systems

Intelligent Executive

Testing & Continuous V&V

System Sensing Optimization

Maintenance Procedures, Planning & Scheduling

Anomaly Detection & Isolation

Component Life Cycle Research Evidence

Component Degradation Detection

Failure Evidence & Correlation Research

Wisdom — Intelligent Executive — Automated Reasoning & Response

Knowledge — Decision Checklist — Decision Requirement

Information — Information Management — Parametric Requirements

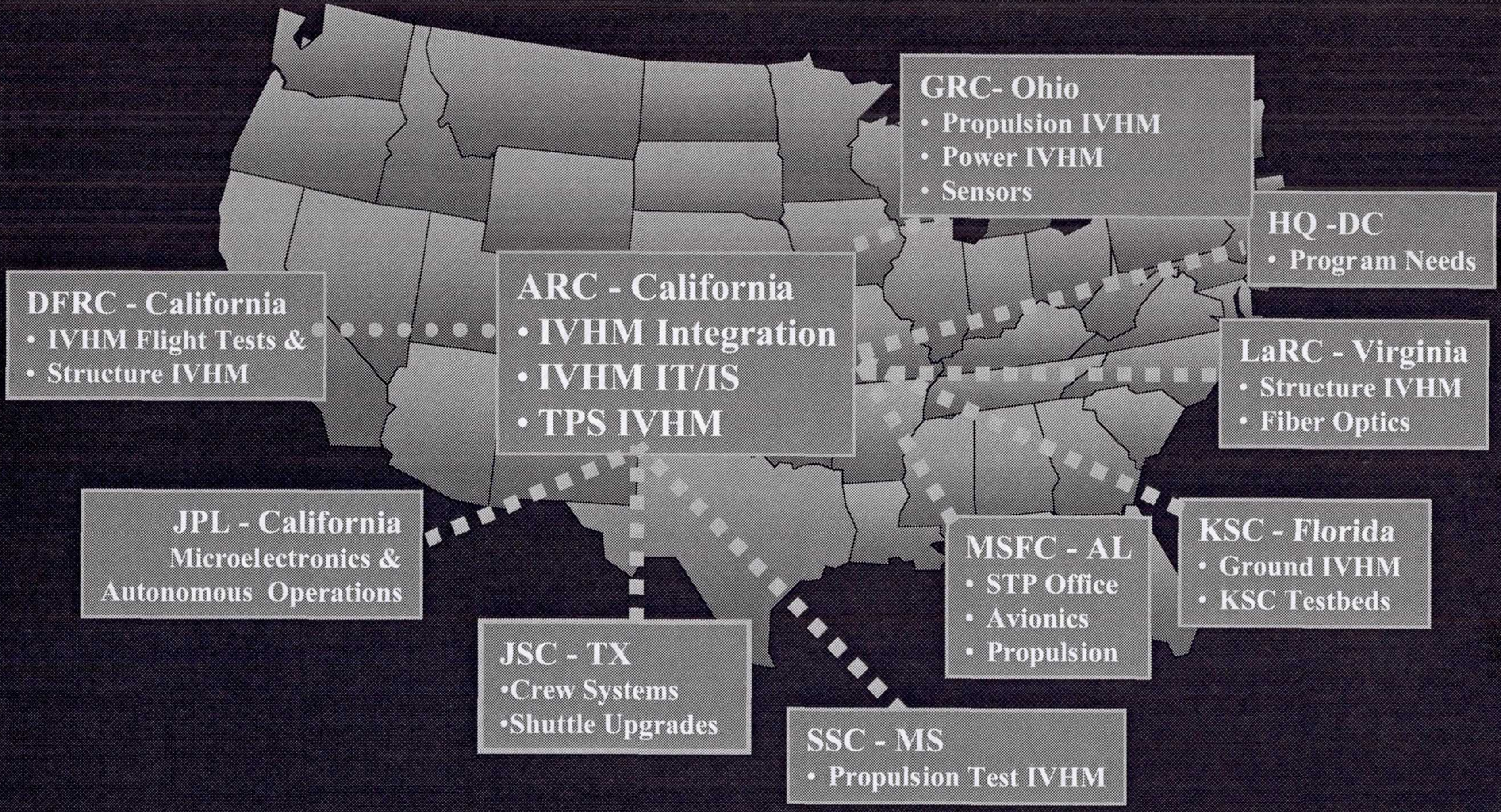
Data — Processors — Request for Data

Signals — Sensors — Physical Measurements

SE&I helps these IVHM pieces work together to meet the goals

Integrated Vehicle Health Management:

IVHM: Convert Data into Knowledge



GRC- Ohio
- Propulsion IVHM
- Power IVHM
- Sensors

HQ -DC
- Program Needs

DFRC - California
- IVHM Flight Tests &
- Structure IVHM

ARC - California
- IVHM Integration
- IVHM IT/IS
- TPS IVHM

LaRC - Virginia
- Structure IVHM
- Fiber Optics

JPL - California
Microelectronics &
Autonomous Operations

MSFC - AL
- STP Office
- Avionics
- Propulsion

KSC - Florida
- Ground IVHM
- KSC Testbeds

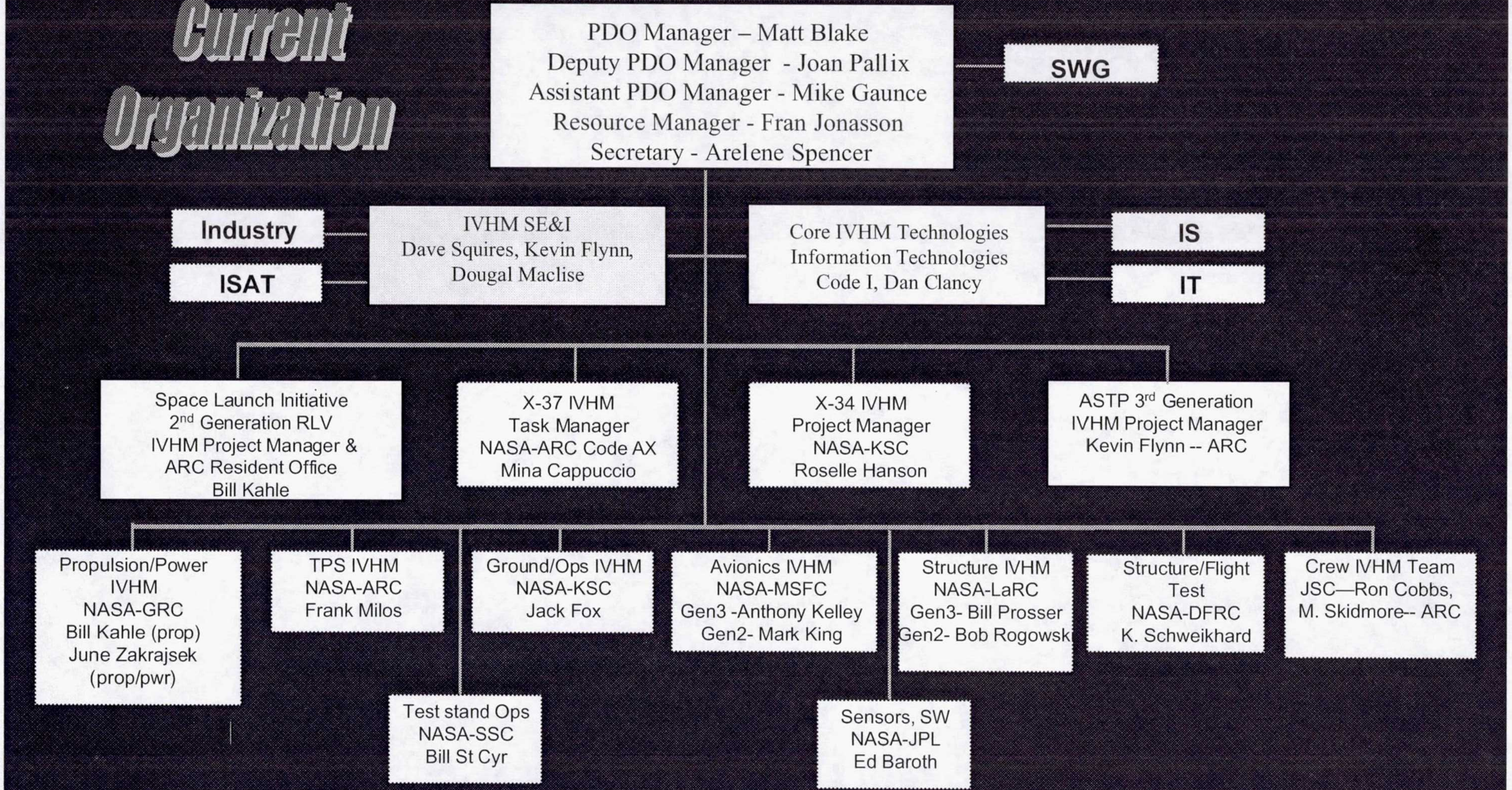
JSC - TX
- Crew Systems
- Shuttle Upgrades

SSC - MS
- Propulsion Test IVHM

Integrated Vehicle Health Management:

Space Transportation Inter-Center IVHM Team

Current Organization



PDO Manager – Matt Blake
Deputy PDO Manager - Joan Pallix
Assistant PDO Manager - Mike Gaunce
Resource Manager - Fran Jonasson
Secretary - Arelene Spencer

SWG

Industry

ISAT

IVHM SE&I
Dave Squires, Kevin Flynn,
Dougal Maclise

Core IVHM Technologies
Information Technologies
Code I, Dan Clancy

IS

IT

Space Launch Initiative
2nd Generation RLV
IVHM Project Manager &
ARC Resident Office
Bill Kahle

X-37 IVHM
Task Manager
NASA-ARC Code AX
Mina Cappuccio

X-34 IVHM
Project Manager
NASA-KSC
Roselle Hanson

ASTP 3rd Generation
IVHM Project Manager
Kevin Flynn -- ARC

Propulsion/Power
IVHM
NASA-GRC
Bill Kahle (prop)
June Zakrajsek
(prop/pwr)

TPS IVHM
NASA-ARC
Frank Milos

Ground/Ops IVHM
NASA-KSC
Jack Fox

Avionics IVHM
NASA-MSFC
Gen3 -Anthony Kelley
Gen2- Mark King

Structure IVHM
NASA-LaRC
Gen3- Bill Prosser
Gen2- Bob Rogowsk

Structure/Flight
Test
NASA-DFRC
K. Schweikhard

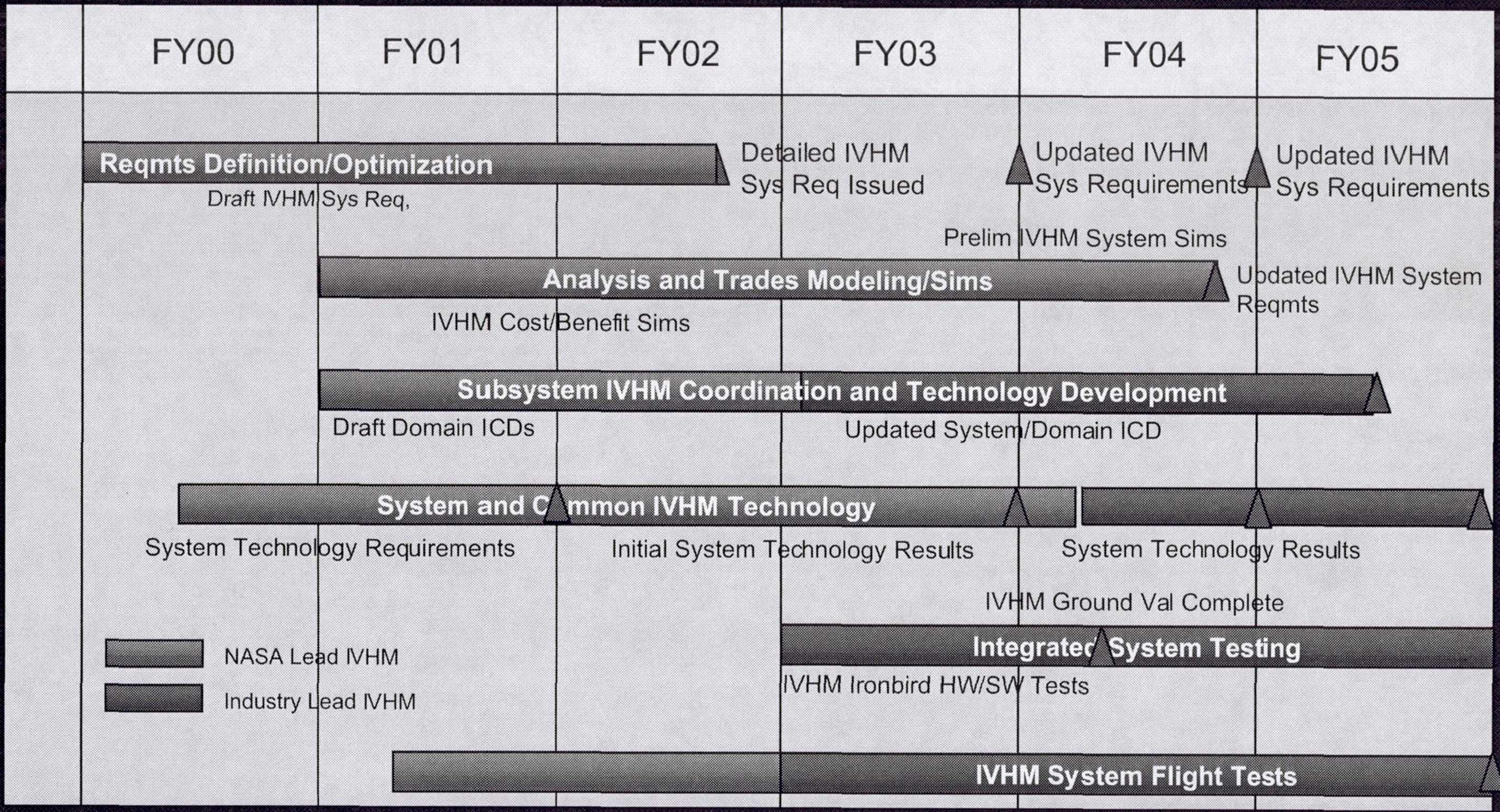
Crew IVHM Team
JSC—Ron Cobbs,
M. Skidmore-- ARC

Test stand Ops
NASA-SSC
Bill St Cyr

Sensors, SW
NASA-JPL
Ed Baroth

Integrated Vehicle Health Management:

Current IVHM Organization



FY00

FY01

FY02

FY03

FY04

FY05

Reqmts Definition/Optimization

Draft IVHM Sys Req,

Detailed IVHM Sys Req Issued

Updated IVHM Sys Requirements

Updated IVHM Sys Requirements

Prelim IVHM System Sims

Analysis and Trades Modeling/Sims

Updated IVHM System Reqmts

IVHM Cost/Benefit Sims

Subsystem IVHM Coordination and Technology Development

Draft Domain ICDs

Updated System/Domain ICD

System and Common IVHM Technology

System Technology Requirements

Initial System Technology Results

System Technology Results

IVHM Ground Val Complete

Integrated System Testing

IVHM Ironbird HW/SW Tests

▭ NASA Lead IVHM

▭ Industry Lead IVHM

IVHM System Flight Tests

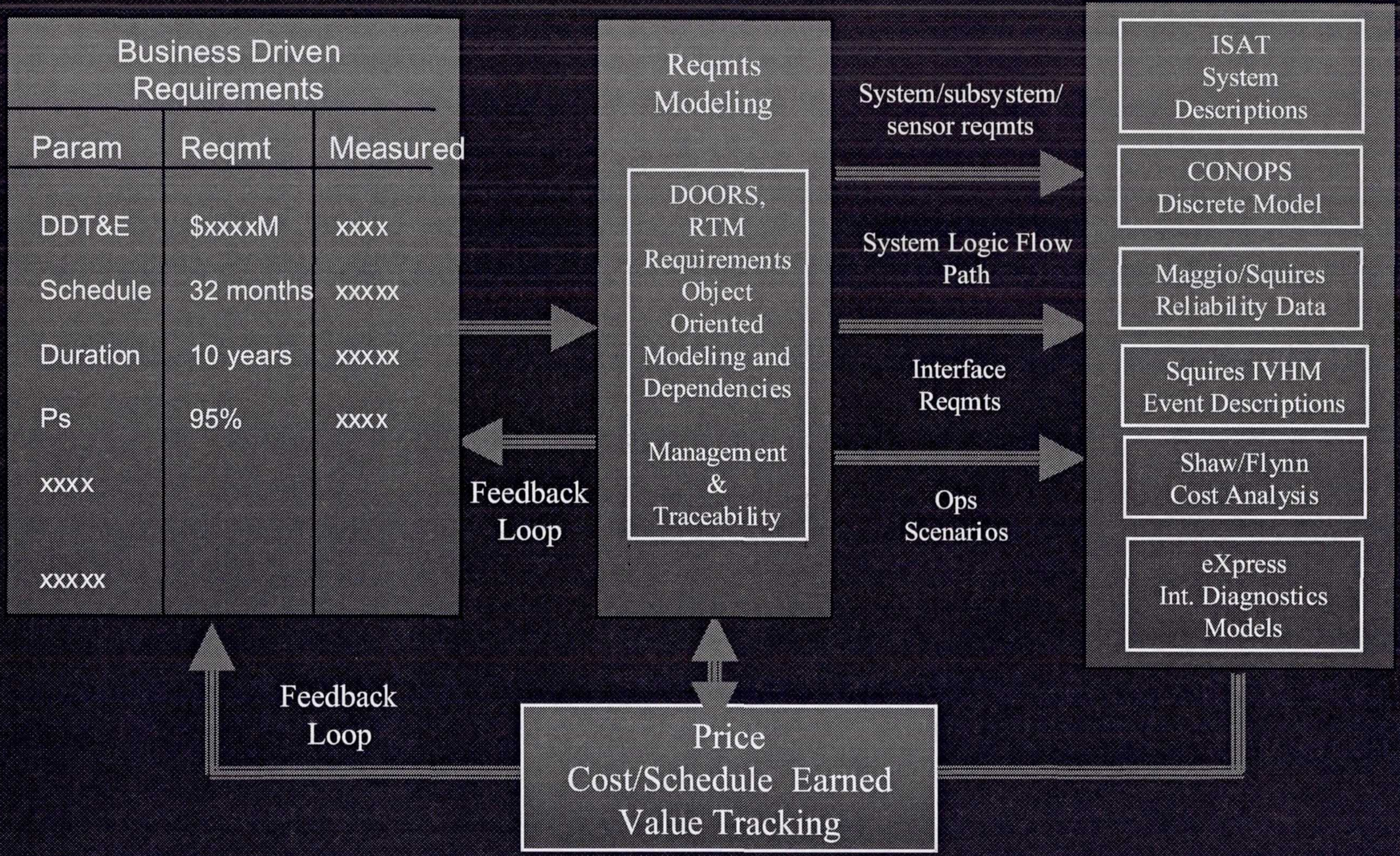
Integrated Vehicle Health Management:

IVHM Systems Integration Project

- IVHM Technologists at other NASA centers
- ISAT
  - **IVHM, new ISAT discipline**
  - **Safety& Reliability**
  - **Economics**
  - **Performance effects**
- MSFC
  - **2nd gen, SE&I**
  - **3rd gen, ASTP**
  - **Operability branch**
- LaRC
  - **Maintainability branch**
- ARC
  - **Systems Analysis branch**
  - **Space Transportation Projects Office**
  - **System Engineering division**
  - **IT directorate**
  - **Thermal Physics branch**
  - **Space payloads branch**
- Industry
  - **Boeing (Seal Bch) NRA 8-27**
  - **DSI International (eXpress modeling tool)**
  - **USA (providing shuttle data)**

Integrated Vehicle Health Management:

IVHM SE&I Working Relationships



Business Driven Requirements

Param	Reqmt	Measured
DDT&E	$xxxxM	xxxx
Schedule	32 months	xxxxx
Duration	10 years	xxxxx
Ps	95%	xxxx
xxxx		
xxxxx		

Reqmts Modeling

DOORS, RTM Requirements Object Oriented Modeling and Dependencies

Management & Traceability

Feedback Loop

System/subsystem/ sensor reqmts

System Logic Flow Path

Interface Reqmts

Ops Scenarios

ISAT System Descriptions

CONOPS Discrete Model

Maggio/Squires Reliability Data

Squires IVHM Event Descriptions

Shaw/Flynn Cost Analysis

eXpress Int. Diagnostics Models

Feedback Loop

Price Cost/Schedule Earned Value Tracking

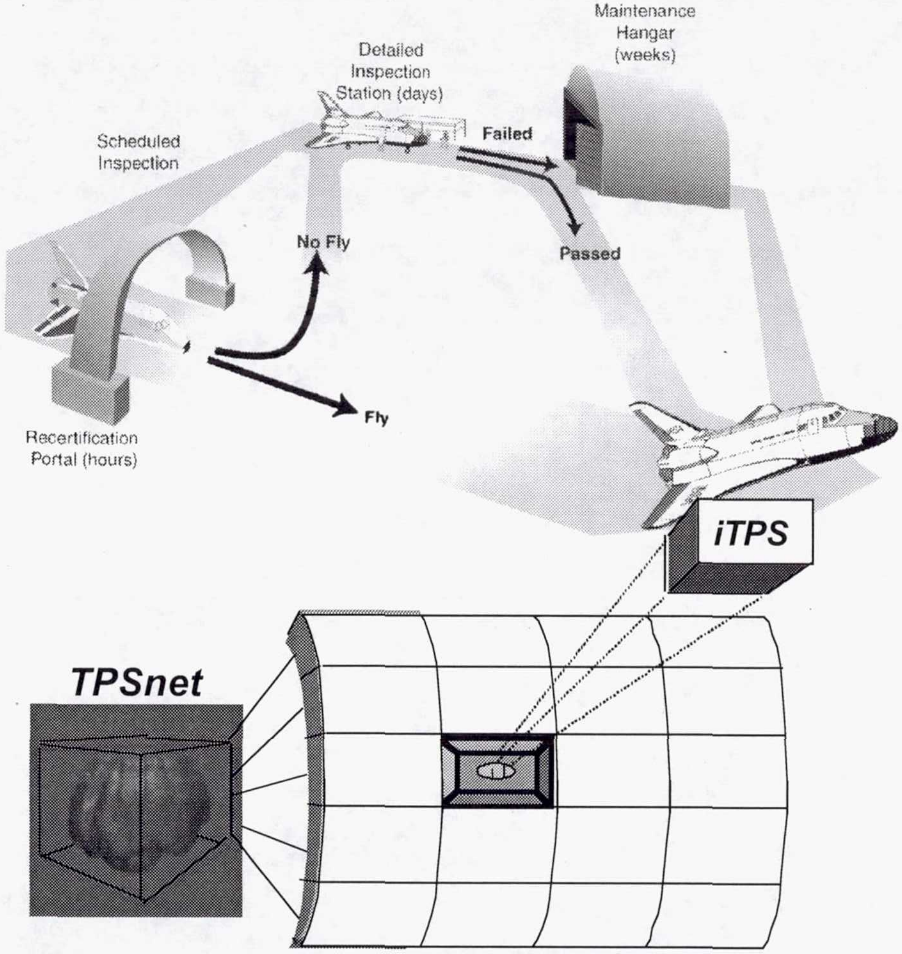
Integrated Vehicle Health Management:

IVHM SE&I Simplified Process Model

Benefit vs Cost Structure

- **Affordability**
  - Minimum LCC
  - Non-recurring Costs
    - Tech investment
    - Acquisition
    - PPPI
  - Recurring Costs
    - Low Sensitivity To Growth
    - Operations & Maintenance
    - Vehicle / System Replacement
    - LV/Booster Prep
    - Insertion to LEO & Assist
    - Payload Integration
    - Insertion to LEO w/ CTV or CRV
- **Dependability**
  - System Reliability
    - LOM
    - LOV
    - LOC
    - Fault Detection
    - False Alarms
  - Operate to Command
  - Robustness
    - Margin
  - No unplanned maintenance
- **Responsiveness**
  - Flexibility
  - Capacity per Vehicle / System
    - Vehicle capacity/ Year
    - System capacity/ Year
  - Operability
    - Fault Isolation
    - Maintainable
    - Touch/non-touch labor
    - Optimize repair time
    - Limit false repair & reconfig
  - Launch On Demand
    - *Op Availability*
    - False Alarm Rate
  - Ease of Vehicle / System Integration
    - Simplicity
    - Resiliency
- **Safety**
  - Vehicle
  - Crew
  - Public
  - Facility
- **Public Support**
  - Environment
  - Public Opinion

Smart TPS Demo – Risk Reduction Is Underway



Shuttle/2nd Gen Smart TPS

- Saves thousands of hours of inspection (touch and non-touch)
- Eliminates the need for set up of scaffolding
- Eliminates the need to disassemble the vehicle to inspect for subsurface defects
- Enabling for 24 hour turnaround 3rd gen goal

Integrated Vehicle Health Management:

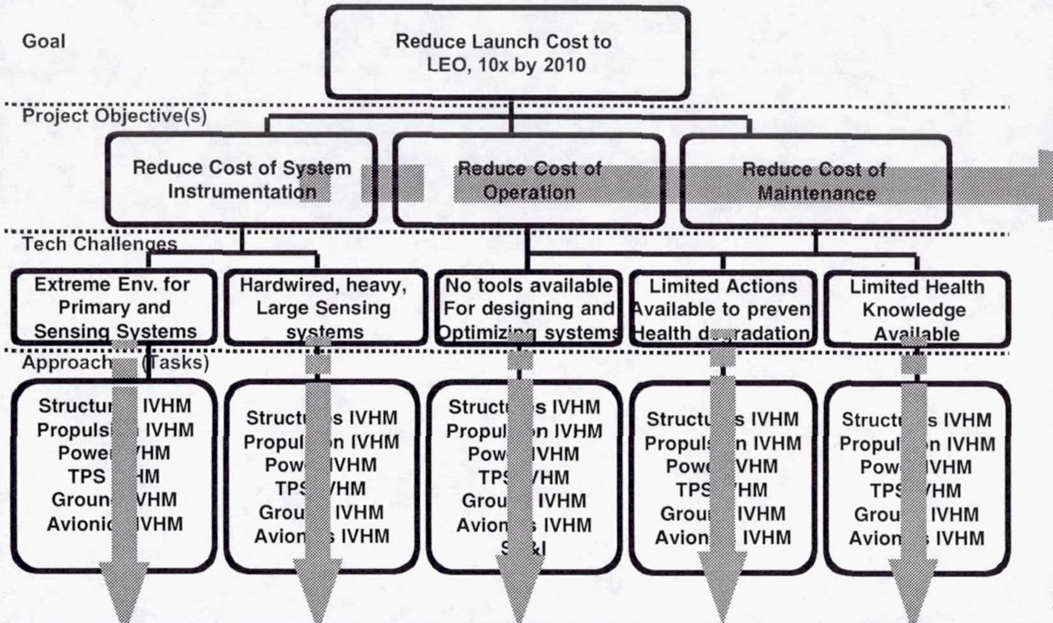
Example of an IVHM technology: TPS IVHM

3rd Gen Adaptive Intelligent TPS:

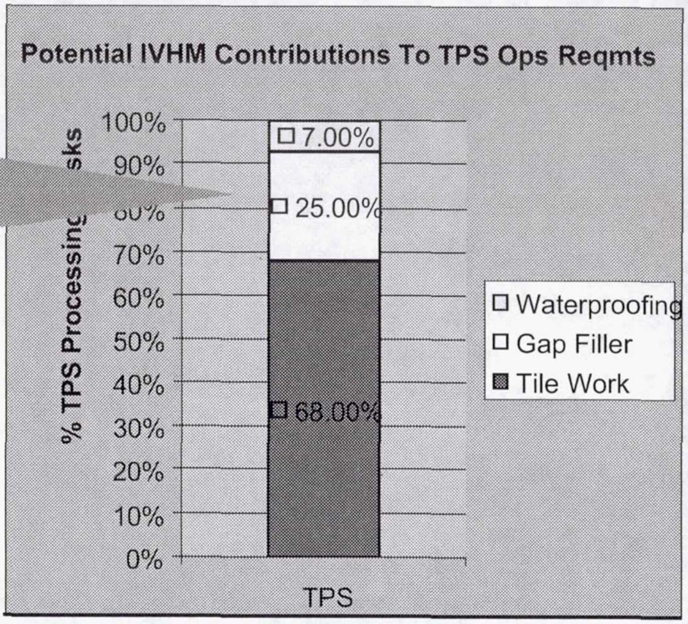
- Evolvable architecture

IVHM Processes Establish Traceability To Program Goals

TPS IVHM Example



Technology	Use for Ref.	Weight reduction	Vehicle Cost Reduction	Ops Cost Reduction	System Reliability Improvement	Safety Improvement	Current Funded Program
IVHM							
Avionics IVHM							
Distributed Architecture/RHNs	a	0/+	0	0	+	0	X33,2nd
FO Network	a	+	0	-	0	+	X33,2nd
Advanced Instrumentation	r	+	0	+	+	+	2nd
TPS IVHM							
Advanced MEMs For On-Board Gap and Overheat	a	0	0	+	+	+	X37, Shuttle, 2nd Gen?
On-Board Neural Network TPS Sensor Models	a	0	0	+	+	+	X37, Shuttle, 2nd Gen?
TPS Smart Sensor and Validation Algorithms	a	0	0	+	+	+	X37, Shuttle, 2nd Gen?
Ground Based Hand-Held NDE/NDI	a	0	0	+	+	+	X37, Shuttle, 2nd Gen?

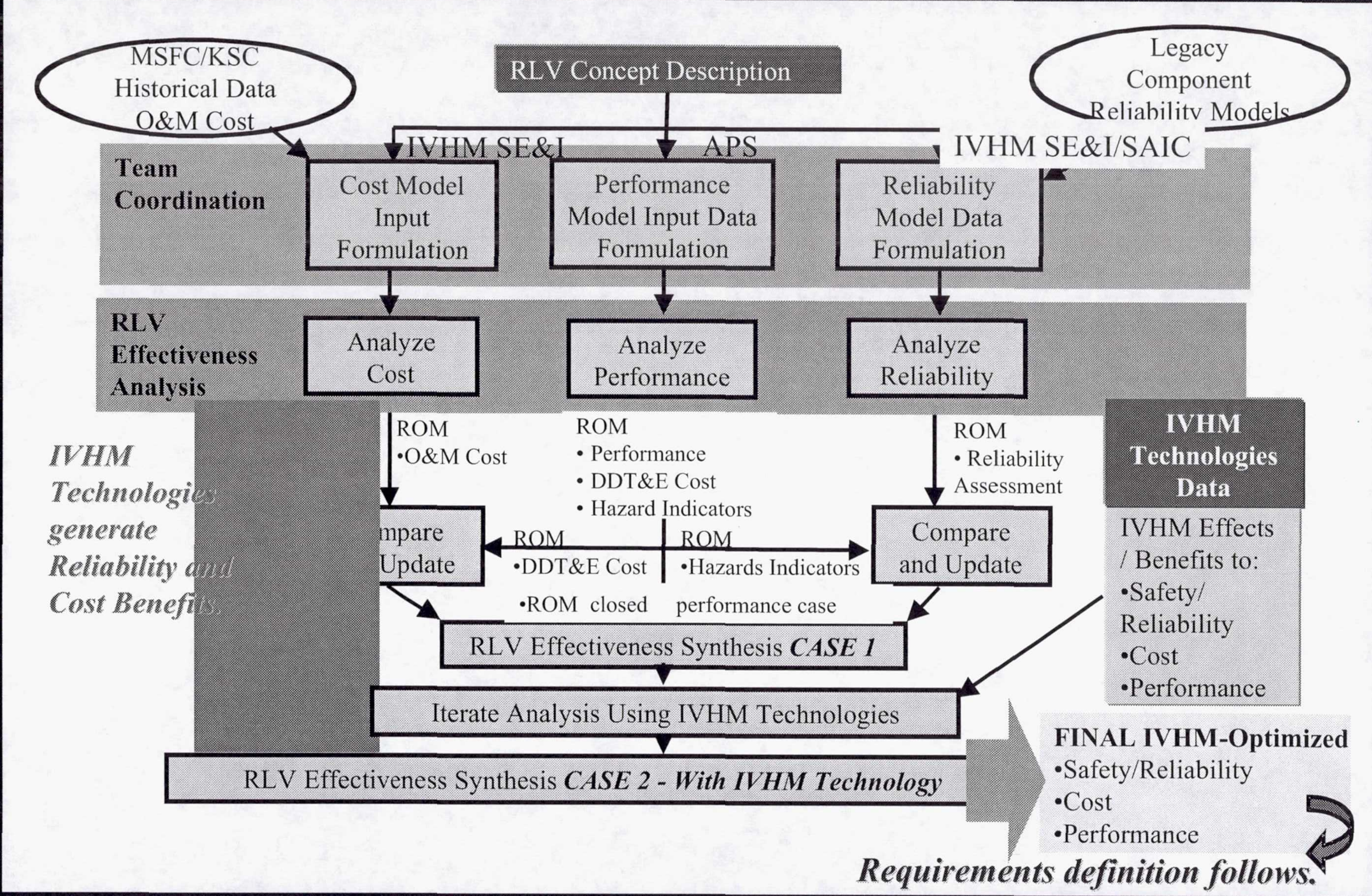


34,000 hrs/flow x 25% (gap filler/barrier) = 8,500 hrs/flow (Touch)
30,000 hrs/flow x 25% = 7,500 hrs/flow (Non)
64,000 hrs/flow x 25% (Total labor) = 16,000 hrs/flow
$3.05M/flow x 25% = $7.0M/Flow

Demonstrate Repeatability on RLV IVHM Airframe Testbeds

Integrated Vehicle Health Management:

IVHM SE&I manages traceability to program goals



MSFC/KSC
Historical Data
O&M Cost

RLV Concept Description

Legacy
Component
Reliability Models

IVHM SE&I

APS

IVHM SE&I/SAIC

Team Coordination

Cost Model Input Formulation

Performance Model Input Data Formulation

Reliability Model Data Formulation

RLV Effectiveness Analysis

Analyze Cost

Analyze Performance

Analyze Reliability

ROM
•O&M Cost

ROM
- Performance
- DDT&E Cost
- Hazard Indicators

ROM
- Reliability Assessment

IVHM Technologies generate Reliability and Cost Benefits.

IVHM Technologies Data

IVHM Effects / Benefits to:
•Safety/ Reliability
•Cost
•Performance

mpare Update

ROM
•DDT&E Cost
•ROM closed

ROM
•Hazards Indicators
performance case

Compare and Update

RLV Effectiveness Synthesis ***CASE 1***

Iterate Analysis Using IVHM Technologies

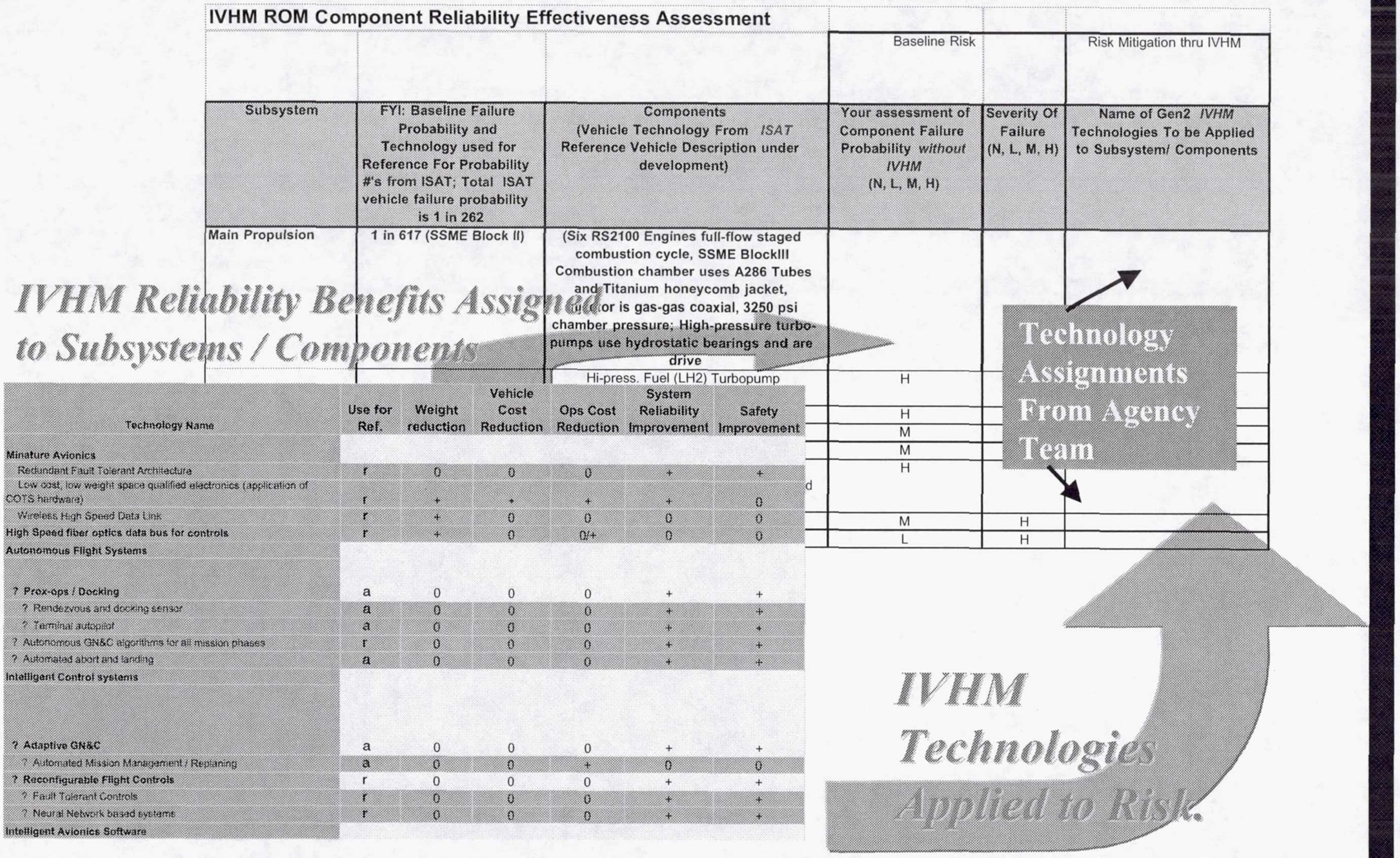
RLV Effectiveness Synthesis ***CASE 2 - With IVHM Technology***

FINAL IVHM-Optimized
•Safety/Reliability
•Cost
•Performance

Requirements definition follows.

Integrated Vehicle Health Management:

Interim IVHM Analysis Approach



IVHM ROM Component Reliability Effectiveness Assessment

			Baseline Risk		Risk Mitigation thru IVHM
Subsystem	FYI: Baseline Failure Probability and Technology used for Reference For Probability #'s from ISAT; Total ISAT vehicle failure probability is 1 in 262	Components (Vehicle Technology From *ISAT* Reference Vehicle Description under development)	Your assessment of Component Failure Probability *without IVHM* (N, L, M, H)	Severity Of Failure (N, L, M, H)	Name of Gen2 *IVHM* Technologies To be Applied to Subsystem/ Components
Main Propulsion	1 in 617 (SSME Block II)	(Six RS2100 Engines full-flow staged combustion cycle, SSME BlockIII Combustion chamber uses A286 Tubes and Titanium honeycomb jacket, [illegible]tor is gas-gas coaxial, 3250 psi chamber pressure; High-pressure turbo-pumps use hydrostatic bearings and are drive			
		Hi-press. Fuel (LH2) Turbopump	H		
			H		
			M		
			M		
		d	H		
			M	H	
			L	H	

IVHM Reliability Benefits Assigned to Subsystems / Components

Technology Name	Use for Ref.	Weight reduction	Vehicle Cost Reduction	Ops Cost Reduction	System Reliability Improvement	Safety Improvement
Minature Avionics						
Redundant Fault Tolerant Architecture	r	0	0	0	+	+
Low cost, low weight space qualified electronics (application of COTS hardware)	r	+	+	+	+	0
Wireless High Speed Data Link	r	+	0	0	0	0
High Speed fiber optics data bus for controls	r	+	0	0/+	0	0
Autonomous Flight Systems						
? Prox-ops / Docking	a	0	0	0	+	+
? Rendezvous and docking sensor	a	0	0	0	+	+
? Terminal autopilot	a	0	0	0	+	+
? Autonomous GN&C algorithms for all mission phases	r	0	0	0	+	+
? Automated abort and landing	a	0	0	0	+	+
Intelligent Control systems						
? Adaptive GN&C	a	0	0	0	+	+
? Automated Mission Management / Replaning	a	0	0	+	0	0
? Reconfigurable Flight Controls	r	0	0	0	+	+
? Fault Tolerant Controls	r	0	0	0	+	+
? Neural Network based systems	r	0	0	0	+	+
Intelligent Avionics Software						

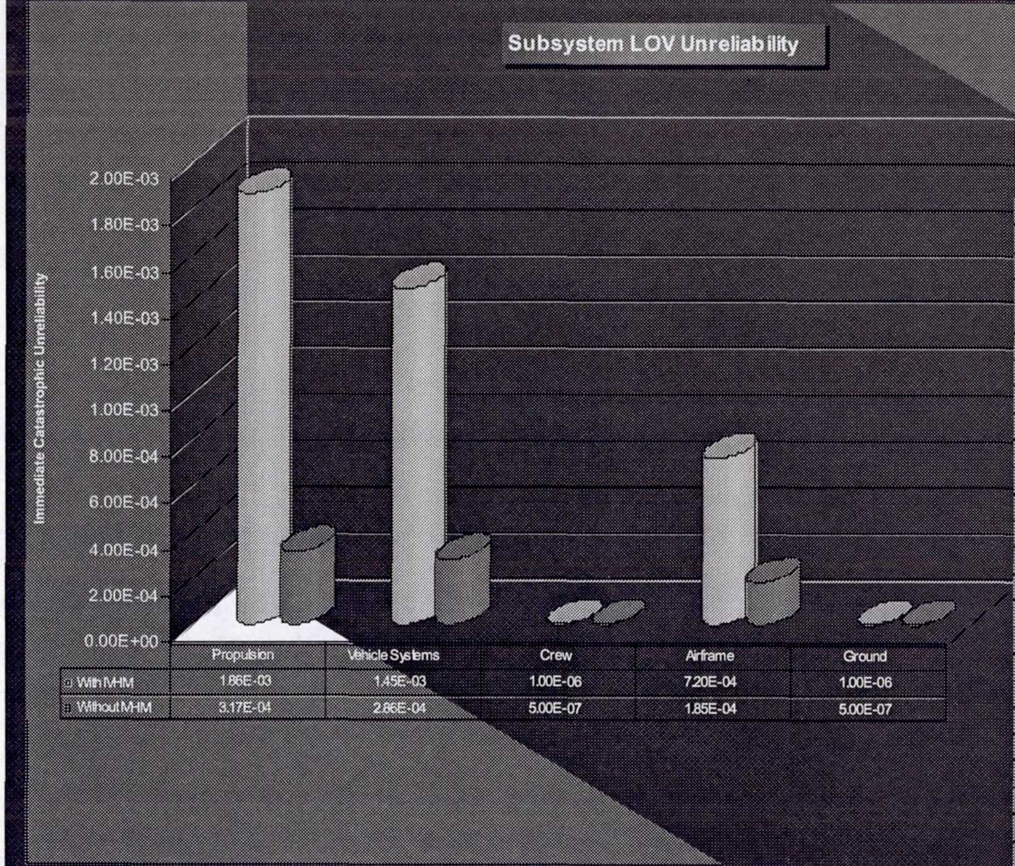
Technology Assignments From Agency Team

IVHM Technologies Applied to Risk.

Integrated Vehicle Health Management:

Technology Plan Linked to Reliability Analysis

Draft Data for Illustration Purposes Only



	Propulsion	Vehicle Systems	Crew	Airframe	Ground
▫ With IVHM	1.86E-03	1.45E-03	1.00E-06	7.20E-04	1.00E-06
▪ Without IVHM	3.17E-04	2.86E-04	5.00E-07	1.85E-04	5.00E-07

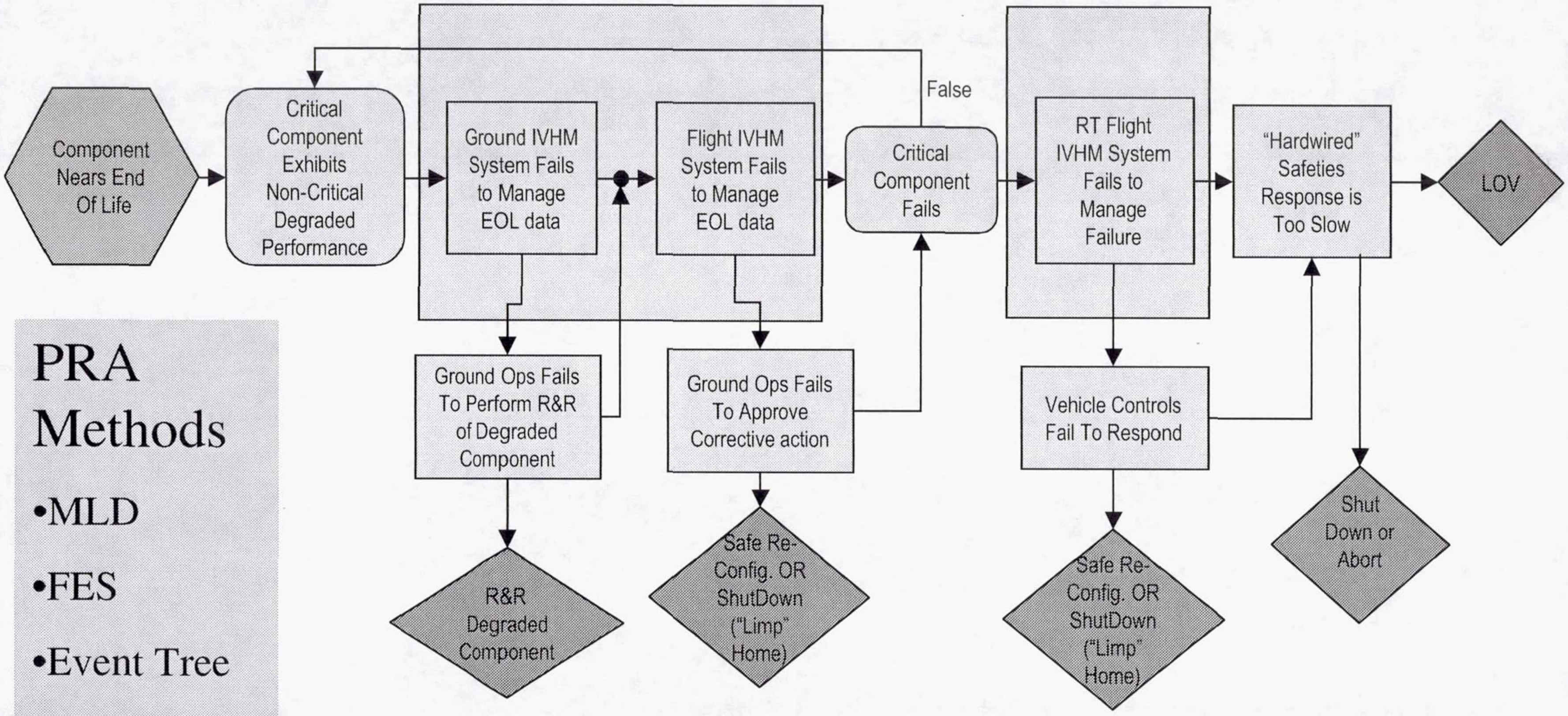
Subsystem/IVHM Technology ICU	ICU-RLV Alone	ICU-RLV w/ IVHM	1/ICU-RLV Alone	1/ICU-RLV w/ IVHM
Propulsion	**1.86E-03**	**3.17E-04**	**537**	**3158**
Engine	1.62E-03	2.44E-04	617	4095
Feed System	3.52E-05	6.40E-06	28409	156250
Main Propelant Containment	1.92E-04	6.40E-05	5208	15624
RCS and OMS	1.39E-05	1.99E-06	71942	503594
Vehicle Systems	**1.45E-03**	**2.86E-04**	**688**	**3502**
Avionics	1.00E-04	3.55E-05	10000	28182
Actuator Power	1.13E-03	1.62E-04	882	6174
Actuators & Control Surfaces	2.16E-04	8.64E-05	4630	11575
Purge Vent and Drain	1.00E-06	4.29E-07	1000000	2333333
Flight Termination	1.00E-06	2.50E-07	1000000	4000000
Other	1.00E-06	1.00E-06	1000000	1000000
Airframe	**7.20E-04**	**1.85E-04**	**1389**	**5412**
Thermal Protection	6.19E-04	1.55E-04	1616	6464
Airframe Structure	1.00E-04	2.97E-05	10000	33636
Undercarriage	1.00E-06	3.33E-07	1000000	3000000
Crew	1.00E-06	5.00E-07	1000000	2000000
Personnel Provision (N/A)	1.00E-06	5.00E-07	1000000	2000000
Ground	1.00E-06	5.00E-07	1000000	2000000
Total	**4.03E-03**	**7.87E-04**	**248**	**1271**

Integrated Vehicle Health Management:

LOV Reliability Analysis Providing IVHM Subsystem Allocations

TOP LEVEL IVHM GENERIC FUNCTIONAL EVENT SEQUENCE

(Payload-Only Mission Scenario)



Component Nears End Of Life

Critical Component Exhibits Non-Critical Degraded Performance

Ground IVHM System Fails to Manage EOL data

Ground Ops Fails To Perform R&R of Degraded Component

R&R Degraded Component

Flight IVHM System Fails to Manage EOL data

Ground Ops Fails To Approve Corrective action

Safe Re-Config. OR ShutDown ("Limp" Home)

Critical Component Fails

False

RT Flight IVHM System Fails to Manage Failure

Vehicle Controls Fail To Respond

Safe Re-Config. OR ShutDown ("Limp" Home)

"Hardwired" Safeties Response is Too Slow

Shut Down or Abort

LOV

PRA Methods

- MLD
- FES
- Event Tree
- Fault Trees

Integrated Vehicle Health Management:

How does IVHM effect Failure Modes?

Ops Cost Savings on SSTO RLV due to IVHM

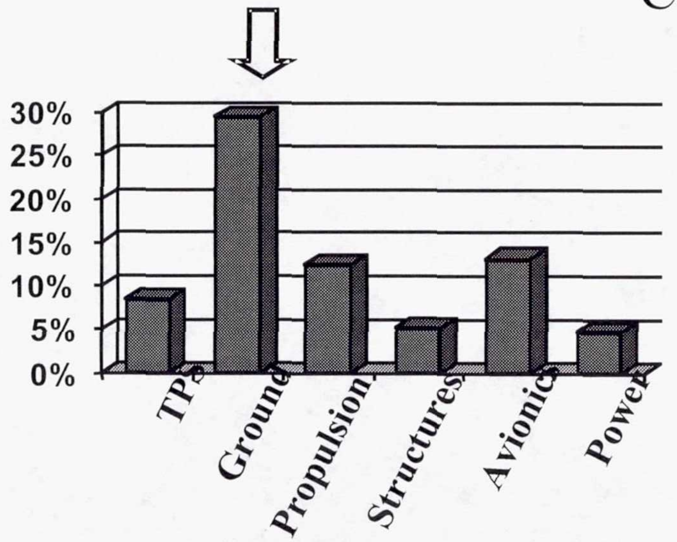
Launch Ops
Vehicle Processing
Process Eng
Recovery Ops
Fixed Support
Facility O&M
Base Support
Propellant Mgt.
GSE Spares

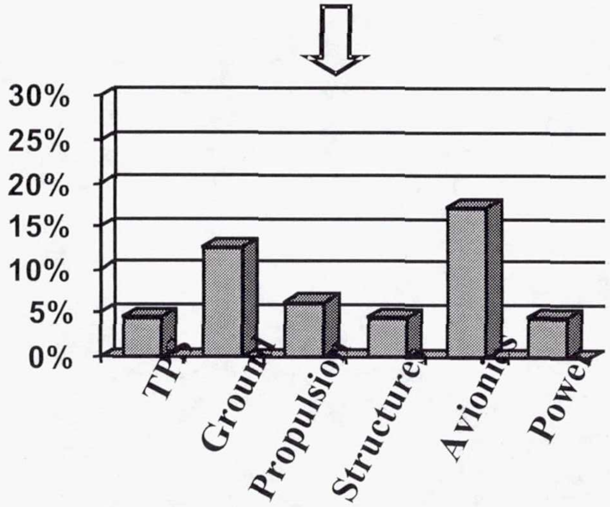
73 %
Reduction in cost due to IVHM

50 %
Reduction in cost due to IVHM

Flight Ops
Flight Planning
Mission S/Ware
Simulation/Training
Mission Control O&M
System Integration
Payload Analysis
Crew Ops
Fixed Support
General Mgt.
Network Support

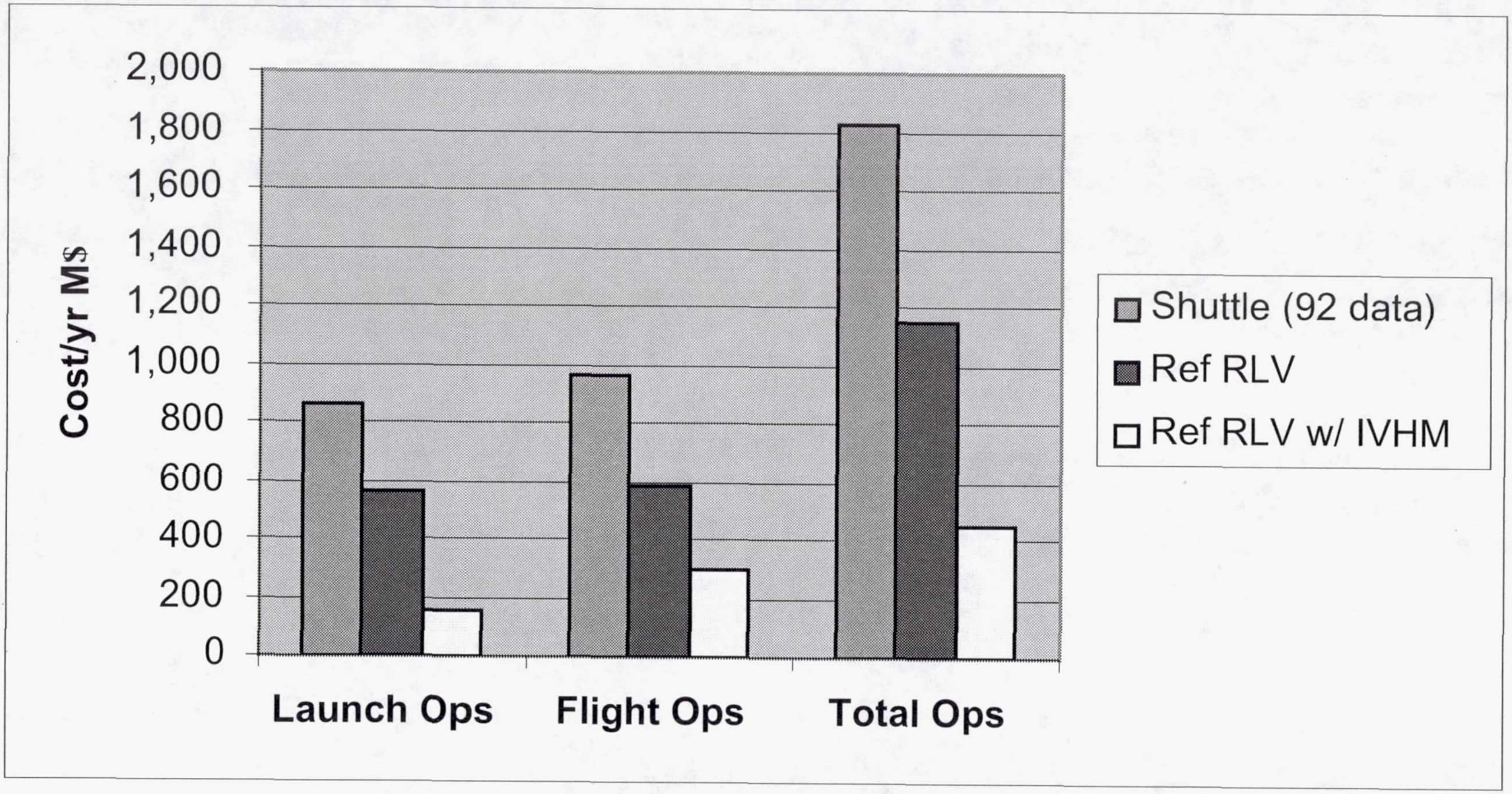
IVHM Technology Categories





Integrated Vehicle Health Management:

Ops Cost Savings due to IVHM



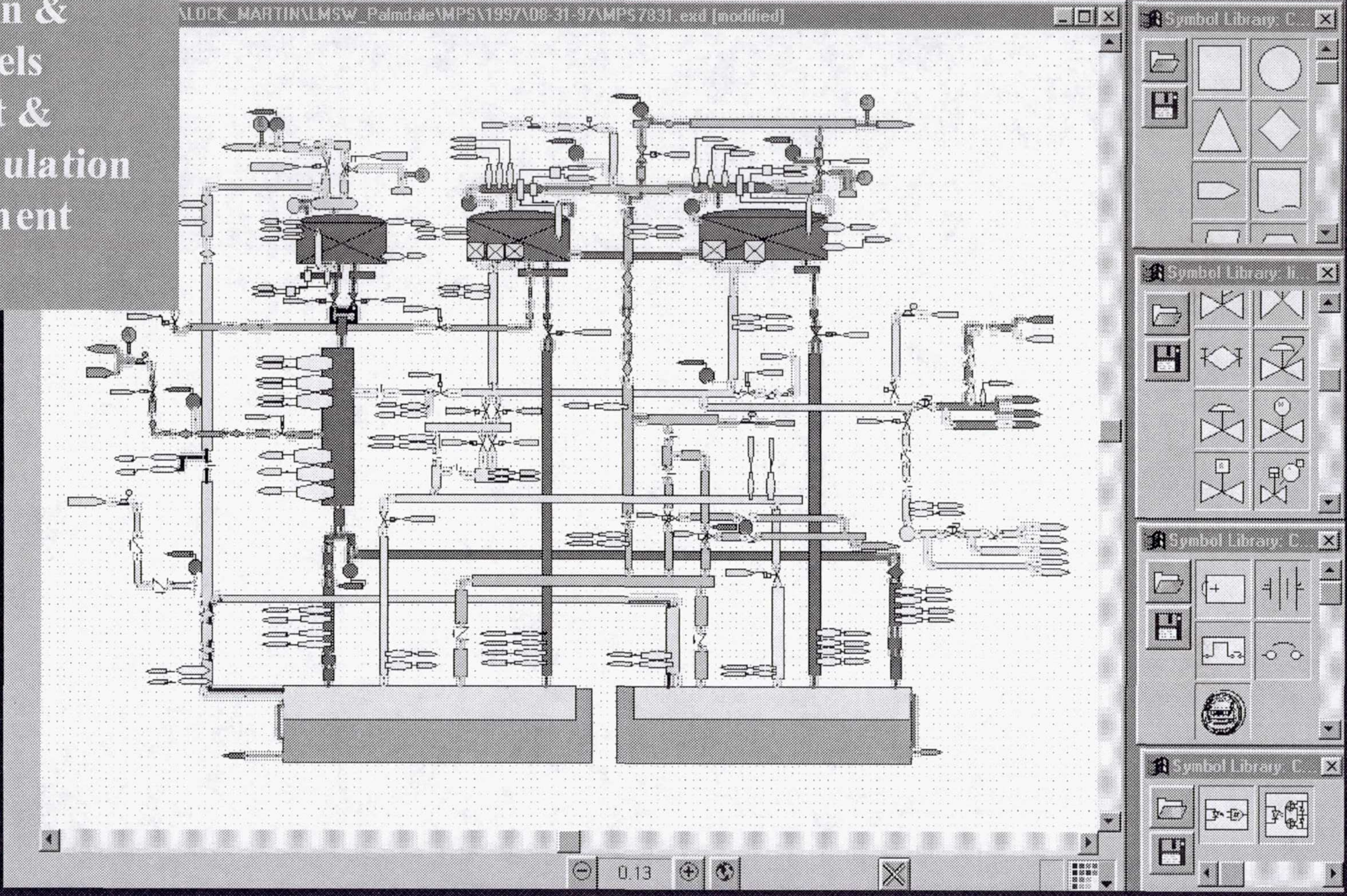
Comparison For Demonstration Purposes Only

Integrated Vehicle Health Management:

Operations Cost/yr Comparison

eXpress modeling tool

- Operability models
- Fault detection & isolation models
- Life cycle cost & reliability simulation
- Sensor placement optimization



Integrated Vehicle Health Management:

IVHM Modeling with DSI International

Integrated Vehicle Health Management:

In summary: Functions of IVHM SE&I

- Provide IVHM Technology descriptions
- Provide input to Operations Modeling/Ops processes
  - Operability
  - Testability
  - Maintainability
  - Availability
- Support development of IVHM+Subsystem Failure Event Models
  - Isolation of subsystem failures
  - Detectability of IVHM false positives
- Support life cycle cost and reliability optimization using eXpress
- Support IVHM technology DDT&E cost estimating
- Flow IVHM Requirements to 2nd gen SE&I and IVHM development tasks

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Conf Paper /IN-16

5
28

SP CE 2000
RANSPORTATION
AY

Risk Reduction
for the Next Generation

In Space Investment Area Overview	Les Johnson
Hall Propulsion Technology	Robert Jankovsky
Ion Propulsion Technology	John Brophy Mike Patterson
Fission Propulsion: SAFE	Mike Houts
Cryogenic Fluid Management Technologies	David Plachta
Solar Thermal Propulsion Technologies	Steve Tucker
Momentum Transfer Tether Technology	Kirk Sorensen
Electrodynamic Tether Coatings for ProSEDS	Jason Vaughn
AeroAssist Technologies	Richard Powell
Solar Sail Technology	Humphrey Price
Mini Magnetospheric Plasma Propulsion (M2P2)	Dennis Gallagher

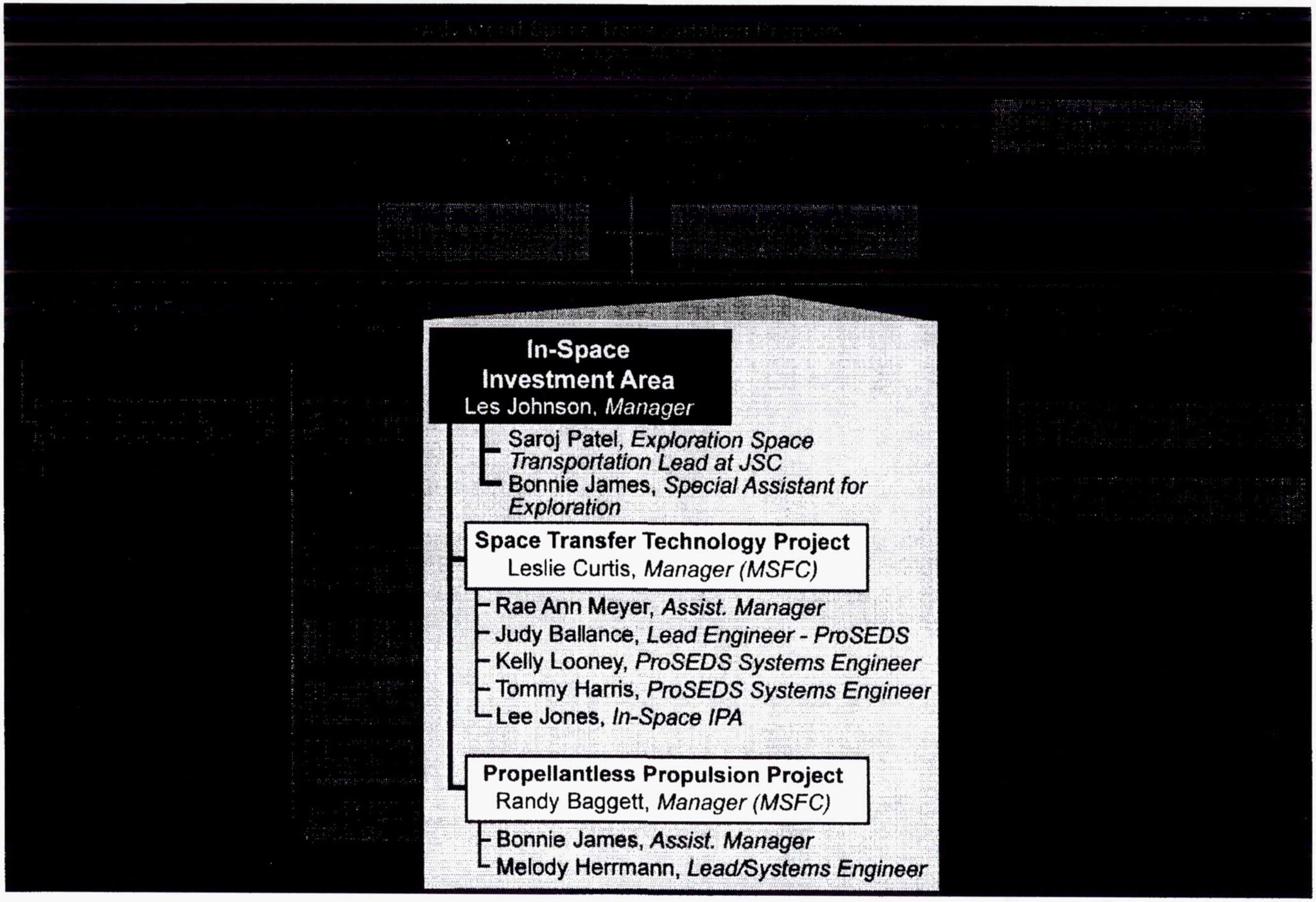
"ST Day 2000: Reducing Risk for the Next Generations" - ASTP

In-Space Agenda

SP CE 2000

RANSPORTATION

AY



In-Space Investment Area
Les Johnson, *Manager*

- Saroj Patel, *Exploration Space Transportation Lead at JSC*
- Bonnie James, *Special Assistant for Exploration*

Space Transfer Technology Project
Leslie Curtis, *Manager (MSFC)*

- Rae Ann Meyer, *Assist. Manager*
- Judy Ballance, *Lead Engineer - ProSEDS*
- Kelly Looney, *ProSEDS Systems Engineer*
- Tommy Harris, *ProSEDS Systems Engineer*
- Lee Jones, *In-Space IPA*

Propellantless Propulsion Project
Randy Baggett, *Manager (MSFC)*

- Bonnie James, *Assist. Manager*
- Melody Herrmann, *Lead/Systems Engineer*

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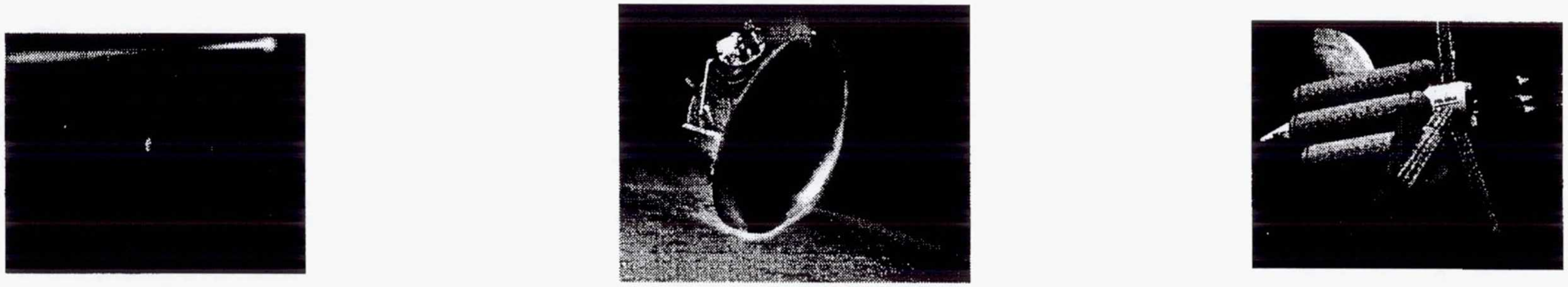
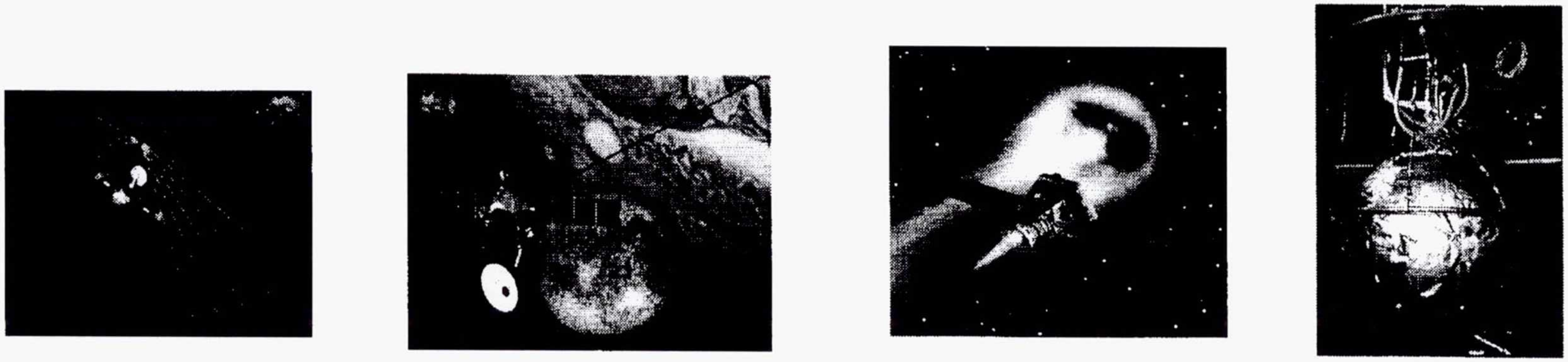
ASTP Organization



- **Achieve within 15 years a factor of 10 reduction in the cost of Earth orbital transportation and a factor of 2 to 3 reduction in propulsion system mass and travel time required for planetary missions. Within 25 years enable bold new missions to the edge of the solar system and beyond by reducing travel times by 1 to 2 orders of magnitude.**



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In-Space Transportation Goals

- High percentage of projected launches to Low-earth Orbit (LEO) will require upper stages.
  - More than 70% go to Geosynchronous Orbit (GEO) or higher.
- Under current total mission cost caps, more ambitious science missions require improvements in propulsion technologies.
  - DS-1 enabled by NSTAR solar electric ion propulsion.
  - Future planned missions require 2 to 3 times more Delta V.
  - Rendezvous and return missions will require similar investments in chemical propulsion systems and aerocapture technologies.
- Per current studies, human exploration missions to Mars, in-space transportation costs are projected to be higher than earth-to-orbit costs.
  - Affordable in-space transportation is enabling for human exploration missions (lighter weight systems, shorter trip time).
  - In-situ propellants offer significant potential to reduce mission costs.
- New opportunities to explore beyond the outer planets will require unparalleled technology advancement and invention.

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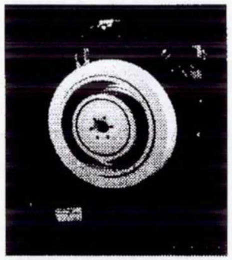
In-Space Investment Rationale

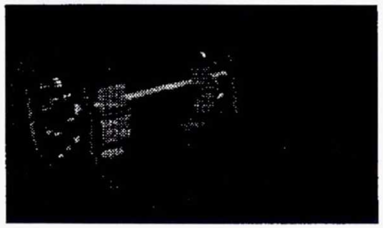


Electric Propulsion

Advance EP systems to reduce mass & cost of orbital transfer and to enable interplanetary missions

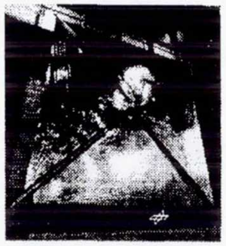
Cryogenic Fluid Management

Advance CFM systems to enable long term storage of cryogens in space



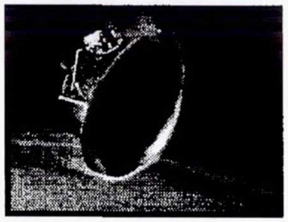
Fission

Develop fission technology to enable rapid, affordable access to any point in the solar system



Sails

Solar and magnetic sails to enable exciting new mission concepts and by reducing mass and overall trip time for interplanetary missions.

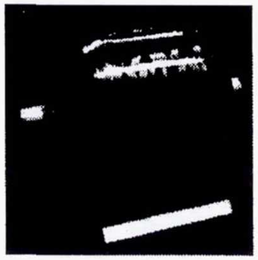


Aeroassist

Utilize aerocapture and aeroassist transportation systems to significantly reduce mass -- by using planetary environments for orbit capture and deceleration

Tethers

Develop reusable electrodynamic and momentum transfer tethers to reduce transportation system mass and cost



Light Weight Components

Develop light weight components to reduce the dry mass of spacecraft propulsion systems

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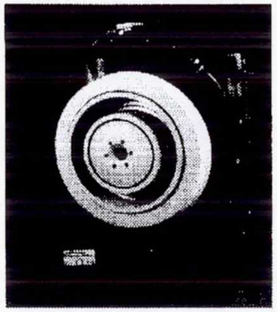
In-Space Transportation Technology Elements



Electric Propulsion

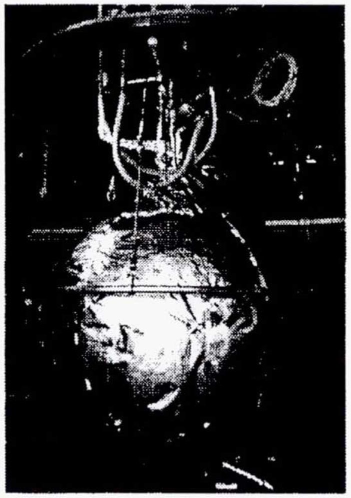
Advance EP systems to reduce mass & cost of orbital transfer and Enable interplanetary missions

- GRC – Hall, Ion, MPD, PIT technologies
- JPL – MPD (lithium), DS-1 tests, ion optics
- JSC – VASIMR Technologies
- MSFC- PIT (switch and ckt design)

Fission

Develop Fission Technology to enable rapid, Affordable access to any point in the solar system

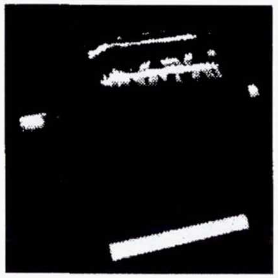
- GRC – Energy Conversion, Fuels, LANTR
- JSC – Two phase systems and technologies
- KSC – Operational and range requirements
- MSFC – Fuels, SAFE, System studies, non nuclear testing



Cryogenic Fluid Management

Advance CFM systems to enable long term Storage of cryogens in space

- ARC- Cryocooler & Refrigerator development, insulation
- GRC- Subscale/Component test, analytical modeling
- JPL - technology requirements
- JSC - In-situ propellant production
- KSC - GSE, quick-disconnects, insulation
- MSFC- System/Large scale test, analytical modeling



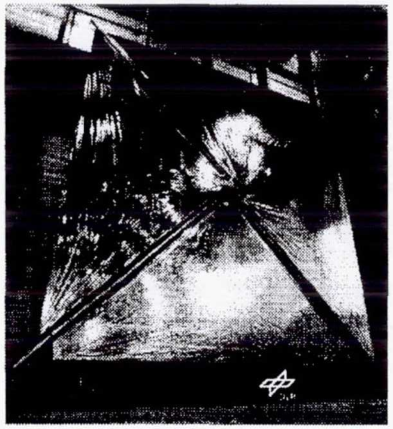
Light Weight Components

Develop light weight components to reduce the dry mass of spacecraft propulsion systems

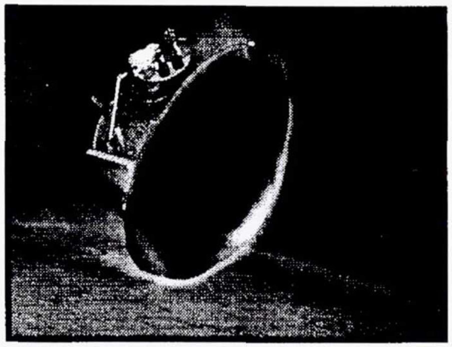
- Center Roles are still being established

"ST Day 2000: Reducing Risk for the Next Generations" - ASTP

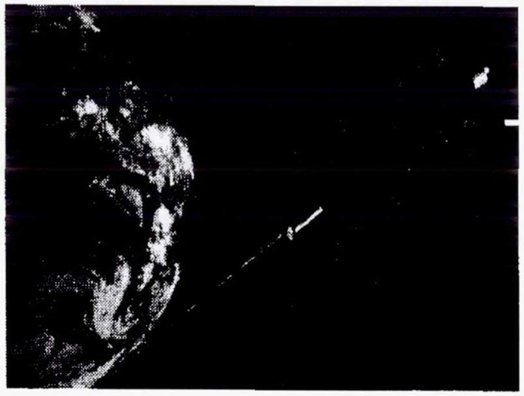
Space Transfer Technology Project Elements



- Sails
  - Solar
  - Magnetic
- Center Roles:
  - JPL: TWG lead; system design; GN&C; Mechanical systems; Large structures; I&T
  - LaRC: materials & Lt. weight structures; mechanical system
  - MSFC: Prop. Physics;M2P2; mt'l & light weight structures
  - JSC: Large Structure environ.



- Aeroassist
- Center Roles:
  - LaRC: TWG Lead; system design/performance; Aero/ Aerothermal analysis; structures; GN&C simulations
  - ARC,JSC,JPL,LaRC,MSFC: Vehicle design/system analysis
  - ARC: TPS; TPS Aerothermal sensors; Aerothermal analysis
  - JSC: GN&C; deceleration systems; Adv.. TPS materials
  - MSFC: Environmental models



- Tethers
  - Electrodynamics
  - Momentum Transfer Tethers
- Center Roles:
  - MSFC: TWG Lead; system design/performance; integrated test; tether survivability; deployer; GN&C; deployment test facilities; orbital tracking & collision avoidance
  - JSC: orbital tracking & collision avoidance

"ST Day 2000: Reducing Risk for the Next Generations" - ASTP

Propellantless Propulsion Technology Project Elements

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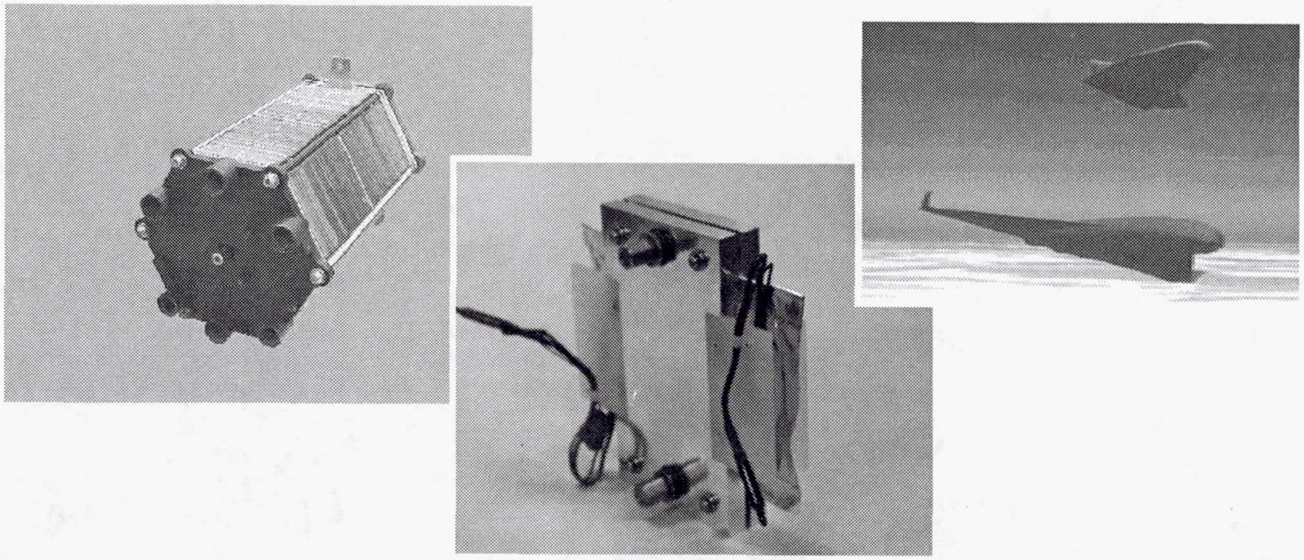
2nd & 3rd Generation Vehicle Subsystems



"ST Day 2000: Reducing Risk for the Next Generations"

◆ 3rd Generation Vehicle Subsystems

Project Overview	Scott Jackson	8:00 - 8:10
University (Cornell U.)	Kathryn Caggiano	8:10 - 8:30
SFINX	Anthony Kelley	8:30 - 9:00
High Performanc G&C	Dan Moerder	9:00 - 9:30
EHW for 3rd Gen.	Wayne Schober	9:30 - 10:00
Advance EA's	Jose Davis	10:00 - 10:20
Hybrids Sources	Jeff Brewer	10:20 - 10:45
Intell. Intern. Therm. Ctrl.	Eric Golliher	10:45 - 11:00

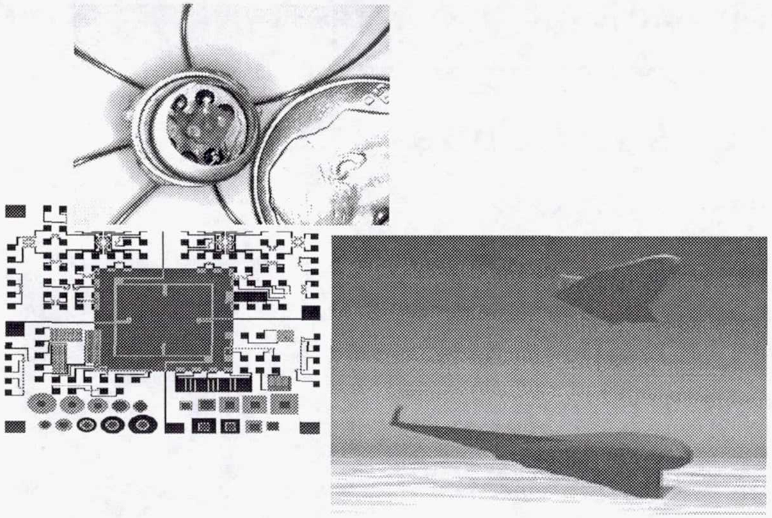
◆ 2rd Generation Vehicle Subsystems

Project Overview	Mike Skor	11:00 - 11:20
PEM Fuel Cell Project	Mark Hoberecht	11:20 - 11:50
Wrap up	All	11:50 - 12:00

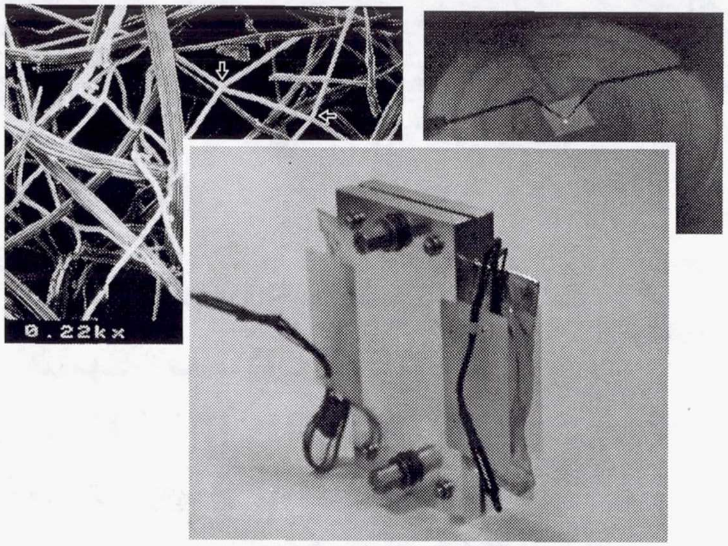
"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Agenda

- ♦ **Technology Objectives:**
  - **Design, develop and test advanced avionics, power systems, power control and distribution components and subsystems for insertion into a highly reliable and low-cost system for a reusable launch vehicle.**



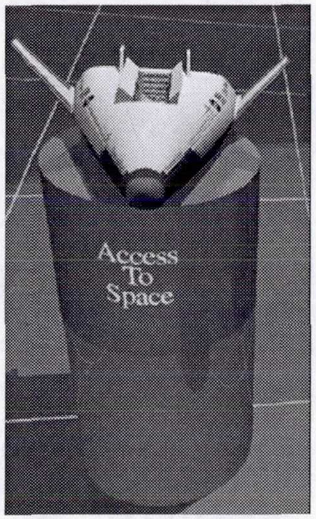
Avionics and Flight Control
Lead Center - MSFC



Power
Lead Center - GRC

Vehicle Subsystems Project, 3nd Gen

- **Earth-to-Orbit :**

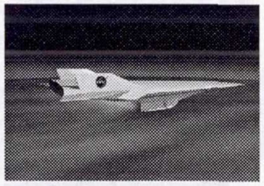


GOALS 9

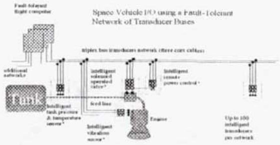
Low-cost Space Access:

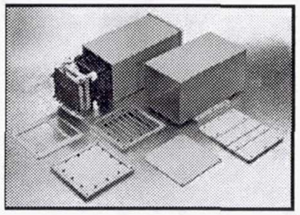
Reduce the payload cost to orbit by an order of magnitude, from $10,000 to $1,000 per pound, within 10 years and by an additional order of magnitude, from thousands to hundreds of dollars per pound, within 25 years

- **Launch Technology Project**
  - Provide basic launch technology building blocks to enable significant improvements in safety and reliability of transportation systems while reducing the life time cost.

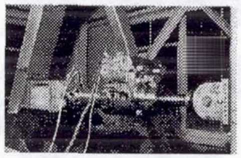


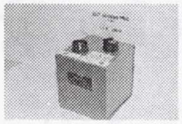
University Studies

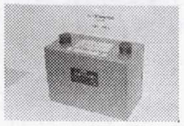


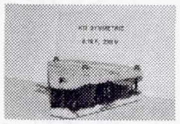


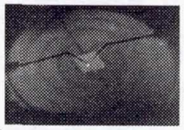
- Project Manager
Scott Jackson
MSFC
  - Avionics Lead Engineer
Anthony Kelley
MSFC
    - University Studies
Anthony Kelley
MSFC
    - SFINX
Anthony Kelley
MSFC
    - EHW for 3rd Gen.
Wayne Schober
JPL
    - Robust Low Cost Avionics
Shawn Wallace
MSFC
    - High Perf, G&C Adpt.
Dan Moerder
LaRC
  - Power Lead Engineer
Jose Davis
GRC
    - Advanced EA's
Mary Roth
GRC
    - Hybrid Sources
Linda Taylor
GRC
    - High Temp Pwr Electronics
Gene Schwarze
GRC
    - IITC
Eric Golliher
GRC

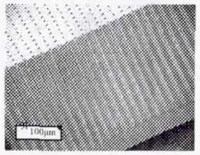












"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

3rd Gen. Project Management Structure

- Achieve 100% Reliability
- Increase Safety
- Operate In Any Environment
- Achieve Near Zero Mass Systems
- Increase Operability & Maintainability

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

3rd Gen. Technical Challenges

- University Studies (Cornell University)
  Kathryn Caggiano (Cornell University) (607) 255-0698

- High-Performance G&C Adaptation
  Dan Moerder (LaRC) 757-864-6495 d.d.moerder@larc.nasa.gov

- Evolvable Hardware (EHW) for 3rd Generation Avionics Description
  Wayne Schober (JPL) 818 354-8581 wayne.r.schober@jpl.nasa.gov

- SFINX Scaleable, Fault-tolerant Intelligent Network or X(trans)ducers
  Anthony Kelley (MSCFC/ED12) 256-544-7646 anthony.kelley@msfc.nasa.gov

- Advanced Electric Actuation Devices and Subsystem Technology
  Jose Davis (GRC) For:
  Mary Roth (GRC) 216-433-6288 Mary.E.Roth@lerc.nasa.gov

- Hybrid Power Sources and Regeneration Technology for Electric Actuators
  Jeff Brewer (MSFC) For:
  Linda Taylor (GRC) 216-433-3370 Linda.M.Taylor@lerc.nasa.gov

- Intelligent Internal Thermal Control
  Eric Golliher (GRC) 216-433-6575 Eric.L.Galliher@lerc.nasa.gov

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

3rd Gen. Subsystems Presenter Contact Info.

NAME	ORG.
José M. Davis (Lead)	GRC
Nang T. Pham	GRC
Mary Ellen Roth	GRC
Gene Schwarze	GRC
Eric Golliher	GRC
Steve Luna	MSFC
Steve Ryan	MSFC
Mark King	MSFC
Rao Surampudi	JPL
David Homan	Wright Lab
Russ Spyker	Wright Lab
Jerry Beam	Wright Lab
Joe Weimer	Wright Lab

3rd Gen. Power Technology Working Group

NAME	ORG.
Anthoney Kelley (Lead)	MSFC
Charles Hall	MSFC
Mike Watson	MSFC
Mike Goode	LaRC
Dan Moerder	LaRC
Gary Hunter	GRC
Bill Espinosa	GRC
Chuck Jorgensen	ARC
Wayne Schober	JPL
Leon Alkalai	JPL
Nikzad Benny Toomariab	JPL
Jean- Pierre Fleurial	JPL
Kevin Wheeler	ARC
Ray Garbos	Lockheed
Bruce Powel Douglas	Private

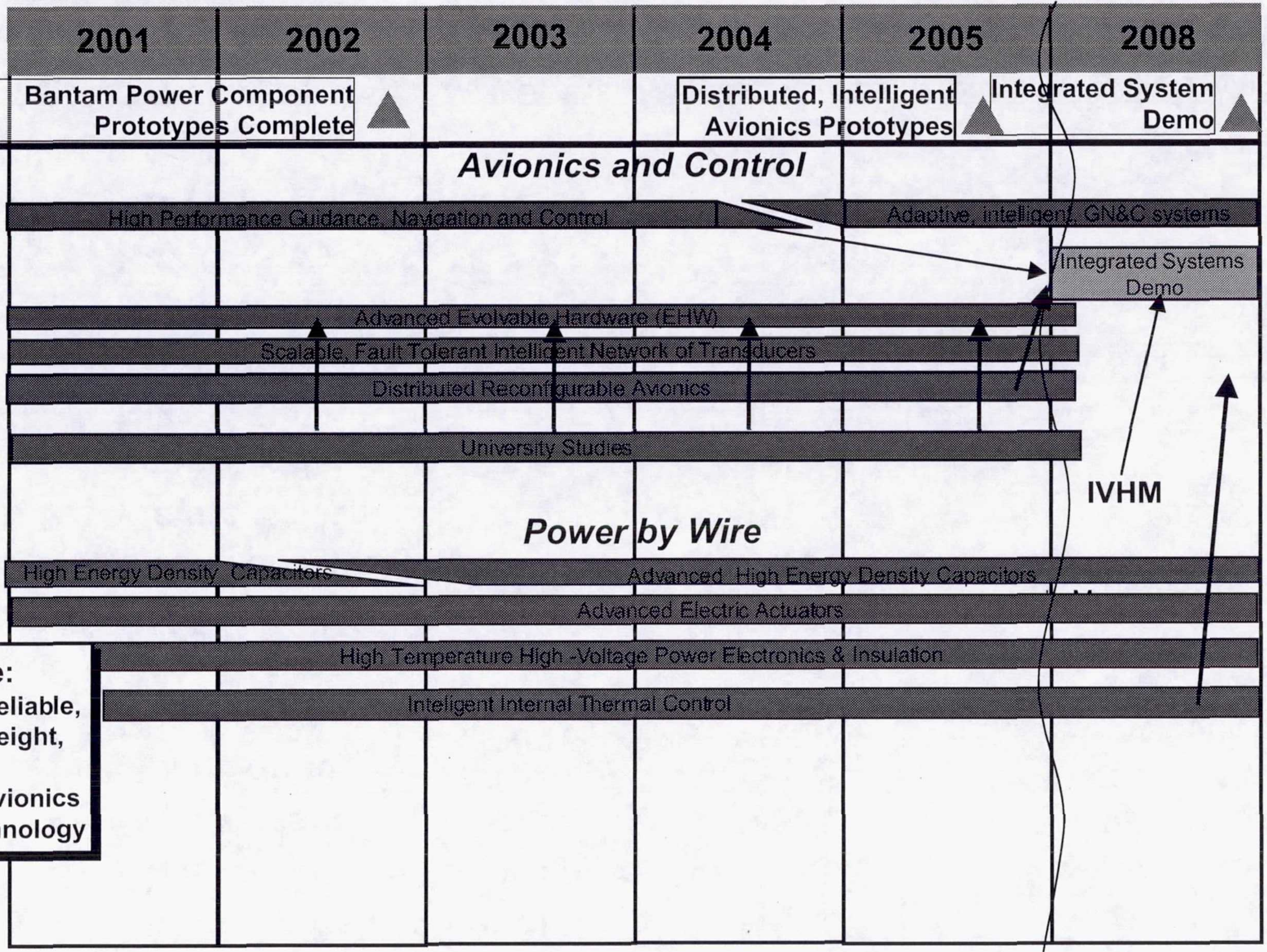
3rd Gen. Avionics Technology Working Group

Launch Technologies Project

Major Milestones

Key Tasks

- **Component/ Subsystem Demo**
- **Integrated Demo**



Objective:

- **Develop safe, reliable, long life, low weight, low cost, high performance Avionics and Power technology**

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

3rd Gen. Launch Technology Roadmap

Supporting the NASA RLV Program

Kathryn E. Caggiano
Peter L. Jackson
John A. Muckstadt

Cornell University
Operations Research and Industrial Engineering

"ST Day 2000: Reducing Risk for the Next Generations"

Develop analysis tools for determining and evaluating spare parts stocking policies for components of Reusable Launch Vehicles

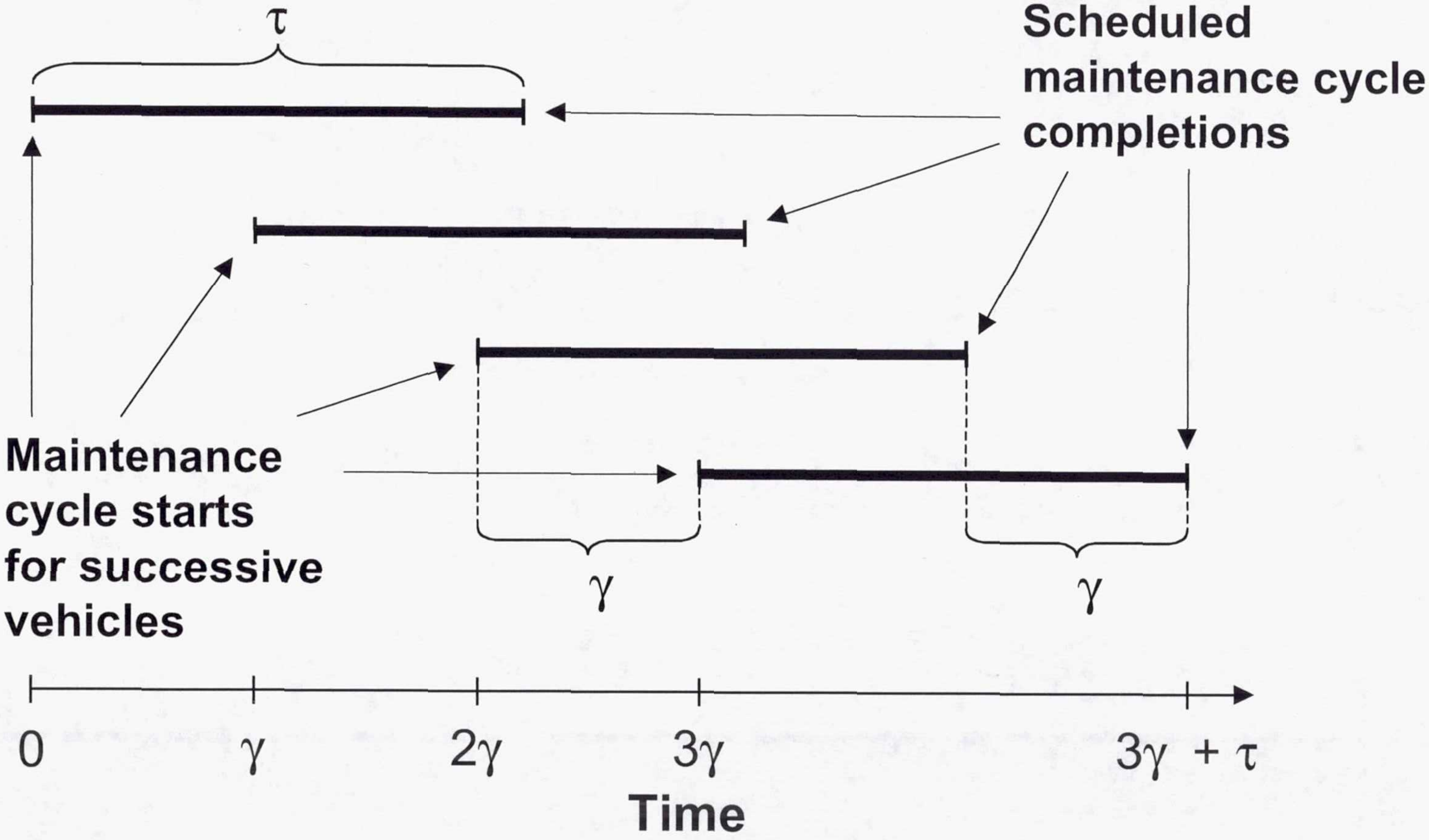
Cornell Project Objective

- System Framework
- Analysis Tools
- Analysis Process (GEM)

Overview

- RLV Ground Maintenance Process
- Line Replaceable Unit (LRU) Repair Process
- Shop Replaceable Unit (SRU) Repair Process

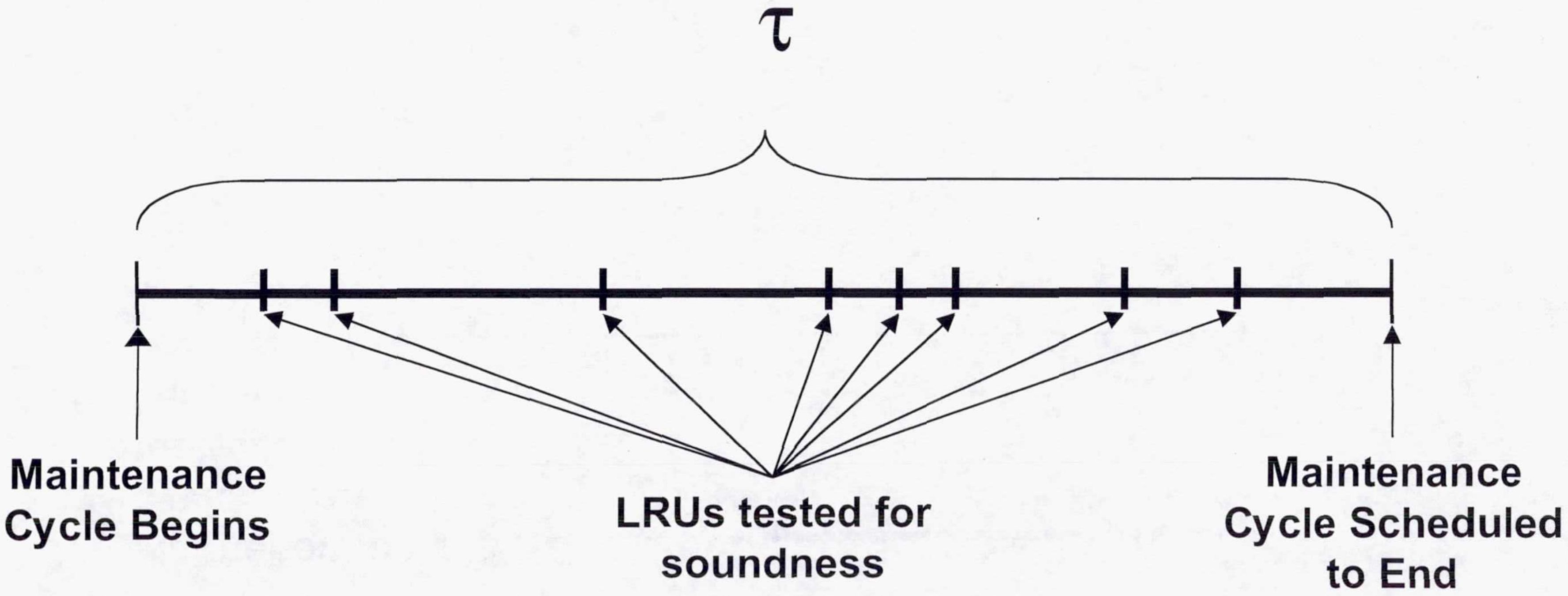
System Framework



Scheduled maintenance cycle completions

Maintenance cycle starts for successive vehicles

RLV Maintenance Cycles



τ

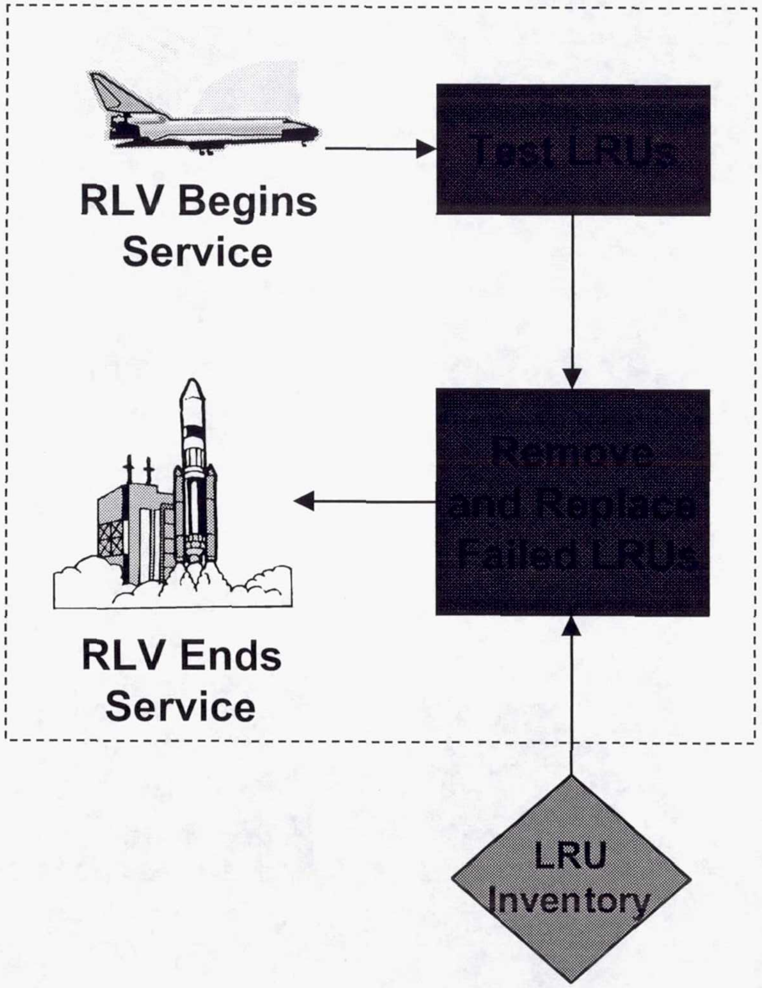
Maintenance Cycle Begins

LRUs tested for soundness

Maintenance Cycle Scheduled to End

Failed LRUs must be replaced by the scheduled end date in order to avoid a delay.

One Maintenance Cycle



RLV Begins Service

Test LRUs

Remove and Replace Failed LRUs

RLV Ends Service

LRU Inventory

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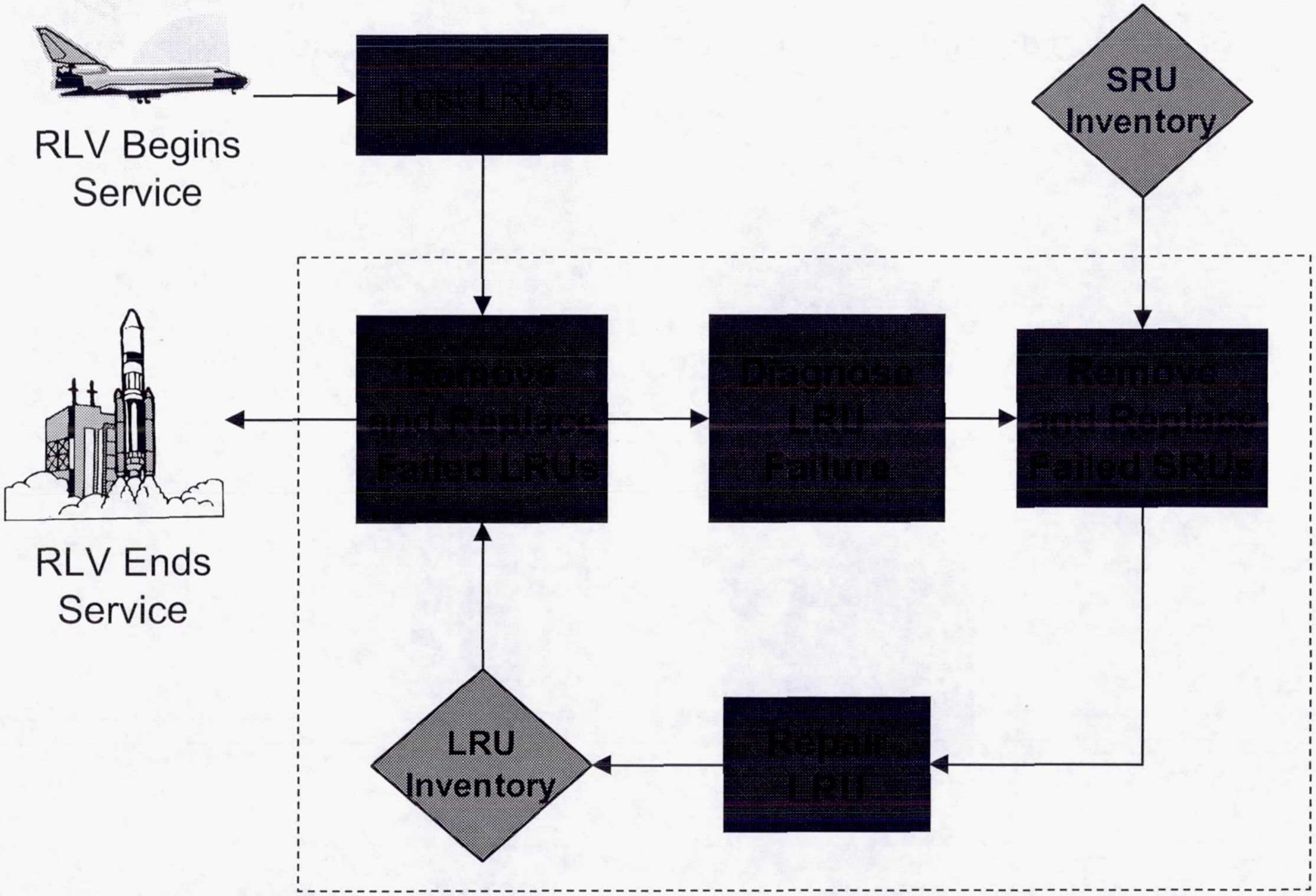
RLV Ground Maintenance



RLV Begins Service

Test LRUs

SRU Inventory

RLV Ends Service

Remove and Replace Failed LRUs

Diagnose LRU Failure

Remove and Replace Failed SRUs

LRU Inventory

Repair LRU

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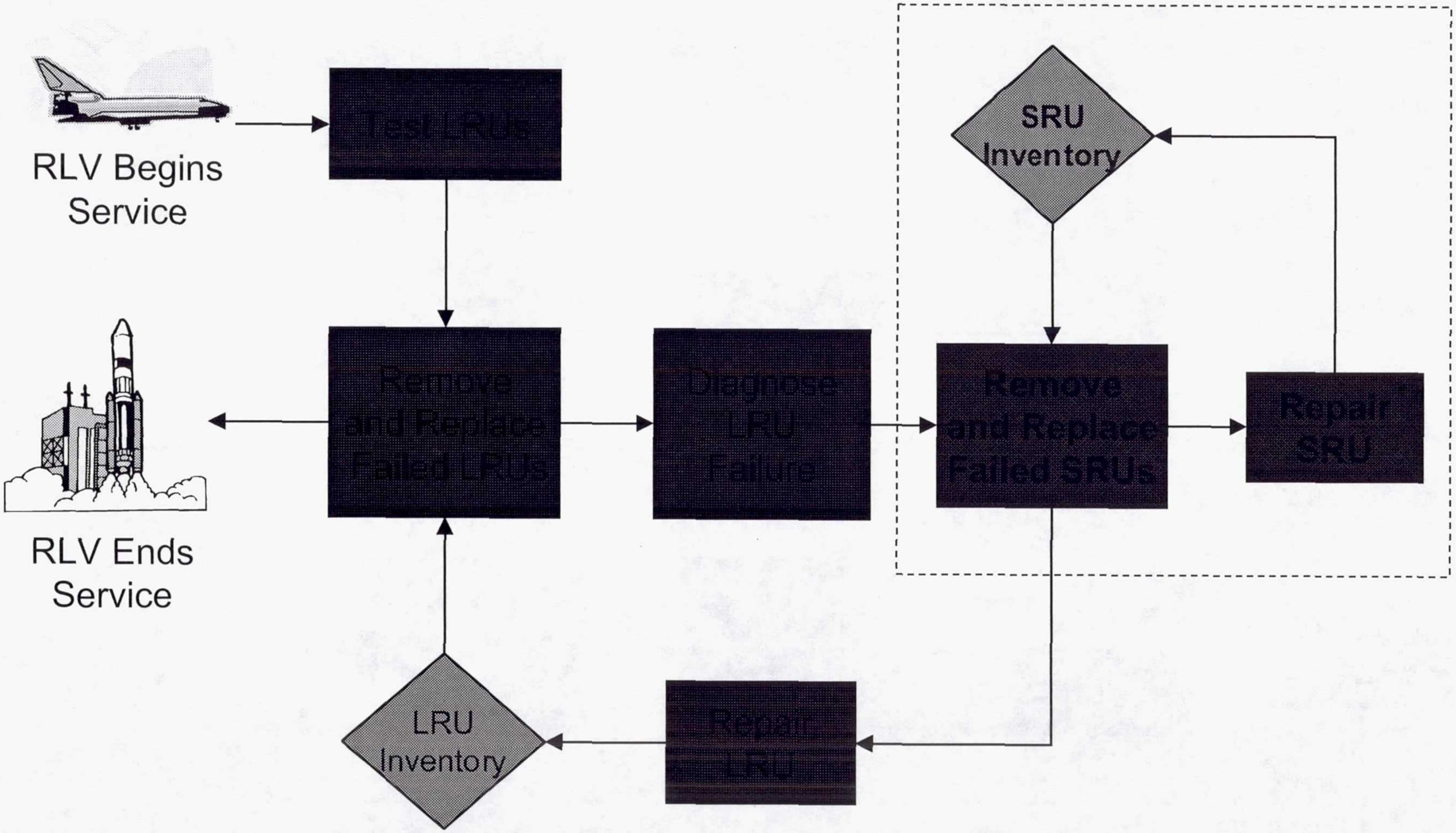
LRU Repair Process

SRU Repair Process



RLV Begins Service

Test LRUs

Remove and Replace Failed LRUs

RLV Ends Service

Diagnose LRU Failure

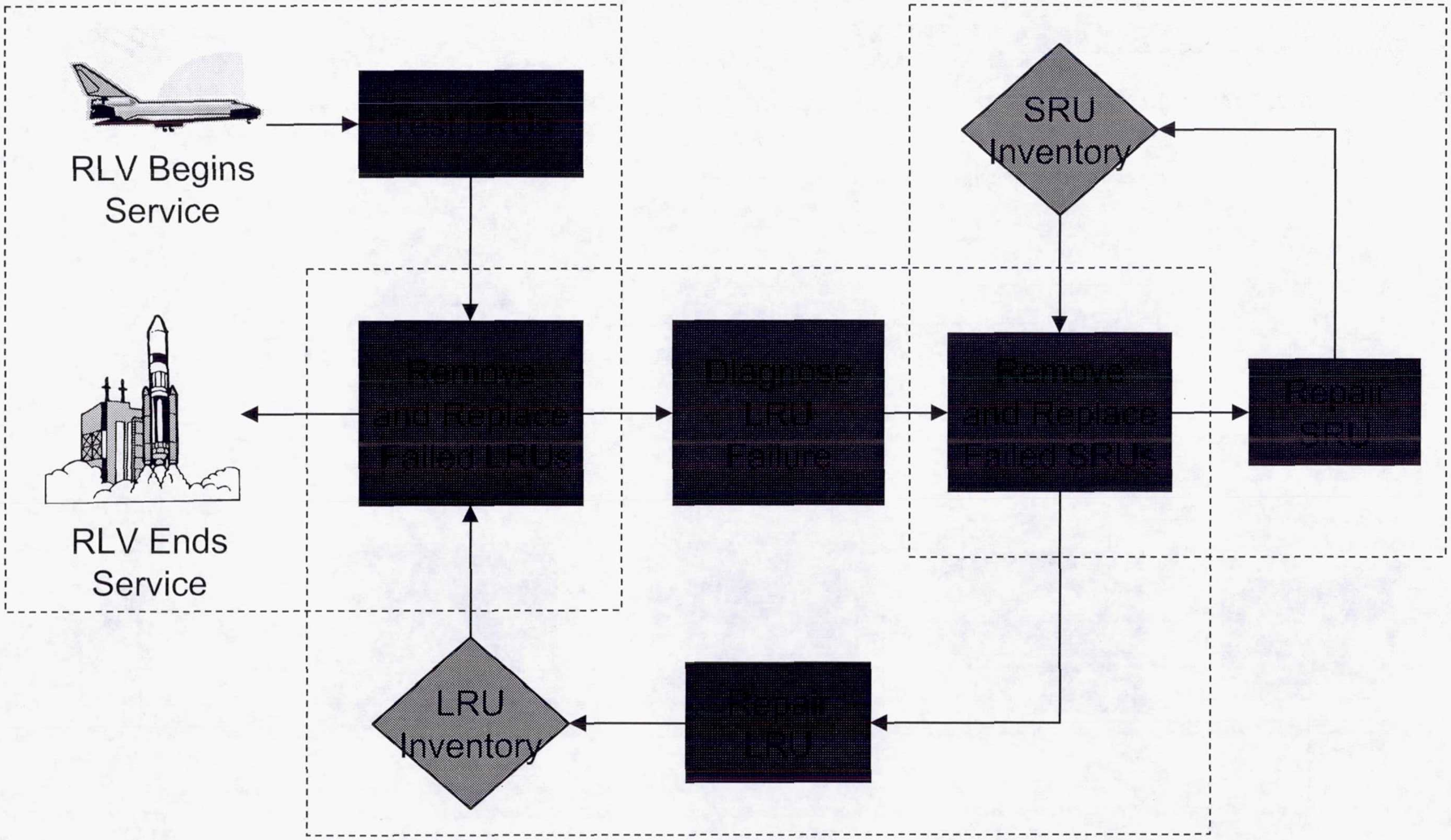
SRU Inventory

Remove and Replace Failed SRUs

Repair SRU

Repair LRU

LRU Inventory



RLV Begins Service

Test RLVs

Remove and Replace Failed LRUs

Diagnose LRU Failure

Remove and Replace Failed SRUs

Repair SRU

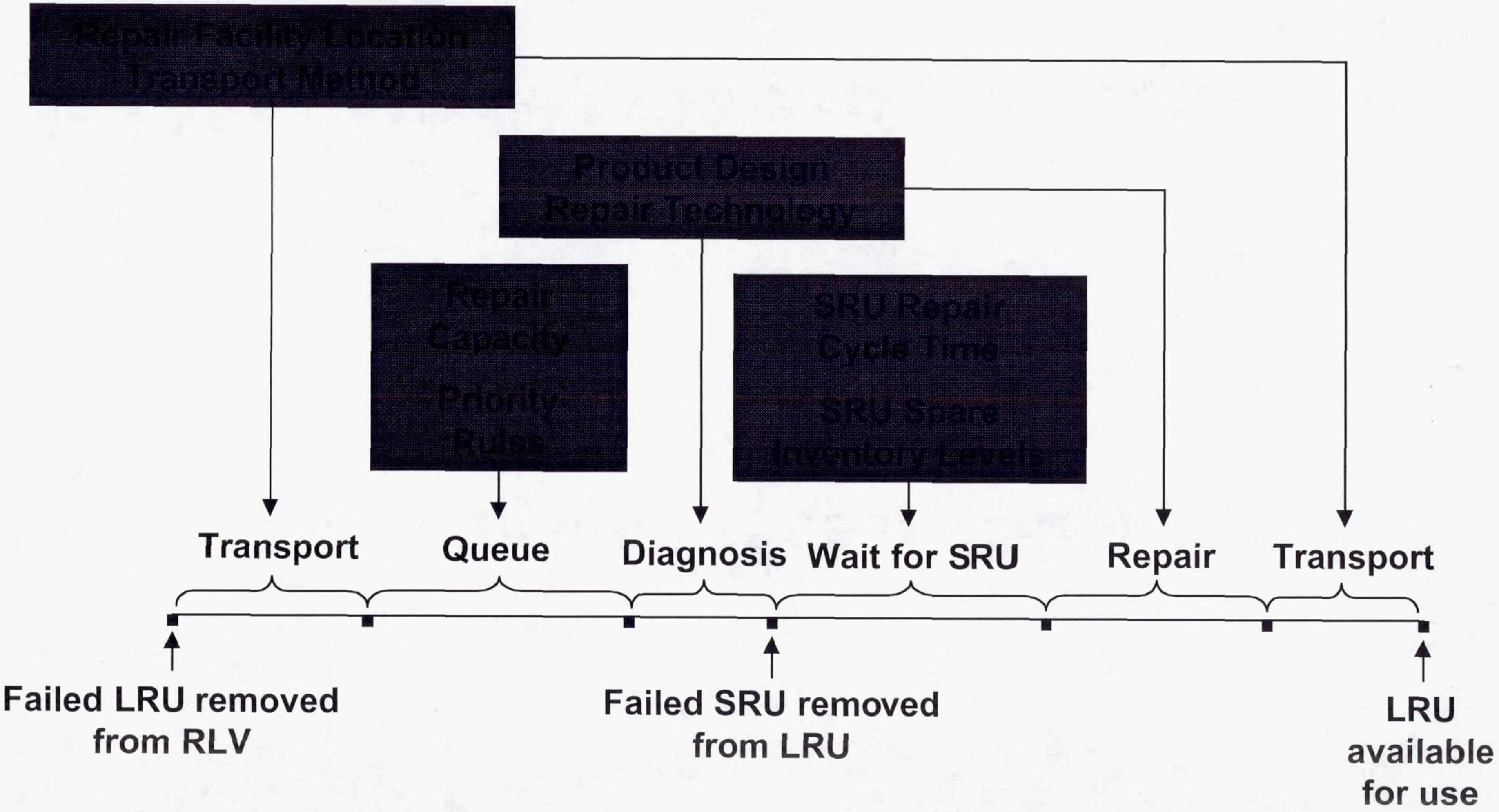
SRU Inventory

RLV Ends Service

Repair LRU

LRU Inventory

System Framework



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LRU Repair Cycle Time

- System Framework
- Analysis Tools
- Analysis Process (GEM)

Overview

- **Mathematical Model**
- **Simulation Model**

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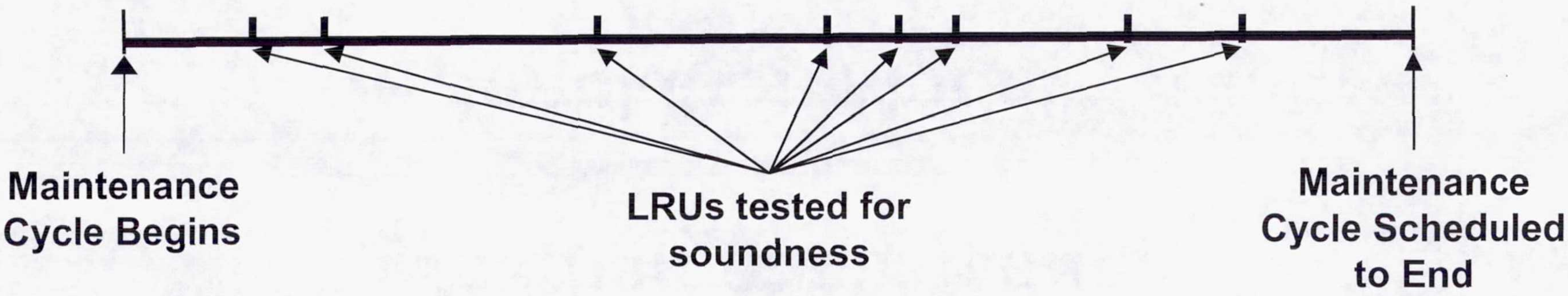
Analysis Tools

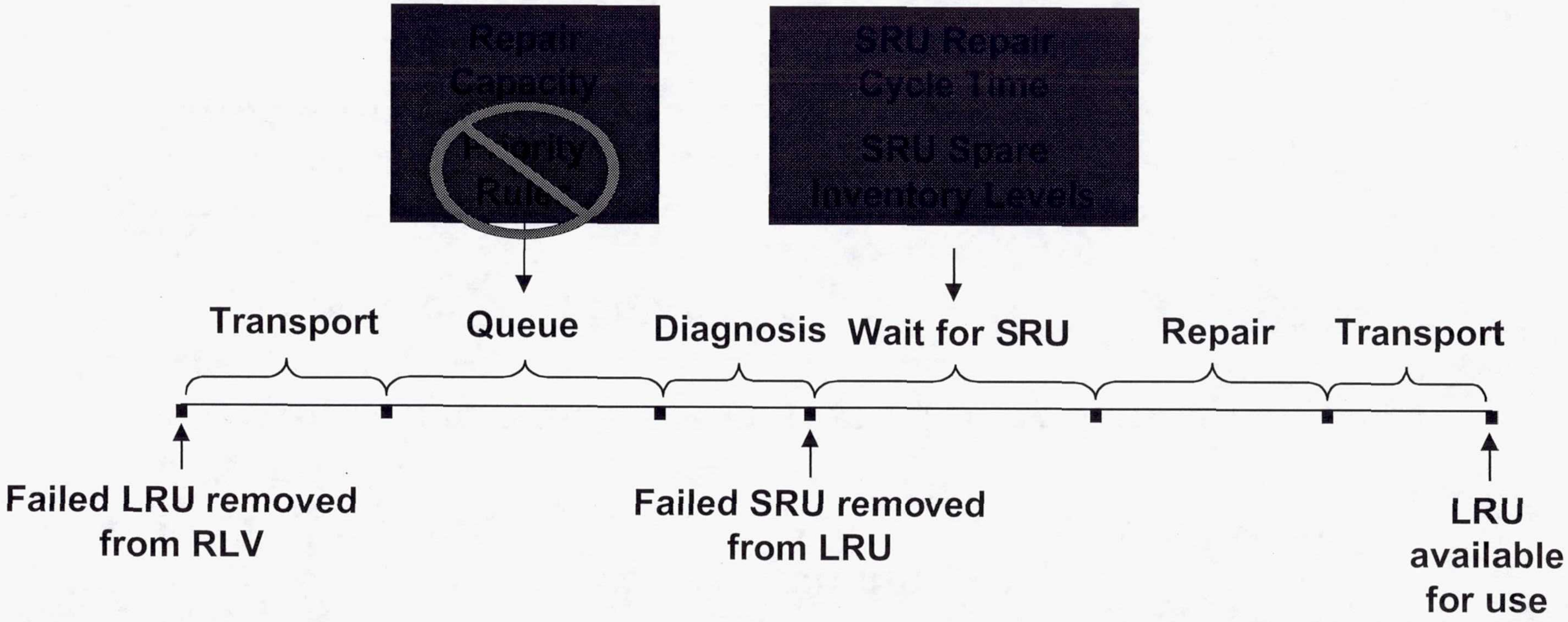
Goal:

Given a target investment level, determine LRU and SRU spare inventory levels that minimize the expected number of "holes" in an RLV at the end of its scheduled maintenance cycle.



Mathematical Model

LRU Repair Cycle Time



Repair Capacity

Priority Rules

SRU Repair Cycle Time

SRU Spare Inventory Levels

Transport

Queue

Diagnosis

Wait for SRU

Repair

Transport

Failed LRU removed from RLV

Failed SRU removed from LRU

LRU available for use

Considerations:

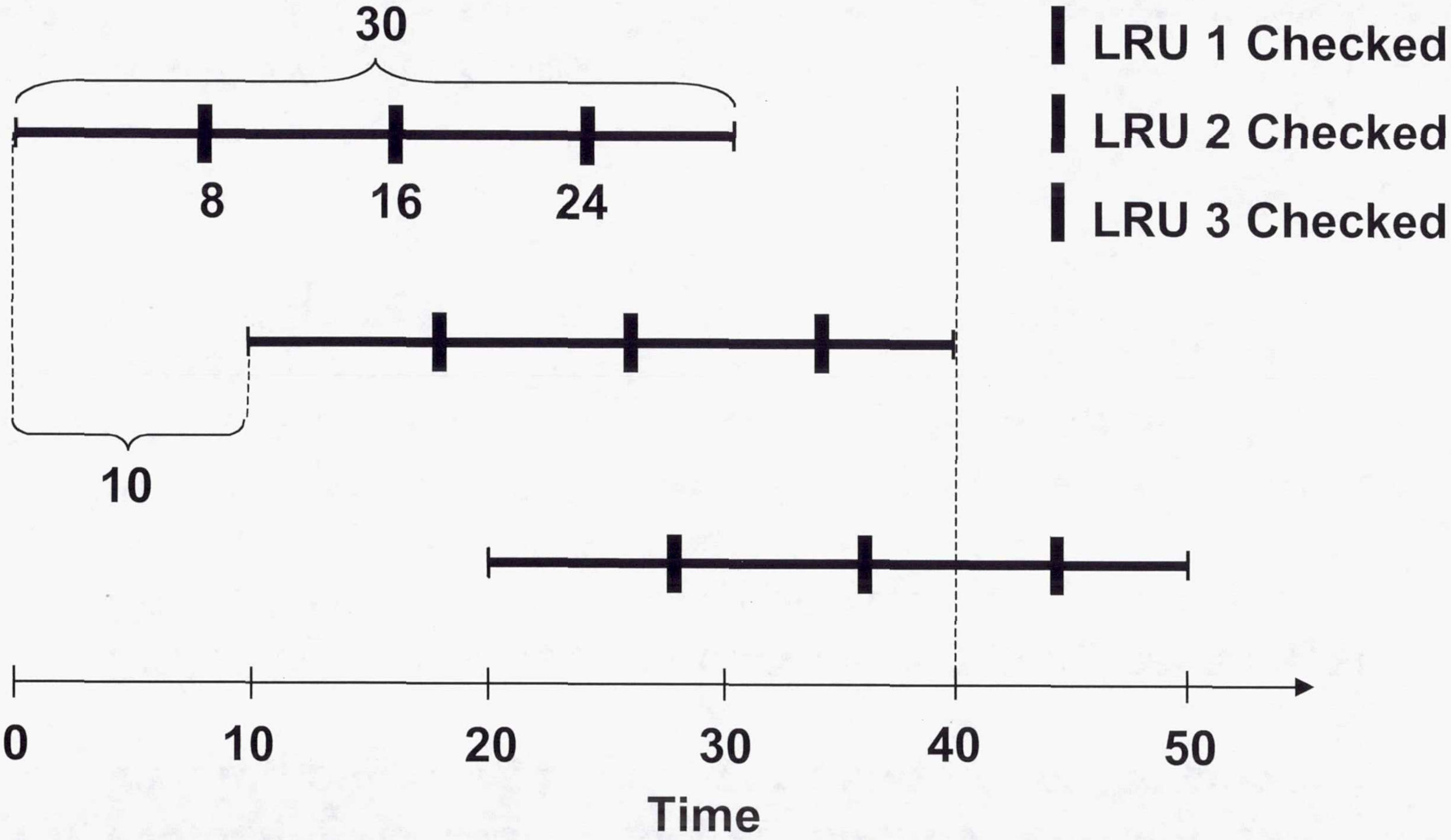
- RLV maintenance schedule parameters (τ, γ, etc.)
- Times at which LRUs are tested (relative to τ)
- Part failure characteristics
- Bill of material relationships
- For LRUs repaired in-house, repair cycle time components (other than queue time and wait time)
- For LRUs with outsourced repair, the repair cycle time distribution
- SRU repair cycle time components (other than queue time)
- Repair capacity
- Target budget level and part costs

Does not capture:

- Variability of transport, queue, and service times
- Work prioritization

Mathematical Model

Example



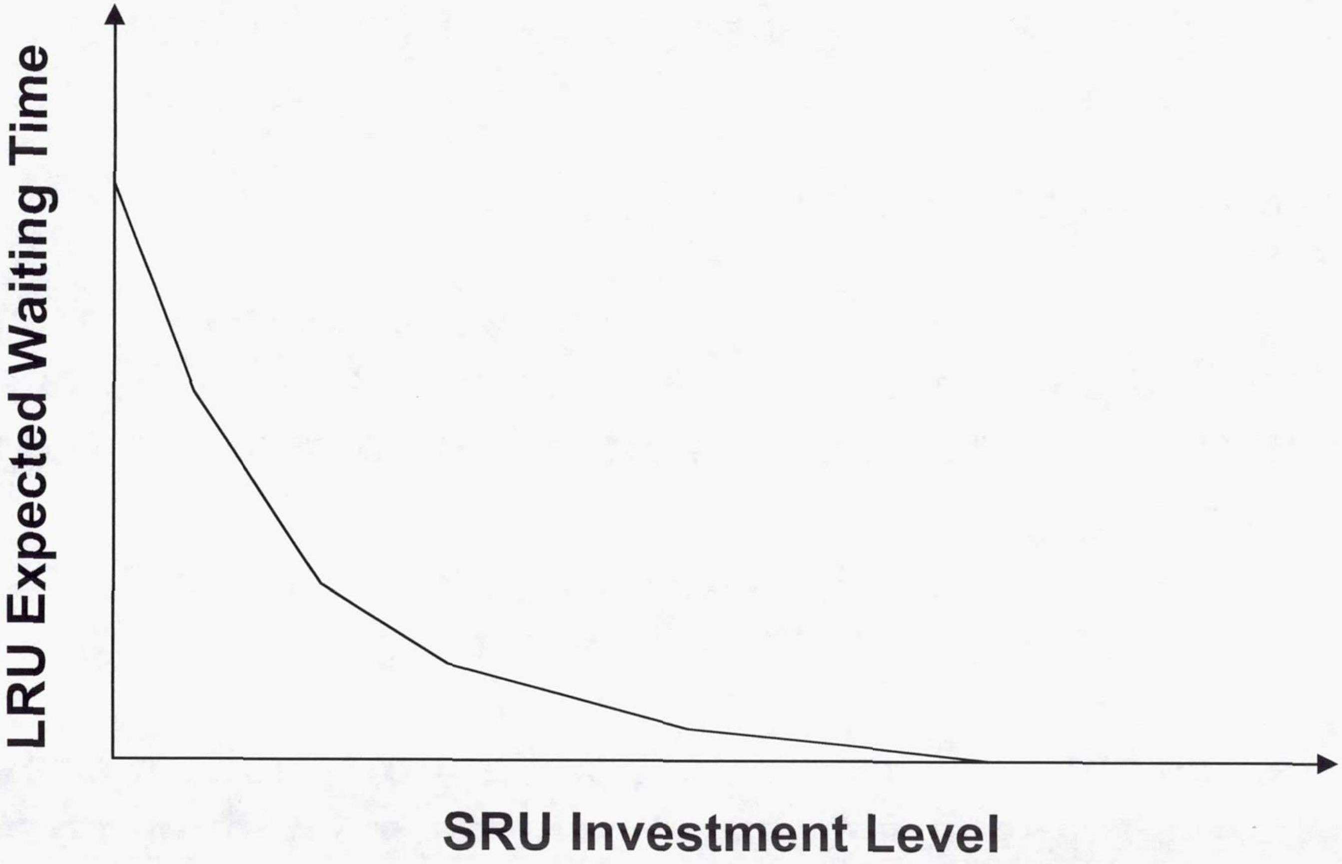
LRU Repair Cycle Time = 11
if no wait for SRUs

SRU Repair Cycle Time = 7

Outline of Method:

- For each LRU type, build the SRU tradeoff curve.
- For each LRU type, build the family tradeoff curve by evaluating LRU/SRU budget allocation strategies, keeping points on the convex minorant of the curve.
- Build the overall tradeoff curve using marginal analysis on the family tradeoff curve points.
- Find the point on the overall tradeoff curve that requires a total investment closest to (but not exceeding) the target investment level.

Determining Spare Levels



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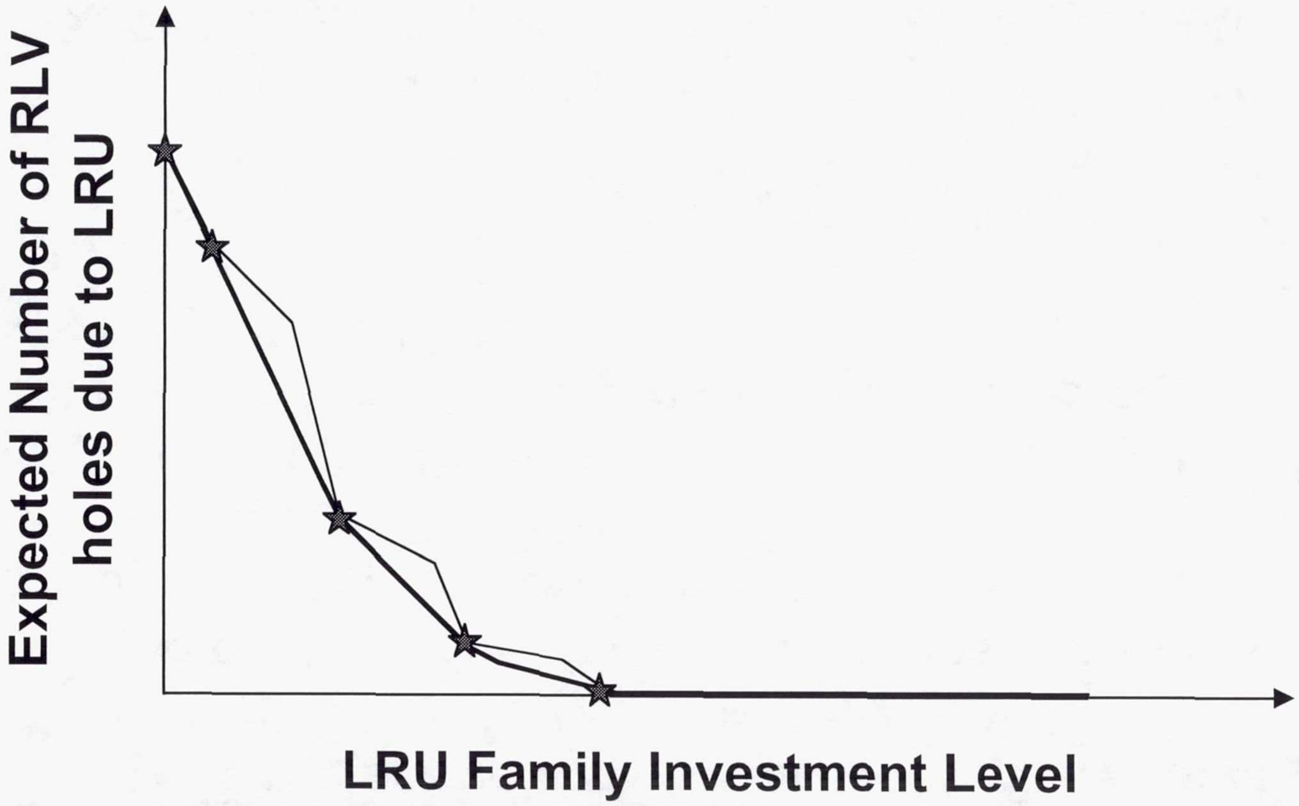
SRU Tradeoff Curve

Outline of Method:

- For each LRU type, build the SRU tradeoff curve.
- For each LRU type, build the family tradeoff curve by evaluating LRU/SRU budget allocation strategies, keeping points on the convex minorant of the curve.
- Build the overall tradeoff curve using marginal analysis on the family tradeoff curve points.
- Find the point on the overall tradeoff curve that requires a total investment closest to (but not exceeding) the target investment level.



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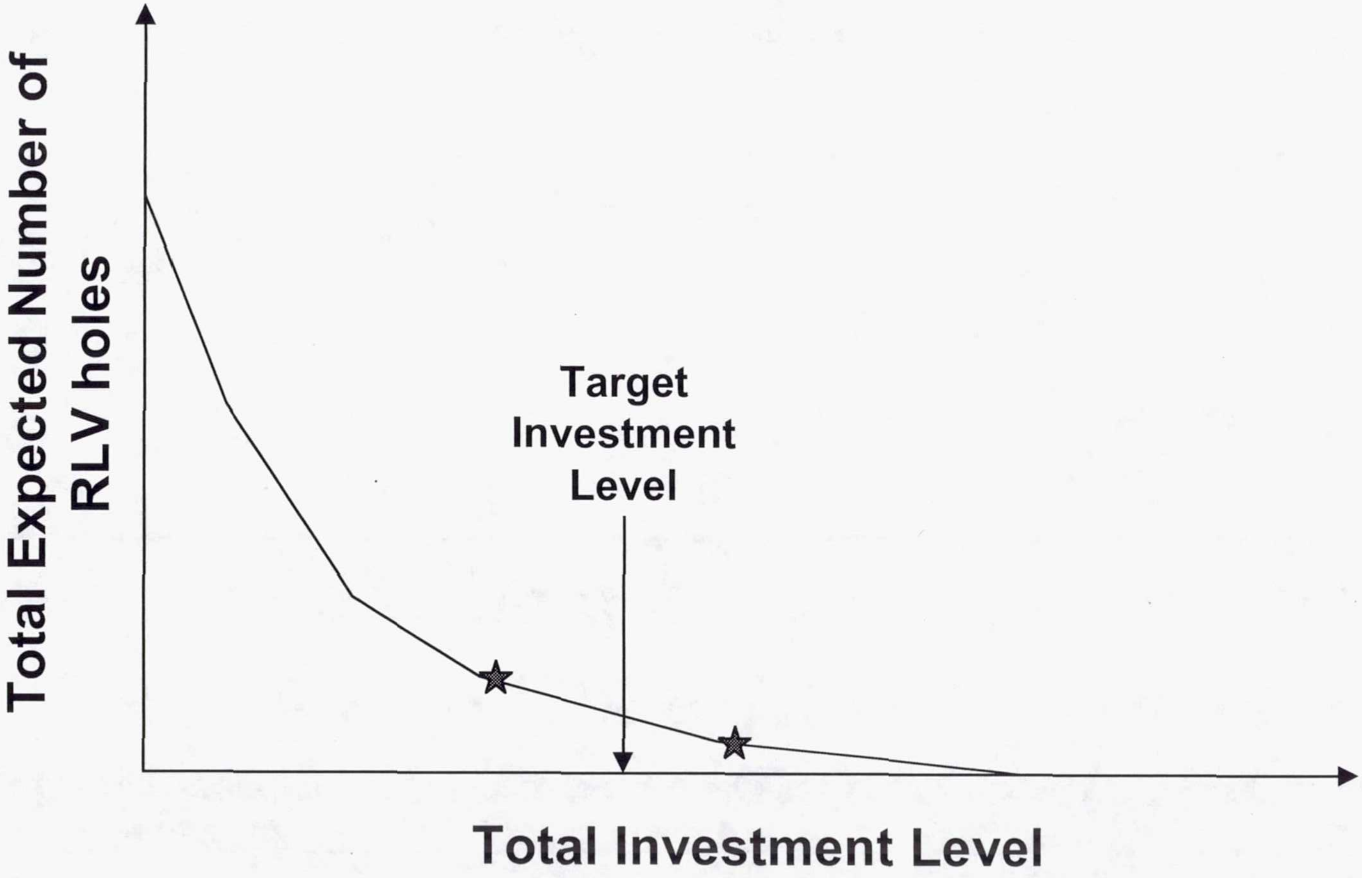
LRU Family Tradeoff Curve

Outline of Method:

- For each LRU type, build the SRU tradeoff curve.
- For each LRU type, build the family tradeoff curve by evaluating LRU/SRU budget allocation strategies, keeping points on the convex minorant of the curve.
- Build the overall tradeoff curve using marginal analysis on the family tradeoff curve points.
- Find the point on the overall tradeoff curve that requires a total investment closest to (but not exceeding) the target investment level.

Determining Spare Levels



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Overall Tradeoff Curve

Goal:

Evaluate maintenance resource strategies, including LRU and SRU spare inventory levels, in the dynamic RLV environment.

Considerations:

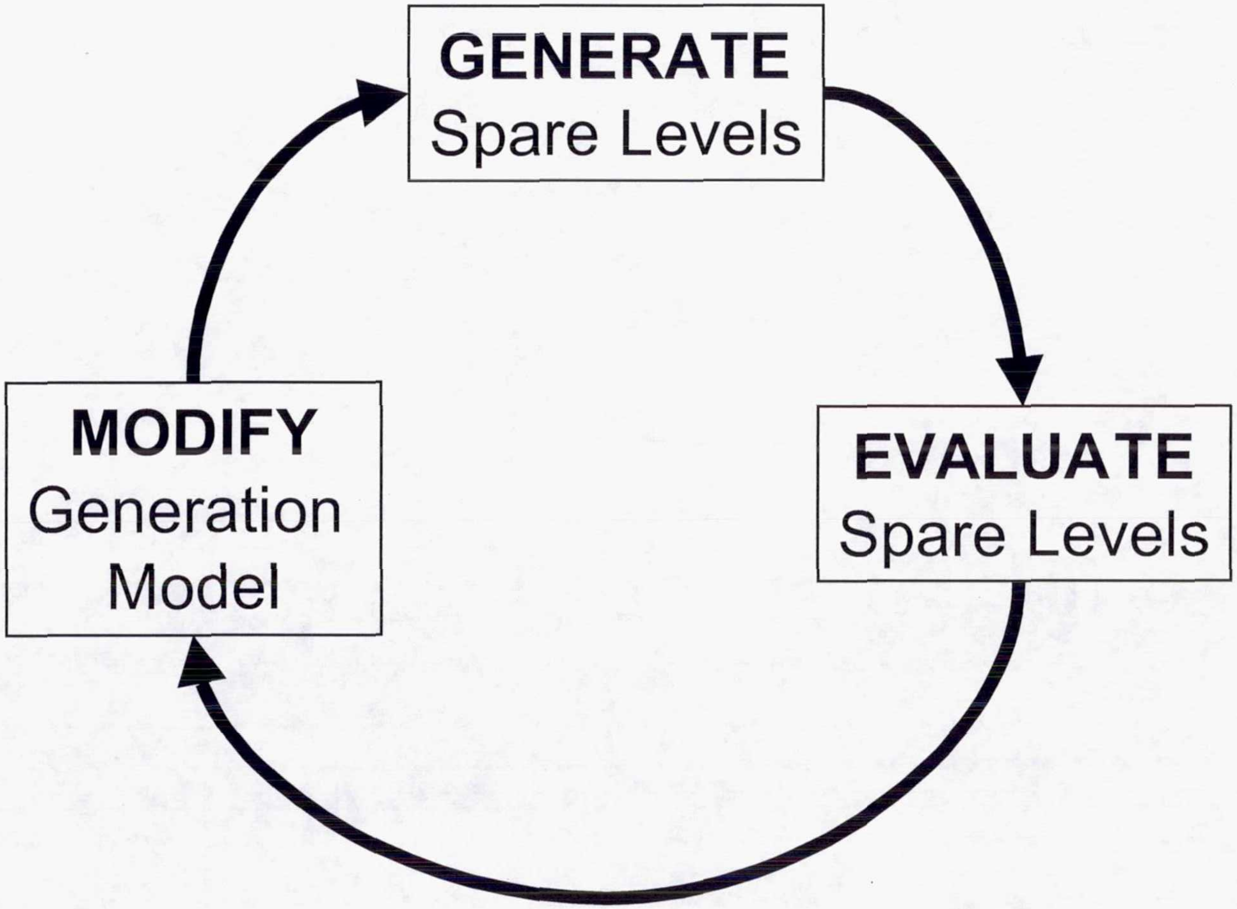
- Outsourcing of repair
- Condemnation
- Limited capacity for in-house diagnosis and repair
- Probabilistic transport and service times
- Limited inventories
- Dynamic work prioritization at repair centers

Simulation Model Features

- Identify Events
- Model Delays Between Events
- Manage Priorities
- Track Inventories
- Select Inputs
- Capture Outputs

- System Framework
- Analysis Tools
- Analysis Process (GEM)

Overview



GENERATE
Spare Levels

EVALUATE
Spare Levels

MODIFY
Generation Model

Analysis Process

- Validate models with realistic data

- Use analytic tools to evaluate alternative maintenance resource strategies

- Enhance the current mathematical model
  - Repair queue time variability
  - Repair capacity decisions
  - Repair facility location decisions
  - Repair facility assignment decisions

Next Steps

SFINIX

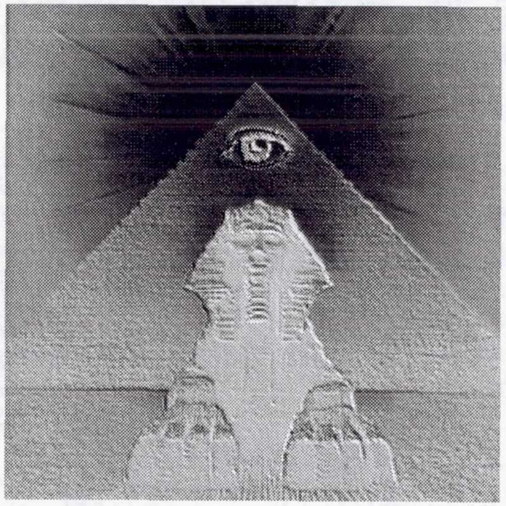
Scaleable, Fault-tolerant Intelligent Network or X(trans)ducers

Anthony Kelley
(MSFC/ED12)
256-544-7646
anthony.kelley@msfc.nasa.gov

"ST Day 2000: Reducing Risk for the Next Generations"

SFINX

The Intelligent I/O Network
for Future NASA Avionics

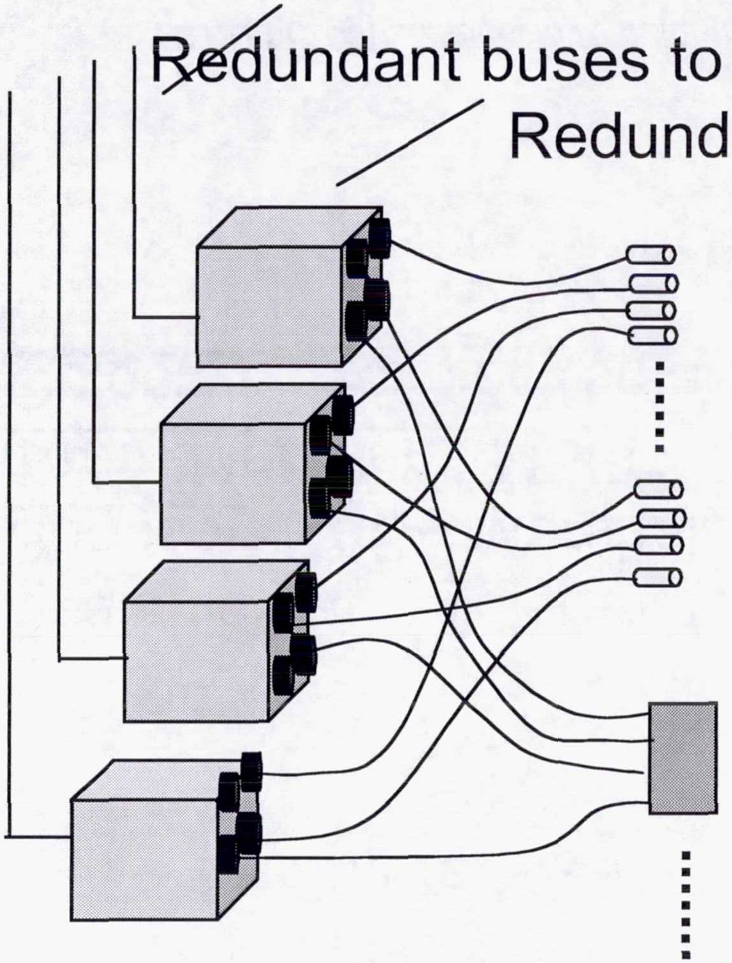


Scalable **F**ault-**T**olerant **I**ntelligent **N**etwork of Trans(**X**)ducers

Sponsor: NASA Marshall Space Flight Center (MSFC)

Team Members: MSFC, Draper, Oak Ridge, GP:50

Objective: Develop “smart” sensor technology for spacecraft



Redundant buses to fault-tolerant flight computer (1553)

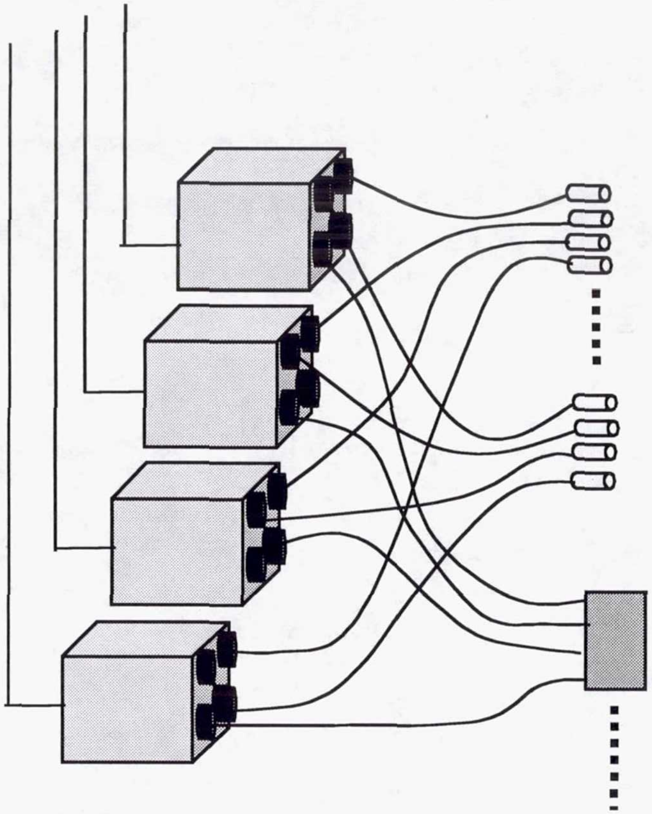
Redundant, custom I/O electronics (MDMs)

Redundant analog output sensors

Redundantly controlled analog actuators (with voting for critical functions)

Today's Reusable Spacecraft Utilize Extensive I/O Electronics

- ♦ Extensive wiring is expensive to install, reduces reliability
- ♦ Growth or change during development is very costly
- ♦ Complexity makes checkout difficult, uncertain
- ♦ Requires many custom electronic units
- ♦ Complex, installation specific software



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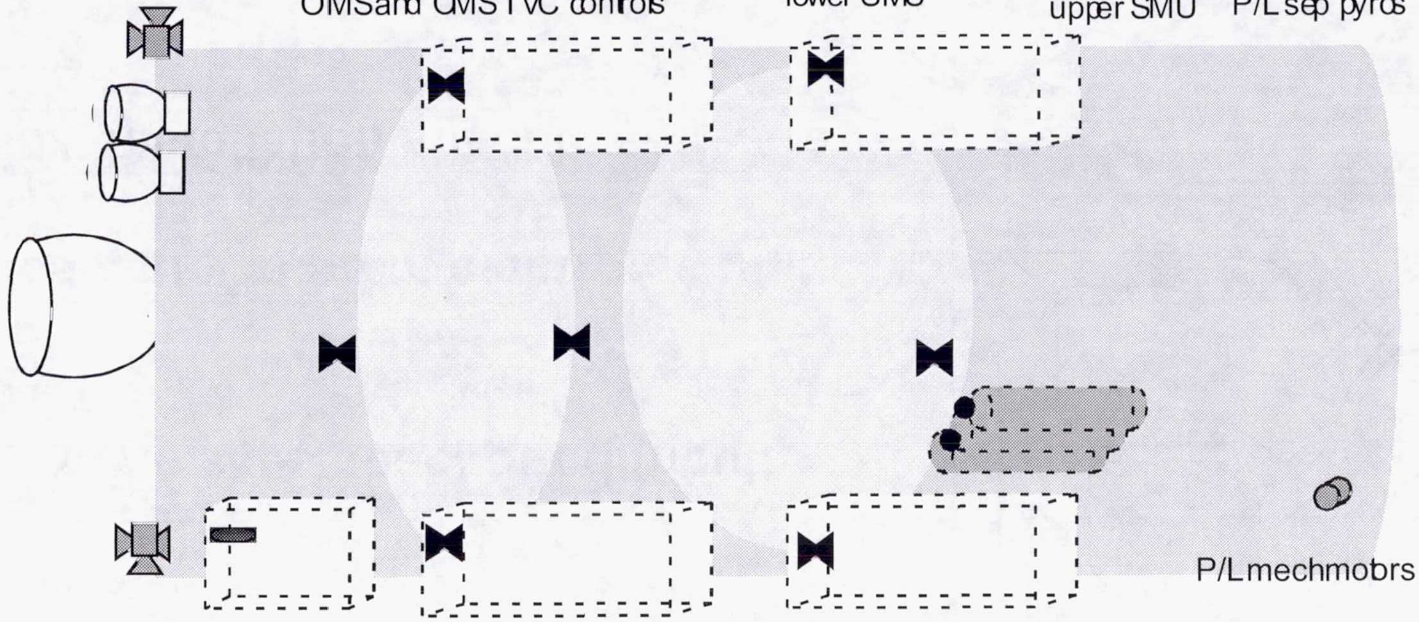
I/O Installation and Development Discourages Use of Electronically Controlled and Fault-tolerant Functions



dual OMS engines w/ solenoid valves and sensors

3 axis ACS thruster solenoid valves (1 of 4)

OMS and OMS TVC controls

lower SMU

1553 bus

batteires

upper SMU

Elect pallet
(VMCs, EGIs,..)

P/L sep pyros

P/L mech motors

main engine w/ pyros,
solenoid vlvs, sensor, TVC

airbag (1 of 4) w/ solenoid valves, pyros, sensors

parachutes & cutters w/ pyros

N2 gas w/ solenoid vlvs, sensors

sensor (temp, pres, position)

electric motor

solenoid controlled valve

pyrotechnic device

computer or I/O electronics

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Typical Spacecraft

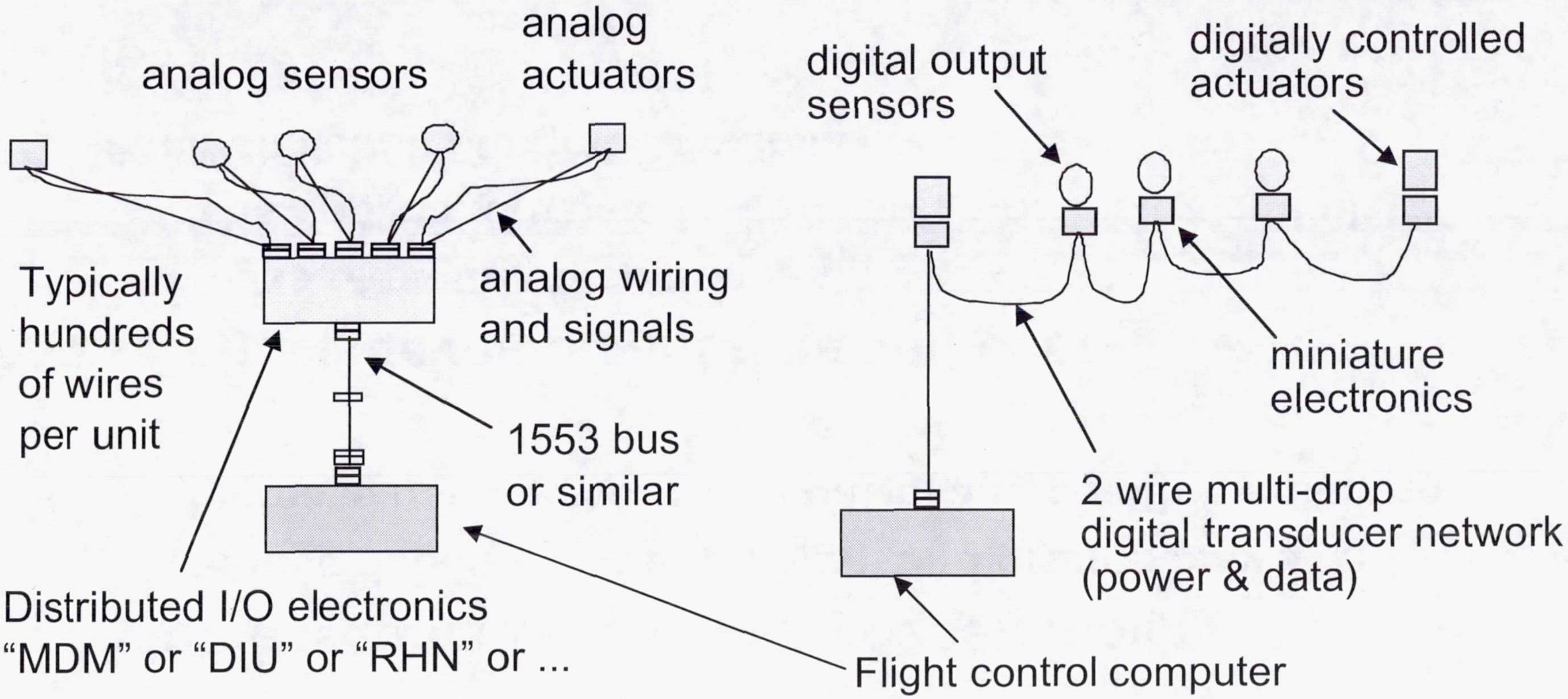
- Reduced avionics weight
  - less wiring and fewer connectors
  - fewer and lighter I/O black boxes

- Increased automation and dependability
  - reduce dependence upon flight and ground crews
  - increase use of electronic control and health monitoring

- Reduce development time and cost
  - reuse of standard components
  - less application specific software, more “plug and play”
  - installation / upgrade flexibility

Why Use Smart Sensors and Actuators?

Traditional Installation **Network of Smart I/O**



analog sensors

analog actuators

analog wiring and signals

Typically hundreds of wires per unit

1553 bus or similar

Distributed I/O electronics "MDM" or "DIU" or "RHN" or ...

digital output sensors

digitally controlled actuators

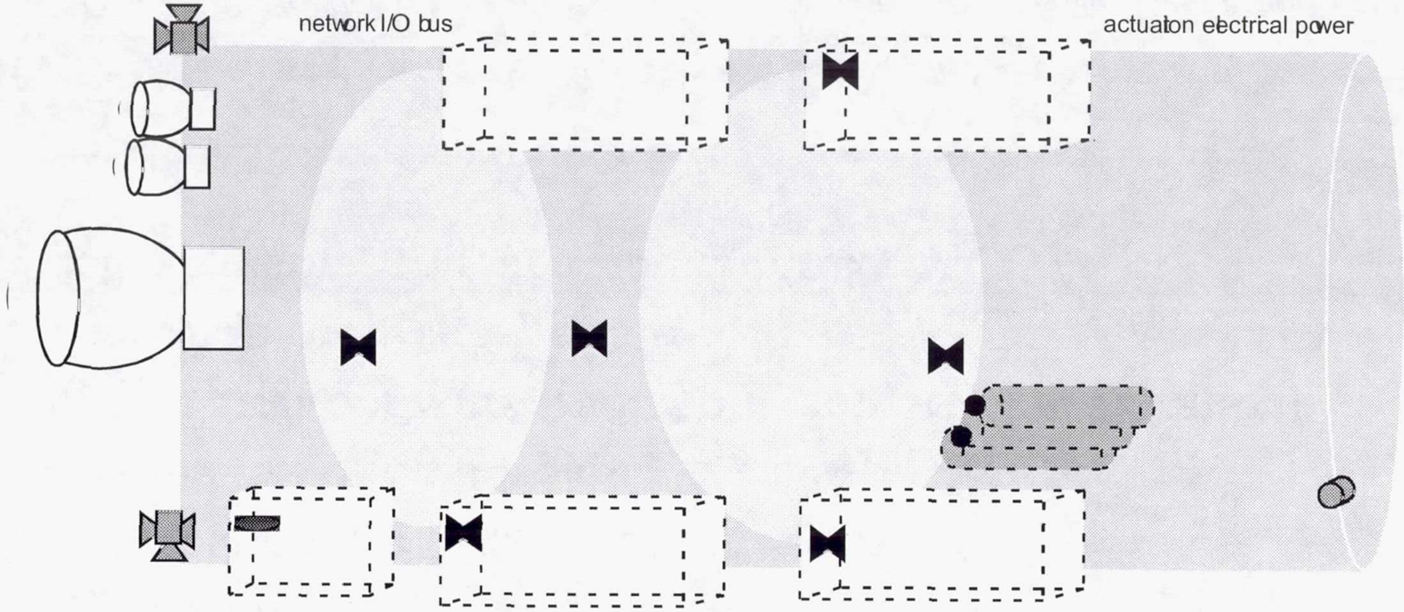
miniature electronics

2 wire multi-drop digital transducer network (power & data)

Flight control computer

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Networks of "Smart" I/O Can Address these Problems



50 - 75% savings in wire weights are possible

smart sensor

electric motor w/ controller

"smart" solenoid controlled valve

pyro w/ companion "smart" driver

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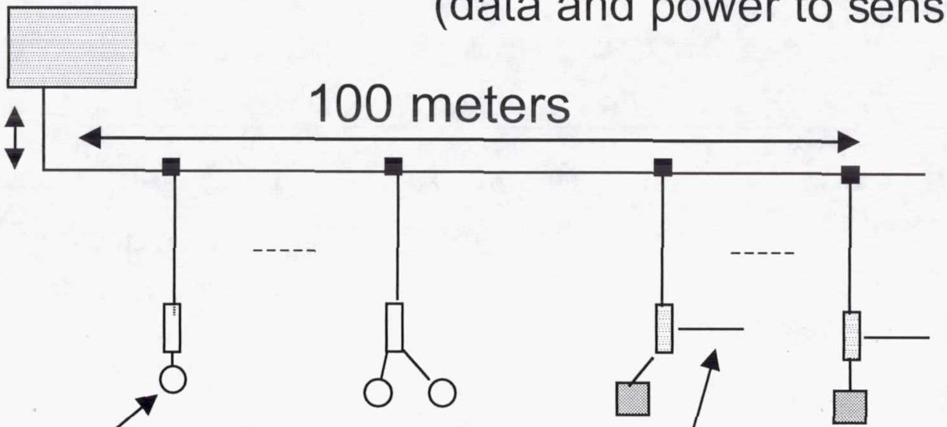
Spacecraft with Multi-drop I/O Network

- “Smart” Network I/O electronics are widely available
  - automotive (CAN bus, J1850,...)
  - industrial control (Fieldbus, Profibus, Lonworks,…)
  - home automation (Intellon, Echelon, Enikia,...)

- The challenge is applying the concept to space applications
  - lightweight, simple to install
  - fault tolerant for life critical functions
  - no repairs during mission
  - severe environments (radiation, temperature, vibration)
  - open, non-proprietary system
  - deterministic command and control

SFINX Challenge - Apply “Smart” I/O Networks to Critical Spacecraft Functions



Network Control Terminal

Multi-drop, 2 wire IEEE -1451 transducer bus (data and power to sensors and actuator controls)

100 meters

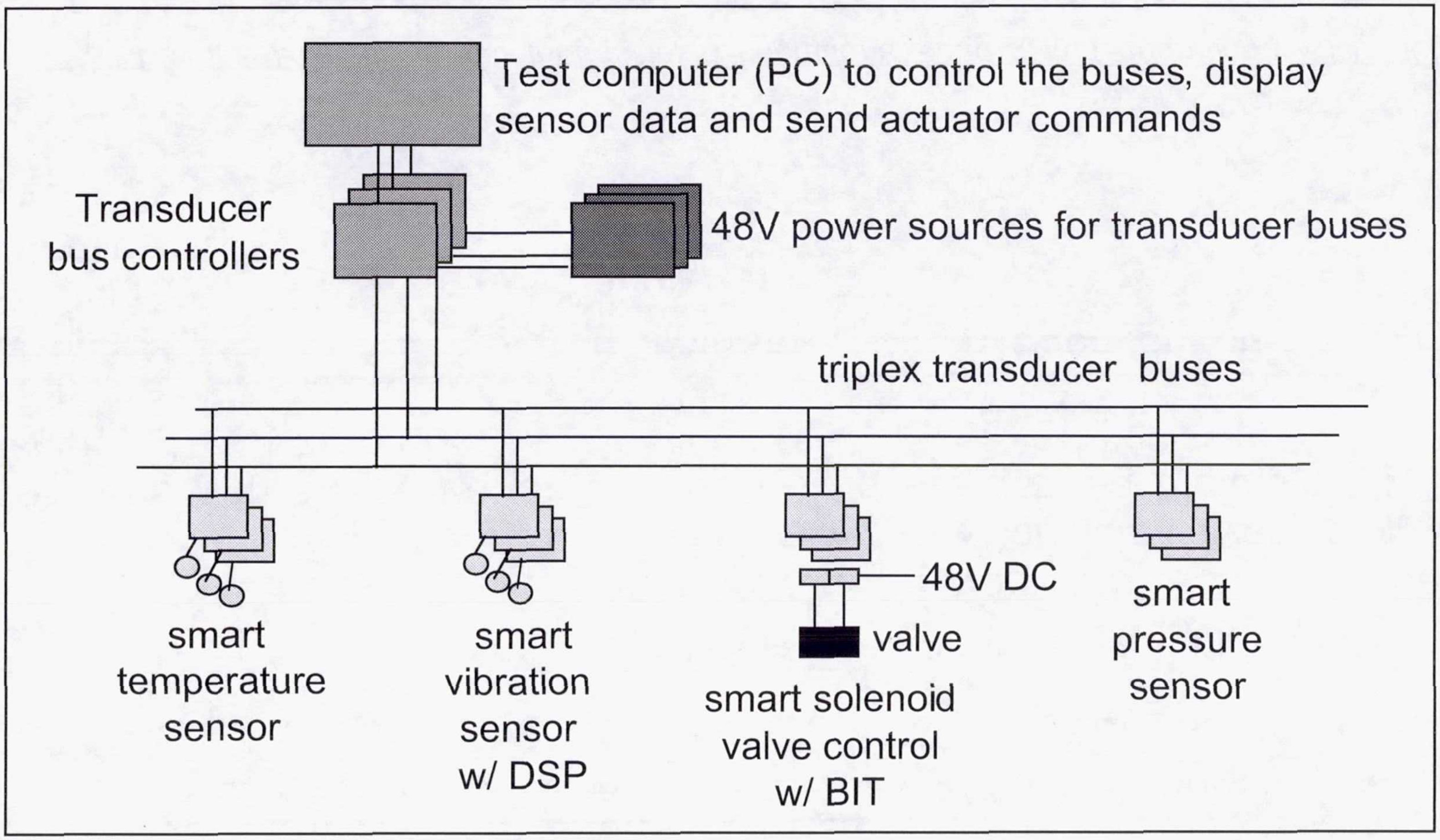
At least 100 sensors or actuator on one branch

Interfaces with a wide variety of "simple" sensor types
- Pressure
- Temperature
- Position
- Vibration

Separate actuation electrical power

Interfaces with a wide variety of actuator types
- Solenoid valves
- Servo-actuators
- Pyros
- EMA
- Power control

SFINX Requirements - Transducer Network Concept



Test computer (PC) to control the buses, display sensor data and send actuator commands

Transducer bus controllers

48V power sources for transducer buses

triplex transducer buses

smart temperature sensor

smart vibration sensor w/ DSP

48V DC

valve

smart solenoid valve control w/ BIT

smart pressure sensor

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SFINX Hardware Demonstration of a Small Scale Sensor / Actuator Network

- FY01--Demonstrate hardware and software for both RF and 2-wire system
  - Refine 1451 object models
  - Complete 1451.3 standard
  - Analyze distributed real-time architectural impacts and reliabilities
  - Start publishing designs
- Future
  - Append 1451.3 with mixed mode fiber and wire system
  - Utilize ground system based on SFINX
  - Fly SFINX hardware
  - Infuse technology through industry groups

Future Plans...

High-Performance Guidance & Control Adaptation for Future RLVs

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"ST Day 2000: Reducing Risk for the Next Generations"

- Motivation for Project
- Technology Goals & Objectives
- Institutional Elements
- Background of Effort
- Current Status & Accomplishments
- Near-Term Plans

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Briefing Overview

- Future launch vehicles will continue to have thin performance margins -- through diverse, complex, and demanding missions
    - A rich variety of abort and off-nominal scenari are likely
    - optimality of performance is relevant
- The dynamics of these vehicles will be complicated, e.g. airframe/scramjet interactions, multimode propulsion, etc.
    - Calculation of efficient (optimal) controls not straightforward
    - Certainly not straightforward for reliable online adaptation to new scenari!
    - Complicated dynamics lead to additional uncertainty in modelling, which must be addressed to preserve performance (alternative is robustness, which costs performance)

Motivation (1)

- ♦ "Airline-like" commercial operation infeasible without automation of guidance & control design/abort/contingency planning functions…
  - "Airline-like" model is rendered difficult by thin performance margins, higher energy levels, and lack of a pilot for responding to unplanned situations.
  - Onboard "optimal" adaptation needed to prevent a combinatorial explosion of preplanned cases!
- ♦ This technology is certainly not "state of the art," and does not exist for complicated nonlinear scenari associated with hardware failures and aborts
  - The technology must be developed, and we hope that this project is successful in doing so.

Motivation (2)

Technology Goals & Objectives

- **Develop theory and computational techniques for:**
  - **high-performance (I.e. optimal) inner/outer loop control which reliably**
    - accommodates and exploits propulsion/airframe interactions
    - changes, for changes in vehicle health or mission
    - provides timely revision of mission profile for abort scenari
    - formally addresses uncertainty in the system
  - **Validate new technology in appropriate experimental environments, as it matures…**

"Baby" simulations

Vehicle simulations

MAST

"Generic" test fixtures

- **People:**
  - **LaRC (0.5-0.75 FTE)**
    - guidance, nonlinear control, preliminary sim development
  - **MSFC (0.5 FTE)**
    - navigation, control, MAST coordination
  - **GRC (1.5 FTE)**
    - control of airframe/propulsion interactions
- **Validation Assets:**
  - **Simulink adaptation of 6DOF "Marshall Aerospace VEhicle Representation In C" (MAVERIC) -LaRC/MSFC**
  - **Flying Flexible Fixture (FFF) - LaRC**
  - **Marshall Avionics System Testbed (MAST), INS/GPS Lab - MSFC**

Institutional Structure of Effort

- **This work extends from GN&C technology developed under Bantam…**
  - **Neighboring Optimal Control (NOC) techniques for systems with constraints**
    - provides reliably available near-optimal performance "near" known missions
  - **uncertainty modelling techniques for μ synthesis and analysis**
    - permit formal balancing of robustness against performance for linear feedback systems
  - **development of "Flying Flexible Fixture" (FFF)**
    - low-cost laboratory scale "difficult, highly nonlinear, unstable" flying system for evaluating nonlinear control concepts
  - **preliminary development of INS/GPS lab at MSFC**
    - permits inclusion of INS/GPS navigation issues in MAST simulations
    - permits high-fidelity evaluation of navigation filter concepts

Background of Effort

- NOC technique being refined…
  - current mix of Matlab and FORTRAN90 software shifting entirely to the latter
  - revision of temporal discretization to satisfy POO principle of optimal control
  - inner/outer-loop numerical optimization technique for improvement of optimal trajectory convergence currently under Monte Carlo testing

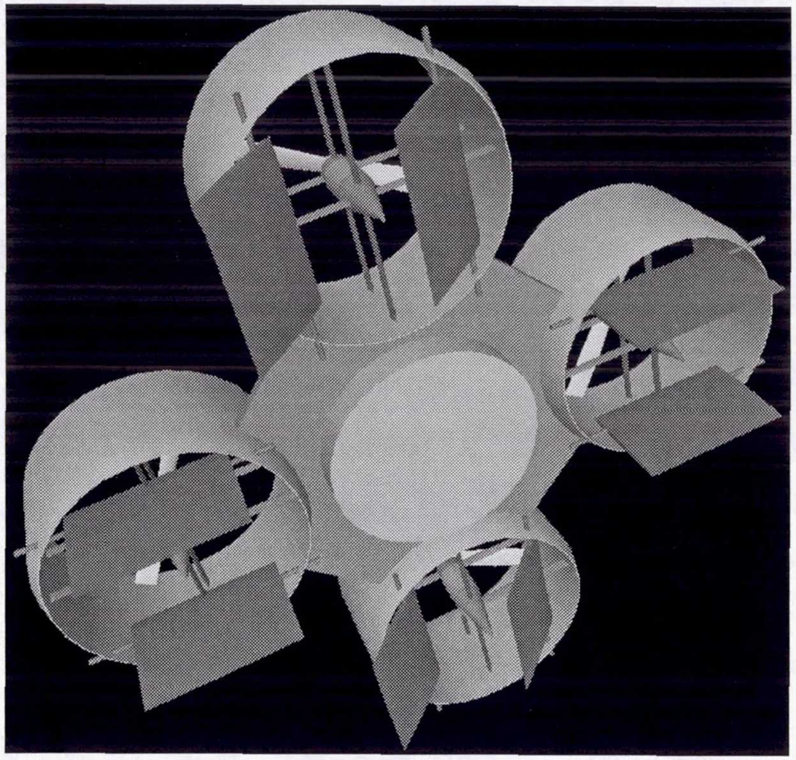
- Matlab toolbox under development to combine μ uncertainty modelling computational algorithms (this work leveraged against NASA Aviation Safety Program effort)

- LaRC & GRC settling on joint dynamical model or family for hypersonic airbreather

Current Status (1)

- MSFC starting an extension of INS/GPS evaluation and development lab to interface with MAST for realistic nav-in-loop technology evaluation.
- LaRC developing Simulink adaptation of 6DOF Maveric for joint LaRC/MSFC/GRC simulation studies.

Current Status (2)



- Electrically powered
- 28 lbm, 40 lbf max thrust
- 12 DOF control
- controlled via radio link to dSpace control system that hosts simulink-based user concepts.

- Aero testing in progress for powered flight
- System certified for safe operation

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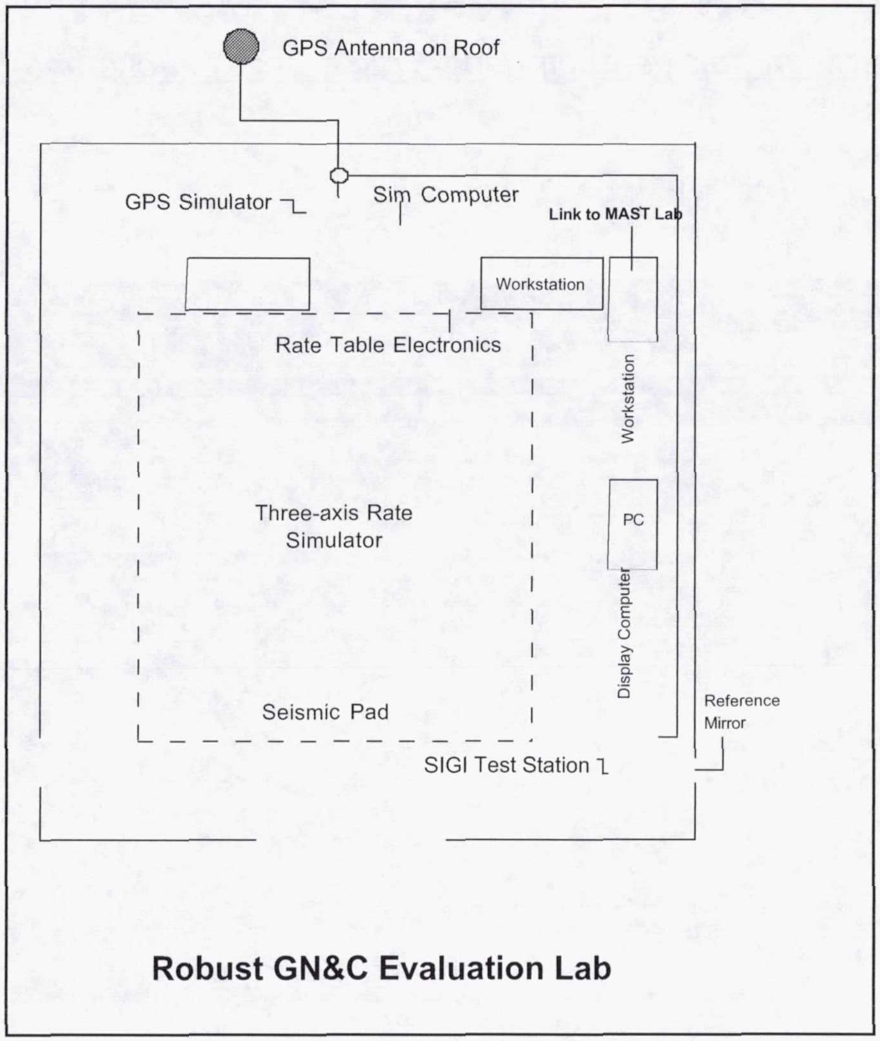
Flying Flexible Fixture Status

- Develop and test GN&C blending filters
- Robust filter design to allow for a variety of inertial measurement units and Global Positioning System (GPS) receivers used in different trajectories
- Develop MSFC expertise in blending filters design for greater mission flexibility with reduced cost



Robust GN&C Evaluation Lab

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Robust Navigation and Guidance

- ♦ **FY01**
  - **(4Q) Complete hardware integration of INS/GPS evaluation and development lab.**
    - Output: lab will be available for developing open-loop sims of INS/GPS systems and tools will be in place for development of easily-configurable kalman filters providing blended INS/GPS nav solutions
  - **(4Q) Develop generic 6DOF Simulink sim, congruent with MAVERIC, suitable for G&C studies, populated with parameters for a relevant vehicle**
    - Output: sim will be available for rapid prototyping of guidance and control architectures, and their simulation-based evaluation. Elements of vehicle dynamics will be easily visible and available for modification and analysis.
- ♦ **FY02**
  - **(4Q) Develop nonlinear probabilistic/uncertainty model structure for RLVs. Populate with parameters for vehicle under study.**
    - Output: vehicle model will be extended to provide probability distributions of quantities related to dynamical response behavior.

Near-Term Milestones

Evolvable Hardware for 3rd Generation Avionics

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A collaboration between JPL and NASA ARC

JPL EHW page: http://cism.jpl.nasa.gov/ehw/darpa/

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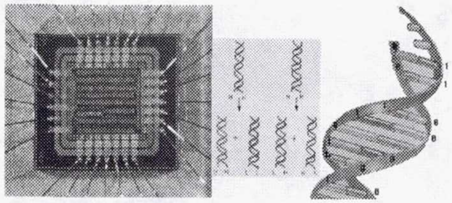
- We propose to develop "evolvable" circuits that would self-reconfigure under the control of biologically inspired genetic and evolutionary algorithms and would be directly implemented/integrated with the hardware itself.

- The objective is to demonstrate by 2006 a flight system prototype based on a "diehard" architecture, seamlessly integrating functional reconfigurable circuits and evolution/self-configuration mechanisms.

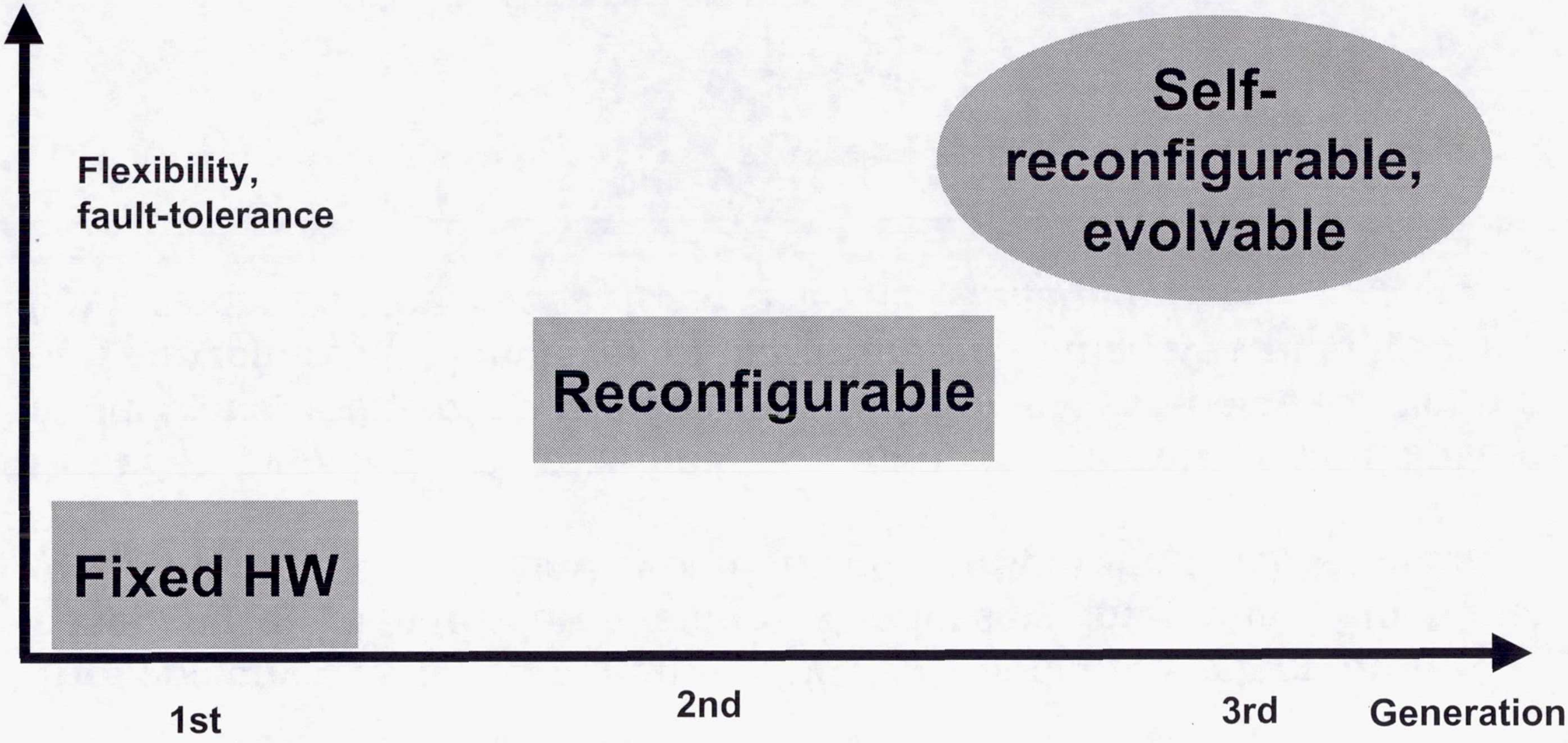
- Circuits evolving in real-time to compensate for unanticipated faults/damage and/or to provide new functionality on-demand, without the conventional high level of hardware redundancy would provide light-weight and low-cost avionics with high reliability.



"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Technology Goals and Objectives

Generation change: fixed hardware, reconfigurable hardware, evolvable hardware



Flexibility, fault-tolerance

Fixed HW

Reconfigurable

Self-reconfigurable, evolvable

1st

2nd

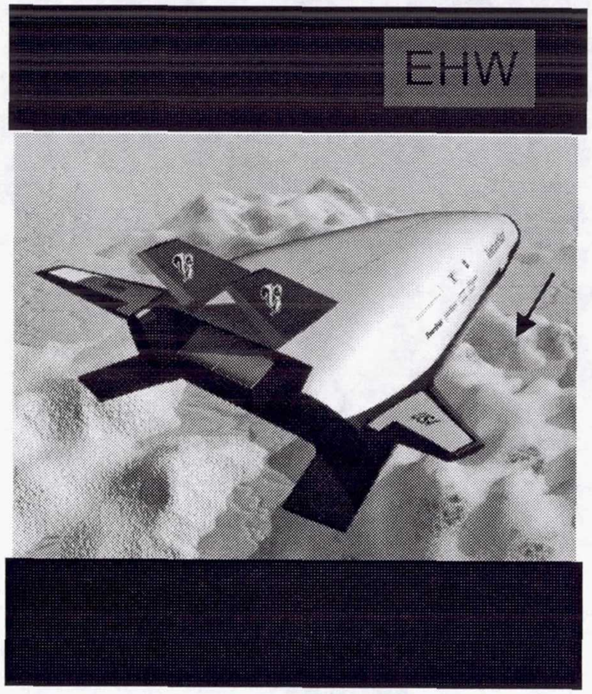
3rd

Generation

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Technology Goals: 3rd Gen. Avionics

Survivability:
Maintain functionality through parametric adjustments even with changes in hardware characteristics (e.g. due to radiation, temperature, aging and malfunctions)

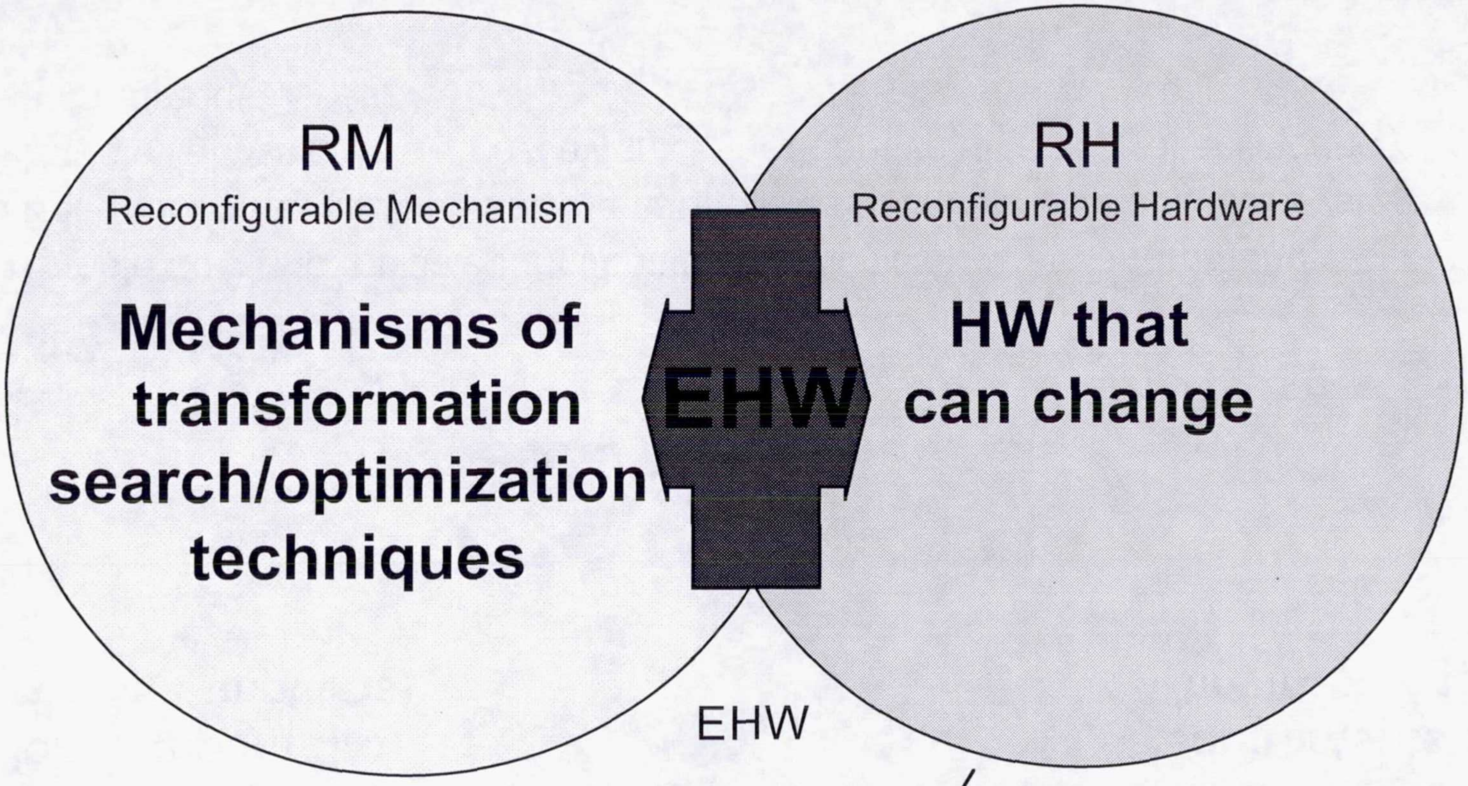


Versatility/Flexibility:
Create new functionality through synthesis of totally new circuits for new missions, dramatic changes in requirements or environment

- **Benefits**
  - Enable new and multiple functionality of avionics system on-demand.
  - Self-monitoring and self-healing capabilities in time-critical avionics system.
  - Enable lightweight, low-cost avionics for adaptive ultrahigh reliability and autonomous GN&C

Background: Motivation

Evolvable Hardware = Reconfigurable Mechanism + Reconfigurable Hardware



RM

Reconfigurable Mechanism

Mechanisms of transformation search/optimization techniques

EHW

RH

Reconfigurable Hardware

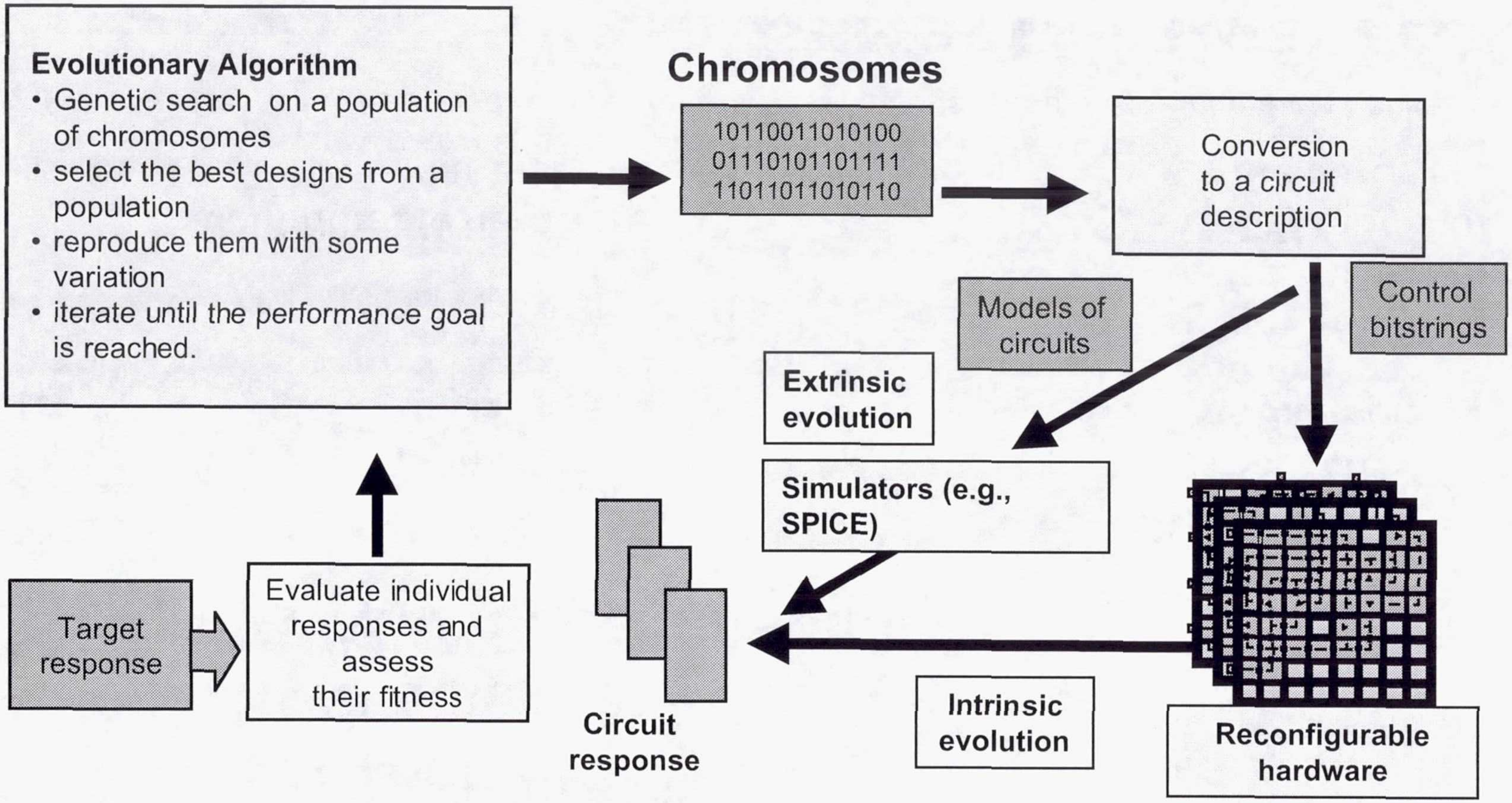
HW that can change

EHW

Current research in EHW focuses on reconfigurable hardware that self-configures for optimal functionality under the control of evolutionary algorithms.

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Background: Evolvable Hardware



Evolutionary Algorithm
- Genetic search on a population of chromosomes
- select the best designs from a population
- reproduce them with some variation
- iterate until the performance goal is reached.

Chromosomes

10110011010100
01110101101111
11011011010110

Conversion to a circuit description

Models of circuits

Control bitstrings

Extrinsic evolution

Simulators (e.g., SPICE)

Target response

Evaluate individual responses and assess their fitness

Circuit response

Intrinsic evolution

Reconfigurable hardware

Potential electronic designs/implementations compete; the best ones are modified to search for increasingly more suitable solutions

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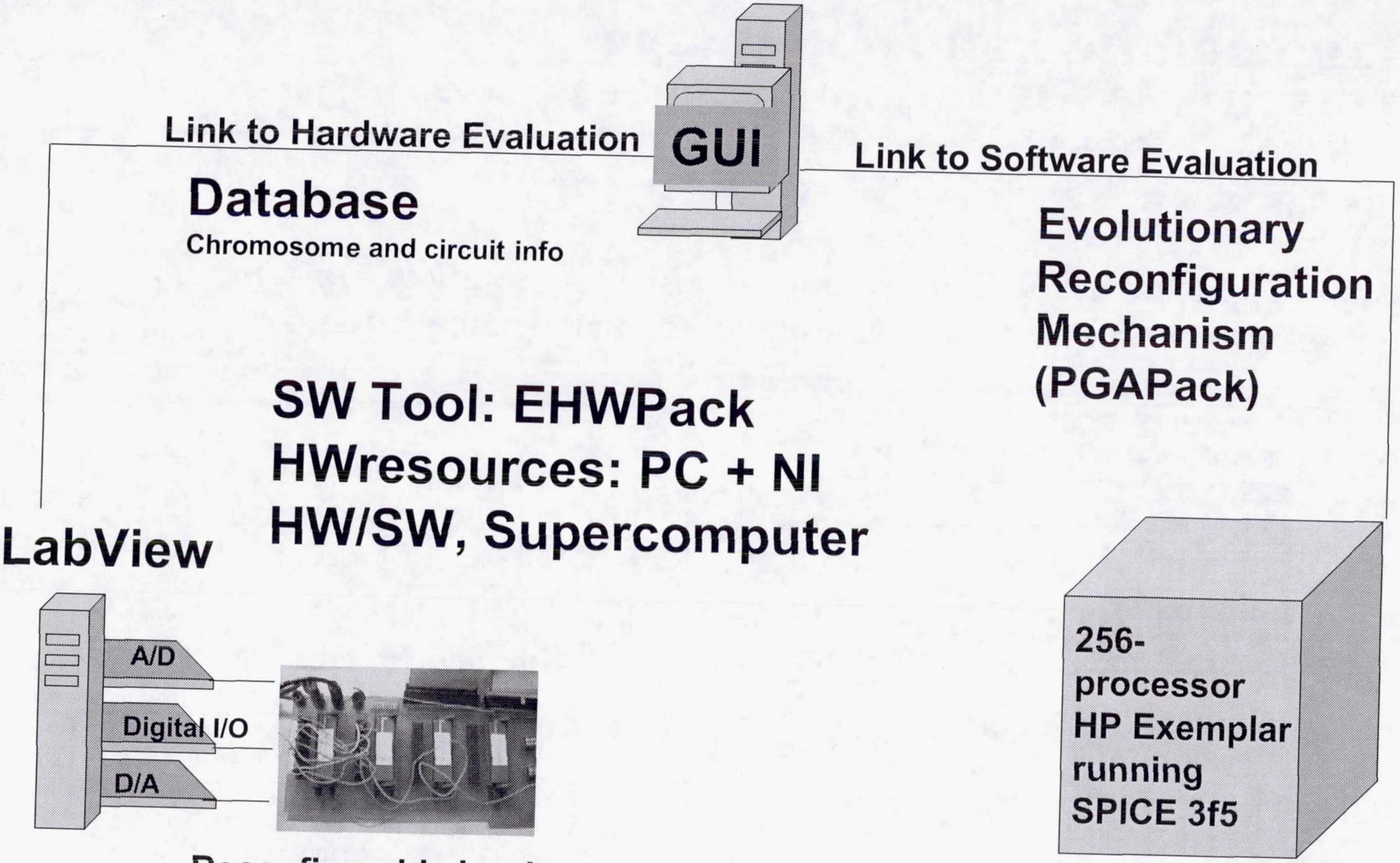
Current Status: Evolutionary synthesis and adaptation of electronic circuits

Current Status: Testbed



Link to Hardware Evaluation

GUI

Link to Software Evaluation

Database

Chromosome and circuit info

Evolutionary Reconfiguration Mechanism (PGAPack)

SW Tool: EHWPack

HWresources: PC + NI HW/SW, Supercomputer

LabView

A/D

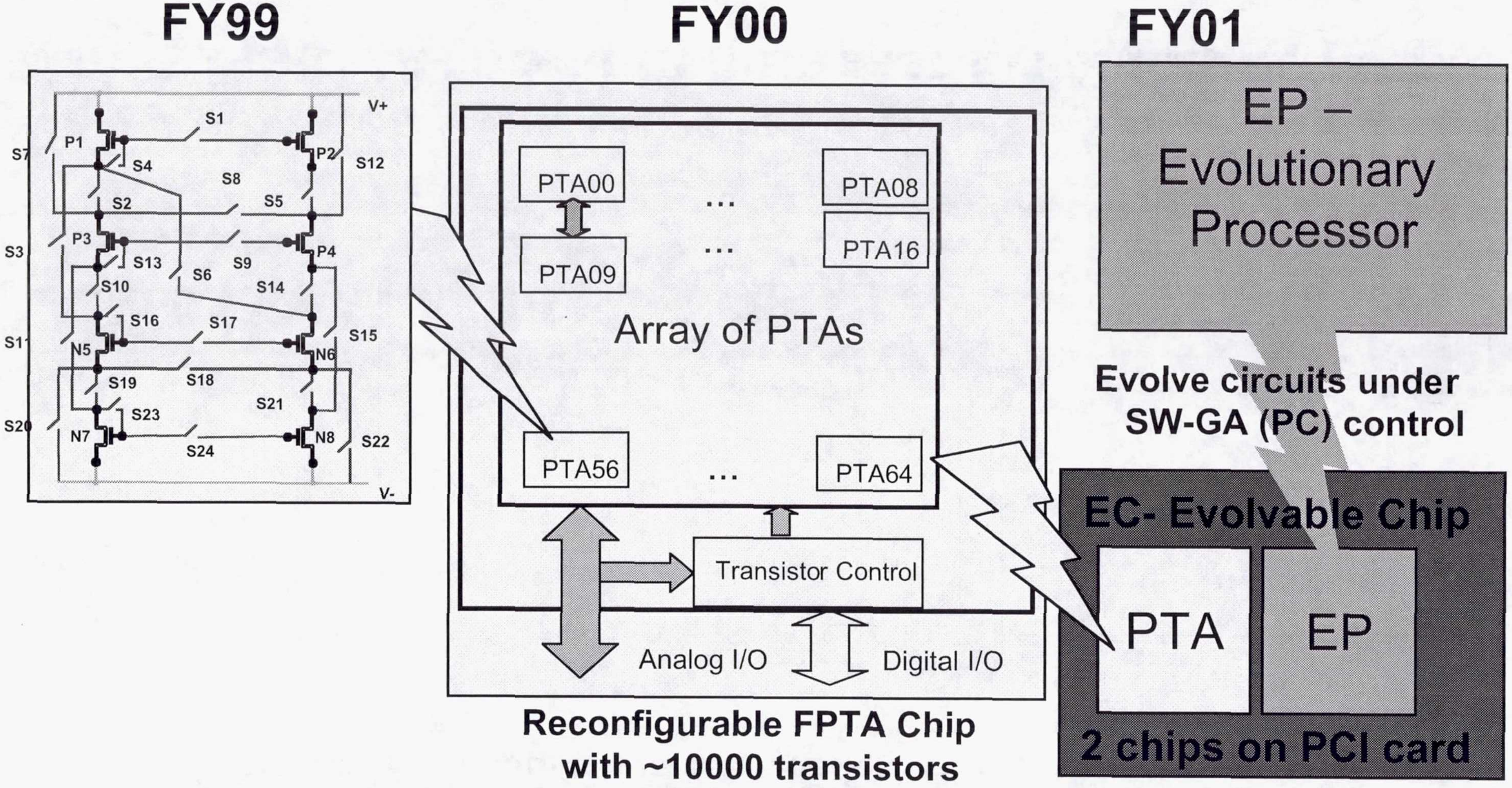
Digital I/O

D/A

256-processor HP Exemplar running SPICE 3f5

Reconfigurable hardware
Chips under test

SW model of the hardware



FY99

FY00

PTA00

PTA09

...

...

PTA08

PTA16

Array of PTAs

PTA56

...

PTA64

Transistor Control

Analog I/O

Digital I/O

Reconfigurable FPTA Chip with ~10000 transistors

FY01

EP – Evolutionary Processor

Evolve circuits under SW-GA (PC) control

EC- Evolvable Chip

PTA

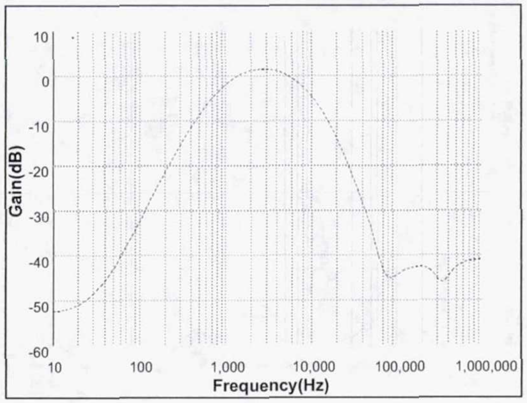
EP

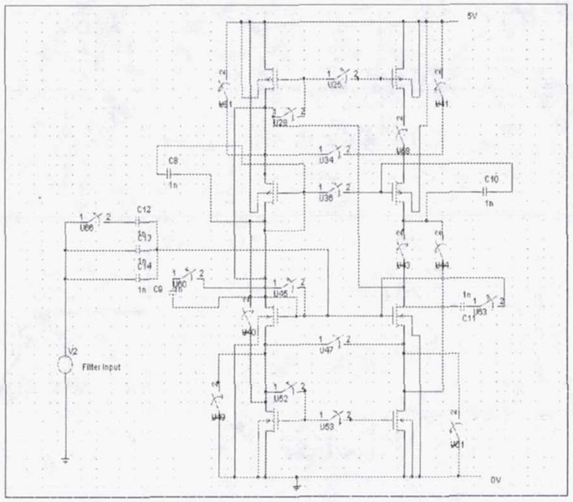
2 chips on PCI card

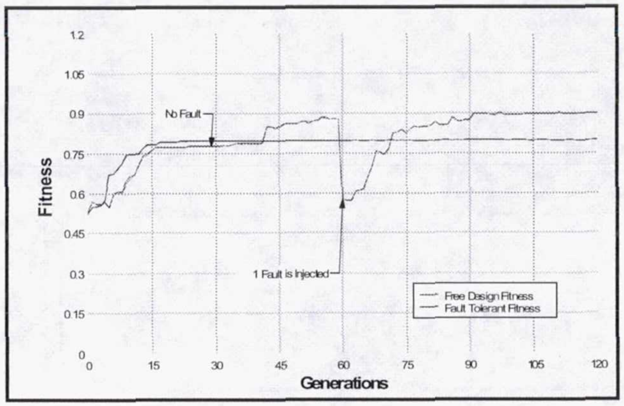
Evolvable Hardware System - Roadmap
From Component to Array on a Chip to System Board

Current Status: DARPA-funded hardware development

- **Evolutionary circuit synthesis and repair**
  - **Synthesis**
    - Analog computational circuits (fuzzy neuron, multipliers)
    - Logic Circuits (XNOR, AND gates)
    - Filters (band-pass)
  - **Repair: From faults and degradation with temperature**







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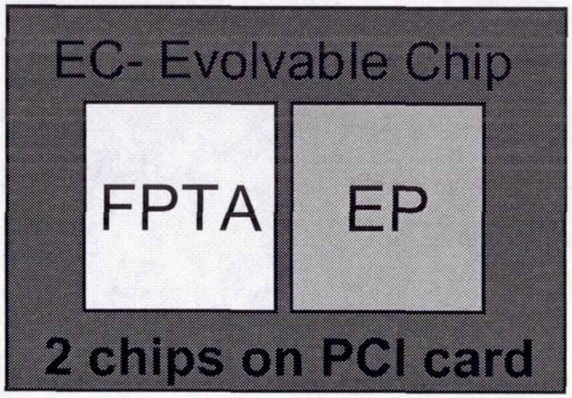
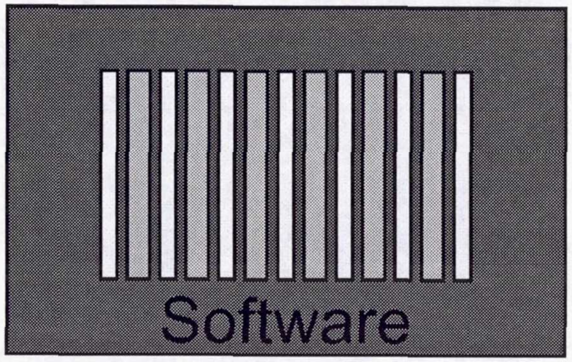
Major Accomplishments: EHW Experiments

- Demonstration of EHW on a PCI card
  - Two chips, one for Field Programmable Transistor Array and one for Evolutionary Processor



- Development and Simulation or a “diehard“ architecture

Seamlessly integrated “Diehard” architecture



Near term plans :FY01

Phase 1: Conceptual development of a “die-hard” architecture, i.e. a way of distributing the adaptation/self-configuration mechanism into the reconfigurable hardware.

Phase 2: Design and building of evolution-oriented chips and testing them in the context of selected, relevant applications. The tests would include synthesizing new electronic functions, recovery from faults, radiation and temperature hardening.

Phase 3: EHW would be integrated with a selected set of sensors within the framework of an on-board avionics computer.

Phase 4: Preparation of flight test.

Plans

- Risks
  - Evolution time is currently around minutes. It must be reduced to a few seconds, otherwise only non-time-critical applications may be impacted.
  - Scalability of the evolutionary approach to complex electronics systems still needs to be proven.
  - Currently, the implementation of the adaptation mechanism must be flawless.
  - If it can not be made fault-tolerant, the mechanism must be isolated in a protected area.

- The EHW technology has the potential to:
  - Enable multiple functionality of avionics systems using the existing resources that are reconfigured as needed.
  - Adapt and self-configure the avionics to new needed functionality
  - Self-heal and be fault-tolerant by rerouting around completely damaged components and reusing components with modified/altered characteristics in new circuit topologies.
  - Autonomous self-configuration.

Risks, Pay-off

EHW technology has the potential to be the underlying technology behind the avionics infrastructure (not only the electronics but also smart optical/structural/thermal subsystems through reconfigurable/morphing/adaptive MEMS/ materials) of the space systems for 2020 and beyond.

Conclusion

Advanced Electric Actuation Devices and Subsystem Technology

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"ST Day 2000: Reducing Risk for the Next Generations"

- Goal:
  - Develop two high horsepower (>80Hp)redundant EA Subsystems using advanced motor and power electronics designs, control techniques and lightweight structures. Demonstrate at a TRL 6 in FY08.
- Objectives:
  - Cost - lowers System O&M costs - no hazardous fluids, easier system checkout
  - Safety - improves system safety - no hazardous fluids
  - System Responsiveness - improves system capacity and operability- faster turnaround
  - System Dependability - improves reliability and maintainability - easier system checkout, fewer or no sensors, robust motor and drive designs

Advanced EA Devices

- Background
    - For Launch vehicles, current SOA - hard switched motor drives, PM motors, RVDT and LVDT sensors, lower horsepower (40Hp - single string, 20 Hp- dual channel)- TRL 4
    - Use of EA's reduces maintenance costs, turn-around times and improves safety vs. conventional centralized hydraulic system

- Current status
    - Grants with University of Alabama and Montana State University in process

    - MSFC in start-up mode for linear motor work

Advanced EA Devices

- Major accomplishments:
  - New start

- Near term plans
  - Initiate grant with University of Alabama – Dynamic,compute-controlled test fixture (January 2001)
  - Initiate grant with Montana State University – Fuzzy logic motor control (January 2001)
  - MSFC begins linear motor work (November 2000)

- Task manager: Mary Ellen Roth

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Advanced EA Devices

Hybrid Power Sources and Regeneration Technology for Electric Actuators

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"ST Day 2000: Reducing Risk for the Next Generations"

- Develop advanced proton-exchange-membrane fuel cell (PEMFC) technology as a replacement for existing alkaline fuel cell (AFC) technology
  - Enhanced safety
  - Higher power
  - Longer life
  - Lower weight
  - Improved reliability and maintainability
  - Higher peak-to-nominal power capability
  - Compatibility with propulsion-grade reactants
  - Reduced ground and mission operations
  - Potential for significantly lower cost

- Assemble an experienced NASA team to direct the effort
  - Team members GRC (lead), JSC, KSC, and MSFC
  - No vendor is clear leader in developing PEMFC technology for space applications
  - NASA has significant space fuel cell experience with Shuttle
  - NASA can direct design efforts to guarantee future vendor competition
    - Modular powerplant approach
  - NASA has most direct access to evolving RLV requirements

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

2nd Gen RLV Program: Technology Goals and Objectives

- Background:
  - Hybrid sources needed for advanced power systems due to high peak power demands of flight surfaces
  - Previous research by MSFC and GRC under the ELV System Modernization Program showed a hybrid source would reduce the overall size and weight of the power source – a supercapacitor would provide the peak power needed, while a battery would handle the nominal requirements

- Current Status/SOA:
  - Carbon and RuOx are most common electrode materials
  - Most devices are low voltage (<15V)
  - Maximum power density ~20kW/kg @ <1kJ/kg
  - Maximum energy density ~10kJ/kg @ <1kW/kg

Hybrid Sources and Regen. Energy

- **Technology Goal:**
  - **Develop high power density, low ESR supercapacitors to provide peak power to EA loads and demonstrate the ability to recapture regenerative energy.**

- **Objectives:**
  - **Cost - Lower System O&M costs – no toxic materials**
  - **Safety - Improve System Safety – no toxic materials**
  - **System Responsiveness – improve system capacity – reduces weight of power source**
  - **System Dependability – improve reliability – high cycle life**
  - **Program goal of 40kW/kg @ 10kJ/kg**

Hybrid Sources and Regen. Energy

- NASA first developed PEMFC technology for Gemini in the 1960's
  - Low power
  - Poor performance
  - Marginal reliability
  - High cost

- NASA developed AFC technology for Shuttle in the 1980's
  - Higher power
  - Excellent performance
  - High reliability
  - High cost

- Commercial market spent hundreds of millions of dollars in the 1990's to advance PEMFC technology for automotive and residential applications; technology spin-off *to* NASA
  - Very high power
  - Excellent performance
  - Very high reliability
  - Very low cost potential (similar to electronics and telecommunications industry)

Background

- NASA team (JSC, GRC, KSC) proposed PEMFC technology for Shuttle Upgrade Program in mid 1990's
  - JSC awarded study contracts to two potential vendors (AlliedSignal, IFC)
  - PEMFC technology showed greatest long-term benefits
  - Improved AFC technology selected because of lower up-front costs to modify AFC than replace entire fleet with PMCFC

- GRC teamed with AlliedSignal (now Honeywell) on successful PEMFC stack development proposal for RLV; part of NRA 8-21 in 1998
  - 26-month effort
  - Component development
  - Stack design
  - Final end-product: 5-kW, 30-V modular PEMFC stack

Background Continued

- Safety/Reliability
  - Reduced hazardous materials in fuel cell stack (no KOH, no asbestos)
  - Reduced critical failure modes (hydrogen over-pressurization, electrolyte wash-out)
  - Graceful performance degradation

- Durability/Supportability
  - Elimination of inherent corrosion
  - Reduced ground servicing from enhanced IVHM

- Cost
  - Total DDT&E cost estimated at \$20 - \$30 million for PEMFC (TRL level 4 to 8)
  - Projected flight powerplant costs: PEMFC < half AFC
  - Evolving and highly competitive commercial market to drive down future stack costs
  - Reduced life-cycle costs
    - Longer life powerplants
    - Improved logistics (bench-top maintenance)

Benefits (PEMFC vs. AFC Technologies)

- PEMFC commercial vendors nearing market readiness for H_2/air systems
  - Full production for automotive model vehicle line by mid-decade
  - Residential fuel cell unit within several years

- Commercial PEMFC technology not directly suitable for space applications
  - Water management issues in zero-g environment
  - Materials compatibility issues for pure O_2 reactant

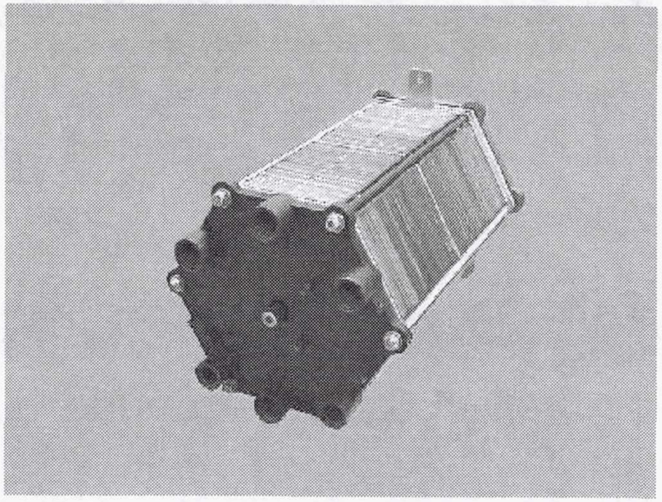
- ERAST program developing regenerative fuel cell (RFC) energy storage based on PEM fuel cell and water electrolysis technology
  - RFC is enabling energy storage technology for high-altitude aircraft and Lunar/Mars bases because of long cycle times (e.g. 12 hrs. daylight/ 12 hrs. darkness)
  - Team members Dryden – lead, GRC, and AeroVironment

- NRA 8-21 PEMFC stack development nearing completion

- NASA-led PEMFC powerplant development proposal selected for 2nd Gen RLV Program

Current Status

- NRA 8-21 PEMFC stack development nearing completion
  - Successful component development
    - Membrane/electrode assemblies, bipolar plates, current collectors
  - Characterization testing of 5-kW modular stack underway
    - Pure O_2 performance $\geq$ air performance

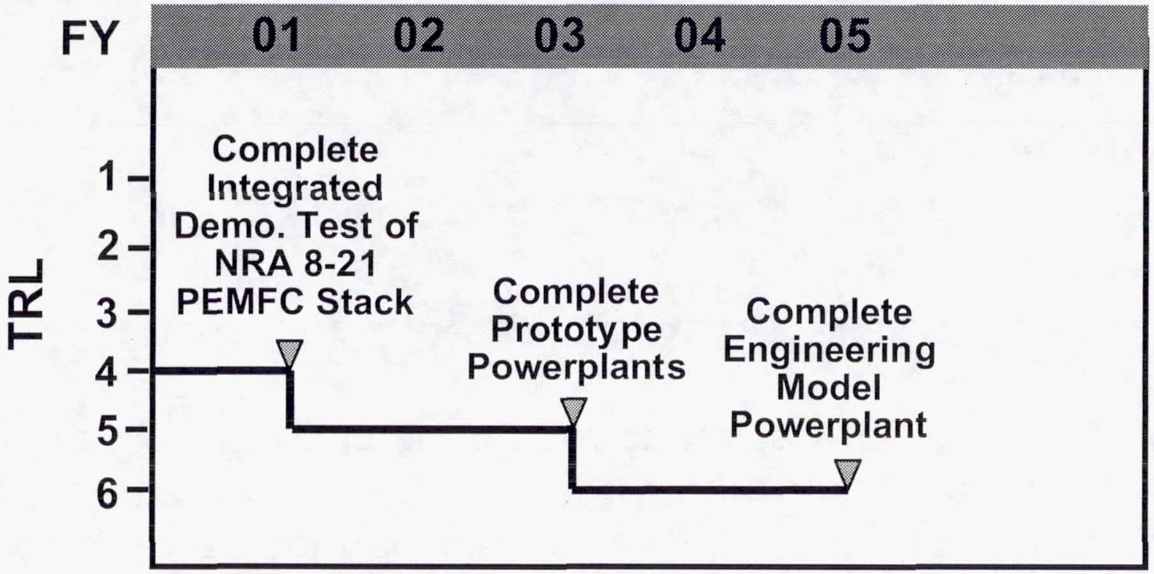


  - Life testing to be incorporated into 2nd Gen RLV Program
    - Integrated stack/ancillary hardware test at JSC

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Major Accomplishments

- NASA-led PEMFC powerplant development proposal selected for 2nd Gen RLV Program
  - Experienced NASA team (GRC – lead, JSC, KSC, MSFC)
  - NASA develops system requirements and design specifications
  - Contract awards allow vendor competition for hardware development
    - Prototype powerplant advances TRL from 4 to 5; two contract awards
    - Engineering model powerplant advances TRL from 5 to 6; single contract award
  - NASA conducts independent testing of vendor hardware



"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Plans

THANK YOU

"ST Day 2000: Reducing Risk for the Next Generations"

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  - GRC
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  - JSC
    - Karla Bradley, 281-483-6019, karla.f.bradley1@jsc.nasa.gov
  - KSC
    - Patricia Gladney, 321-861-3927, patricia.gladney-1@ksc.nasa.gov
  - MSFC
    - Lou Maus, 256-544-0484, louis.c.maus@msfc.nasa.gov

Points of Contact

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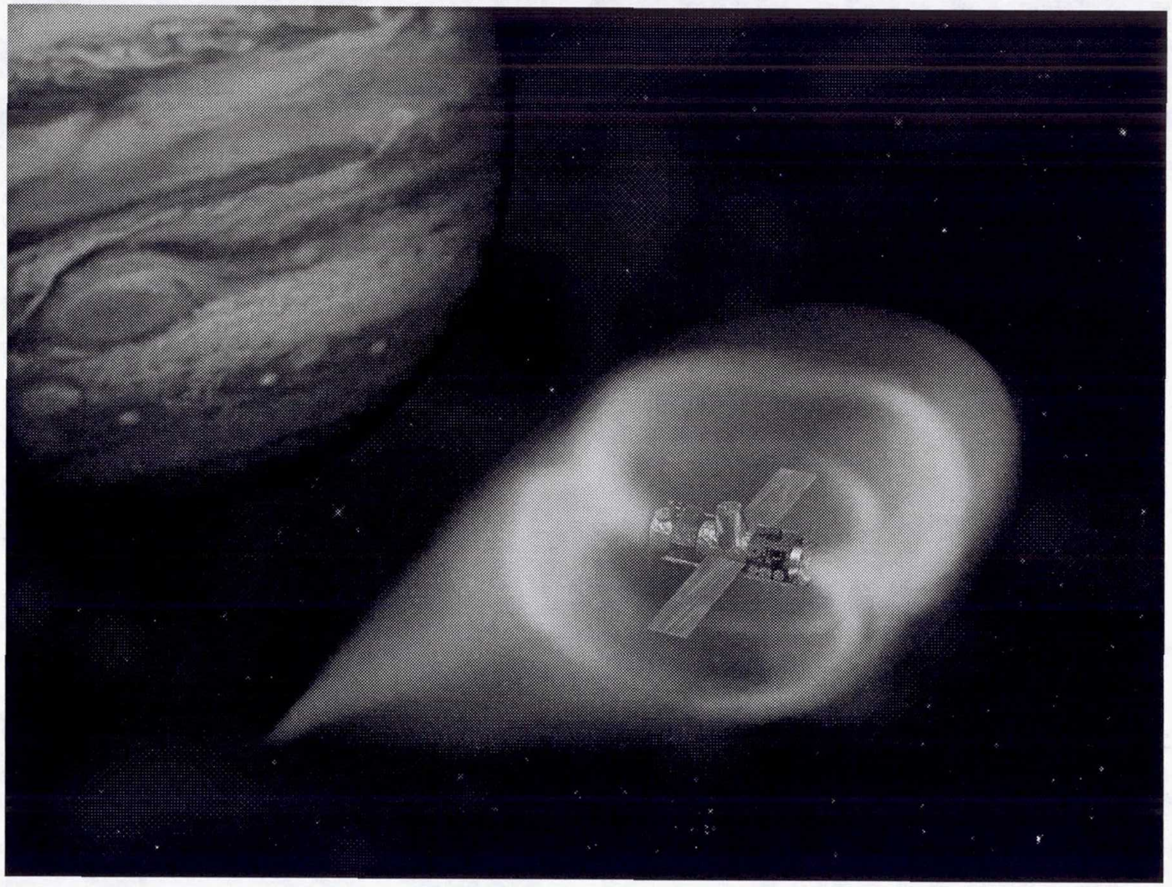
Mini Magnetospheric Plasma Propulsion (M2P2)

Space Transportation Technology Workshop or Section Title:

- The M2P2 concept is based on the Transfer of momentum from the solar wind to an artificial magnet field structure like that naturally occurs at all magnetized Planets in the solar system, called a Magnetosphere.



Space Transportation Technology Workshop or Section Title:

Mini Magnetospheric Plasma Propulsion

(M2P2)

- Demonstrate artificial magnetospheric inflation through cold plasma filling in vacuum.
- Demonstrate deflection of a surrogate solar wind by an artificial magnetosphere in the laboratory vacuum chamber.
- Compare theoretical calculations for thrust forces with laboratory measurements.
- Develop flight control algorithms for planning mission specific trajectories.
- Develop M2P2 system concept

Technology Goals and Objectives

- Two experiment campaigns were completed in FY'00:
  - Two weeks in July and two weeks in September.
- Experiments were conducted in the MSFC Test Area 300 large vacuum chamber, which is a cylinder 20 feet in diameter and 35 feet long, oriented vertically
- Work was performed in partnership with the University of Washington, with support from the University of Alabama, Southwest Research Institute, and Arnold Air Force Base personnel.

Current Status

- A dipole magnetic field line inflation of almost a factor of 30 was demonstrated, in a laboratory vacuum chamber, limited by chamber size

- The M2P2 plasma filled magnetic bubble was shown to push against the Earth's magnetic field and against an artificial solar wind.

- Even in an otherwise collisional plasma regime, plasma confinement within the M2P2 magnetic bubble was observed to a distance approximately 30 times the magnetic coil radius.

- Plasma density and temperature measurements were performed near the M2P2 device and in the magnetic equatorial plane a multiple distances from the device.

- Initial estimates for possible M2P2 radiation shielding were obtained

Space Transportation Technology Workshop or Section Title:

Major Accomplishments

- Quantitatively measure force exerted on the M2P2 magnetic bubble by the Earth's magnetic field and by an artificial solar wind
- Measure (quantitatively) in situ plasma and magnetic field conditions simultaneously at multiple locations through the M2P2 magnetic field structure
- Extend modeling of M2P2 radiation shielding properties
- Create a technology roadmap for the development of a flight M2P2 propulsion system

Near-Term Plans

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  - MSFC/SD50
  - Phone: 256-544-7587
  - Dennis.gallagher@msfc.nasa.gov

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  - University of Washington
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Contact Information

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Integrated Vehicle Health Management for the 2nd Generation RLV Program

October 11,2000

Marshal L. Merriam
Ames Research Center

mmerriam@mail.arc.nasa.gov (650) 604-4737

- 2nd Generation RLV Program
- 3rd Generation RLV Program
- The NASA X-37 IVHM Flight Experiment
- Propulsion and Power IVHM
- Integrated Vehicle Health Management (IVHM) Activity at Kennedy Space Center
- IVHM Technology at JPL
- Structures IVHM for 3rd Generation RLVs
- IVHM Systems Engineering and Integration

Integrated Vehicle Health Management

Session Overview

Space Launch Initiative Goals

- Commercial Convergence – Flying on Privately Owned and Operated Launch Vehicles
- Competition - bringing innovation and new ideas to bear
- Assured Access – ensuring alternate means of getting to space despite launch mishaps
- The Ability to Evolve – adding new capabilities affordably as new mission needs emerge

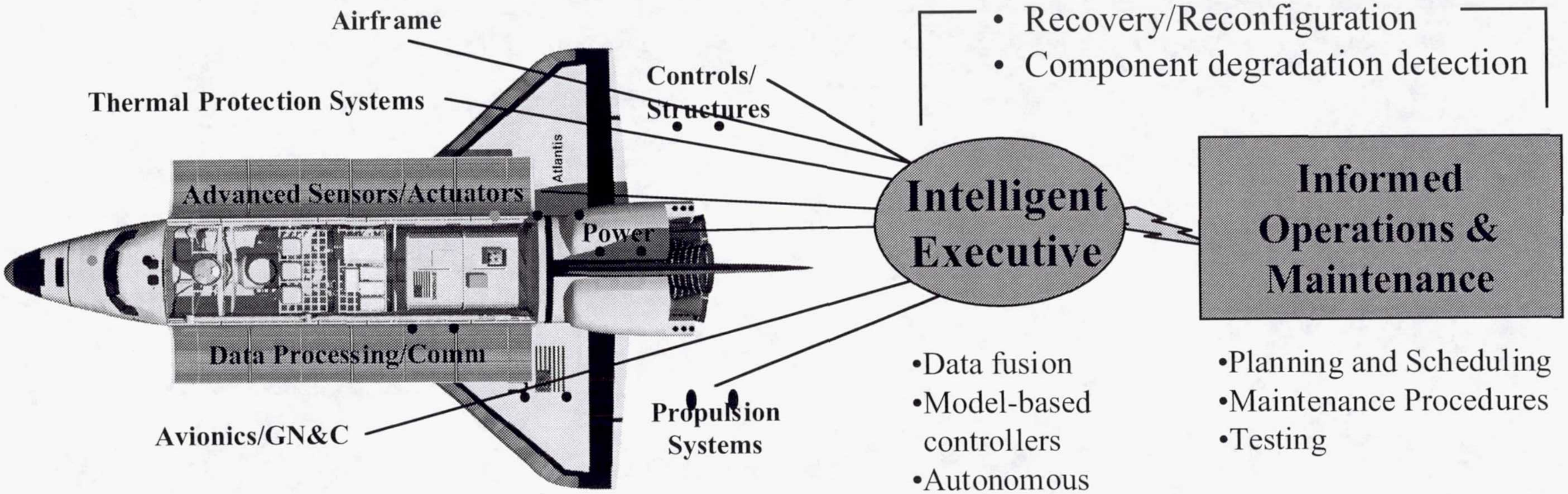
2nd Generation RLV Program Goals

- Safety – Fewer than 1 loss of crew incident every 10,000 flights
- Reliability – Fewer than 1 loss of vehicle every 1,000 flights
- Cost – Less than $1000/lb payload cost to low earth orbit

Integrated Vehicle Health Management

2nd Gen Program Goals

Collect, process, and integrate information about the health of a launch system including the vehicle, subsystems, components, sensors, and ground support systems to make informed decisions and take appropriate actions to ensure the success of a mission



- Anomaly detection and isolation
- Recovery/Reconfiguration
- Component degradation detection

Intelligent Executive

- Data fusion
- Model-based controllers
- Autonomous Software Agents

Informed Operations & Maintenance

- Planning and Scheduling
- Maintenance Procedures
- Testing

The Union of Advanced Hardware and Software -
Providing higher reliability, with greater robustness, at lower costs

Integrated Vehicle Health Management

IVHM

Integrated Vehicle Health Management

Some IVHM Technologies

Propulsion/Engine/OMS

- Automated Data Analysis
- Condition based maintenance
- Advanced Real-time Anomaly Detection
- Advanced Instrumentation -MEMS, Hi temp, plum spec, high freq
- On-Board Automated Leak detection

Thermal Protection

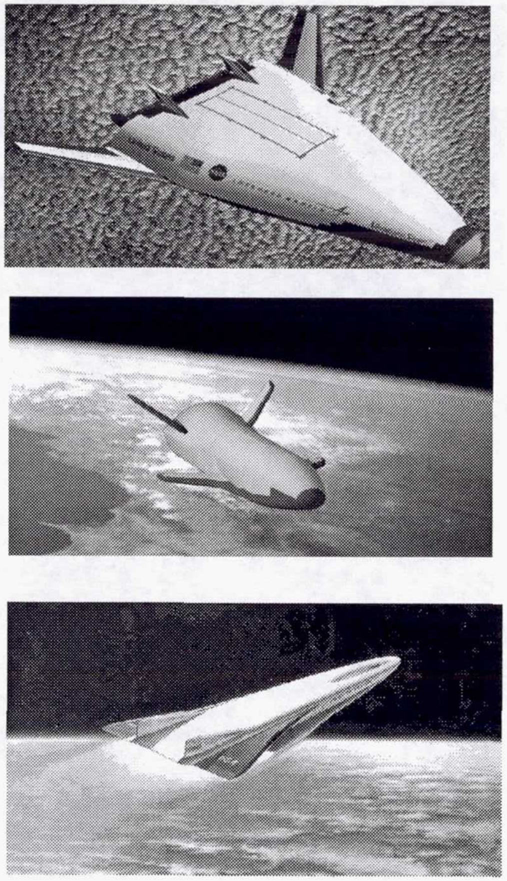
- MEMs Temp/Pressure Sensors for Overgap Filling
- Real-Time Smart TPS Diagnostic SW

Airframe Structure

- Flight Fiber Optic (FO) Tunable Lasers
- Real-time Dynamic FO Measurements
- Acoustic Emission/Acoustic Ultrasound
- Advanced low/high temp sensitivity

Crew System

- Crew Monitoring/Diagnostic Systems
- Human-centered computing (HCC) Crew Smart Sensor Algorithms

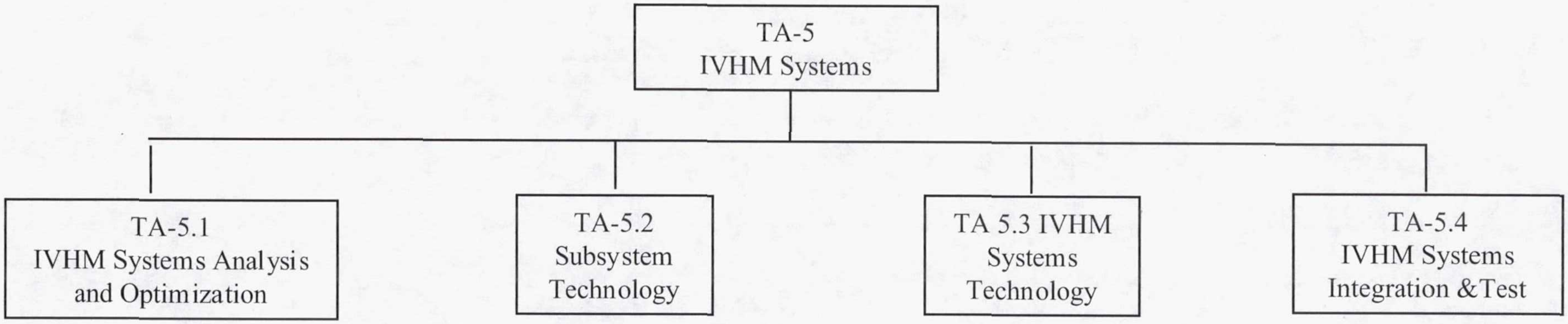


Avionics

- Non-intrusive high response measurements of Pressure, Temp, Strain, Acceleration
- Fiber Optic Network Management SW
- Wireless High Speed Data Mgmt
- Multi-tasked/cause-effect data mining
- Multi-use Smart Sensor Algorithms
- Distributed decision-making software
- Vehicle and Subsystem MBR Tech
- Automated feature recognition
- Real-time fault prediction software
- Reprogrammable/Reconfigurable FDIR
- Automated software V&V technologies.
- Auto mission planners/schedulers

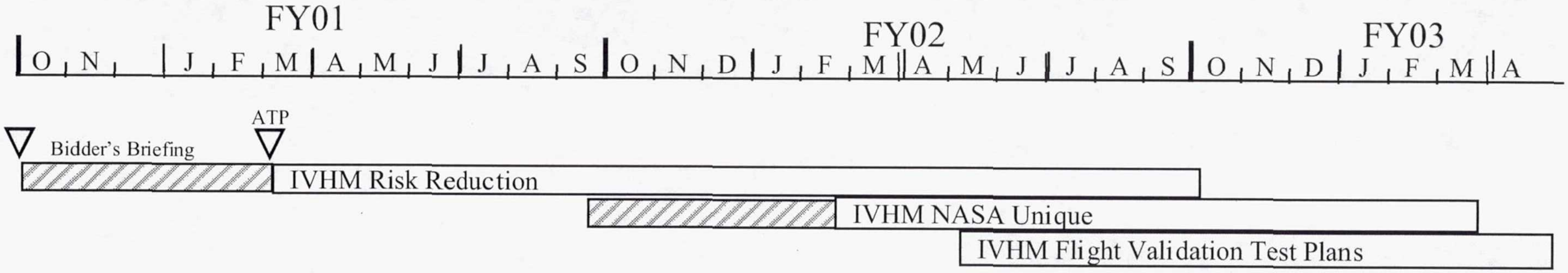
Ground System

- Advanced Launch/Mission Diagnostics/Prog
- Automated ground-based maintenance planners/schedulers/work order generator
- Facility Automated Leak detection Hand-Held Portable Maintenance Aid HW
- Automated TPS/Airframe NDE/NDI



TA-5
IVHM Systems

- TA-5.1 IVHM Systems Analysis and Optimization
- TA-5.2 Subsystem Technology
- TA 5.3 IVHM Systems Technology
- TA-5.4 IVHM Systems Integration &Test



Milestones

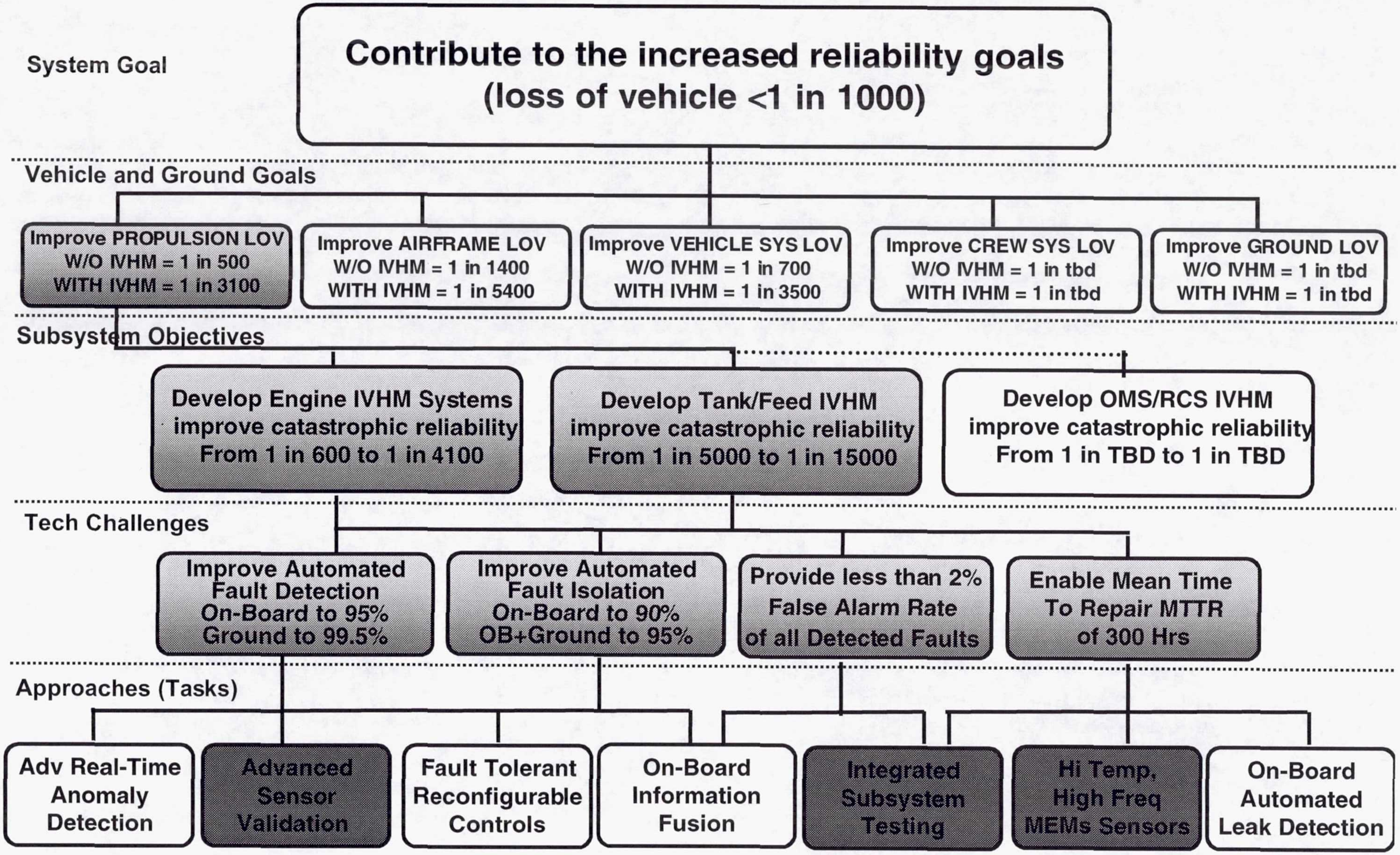
Industry Lead Tasks

- Commercial Req'ts Baselined
- IVHM Systems Integration Plan
- IVHM System Simulations Initiated
- HWIL/SWIL Bench Top Testing Initiated
- HWIL/SWIL Subsystem Testing Initiated

- Verification Data Defined
- Ground Test Plan Defined
- Flight Exp'ts Defined
- Qualification Data and out-year Plans
- IVHM System Sims Downselected
- Qualification Data and Metric Evaluation

Integrated Vehicle Health Management

Roadmap



System Goal

Contribute to the increased reliability goals (loss of vehicle <1 in 1000)

Vehicle and Ground Goals

- Improve PROPULSION LOV
W/O IVHM = 1 in 500
WITH IVHM = 1 in 3100
- Improve AIRFRAME LOV
W/O IVHM = 1 in 1400
WITH IVHM = 1 in 5400
- Improve VEHICLE SYS LOV
W/O IVHM = 1 in 700
WITH IVHM = 1 in 3500
- Improve CREW SYS LOV
W/O IVHM = 1 in tbd
WITH IVHM = 1 in tbd
- Improve GROUND LOV
W/O IVHM = 1 in tbd
WITH IVHM = 1 in tbd

Subsystem Objectives

- Develop Engine IVHM Systems improve catastrophic reliability From 1 in 600 to 1 in 4100
- Develop Tank/Feed IVHM improve catastrophic reliability From 1 in 5000 to 1 in 15000
- Develop OMS/RCS IVHM improve catastrophic reliability From 1 in TBD to 1 in TBD

Tech Challenges

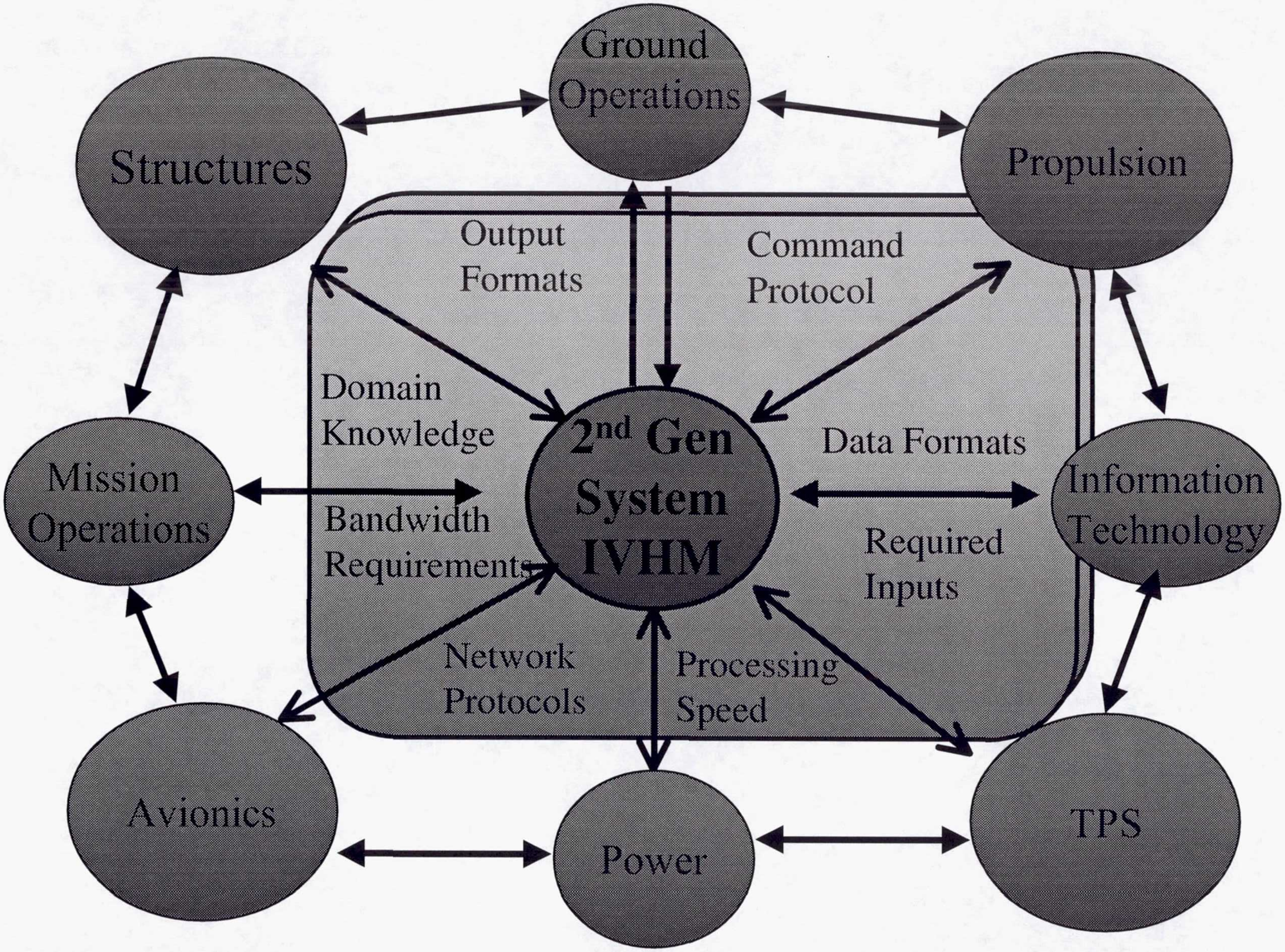
- Improve Automated Fault Detection On-Board to 95% Ground to 99.5%
- Improve Automated Fault Isolation On-Board to 90% OB+Ground to 95%
- Provide less than 2% False Alarm Rate of all Detected Faults
- Enable Mean Time To Repair MTTR of 300 Hrs

Approaches (Tasks)

- Adv Real-Time Anomaly Detection
- Advanced Sensor Validation
- Fault Tolerant Reconfigurable Controls
- On-Board Information Fusion
- Integrated Subsystem Testing
- Hi Temp, High Freq MEMs Sensors
- On-Board Automated Leak Detection

Integrated Vehicle Health Management

Requirements Flowdown (TA-5.1)



Ground Operations

Structures

Propulsion

Output Formats

Command Protocol

Domain Knowledge

2nd Gen System IVHM

Data Formats

Mission Operations

Information Technology

Bandwidth Requirements

Required Inputs

Network Protocols

Processing Speed

Avionics

Power

TPS

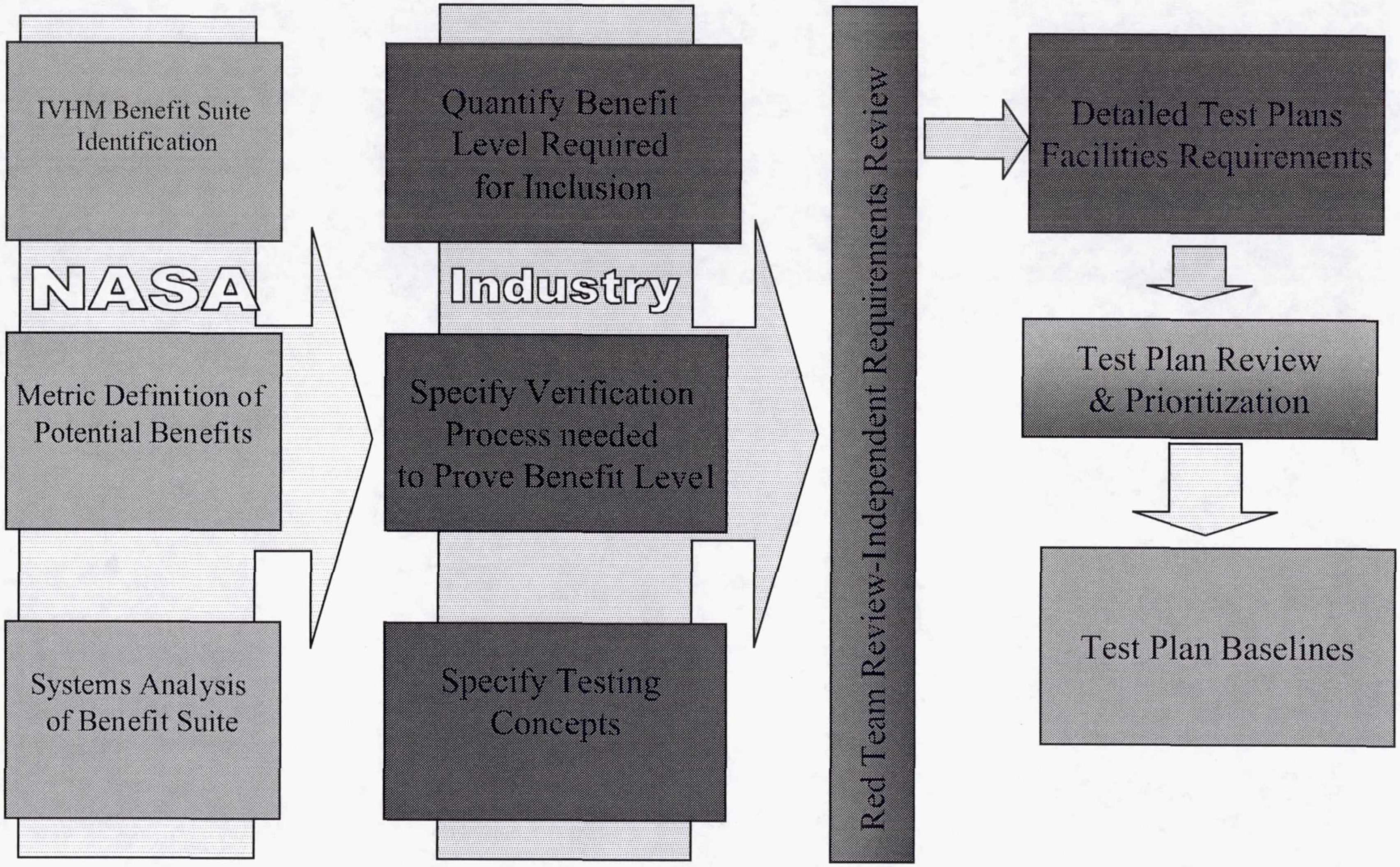
Integrated Vehicle Health Management

Interface Definitions TA-5.2

- The introduction of IVHM will dramatically increase the amount of software required. Overall viability of IVHM may hinge on developing the ability to write and flight certify this software more cheaply than present practice, but with no compromise on safety. How can we do this?
  - Formal Methods- Provable adherence to standards and requirements
  - Agency Best Practices – Example: Shuttle software team
  - Software Health Monitoring – On board monitoring of software state. Internal consistency checks against test data. Redlines.
  - Automated verification strategies. Use of Cardinality.
  - Fault Tolerant software.
  - Automated software generation environments

Integrated Vehicle Health Management

Software Costs TA-5.3



NASA

IVHM Benefit Suite Identification

Metric Definition of Potential Benefits

Systems Analysis of Benefit Suite

Industry

Quantify Benefit Level Required for Inclusion

Specify Verification Process needed to Prove Benefit Level

Specify Testing Concepts

Red Team Review-Independent Requirements Review

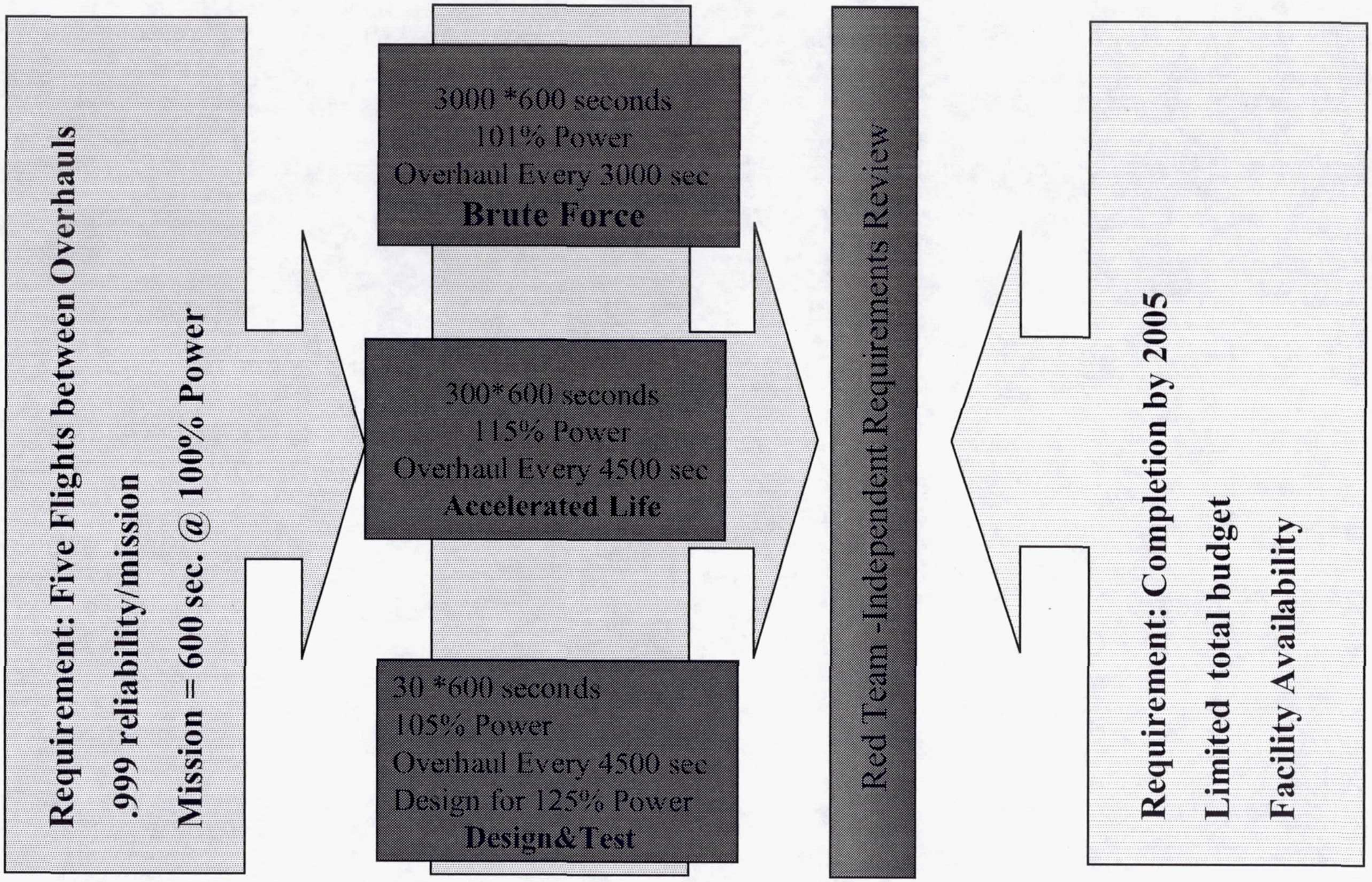
Detailed Test Plans Facilities Requirements

Test Plan Review & Prioritization

Test Plan Baselines

Integrated Vehicle Health Management

Requirements Definition (TA-5.4)



Requirement: Five Flights between Overhauls

.999 reliability/mission

Mission = 600 sec. @ 100% Power

3000 *600 seconds
101% Power
Overhaul Every 3000 sec
Brute Force

300*600 seconds
115% Power
Overhaul Every 4500 sec
Accelerated Life

30 *600 seconds
105% Power
Overhaul Every 4500 sec
Design for 125% Power
Design&Test

Red Team -Independent Requirements Review

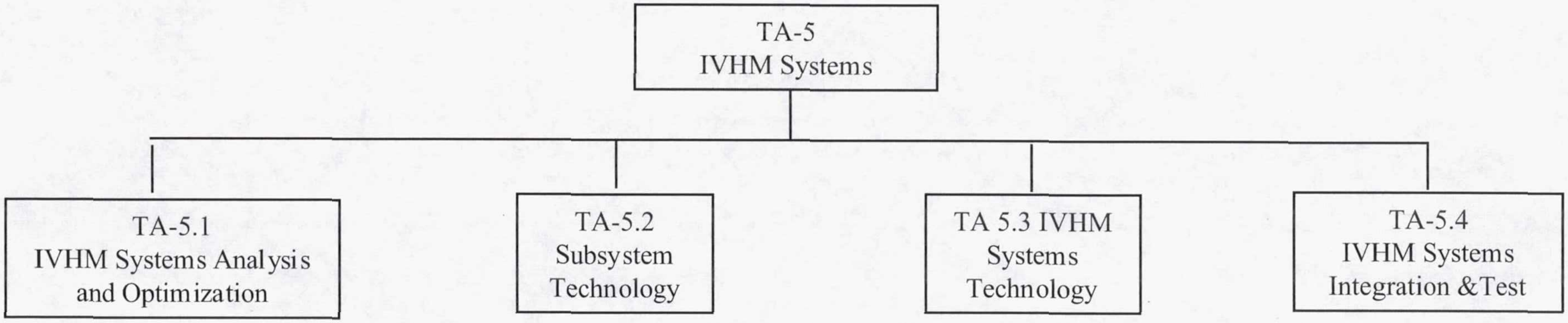
Requirement: Completion by 2005

Limited total budget

Facility Availability

Integrated Vehicle Health Management

Requirements Verification & Testing (TA-5.4)



TA-5
IVHM Systems

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Subsystem Technology

TA 5.3 IVHM Systems Technology

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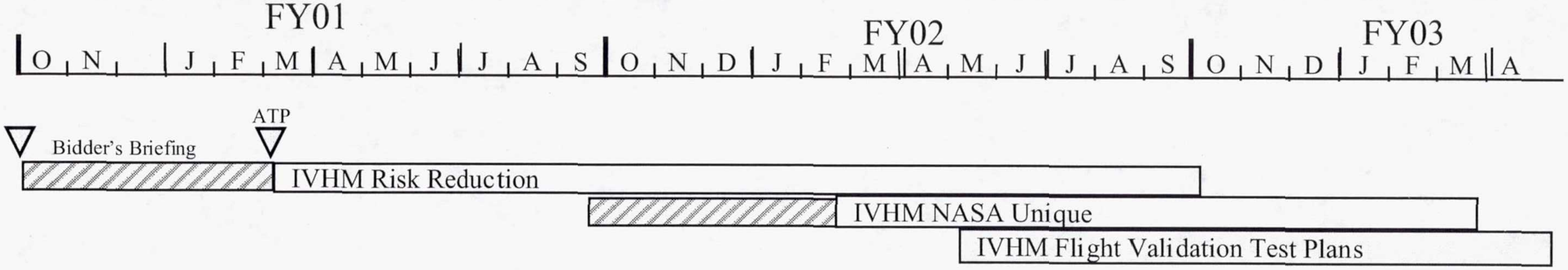
IVHM Systems Integration &Test



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- Qualification Data and Metric Eval

Integrated Vehicle Health Management

Roadmap

Technical Area	Name	Phone
2nd Gen Manager	Bill Kahle	256-544-3225
Propulsion	Jim Snoddy June Zakrajsek	256 544-4972 216-977-7470
TPS	Carol Carroll	650-604-0267
Systems Engineering	Kevin Flynn Dave Squires	650-604-4062 650-604-0072
Avionics	Anthony Kelly	256-544-7646
Launch Operations Mission Operations	Jack Fox Ron Cobbs	321-867-4413 281-483-5894
Vehicle Power	June Zakrajsek	216-977-7470
Structures	Bob Rogowski	757 864-4990
System IVHM	Tom Gormley	650-604-1831
Flight Planning	Keith Schweikhard	661-276-3411

Integrated Vehicle Health Management

IVHM Interfaces

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IVHM for the 3rd Generation RLV Program –Technology Development

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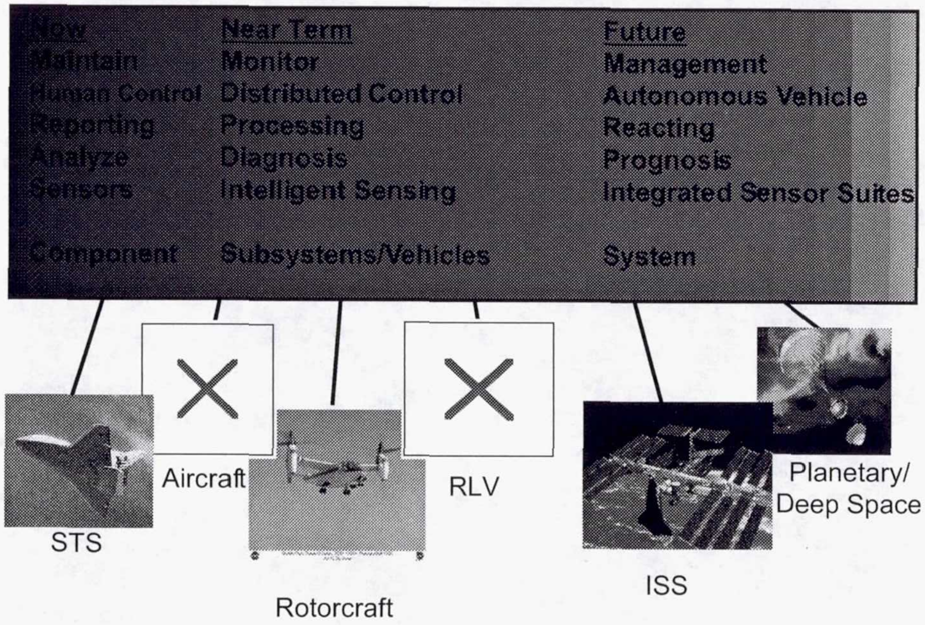
Integrated Vehicle Health Management

- **Project Objectives:**

Develop and integrate the technologies which can provide a continuous, intelligent, and adaptive health state of a vehicle and use this information to improve safety and reduce costs of operations.

- **Technology Objectives:**

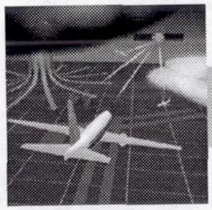
  - Develop, validate, and transfer next generation IVHM technologies to near term industry and government reusable launch systems.
  - Focus NASA on the next generation and highly advanced sensor and software technologies
  - Validate IVHM systems engineering design process for future programs



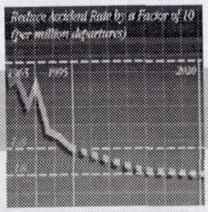
Now	Near Term	Future
Maintain	Monitor	Management
Human Control	Distributed Control	Autonomous Vehicle
Reporting	Processing	Reacting
Analyze	Diagnosis	Prognosis
Sensors	Intelligent Sensing	Integrated Sensor Suites
Component	Subsystems/Vehicles	System

Integrated Vehicle Health Management

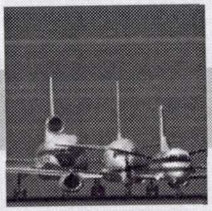
IVHM Project



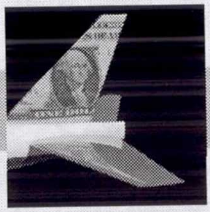
Global Civil Aviation



Reduce Accident Rates, 10x



Increase System Throughput, 3x



Reduce Cost of Air Travel by 50%

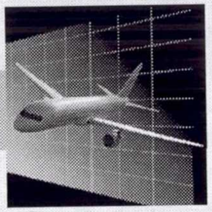
Reduce Emissions, 5x

Reduce Noise, 4x

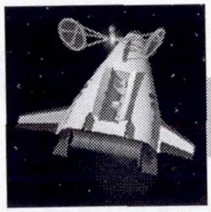
Revolutionary Technology Leaps

Reduce Trans-oceanic Travel time by 50%

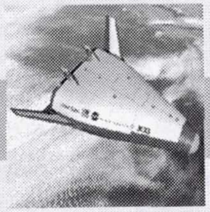
Invigorate GA 20K units Annually



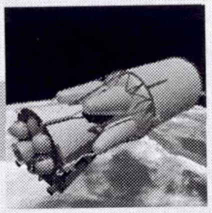
Cut Development Cycle Time in Half



Access to Space



Reduce Launch Cost to LEO, 100x by 2020



Reduce In-Space Transport cost, 10x by 2022

IVHM Objectives

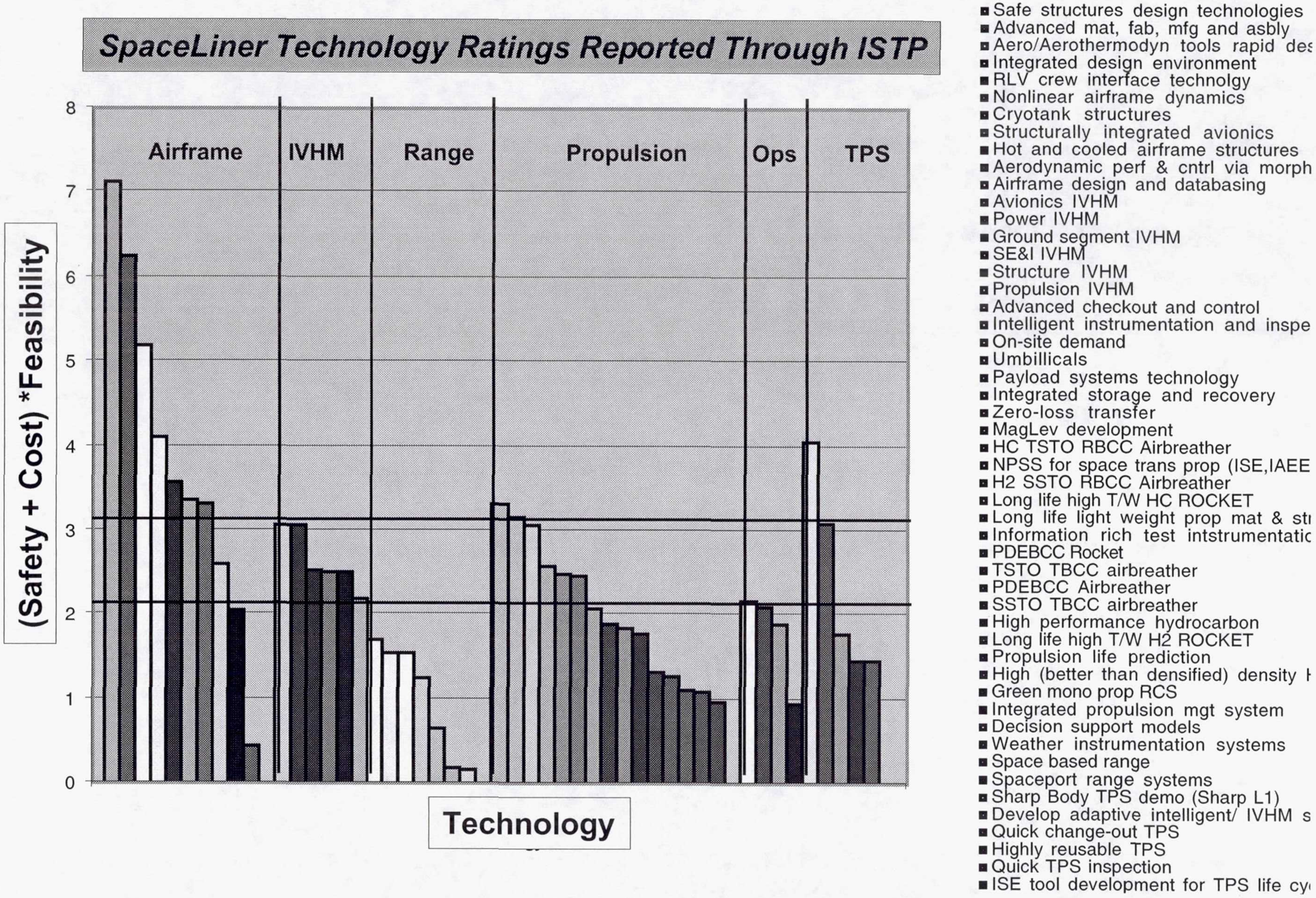
- *Safety*
- *Reliability*
- *Mission Assurance*
- *Reduced Maintenance Costs*
- *Efficient Vehicle Turn-Around*

IVHM Methodologies

- *Sensor Technology*
- *Information Technology*
- *Communication Technology*

Integrated Vehicle Health Management

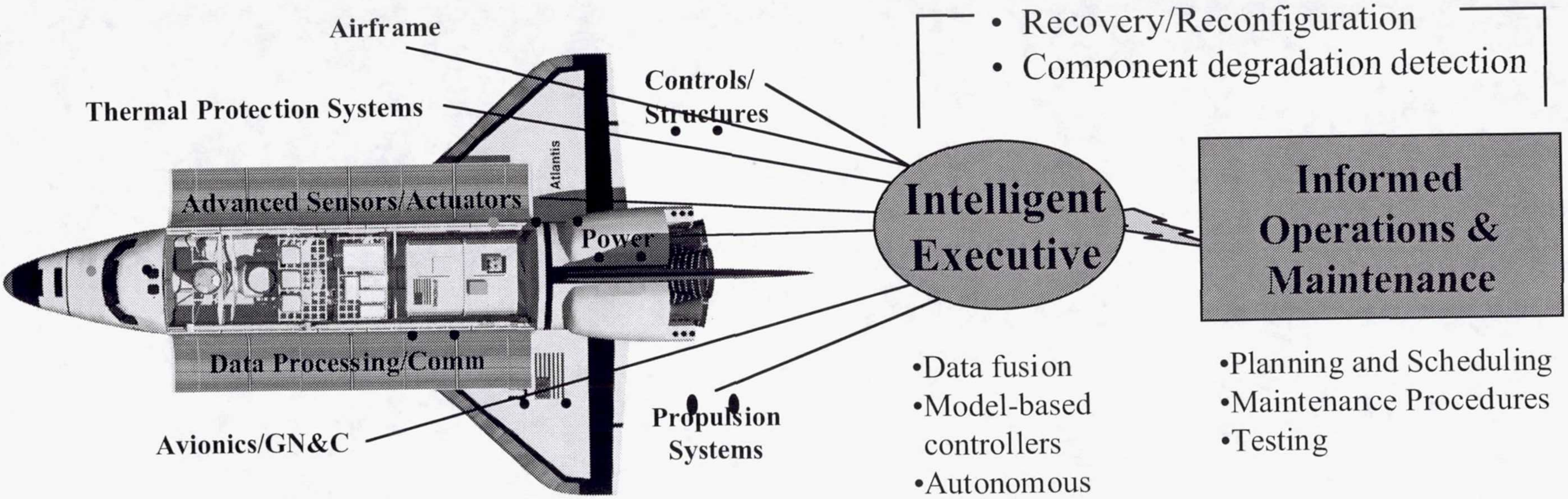
IVHM Support of NASA Pillars and Goals



Integrated Vehicle Health Management

3rd Generation RLV Technology Ratings

Collect, process, and integrate information about the health of a launch system including the vehicle, subsystems, components, sensors, and ground support systems to make informed decisions and take appropriate actions to ensure the success of a mission



- Anomaly detection and isolation
- Recovery/Reconfiguration
- Component degradation detection

Airframe

Thermal Protection Systems

Controls/ Structures

Advanced Sensors/Actuators

Power

Data Processing/Comm

Avionics/GN&C

Propulsion Systems

Intelligent Executive

- Data fusion
- Model-based controllers
- Autonomous Software Agents

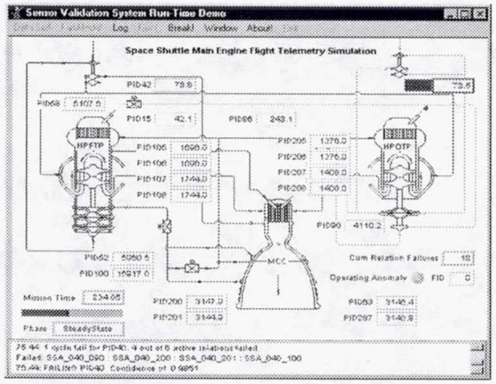
Informed Operations & Maintenance

- Planning and Scheduling
- Maintenance Procedures
- Testing

The Union of Advanced Hardware and Software -
Providing higher reliability, with greater robustness, at lower costs

Integrated Vehicle Health Management

IVHM



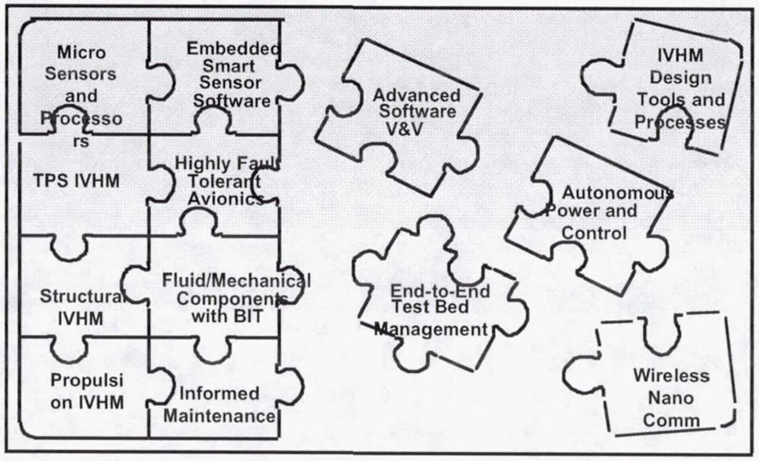
Space Shuttle Main Engine Flight Telemetry Simulation

PID42 73.8
PID68 5107.0
PID15 42.1
PID86 243.1
PID105 1090.0
PID106 1090.0
PID107 1744.0
PID108 1744.0
PID205 1270.0
PID206 1276.0
PID207 1409.0
PID208 1408.0
PID90 4110.2
PID52 5060.5
PID100 15917.0
Cum Relation Failures 18
Operating Anomaly FID 0
Mission Time 234.06
Phase SteadyState
PID200 3147.0
PID201 3144.0
PID63 3140.4
PID297 3140.8

```
75:44: 1 cycle fail for PID40: 4 out of 6 active relations failed
Failed: SSA_040_090 : SSA_040_200 : SSA_040_201 : SSA_040_100
75:44: FAILING PID40 Confidence of 0.9851
```

Propulsion IVHM

GRC and MSFC



Micro Sensors and Processors

Embedded Smart Sensor Software

Advanced Software V&V

IVHM Design Tools and Processes

TPS IVHM

Highly Fault Tolerant Avionics

Autonomous Power and Control

Structural IVHM

Fluid/Mechanical Components with BIT

End-to-End Test Bed Management

Propulsion IVHM

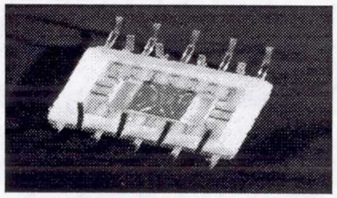
Informed Maintenance

Wireless Nano Comm

Systems Engineering and Integration IVHM

ARC

Core Technologies (ARC)
Information Technologies
Sensors
Communications

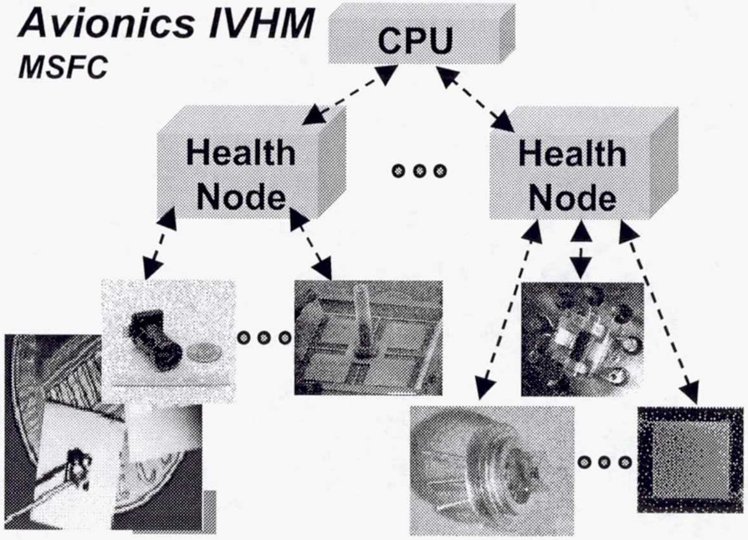


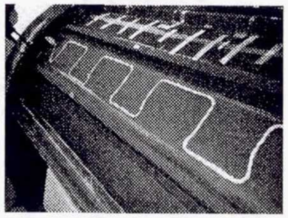
Power IVHM

GRC

Avionics IVHM

MSFC



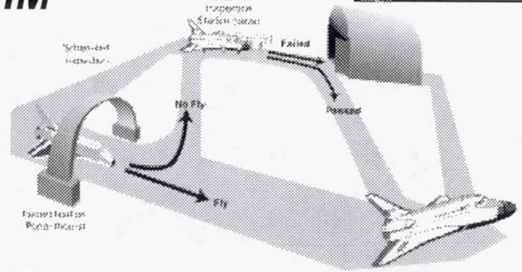


Structures IVHM

LaRC

Ground IVHM

KSC

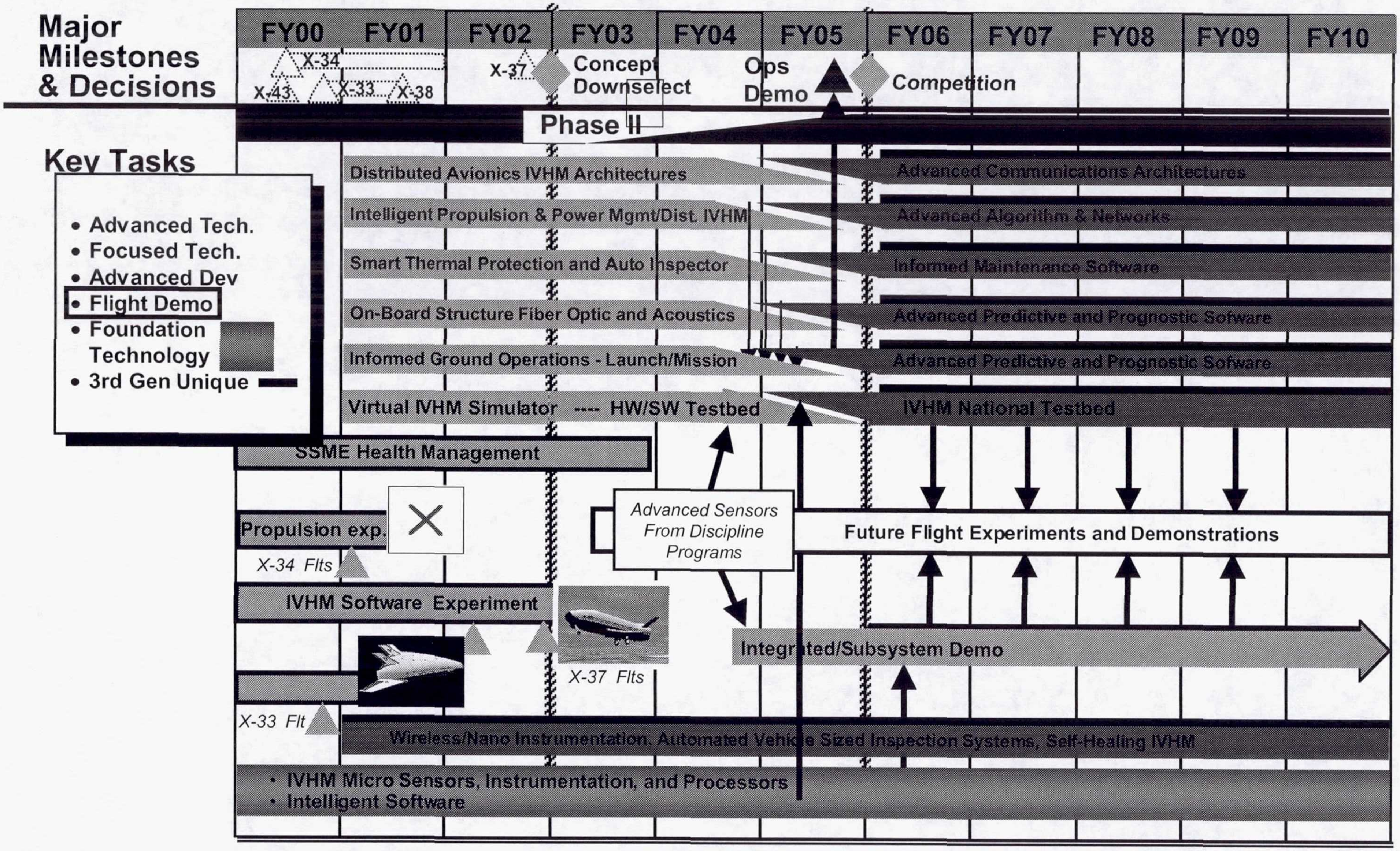


Thermal Protection Systems IVHM

ARC

Integrated Vehicle Health Management

IVHM Elements



Major Milestones & Decisions

FY00 FY01 FY02 FY03 FY04 FY05 FY06 FY07 FY08 FY09 FY10

X-34

X-43

X-33

X-38

X-37

Concept Downselect

Ops Demo

Competition

Phase II

Key Tasks

- Advanced Tech.
- Focused Tech.
- Advanced Dev
- Flight Demo
- Foundation Technology ▨
- 3rd Gen Unique ▬

Distributed Avionics IVHM Architectures

Intelligent Propulsion & Power Mgmt/Dist. IVHM

Smart Thermal Protection and Auto Inspector

On-Board Structure Fiber Optic and Acoustics

Informed Ground Operations - Launch/Mission

Virtual IVHM Simulator ---- HW/SW Testbed

Advanced Communications Architectures

Advanced Algorithm & Networks

Informed Maintenance Software

Advanced Predictive and Prognostic Sofware

Advanced Predictive and Prognostic Sofware

IVHM National Testbed

SSME Health Management

Propulsion exp.

X-34 Flts

IVHM Software Experiment

X-37 Flts

X-33 Flt

Advanced Sensors From Discipline Programs

Future Flight Experiments and Demonstrations

Integrated/Subsystem Demo

Wireless/Nano Instrumentation, Automated Vehicle Sized Inspection Systems, Self-Healing IVHM

- IVHM Micro Sensors, Instrumentation, and Processors
- Intelligent Software

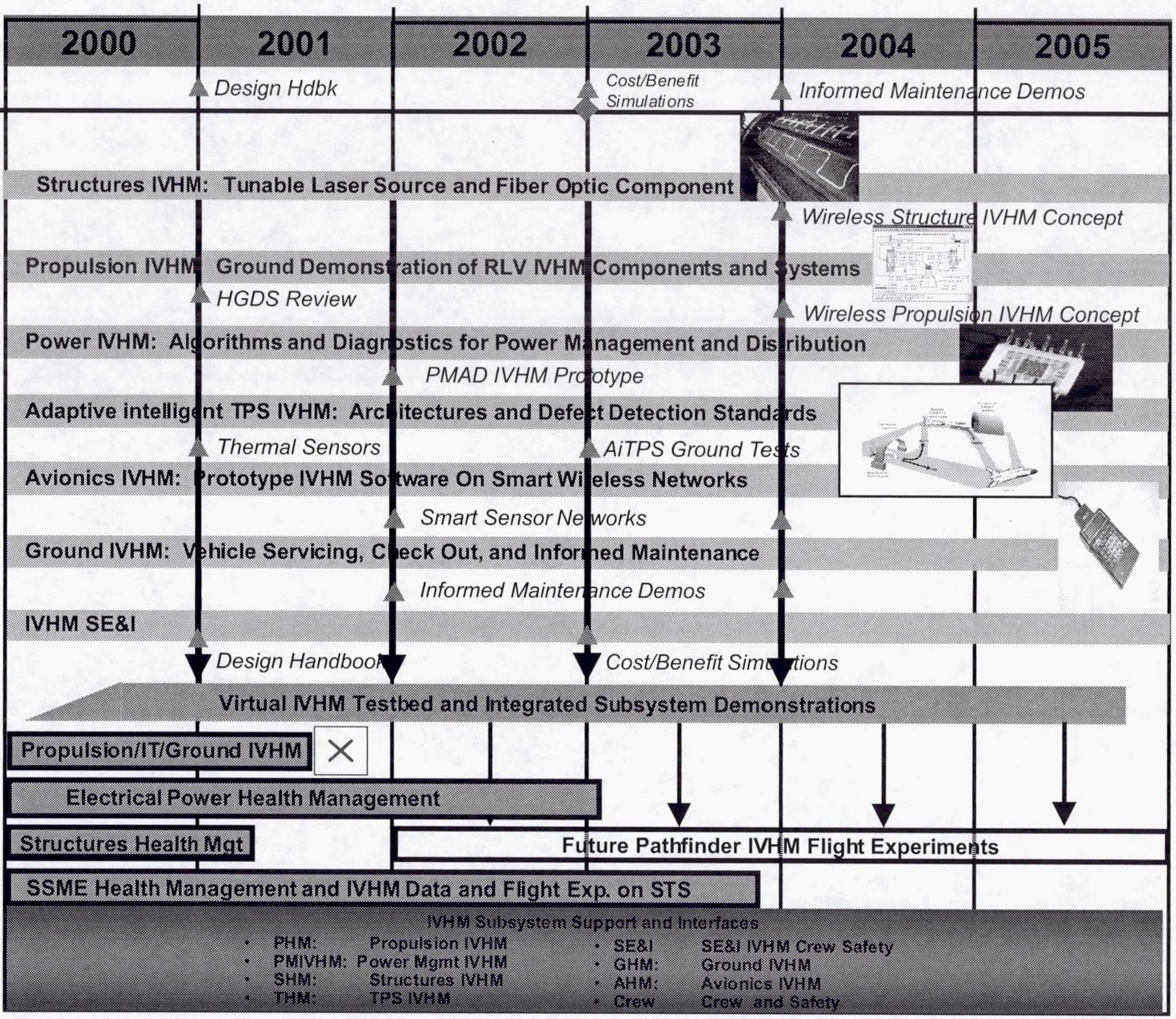
Integrated Vehicle Health Management

IVHM Level II Roadm

Major Milestones ▲
Commit to flight configuration Decisions ◆

Key Tasks

- Component/ Subsystem Demo
- Integrated Demo
- **Flight Demo**
- Foundation Technologies
- Companion System Definition



IVHM Subsystem Support and Interfaces

- PHM: Propulsion IVHM
- PMIVHM: Power Mgmt IVHM
- SHM: Structures IVHM
- THM: TPS IVHM
- SE&I SE&I IVHM Crew Safety
- GHM: Ground IVHM
- AHM: Avionics IVHM
- Crew Crew and Safety

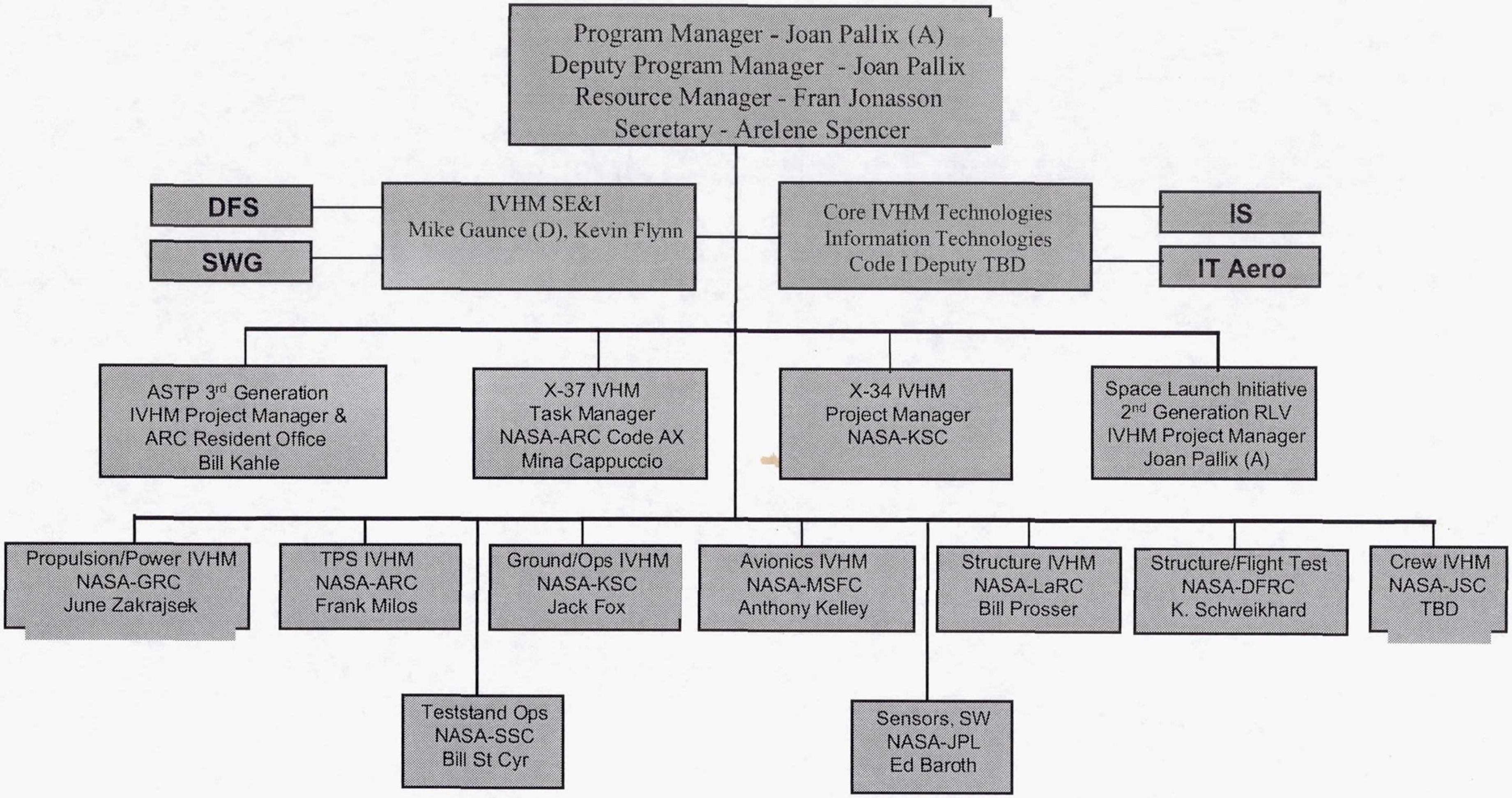
Integrated Vehicle Health Management

IVHM Roadmap

- Advice
  - Scope - Develop a university and university sponsored research institute team to act as a peer review for project and program strategies and tactical planning
  - Initial discussions held with a few universities. Others to follow.
  - Continue to leverage activities of the IVHM National Team to survey and gain access to the best ideas from universities.
- Collaboration
  - Scope - Universities identified as contributors in IVHM Projects:
    - Smart, Self Healing Sensory Systems
    - Self Learning, Self Correcting Propulsion Systems
    - Structures IVHM
- The project office is seeking new partnerships with the academic community.

Integrated Vehicle Health Management

University Partnerships



Program Manager - Joan Pallix (A)
Deputy Program Manager - Joan Pallix
Resource Manager - Fran Jonasson
Secretary - Arelene Spencer

DFS

SWG

IVHM SE&I
Mike Gaunce (D), Kevin Flynn

Core IVHM Technologies
Information Technologies
Code I Deputy TBD

IS

IT Aero

ASTP 3rd Generation
IVHM Project Manager &
ARC Resident Office
Bill Kahle

X-37 IVHM
Task Manager
NASA-ARC Code AX
Mina Cappuccio

X-34 IVHM
Project Manager
NASA-KSC

Space Launch Initiative
2nd Generation RLV
IVHM Project Manager
Joan Pallix (A)

Propulsion/Power IVHM
NASA-GRC
June Zakrajsek

TPS IVHM
NASA-ARC
Frank Milos

Ground/Ops IVHM
NASA-KSC
Jack Fox

Avionics IVHM
NASA-MSFC
Anthony Kelley

Structure IVHM
NASA-LaRC
Bill Prosser

Structure/Flight Test
NASA-DFRC
K. Schweikhard

Crew IVHM
NASA-JSC
TBD

Teststand Ops
NASA-SSC
Bill St Cyr

Sensors, SW
NASA-JPL
Ed Baroth

Integrated Vehicle Health Management

ARC Is Coordinating IVHM For Space Transportation

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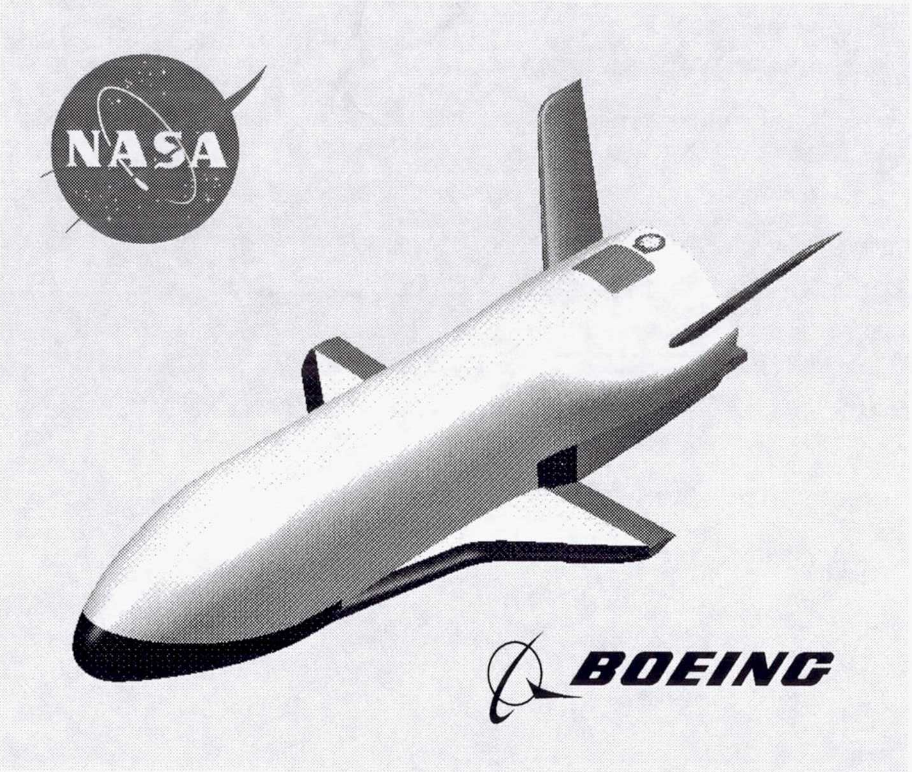


The NASA IVHM Technology Experiment for X-37

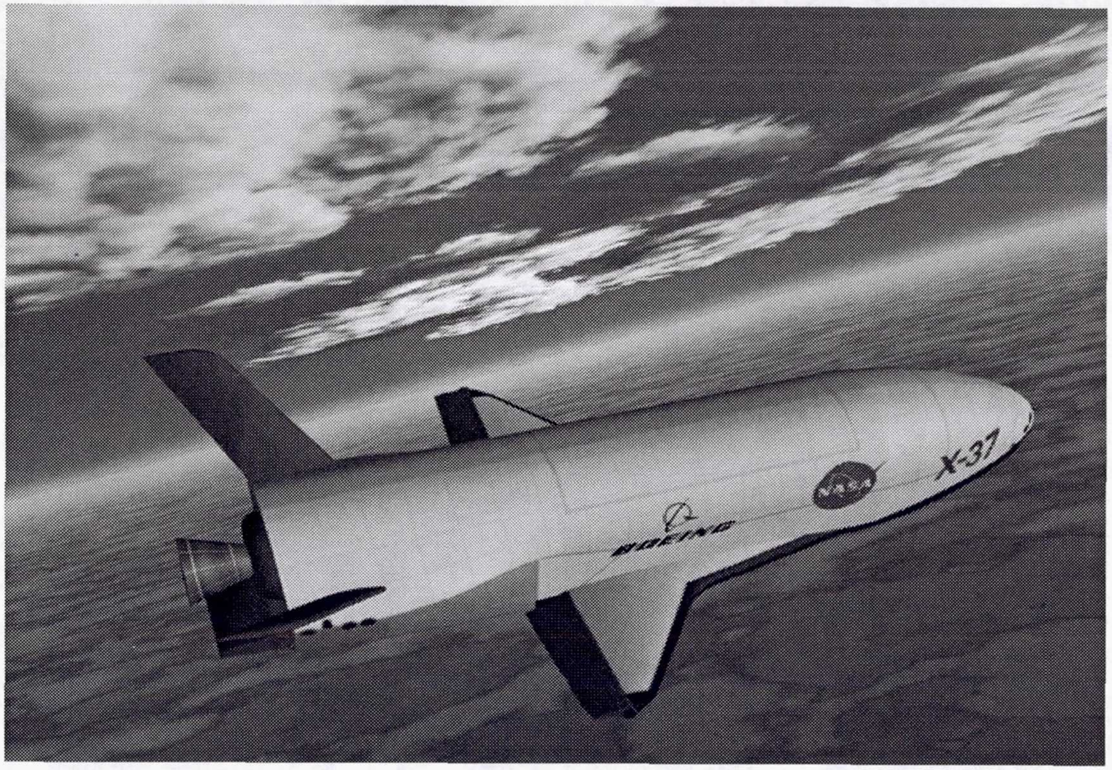
Mark Schwabacher
NASA Ames Research Center

Space Transportation Technology IVHM Session

- Long-term goal: Reduce cost and increase reliability of space transportation
- Demonstrate benefits of in-flight IVHM to the operation of a Reusable Launch Vehicle
- Advance this IVHM technology to Technology Readiness Level ~7 within a flight environment
- Operate IVHM software on the Vehicle Management Computer

Space Transportation Technology IVHM Session

Technology Goals and Objectives

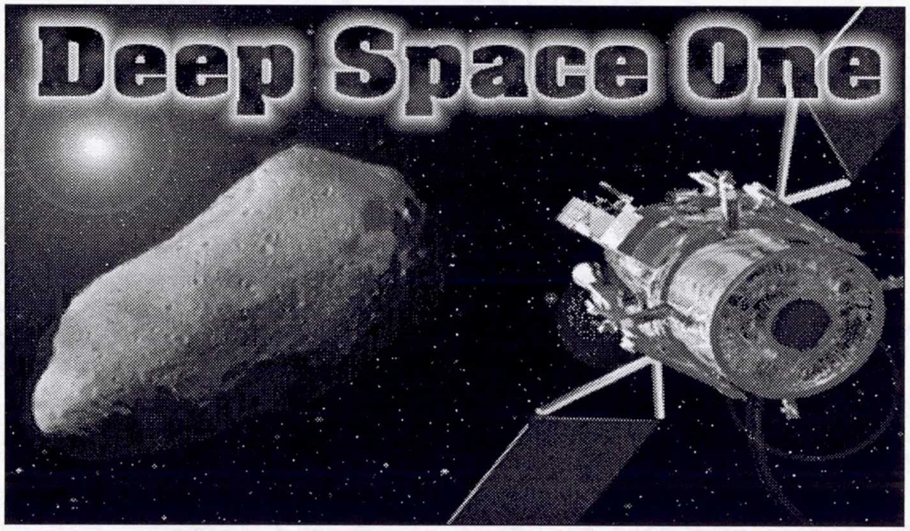


- Unpiloted
- Reusable
- 27.5 feet long
- Mission:
  - launch from Shuttle's cargo bay
  - orbit Earth 21 days
  - De-orbit and land on runway autonomously
- First flight in 2002
- Being built by Boeing for NASA MSFC

Space Transportation Technology IVHM Session

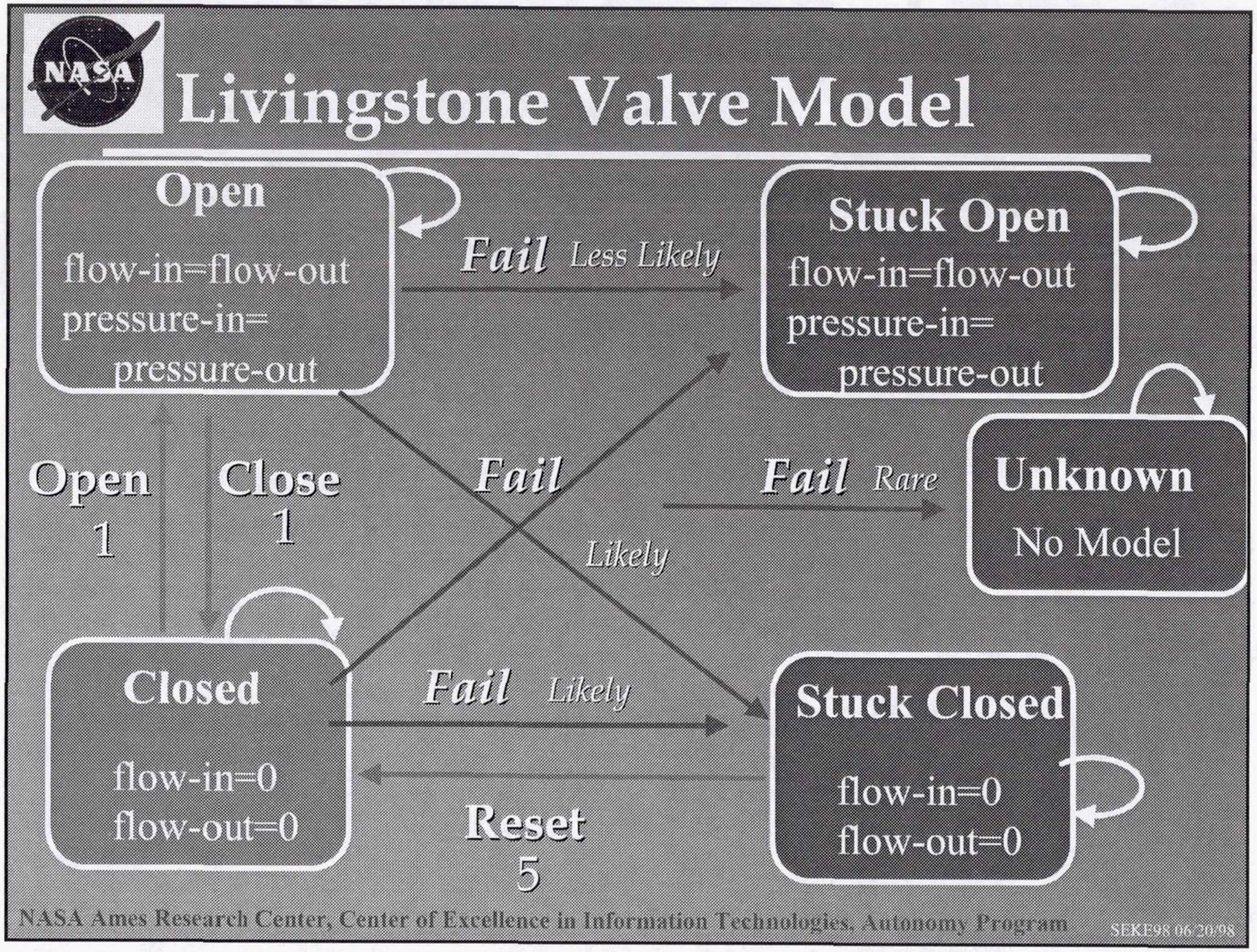
Background: X-37

- Livingstone automates system-level fault diagnosis
- Qualitative, Model-based Reasoning
  - Searches system-wide interactions to detect and isolate failures
  - Eliminates 'hardwiring' pre-defined set of failures
  - Updating and verifying the model is straightforward
  - Streamlines development and maximizes code reusability
- Accomplishment: Successfully flown on Deep Space One
- Also scheduled to fly on X-34



Space Transportation Technology IVHM Session

Background: Livingstone



Livingstone Valve Model

Open
flow-in=flow-out
pressure-in=
pressure-out

Stuck Open
flow-in=flow-out
pressure-in=
pressure-out

Fail *Less Likely*

Open
1

Close
1

Fail

Likely

Fail *Rare*

Unknown
No Model

Closed
flow-in=0
flow-out=0

Fail *Likely*

Reset
5

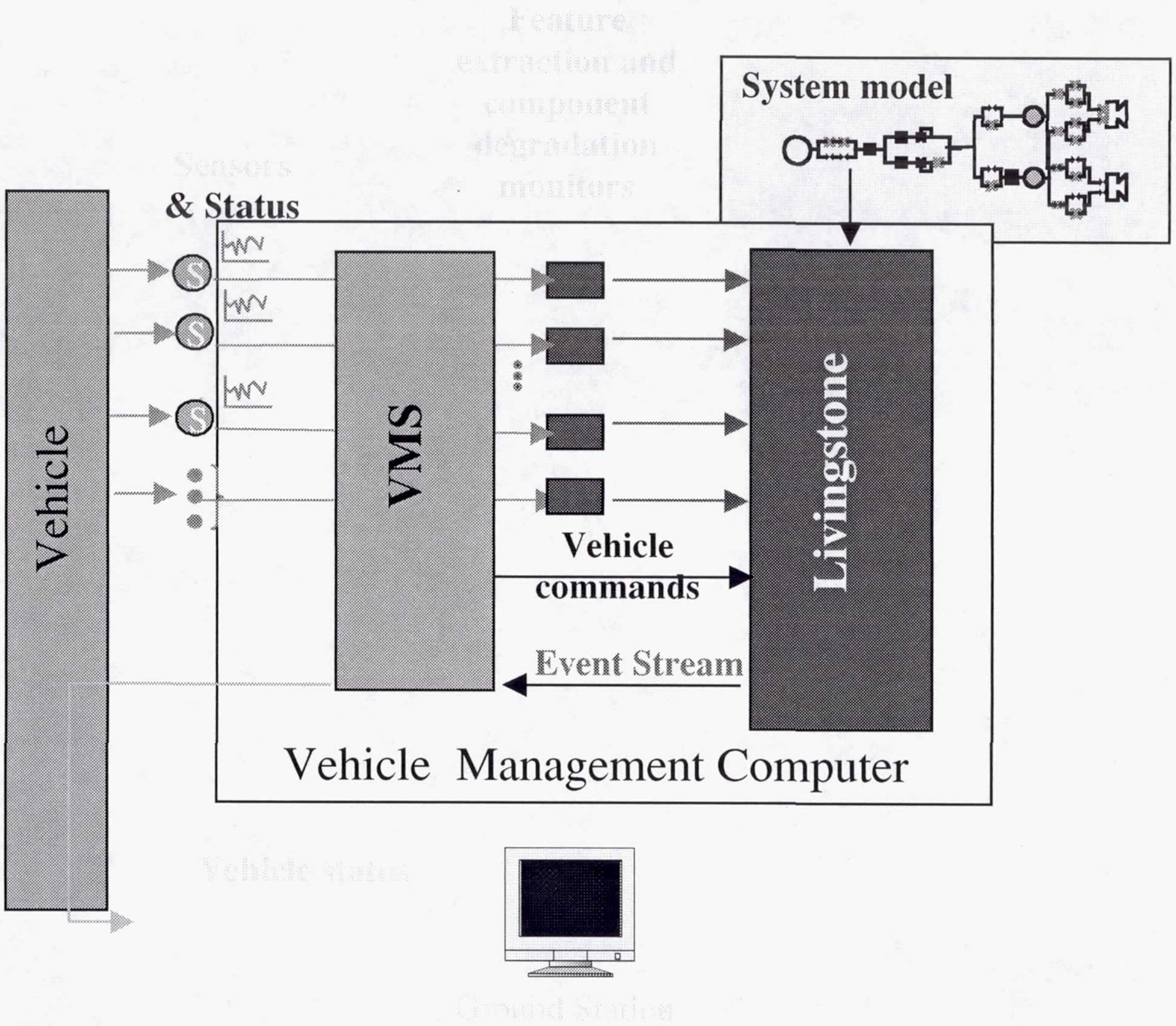
Stuck Closed
flow-in=0
flow-out=0

NASA Ames Research Center, Center of Excellence in Information Technologies, Autonomy Program

SEKE98 06/20/98

Space Transportation Technology IVHM Session

Livingstone Model Example from DS-1



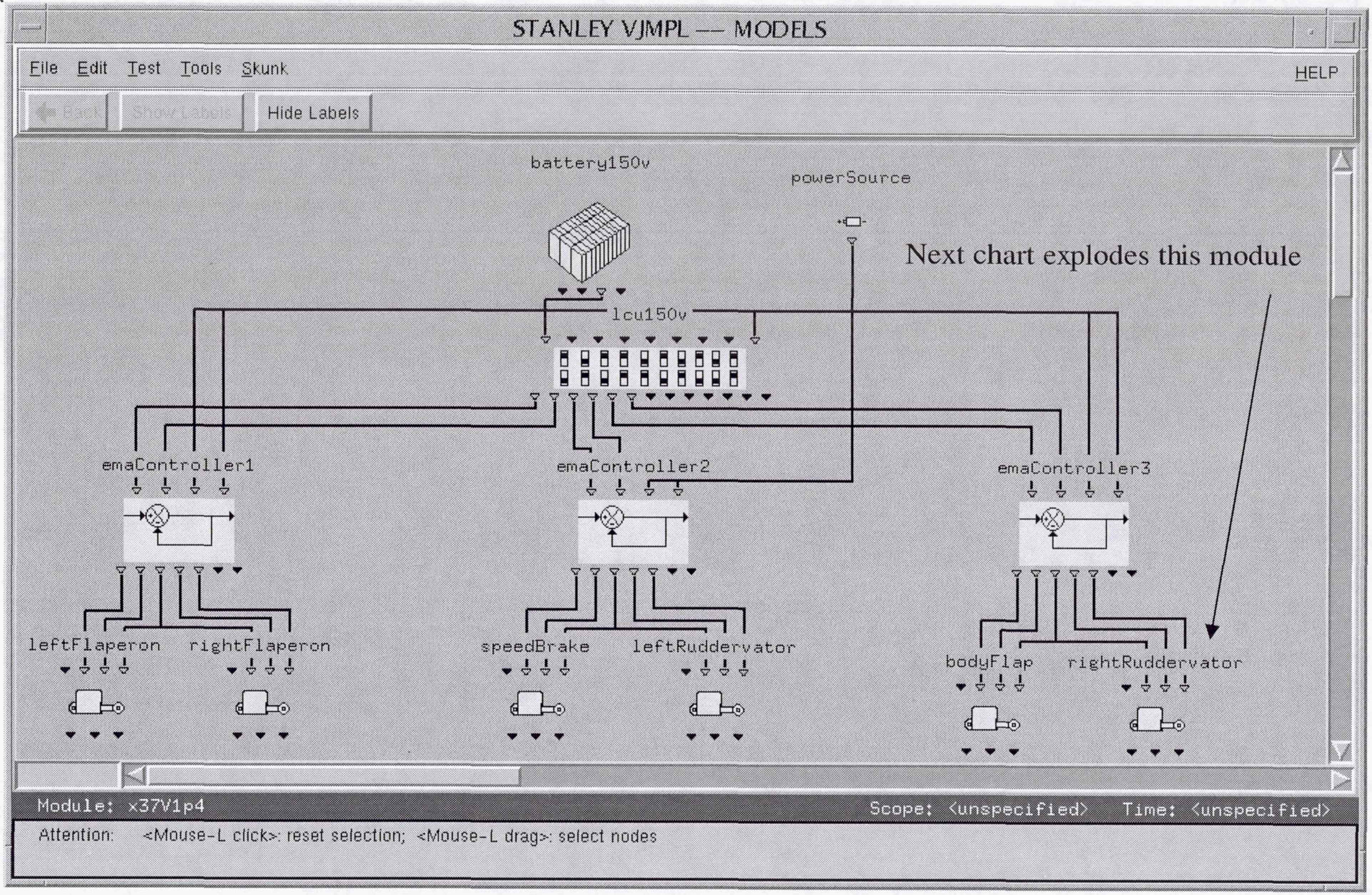
Space Transportation Technology IVHM Session

Experiment Overview

- Monitor and diagnose:
  - Electro-Mechanical Actuators (EMA) for control surfaces
  - Associated Electrical Power System components
- Real-time fault detection and isolation
- Diagnosis, not prognosis
- Shadow mode only (no reconfiguration commands)
- Generate advisory recommendations for ground ops

Space Transportation Technology IVHM Session

X-37 IVHM Scope



Next chart explodes this module

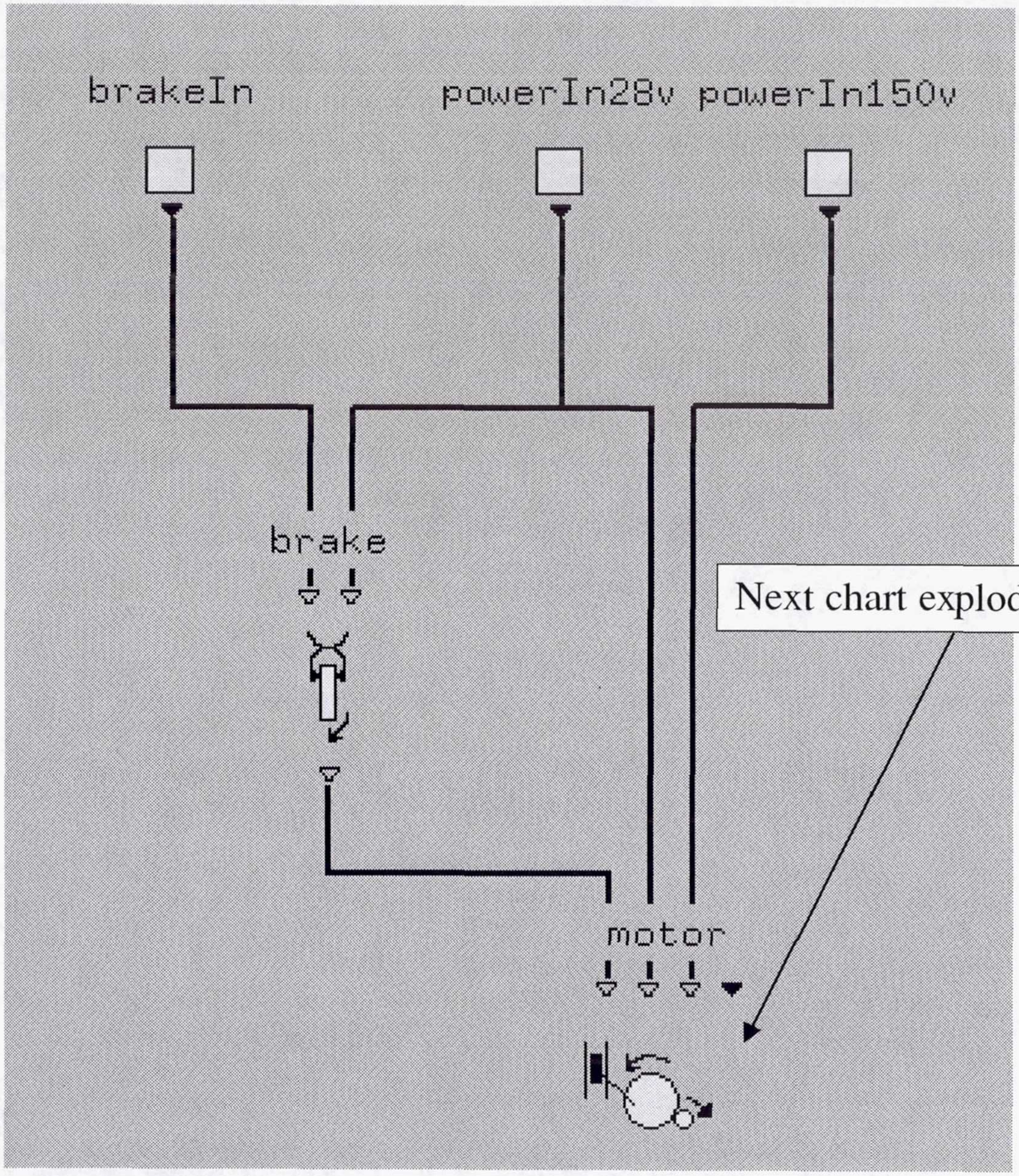
Module: x37V1p4

Scope: <unspecified>   Time: <unspecified>

Attention: <Mouse-L click>: reset selection; <Mouse-L drag>: select nodes

Space Transportation Technology IVHM Session

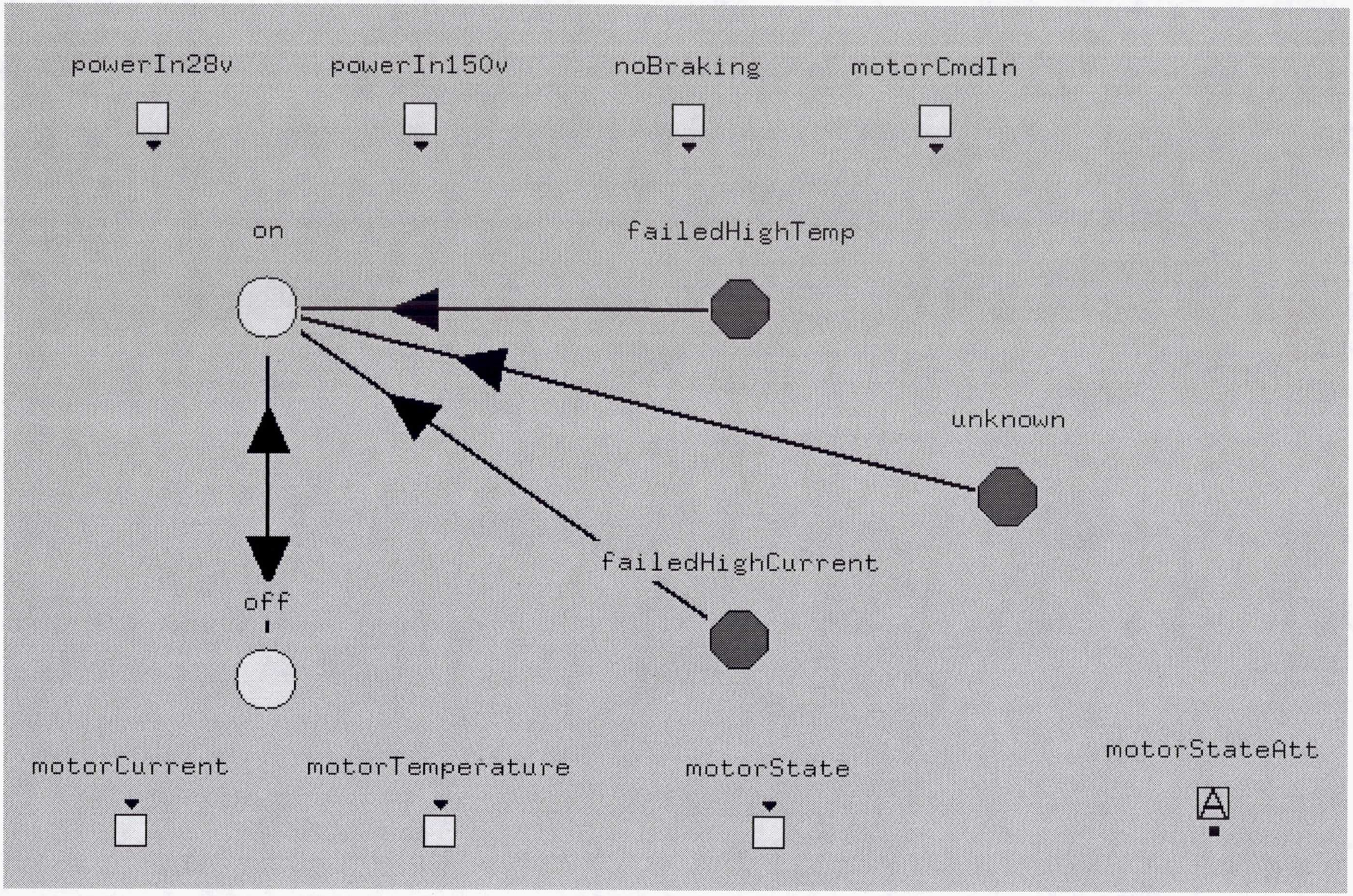
Stanley Interface to Livingstone Model



Next chart explodes this module

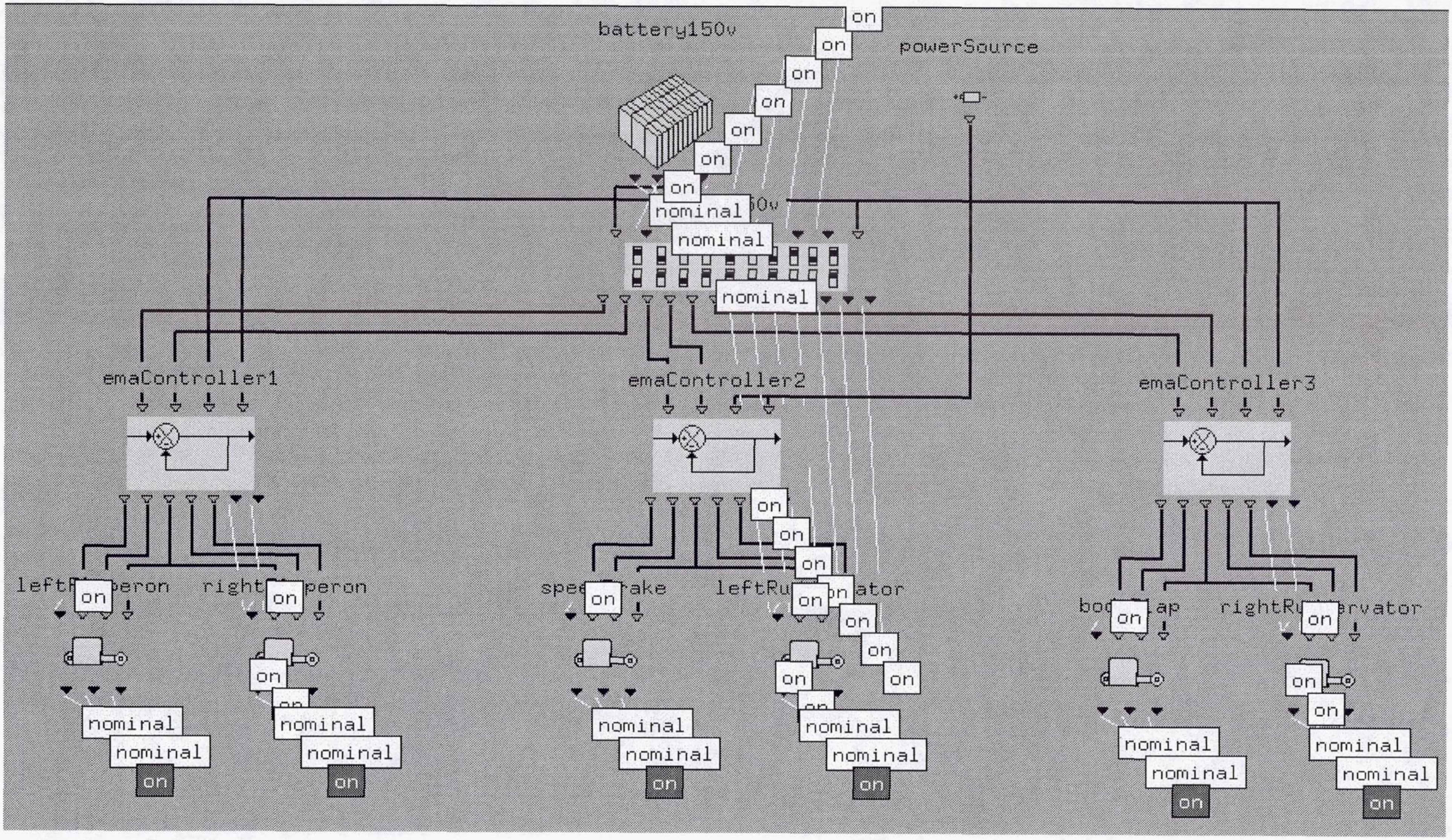
Space Transportation Technology IVHM Session

Right Ruddervator Actuator Detail



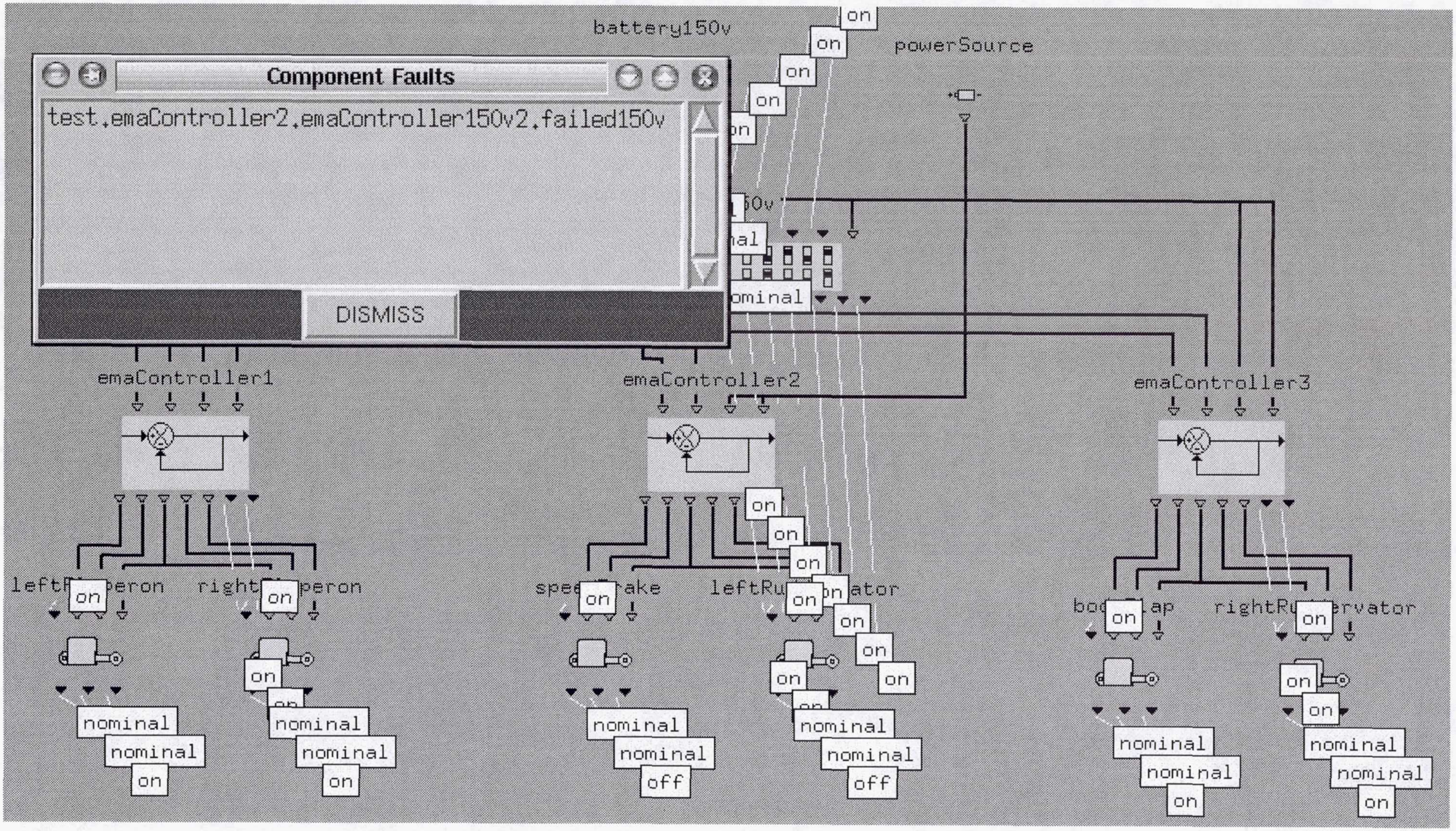
Space Transportation Technology IVHM Session

Motor state diagram



Space Transportation Technology IVHM Session

Inferred Nominal State



```
test.emaController2.emaController150v2.failed150v
```

Space Transportation Technology IVHM Session

Inferred Failure

- The IVHM Experiment's outputs will be provided as inputs to the X-37 Informed Maintenance (IM) Experiment
- The IM software will run in the X-37 ground station, processing IVHM Experiment flight data in real-time
- IM Experiment is being performed by NASA KSC and Boeing
- The IM Experiment's goal is to reduce the cost and time needed to maintain the vehicle

X-37 Informed Maintenance Experiment

- During the second orbital mission, we will use simulated faults to demonstrate the IVHM software's ability to diagnose them

Space Transportation Technology IVHM Session

Simulated Faults

- Livingstone ported from LISP to C++ under VxWorks
- Preliminary design of Interface with Boeing software completed
- Knowledge of X-37 subsystems gained from Boeing experts
- First subset of X-37 model completed

Space Transportation Technology IVHM Session

Current Status

- Limited vehicle resources available to IVHM
  - CPU
  - Memory
  - Telemetry
  - May need to descope experiment to fit resource constraints
- Rigorous software safety standards

Space Transportation Technology IVHM Session

Challenges

- 03/01/01: Deliver IVHM Ver1 Software to Boeing for B-52-based autonomous approach and landing tests
- 03/01/02: Deliver IVHM Ver2 Software to Boeing for orbital flights

Space Transportation Technology IVHM Session

Upcoming Milestones

- **Mina Cappuccio**: X-37 L3 PM & Expt Programmatic Lead, mcappuccio@arc.nasa.gov, 650-604-1313
- **Jeff Samuels**: Technical Lead, jsamuels@arc.nasa.gov, 650-604-4235
- **Mark Schwabacher**: Software Lead, mark.schwabacher@arc.nasa.gov, 650-604-4274
- **Scott Poll, Kevin Carbajal**: X-37 Models & Monitors
- **Scott Christa, Benoit Hudson**: Software Integration & Test
- **Dan Clancy, Jim Kurien**: Consulting

Space Transportation Technology IVHM Session

People and Contact Information

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Space Transportation Technology Workshop or Section Title:

Electromagnetic Propulsion

- Overview

  Specific Electromagnetic Propulsion Topics

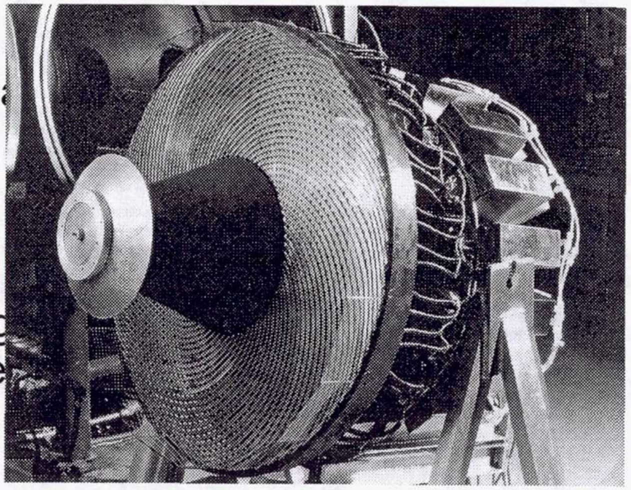
    Technology for Pulse Inductive Thruster

    Flight Weight Magnet Survey

    Magnetic Flux Compression

- Summary

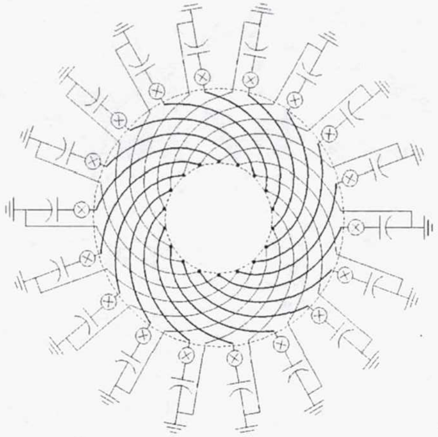
- **Technology goals and objectives**
  - **Revisit PIT technology and design, build, and test a multi-repetition rate pulsed inductive thruster.**
  - **Solid-State Switch Technology**
    - High repetition rate and extreme long lifetime
    - High peak currents and high/rapid initial current rise time
  - **Pulse Driver Network and Architecture**
    - Recovery of reflected energy
    - Pulse shape control for optimum pulse waveform
- **Background**
  - **Research history since 70's at TRW**
  - **Characterized by μ-second, MW-power pulsed operation providing high thrust efficiency over wide range of specific impulse.**
  - **Single-shot spark gap operation**
    - Severe lifetime limitations
    - Multi-rep rate operation severely limited
    - Require gaseous working medium to enable hi
    - Require extreme simultaneous discharge trigge operation



Space Transportation Technology Workshop or Section Title:

Electromagnetic Propulsion (PIT)

- **Current status**
  - **PIT Performance Characteristics**
    - Spec. Impulse: 2,000-8,000 s
    - Efficiency: 20-50%
    - Single shot operation using spark gaps
      - Initial Rise Time in one switch: **dI/dt=30kA/μ**
      - Peak Current: **15kA**
  - **Solid-State Switch Technology**
    - SCR: 5 kV, 4.6 kA, dI/dt=20 kA/μs
    - IGBT: 15 kV, 3kA, 10's of kHz



- **Major accomplishments**
  - **Designed two test circuits to conduct testing of key parameters**
  - **Procured test equipment and circuit components**
  - **Identified manufacturers to supply high-power solid-state switch technology**
- **Near term plans**
  - **Test and evaluate candidate switch components**

Space Transportation Technology Workshop or Section Title:

Electromagnetic Propulsion (PIT)

FLIGHT WEIGHT MAGNETICS

MAJOR RESEARCH GOALS:

- **Determine/develop light weight high performance magnetic materials. for potential application Advanced Space Flight Systems as these systems develop.**

MAJOR ACCOMPLISHMENTS:

- **Literature searches resulted in selection of Ultra Pure Aluminum to fabricate an electromagnet to generate a pulsed magnetic field in a cryogenic temperature environment . This selection was based on density, temperature-dependant and residual resistivity, as well as magneto-resistance characteristics.**
- **Acquired magnetic pressure equations (stress analysis).**
- **Located experienced source for electromagnet fabrication and testing**

STATUS:

- **A grant is currently in place with Louisiana State University (LSU) to construct a 99.999% Purity Aluminum solenoid. Will be delivered to MSFC after fabrication and testing is completed.**

FLIGHT WEIGHT MAGNETICS

MILESTONES:

November 2000

- **Solenoid to be completed by LSU.**
- **Testing at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, FL. which includes:**
  - **Magneto-resistance recorded while exposed to externally applied steady state magnetic fields up to 20 Tesla and temperatures ranging from 4 to 300 Kelvin.**

December 2000

- **Testing at the NHMFL in Los Alamos, NM. which includes:**
- **Pulsed excitation to field maximum of 2 Tesla.**
- **Solenoid and cryogenic system temperature recorded during excitation.**
- **Measurements of the total solenoid resistance, inductance, and stress/stain before, during, after each excitation.**

January 2001

- **Solenoid and all data delivered to MSFC.**

Electromagnetic Propulsion – Magnetic Flux Compression Reactors

Goals …

Enable rapid/robust/reliable omni-planetary space transportation within realistic development and operational costs constraints

Objectives …

10× improvement propulsion capability
- high thrust-to-weight ratio
- high specific impulse
- high Δv maneuvering

Abundant spacecraft electrical power
- deep space capability (non-solar)
- high capacity (multi-MW)
- high specific power (> 10 kW/kg)

Technical Challenges …

Demonstrate the feasibility of pulsed magnetic flux compression reactor concepts using detonation plasma

Research and develop flightweight pulsed magnet technologies based on ultra conductors and superconductors

Fundamental plasmadynamics research
- electrical conductivity / R_m
- interactions with magnetic field
- plasma instabilities
- magnetic flux diffusion
- plasma turnaround

Fundamental magnetics research
- high purity aluminum windings
- type I / type II SC windings
- HTSC flux compression surfaces
- lightweight structure issues
- pulsed operation issues

Approach …

Develop and test a moderate scale (1/2-m) prototype flux compression reactor using non-nuclear plasma detonation source

Rationale

Plasma micro-detonation flux compression reactors …

- amenable to propulsion & electrical power reactor concepts
  - high jet power / multi-megajoule energy bursts
  - inductive energy storage / pulse power for ignition driver
  - production of spacecraft bus power
- compatible with advanced target concepts
  - inertial confinement fusion (ICF)
  - magnetized target fusion (MTF)
  - high energy density chemical detonations
- low-weight / compact / low-cost

… capable of satisfying omni-planetary exploration goals

Magnetic Flux Compression Reactor Principles

Energy Conversion Processes

chemical/nuclear → kinetic → electrical → kinetic

Principle of Operation

- detonation charge transformed into kinetic energy of moving conductor
- magnetic seed field is trapped and compressed by moving conductor
- kinetic energy is temporarily stored in rapidly compressed magnetic field
- electrical power can be extracted inductively through loaded circuit
- compressed field energy reverses conductor motion and returns kinetic energy

Global Energy Conservation

> 80%

[illegible]WW

conversion efficiency

Major Research Tasks

- Modeling of reactor performance
  - first order performance analyses
  - MHD code development
  - finite element model of coupled circuits

- Investigation of pulsed magnetic fields on HTSC materials
  - laboratory measurements of magnetic diffusion properties
  - validation of magnetic diffusion model

- Basic plasma physics experiments
  - fundamental flux compression experiment
  - inductive measurement of plasma jet electrical conductivity
  - plasma jet collisional processes
  - validation of MHD codes
  - Rayleigh-Taylor instability (revisited)

- Flightweight pulsed magnet technology
  - high purity aluminum winding magnet
  - superconductor winding magnet

Key Summary Points

- magnetic flux compression suitable for spacecraft propulsion & power
  - enables omniplanetary exploration
  - multimegawatt energy bursts
  - terawatt power bursts
  - pulse power for low impedance dense plasma devices
  - direct thrust production
- innovative design strategy
  - detonation plasma armature
  - type-II superconductor stator
  - intermittent firing capability
- constrains weight and size of overall system
- inductive storage pulse power source
- near-term (≈18 month) scientific feasibility program
- concept based on feasible extrapolations of current technology

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Advanced Chemical Propulsion

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Propulsion Research Center (TD-40)
Space Transportation Directorate
Marshall Space Flight Center /NASA
Huntsville, AL 35812

"ST Day 2000: Reducing Risk for the Next Generations"

- **Revolutionary Rockets**
- **Advanced Fuels and High Energy Density Materials**
  - **Strained Ring Hydrocarbons (Bai/TD40)**
  - **Azide Fuel (US Army - Bai/TD40)**
  - **Solid Hydrogen**
  - **Recombination Energy Fuels (Palaszewski /GRC)**
    - Penta Nitrogen (Palaszewski /GRC)
    - Poly-Oxygen (Palaszewski /GRC)
    - Metallized and Gelled Fuels (Palaszewski /GRC)
    - Powdered Aluminum Combustion (Litchford/TD15)
- **Launch Assist**
  - **Cannons, Balloons, Aerial Refueling, Catapults, etc (Nolen/ED31, Jones/TD40)**

Agenda

Advanced Fuels Development Objective & Goal

- Identify and develop advanced chemical propellants
  - Hydrocarbons for LEO propulsion
  - Monopropellants or Cryogenic propellants for upper stages

- Improve access to space capability
  - Smaller vehicle
  - larger payload
  - low cost

- Revolutionary Rockets
- Advanced Fuels and High Energy Density Materials
  - Strained Ring Hydrocarbons (Bai/TD40)
  - Azide Fuel (US Army - Bai/TD40)
  - Solid Hydrogen
  - Recombination Energy Fuels (Palaszewski /GRC)
    - Penta Nitrogen (Palaszewski /GRC)
    - Poly-Oxygen (Palaszewski /GRC)
    - Metallized and Gelled Fuels (Palaszewski /GRC)
    - Powdered Aluminum Combustion (Litchford/TD15)
- Launch Assist
  - Cannons, Balloons, Aerial Refueling, Catapults, etc (Nolen/ED31, Jones/TD40)

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Agenda

- **Criteria for Fuel Selection**
  - **Predicts Better Performance (Isp) Over LOX/RP-1 System**
  - **Most Desirable Physical Properties**
    - Lower Vapor Pressure Compared to RP-1
    - Higher Density (≥ RP-1 = 0.801 g/mL)
    - Freezing Point (≤ -10 °C; RP-1 = -41.4 °C)
    - Boiling Point ≥ B. P. of RP-1
  - **Thermally Stable**
  - **Compatible with the Current System**

Strained Ring Hydrocarbons

Performance Screening Test

- Small Scale Combustion Test
  - ~50 pounds Thrust Hot Fire Tests (limited by amount Of fuels)
  - C* Efficiency
  - Isp
  - Material Comparability test
  - Initial Aging Studies

Initial Screening - 10 Grams

- Computational Chemistry
- Synthesis Routes
- Preliminary Characterization
  - Chemical, Physical, Hazard Properties
- Toxicity if Known?
- Synthesis Cost Evaluation

Development and Characterization

- Synthesis Scale-Up - 10 Pounds
  - Additional Characterization
    - Chemical, Physical, Hazard Properties
  - Formulation
  - Initial Aging Studies
  - Initial Compatibility
  - Initial Thermal Studies
  - Initial Toxicity Studies

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Strained Ring Hydrocarbons

- **Structural Requirement for High Energy Contents**
  - **The energy contents can be increased by adding unsaturation in the molecule**

	$-(CH_2)-$	$CH_2{=}CH_2$	$HC{\equiv}CH$	
$\Delta H_f/C$	**~ -5**	**~ 6.25**	**~ 27.1**	**Kcal/mole**

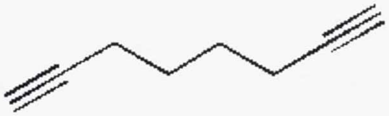
Fuels

1,5-Hexadiyne

$\Delta H_f = 91.8$ Kcal/mole

$= 1.18$ Kcal/g

$I_{sp} = 311.8$ Sec



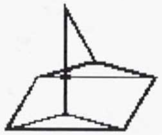
1,7-Octadiyne

$\Delta H_f = 79.9$ Kcal/mole

$= 0.75$ Kcal/g

$I_{sp} = 308.2$ Sec

C8H10



Quadricyclane

$\Delta H_f = 72.2$ Kcal/mole

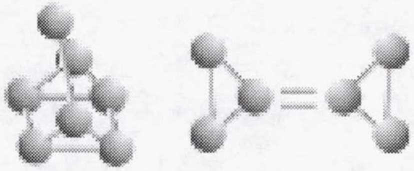
$= 0.78$ Kcal/g

$I_{sp} = 307$ Sec

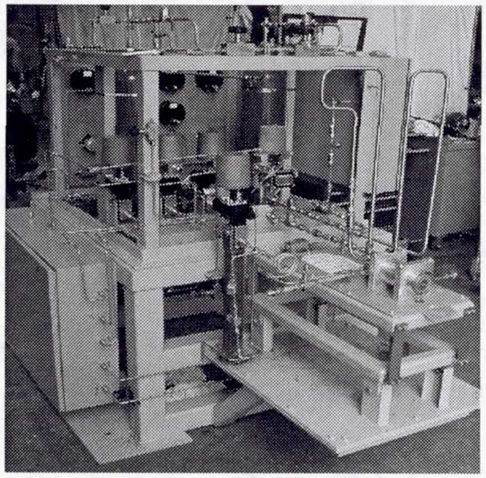
C7H8

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Strained Ring Hydrocarbons



- **SUMMARY:**
  - **With cooperation with Air Force Research Laboratory and Army, the performances of advanced hydrocarbon fuels will be compared with a base fuel (RP-1).**



  - **The fuels are: Quadricyclane, bi-cyclo-propylidine, AFRL-1, 1,7 Octadiyne, AFRL-1 and Dimethyl amino ehtyl azide (DMAZ). The theoretical performance of these fuels indicates that all of these fuels have higher ISP than RP-1.**
  - **Principle Investigator:**
    - S. Don Bai - NASA/MSFC TD40, 256-544-9036 don.bai@msfc.nasa.gov

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Strained Ring Hydrocarbon Fuel Testing

Project Team Members

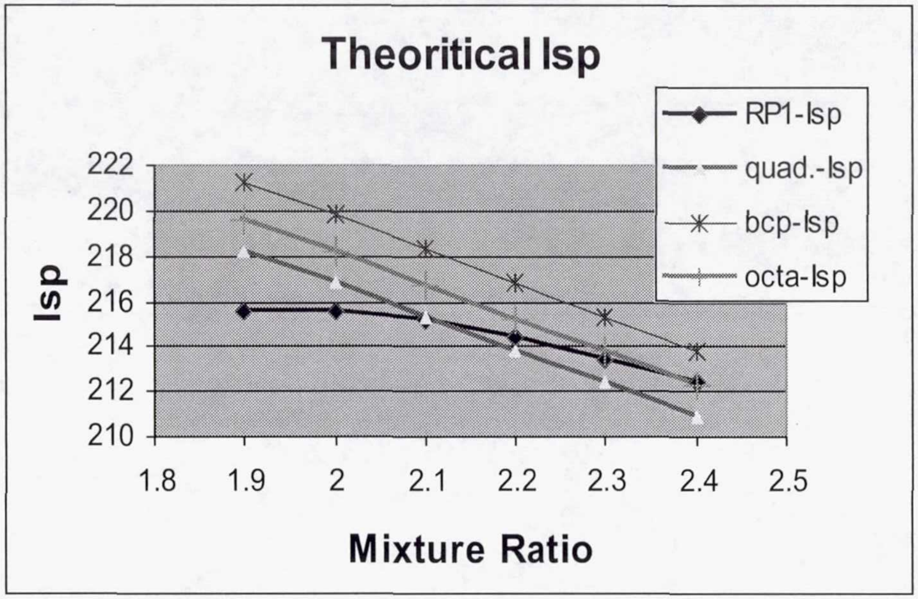
♦ Project Manager	John Cole	TD-15
♦ System Engineer	Scott Jackson	TD-15
♦ MSFC PI	S. Don Bai	TD-40
♦ NASA/GRC		
♦ AFRL		

MSFC Test Team Members

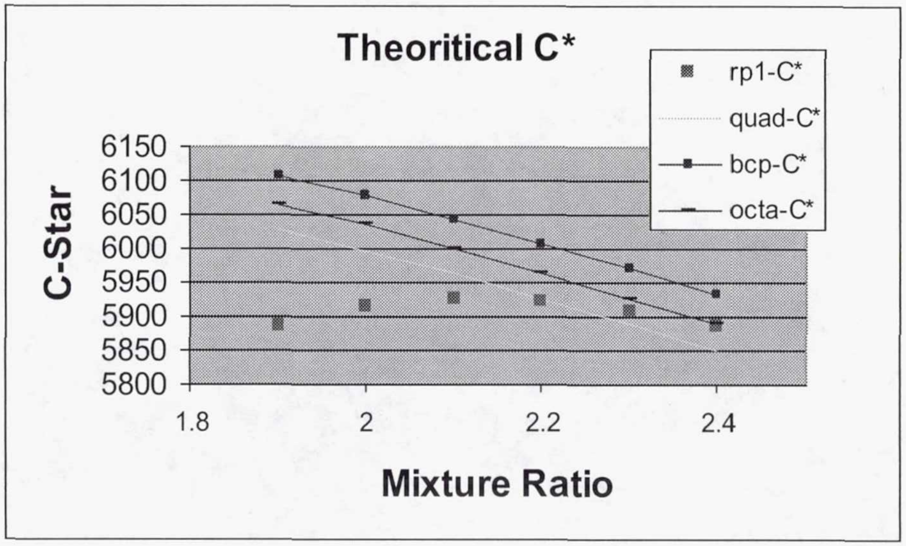
♦ Test Requester	S. Don Bai	TD-40
♦ Test Project Engineer	Paul Dumbacher	TD-71
♦ Test Instrument Engineer	Smith/Wiley	TD-72
♦ Test Control Engineer	Gregory/Trieu	TD-73
♦ Material Testing	James Perkins	ED-36
♦ Safety	Rosalyn Patrick	QS-10

- **Test Requirements**
  - **Measure the performance parameters**
    - Chamber Pressure
    - Fuel & Oxidizer Flow Rate
      - Venturi upstream and downstream conditions.
    - Thrust
  - **Characteristic exhaust velocity (C*)**
    - Comparing relative performance of different chemical propellants.
  - **Specific Impulse Is**
    - Integrated thrust per mass over the time.

Theoretical Comparison



Estimated Performances

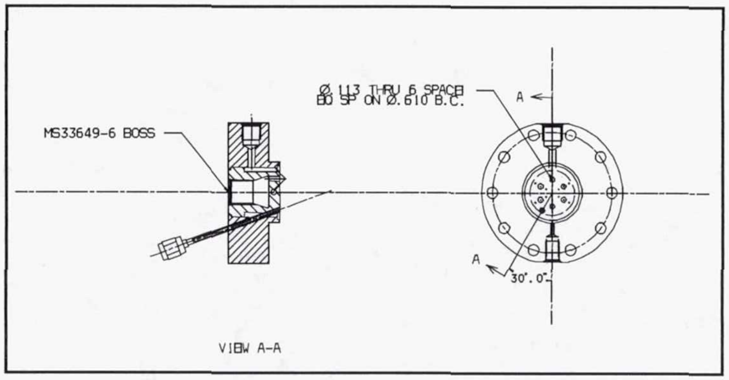


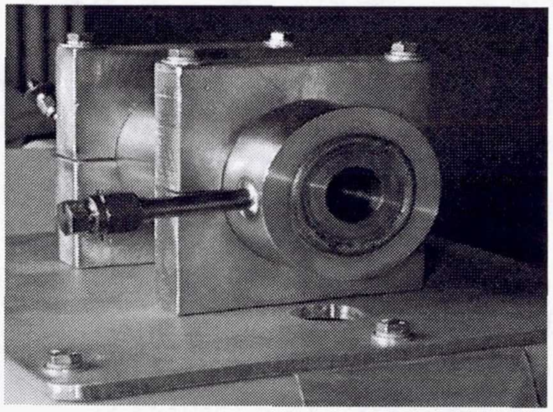
"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Strained Ring Hydrocarbon Fuel Testing

- ♦ **Test Engine & Rig - Combustor**
  - **Designed & Fabricated by G. G. Industries (Scot Claflin) for MSFC.**
    - – Overall Design
      - Propellants: LOX/kerosene - Modified for GOX/RP-1
      - Fuel flow rate: 0.08 lb/sec
      - Theoretical c*: 5890 ft/sec
      - Thrust coefficient, Cf: 1.35

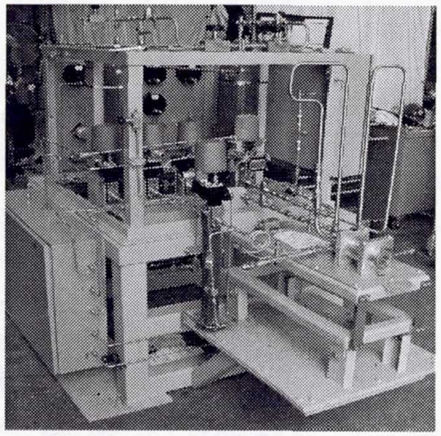
Mixture Ratio : 2.0
c* efficiency: 90%
Thrust: 52 lbs.

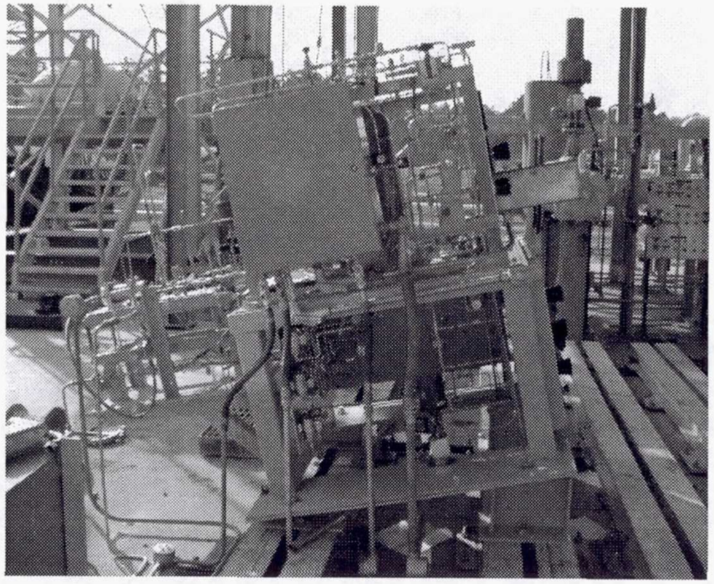




Strained Ring Hydrocarbon Fuel Testing

- Test Rig
  - **Originally Designed & Fabricated by Mason-Holodyne.**
  - **Extensive Modification by STD Technology Evaluation Department.**
    - Flexibility
    - Serviceable parts
    - Incorporation of MSFC expertise of testing
    - LOX system to GOX system
    - Instrumentation

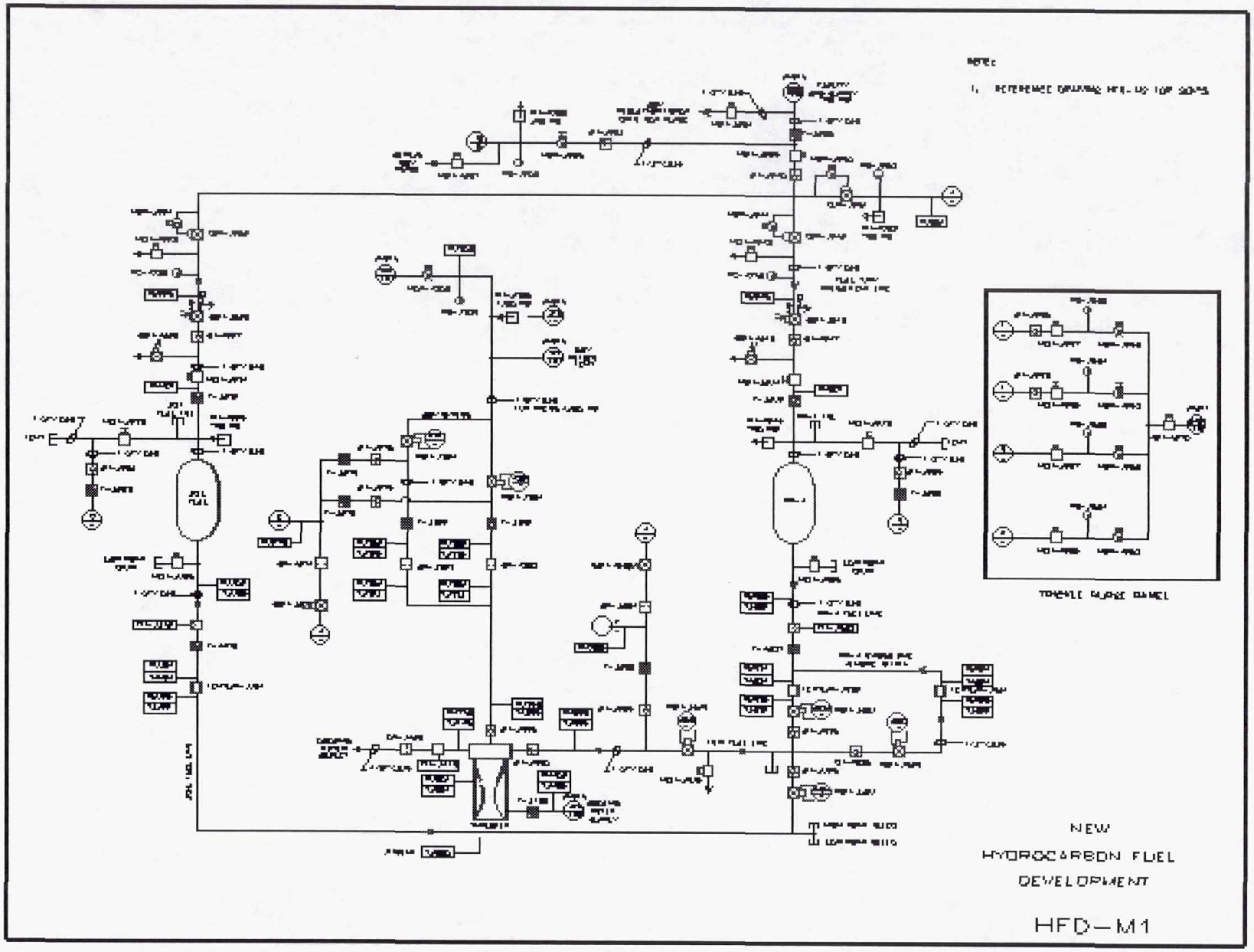




"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Strained Ring Hydrocarbon Fuel Testing

Test Rig - Schematic Diagram



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Strained Ring Hydrocarbon Fuel Testing

- **Test Matrix**
  - **A successful test must go full duration, reach set point conditions for the chamber pressure, flow rate, etc, and involves the accurate measurements fuel and oxidizer flow rates, temperatures, chamber pressure, thrust and cooling water flow rate. Fuel will be switched from RP-1 tank to advanced fuel tank after ~12 seconds of ignition for Test 3 to Test 12. The cooling water flow rate is 0.65 #/sec. The cleaning of advanced fuel tank with Pentane is required after each different type of fuel in the test series. The test matrix is listed below.**

Run	Chamber Pc (psi)	GOX (#/sec)	Tank 1- RP-1 (#/sec)	Tank2	Tank 2 (#/sec)	Test Duration (sec)	
1	175	0.16	0.08	RP-1	0.08	Tbd	system check out
2	175	0.16	0.08	RP-1	0.08	Tbd	Ignition check out
3	175	0.16	0.08	RP-1	0.08	Tbd	Switching check out
4	175	0.16	0.08	RP-1	0.08	~20	Base Line Data
5	175	0.16	0.08	NF#1	0.08	~20	AF#1: Quadracycline
6	175	0.16	0.08	NF#1	0.08	~20	Repeat
7	175	0.16	0.08	RP-1	0.08	~20	AF#2 BCP
8	175	0.16	0.08	NF#2	0.08	~20	Repeat
9	175	0.16	0.08	NF#2	0.08	~20	AF #3 1,7 Octadiyne
10	175	0.16	0.08	RP-1	0.08	~20	Repeat
11	175	0.16	0.08	NF#3	0.08	~20	AF#4 Azide
12	175	0.16	0.08	NF#3	0.08	~20	Repeat

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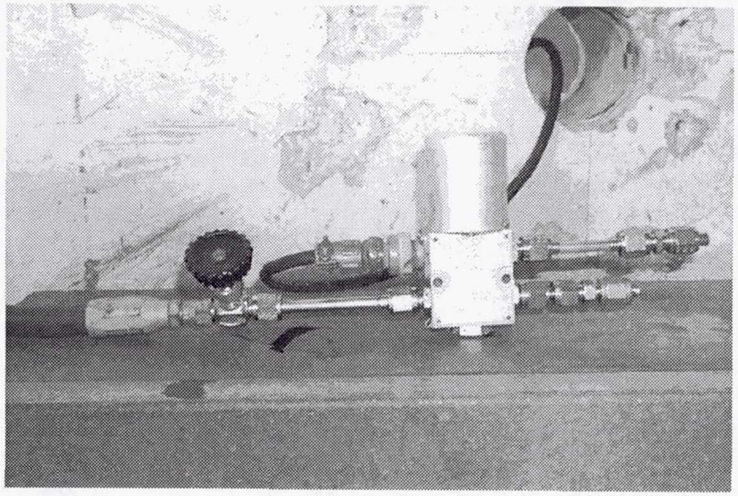
Strained Ring Hydrocarbon Fuel Testing

- Pre-testing Activities
  - Valve Impact Tests at AFRL
  - Short Term Aging Study
  - Material Comparability Tests
  - Dynamic Load Test of Thrust Measurement System

- Objectives:
  - To test the detonation nature of the control valve while actuating it with the following advance HEDM fuels; Bicyclopropylidene, Cyclopropylacetylene 1,7-Octadiyne.
- Conclusions/Recommendation:
  - Based on the results from this test, the HEDM fuels; Bicyclopropylidene, Cyclopropylacetylene, and 1,7-Octadiyne should not have any reactions with different Marotta valves used on the NASA/Marshall.



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Valve Impact Tests at AFRL

Handling of Fuels require personal protective equipment

	Quadracyclane Lot #1001	Bicyclopropylidene (aged)	1,7 Octadiyne 99%	Dimethyl-2-Azido Ethylamine	AFRL-1	RP-1 Fuel
Alumel Ribbon	Strong Odor No visible reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction	Very strong odor No visible Reaction	Some Odor No visible reaction
Chromel Ribbon	Strong Odor No visible Reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction	Very strong odor No visible Reaction	Some Odor No visible reaction
Magnesium Oxide Core	Strong Odor No visible Reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction		Some Odor No visible reaction
Krytox 240AC	Strong Odor No visible Reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction		Some Odor No visible reaction
Sauerisen Cement	Strong Odor No visible Reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction	Very strong odor No visible Reaction	Some Odor No visible reaction
E Constantan	Strong Odor No visible Reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction	Very strong odor No visible Reaction	Some Odor No visible reaction

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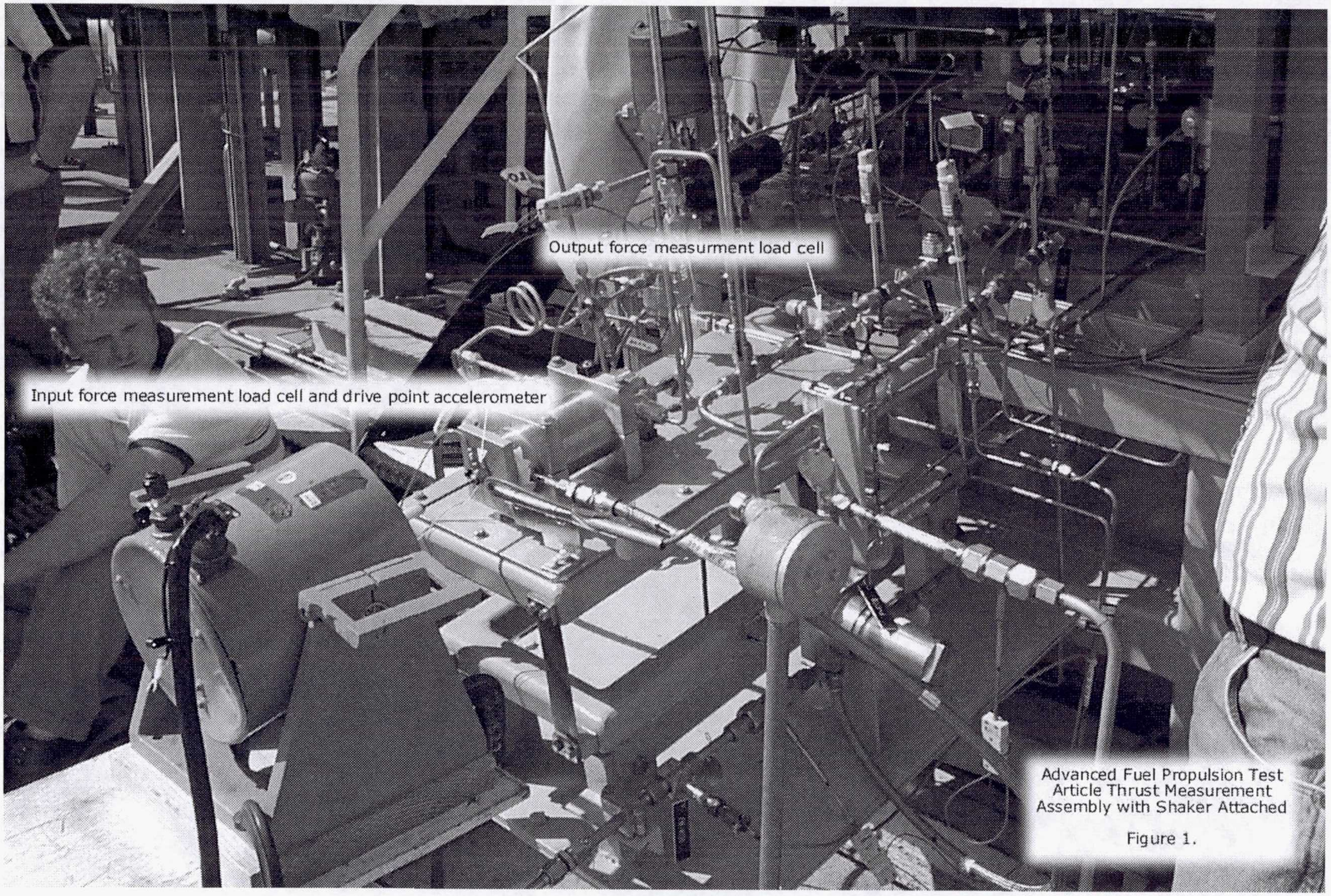
Short Term Aging Study
Material Comparability Tests



Advanced Fuel Propulsion Test Article Thrust Measurement Assembly with Shaker Attached

Figure 1.

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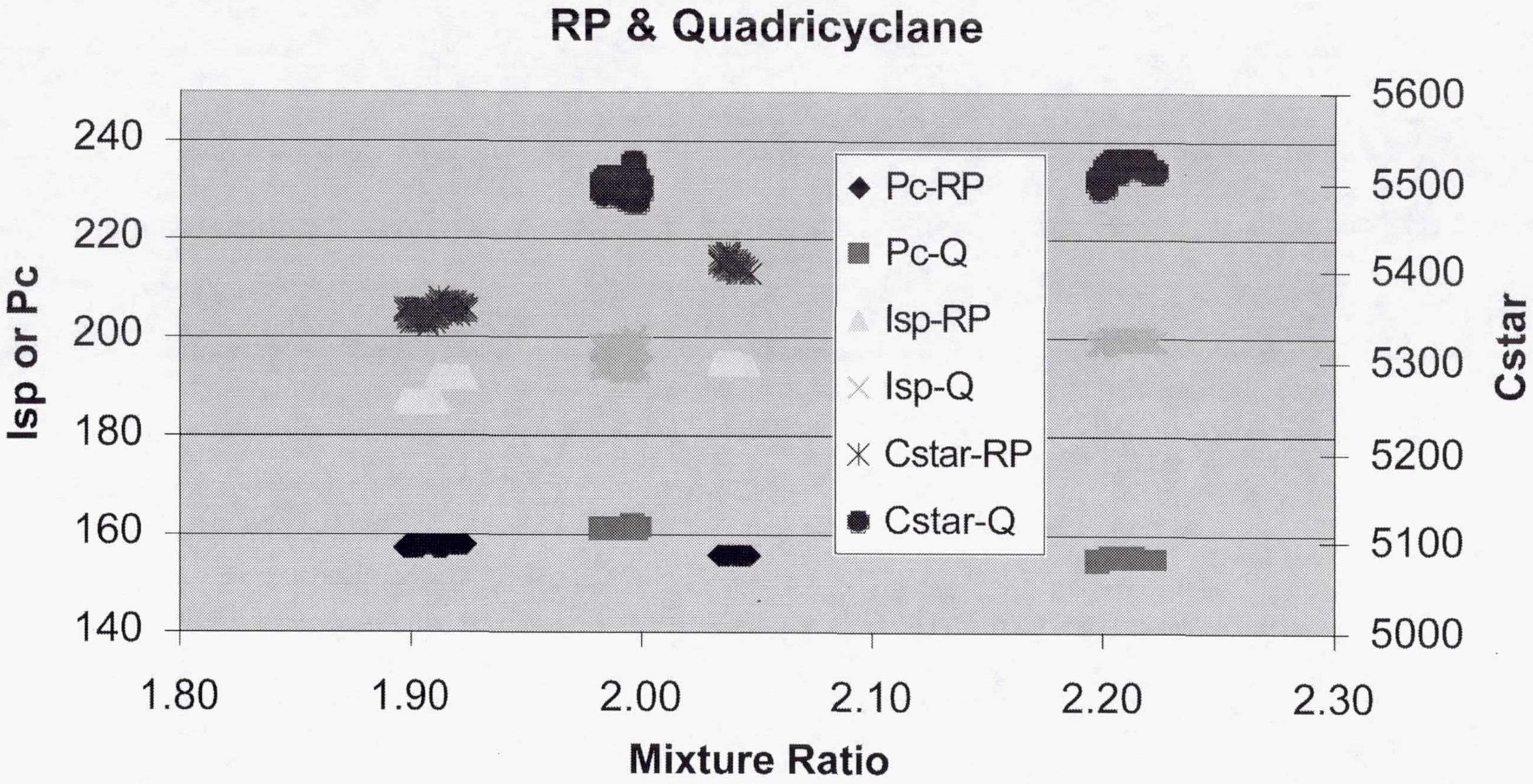
Dynamic Load Test of Thrust Measurement System



- **Specific Gravity Ratio Quadricyclane / RP-1 = 1.17**
- **Cstar efficiency (~1.8%) & Isp(~5 sec) are better than RP-1**

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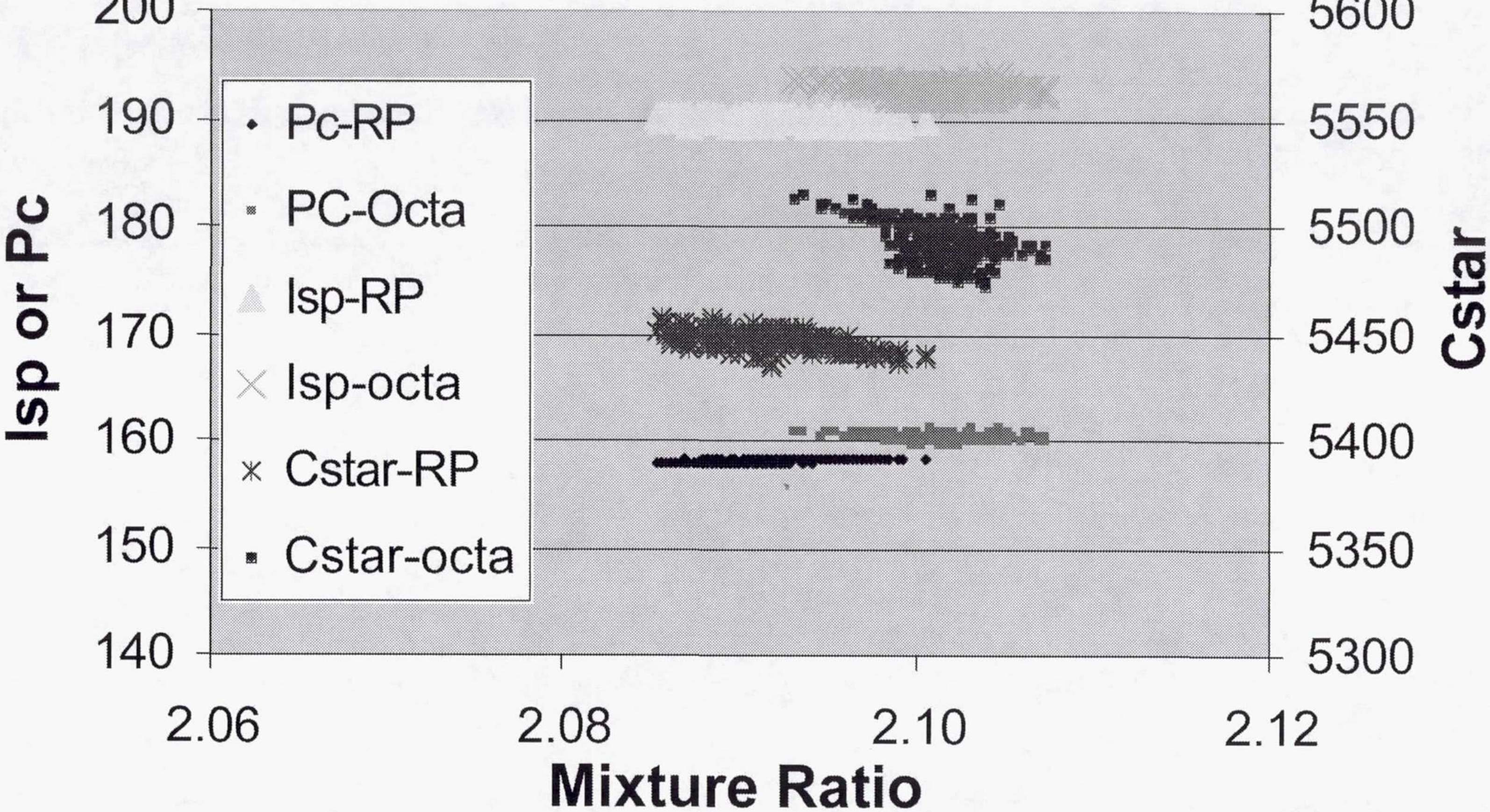
Test Results: Quadricyclane

Test 23: RP-1 vs 1,7 Octadiyne



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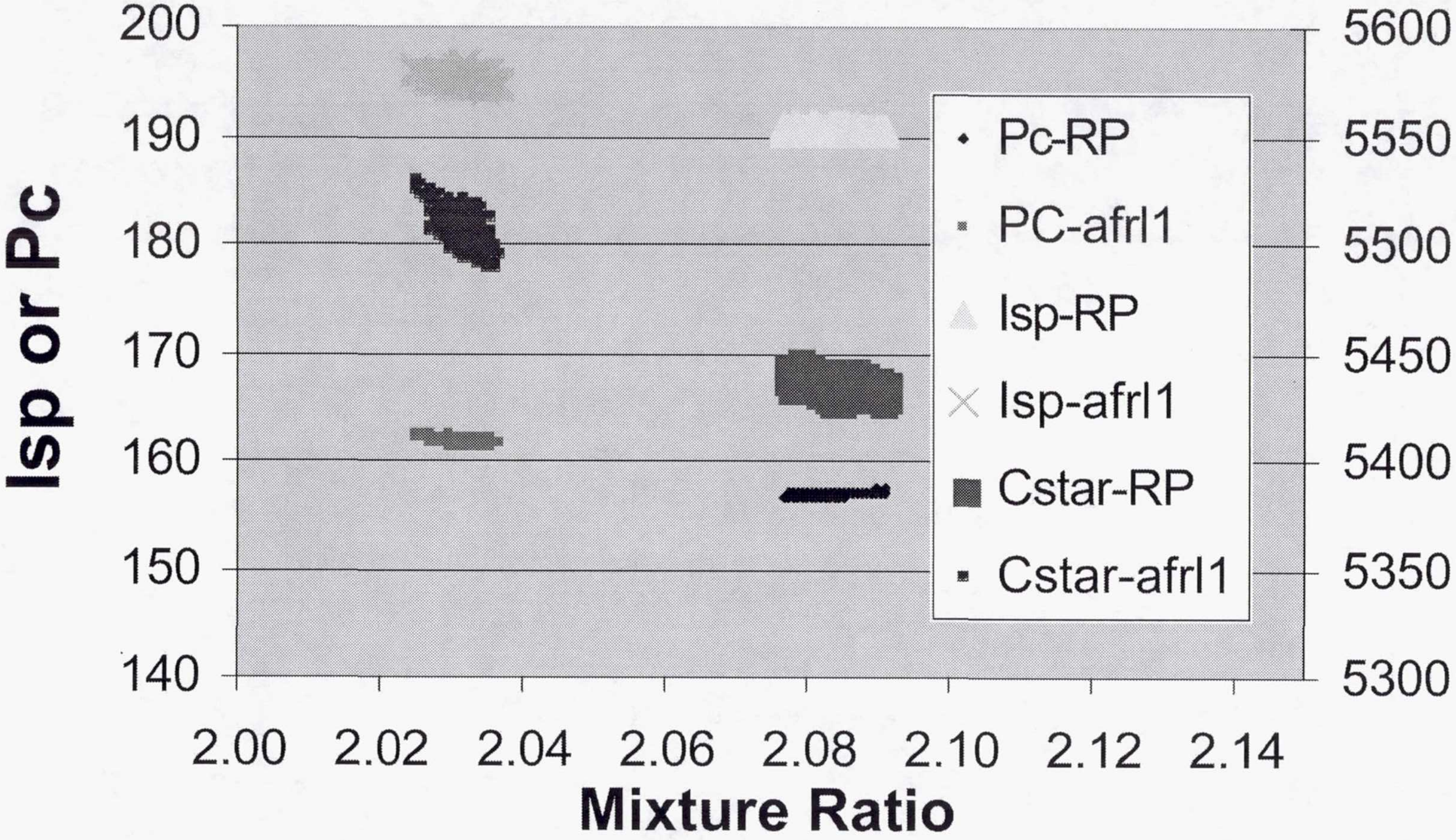
Preliminary Test Result: 1,7 Octadiyne

Test 25: RP-1 vs AFRL-1



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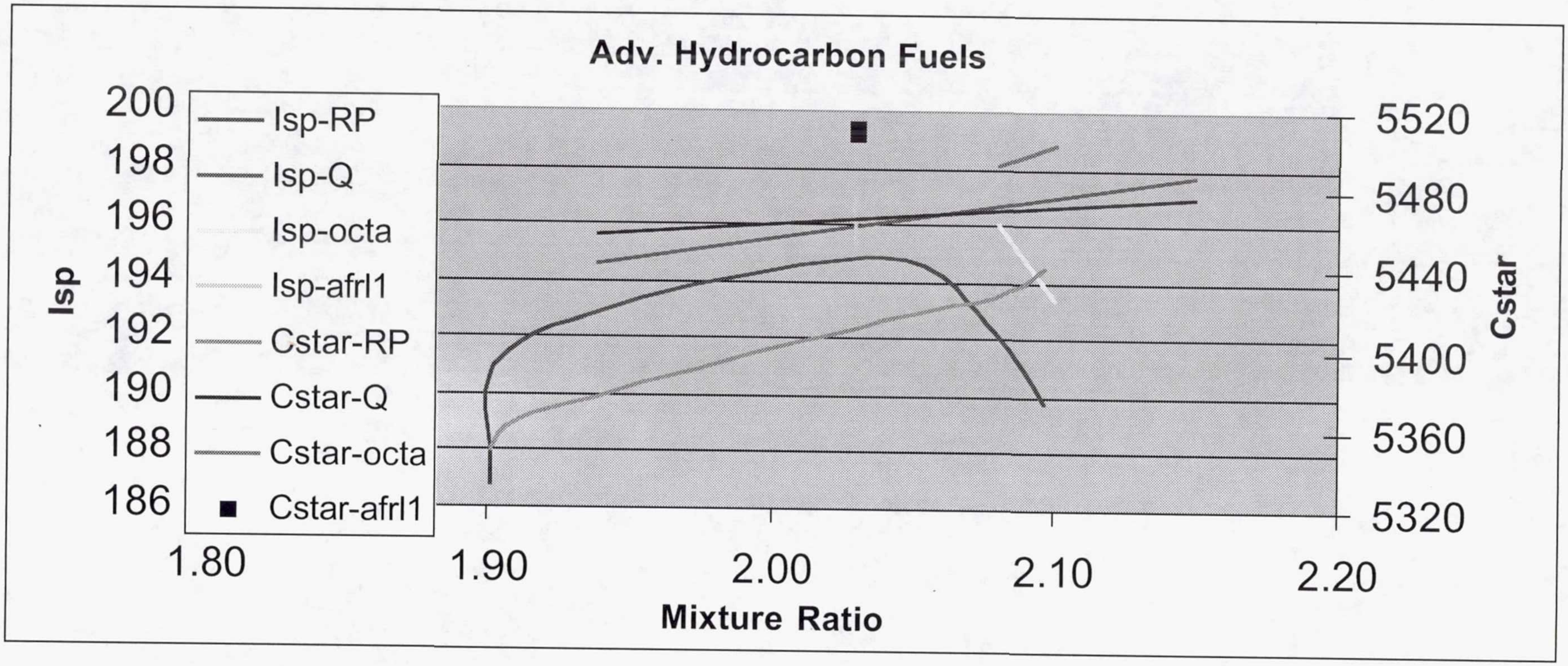
Preliminary Test Result: AFRL-1



	RP-1		Quadricyclane		1,7 Octadiyne
Mixture Ratio	1.9	2.04	*1.94*	*2.15*	2.1
Cstar(Theory)	5887(100%)	6020(100%)	6017(100%)	5942(100%)	6000(100%)
Cstar(Experiment)	5348(90.8%)	5414(90%)	5456(90.7%)	5476(92.1%)	5503(91.7%)
Isp(Theory)	273.1(100%)	279.1(100%)	279.4(100%)	275.7(100%)	278.5(100%)
Isp(Experiment)	186.7(68.4%)	194.8(69.8%)	194.5(69.6%)	197.7(71.7%)	193.3(69.4%)

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Preliminary Test Result

- BCP
- DMAZ
- AFRL-?
- LM-1 ?
- RG-1 ?

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Fuels To Be Tested

Future R&D with AFRL

- Additional Compatibility Studies
  - Screening with More Materials
    - Polymers, Elastomers, Metals,
- Decomposition Studies
  - Gas Phase
  - Liquid Phase
- Additional Toxicity
  - Long Term Studies + 90 Day
- Environmental Studies
- Ignition / Combustion Studies
  - Gas Phase
  - Liquid Phase
  - WSR
  - Ignition Delay
  - Combustion Gases
- Refined Synthesis Cost Estimate
  - Number of Steps in Reaction
  - Cost of Materials
  - Heat Transfer - Heat or Cooling Issues
  - Waste Disposal
- System Analysis
  - Studies with Existing Systems
- Logistics
  - Transportation Costs
  - Storage Costs
  - Handling Costs
  - Disposal Costs
- Medium Scale Combustor - 1000 Pounds
  - (NASA/DOD/Industry)
  - Flame Temperature
  - Flow Rates - Pressure - Volume
  - Isp - Delivered
  - XXXXX......

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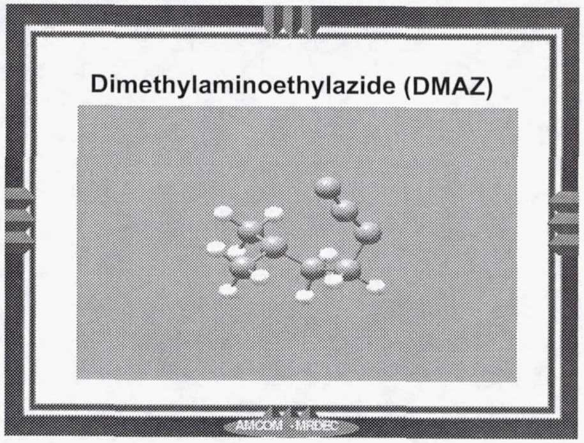
Strained Ring Hydrocarbons: Joint Project with AFRL

- Revolutionary Rockets
- Advanced Fuels and High Energy Density Materials
  - Strained Ring Hydrocarbons (Bai/TD40)
  - Azide Fuel (US Army - Bai/TD40)
  - Solid Hydrogen
    - Recombination Energy Fuels (Palaszewski /GRC)
    - Penta Nitrogen (Palaszewski /GRC)
    - Poly-Oxygen (Palaszewski /GRC)
    - Metallized and Gelled Fuels (Palaszewski /GRC)
    - Powdered Aluminum Combustion (Litchford/TD15)
- Launch Assist
  - Cannons, Balloons, Aerial Refueling, Catapults, etc (Nolen/ED31, Jones/TD40)

Agenda

Azide Fuel (DMAZ)

DOD/US Army/AF - NASA Project
Initiated for an alternate fuel to Hydrazine
NASA/White Sands Test Facility funded
NASA/MSFC will test as a bipropellant fuel


Dimethylaminoethylazide (DMAZ)

Darren M. Thompson
U.S. Army AMCOM
AMSAM-PS-RD-R
(256)955-8556, Fax: (256)955-7748
darren.thompson@redstone.army.mil

NASA Glenn Research Center Tasks

- Create highest specific impulse atomic rocket propellants with atomic boron, carbon, or hydrogen in solid hydrogen particles
- Mass and Energy Balance for Solid Hydrogen and Atomic Propellants: Complete solid hydrogen freezing experiments with improved mass flow rate measurements and estimates of energy for hydrogen freezing
  - the quality (temperature, pressure, and state) and flow rate of the hydrogen delivered to the liquid helium dewar would be quantified,
  - the temperature profile in the liquid helium dewar would be more accurately known, and
  - the quality (temperature and pressure) and composition of the LHe dewar vent gases would be determined
- Plan for completion of project in 4th quarter of FY 2001, with AIAA paper documenting the test series results
- Contact - Bryan Palaszewski, NASA GRC, (216) 977-7493

Atomic Propellants

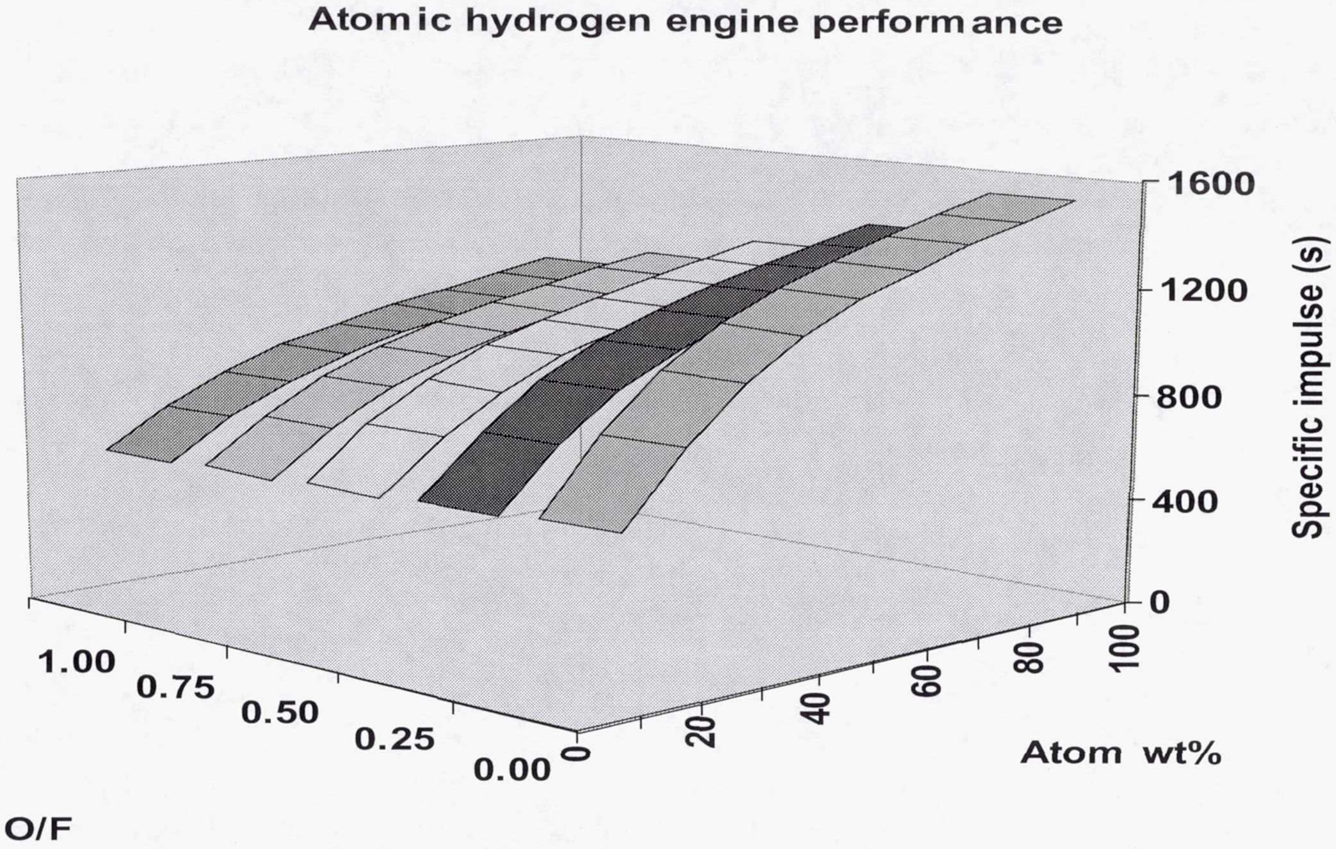
- **Revolutionary Rockets**
- **Advanced Fuels and High Energy Density Materials**
  - **Strained Ring Hydrocarbons (Bai/TD40)**
  - **Azide Fuel (US Army - Bai/TD40)**
  - **Solid Hydrogen**
    - Recombination Energy Fuels (Palaszewski /GRC)
    - Penta Nitrogen (Palaszewski /GRC)
    - Poly-Oxygen (Palaszewski /GRC)
    - Metallized and Gelled Fuels (Palaszewski /GRC)
    - Powdered Aluminum Combustion (Litchford/TD15)
- **Launch Assist**
  - **Cannons, Balloons, Aerial Refueling, Catapults, etc (Nolen/ED31, Jones/TD40)**

Agenda

- Vision
  - Atomic propellant offer large potential increases in rocket specific impulse (Isp)
  - Isp increases of hundreds of seconds over O2 /H2 are theoretically possible
  - Isp increases can reduce vehicle gross liftoff weight (GLOW) up to 80%
  - A long history of research has opened new possibilities to harness atomic fuels
  - Cryogenic storage temperatures of 4 K or lower are required

Atomic Propellants: Why Atomic Propellants?

Specific Impulse (Isp) Map for Atomic Hydrogen



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Atomic Propellants

- **Revolutionary Rockets**
  - **PDRE Development Project (Ryan/TD51)**
    - Pulse Detonation Engine / Pulse Detonation Rocket Engine
      - PDRE Bench Unit (Litchford/TD15)
      - Revolutionary Concept (REVCON) PDE (Hueter/TD15)
      - PDE Performance Code Development (Seymour/TD53)
    - Advanced Ejector (Blevins/TD40)
    - Air Augmented Aerospike CFD Analyses (Garcia/TD64)
    - Deeply Cooled Air Rocket Engine (Bai/TD40)
    - Liquid Air Combustion Engine(LACE) (Bai/TD40)
    - Multiple Reaction HE Explosive (Bonometti/TD40)
- **Advanced Fuels and High Energy Density Materials**

Agenda

- Pulse Detonation Engine / Pulse Detonation Rocket Engine
  - PDE Concept
  - NASA MSFC PDRE Activities
  - Office of Naval Research's Multi-University Research Initiative on Pulse Detonation Engines

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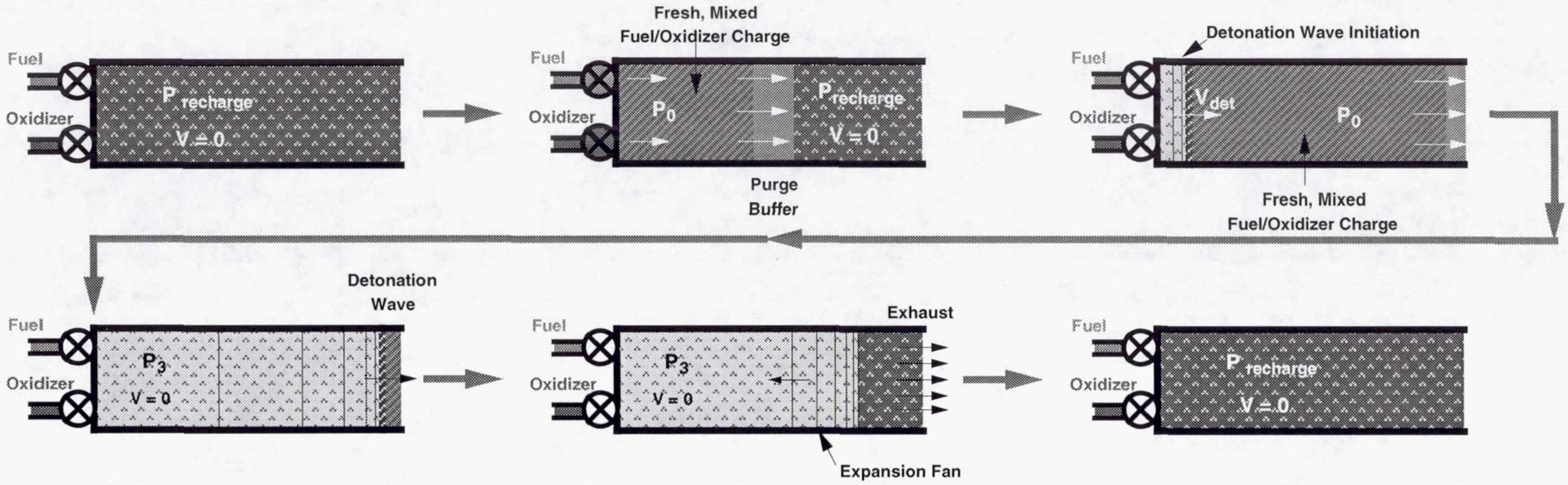
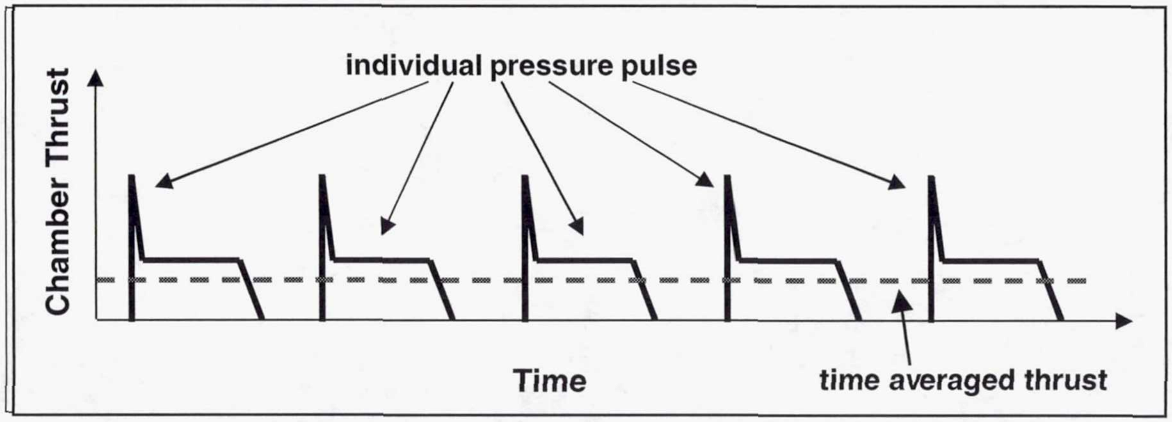
Revolutionary Rockets

ASI
ADROIT SYSTEMS INC.



- Detonation process is self pressurizing
- High peak temperatures and pressures occur at microsecond time scales
- High cycle rates and multiple combustors produce even thrust



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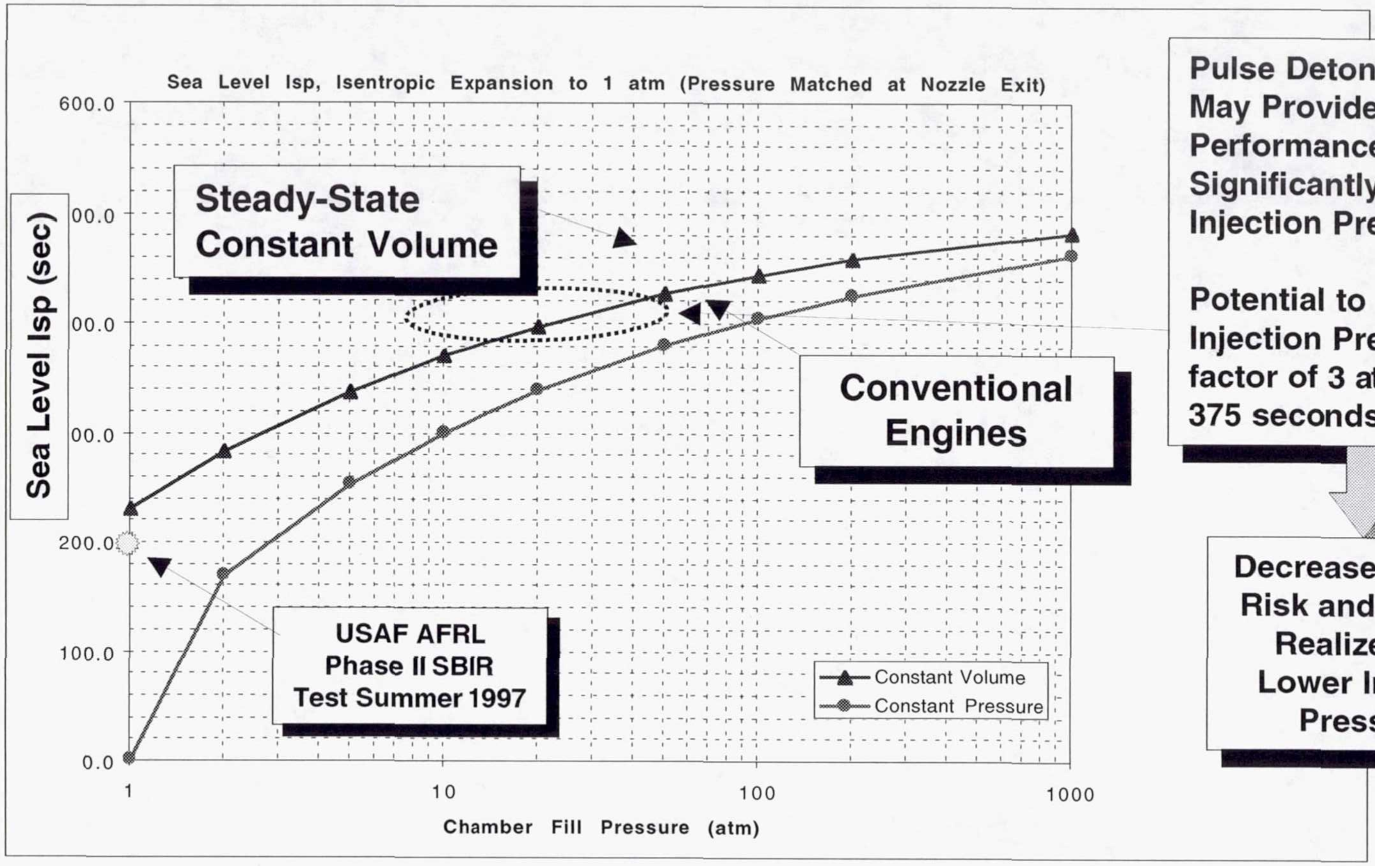
Pulse Detonation Propulsion Uses "Fill and Fire" Operations

- **Preliminary ASI tests are successfully demonstrating PDRE performance at 1 atm test condition**



Steady-State Constant Volume

Conventional Engines

USAF AFRL Phase II SBIR Test Summer 1997

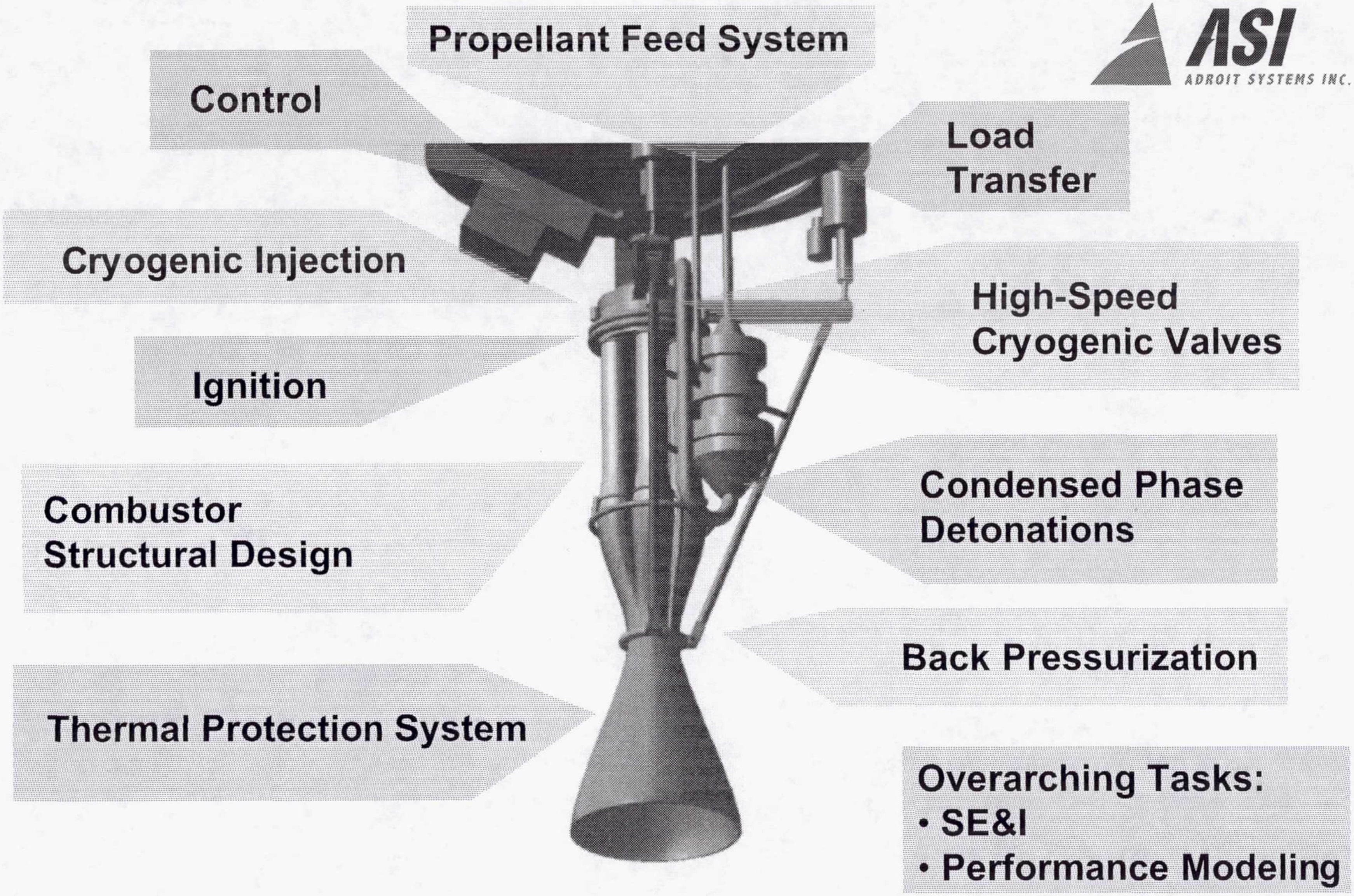
Pulse Detonation Cycle May Provide Equivalent Performance for Significantly Reduced Injection Pressure

Potential to Lower Injection Pressure by factor of 3 at an Isp of 375 seconds

Decreased System Risk and Cost are Realized with Lower Injection Pressures

PDRE Potential Based on Higher Thermodynamic Efficiency and a Self Pressurizing Process

ASI
ADROIT SYSTEMS INC.



Propellant Feed System

Control

Load Transfer

Cryogenic Injection

High-Speed Cryogenic Valves

Ignition

Combustor Structural Design

Condensed Phase Detonations

Back Pressurization

Thermal Protection System

Overarching Tasks:
- SE&I
- Performance Modeling

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PDRE Critical Technologies

Revolutionary Rockets

Pulse Detonation Engine / Pulse Detonation Rocket Engine

PDE Concept

NASA MSFC PDRE Activities

<u>ASTP PDRE Development Projects</u>

POC NASA/MSFC Hueter/Richard M Ryan
256-544-4172

<u>ASTP PDRE Research projects</u>

In-House PDR Testing

POC NASA/MSFC Cole/Ron Litchford
256-544-1740

Analysis

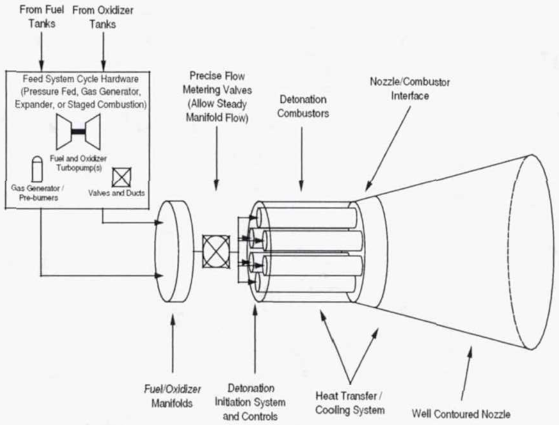
POC NASA/MSFC Cole/Dave Seymour
256-544-7116

Office of Naval Research's Multi-University Research Initiative on Pulse Detonation Engines

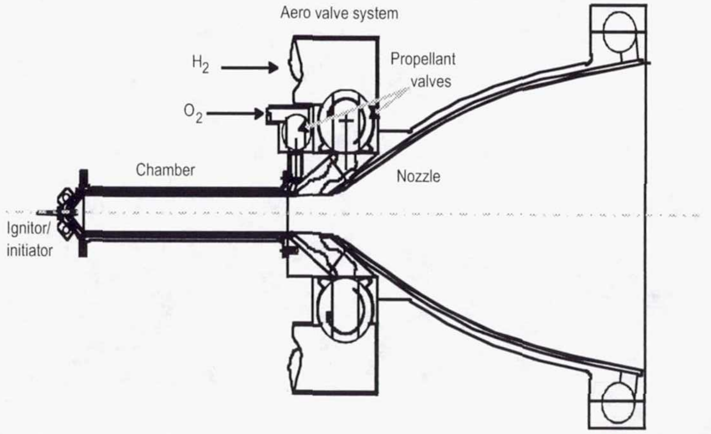
"STI Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

- **Pulse Detonation Engine / Pulse Detonation Rocket Engine**
  - **PDE Concept**
  - **NASA MSFC PDRE Activities**
    - ASTP PDRE Development Projects
      - POC NASA/MSFC Hueter/Richard M Ryan - 256-544-4172
    - ASTP PDRE Research projects
      - In-House PDR Testing
        - POC NASA/MSFC Cole/Ron Litchford - 256-544-1740
      - Analysis
        - POC NASA/MSFC Cole/Dave Seymour - 256-544-7116
  - **Office of Naval Research's Multi-University Research Initiative on Pulse Detonation Engines**

- Two contracts awarded to develop PDRE technology
  - ASI
  - UTRC
- Each exploring different back pressure control mechanisms
  - Fixed throat
  - Aerodynamic throat
- In 3rd year of 3 year contract
- Further work will require new procurement activity



Multi tube PDRE w/ nozzle



Single tube PDRE w/ nozzle and aerodynamic throat

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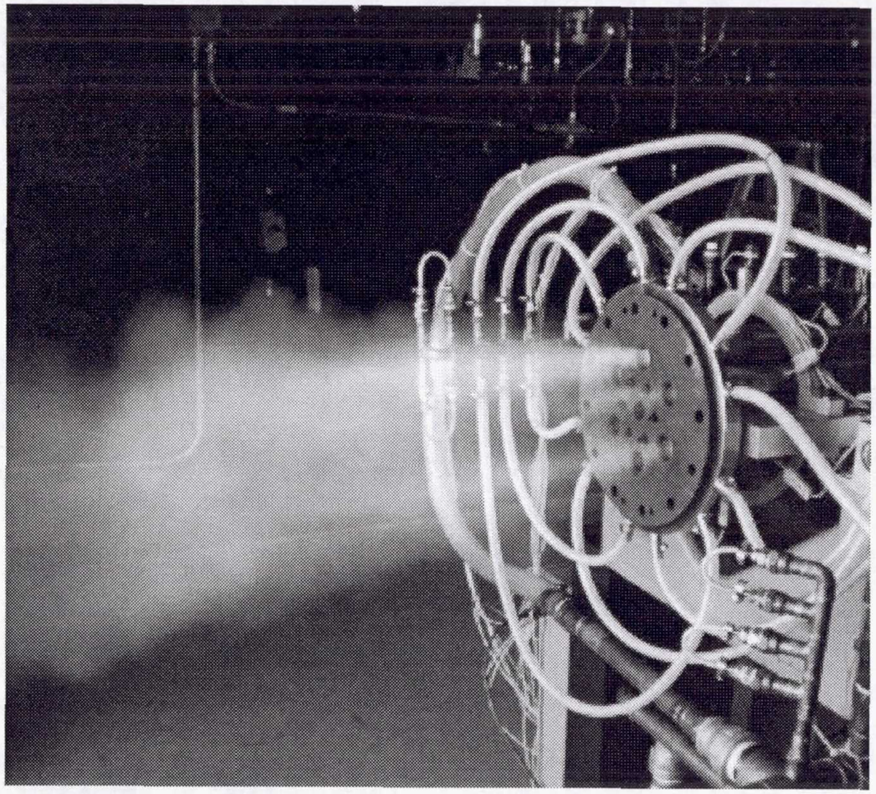
ASTP PDRE Projects

ASI Accomplishments to Date

- In Just Four Years, ASI/NASA/AFRL Have Demonstrated:
  - PDRE proof-of-concept
  - 30-sec firing durations
  - Repeatability & reliability at high frequencies
  - Performance prediction
  - Back pressurization with a common nozzle
  - Vacuum start capability
  - Working injector concept
  - Full-scale, high-speed valves (simulant testing)



ASTP PDRE Projects

UTRC Accomplishments to Date

- Proof-of-Concept Tests
  - Demonstrated PDRE operation with physical throat
  - Developed operating-characteristics database
- Aerovalve Development
  - Developed design and analysis capabilities
  - Demonstrated concept in single-shot, cold-flow tests
- Advanced Concept Engine Demonstration
  - Identified test facility; Test Requirements Document distributed
  - Completed demonstrator design; testing summer/fall 2000

ASTP PDRE Projects

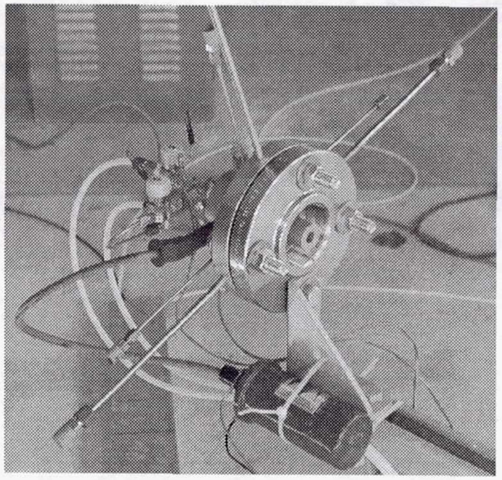
PDRE Future Planning Guidelines

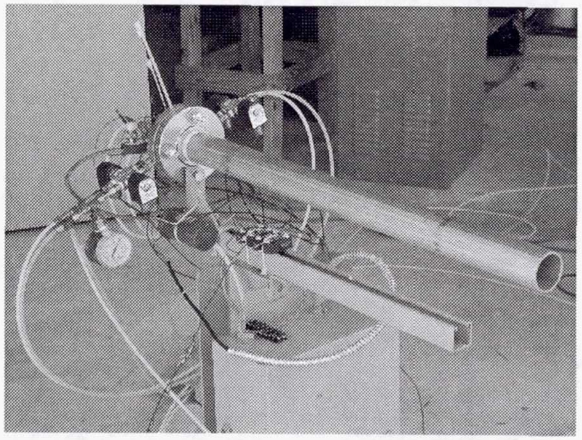
- Project given $2.5M per year for next 3 years to mature technology before commitment to demonstrator
  - $200K of FY2001 money must be used to reimburse GRC for testing support for the UTRC on going activity
- This level of funding will force some hard decisions in the next procurement
  - Could result in a partnering between current contractors or
  - Will probably result in a down select between concepts
- For next 3 years need to focus on critical questions that support demonstrator decision in FY2004
  - Can the PDRE concept meet advertised performance and weight goals?
  - Is the physics of the concept well understood and accepted by industry and academia?
  - Are there any fundamental technologies that must be proven before commitment to a flight weight demonstrator?
- Money for the demonstrator program has not been identified at this time

Key Objectives of the Next Few Years

- Demonstrate feasibility of PDRE to achieve performance and weight goals
  - Must have solid credible system concept that can be used in vehicle trades to assess benefits
- Develop and release a public performance code that is anchored with experimental data
  - Must be able to pass scrutiny of industry and academia
  - Necessary to have an analytical code that matches test data to demonstrate that physics of concept is understood
- Enable all critical technologies necessary for PDREs
  - Cannot have any critical enabling technologies not developed before commitment to flight weight demonstration

- Gaseous H_2/O_2 laboratory-scale rocket engine simulator
  - Support development of theoretical/CFD analysis tools
  - Improve definition of system operational requirements
  - Test bed for major sub-systems/components
  - Explore strategies for optimizing propellant injection
  - Explore strategies for optimizing nozzle shape
  - Explore alternative engine design configurations
  - System performance optimization
  - Develop/validate PDE design scaling laws
  - Lay groundwork for liquid propellant PDEs
  - Improve understanding of detonation physics





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ASTP Research PDRE Projects: In-House ASTP Research

- **Development status**
  - **Electronic control circuits designed, fabricated and tested**
    - computer based low-voltage digital (TTL) signal pulses
    - fiber optic signal transmission (low power / electrical isolation)
    - high precision timing of duty cycle and phase lag
  - **Spark ignition system designed, fabricated, and tested**
    - automotive type capacitor discharge system
  - **Detonation initiator designed, fabricated, and tested**
    - coaxial gaseous injector
    - industrial solenoid valves
    - demonstrated DDT with Schelkin spiral (40 Hz / >2000 m/s)
  - **Bench unit assembly designed, fabricated, and tested**
    - integrated initiator/injector head design
    - 2-inch diameter/ 36-inch long primary tube
    - coaxial gaseous injectors
    - industrial solenoid valves
    - demonstrated detonation propagation to primary tube

ASTP Research PDRE Projects:

In-House ASTP Research

UTSI Performance Analysis

- **1-D Pulsed Detonation Engine Cycle Deck (PDECD) Modification**
  - Include the effects of variable mixture ratio
    - Provision for opening and closing the fuel and oxidizer valves independently so that effects such as a fuel purge and variable O/F ratio during a cycle can be simulated
  - Include global dynamic effects in the feed lines and valves.
    - A lumped parameter analysis of the feed line dynamics for use in simulating representative experimental test facilities will be added.
  - Modeling of Multiple Tube PDE Operation:
    - Simulations of the effects of multiple pulsed detonation tubes exhausting to a common nozzle. Flow from the common nozzle shall be exhausted through a divergent or convergent-divergent tube using quasi-steady flow analysis.
  - Air Augmented PDE:
    - Predicting the performance characteristics of an air-augmented pulsed detonation engine rocket. The model should be appropriate for making qualitative assessments of the effect of coupling a PDE into a combined cycle engine.

- **Future MSFC Research Plan**
  - **Continuation of current activities**
  - **PDR/PDRE Standard Performance Analysis Code (Government team sponsorship is desirable)**
    - System level Code
    - Subsystem CFD Code
      - Generic
      - Full 3D Transient
      - Experiments for Code Validation
  - **Advanced Fuel for PDRE**
    - Advanced hydrocarbon fuels for a rocket are in development. Are these fuels applicable for PDRE ?

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ASTP Research Future Planning

- Pulse Detonation Engine / Pulse Detonation Rocket Engine
  - PDE Concept
  - NASA MSFC PDRE Activities
  - Office of Naval Research's Multi-University Research Initiative on Pulse Detonation Engines

ONR CHARTS

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GRCop-84 Development for Combustion Chamber Liners

David Ellis[1], Michael Nathal[2], Hee Man Yun[3], Bradley Lerch[2], Leslie Greenbauer-Seng[2], Linus Thomas-Ogbuji[4], Richard Holmes[5]

[1]Case Western Reserve University
[2]NASA Glenn Research Center
[3]Cleveland State University
[4]Dynacs Engineering Company
[5]NASA Marshall Space Flight Center

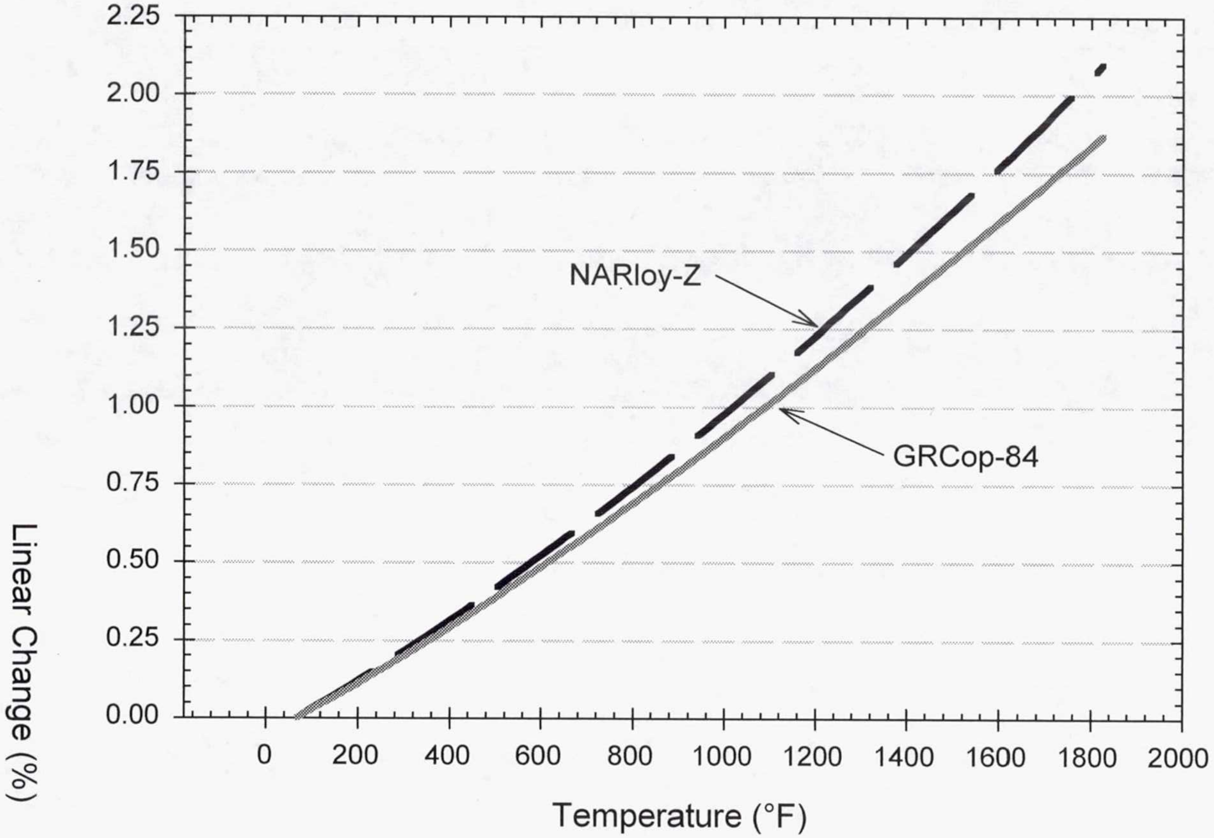
Space Transportation Technology Workshop - Propulsion:

(

- Originally began as series of experimental Cu-Cr-Nb alloys produced by chill block melt spinning
  - Focused on alloys with 2:1 atomic Cr to Nb ratios
  - Varied total amount of Cr+Nb to vary volume fraction of Cr_2Nb
  - Ribbons examined metallographically, tensile tested and electrical conductivity measured
- Cu-8 at.% Cr-4 at.% Cr was selected as composition with best combination of conductivity and strength
- Composition scaled up using conventional argon gas atomization (Special Metals) and extrusion to verify good properties of alloy
- Full thermophysical and mechanical properties database developed on GRCop-84 under RLV Focused Program for GRCop-84 produced by Crucible Research

Space Transportation Technology Workshop - Propulsion:

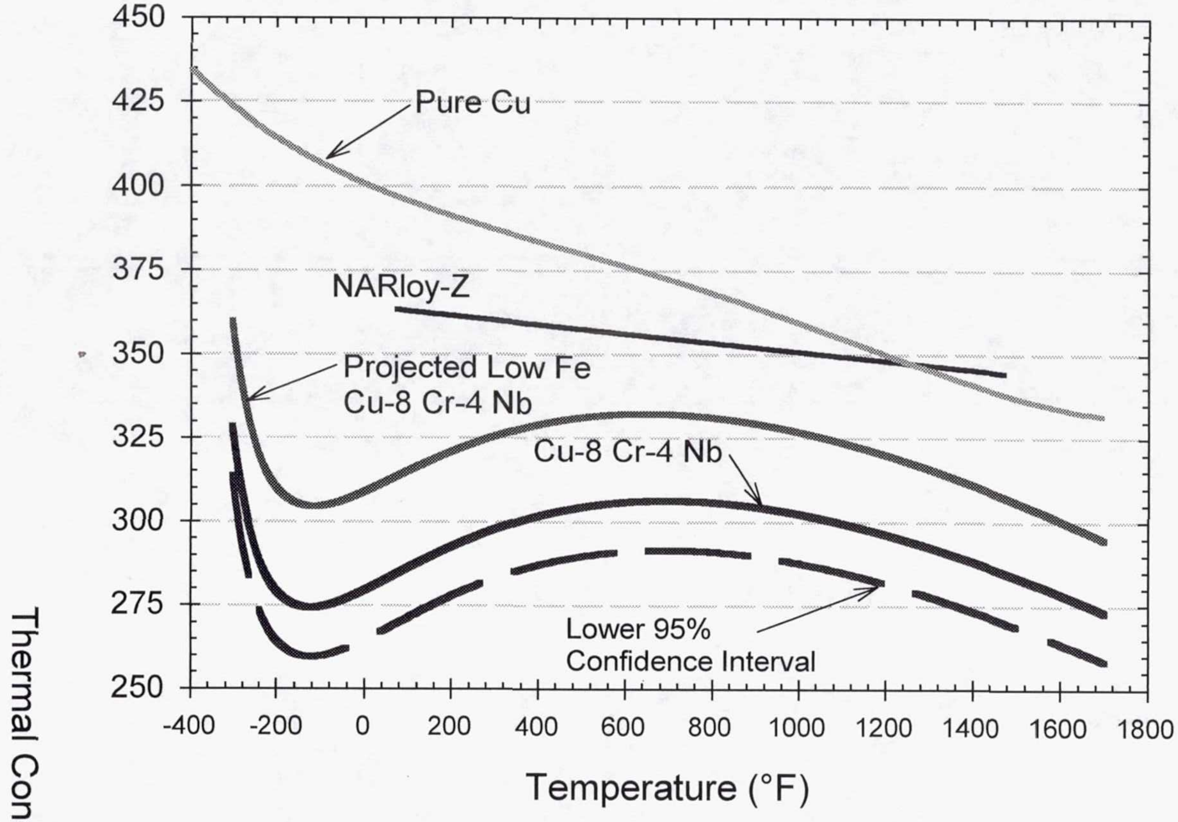
History of GRCop-84 Development



- ♦ **Thermally induced stresses from constrained thermal expansion dominate in liners**
- ♦ **Decreased thermal expansion decreases thermal stresses**
- ♦ **Decreased stresses and strains result in longer liner lives**

Space Transportation Technology Workshop - Propulsion:

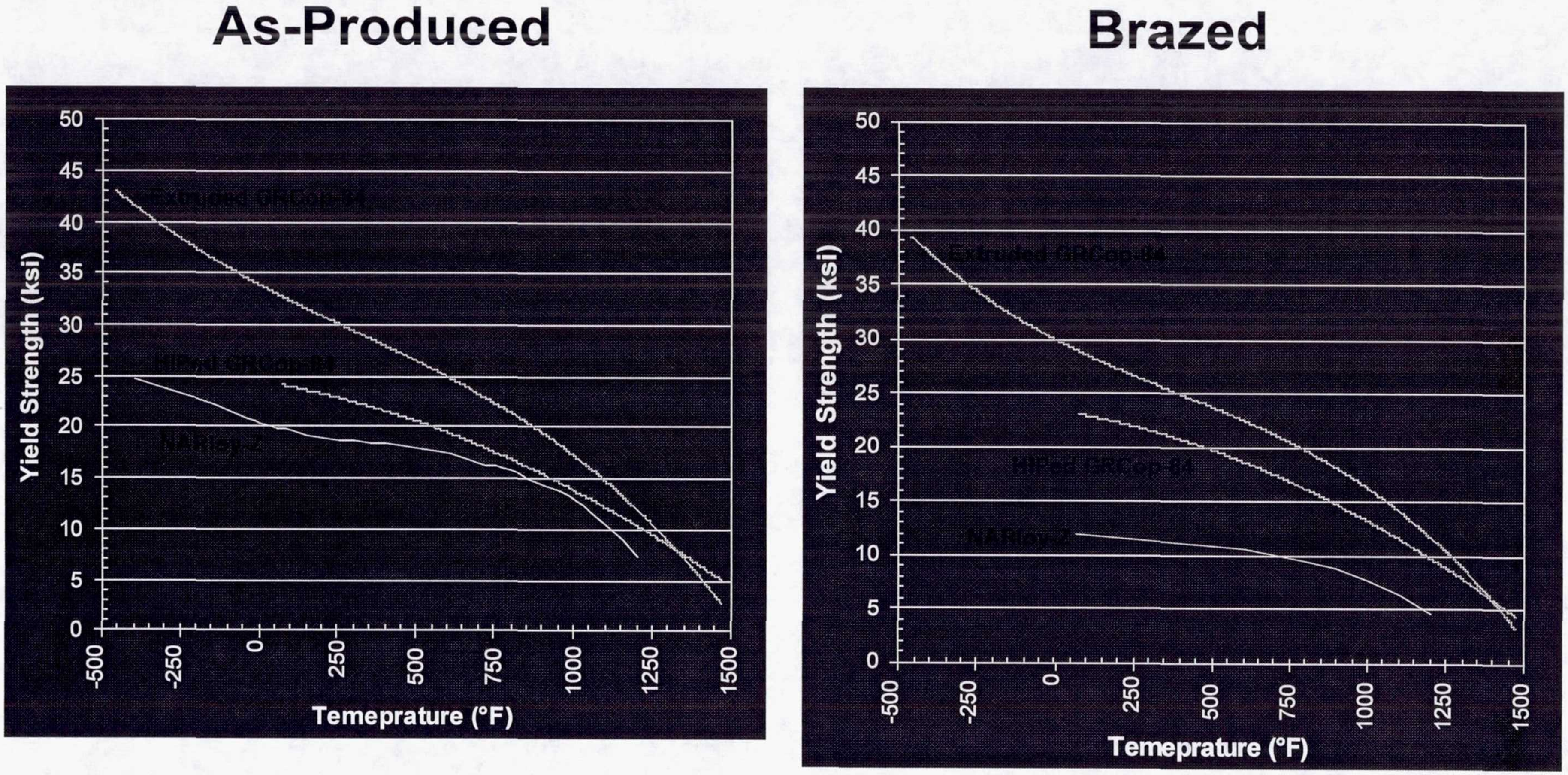
GRCop-84 Thermal Expansion



- **Statistical analysis allows determination of equations for average thermal conductivity and lower confidence interval**
- **Average conductivity is between 70% and 83% of pure Cu over temperature range of interest for liners**
- **Elimination of 200 ppm Fe contamination in alloy *may* increase thermal conductivity significantly**

Space Transportation Technology Workshop - Propulsion:

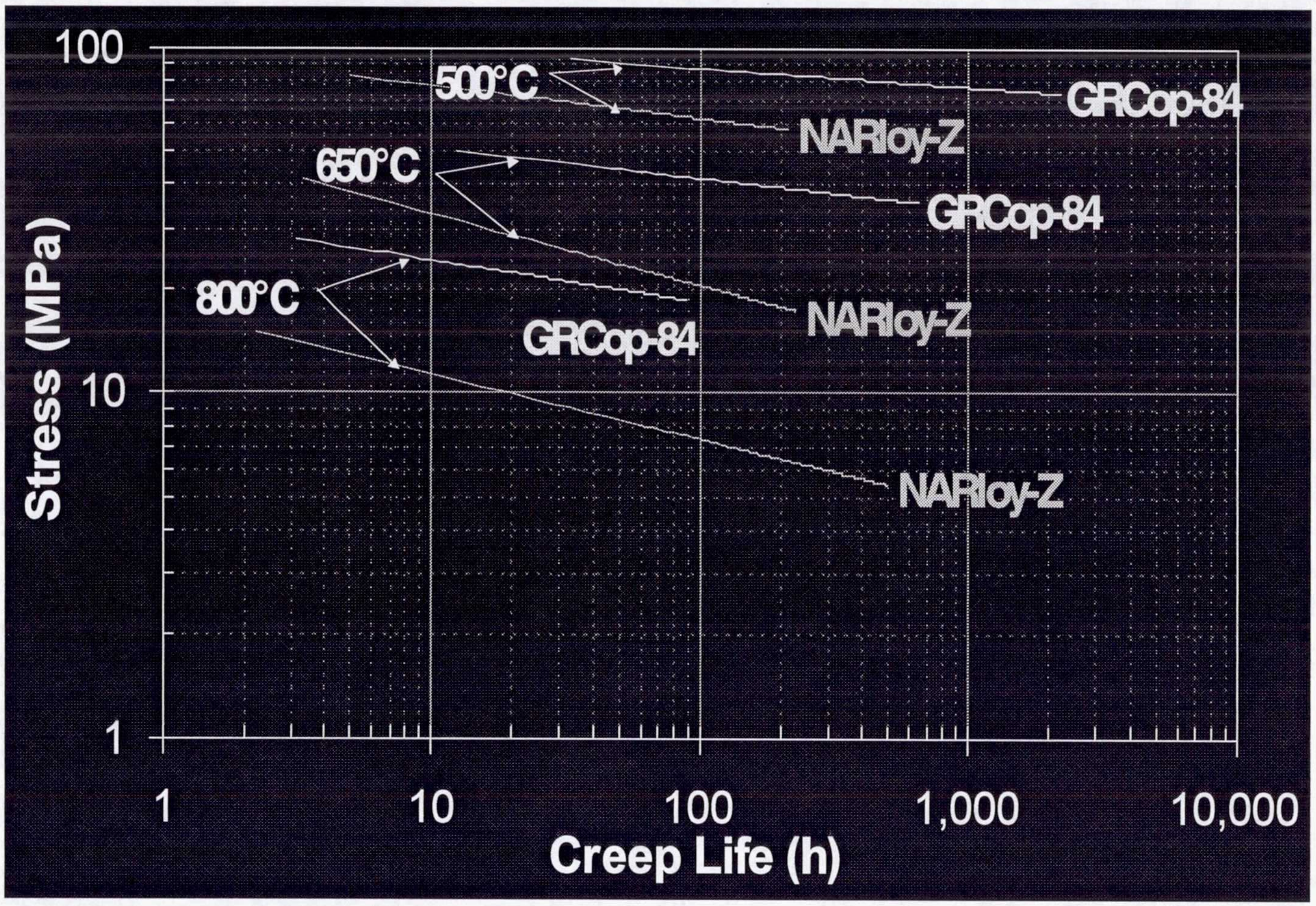
Thermal Conductivity of GRCop-84



- Following a simulated braze cycle at 935°C (1715°F), GRCop-84 exhibits a minimal decrease in 0.2% yield strength
- NARloy-Z shows significant strength loss

Space Transportation Technology Workshop - Propulsion:

0.2% Yield Strength of GRCop-84



- GRCop-84 enjoys significant creep life advantages over NARloy-Z
- Additional data for Crucible Research material being generated under RLV Focused program

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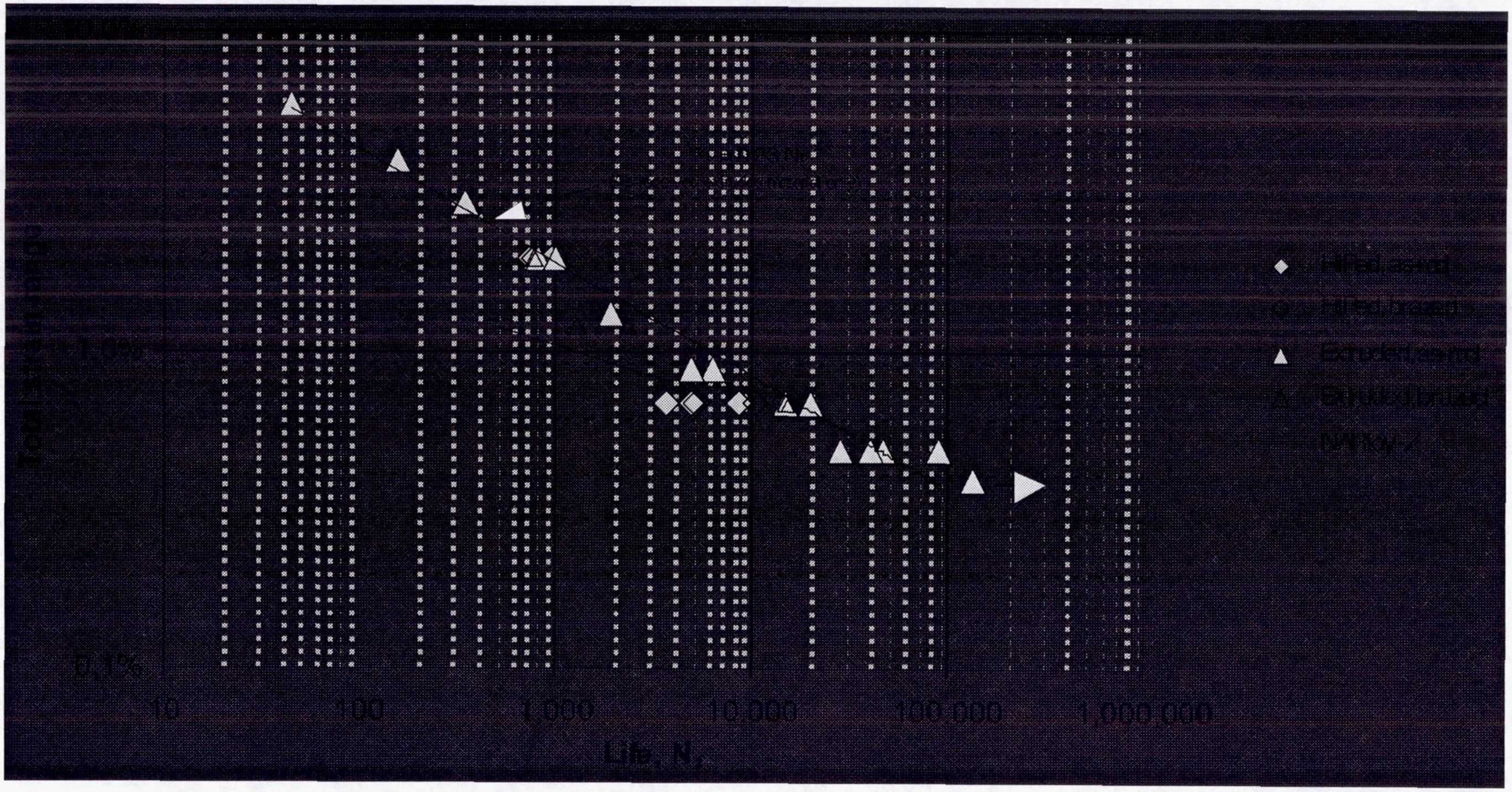
GRCop-84 Creep Lives



- ♦ GRCop-84 has significantly longer LCF lives than NARloy-Z
- ♦ The simulated braze has minimal effects on LCF lives

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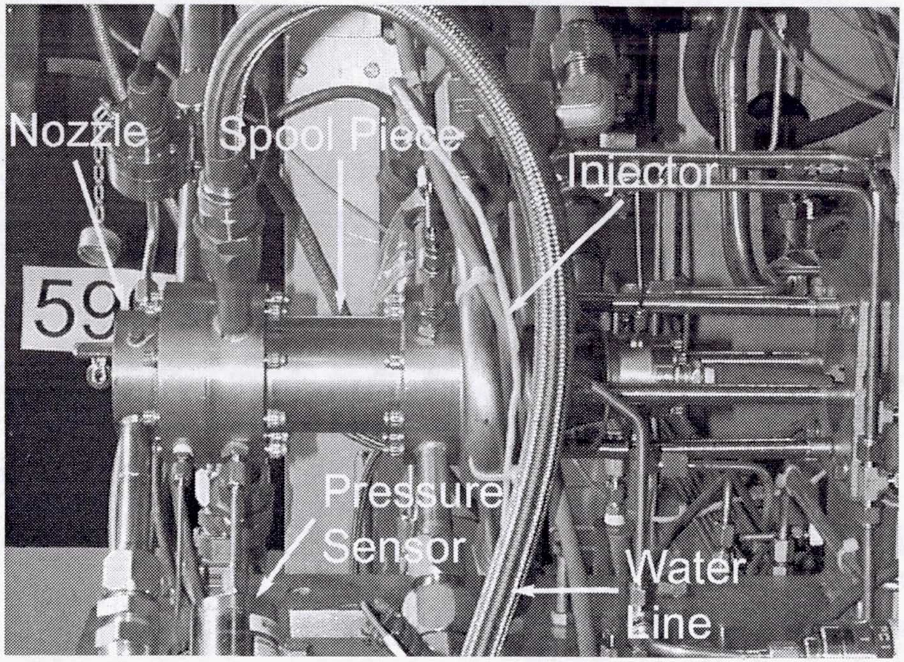
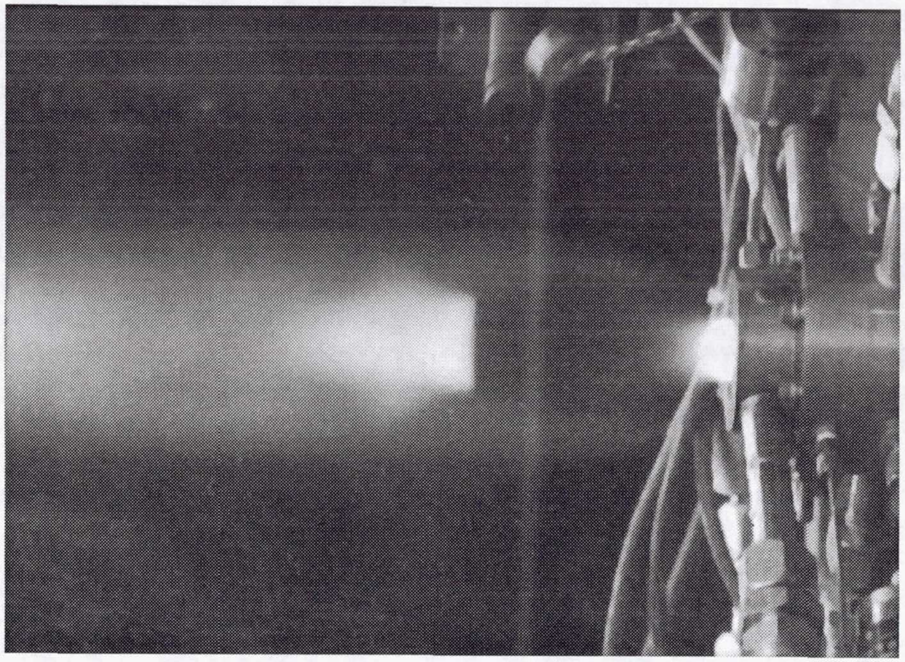
GRCop-84 Low Cycle Fatigue (LCF) Lives





- Spool pieces produced at MSFC using vacuum plasma spraying to produce 2” ID x 6” long liners with and without NiCrAlY coatings
- Twenty-seven hot fire tests totaling 482 seconds of hot fire testing conducted on uncoated and coated spool pieces
- No degradation of liner or coating observed
- Further testing of liners under RLV Focused program to be done at MSFC

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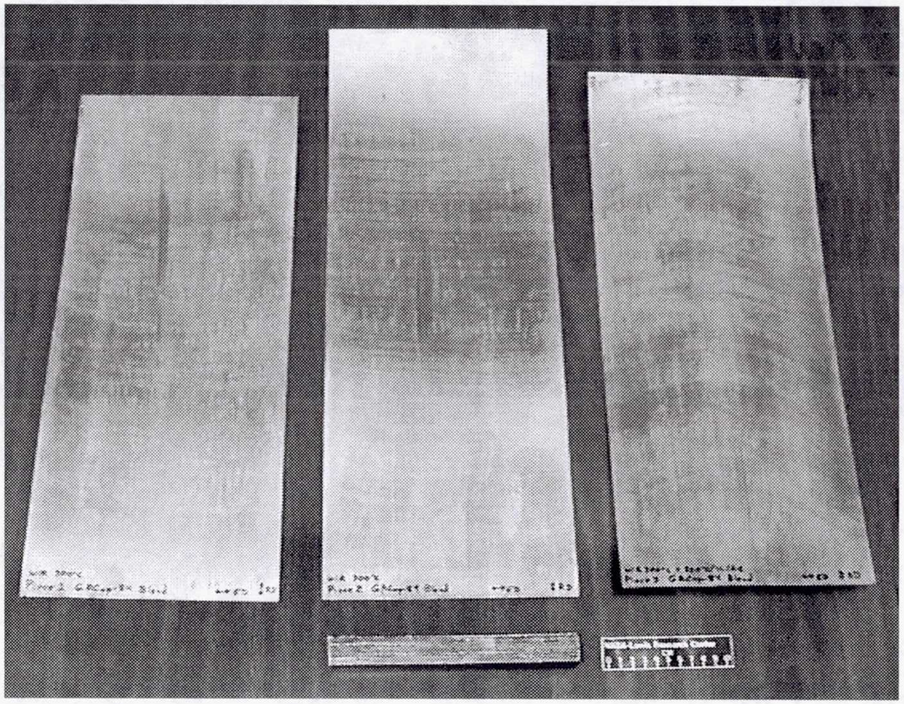
Hot Fire Testing of GRCop-84 Spool Pieces



Warm rolled GRCop-84 sheet
(~9" x 20")

Example of metal spun part

- **Metal spinning represents possible low cost, quick turnaround method of producing large thrust cell liners**
- **Plan to produce large (~3'x15') sheet under RLV 2nd Generation Program**

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Production of Large GRCop-84 Sheet Product

GRCop-84 Summary

- GRCop-84 offers many advantages over NARloy-Z and other copper-based alloys
    - Lower thermal expansion
    - Good conductivity
    - High yield strength up to 1300°F (700°C)
    - Increased creep lives/stresses
    - Superior LCF lives
- GRCop-84 spool piece testing demonstrated GRCop-84 as a liner material with and without a coating
- Alternative fabrication techniques can reduce costs and manufacturing times
- Coatings can be used to stop environmental attack and increase liner life and engine performance
- Copper-based MMC composites have the potential for higher strength and conductivity

GRCop-84

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Coatings

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Space Transportation Technology Workshop - Propulsion:

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2nd Generation Reusable Launch Vehicle
NASA Led Propulsion Tasks

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Space Transportation Technology Workshop

Agenda

- 2nd Generation RLV Propulsion Project
- Overview of NASA Led Tasks in Propulsion
- Gen2 Turbo Machinery Technology Demonstrator
- Combustion Devices Test Bed
- GRCop-84 Sheet For Combustion Chambers, Nozzles And Large Actively Cooled Structures

- The Propulsion Project has been formulated to reduce risk in support of a Full Scale Development decision as early as 2005
- Propulsion Project includes the following elements for Earth-to-Orbit Launch Vehicles
  - Main Engine
  - Main Propulsion System
  - Auxiliary Propulsion Systems
- Cryogenic Upper Stage Propulsion is included in the Propulsion Project

- **The 2nd Generation RLV Program Has Provided for NASA-Led Tasks within the Projects**
- **'Gated' Selection Approach**
  - **Gate 1**
    - Does task address the Program Goals
      - Contribute to the safety and cost goals
  - **Gate 2**
    - Is task appropriate for NASA to lead
      - Gov't can do it better and cheaper than anyone else
      - If the Gov't doesn't do it, it won't get done
      - Cross-cutting ... supports multiple architectures
  - **Gate 3**
    - Does it need immediate start
      - Loss of a unique and necessary capability if not funded.
      - Schedule supports TRL6 by 05 ... OR
      - Task is needed to support the 2 year Program focusing
- **Only Tasks That Passed All Three Gates Were Selected**
- **The Propulsion Project Has Selected Eight Tasks for Execution in FY01.**

Final Selection Process

This Session Will Provide Information on Each of the NASA-Led Tasks Selected by the Propulsion Project

Summarized by Introduction

- Large Composite Valve Technology
- Actively Cooled Ceramic Matrix Composite Nozzle RampLOX/H2
- Smart Leak Sensor
- Test of Large Scale Liquid Hydrogen Propellant Densification Hardware
- Full Flow Staged Combustion Injectors

Presentations Following Introduction

- GRCop-84 Sheet For Combustion Chambers, Nozzles And Large Actively Cooled Structures
- Combustion Devices Test Bed
- Gen2 Turbo Machinery Technology Demonstrator

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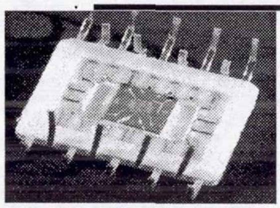
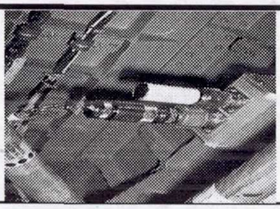
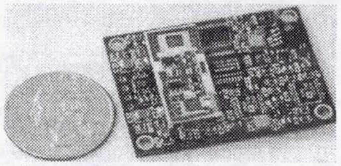
Funded Task List for Propulsion



Microfabricated Hydrogen Sensor



Hydrogen Sensors on Space Shuttle



Prototype Hydrogen/Oxygen Sensor System with Electronics

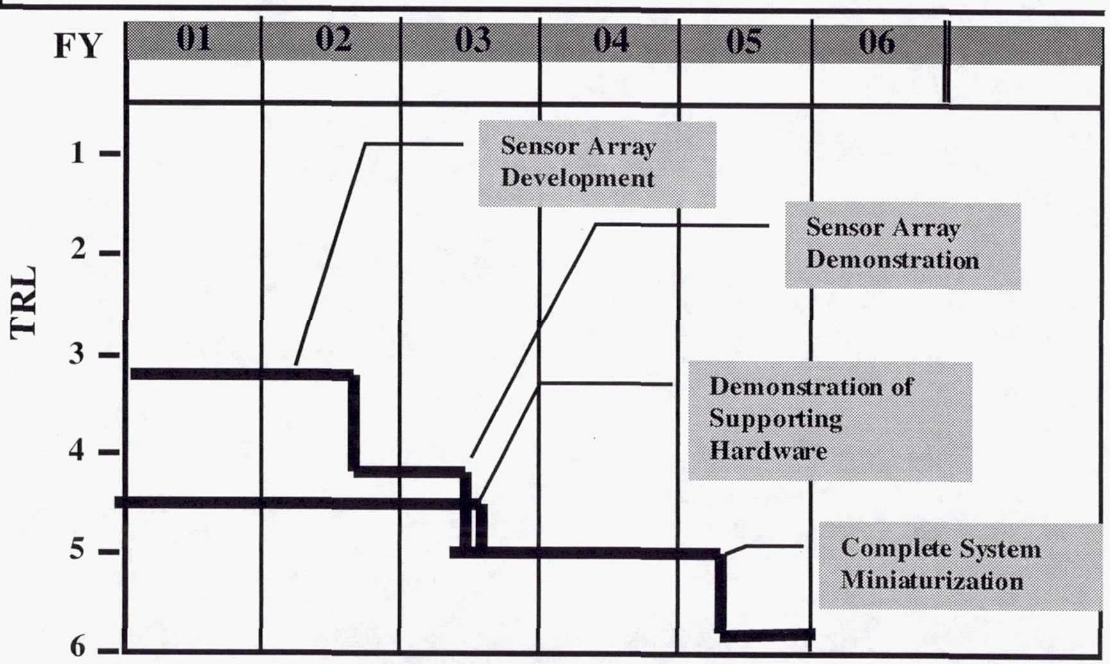
Demonstrate Stand-alone Smart Leak Detection System With a Surface Area the Size of Postage Stamp

Products / Benefits

- Products
  - Stand-alone Leak Detection System With a Surface Area the Size of Postage Stamp
  - Detection of Both Fuel and Oxygen at the Same Time
  - Integrated Signal Conditioning, Data Storage, Power, and Telemetry
- Benefits
  - Fundamental Need for Gen II vehicle for Increased vehicle safety, Increased reliability and maintainability, Reduced testing time and costs,
- Customers
  - Any 2nd Gen Vehicle
- Unique / Enabling and Enhancing

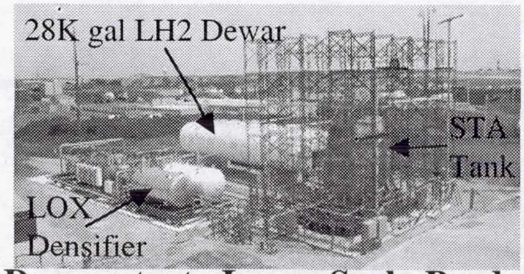
Implementation / Metrics

- Current State of the Art
  - Hydrogen sensor Shuttle-tested
  - Oxygen/Hydrocarbon sensors under development
  - Prototype hydrogen/oxygen sensor system fabricated with limited miniaturization of electronics
- Performance Metrics
  - 20x decrease in individual sensor system size over present Shuttle tested technology/10x increase of *sensor coverage*
  - Reduction in Maintenance Time and Costs by an order of magnitude
- Risks
  - Technology readiness of hydrocarbon sensor
- USG Participants
  - GRC (Lead Center), KSC, Makel Engineering, Case Western Reserve University



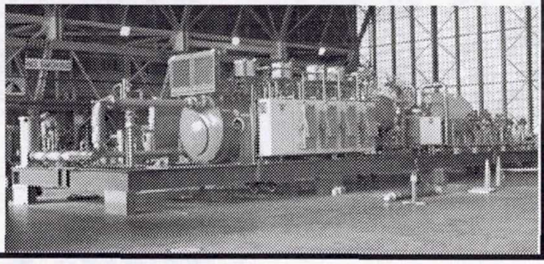
Miniaturized Smart Leak Sensor System

Test of Large Scale LH2 Densification Hardware



GRC South 40 Propellant Densification Test Site Configured for LOX Densification

Demonstrate Large Scale Production and Tanking of 27°R LH2



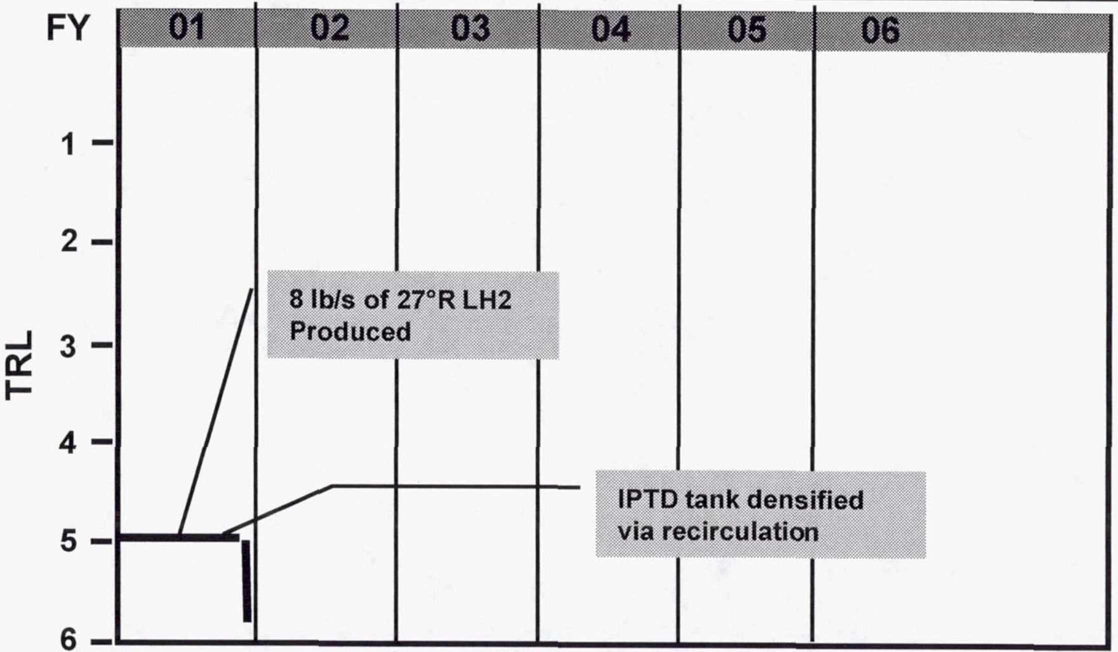
8 lbm/sec LH2 Densification Unit in storage at GRC Hangar

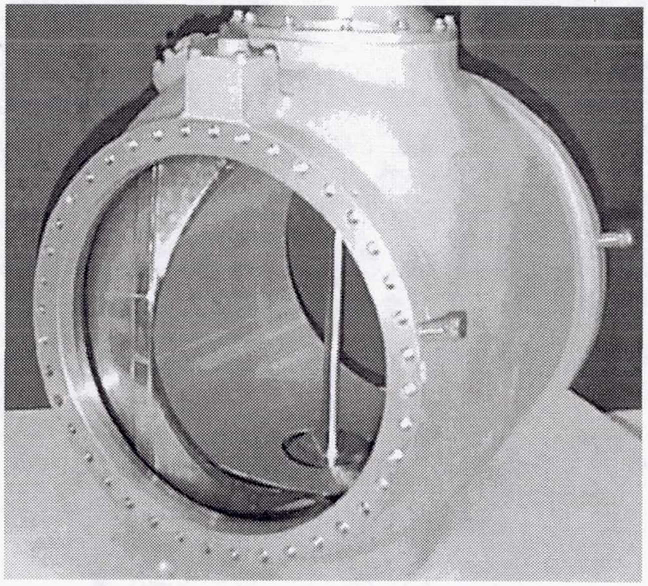
Products / Benefits

- Products
  - Validation of LH2 densification process at large scale (TRL=6)
  - Operable (portable) densification skid available for flight experiment or engine test program
- Benefits
  - Densification can reduce vehicle weight significantly (RLV studies showed ~18% weight reduction)
- Customers
  - Multiple STAS vehicles utilize densified LH2

Implementation / Metrics

- Current State of the Art
  - TRL 5, Small Breadboard Densification Unit tested in 1996=>30°R LH2; X-33 scale unit fabricated and in storage
- Performance Metrics
  - 8 lbs/sec LH2 densification rate from 37°R to 27°R
  - Demonstrate recirculation tank loading process (thermal stratification)
- Risks
  - SOA 4-stage compressor performance
- USG Participants
  - GRC lead



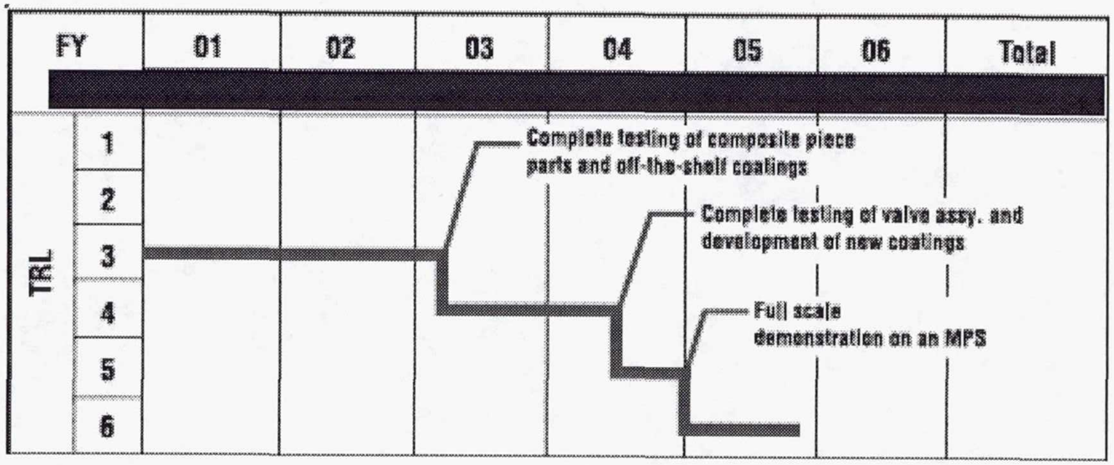


Products/Benefits

- **Products**
  - A large diameter LH2 valve made from PMC material.
  - A series of protective coatings that can be applied to composites and be used in a cryogenic environment. These coatings will increase the materials damage resistance.
- **Benefits**
  - The composite valve technology will enable weight reduction of large MPS components on a vehicle.
  - The coating technology will enable the program to operate at a higher confidence level since the risks of impact damage are greatly reduced.
- **Customers**
  - Second Generation Program, Shuttle, Aerospace Industry
- **Cross-Cutting Benefits**
  - Lightweight components are applicable to all present and future launch vehicles.

Implementation/Metrics

- **Current State of the Art**
  - Small PMC valve built for DC-XA vehicle
  - No large composite valves built
- **Performance Metrics**
  - Demonstrate a composite valve can be built and meet Shuttle requirements while at the same time reduce weight
- **Risks**
  - Composite parts and assembly do not meet Shuttle requirements.
- **USG Participants**
  - MSFC (Lead center), JSC



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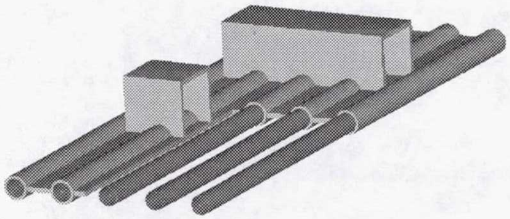
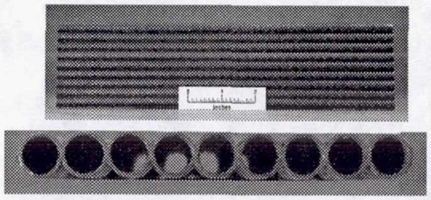
Large Composite Valve Technology

Actively Cooled Composite Nozzle

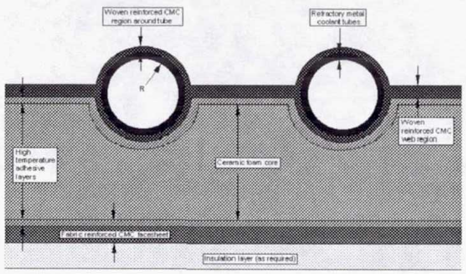
Refractory Composites Inc. Design



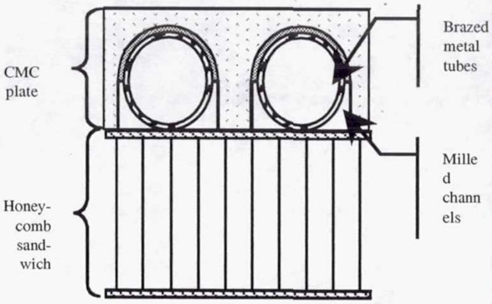
Rockwell Science Center



Honeywell Concept

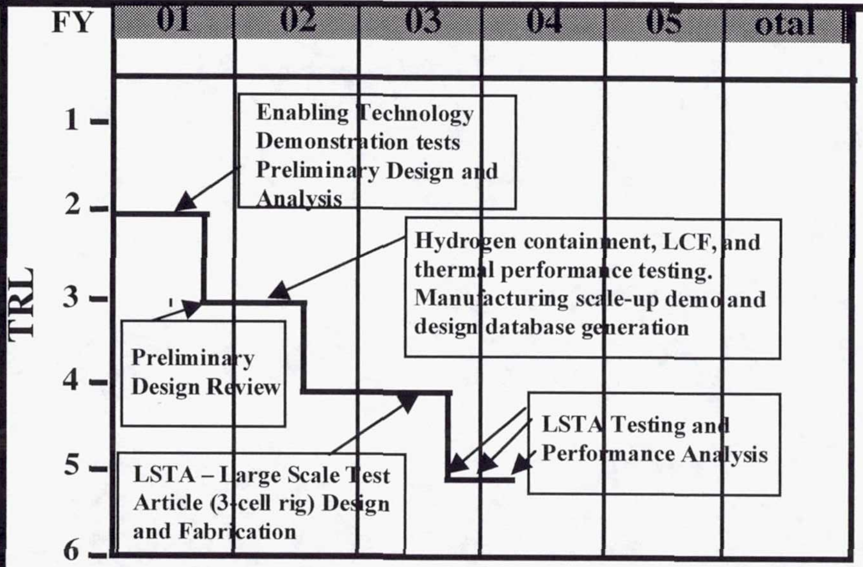


Snecma SEP Concept



- Products
  - Design level mechanical, physical, and thermal property database
  - Test validated thermal and thermostructural models
  - Demonstrated thermal performance and ability to contain high pressure hydrogen
  - Demonstrated manufacturing scale-up and manifolding
- Benefits
  - Potential performance, operability, and safety pay-offs for high temperature capability CMC materials are high
  - Strength-to-weight of advanced CMCs at high temperature may provide a significant weight reduction at far aft end of vehicle where benefit is needed
  - High use temperature of CMCs provides additional temperature margin for uncooled reentry
  - High temperature capability expected to increase safety margins and allow significant *simplification of aerospike engine features required for engine-out operation*
- Customers
  - Primary industry customer, Lockheed Martin, has identified a wide variety of vehicles that would benefit from this technology including SSTO, TSTO, Shuttle Derived, CRV, CTV, and LFBB concepts
  - 3rd Generation RLV and all Rocket Based Combined Cycle (RBCC) propulsion concepts
- This project is essential to maintain viable technology development schedule consistent with 2nd Generation RLV

- Current State-of-the-Art (SOTA)
  - No other concepts existing or in development capable of meeting nozzle ramp requirements
  - These NASA-Funded concepts represent the SOTA
- Performance Metrics
  - Areal weight requirement is 2.0 lb/ft^2 with a goal of 1.5 lb/ft^2 for the heat exchanger
- Risks
  - Aggressive development schedule
  - Manufacturing scale-up to flight design (industry task)
- USG participants
  - MSFC (lead Center), LaRC, GRC, AFRL/ML



Enabling Technology Demonstration tests Preliminary Design and Analysis

Hydrogen containment, LCF, and thermal performance testing. Manufacturing scale-up demo and design database generation

Preliminary Design Review

LSTA Testing and Performance Analysis

LSTA – Large Scale Test Article (3-cell rig) Design and Fabrication

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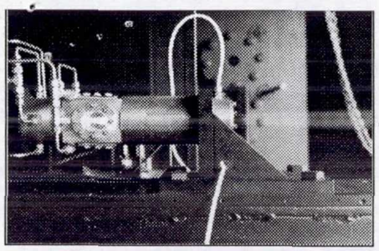

Single Element Testing

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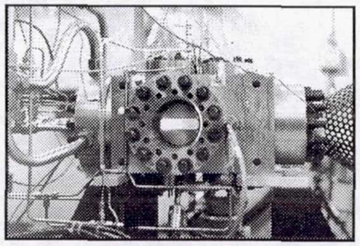

Multi-Element Testing

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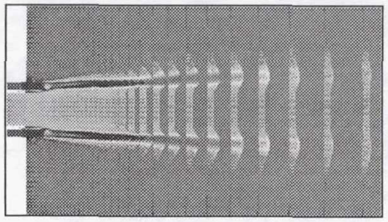

Validated Analysis Tools

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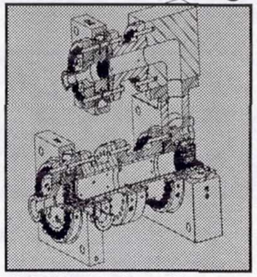


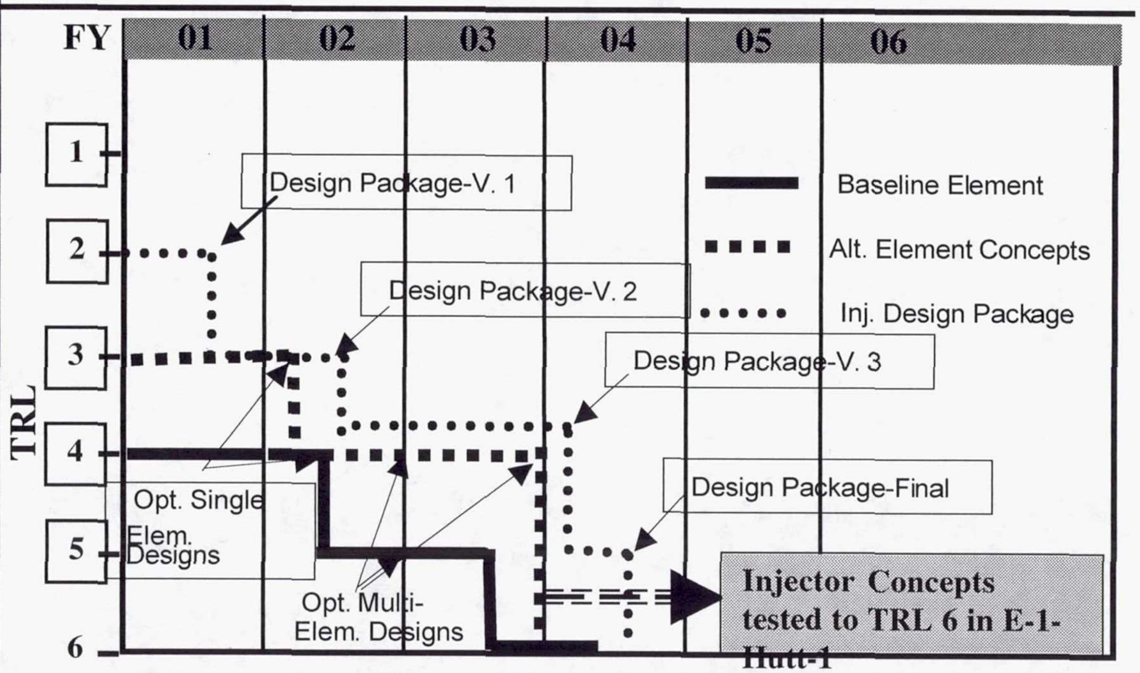
Robust 60K Injector Concepts

Products / Benefits

- Products
  - **Optimized MCC injector concept that fully meets Gen 2 operability, life and performance goals (timed to support concept downselect)**
  - **Optimized MCC injector concept(s) that exceed Gen2 requirements**
  - **Experience in design and operation of LOX-rich preburners**
  - **Seamless injector design package with tools validated to TRL 6-can be used to calculate environments for life predictions**
- Benefits
  - **High performing injectors with manageable heat fluxes**
  - **Lower part count that increases reliability and lowers costs**
- Customers
  - **Injector Element Concepts-2nd Generation RLV (FFSC cycle)**
  - **Injector Design Package- all projected 2nd Generation RLV cycles, 3rd Gen and SSME**

Implementation / Metrics

- Current State of the Art
  - **Limited data base and empirical design methodologies create high-risk designs**
- Performance Metric
  - **Increase reliability by reducing part count (10x) and lowering heat fluxes (30%)**
  - **Decrease injector development cost (2x), ops cost (2x) and weight (20%)**
- Risks
  - **Tight schedule to complete portions of task before cycle down-select**
- USG Participants: **MSFC (Lead)/GRC**



Full Flow Staged Combustion Cycle Injector

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- **Technology Goals and Objectives**
  - **Mitigate risk**
    - Identify problem areas early
    - Develop alternative designs
    - Demonstrate manufacturing feasibility at subscale level
    - Establish vehicle to evaluate component design fixes during FSD
  - **Increase Technology Readiness Level**
    - Demonstrate component designs at subscale level
      - time- and cost-effective
    - Validate design tools
    - Evaluate/demonstrate peripheral technologies
      - valves, sensors for health monitoring, etc.
  - **Improve combustion device designs**
    - Use and validate advanced analytical models for more precise prediction of design margins
    - Explore innovative designs
    - Prove scaling methodology
  - **Reduce full-scale development time**

60K Combustion Devices Testbed

- **Background**
  - **Engine drives vehicle system reliability**
  - **Combustion Devices are major contributor to engine reliability**
    - Preburner design and transient operation
    - Main combustion chamber and injector
    - Nozzle
  - **Space Transportation Architecture Study (STAS) indicated need for development of different engine cycles**
    - Full flow staged combustion (FFSC) cycle is initial testbed focus
      - prominent in STAS results
      - eliminates interpropellant seals and oxidizer heat exchanger
      - reduces turbine inlet temperatures
    - Testbed addresses major concerns with FFSC cycle
      - oxidizer-rich preburner
      - high propellant temperatures at main combustion chamber inlet
      - lack of practical experience with cycle
  - **Testbed provides timely information for program decisions**

Space Transportation Technology Workshop - 2nd Generation Propulsion

60K Combustion Devices Testbed

- Status
  - Task Plan generated and submitted

- Near Term Plans
  - Develop detailed program plan
  - Develop alternative designs and design optimization algorithm
  - Test initial configuration in ‘02
  - Test alternative configurations in ‘03

- Point of Contact
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60K Combustion Devices Testbed

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2^{nd} Generation Turbomachinery Technology Demonstrator

Space Transportation Technology Workshop or Section Title:

- **Background**
  - **Short schedule for Prototype Engine would not permit incorporation of new turbomachinery technology**
  - **Needed time to mature technology to TRL 4**
  - **Demonstrator Turbopump required to advance technology from TRL 4 to TRL 5/6 in time for insertion into FSD**
- **Approach (**All work in parallel with Prototype Engine**)**
  - **Define requirements**
  - **Perform concept definition**
  - **Down select most promising technology for demonstrator, TRL 4**
  - **Design turbopump demonstrator, fabricate hardware, and assemble TP**
  - **Perform hot fire testing, Turbomachinery Technology TRL 6**
- **Deliverables**
  - **Representative turbopump, which incorporates advanced turbomachinery technology, ready for hot fire tested**
  - **Hot fire test results of turbomachinery technology**
  - **Turbomachinery technology advanced to TRL 6, ready for FSD**

Gen 2 Turbomachinery Technology Demonstrator

MSFC Point of contact: James Cannon (256) 544-7072

- **State of the Art**
  - **IPD Turbopumps, LOX and LH2, with Hydrostatic bearings**
- **Need**
  - **A turbopump demonstrator is needed to advance the development of Gen 2 turbomachinery technology**
- **Relationship to 2nd Generation Goals**
  - **Technology for LOX and LH2 turbomachinery will address cost, reduced weight and improved reliability**
  - **A partial list of potential technologies**
    - Lighter weight housing materials
    - Enhanced inducer and impeller performance
    - Enhance rotordynamic stability seal
    - Enhanced turbine performance
  - **Turbomachinery technology is cross-cutting among the proposed engine concepts.**

Space Transportation Technology Workshop or Section Title:

Gen 2 Turbomachinery Technology Demonstrator

MSFC Point of contact: James Cannon (256) 544-7072

Gen 2 Turbomachinery Technology Demonstrator

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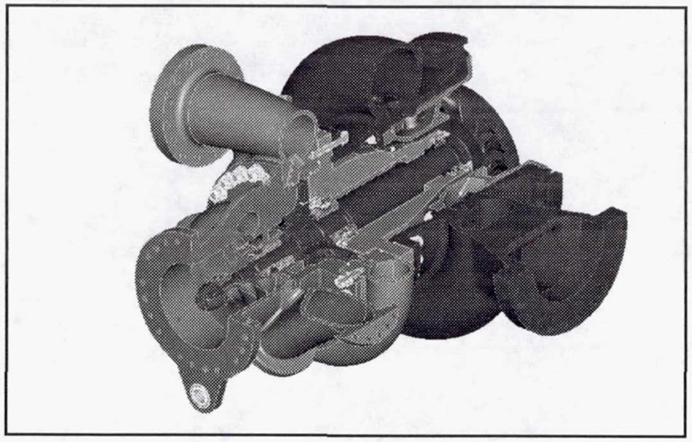
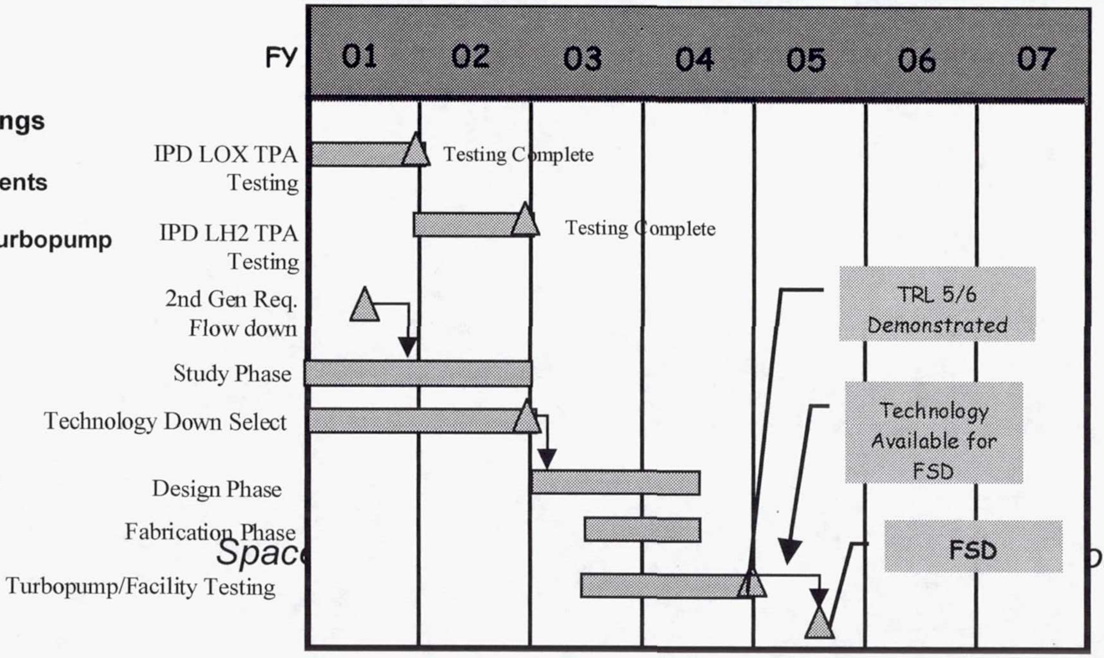


Products/Benefits

- Products
  - Incorporate Gen 2 turbomachinery technology into a turbopump demonstrator(s)
  - Advance turbomachinery technology to TRL5/6, available for FSD
- Benefits
  - Demonstrate turbomachinery technology which addresses improved pump performance, turbine performance, seals, materials, and bearings which address engine T/W, decreased costs and improved reliability.
- Customers
  - Industry Partners, DOD, and NASA
  - Technology is cross-cutting among the proposed engine concepts

Implementation/Metrics

- Current State of the Art
  - IPD Turbopumps with hydrostatic bearings
- Approach
  - Define the engine/turbomachinery requirements
  - Assess technology needs
  - Develop technology for incorporation into turbopump
  - Demonstrate technology in turbopump
- Performance Metrics
  - Reduce Turbomachinery weight
  - Improved Turbine Performance
  - Reliability Enhancement
- Risks
  - Testing IPD turbopump
  - Maturing necessary technology in time



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