Technical Fellowship

Technical Fellowship Advisory Board Study

Hypersonic Technology Status and Development Roadmap

Presentation to AIAA HyTASP Program Committee

December 18, 2003

Dr. Kevin G. Bowcutt
TFAB #1 Chairman

Briefing Outline

- Study Objectives, Scope and Approach
- Hypersonic Technology Assessment
- Technology Findings, Recommendations and Roadmaps
- Overall Findings and Recommendations

Study Process

Planning

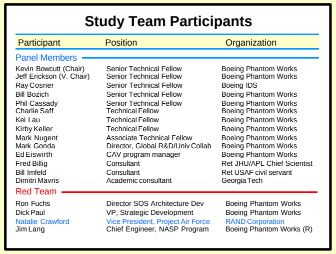
Ground Rules

Assumptions

Terms of Reference

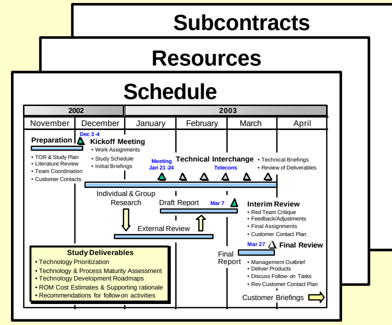
- Objectives
- Scope
- Tasking
- Customers
- Deliverables

Team Selection

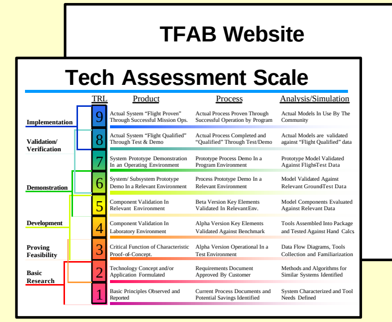


Literature Review

Business Plan



Tools & Procedures



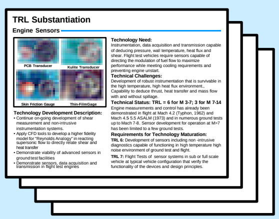
Kickoff Meeting

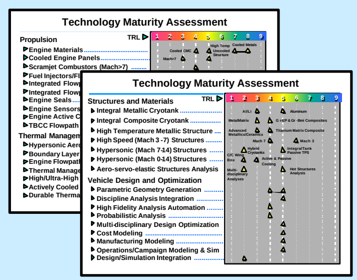
Execution

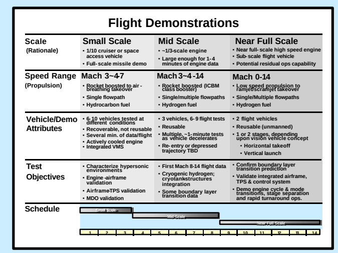
Technology Prioritization → Maturity Assessment → Development Roadmaps

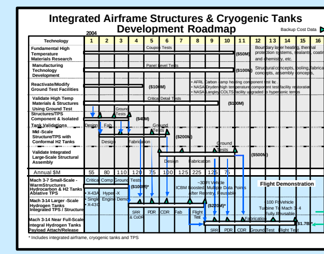
- Propulsion
- Thermal Mgmt
- Structures
- Vehicle Design

33 Component Technologies

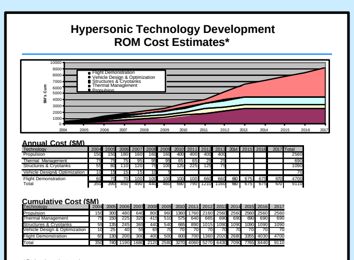


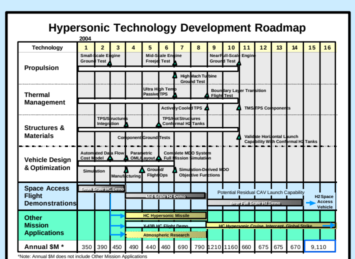






ROM Cost Estimate → Program Roadmap → Recommendations → Follow-on Actions





Recommendations

- Establish focused initiative to mature technologies critical to air-breathing hypersonic space access and global response
  - Create a framework that ties academia, industry and government with focus on enabling technologies
  - Conduct a three-phase flight test program for space access applications (utilize NAI framework?)
  - Develop/upgrade required national test facilities
- Decouple missions and platforms from critical technology development
  - Avoids feast or famine funding cycles
  - Structure program to enable "off-ramps" to other applications and capabilities
  - Mature technologies prior to developing platforms– conduct vehicle design studies to establish technology requirements
- Focus only on "enabling" technologies
  - Propulsion, Thermal Management, Structures & Materials, and Vehicle Design/Optimization

High-Speed capability should be evaluated as a National Priority

Follow-on Actions

- Management Briefings
- Customer Briefings
- Lessons-Learned
- TFAB Guidebook

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Study Team Participants

Participant	Position	Organization
Panel Members		
Kevin Bowcutt (Chair)	Senior Technical Fellow	Boeing Phantom Works
Jeff Erickson (V. Chair)	Senior Technical Fellow	Boeing Phantom Works
Ray Cosner	Senior Technical Fellow	Boeing IDS
Bill Bozich	Senior Technical Fellow	Boeing Phantom Works
Phil Cassady	Senior Technical Fellow	Boeing Phantom Works
Charlie Saff	Technical Fellow	Boeing Phantom Works
Kei Lau	Technical Fellow	Boeing Phantom Works
Kirby Keller	Technical Fellow	Boeing Phantom Works
Mark Nugent	Associate Technical Fellow	Boeing Phantom Works
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Fred Billig	Consultant	Ret JHU/APL Chief Scientist
Bill Imfeld	Consultant	Ret USAF civil servant
Dimitri Mavris	Academic consultant	Georgia Tech
Red Team		
Ron Fuchs	Director SOS Architecture Dev	Boeing Phantom Works
Dick Paul	VP, Strategic Development	Boeing Phantom Works
Natalie Crawford	Vice President, Project Air Force	RAND Corporation
Jim Lang	Chief Engineer, NASP Program	Boeing Phantom Works (R)

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Background & Historical Perspective

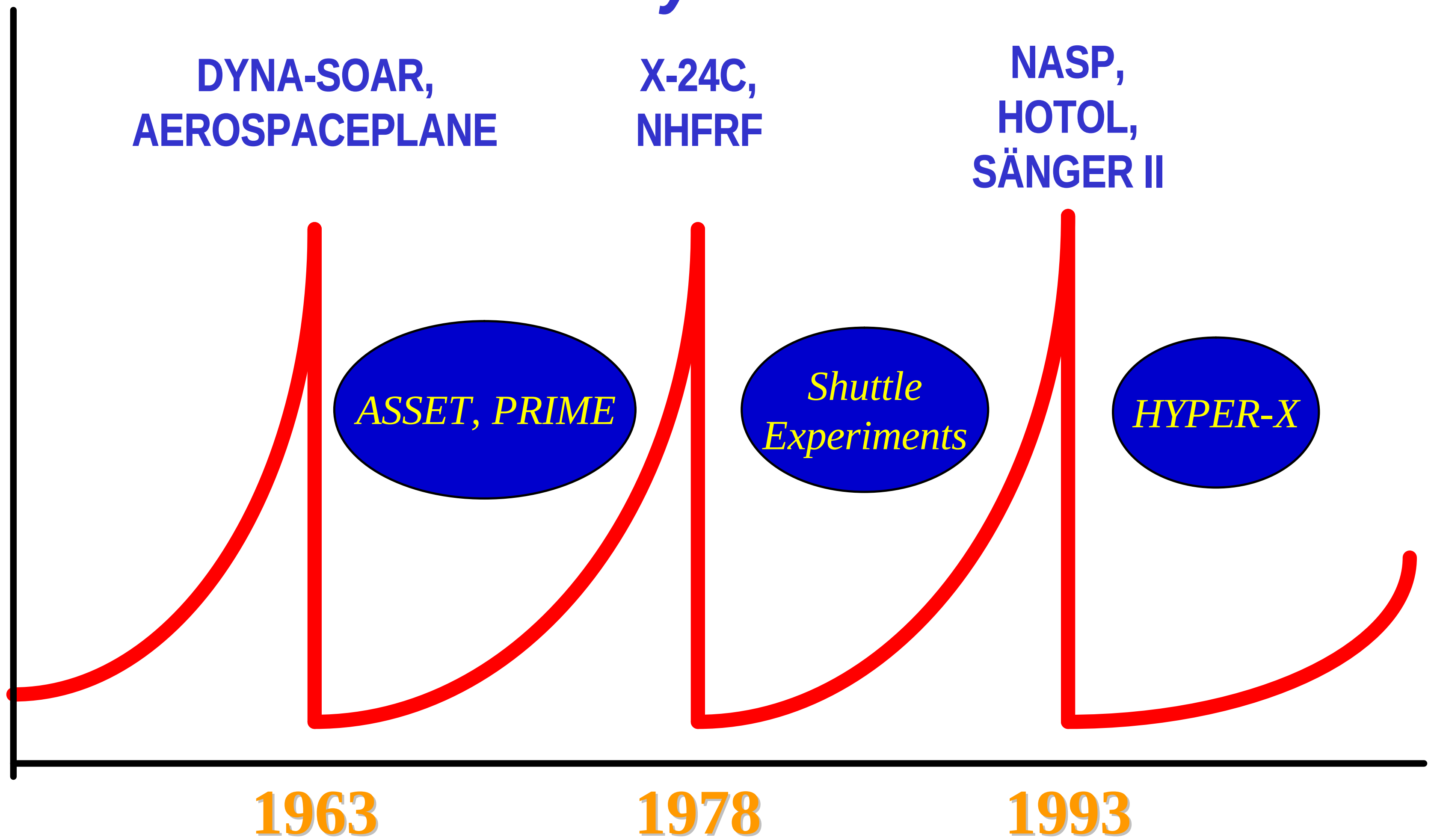
- Funding has been largely directed toward specific platforms with *overly ambitious* technology goals
- Platforms get canceled due to impatience with rate of technology maturation - lack of sustained focus on “critical path” technologies
- Critical technology development and knowledge base evaporate when platform development is canceled
- Current resource-limited funding environment leads to program instability – frequent starts, stops and redirections
- Fledgling DDR&E National Aerospace Initiative formed to address issues, but today is too broad and primarily a collection of NASA & DOD programs

A sustained national vision and commitment to development of technologies critical to enabling hypersonic operations is lacking

History of Hypersonics

(SAB Study, 2000)

"Old Faithful:" Cyclical Fits and Starts



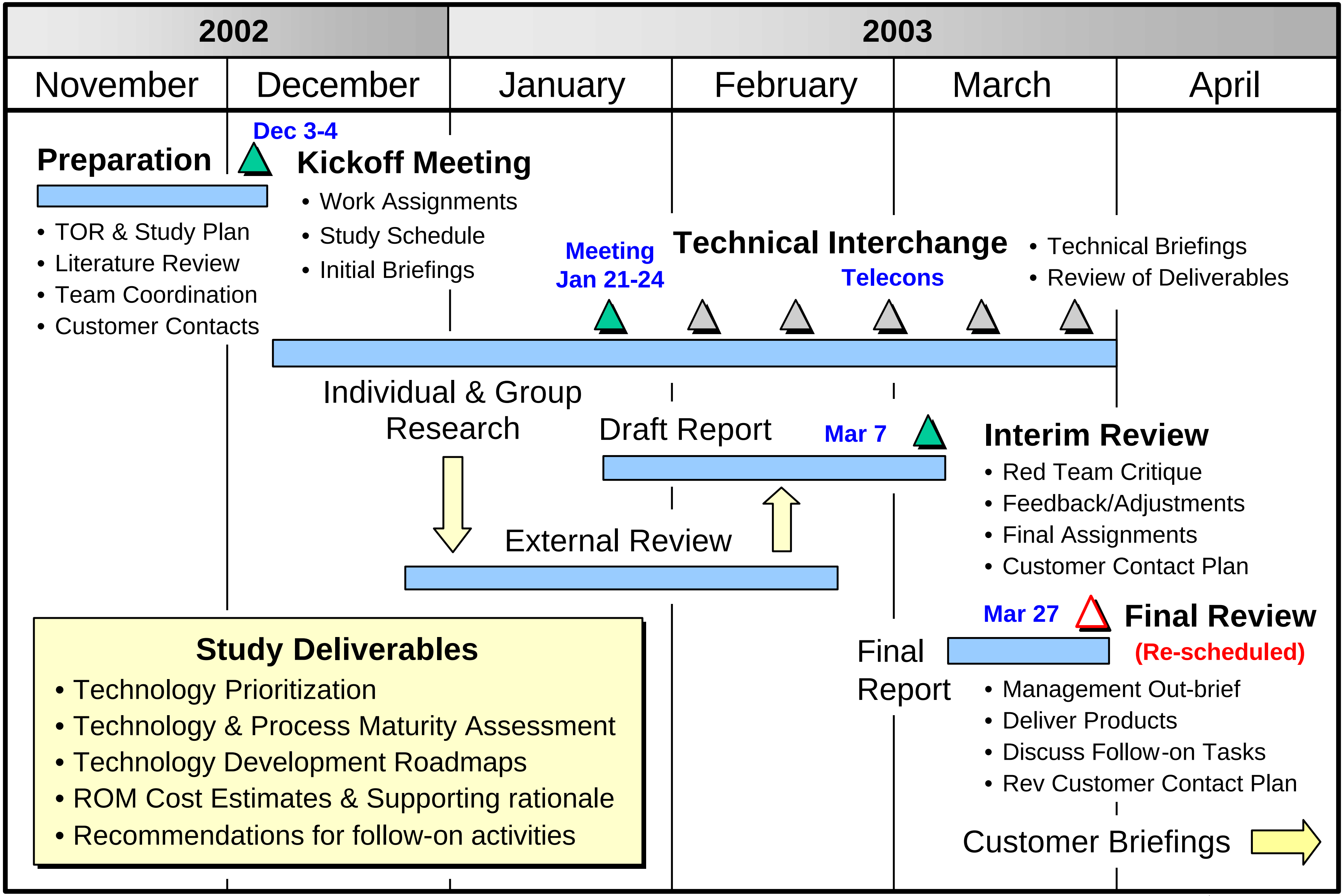
Study Tasks

- **Identify and assess state of the art of critical technologies, design processes and test capabilities for hypersonic vehicles**
  - establish TRL level of each technology, with rationale
- **Gather available hypersonic technology and system development roadmaps from NASA, DoD and international organizations**
- **Develop comprehensive roadmap for maturing critical technologies (including design processes & test capabilities)**
  - to levels required for flight demonstration (TRL = 6)
  - to levels required for subsequent entry into EMD for operational military and/or commercial systems (TRL = 7)
- **Develop actionable recommendations and TFAB follow-on tasking**

Ground Rules & Assumptions

- **Use Hypersonic SAB recommendations as a point of departure**
  - Space access vehicle focus of tech development roadmap, but …
  - Include critical technologies for other hypersonic vehicles that are potential off-ramps to the primary roadmap
- **Keep RLV design options open (# of stages, staging Mach, fuel type, horizontal vs. vertical, etc.)**
  - Maintain some element of air-breathing propulsion (potentially to speeds as high as Mach 15)
- **R&D roadmap timelines based upon earliest availability (tech push)**
  - But establish potential synergy/connectivity with NAI schedule
- **Account for aircraft-like operations/affordability requirements in technology roadmaps**
- **Only first-digit accuracy required for tech development ROM costs**

TFAB Study Schedule and Products



Technology Readiness Level (TRL) Descriptions
Product, Process, Simulation

Phase	TRL	Product	Process	Analysis/Simulation
Implementation	9	Actual System "Flight Proven" Through Successful Mission Ops.	Actual Process Proven Through Successful Operation by Program	Actual Models In Use By The Community
Validation/ Verification	8	Actual System "Flight Qualified" Through Test & Demo	Actual Process Completed and "Qualified" Through Test/Demo	Actual Models are validated against "Flight Qualified" data
Validation/ Verification	7	System Prototype Demonstration In an Operating Environment	Prototype Process Demo In a Program Environment	Prototype Model Validated Against Flight-Test Data
Demonstration	6	System/ Subsystem Prototype Demo In a Relevant Environment	Process Prototype Demo In a Relevant Environment	Model Validated Against Relevant Ground-Test Data
Demonstration	5	Component Validation In Relevant Environment	Beta Version Key Elements Validated In Relevant Env.	Model Components Evaluated Against Relevant Data
Development	4	Component Validation In Laboratory Environment	Alpha Version Key Elements Validated Against Benchmark	Tools Assembled Into Package and Tested Against Hand Calcs.
Proving Feasibility	3	Critical Function of Characteristic Proof-of-Concept.	Alpha Version Operational In a Test Environment	Data Flow Diagrams, Tools Collection and Familiarization
Basic Research	2	Technology Concept and/or Application Formulated	Requirements Document Approved By Customer	Methods and Algorithms for Similar Systems Identified
Basic Research	1	Basic Principles Observed and Reported	Current Process Documents and Potential Savings Identified	System Characterized and Tool Needs Defined

Critical Technologies Identified

All essential technologies evaluated to identify enabling set requiring focused R&D before operational hypersonic systems feasible

aerodynamics, propulsion, aerodynamic heating and thermal management, high temperature materials and TPS, cryogenic tanks and airframe structures, manufacturing, autonomous flight systems, hypersonic-unique subsystems, IVHM, vehicle design

Four technologies identified as critical/enabling (in priority order)

- Propulsion
- Thermal environment prediction, protection and management
- Integrated airframe structures and cryogenic tanks
- Vehicle design, optimization and simulation

Remaining technologies are important, but:

- Are not crucial to hypersonic vehicle feasibility, or
- Are being matured for other applications and will be available for hypersonic systems in the required timeframe

Critical Hypersonic Technologies

Key Enabling Technologies Requiring Focused Research, Development and Demonstration to TRL Level 6 and 7

Propulsion – low-speed, mid-speed & hypersonic - Bowcutt & Billig

- Flowpath performance, verification, thermal survivability, scale-up

Thermal environment prediction, protection & mgmt - Lau, Eiswirth & Bozich

- Aeroheating prediction methodology (including BLT prediction)
- High temperature airframe materials, TPS & thermal management systems

Integrated airframe structures and cryogenic tanks - Bozich & Saff

- Composites, advanced metals, scale-up, affordability, durability/life
- Aero-thermo-servo-elastic design, analysis and test

Vehicle design, optimization & simulation – Bowcutt & Mavris

- Including MDO, design for uncertainty, cost modeling & operations sim

Other Technologies Requiring Maturation

Technology	TRL	Status / Readiness Projection
Aerodynamics	5	Analysis & test methods mature, but validation remains difficult at hypervelocity speeds (Mach > 8)
Vehicle Control System	5	Closed-loop engine-airframe control systems being developed for X-43A, X-43C, HyFly and Waverider SED
Autonomous Flight	5	Leverage ongoing autonomous air/space vehicle R&D
Vehicle Subsystems	4-5	Being addressed by SLI/NGLT/Shuttle Upgrade
Crew Systems	6	Synthetic vision flight demo on NASA HSR Program
	2	Crew escape addressed by SLI / Shuttle Upgrade
Vehicle Health Mgmt.	4	Requires engineering development; Extend NASP, SLI and OSP work
Antennas/Sensor Windows	4	Exist for weapons; Development required for reusable apps.
Manufacturing	3-4	Manufacturing experience and infrastructure required to fabricate large, lightweight, non-circular structures from advanced high temperature materials is lacking
Ground Operations	2-3	SOV Ground Operations studies underway. Life cycle simulations including ground operations in planning stages for NGLT

Technology Readiness Assessment

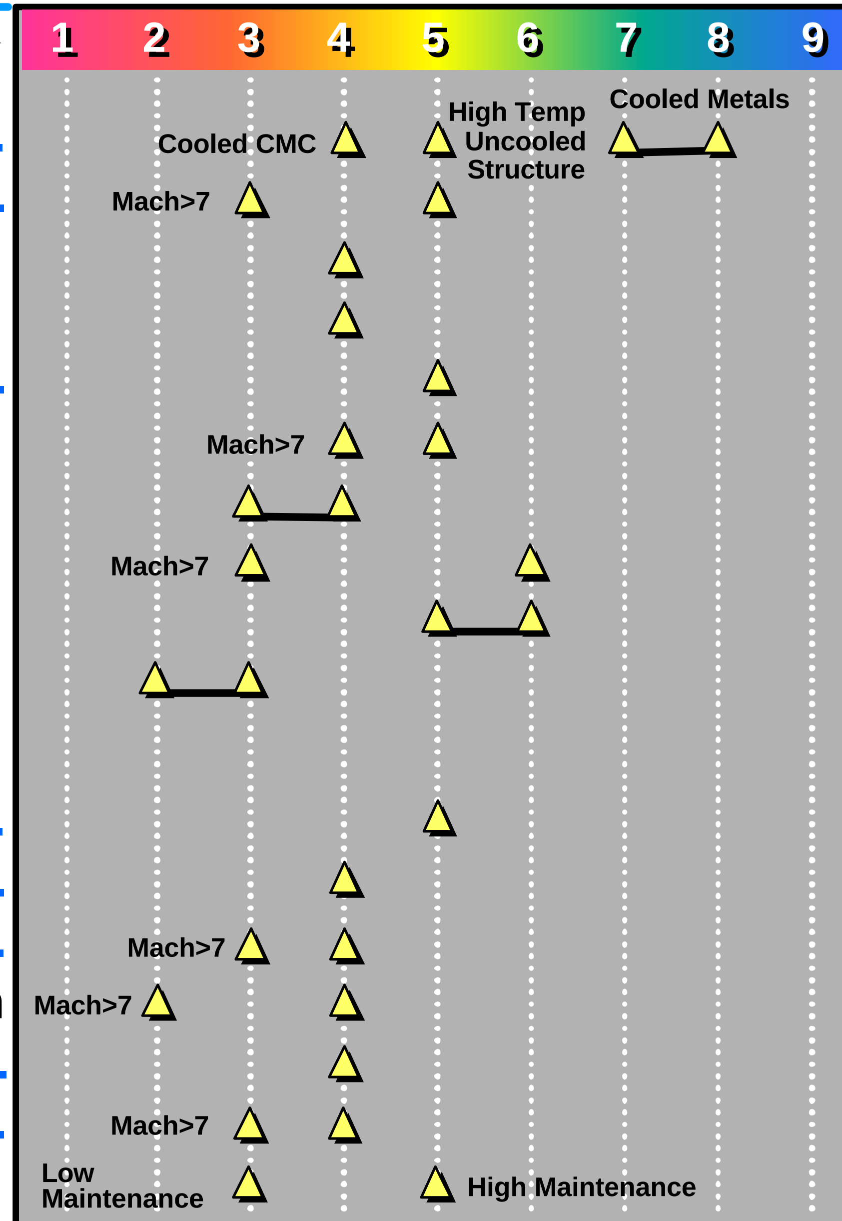
TRL ▷

Propulsion

- Engine Materials
- Cooled Engine Panels
- Scramjet Combustors (Mach>7)
- Fuel Injectors/Flame Holders
- Integrated Flowpath-Hydrocarbon
- Integrated Flowpath-Hydrogen
- Engine Seals
- Engine Sensors
- Engine Active Control System
- TBCC Flowpath Integration

Thermal Management

- Hypersonic Aerothermodynamics
- Boundary Layer Transition
- Engine Flowpath Thermal Design
- Thermal Management/Control System
- High/Ultra-High Temp M & S
- Actively Cooled Thermal Protection
- Durable Thermal Protection



Technology Readiness Assessment

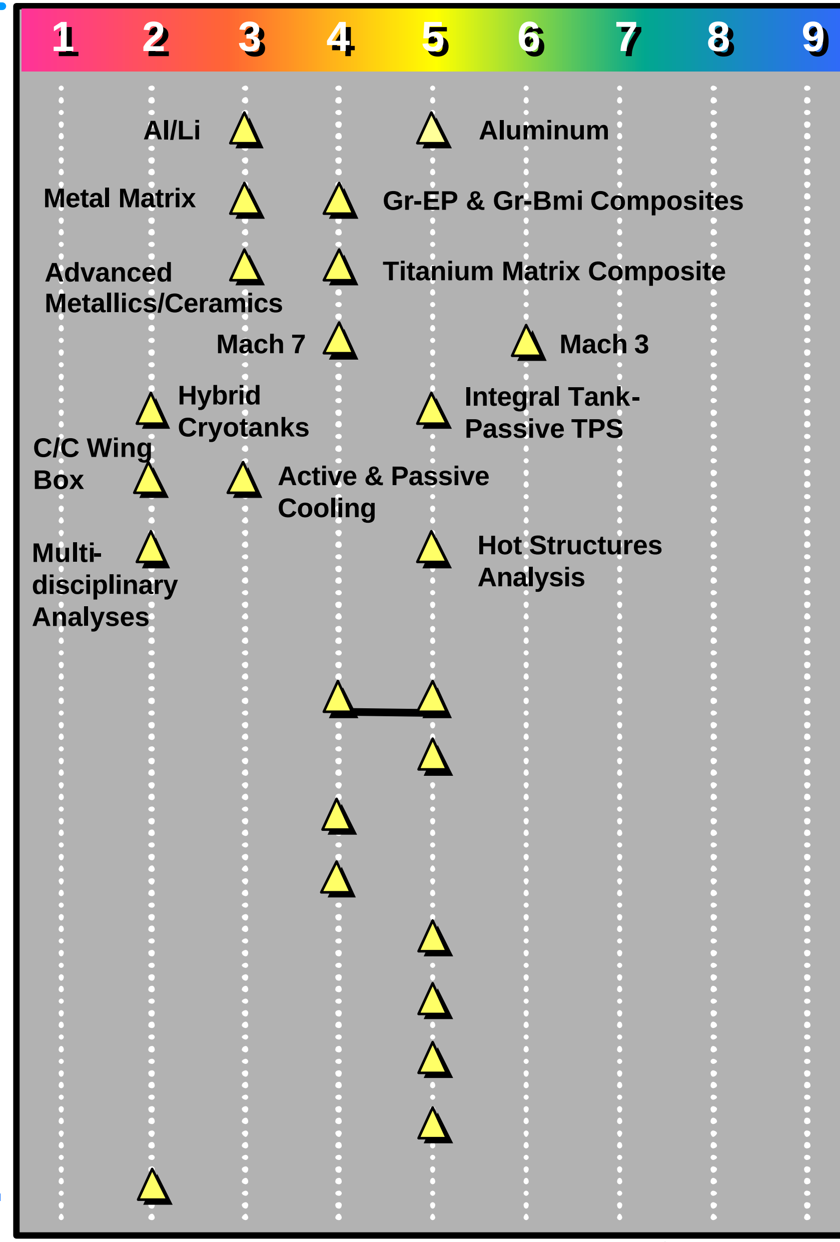
TRL ▷

Structures and Materials

- Integral Metallic Cryotank ....
- Integral Composite Cryotank ....
- High Temperature Metallic Structure ....
- High Speed (Mach 3-7) Structures ....
- Hypersonic (Mach 7-14) Structures ....
- Hypersonic (Mach 0-14) Structures ....
- Aero-servo-elastic Structures Analysis

Vehicle Design and Optimization

- Parametric Geometry Generation ....
- Discipline Analysis Integration ....
- High Fidelity Analysis Automation ....
- Probabilistic Analysis ....
- Multi-disciplinary Design Optimization
- Cost Modeling ....
- Manufacturing Modeling ....
- Operations/Campaign Modeling & Sim
- Design/Simulation Integration ....



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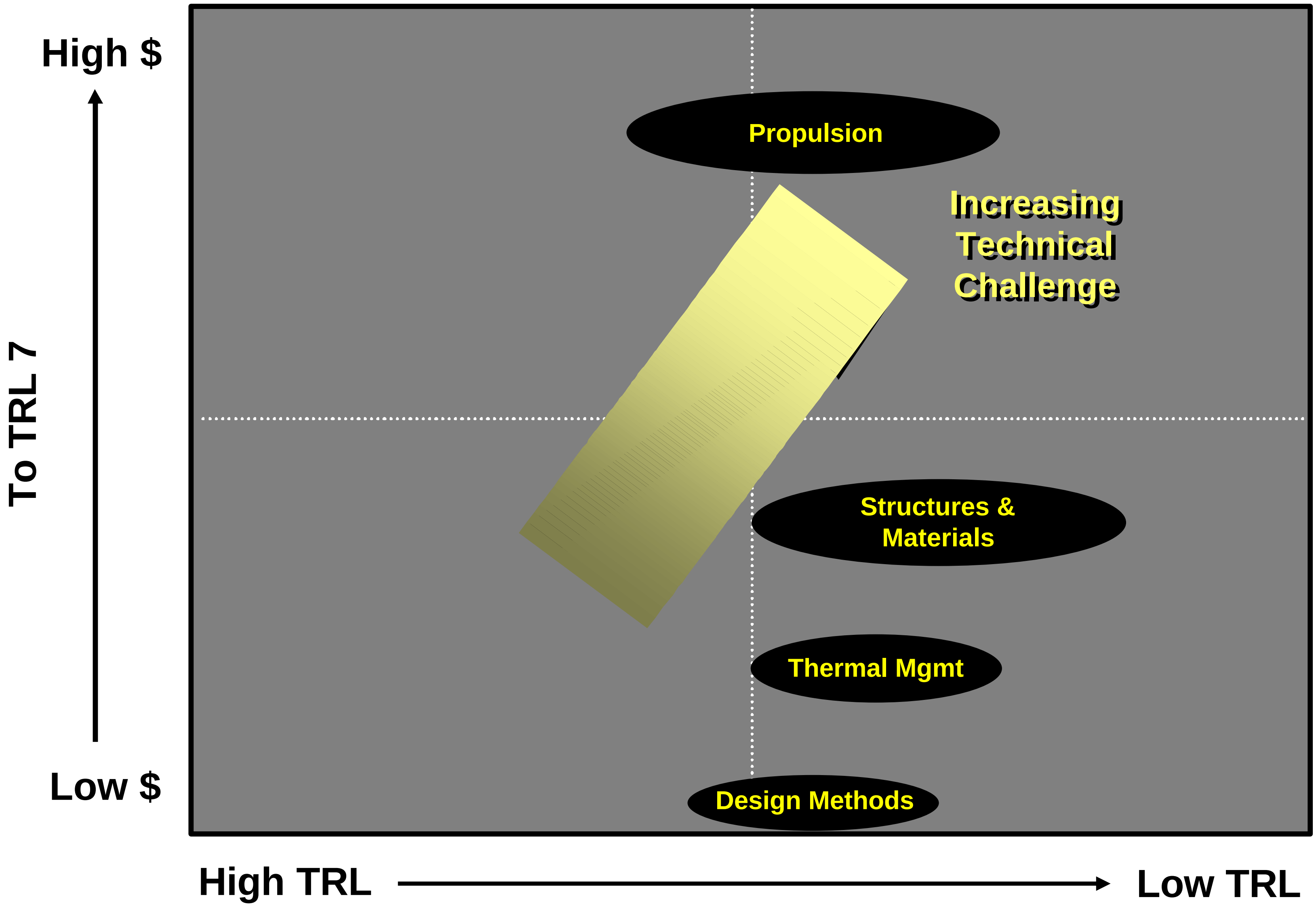
Required Maturation Investment is a Strong Function of Technology Category



Technologies Requiring Flight Test for Sufficient Maturation

- **Demonstrate dual-mode scramjet from Mach 3~4-14**
  - Mach 3~4-7, 1/10th scale cruiser or space access vehicle (full scale missile), HC
  - Mach 3~4-14, mid-scale, vehicle sized for 1- 4 minutes of data, H2 fuel
    - Test ~1-minute at multiple Mach numbers (e.g., 14, 12, 10, 8, …) on descent
  - Mach 3~4-14, near full scale TSTO engine on a sub-scale flight vehicle, H2 fuel
- **Low speed propulsion (assumption for TFAB is turbine engine)**
  - Engine may not require flight demo itself, but may be required to accelerate demo vehicle to scramjet takeover condition
  - Transition from turbine to scramjet (and/or staging) must be flight demo'd
- **Characterize thermal environment of airframe & engine from Mach 3~4-14**
  - BL transition
  - Local interference heating, leading edges, acreage, etc.
  - Engine flowpath heating
- **Durability and effectiveness of integrated airframe-TPS**
  - Combined thermal and mechanical loads
  - Aero-thermo-servo-elastic methods verification
  - Vibration & acoustic loads (environmental data)
  - Rapid vehicle turnaround demonstration
- **Validate performance of integrated vehicles designed using MDO methods**

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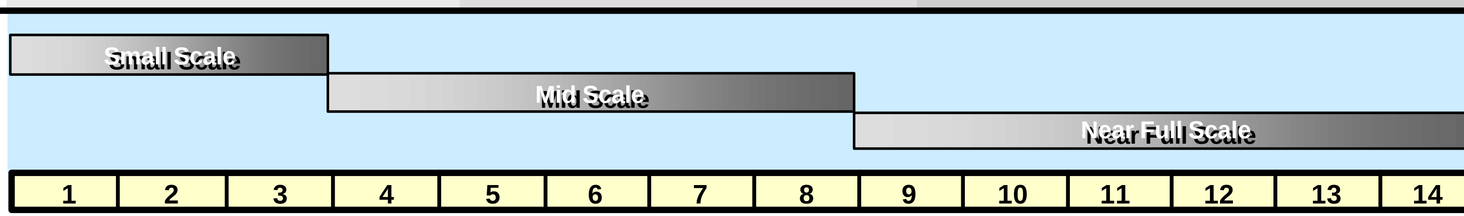
Flight Demonstrations

Scale (Rationale)	Small Scale	Mid Scale	Near Full Scale
	• 1/10 cruiser or space access vehicle • Full-scale missile demo	• ~1/3-scale engine • Large enough for 1-4 minutes of engine data	• Near full-scale high speed engine • Sub-scale flight vehicle • Potential residual ops capability
Speed Range (Propulsion)	**Mach 3~4-7** • Rocket boosted to air-breathing takeover • Single flowpath • Hydrocarbon fuel	**Mach 3~4-14** • Rocket boosted (ICBM class booster) • Single/multiple flowpaths • Hydrogen fuel	**Mach 0-14** • Low speed propulsion to ramjet/scramjet takeover • Single/Multiple flowpaths • Hydrogen fuel

Vehicle/Demo Attributes	• 6-10 vehicles tested at different conditions
	• Recoverable, not reusable
	• Several min. of data/flight
	• Actively cooled engine
	• Integrated VMS
		• 3 vehicles, 6-9 flight tests
		• Reusable
		• Multiple, ~1-minute tests as vehicle decelerates
		• Re-entry or depressed trajectory TBD
			• 2 flight vehicles
			• Reusable (unmanned)
			• 1 or 2 stages, depending upon vision vehicle concept
			  • Horizontal takeoff
			  • Vertical launch

Test Objectives	• Characterize hypersonic environments • Engine-airframe validation • Airframe-TPS validation • MDO validation	• First Mach 8-14 flight data • Cryogenic hydrogen; cryotank-structures integration • Some boundary layer transition data	• Confirm boundary layer transition prediction • Validate integrated airframe, TPS & control system • Demo engine cycle & mode transitions, stage separation and rapid turnaround ops.

Schedule



Comments on X- 43B (RCCFD) Flight Demo

- **A logical mid-scale flight demonstration for hypersonic cruise vehicle development**
- **Can also contribute to space access vehicle development**
  - Low-speed to high-speed propulsion mode transition risk reduction
  - Propulsion-airframe integration and integrated vehicle performance/operability validation
  - Integrated materials/structures/TPS verification
  - Vehicle Management System verification for integrated hypersonic vehicles

TFAB charter was to outline a minimal technology development roadmap for <u>space access vehicles</u> with aircraft-like operations (i.e., employing air-breathing propulsion)

Propulsion

Findings:

- **Sound departure points exist for hypersonic air-breathing engine maturation**
  - Current programs (HyTech, HyFly and X-43C) and planned programs (Single Engine Demo) address most hydrocarbon risk issues
  - NASP and X-43A provide a solid foundation for hydrogen engine development
- **Mach > 8 propulsion challenging and requires focused development**
  - Databases for combustors, engine performance and thermal survivability insufficient to commit to vehicle design
  - Existing ground test capabilities insufficient for engine development
  - Current weights of actively cooled engine flowpaths excessive for space access
  - Engine robustness and ability to support aircraft-like operations not yet established
- **Flight Demonstration required for engine design verification**
  - No current plan addresses all propulsion tech maturation needs for space access
  - TFAB suggested flight demos compatible with NAI content and schedule

Propulsion

Recommendations:

- **Pursue planned hypersonic air-breathing engine development**
  - Hydrocarbon programs, with no unnecessary duplication
  - NASA/USAF high-Mach turbine engine development for low speed propulsion
- **Increase technology maturation focus above Mach 8**
  - Pursue engine development activities that build-up in Mach and scale
  - Reactivate, modify and build new test facilities to address Mach > 8 and large scale (arc-heated, large impulse, and large direct-connect combustor test facilities)
  - Mature lightweight, high-temperature materials for engine structures
- **Utilize 3 flight demonstrations at increasing scale to verify engine performance, robustness and operational utility**
  - Use the NAI infrastructure to execute flight demos

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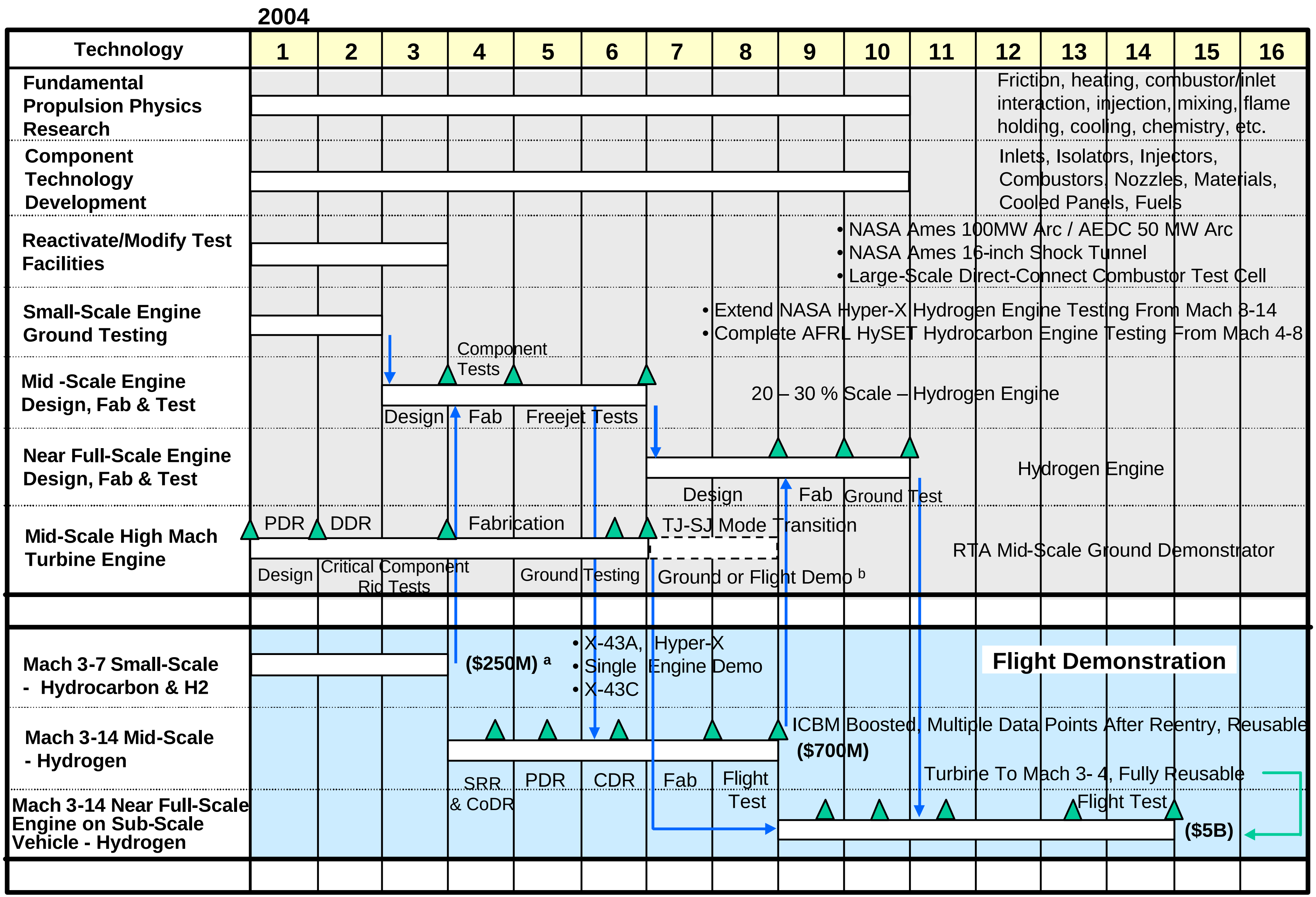
High-Speed Propulsion Development Roadmap



(a) Cost for one small-scale hydrocarbon flight demo only

(b) X-43B could satisfy test objective

Thermal Environment Prediction, Protection and Management

Findings:

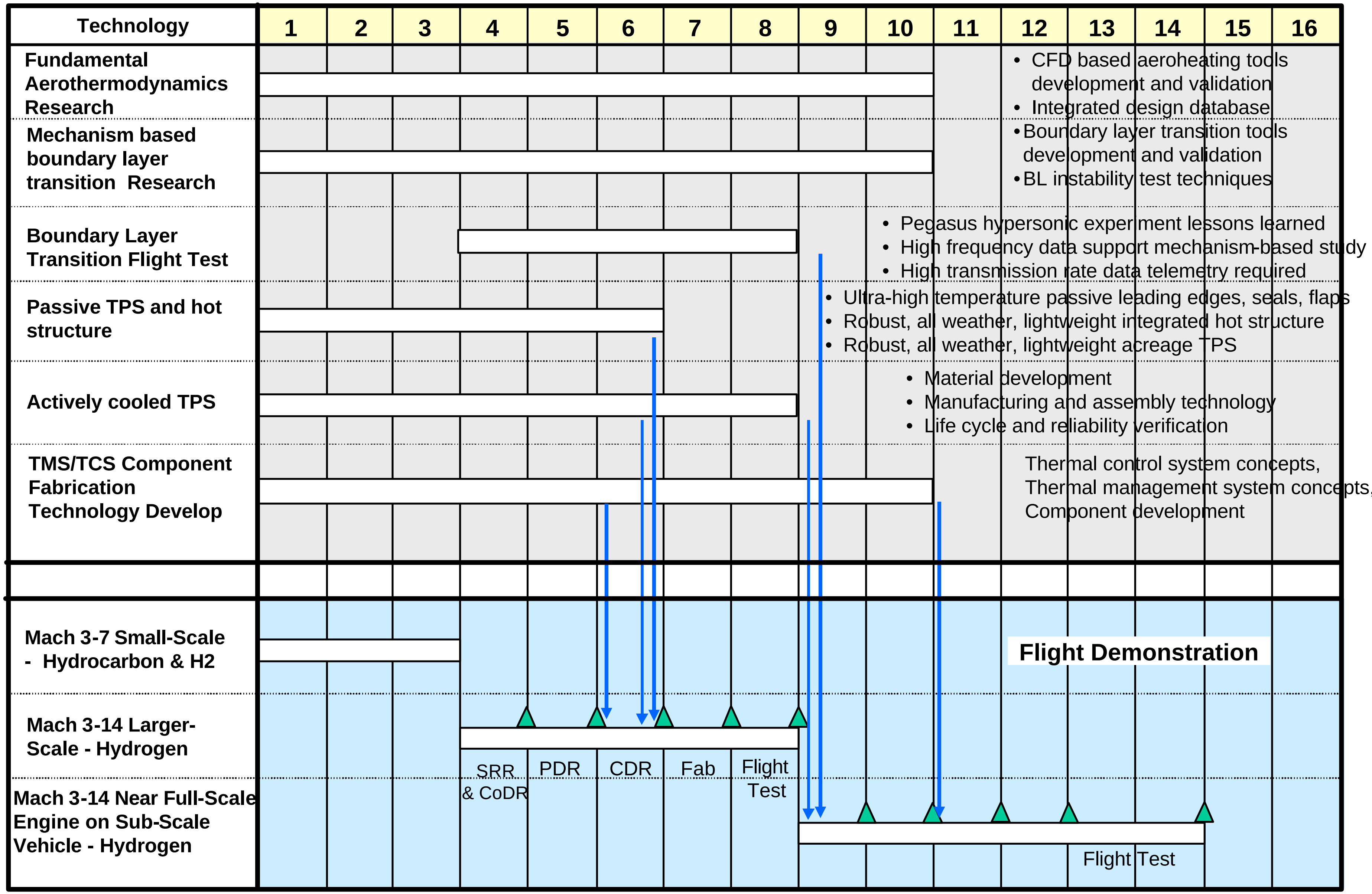
- **High uncertainty in environment prediction, including boundary layer transition, mandates conservative TPS/TMS design**
- **Vehicle-level thermal design tools are cumbersome**
- **Advanced all-weather, durable thermal protection materials and components are immature (TRL<6)**
- **High temperature material supplier infrastructure is sparse**
- **Thermal management/control requirements are insufficiently defined**

Thermal Environment Prediction, Protection and Management

Recommendations:

- **Form national team focused on boundary layer transition prediction**
  - Conduct boundary layer transition flight experiments
  - Develop physics-based prediction methods for complex geometries
  - Integrate BLT prediction into CFD and design analysis
- **Define focused requirements for access-to-space material and thermal control system development**
- **Expand candidate material research and develop high temperature materials database**
- **Design and test full-scale advanced components, e.g., tanks with integrated TPS, leading edges, control surfaces, windows, seals, etc.**

Thermal Management System Development Roadmap



Integrated Airframe Structures and Cryogenic Tanks

Findings:

- **No cryogenic tanks exist that are lightweight, reliable and reusable**
  - Composite cryo-tanks have been plagued by failures
  - Metallic cryo-tanks are successful, but may be heavy for reusable applications
  - Non-circular, conformal tanks are still a manufacturing and design challenge
- **Integration and compatibility of TPS, structural concept, and tank concept are not addressed in current integrated design tools**
- **Limited work on acreage hot structures since NASP**
- **No ground test facilities exist to certify full-scale integrated airframes/cryo-tanks under thermal-mechanical loading with cryogenic propellants**

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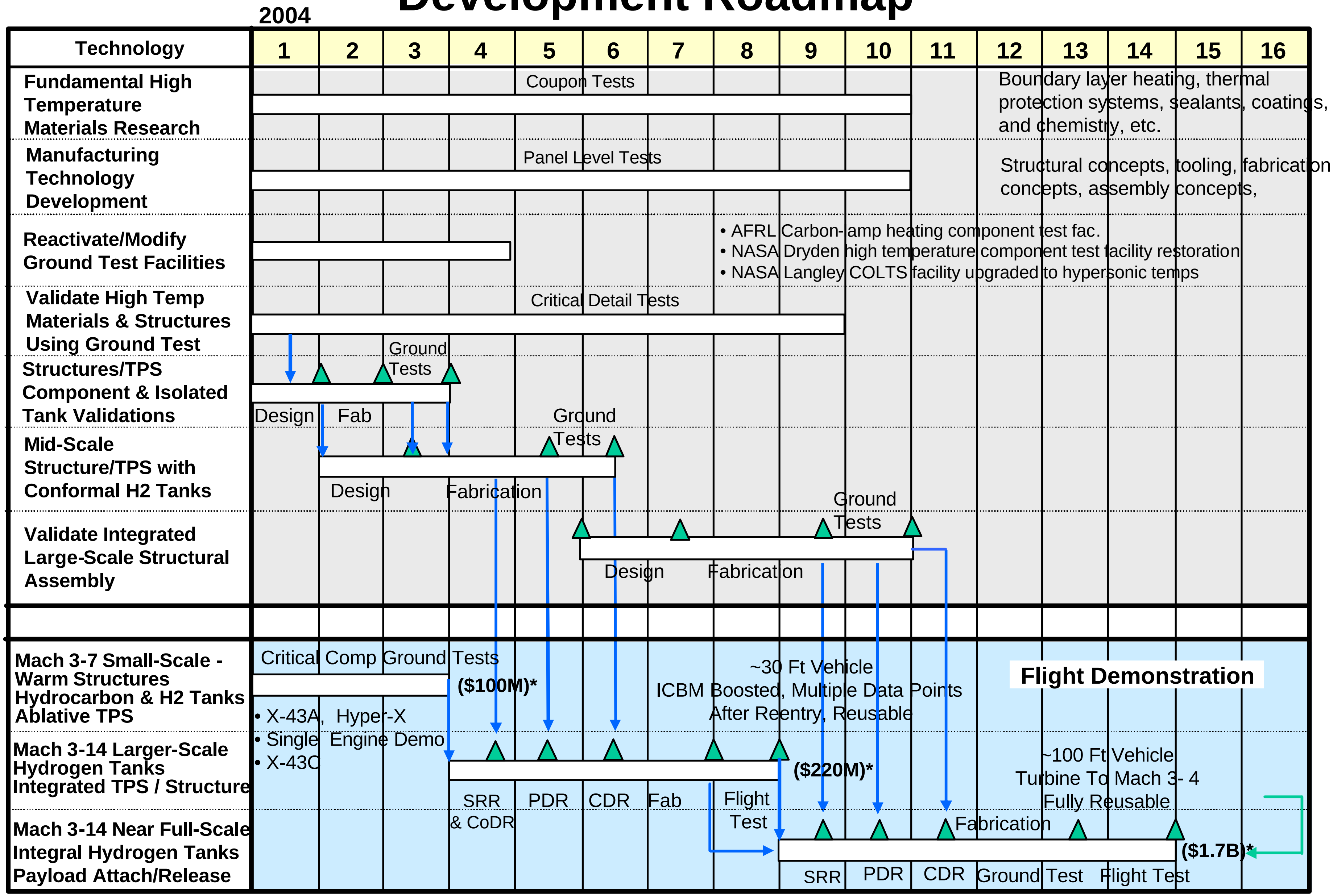
Integrated Airframe Structures and Cryogenic Tanks

Recommendations:

- **Develop and validate alternate advanced concepts to minimize weight and/or reduce risk**
  - Cryo-tanks (advanced metallics, composites, and hybrid materials)
  - Integral and non-integral tank concepts
  - Hot and cold (protected) structural concepts and materials
- **Develop and validate analysis capability for combined thermal and mechanical loads for integrated structures & TPS systems**
- **Implement a long term plan to upgrade or develop ground test facilities in conjunction with program test requirements**

Integrated Airframe Structures & Cryogenic Tanks Development Roadmap



* Includes integrated airframe, cryogenic tanks and TPS only

Vehicle Design System

Findings:

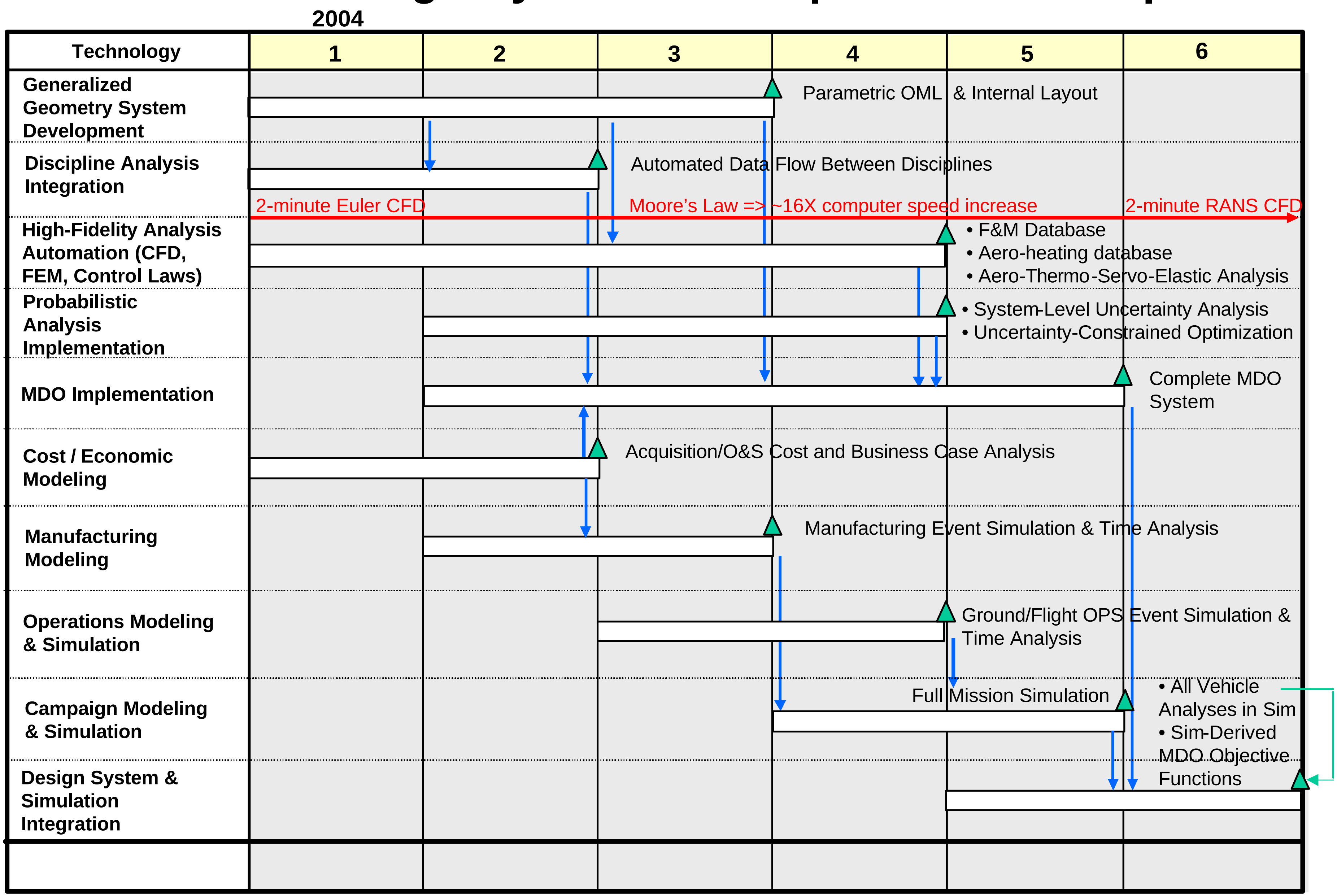
- **Conventional design practices are inadequate to deal with the technical challenges of hypersonic vehicles**
  - Highly integrated nature of hypersonic vehicles, combined with non-linear physics and flight characteristics, challenge design process
  - High levels of uncertainty (technological and economic) are prevalent
- **Successful development of operational hypersonic systems is not possible without improved, fully integrated design methods employing numerical optimization**
  - Need new design methods that account for, and take advantage of, the unique nature of highly integrated vehicles
  - Most elements of an integrated design system are currently being developed in isolation
  - Some elements are immature and lack empirical validation

Vehicle Design System

Recommendations:

- **Formulate, develop, integrate and validate advanced design methods:**
  - Parametric geometry generation system
  - Automation of data transfer between analysis tools
  - Automated execution of high fidelity computational analyses
  - Multi-disciplinary design optimization techniques
  - Probabilistic tools enabling SoS level risk assessment & mitigation
  - Accurate cost modeling
  - Integration of vehicle design/optimization and operations/mission simulation tools

Vehicle Design System Development Roadmap



Potential Disruptive Technologies

Propulsion:

- Materials and design processes that result in reliable high thrust-to-weight rocket engines, and/or high energy-density fuels, would enable rocket SSTO - but also greatly reduce TOGW of air-breathing vehicles
- Controlled plasma generation for improved engine performance, and engine flowpath magneto-hydro-dynamics for in-flight power generation

Thermal Protection:

- Structures/TPS based on nanomaterials with ultra-lightweight insulation would alter vehicle design and fabrication approaches, and lead to significant weight and life cycle cost reductions
- Intelligent self-healing TPS would permit highly optimized designs that reduce weight and life cycle cost

Airframe Structures:

- Low density intermetallics and nanomaterials show promise for future dramatic airframe performance improvements
- Morphable structures for variable geometry engines without hinges & seals, and for airframes/control surfaces, could dramatically reduce risk and improve performance

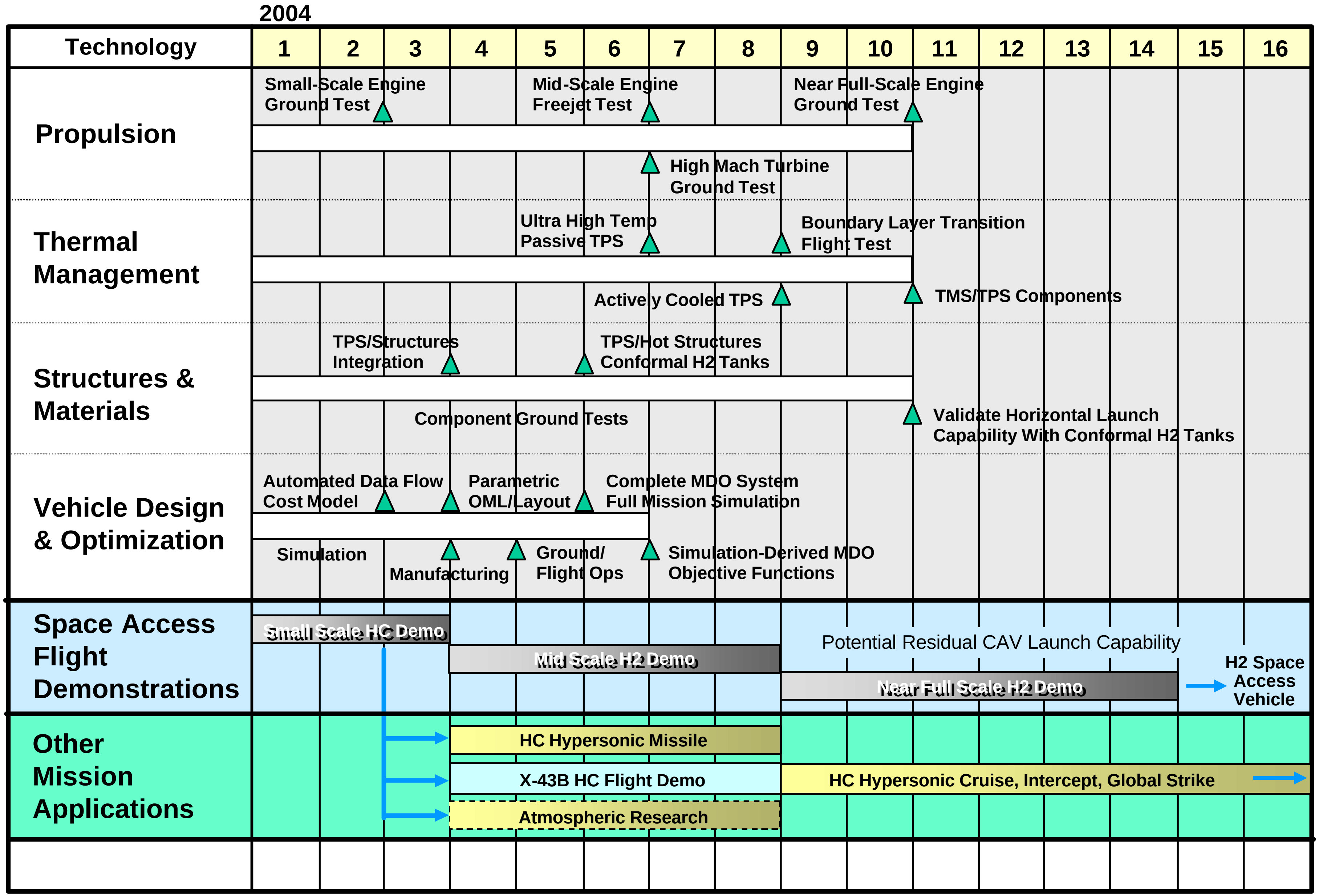
Vehicle Design System:

- Dramatic increase in computing speed (e.g., quantum computing) would enable:
  - Advance of probabilistic methods in system design
  - Higher fidelity, physics-based formulations from the outset of vehicle design

Critical Skill Shortfalls

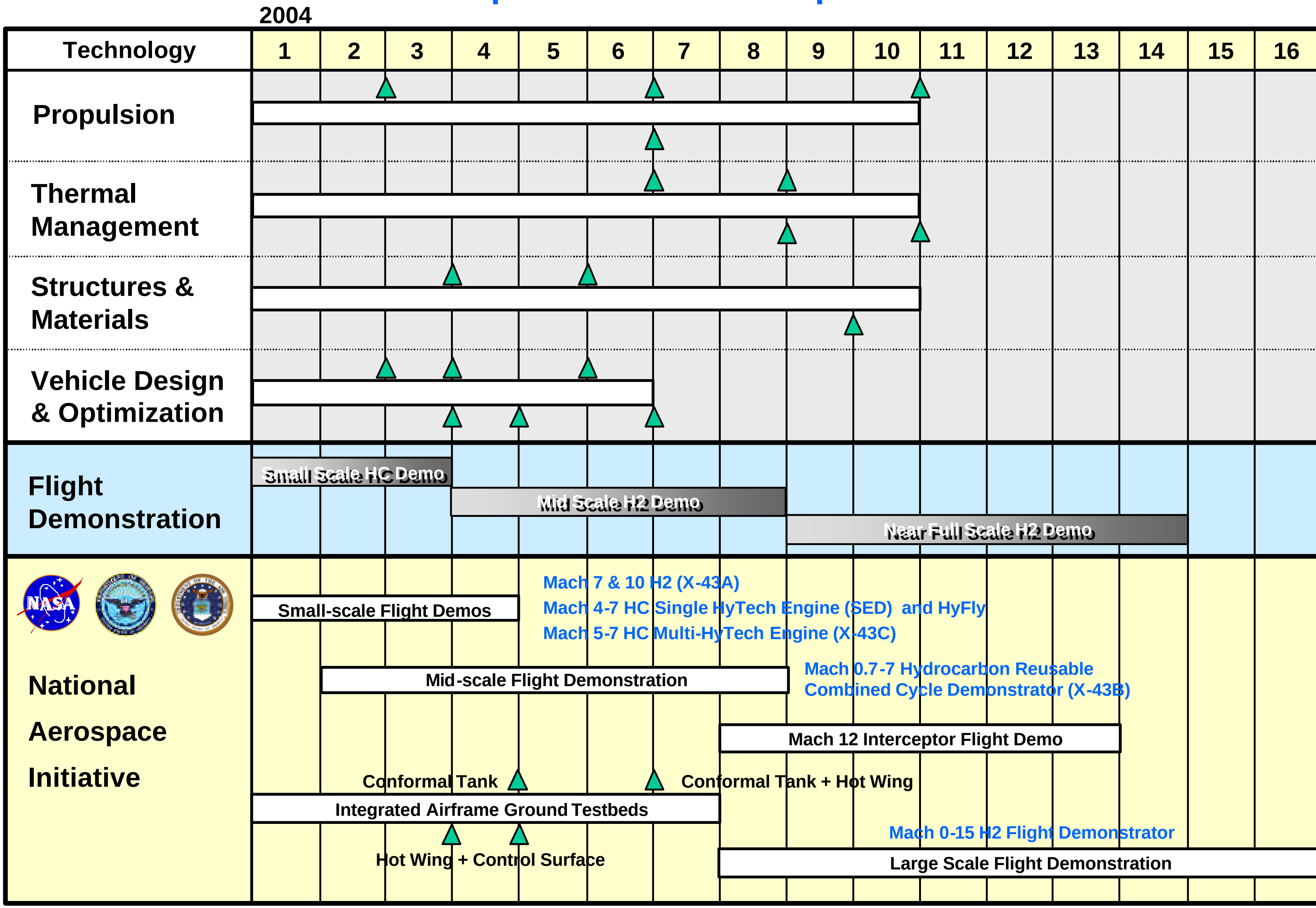
- **Propulsion**
  - Flowfield modeling (CFD) with fuel-air mixing and finite-rate chemistry
  - Hypersonic engine-airframe integration and aero-propulsion testing
  - Engine component and integrated engine design and testing
- **Aerothermal**
  - Aerothermodynamic environment definition including CFD, BLT and testing
  - TPS design, testing and qualification
  - Cryogenic fuel system design
- **Airframe**
  - Hot structure aero-thermo-servo-elastic design and analysis
  - Fabrication using advanced materials for hypersonic vehicles
  - Hot structure testing and qualification
- **Vehicle design & optimization**
  - Multidisciplinary design, trades and optimization
  - System-level probabilistic design & analysis
- **System**
  - System and system-of-system engineering
  - Hypersonic vehicle flight testing

Hypersonic Technology Development Roadmap



Hypersonic Technology Development Roadmap

Relationship to National Aerospace Initiative



Key Findings

- **Maturation of four technologies critical to success of air-breathing hypersonic space access**
  - Propulsion is the primary driver of development risk, cost, schedule and operational success
  - Managing the thermal environment is the next most critical technology driver
- **Existing test facilities inadequate for required technology development**
  - Mach > 8 propulsion development
  - Large scale, integrated thermal-structural testing
- **Flight testing essential to validate and mitigate risks for critical technologies in a relevant environment**
  - Three-step risk reduction flight test program balances cost and technology maturation requirements
  - Focused on physics, scale-up and integration
- **NAI provides potential framework for a hypersonic technology program**
  - NAI centered on flight demonstrations of increasing scale and complexity
  - Not yet a focused technology development program

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Overall Recommendations

- **Establish focused initiative to mature technologies critical to air-breathing hypersonic space access and global response**
  - Create a framework that ties academia, industry and government with focus on enabling technologies
  - Conduct a three-phase flight test program for space access applications (utilize NAI framework?)
  - Develop/upgrade required national test facilities
- **Decouple missions and platforms from critical technology development**
  - Avoids feast or famine funding cycles
  - Structure program to enable “off-ramps” to other applications and capabilities
  - Mature technologies prior to developing platforms – conduct vehicle design studies to establish technology requirements
- **Focus only on “enabling” technologies**
  - Propulsion, Thermal Management, Structures & Materials, and Vehicle Design/Optimization

High-Speed capability should be evaluated as a National Priority

Supporting Data Example: Hypersonic Propulsion

Hypersonic Air-Breathing Propulsion TRL Assessment*

	Mach 0 - 4 Turbine Hydrocarbon	Mach 3 - 7 Hydrocarbon	Mach 3 - 7 Hydrogen	Mach 7 - 14 Hydrogen
Engine Performance & Operability				
Inlet	5	5-6	5-6	5
Isolator	N/A	5-6	5-6	N/A
Fuel Injectors/Flameholders	4 (AB)	5-6	6	4-5
Combustor	6	5	5-6	4
Nozzle	4-5 (TMS)	5-6	5-6	4
Integrated Flowpath	4 (including AB & TMS)	5	5	4
Structures & Materials				
Cooled Materials	5 (turbomachinery)	7-8	7-8	4
Uncooled Materials	5	5	5	4
Cooling Panels	4 (nozzle & combustor)	5-6	5	3
Variable Geometry (e.g., seals)	4 to 5	4	4	3
Engine Subsystems				
Sensors	4 to 5	6	6	3
Valves	N/A	5	5	4
Pumps	N/A	6	6	6
Active Control System	4	4-5	6	5
Fuel to Air Heat Exchanger	3 to 4	N/A	N/A	N/A

Notes: Items in parentheses reflect requirements for a TBCC system.
AB = afterburner
TMS = thermal management system

* Inputs from Chuck McClinton – NASA Langley, Robert Mercier - AFRL, Paul Bartolotta – NASA Glenn, Fred Billig – Pyrodyne (JHU/APL retired), Bill Imfeld – ASC retired, Allen Goldman and George O'connor - Boeing Rocketdyne, Steve Beckel - Pratt & Whitney, and Kevin Bowcutt - Boeing

Boeing Supports NAI Hypersonic Flight Demonstration Programs

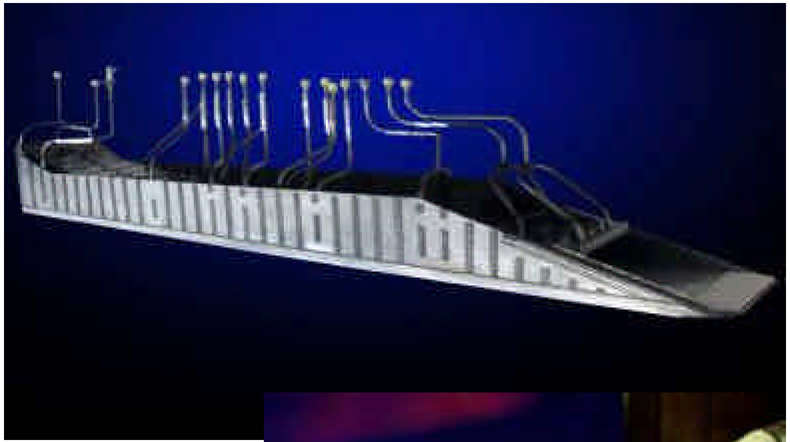
- Joint DoD and NASA plan to leverage Air Force HyTech program through a series of critical flight demonstrations
  - Demonstrate technologies required for first generation hypersonic vehicles
  - Single Engine Demonstration: Single hydrocarbon fueled scramjet engine
  - X-43C: Combines three Hytech engines in an aircraft-like configuration
  - X-43B: Combines HyTech advances with high-speed turbine to enable a reusable x-plane in the tradition of the X-15

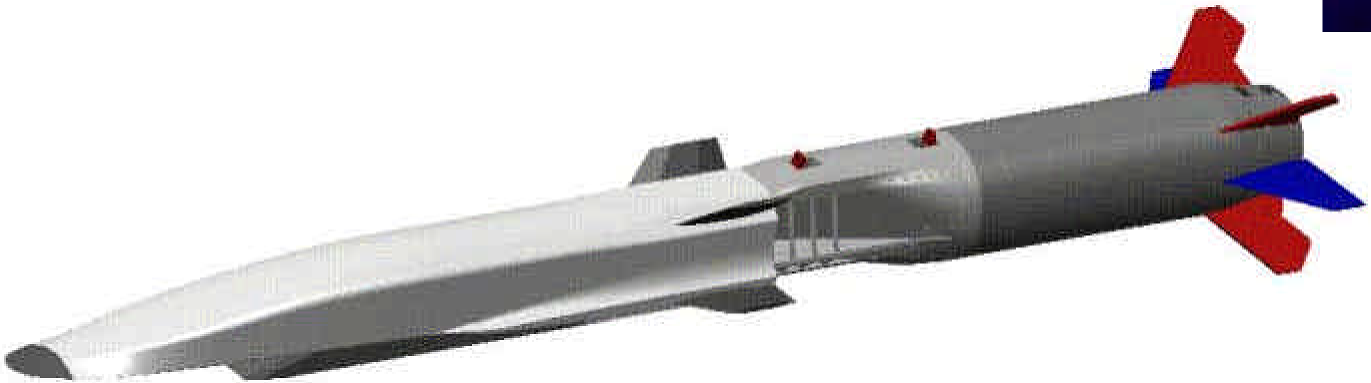
Will enable capabilities for responding to future time-critical threats rapidly from CONUS, and provide for reusable, cost-effective access to space

- Hypersonic missiles
- Hypersonic aircraft
- Air-breathing Reusable Launch Vehicles

AFRL/NAI Single Engine Demonstrator - Waverider Flight Demonstration Program

- Mach 7+ extended range flight test
- 5 flights, beginning in 2006
- Modular, scaleable HySET engine
  - developed by Pratt & Whitney
  - currently being flight-weight tested at Mach 4.5 and 6.0 at GASL
- Boeing integrated flight vehicle lead as subcontractor to Pratt & Whitney





NASA X-43 Series of Flight Demonstrators Will Provide Technology for Future Hypersonic Vehicles

- **Exploring hypersonic aero-propulsion technologies from transonic to Mach 15 speeds**
  - **Hydrogen and hydrocarbon scramjets**
  - **Combined cycle propulsion**
  - **Flight validation of design methods, tools and scaling laws**

X-43C

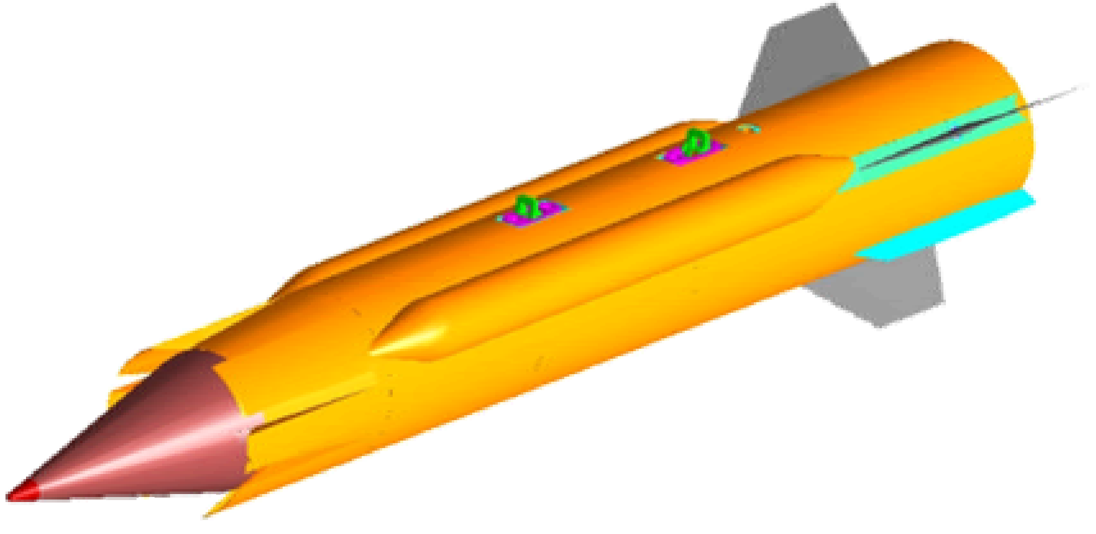
X-43B

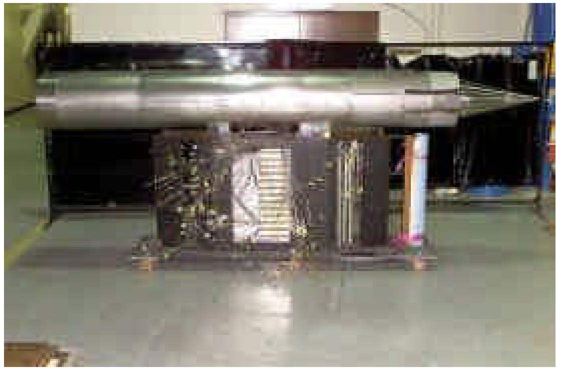
X-43A

X-43D

DARPA/ONR "HyFly" Hypersonic Missile Flight Demonstration Program

- Mach 6 flight demo
- 400-600 nm range
- 11 flights, beginning in 2004
- Powered by Dual Combustion Ramjet (DCR) engine
  - developed by JHU/APL
  - currently being ground tested
- Boeing lead contractor with Aerojet as engine subcontractor





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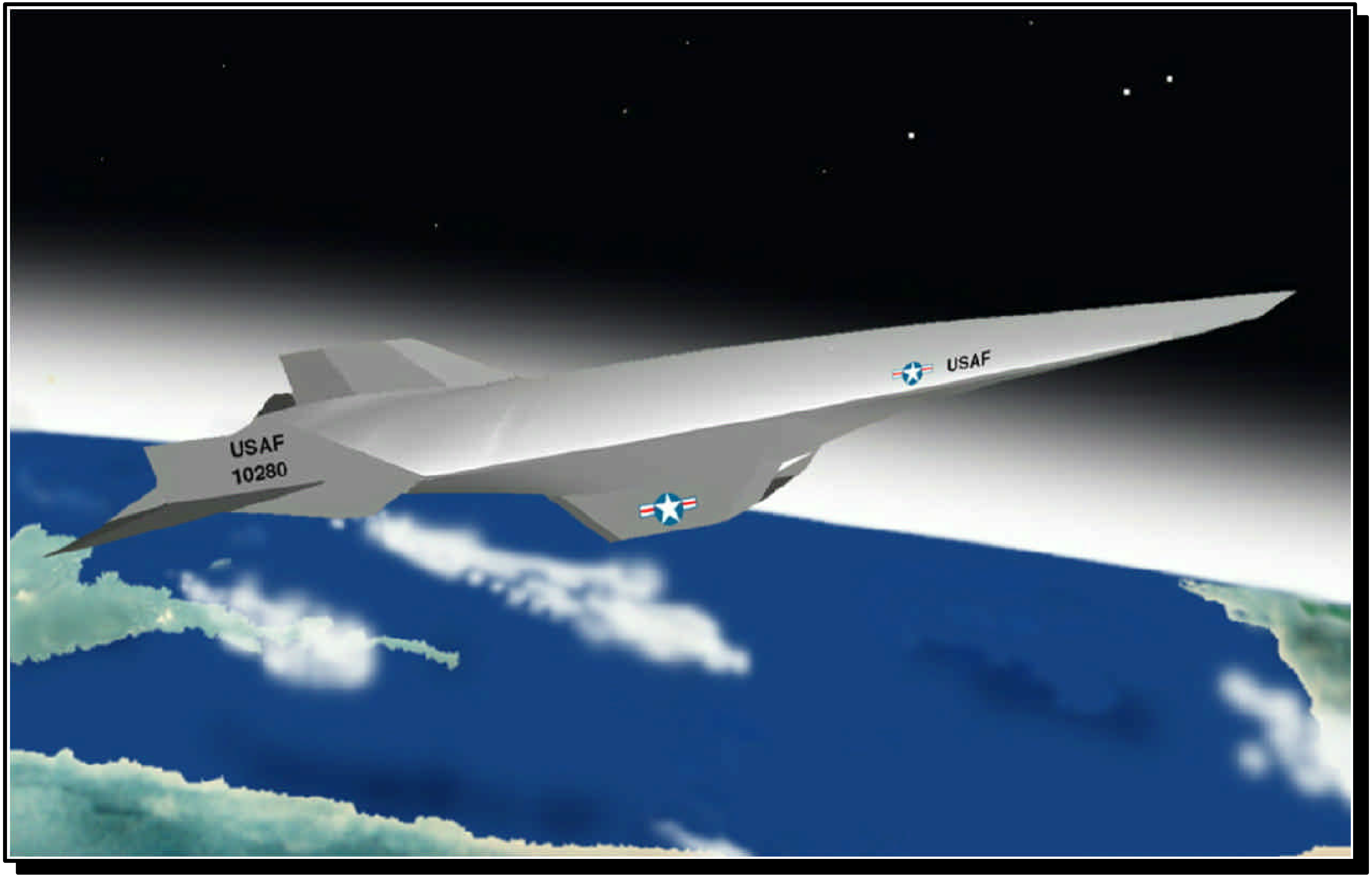
Mach 10 Global Strike Aircraft



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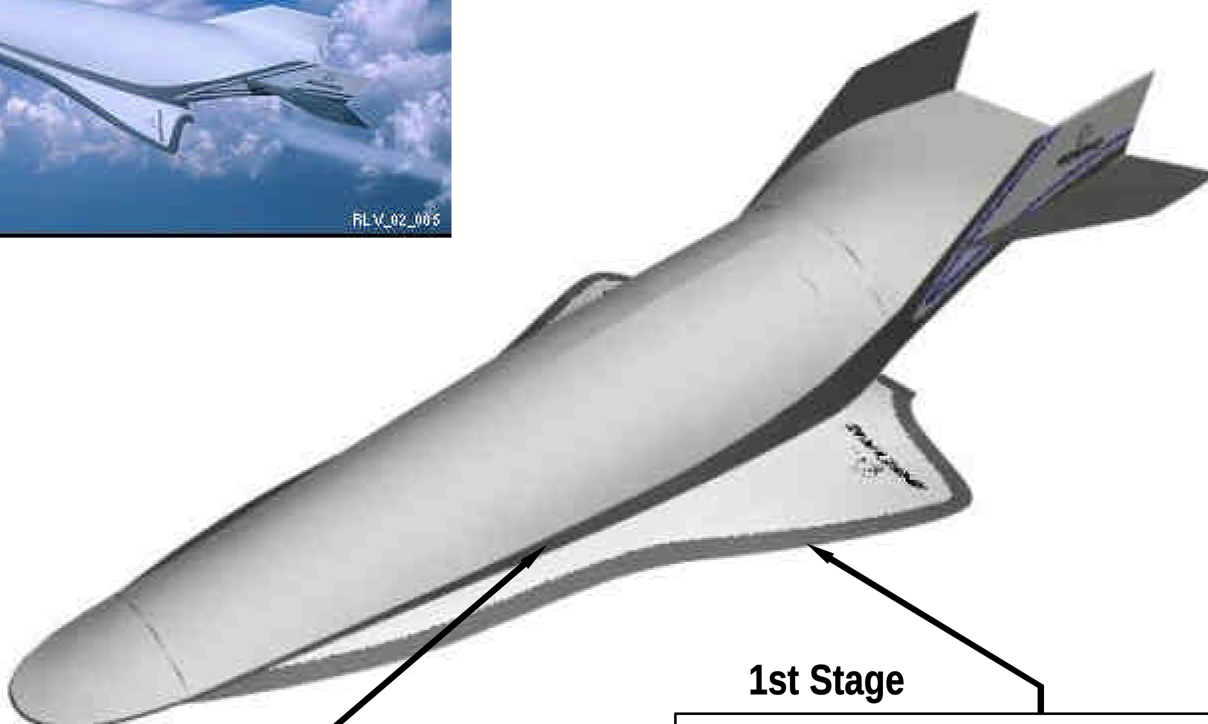
FASST TSTO Configuration Baseline – NGLT Architecture 6



2nd Stage

- RBCC Mach 4 to Orbit
- AAR/Rocket for Subsonic Abort
- LOX/LH2 for High Isp

1st Stage

- Revolutionary Turbine Accelerator (RTA) to Mach 4
- All Hydrocarbon Fuel