HYPERSONIC ENGINE TECHNOLOGY

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Sealing Issues for Hypersonic Engines

In most applications, air-breathing propulsion systems must operate over a wide range of flight conditions. Variable geometry in the flowpath is generally required in order to achieve adequate performance levels. The variable geometry elements must be sealed to prevent performance loss due to leakage of high pressure air and combustion products. In hypersonic applications, the sensitivity of performance to leakage is high. Furthermore, any leakage of air in a hypersonic application can lead to a catastrophic structural failure due to the high temperatures involved.

Stagnation Conditions Along Air-Breathing Flight Corridor

Unlike rockets, air-breathing engines must operate within the atmosphere. This chart depicts the stagnation conditions along the air-breathing flight "corridor." Stagnation temperatures reach 7000 degrees Rankine at Mach 10 (about 10,000 ft/sec).

Temperatures in Hypersonic Air-Breathing Engines

Fortunately, seals do not have to withstand the freestream stagnation temperature. The maximum temperature in the inlet boundary layer is much less, only about 3000 degrees Rankine at Mach 10. This is largely due to wall cooling effects. Throughout the flowpath, maximum temperatures in the boundary layers will be in this range given the wall cooling required for current materials. This is a good measure of the secondary or leakage flow temperature against which the seals must act.

Three major programs...

The three major programs currently funded in the United States cover three distinct applications of hypersonic air-breathing propulsion. NASA's Advanced Reusable Transportation Technologies (ARTT) program is exploring the use of air-breathing propulsion for space access. This application generally requires a highly integrated propulsion system that accelerates from sea-level static conditions to orbital velocities. Low structural weight and high reliability are of paramount importance.

The primary objective of NASA's Hyper-X program is to demonstrate that a supersonic combustion ramjet or "scramjet" engine can power a flight vehicle at speeds up to Mach

10. The application for this type of propulsion system is mainly for a high speed cruise or "Global Access" vehicle. The thermal environment within this class of flowpath is more severe due to the extended period during which it cruises in the atmosphere. The design of this type of propulsion system is biased toward cruise efficiency. Cooling requirements dictate the use of liquid hydrogen fuel for at least the high speed portions of the flight.

The United States Air Force Hypersonic Technology or "HyTech" program is developing air-breathing engine technology for high-speed cruise missiles. The air-breathing propulsion systems for this application have the additional requirement of long shelf life, which dictates the use of storable fuels such as gelled or liquid hydrocarbons. They must also endure much higher g-loading, and since they are expendable, be inexpensive.

Advanced Reusable Transportation Technologies (ARTT)

The following 11 charts describe the ARTT program as of September 6, 1996. The ARTT program is one of many under an overall effort known as the Advanced Space Transportation Program (ASTP). Under ARTT, Contracts were issued to Aerojet, Kaiser-Marquardt, Pratt-Whitney, and Rocketdyne to develop technologies relevant to their particular concept for a rocket-based combined-cycle propulsion system that would power a launch vehicle into low earth orbit. Guidelines given to the contractors were that the vehicle be reusable, single-stage-to-orbit, and LOX-LH_2 fueled in order to maximize the impact of air-breathing propulsion on the reduction of launch costs.

Hyper-X Program

The following 7 charts describe NASA's Hyper-X program. The primary goal of the Hyper-X program is to flight-validate the performance of an airframe-integrated dual-mode scramjet flowpath at Mach numbers up to and including 10. Four flight vehicles will be built. Each will be ground-tested to the maximum Mach number attainable in ground-test facilities.

Hypersonic Technology Program (HyTech)

The following 9 charts provide an overview of the Air Force HyTech program. The objectives of this effort are to develop and demonstrate hydrocarbon-fueled scramjet engine technology with application to hypersonic cruise missiles.

Outline

Seals and Secondary Flow Issues

Hypersonic Environment

Current U.S. Programs

- Background and objectives
- Technical approach
- Schedule and status
- Budget
- Point of contact

Questions

Sealing Issues for Hypersonic Engines

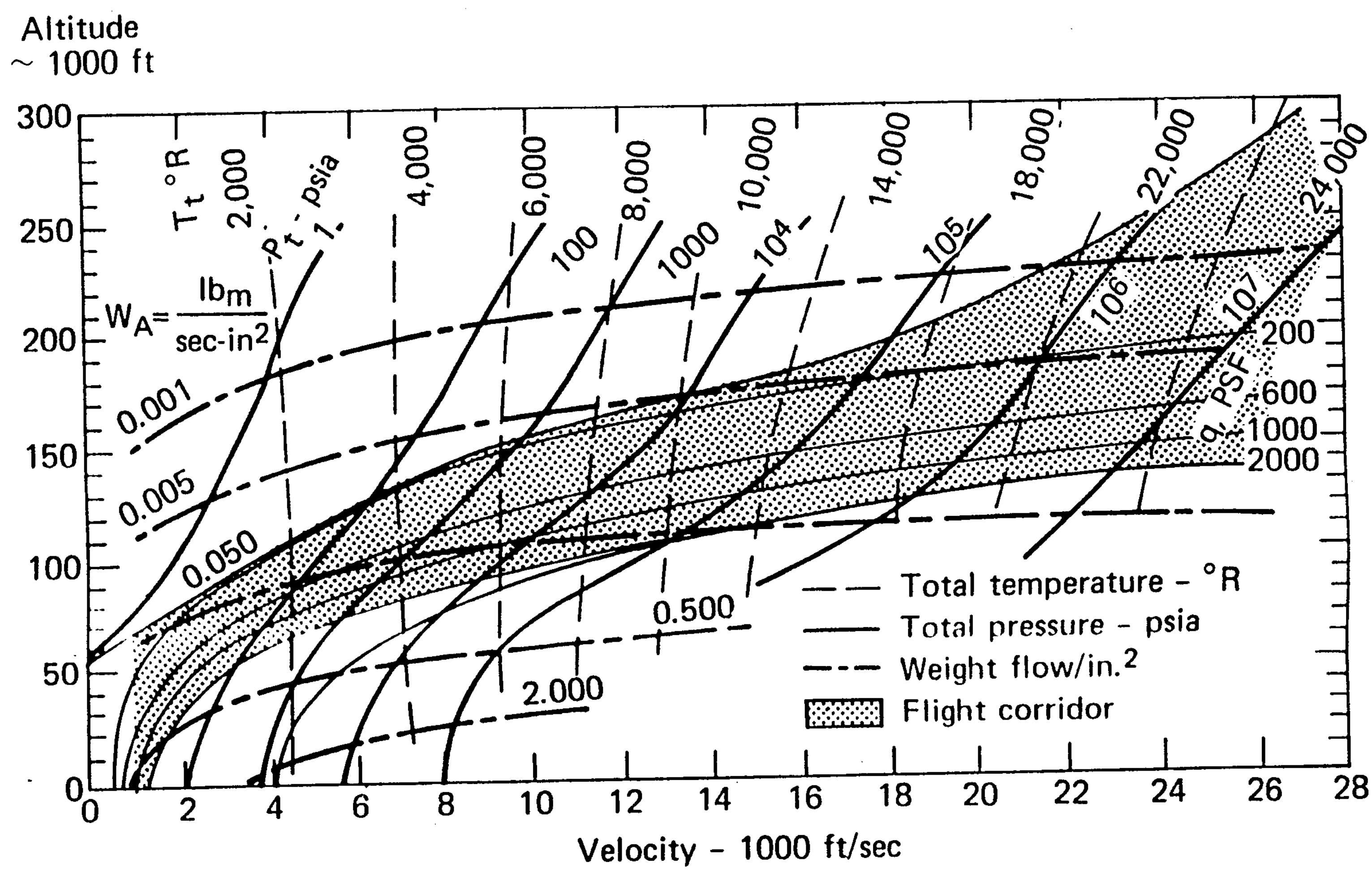
Variable inlet and nozzle geometry is generally required for acceptable performance over a wide Mach no. range

Secondary flows (leaks) of hot gas reduce performance, and can lead to catastrophic failures.

Flowpath sealing is therefore a major issue in the development of hypersonic air-breathing engines.

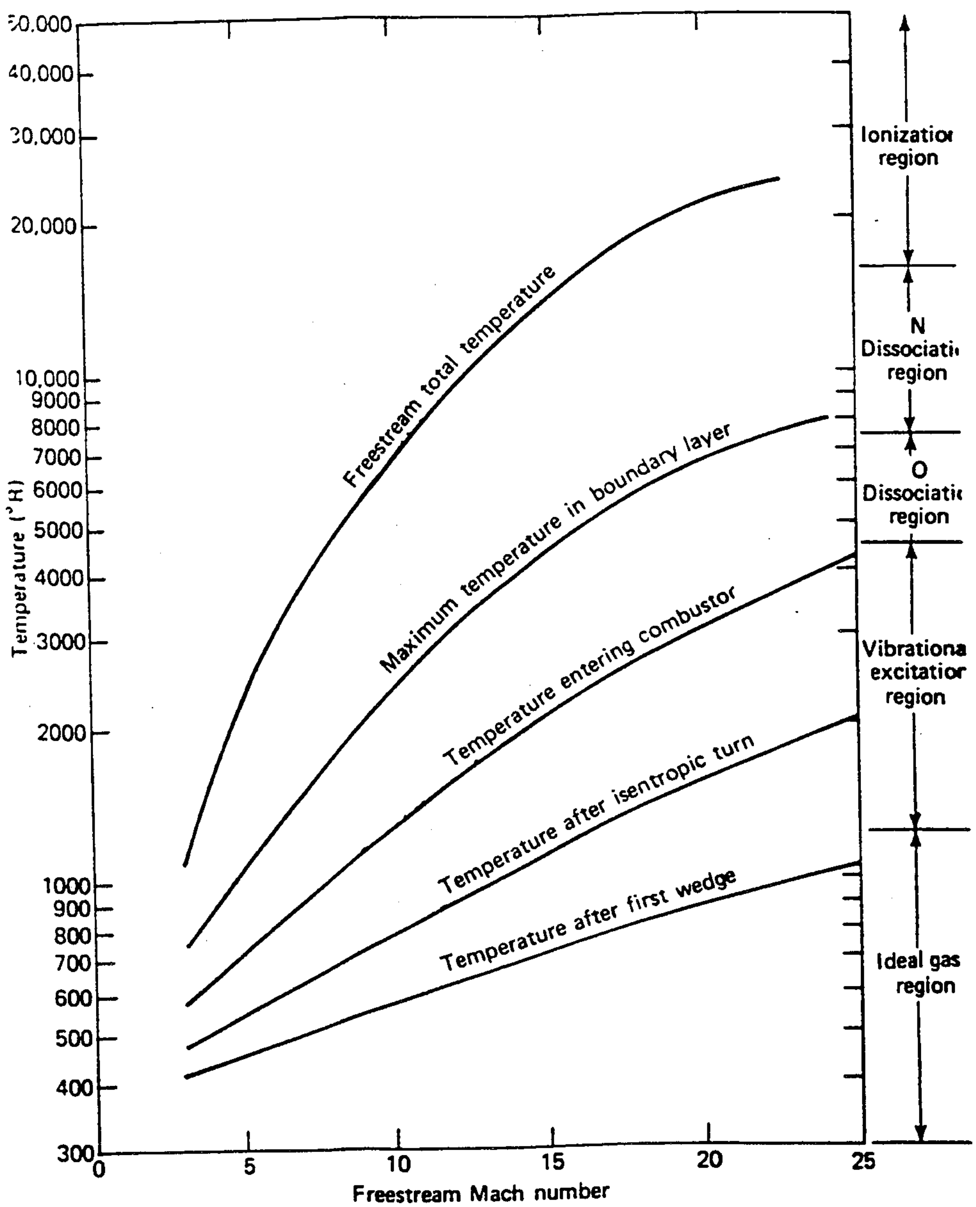
Demand on cryogenic turbopumps in air-breathing hypersonic engines is as severe as in rockets.

Stagnation Conditions Along Air-Breathing Flight Corridor



Lewis Research Center

Temperatures in Hypersonic Air-Breathing Engines



Three major programs involving hypersonic air-breathing propulsion are currently active in the U.S.

- NASA Advanced Reusable Transportation Technologies (ARTT) program
  Space access

- NASA Hypersonic X-Program
  Military/Civilian global access

- USAF Hypersonic Technology (HyTech) Program
  Military weapons systems

Advanced Reusable Transportation Technologies (ARTT)

Project Status

September 6, 1996

Advanced Space Transportation Technology Program

The Need

Space Transportation is like the point of an inverted pyramid,
it enables everything else

Launch cost limits NASA's ability to conduct Earth and space science and limits commercial launch services from competing effectively with foreign launch services

Transportation costs account for about 25 percent of NASA's FY1997 budget

Earth and space science spacecraft are becoming smaller and cheaper, driving the need for lower launch cost

AST

Strategy Implementation

Strategy	Technologies	Focused Projects	Transportation Applications
Enable Small Payload Transportation	• Advanced Low-Cost Manufacturing • Simple Robust Design • Streamlined Processes • Recovery Options	Low-Cost Boost Stages	• Small Launchers • Upper Stages • Heavy Lift Boost
Extend U.S. Lead in High-Performance Reusable Transportation	• Composite Structures • Advanced TPS • Simple Avionics • Improved Rocket Propulsion	RLV	• Medium Class Payloads • Shuttle Improvement • Medium Commercial Launchers
Revitalize U.S. ETO Transportation	• Combined Airbreathing Rocket Propulsion • Advanced, High-Risk Launch	Advanced Reusable Propulsion	
Enable Low-Cost, High-Efficiency Cargo Orbit Transfer Enable Low-Cost Exploration	• Advanced Control Systems • Low-Mass Structures • High-Temperature Materials • Propellant Technology • In Situ Propellant Research • Propulsion Augmentation Research • Nonchemical Propulsion Research • Advanced Propulsion Physics	Space Transfer Research and Technology	• On-Board Propulsion and Power • Orbit Transfer Upper Stages

Transportation Plan —1229b

Contract Focus

- **Aerojet**
  - Rocket/RAM/SCRAM Configuration (Strut-Jet Injectors)
  - Mach 0-8 Testing
  - Combustor Panel Testing
  - Proof of Concept Flight using SR-71

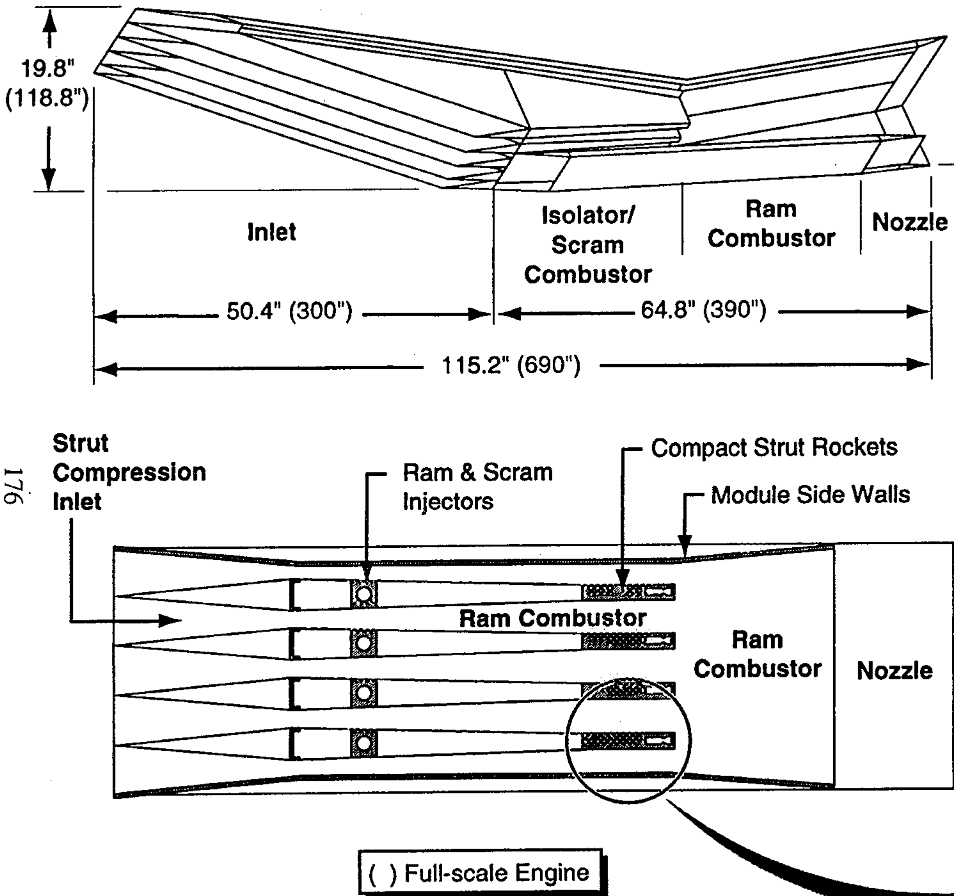
- **Kaiser-Marquardt**
  - Turbine Based Rocket/RAM Configuration (Annular Injectors)
  - Mach 0-8 Testing
  - Proof of Concept Flight using SR-71

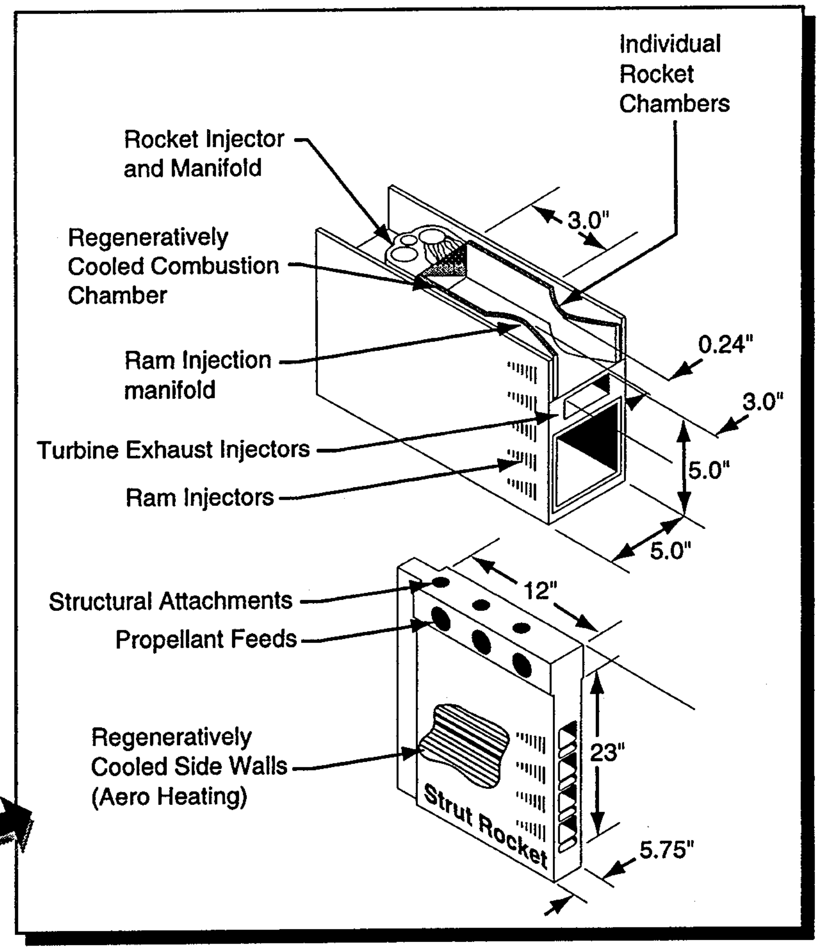
- **Pratt & Whitney**
  - Rocket/RAM/SCRAM Configuration (Fin Injectors)
  - Mach 0-3 Testing
  - Proof of Concept Flight using Hyper-X Plane

- **Rocketdyne**
  - Rocket/RAM/SCRAM Configuration (Ramp Injectors)
  - Mach 0-8 Testing
  - Proof of Concept Flight using New Axisymmetric Vehicle

- **Pennsylvania State University**
  - Primary/Secondary Flow Analysis/Testing
  - O/F Ratio Variations Analysis/Testing
  - Thermal Chocking Analysis/Testing
  - CFD Code Validation

Aerojet RBCC Engine Concept

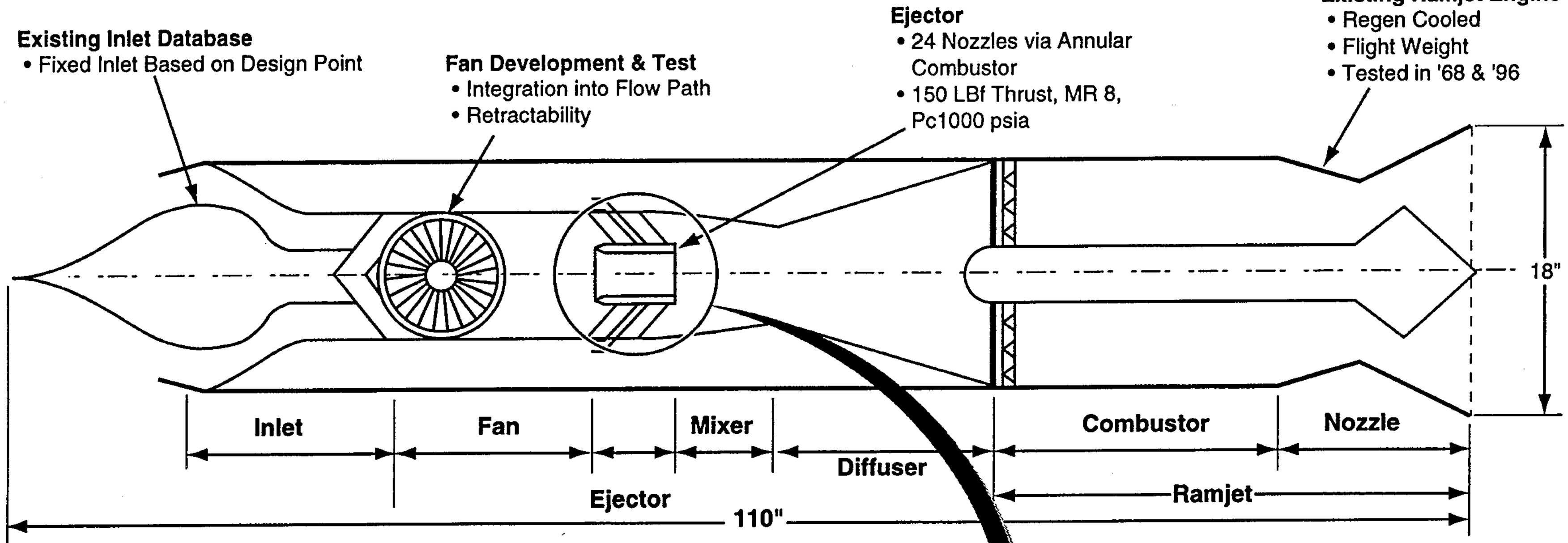




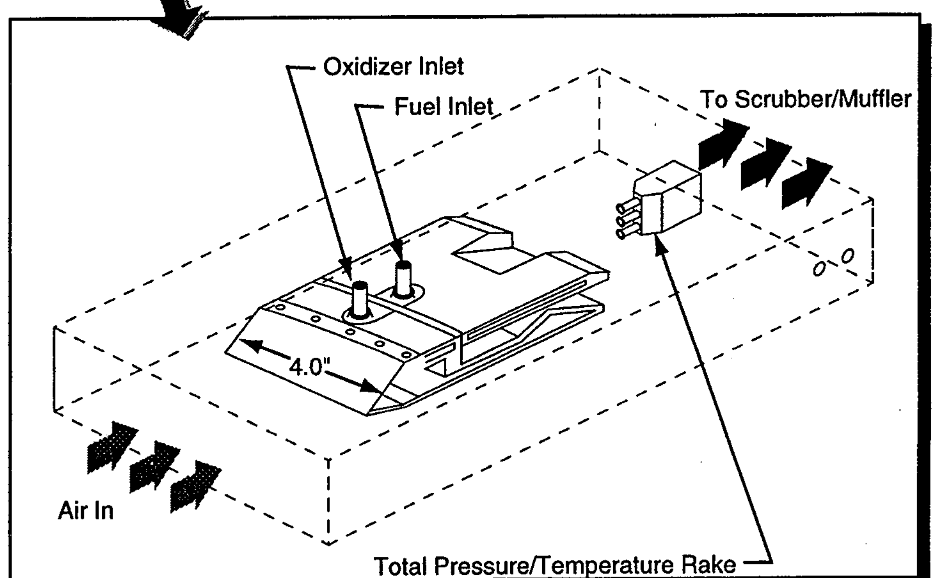
- **Engine Flow Path Preliminary Design**
  - 1/6 Scale Dimensionally Scaled Test Article – ~1 Klb Thrust/Engine
  - Full-scale Vehicle Design – 315 Klb Thrust/Engine

Advanced Reusable Transportation Technologies Project

Kaiser-Marquardt RBCC Engine Concept

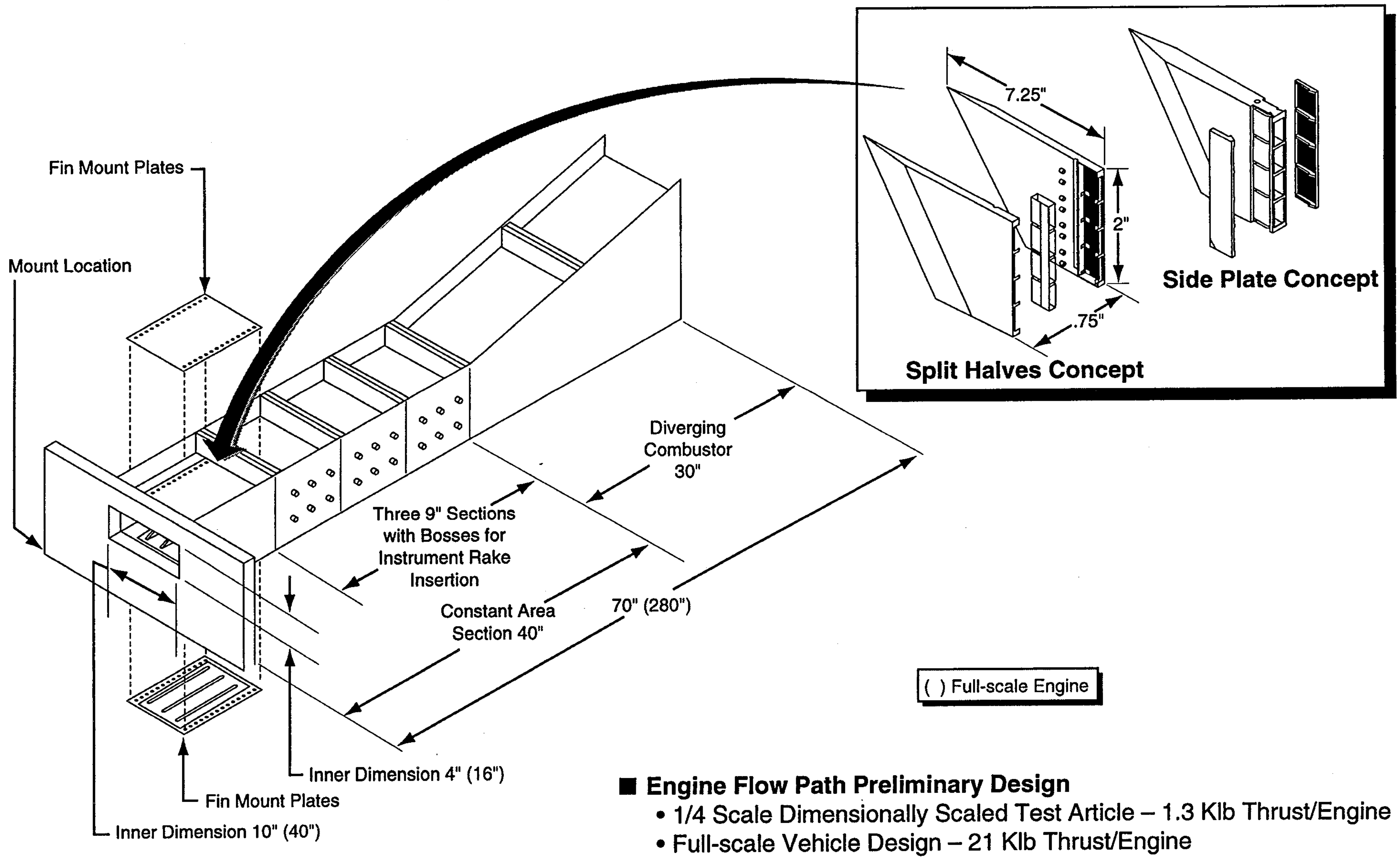


- **Engine Flow Path Preliminary Design**
  - 1/4 Scale Test Article – 4 Klb Thrust/Engine (SLS)
  - Full Scale Vehicle Design – 125 Klb Thrust/Engine (SLS)



ASTP—2357

Pratt & Whitney Engine Configuration Ground Test Rig

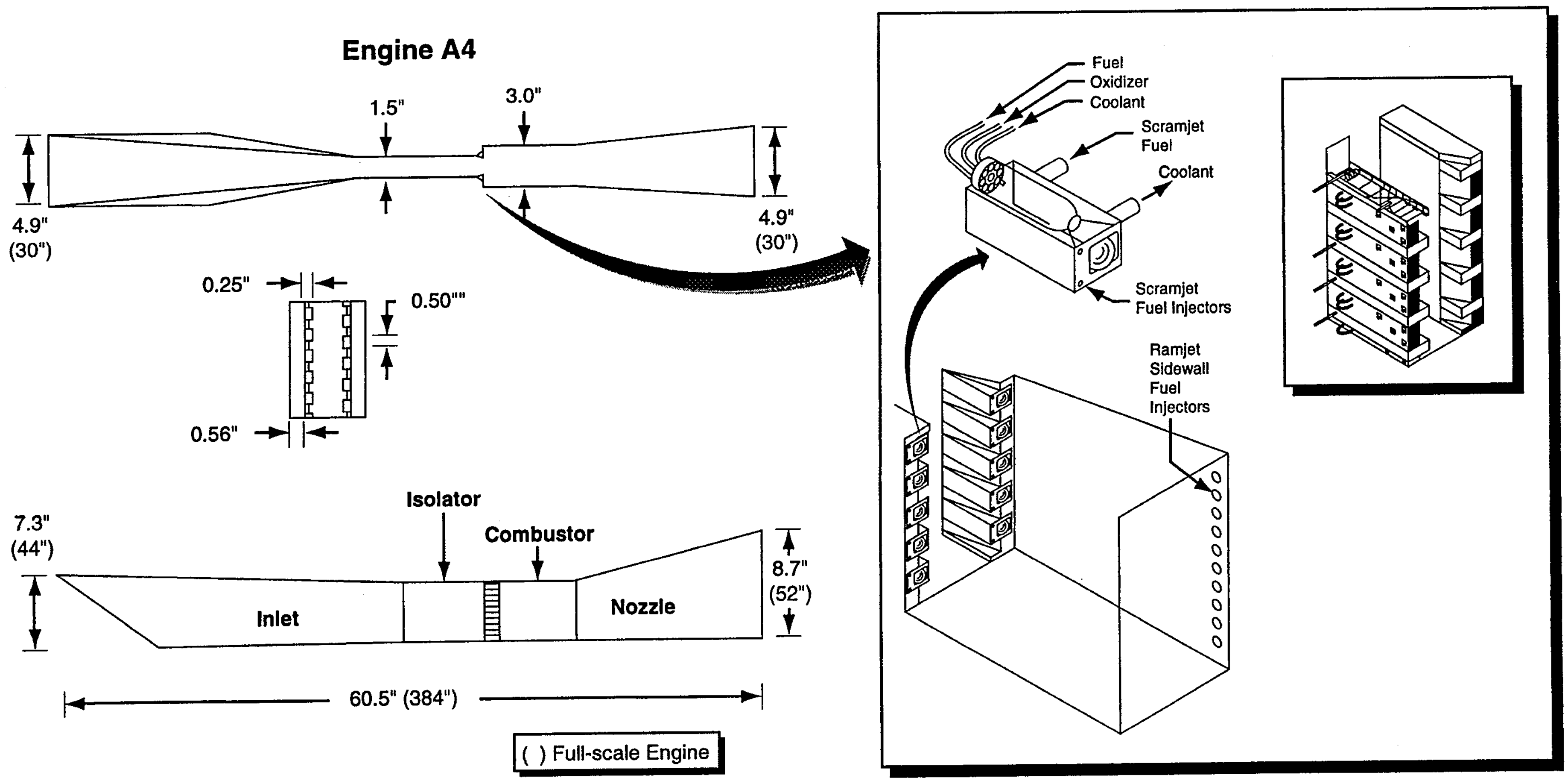


( ) Full-scale Engine

- **Engine Flow Path Preliminary Design**
  - 1/4 Scale Dimensionally Scaled Test Article – 1.3 Klb Thrust/Engine
  - Full-scale Vehicle Design – 21 Klb Thrust/Engine

ASTP—2359

Rocketdyne RBCC Engine Concept

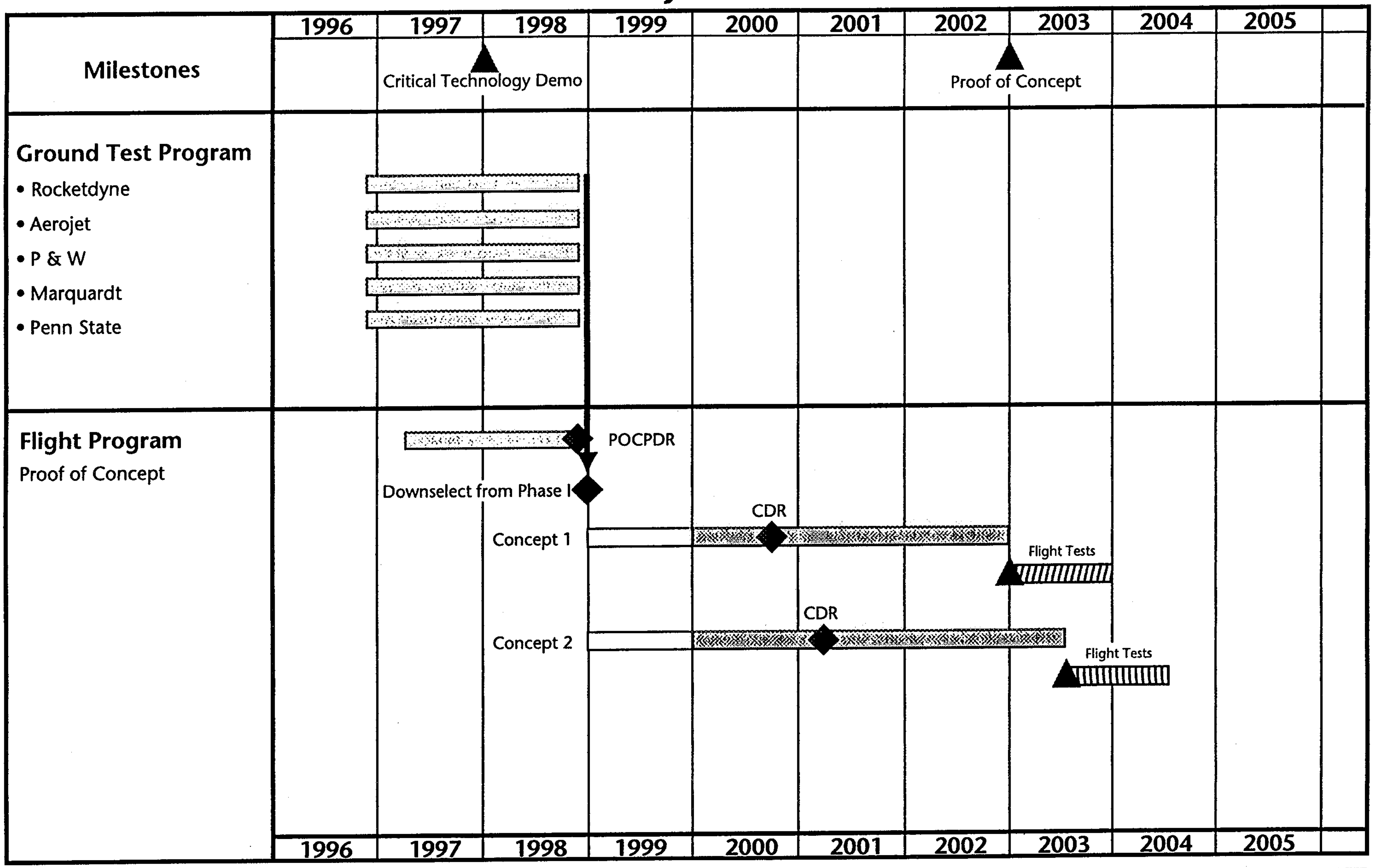


- **Engine Flow Path Preliminary Design**
  - 1/6 Scale Dimensionally Scaled Test Article – 1.1 Klb Thrust/Engine
  - Full-scale Vehicle Design – 55 Klb Thrust/Engine

ASTP—2361

Advanced Space Transportation Program

ARTT Project Schedule



ASTP—2462

NASA Advanced Reusable Transportation Technologies (ARTT) program

BUDGET ($M)

FY96	FY97	FY98	FY99	FY00	FY01	FY02	TOT
5.5	24.3	2.0	1.7	24.7	27.4	53.0	138.6

<u>Contracts ($M total):</u>

Aerojet	5.3
Kaiser Marquardt	5.5
Penn State	0.6
Pratt-Whitney	2.8
Rocketdyne	8.4

NASA Advanced Reusable Transportation Technologies (ARTT) program

Point of Contact:

Mr. Uwe Hueter
NASA Marshall Space Flight Center
(205) 544-5033

Background

- NASA Aeronautics “Blue Team” identifies approximately 12 candidate “X-programs” -- Dec 95
  - Two survive review process --> hypersonic X-program and general aviation propulsion
- Dual-Fuel Airbreathing Hypersonic Vehicle Design Study

  Phase I: Global Reach Aircraft Concept Definition
  Aug 95 -- Mar 96

  Phase III: Hyper-X Research Vehicle and Vehicle-to-Booster Adapter Candidate Design
  Mar 96 -- 3 Oct 96
- Hyper-X program go-ahead -- Jul 96

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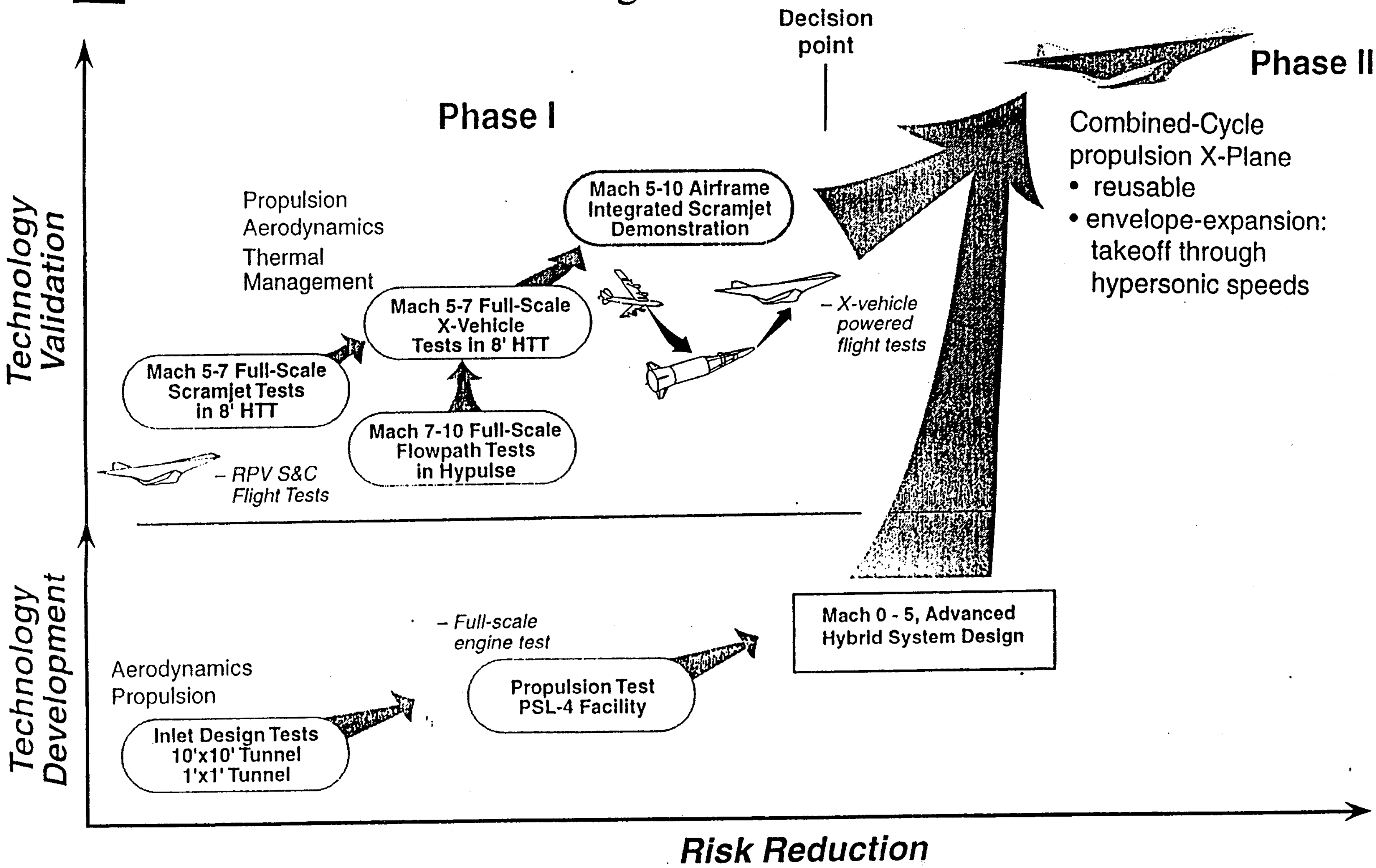
Program Concept

Ground-Flight Data Correlation for Integrated Systems Design Validation



Hyper-X Phase 1

- Goal: *for the first time ever,* validate airframe-integrated, dual-mode scramjet performance in flight
- Approach: Build, ground test, fly four scramjet research vehicles (FY 97 - 01)
  - Rocket boost each autonomous research vehicle to one of four test conditions:
    - Mach 5: transition from ramjet
    - Mach 7: scramjet mode
    - Mach 10: scramjet cruise; accelerating flight
  - Fly the first research vehicle in 1998; fly one per year thereafter
  - Take 5+ seconds of unique data per flight
    - limited test time allows use of existing materials, simple structures
  - Use existing design methods, facilities and boosters
  - Integrate NASA processes with industry "rapid prototyping"
  - Correlate results from flight and ground tests (including test of research vehicle as "model") and validate/update design/analysis methods

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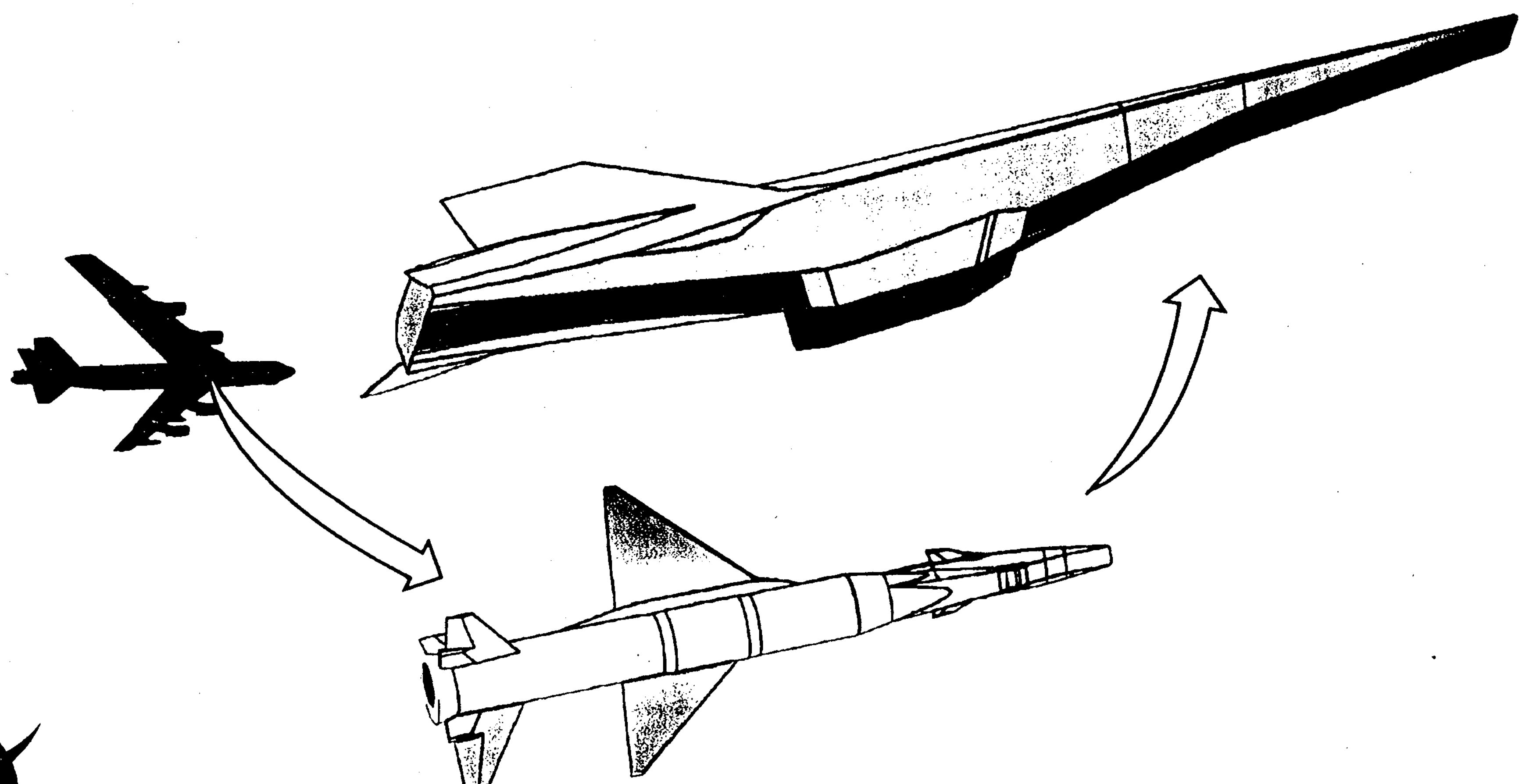
HYPER-X FLIGHT EXPERIMENT

- Demonstrates Hydrogen Scramjet Performance and Operability
- Demonstates Powered Stability and Control Characteristics



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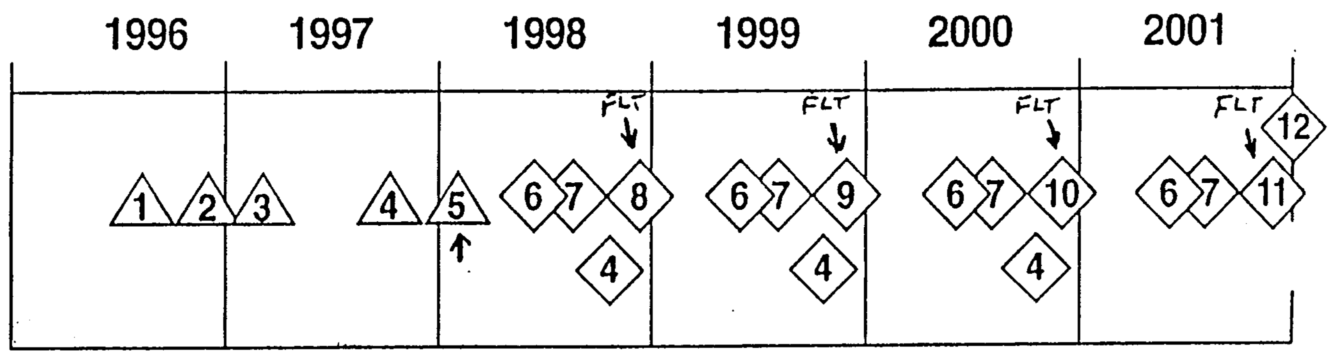
Level I Schedule



1 Quick-look data acquired
2 X-vehicle design "completed"; RFP issued
3 X-vehicle fabrication contract awarded
4 X-vehicle fabricated
5 X-vehicle test in 8-ft. HTT
6 Methodology & tools updated from wind tunnel and/or flight data
7. Mach 10 airplane design sensitivity analysis
8 Mach 7 X-vehicle flight test
9 Mach 5 X-vehicle flight test
10 Mach 10 X-vehicle flight test—cruise
11 Mach 10 X-vehicle flight test—acceleration
12 Improved and validated methodology & tools documented

△ Milestones ◇ Deliverables

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NASA Hyper-X Scramjet Flight Experiment

BUDGET ($M)

FY96	FY97	FY98	FY99	FY00	FY01	FY02	TOT
-	27.6	30.5	42.0	42.2	26.0	-	168.3

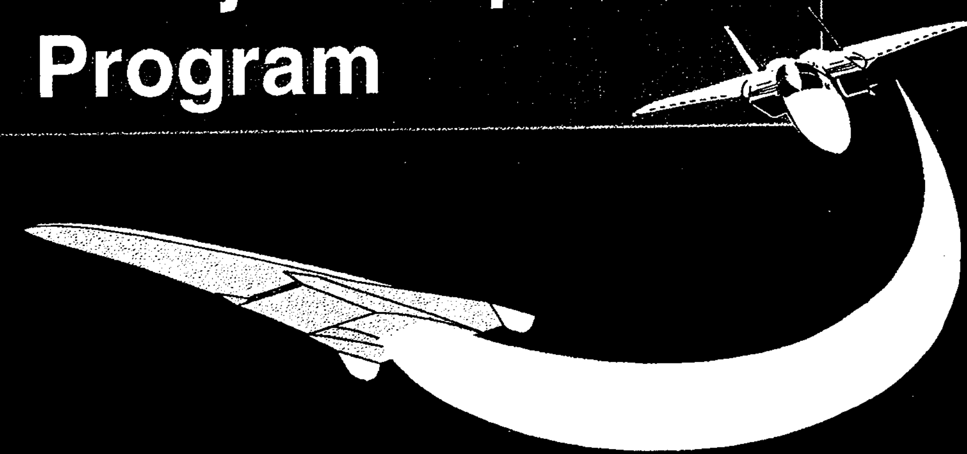
NASA Hyper-X Scramjet Flight Experiment

Point of Contact: Mr. Vince Rausch
NASA Langley Research Center
(757) 864-9127

Hypersonic Technology Program (HyTech) Overview

Wright Laboratory
Wright-Patterson AFB, OH

HyTech Scramjet Propulsion Program



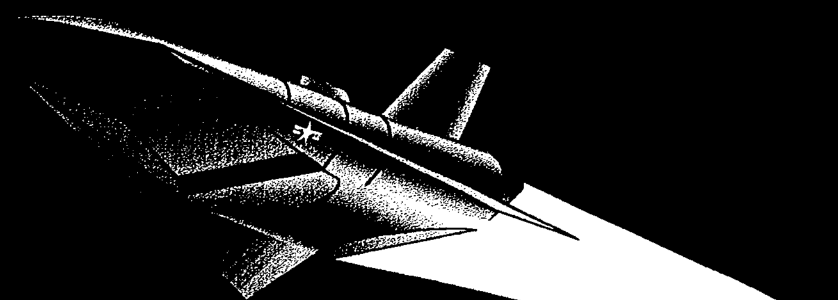
Primary Goal

- Develop/Demonstrate Mach 4-8 Hydrocarbon-Fueled Engine Capability
  - Operability
  - Performance
  - Durability

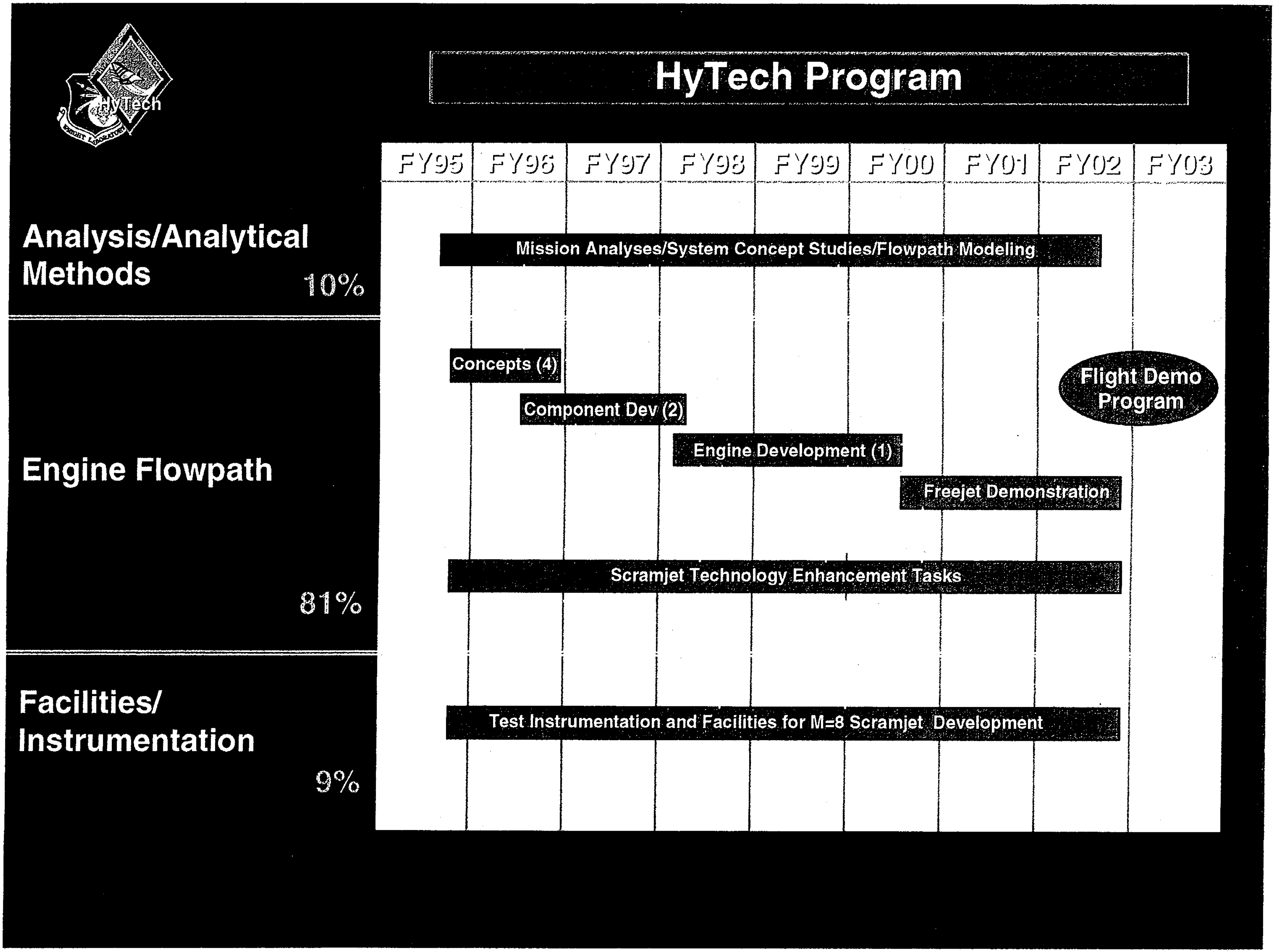
Payoff

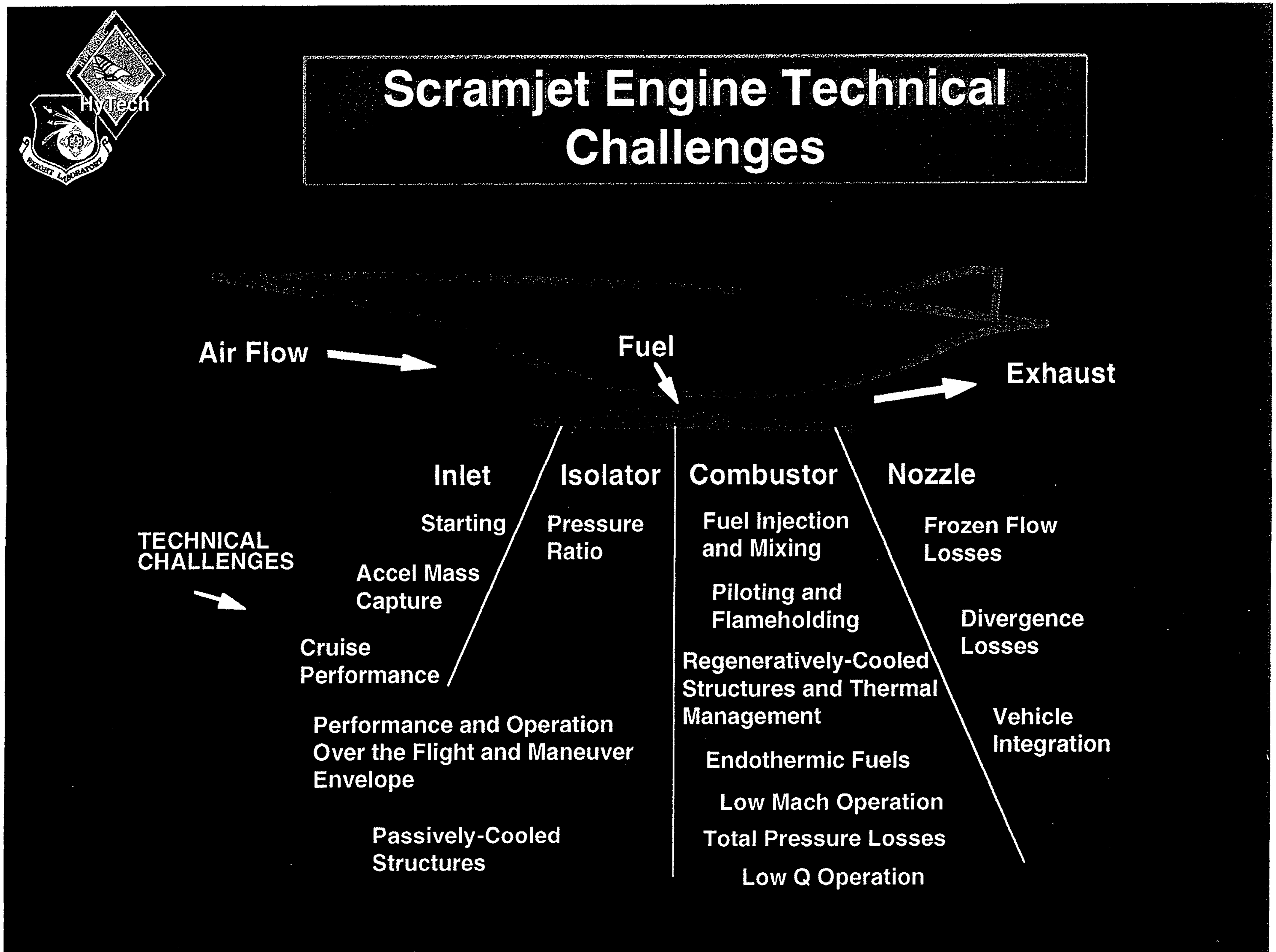
- Potential Near-Term Application to Hypersonic Cruise Missile
  - Survivable Without Stealth
  - Kills Time-Critical Targets
  - Force Multiplication/Flexibility
  - Logistically Supportable in Combat
- Key Stepping-Stone to Family of Hypersonic Vehicles

Notional Hypersonic Weapon



- Speed: Mach 8
- Range: 750 NM
- Altitude: 100,000 ft +
- Guidance: INS + GPS
- Propulsion: Hydrocarbon Scramjet + Solid Rocket Booster
- Warhead:
  - Penetrator
  - General Purpose KE
  - Smart Submunitions


HyTech
HyTech Program
Analysis/Analytical Methods
10%
Engine Flowpath
81%
Facilities/ Instrumentation
9%
FY95
FY96
FY97
FY98
FY99
FY00
FY01
FY02
FY03
Mission Analyses/System Concept Studies/Flowpath Modeling
Concepts (4)
Component Dev (2)
Engine Development (1)
Freejet Demonstration
Flight Demo Program
Scramjet Technology Enhancement Tasks
Test Instrumentation and Facilities for M=8 Scramjet Development


HyTech
Scramjet Engine Technical Challenges
Air Flow
Fuel
Exhaust
TECHNICAL CHALLENGES
Inlet
Starting
Accel Mass Capture
Cruise Performance
Performance and Operation Over the Flight and Maneuver Envelope
Passively-Cooled Structures
Isolator
Pressure Ratio
Combustor
Fuel Injection and Mixing
Piloting and Flameholding
Regeneratively-Cooled Structures and Thermal Management
Endothermic Fuels
Low Mach Operation
Total Pressure Losses
Low Q Operation
Nozzle
Frozen Flow Losses
Divergence Losses
Vehicle Integration

Technology Issues/Concerns
Hydrocarbon Scramjet Development

- **Combustors**
  - Injection/Mixing/Scheduling
  - Ignition/Combustion Aids
  - Low q Operations
  - High Combustion Efficiency with Small Pressure Drops
- **Starting**
  - Cold Start
  - Low Speed Ramjet Operation
  - Variable Geometry
- **Integrated Engine Performance**
  - Operability Across Envelope
  - Low-Mach Thrust Pinch
- **Structures/Materials**
  - Heat/Acoustic Loads Characterization
  - Inlet Leading Edge Radius/Erosion
  - Fuel Compatibility
  - Active vs. Passive Cooling
  - Coatings
  - Seals and Gaps
  - Manufacturability/Affordability
- **Thermal Management**
  - Fuel Flow/Active Cooling
- **Fuels**
  - Efficient Endothermics
  - "Environmentally Friendly" Additives

Pratt & Whitney (United Technologies) Engine Concept

- **Flowpath**
  - 2-D Inlet/Combustor with Body-Side Start Door
  - 2-D Diverging Combustor
  - Mini-Ramburner Pilots
  - Single Expansion Ramp Nozzle
  - Gaseous Hydrocarbon Fueled (Endothermic)
- **Structures**
  - Passively Cooled Leading Edges (Ceramic Composites)
  - Passively Cooled Inlet
    (Metallic with Thermal Barrier Coatings)
  - Endothermically Fuel-Cooled Metallic Combustor and Fuel Inlet/Pilot
  - Passively Cooled Nozzle
    (Carbon-Carbon or Ceramic Composites)

Aerojet Engine Concept

- **Flowpath**
  - 3-D Sidewall Compression Inlet
    - Self-Starting
  - 2-D Combustor With Struts for Fuel Injection
  - Cavity Pilots (Liquid and Gaseous Hydrocarbon Fuel)
  - Single Expansion Ramp Nozzle
- **Structures**
  - Passively Cooled Ceramic Composite Leading Edges
  - Radiatively Cooled Inlet/Combustor/Nozzle (One-Piece C/SiC Shell)
  - Fuel-Cooled Metallic Struts With Ceramic Composite Outer Shells

USAF Hypersonic Technology (HyTech) Program

BUDGET

- Nominally $20M / yr (total) FY96-FY02

- Aerojet and Pratt-Whitney (UTRC) contracts ($M):

FY96	FY97	FY98	FY99	FY00	FY01	FY02	TOT
5.2	3.8	10.5	10.5	10.0	10.0	12.0	52.0

- Balance to high risk research efforts

USAF Hypersonic Technology (HyTech) Program

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