Overview of Commercial High-Speed Market Studies and NASA's Hypersonic Technology Project

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Invited Lecture to AIAA Northern Ohio Section

25 July 2023

Presentation Outline

- Introduction to Aeronautics Research Mission Directorate (ARMD)
- Independent High-Speed Commercial Vehicle Market Study Results
- Next Steps in Developing NASA's High-Speed Commercial Strategy
- Hypersonic Technology Project Overview
- Summary

NASA Aeronautics – Vision for Aviation in the 21st Century

ARMD continues to evolve and execute the Aeronautics Strategy *https://www.nasa.gov/aeroresearch/strategy*

6 Strategic Thrusts

- Safe, Efficient Growth in Global Operations
- Safe, Quiet, and Affordable Vertical Lift Air Vehicles
- Innovation in Commercial Supersonic Aircraft
- In-Time System-Wide Safety Assurance
- Ultra-Efficient Subsonic Transports
- Assured Autonomy for Aviation Transformation

U.S. leadership for a new era of flight

www.nasa.gov

Four Transformations for Sustainability, Greater Mobility, and Economic Growth

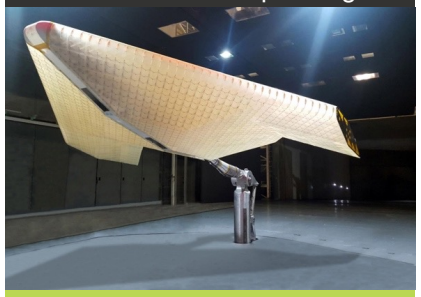
ARMD PROGRAMS

Airspace Operations and Safety Program

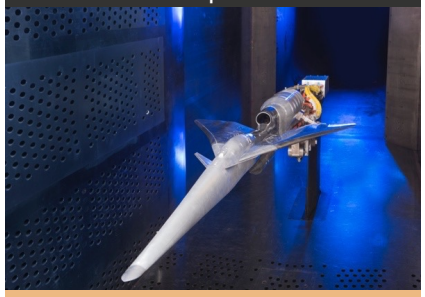
Advanced Air Vehicles Program

Integrated Aviation Systems Program

Transformative Aeronautics Concepts Program



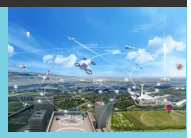
Aerosciences Evaluation and Test Capabilities Portfolio



Research Programs Align with Strategic Thrusts

MISSION PROGRAMS

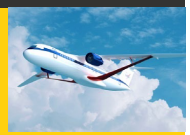
Airspace Operations & Safety (AOSP)



PROJECTS

- Advanced Air Mobility
- Advanced Capabilities for Emergency Response Operations
- ATM-X
- System-Wide Safety

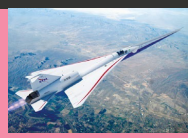
Advanced Air Vehicles Program (AAVP)



PROJECTS

- Advanced Air Transport Technology
- Hybrid Thermally Efficient Core
- Hi-Rate Composite Aircraft Manufacturing
- Commercial Supersonic Technology
- Revolutionary Vertical Lift Technology
- Hypersonic Technology

Integrated Aviation Systems Program (IASP)



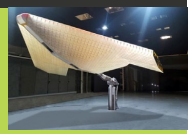
PROJECTS

- Electrified Powertrain Flight Demonstration
- Flight Demonstrations and Capabilities
- Low Boom Flight Demonstrator
- Sustainable Flight Demonstrator

Integration & Flight

SEEDLING PROGRAM

Transformative Aeronautics Concepts Program (TACP)

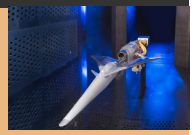


PROJECTS

- Convergent Aeronautics Solutions
- Transformational Tools & Technologies
- University Innovation

PORTFOLIO OFFICE

Aerosciences Evaluation and Test Capabilities (AETC)



GROUND FACILITIES

- Subsonic
- Transonic
- Supersonic
- Hypersonic
- Propulsion
- Test Technology

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Four Transformations for Sustainability, Greater Mobility, and Economic Growth

What Are We Trying To Do?

Enable high-speed commercial flight

To connect people and businesses faster

High-Speed Commercial Vehicle Workshops

4 Govt/Industry Workshops held 2020-2022

Jan 2020

February 2021- Virtual

June 2022

December 2022- Virtual

Industry Feedback On Opportunities/Needs:

- Independent market study
- Hypersonic ground and flight test capability
- Technology development through collaborative agreements
- Regulatory concerns
- International partnerships
- Data protection concerns (export control, classified, CUI, etc.)
- Integration into NAS

FY20/21 High-Speed Market Studies

- **The overwhelming number one request that industry had for NASA from the first Commercial High-Speed Workshop was to conduct an independent market study to determine the viability of high-speed / hypersonic commercial travel.**
- **NASA subsequently funded two contracts, one to Deloitte/SpaceWorks and one to SAIC/Bryce, to study the market given three specific tasks:**
  1. Define the market – how many people would be willing to travel and how much revenue could be generated?
  2. Define the business case – can an aircraft (Mach 2-5+) be fielded to serve this market and be able to generate enough profit to make it economically viable?
  3. What are the barriers preventing this market from becoming reality?
- **Deloitte and SAIC spent six months studying the problem; final reports are public**

SAIC/Bryce

– SAIC Report: https://ntrs.nasa.gov/citations/20210015471
– SAIC Presentation: https://ntrs.nasa.gov/citations/20210015472
– Deloitte Report: https://ntrs.nasa.gov/citations/20210014711
– Deloitte Presentation: https://ntrs.nasa.gov/citations/20210014932

Deloitte/SpaceWorks

Results– Commercial Markets Exists

Favorable High-Speed Market Characteristics

	SAIC (with Bryce Space and Technology)	Deloitte (with SpaceWorks and NIA)
Mach	3	2 to 4[1]
Range	4,500 nmi	4,000 nmi to 4,500 nmi
Number of routes[2]	300	90
Aircraft Size (# PAX)	10 GA or 50 Commercial	20 to 50
Aircraft Cost	$200M to $300M	$131M to $228M[3]

References:
- SAIC Final Report: https://ntrs.nasa.gov/citations/20210015471
- Deloitte Final Report: https://ntrs.nasa.gov/citations/20210014711

[1] Analysis showed profitable routes up to M5.25
[2] Deloitte only considers over-water routes
[3] Mach 3 at 4,500 nmi

Results– Market Demand

Deloitte Market Forecasts

PASSENGER

- Market appears strong with several stand-out routes to start.
- Identified a total addressable market of 90 transoceanic routes.
- Includes 2.25M annual passengers and a potential for $16.5B in revenue.

CARGO

- 40% of consumers surveyed were willing to pay for faster shipping services.
- Would create between a $7B market for 12-hour shipping to a $14B market for 5-hour shipping in the first year.

PRIVATE

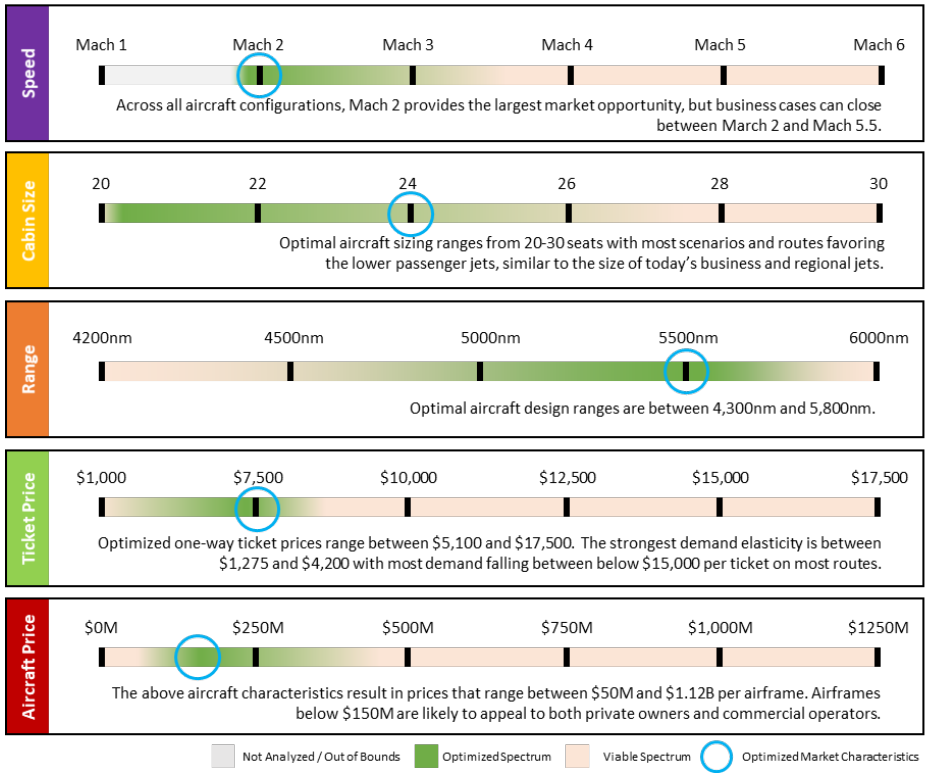
- Historical private aircraft at comparable sizes and prices indicate that the market would tolerate a Mach 2 jet at $79M.
- Price much lower than current manufacturers are projecting.

To achieve optimal ROI, industry and government stakeholders will need to leverage existing resources in the defense industrial base while building out the civil side of the market.

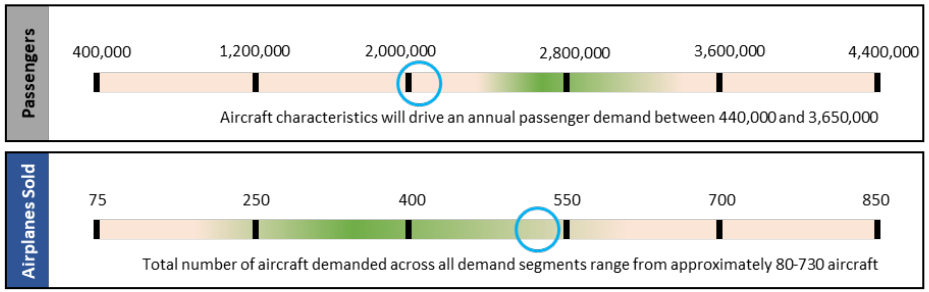
Deloitte/SpaceWorks – High-Speed Market Business Case

There are multiple markets scenarios that close economically with technically achievable solutions between Mach 2 and Mach 5.5. The market conditions point towards a March 2 to Mach 3 jet that can serve key transatlantic and transpacific routes at market entry and can be utilized for both passenger and private air service.

Aircraft Characteristics



Market Characteristics



A Strong Market Picture

Though there are multiple markets scenarios that close economically with technically achievable solutions, our analysis suggests a likely optimized outcome:

Mach 2
Aircraft

$120M
Approximate Aircraft Cost

541
Total Aircraft Demand

20
Passengers Capacity

5,500 NM
Aircraft Range

2.1M
Annualized Passengers

Primary Demand Categories:

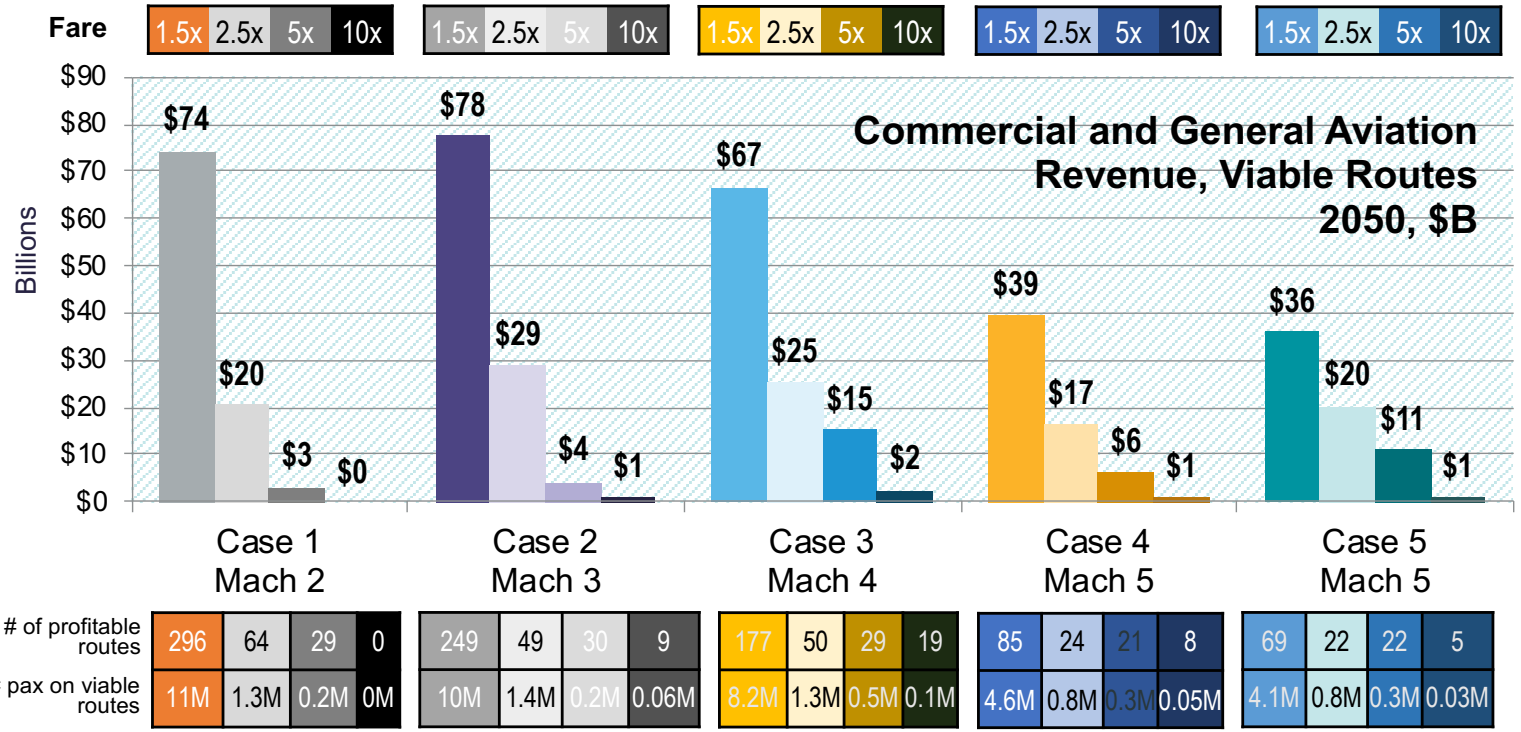
1. Scheduled passenger service providers (i.e., airlines) for transoceanic routes
2. Jet Card Memberships and Charter (i.e., on-demand) service providers for transoceanic routes
3. High net worth individuals that travel transoceanic routes, often between global wealth centers

While the likely market scenario is economically sustainable and technically feasible, the current regulatory environment, specifically sonic boom restrictions, significant limits the ability to serve primarily overland routes, such as Los Angeles (LAX) to London (LHR) or London (LHR) to Singapore (SIN) which could attract an additional 1M annual passengers and result in an additional $3.94B in revenue.

Deloitte/SpaceWorks – Top-Level Economic Findings

1. **There are multiple aircraft configurations and market approaches that result in positive business cases for their manufacturers and operators (assumed as Initial Rate of Return (IRR) > 25%)**
   - Smaller aircraft (20 – 50 pax) tend to be favored over larger aircraft for several factors, including sales synergies with the private/charter market and higher average passenger load factors on thin routes
   - Slower cruise speed aircraft (Mach 2 – 3) in the 4,000 nmi – 4,500 nmi class are also slightly favored and result in lower ticket prices and therefore larger market sizes. This seems to be a more robust part of the market, but profitable markets exist up to Mach 5
   - North-Atlantic markets remain the largest economic prize, but longer trans-Pacific ranges remain interesting for smaller Mach 2 – 3 vehicles that can reach to 6,000 nmi+
2. **Results are most sensitive to potential reductions in estimated passenger market size**
   - Fuel cost increases, engine development cost increases, and loss of private/charter sales are also important
3. **Government contributions via non-recurring offsets or "anchor buys" are helpful**
   - More beneficial for 1) smaller overall aircraft development program (gov't contributes a larger percentage of the total cost) or 2) higher speed aircraft where predicted annual airframe sales are not as large. However, government contributions are not required for success

SAIC– High-Speed Market Business Case



- Passenger demand is greatest for Case 1 (Mach 2) with 11M passengers
- Revenue is greatest for Case 2 (Mach 3) at $78B
- Demand (as well as revenue) take a deep fall as the fare increase to 2.5X standard

How is This Different Than Concorde?

Significant increase in the number of wealthy individuals

Then
2M in U.S. Worth $1M

Now
10M in U.S. Worth $1M

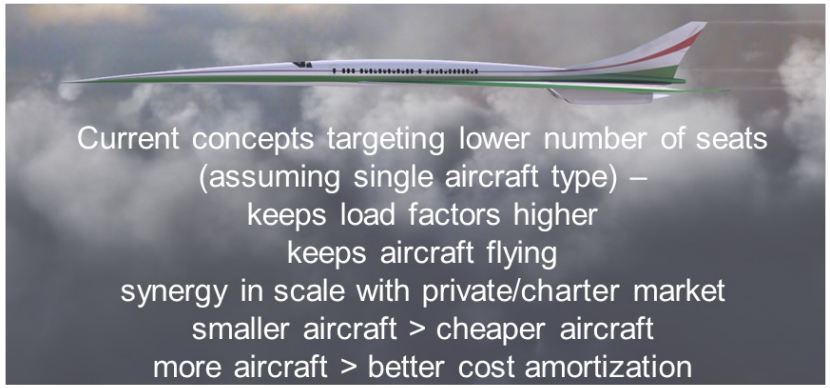
Today, business travelers account for 12% percent of airlines' passengers, but they are typically twice as lucrative – accounting for as much as 75% of profits.

1980 — 2019

Then
600M World-wide PAX

Now
4.5B World-wide PAX

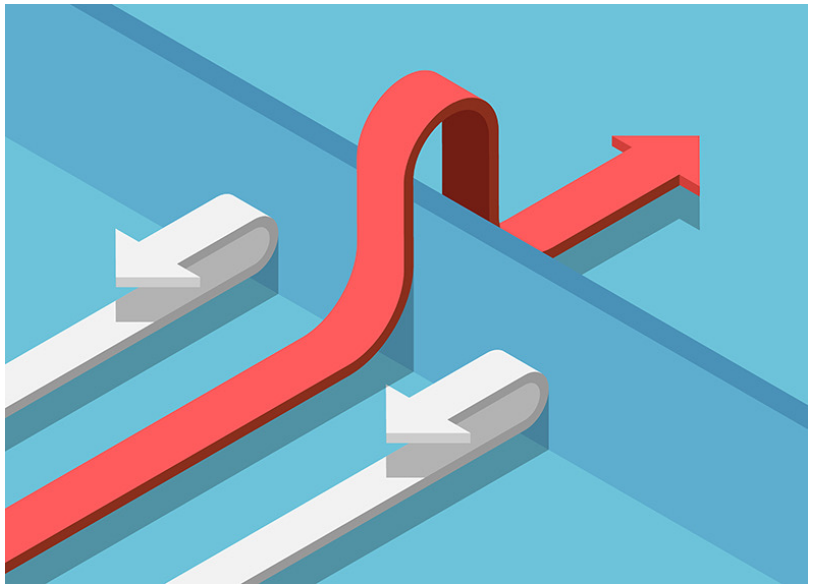
Significant increase in number of travelers in general, as well as those willing to pay premium (wealthy individuals & corporations)

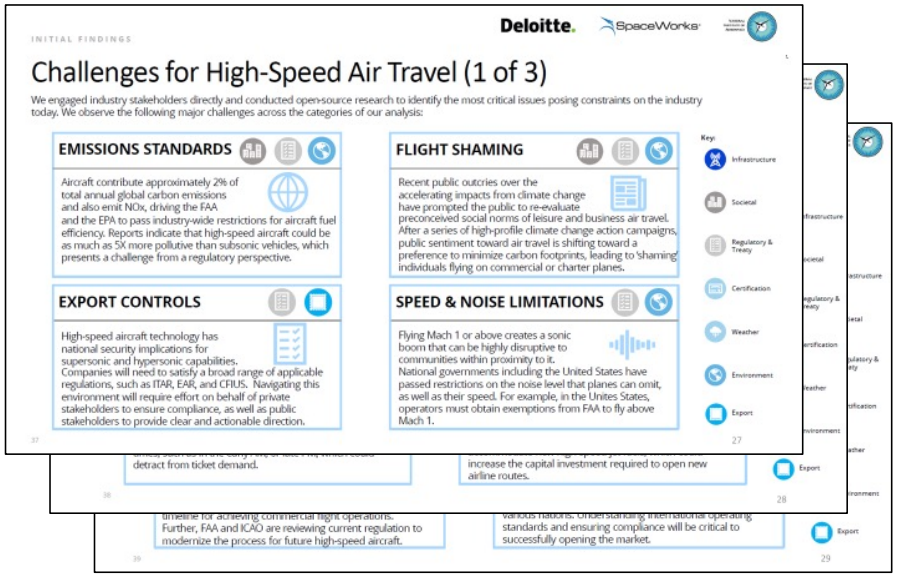


Concorde		~M3 Aircraft
100	Aircraft Seats	20-50
50%	Average Load Factor	85%
3	Profitable Routes	~100 (over water)
20	Production Size	300
400 Klb	GTOW	200 Klb
1000s	Annual PAX	3M

To a lesser extent, but not insignificant,
are improvements in airframe and propulsion technologies

What Needs To Be Done?





Eliminating technical and regulatory barriers

Deloitte/SpaceWorks – Barriers / Challenges Heat Map

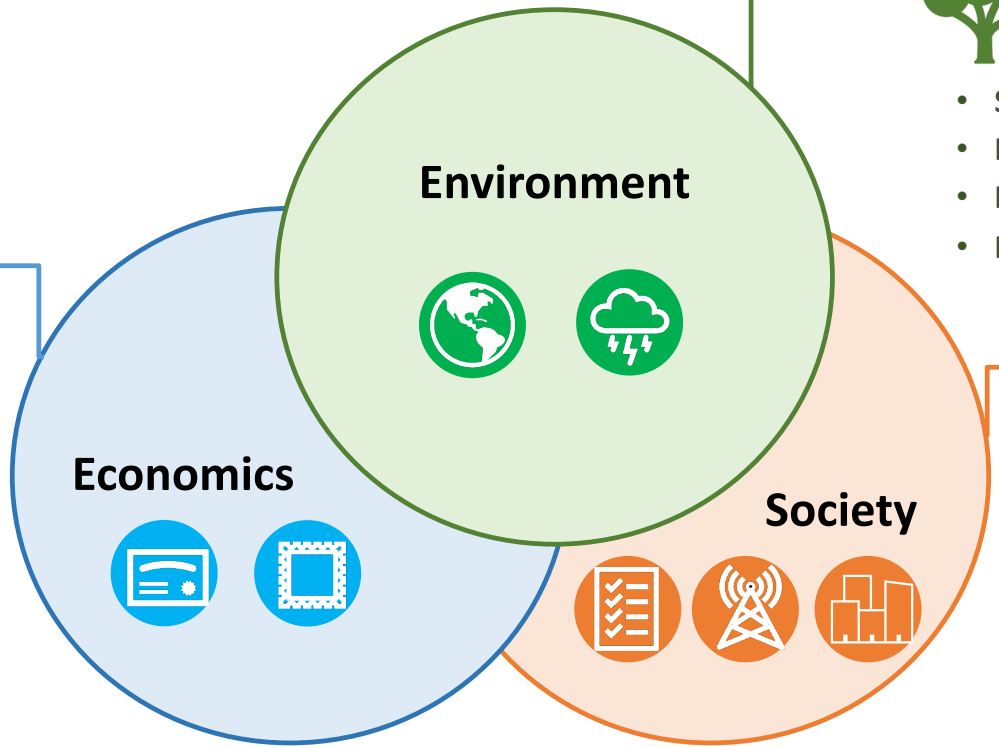
Challenge	Compliance	Solution	Investment	Ease of Use	Community	Total	Rank Categorization[1]
1. Sonic Boom Restrictions	3	2	3	2	3	13	Barrier
2. Aircraft Certification	3	3	3	1	2	12	Barrier
3. Landing & Takeoff Noise	2	2	2	1	3	10	Barrier
4. Emissions Standards	2	2	2	1	2	9	Significant Challenge
5. Export Controls	3	1	2	2	1	9	Significant Challenge
6. Depressurization Event	1	1	2	2	2	8	Minor Challenge
7. Alternative Fuels	2	2	2	1	1	8	Minor Challenge
8. International Laws	2	2	2	1	1	8	Minor Challenge
9. Heat Sensitivity	1	2	2	2	1	8	Minor Challenge
10. NAS Integration	2	1	1	2	1	7	Minor Challenge
11. Anomalous Radiation Events	2	1	1	1	2	7	Minor Challenge
12. Flight Shaming	1	1	2	1	2	7	Minor Challenge
13. Runway Length	1	3	1	1	1	7	Minor Challenge
14. Time Zone Gaps	1	1	1	2	1	6	Minor Challenge
15. Pilot Certification	1	1	1	1	1	5	Minor Challenge

Rank Categorization Key Definitions:

- **Barrier**: an issue that could outright prevent the market from starting.
- **Significant Challenge**: an issue that will likely materially impact the business case.
- **Minor Challenge**: an issue will likely impact the business case only minimally.

What Is New in Our Approach?

Sustainability



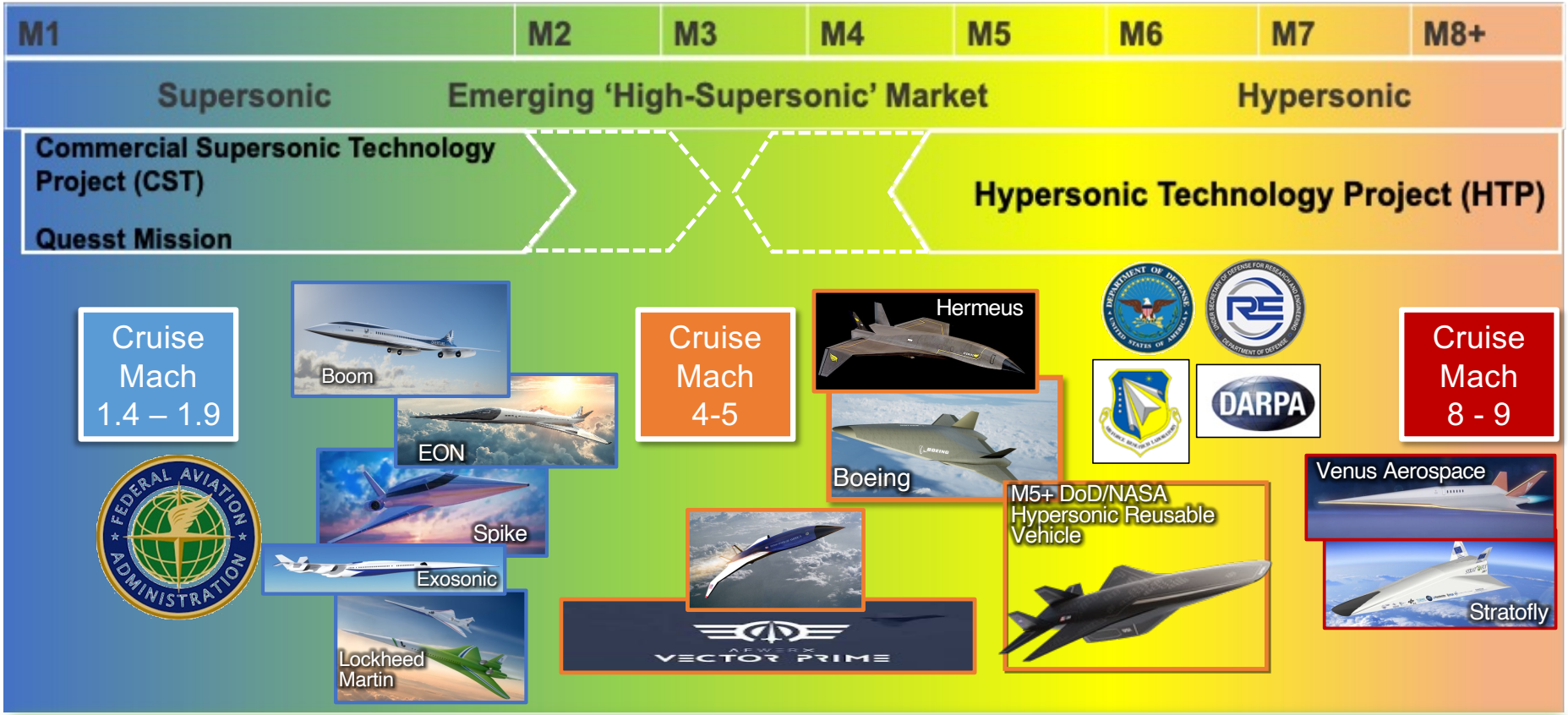
- SONIC BOOM STANDARDS
- LTO NOISE STANDARDS
- HIGH ALTITUDE EMISSIONS STANDARDS
- FUEL STORAGE

- AIRCRAFT CERTIFICATION
- PILOT CERTIFICATION
- AIRCRAFT FUEL

- EXPORT CONTROL REGULATIONS
- INTERNATIONAL LAWS
- FLIGHT SHAMING
- TIME ZONE GAPS

Address sustainability from day one

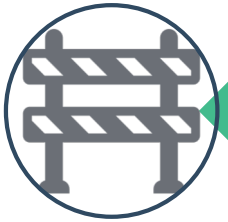
NASA High-Speed Strategy: Stakeholders



Industry is aggressively pursuing high-speed market; NASA's role is to help make it sustainable

Key Takeaways

Studies concluded potential commercial high-speed markets exist at Mach 2-4, as well as up to Mach 5-5.25



Many of the key barriers for commercial supersonic and hypersonic flight appear to be similar, but there are significant differences resulting from differences in Mach and associated flight conditions

Industry feedback from 3rd High-Speed Commercial Vehicle Workshop (June 2022) reinforced the need for conceptual vehicle studies to assess these barriers and potential solutions in the $2 \leq M \leq 5$ range

High-Speed Investment Opportunities to be Identified by 3QFY24

High-Speed Strategy Next Steps In Work

Development of New High-Speed Commercial Vehicle Conceptual Designs and Technology Roadmaps

- Award contracts for 12-month effort to develop baseline conceptual designs (or preferably families of concepts) and technology roadmaps in the Mach 2-5 range
- Non-proprietary concepts will be key for use in regulatory studies
- Use roadmaps to identify technologies for future NASA investment in FY24 and beyond

Legacy Supersonic N+2/N+3 Conceptual Designs

Acquisition Schedule

- ✓ July 19, 2022- Industry Day Held
- ✓ August 8, 2022 – Released Final Request for Proposal
- ✓ September 20, 2022 – Proposals Received
- ✓ December 16, 2022 –Contracts Awarded
- ✓ February 24, 2023- Contract Kickoff w/Northrop Grumman
- ✓ June 27, 2023- Contract Kickoff w/Boeing

Image Credit: The Boeing Company

Technology Roadmaps Will Help Identify Areas For Future NASA Investments

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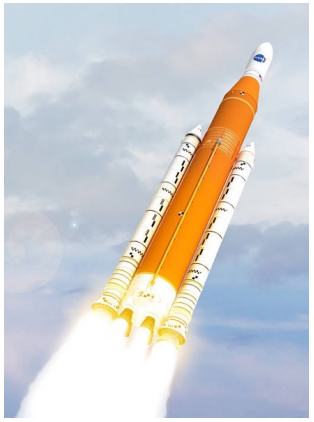
NASA Hypersonic Applications

HYPERSONICS

- **Blunt Body Re-entry**
- **Launch**
- **Unpowered Atmospheric Flight**
- **Powered Atmospheric Flight**



Multiple NASA applications require mastery of hypersonic flight

HTP Research Focused on Reusable Applications

Hypersonic Powered Atmospheric Flight

Weapons

Sustained Atmospheric Cruise

Space Access

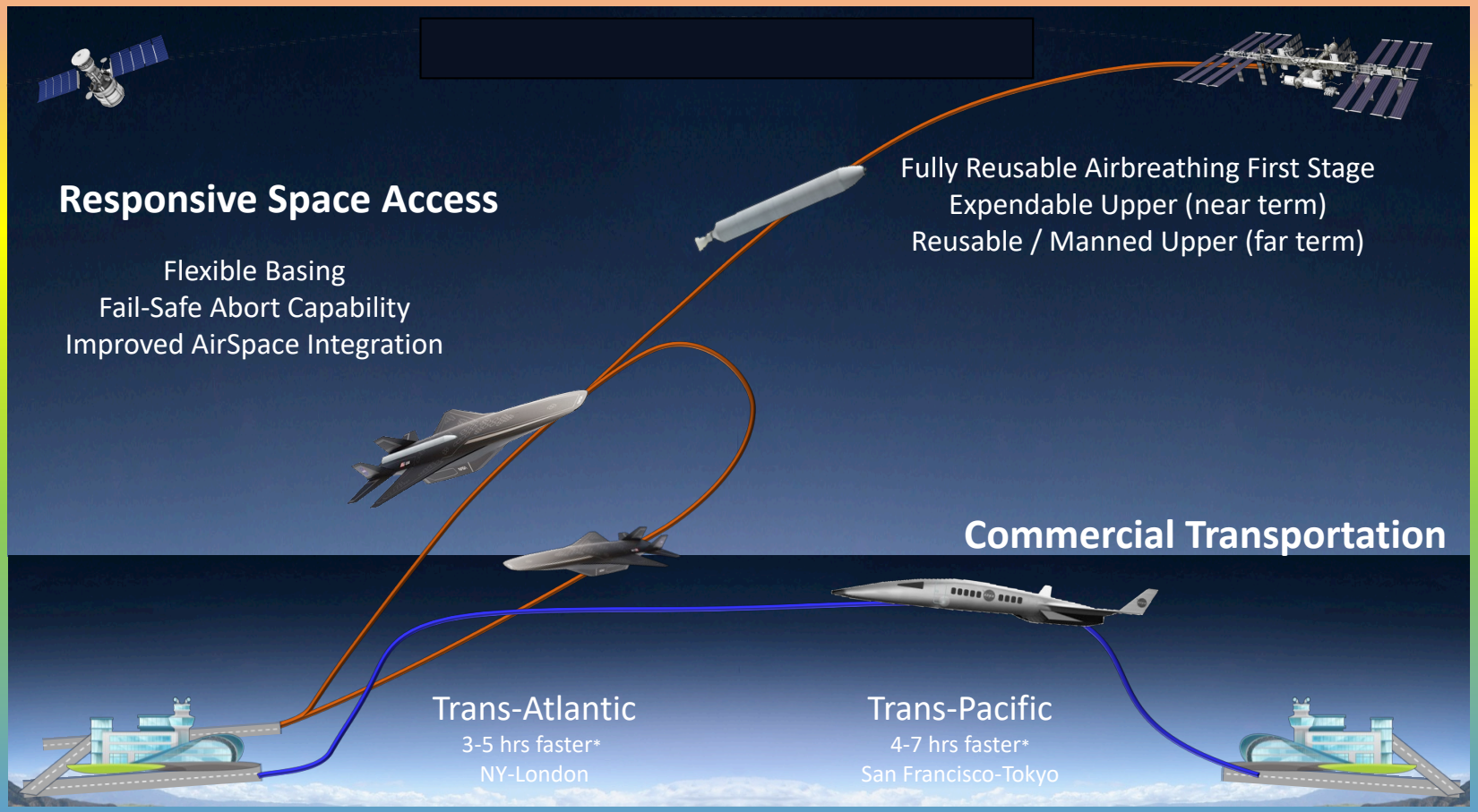
Commercial Point to Point

Long Range Strike; Penetrating ISR

Civil Applications

Partnership between NASA and DoD is critical to progress in hypersonic flight

Envisioning High-Speed Civilian Airspace of Tomorrow



*Mach 2-5 cruise vs subsonic

HTP Long-Term Strategy

VISION

Enable routine, reusable, airbreathing hypersonic flight

MISSION

Advance core capabilities and critical technologies underpinning the mastery of hypersonic flight to support U.S. supremacy in hypersonics

APPROACH

Conduct fundamental and applied research to enable a broad spectrum of hypersonic systems and missions

Overarching Strategic Goal

Develop dual-use technologies aligned to reusable vehicle requirements for both civilian and military missions

Key External Partners / Stakeholders

AFRL / DARPA / JHTO-UCAH / AFOSR / ONR / INDUSTRY / UNIVERSITIES

Applied Research Focus- TRL 6 by 2030 | **Long-Term Strategic Goals** | Fundamental Research Focus- TRL 6 by 2040

First Generation Reusable Airbreathing High-Supersonic/Hypersonic Vehicle for Commercial Point-to-Point Mission

Develop enabling technologies via ModSim, Ground Test, and Flight Test for reusable aircraft with speeds up to Mach 8

Next Generation Reusable Airbreathing Hypersonic Vehicle (Sustainable) for Commercial Access to Space Mission

Develop enabling technologies via ModSim, Ground Test, and Flight Test for sustainably-fueled, reusable aircraft with speeds up to Mach 12

Enduring Project Priorities

#1 - Support NASA/DOD partnerships and deliver on external commitments

#2 - Execute Technical Challenges to deliver critical enabling technologies

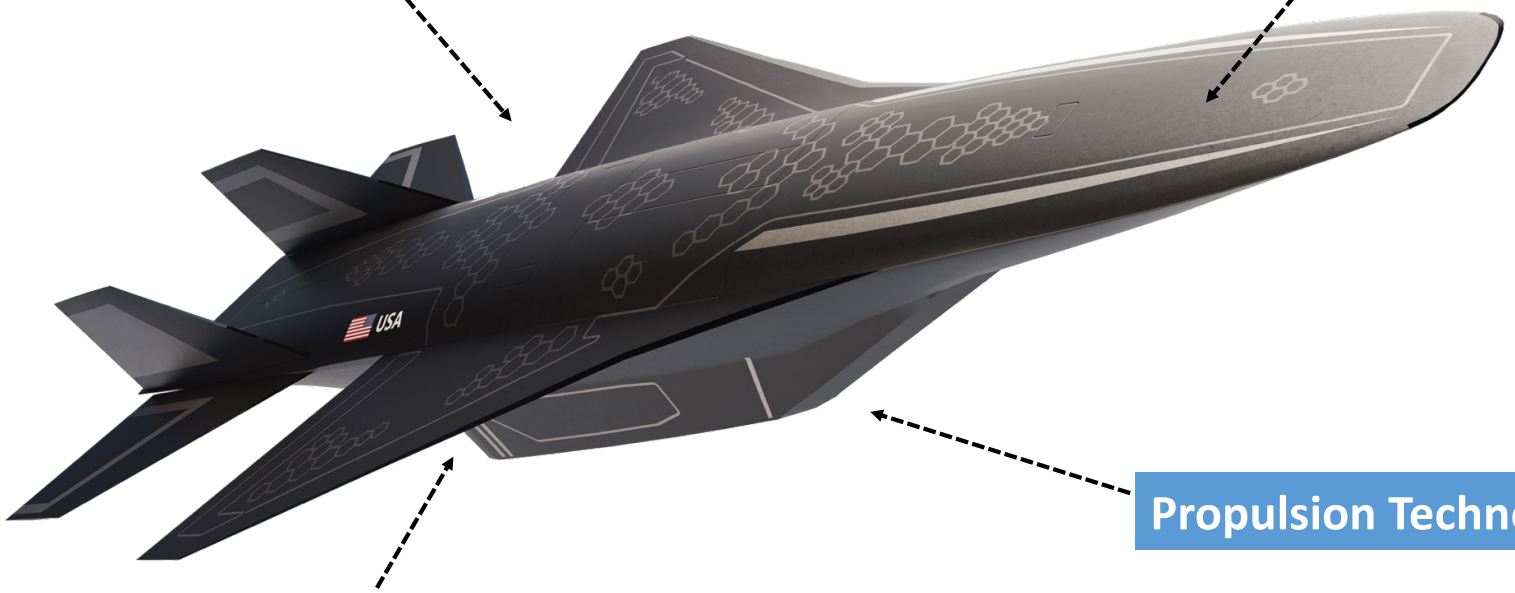
#3 - Continue NASA-directed research; sustain/grow core competencies and capabilities

#4 - Develop the next generation of U.S. hypersonic experts

HTP Investment Areas
in the Barriers to Reusable Hypersonic Flight

System-Level Design, Analysis, and Validation

Vehicle Technologies



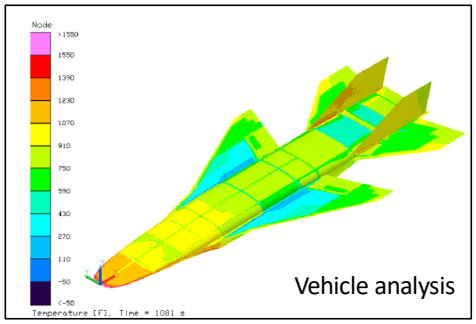
Propulsion Technologies

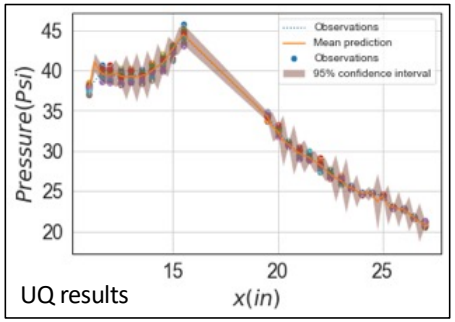
High Temperature, Durable Materials

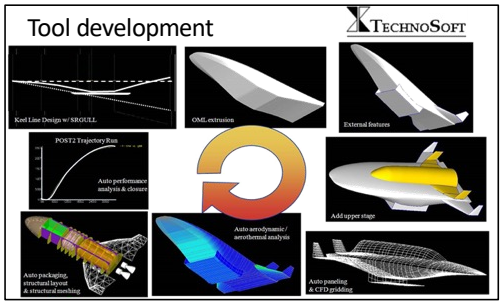
System Level Design, Analysis, and Validation

Design and analyze civil-relevant reference vehicles and inform programmatic decision-making

Technical Lead: Tom West (LaRC)







RT-1.1:
Multidisciplinary Design/Optimization and Uncertainty Quantification (MDAO & UQ)

RT-1.2:
Fluid-Thermal-Structural Interaction (FTSI)

RT-1.3:
Power and Thermal Management Systems (PTMS)

RT-1.4:
Vehicle Design

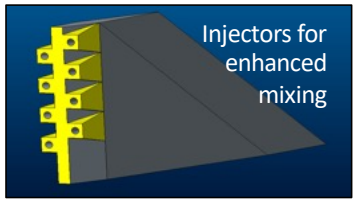
RT-1.5:
Aerosciences Capability Development

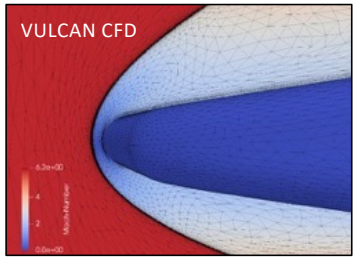
RT-1.6:
Design Fidelity Enhancement

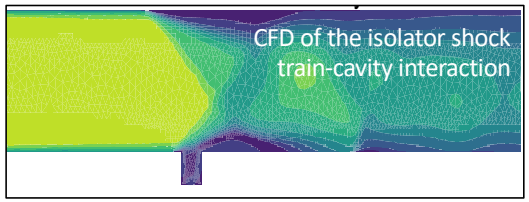
Propulsion Technologies

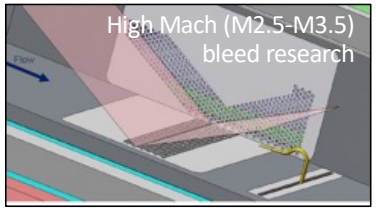
Maturing airbreathing propulsion technologies necessary for hypersonic TBCC vehicles

Co-Technical Leads: Tom Drozda (LaRC) and Lancert Foster (GRC)







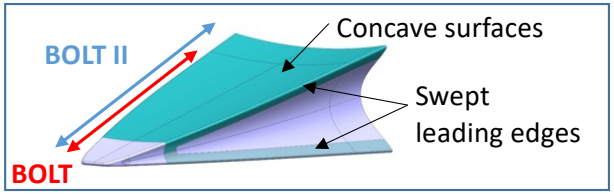


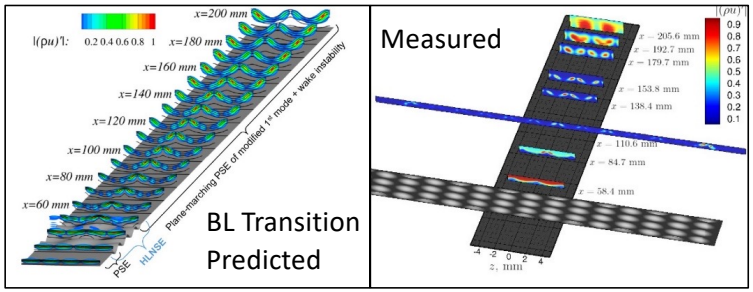
- RT-2.1: Enhanced Injection and Mixing
- RT-2.2: VULCAN-CFD Development
- RT-2.4: Advanced Pressure Sensors for Adaptive Controls and Health Monitoring
- RT-2.6: Isolator Dynamics Research Lab (IDRL)
- RT-2.8: Turboramjet Technology Development
- RT-2.9: Aether Subscale Ground Test Propulsion Database Development

Vehicle Technologies

Foster the development of tools and technologies from fundamental to applied hypersonic vehicles

Technical Lead: Amanda Chou (LaRC)



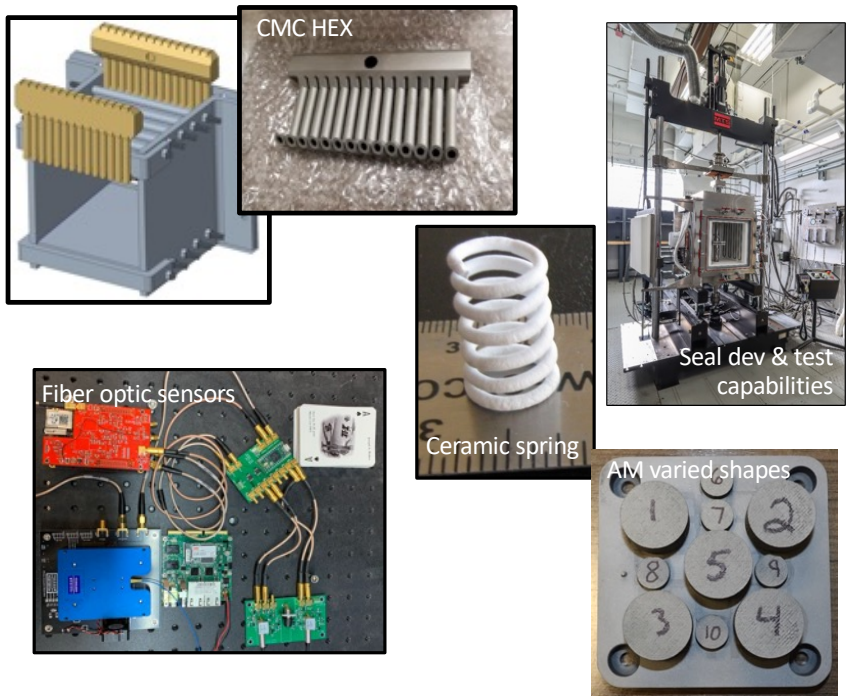


- RT-3.1: Flight Testing/Program Support
- RT-3.2: Boundary Layer Transition Validation and Computational Tools
- RT-3.3: Fluid-Structure Interaction
- RT-3.4: Shock-Shock/Shock-Boundary Layer Interactions
- RT-3.5: Flow Control Applications

High Temperature, Durable Materials

Provide demonstrated high temperature material and component solutions/ data/ lessons learned to enable reusable hypersonic vehicles

Technical Lead: Chris Kostyk (AFRC)



RT-4.1: Conclude in FY24
Ceramic Matrix Composite (CMC) Heat Exchanger (HEX)

RT-4.2:
High Temperature Seals

RT-4.4: Conclude in FY24
Additive Manufacturing for Hypersonic Engines

RT-4.5:
High-Temperature Fiber Optic Sensors

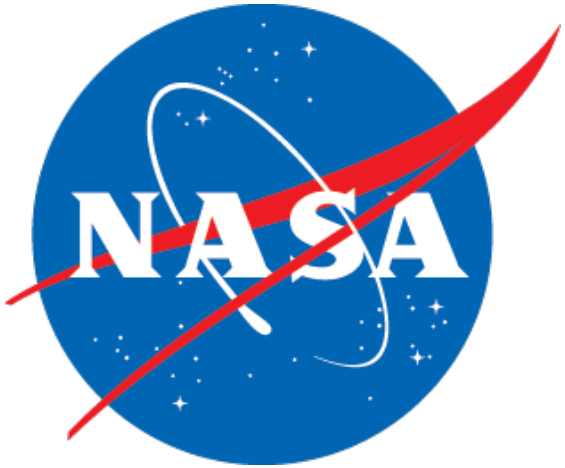
RT-4.6: NEW START in FY24
Materials and Structures for Hypersonic Airframe Components

RT-4.7: NEW START in FY24
Materials and Structures for Hypersonic Propulsion Components

Summary

- NASA is developing a strategy to support the commercial high-speed market
- NASA Hypersonic Technology Project (HTP) investments are aligned with dual-use / civil applications
- HTP is addressing major technical barriers
  - System design and analysis including uncertainty quantification
  - Turbine-based combined-cycle propulsion system component research
  - Fundamental research in aerothermodynamics
  - High-temperature, durable materials for engine and airframe applications

Working to enable routine, reusable, airbreathing hypersonic flight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