From Aerospace Planes to Cruise Missiles: a 37-year Journey at Hypersonic Speeds

Dr. Mark Lewis
CEO
Purdue Applied Research Institute

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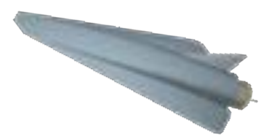
Why Hypersonics?

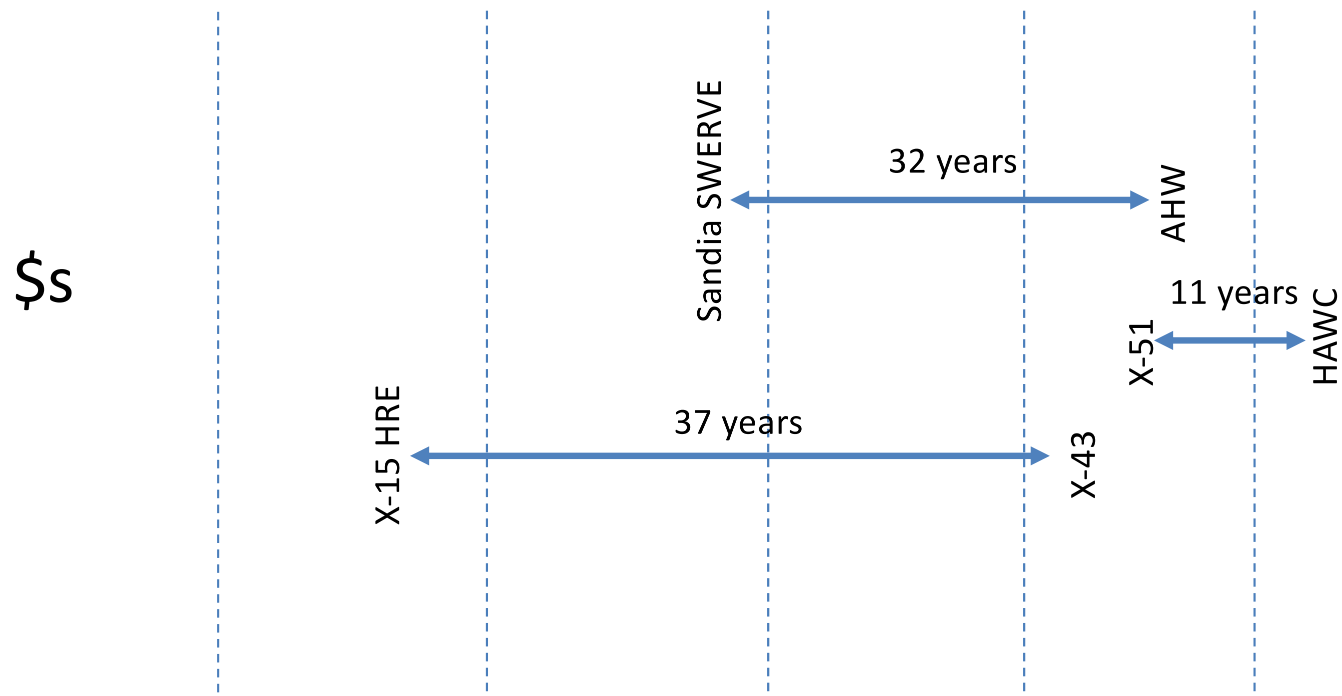
- **Space Access**
  - **All reentry systems**
  - **Airplane-like operations in space**



- **Military applications**
  - **Speed + Maneuverability + Altitude = Survivability**
    - **Difficult to detect and track**
    - **Ambiguity in purpose**
    - **Challenging (not impossible) to stop**
  - **Rapid response against time-sensitive targets**
  - **Precision-strike alternative to nuclear options**
  - **Gets inside an opponent's "OODA Loop"**

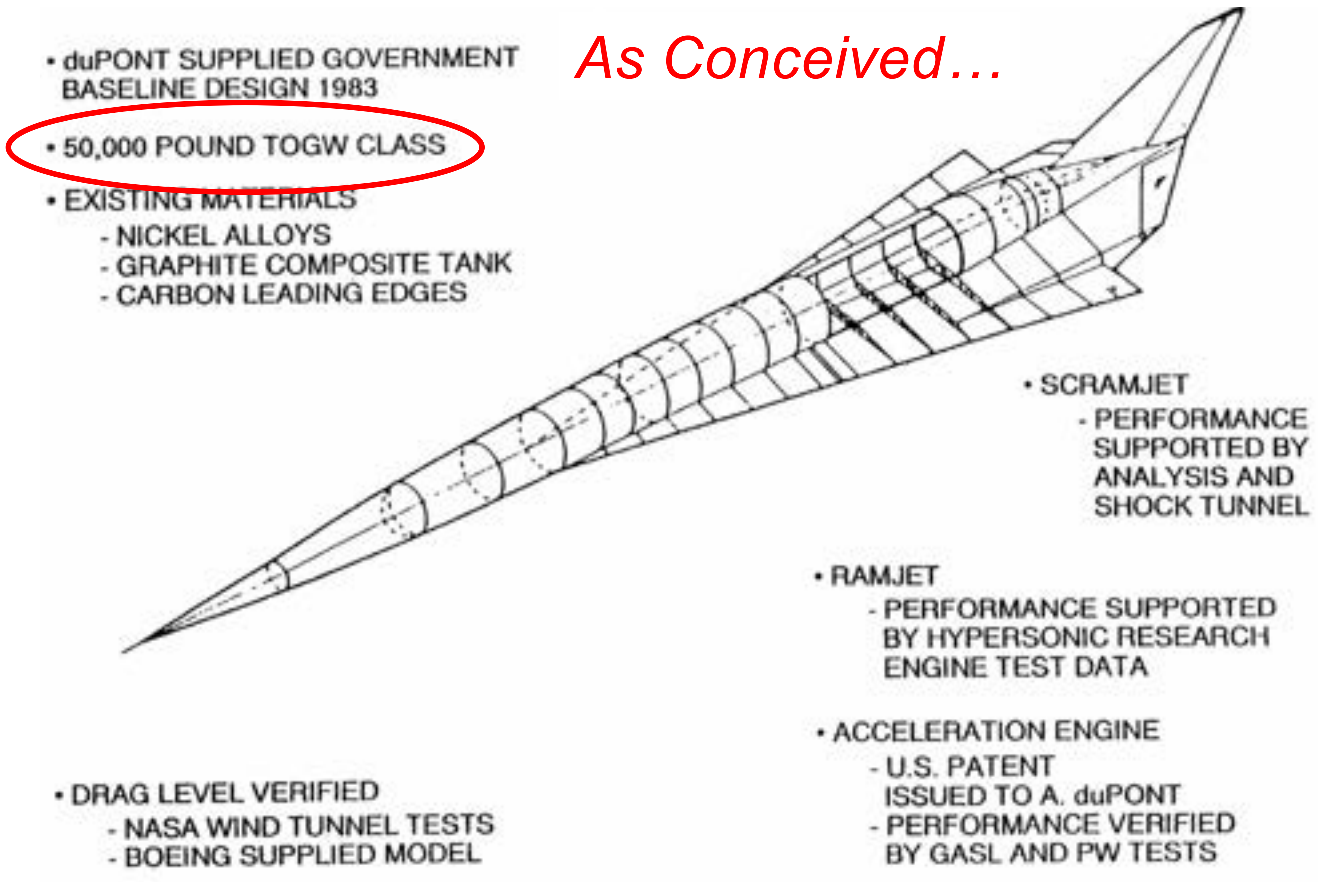
- **Commercial interest**
  - **Reduce travel times by > 6x**

The “Hallion Cycle”



X-30 NASP 1985

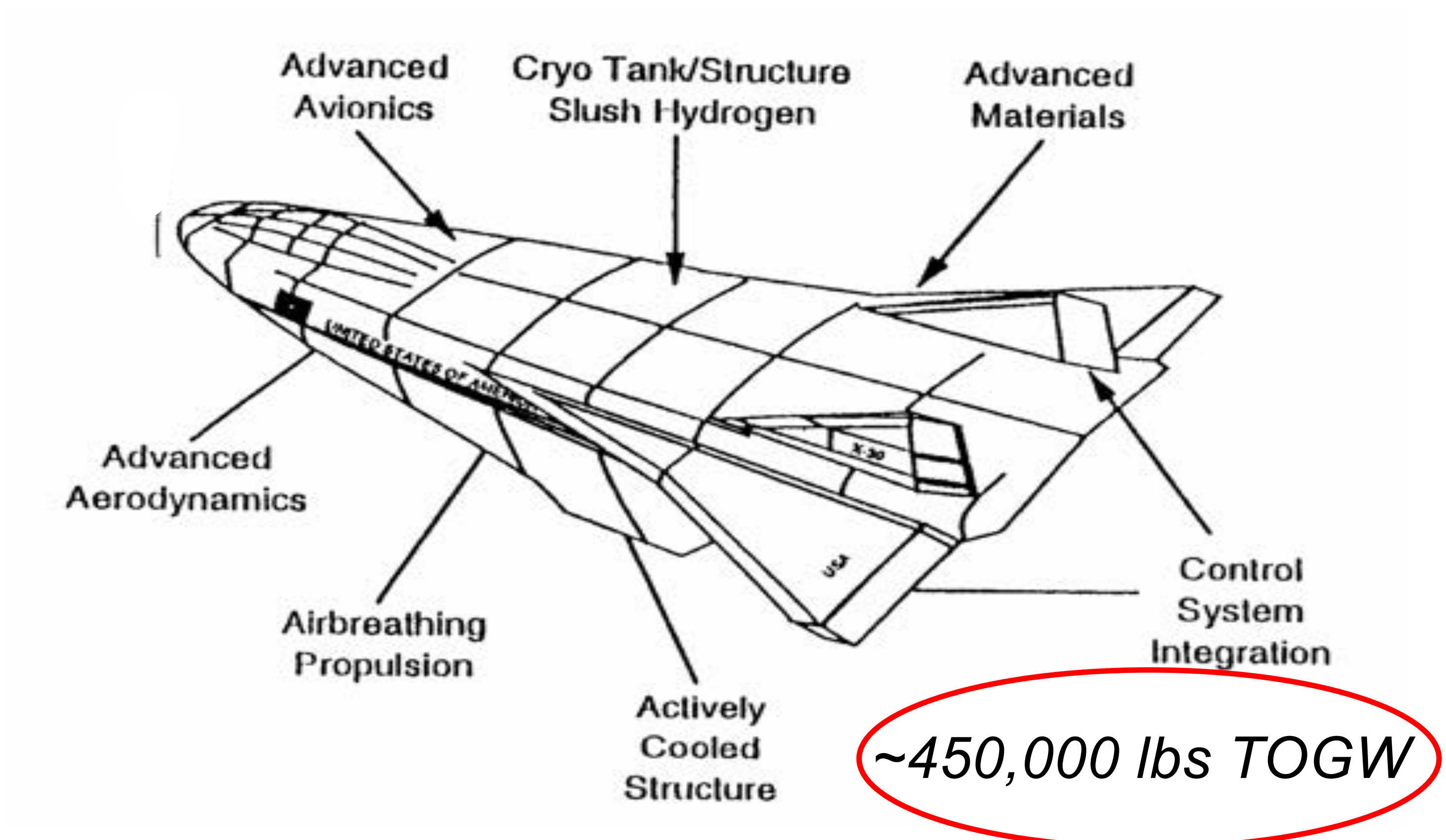
Where I started as a grad student



Courtesy: R.P Hallion

X-30 NASP 1993 At Program Cancellation

As I was getting tenure



NASA Dwg

USAF Hypersonic Attack Cruise Missile

Now that I'm Prof. Emeritus

SOURCE: AFRL

Where We Are Today: Over 70 DOD Programs

- Conventional Prompt Strike (CPS) / Common Hypersonic Glide Body
  - Advanced Hypersonic Weapon (AHW)
  - FE-1 Navy derivative
  - U.S. Army Long-Range Hypersonic Weapon (LRHW)
- DARPA Tactical Boost-Glide (TBG)/USAF Air-Launched Rapid Response Weapon (ARRW)
- DARPA Hypersonic Airbreathing Weapon Concept (HAWC)/USAF Hypersonic Attack Cruise Missile (HACM)
- JHTO propulsion portfolio
- Air Force Research Laboratory portfolio
- AFOSR/ONR basic research
- University Consortium for Advanced Hypersonics
- US-Australia HIFiRE, SCIFiRE
- MDA/SDA “defense-against” portfolio including Hypersonic and Ballistic Tracking Space Sensors (HBTSS)

…Two Steps Forward, One Step Back?

- **Will support for hypersonics continue?**
  - **FY22 budget unchanged between Administrations, growth in FY23**
  - **Positive comments from Shyu, Hicks**
  - **House Hypersonics Caucus reactivated**
  - **"This time it's different!"**
- **Recent Skepticism receiving attention (UCS, CBO, USAF)**
  - **USAF stepping back from ARRW**
  - **Russian systems ineffective in Ukraine**
- **Can the Defense Industrial Base scale up?**
- **Test infrastructure**
  - **Ground test backlog**
  - **Flight test – we need REPEATED ACCESS with RECOVERABLE TESTBEDS**
- **International engagements**

There is a Hypersonics Arms Race (whether we race or not)

Chinese programs:

1) DF-ZF (launched from the DF-17 MRBM)
2) Starry Sky-2 (XingKong-2)
3) Feitian-1

Russian programs:

1) The Avangard
2) 3M22 Tsirkon (or Zircon)
3) Has reportedly fielded the Kinzhal ("Dagger")

U.S. programs:

1) Air Force (3 total)
2) Navy (2 total)
3) Army (collaborates w/ Navy)
4) DARPA (3 total)
5) OUSD R&E

And They're Not Quiet About It…

- **China**

China's test of nuclear-capable hypersonic vehicle is concerning to analysts

WASHINGTON — China is in the midst of a rapid expansion of its strategic and nuclear weapons systems, and its progress has alarmed U.S. national security officials.

- **Russia**

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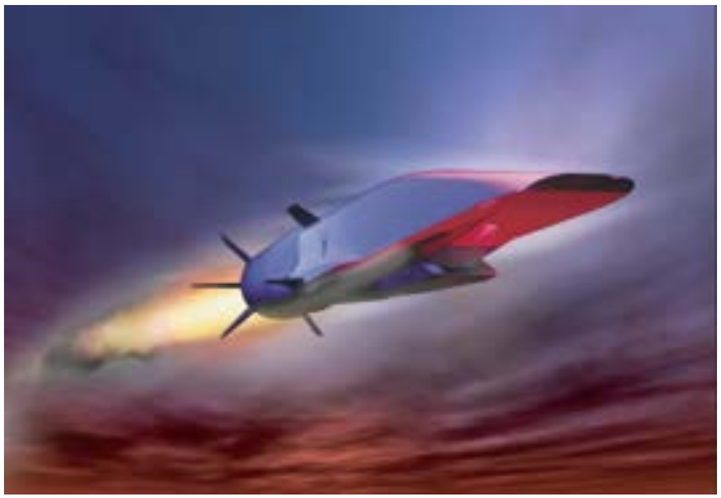
ALL SYSTEMS GO Putin boasts hypersonic nukes capable of wiping out US cities are bigger, better & already 'on alert' sparking WW3 fears

VLADIMIR Putin today boasted that Russian hypersonic nukes capable of wiping out entire US cities are already "on alert".

The Russian leader sparked World War III fears as he revealed his country has developed a weapon that flies more than five times faster those being developed in the States.

Two Basic Approaches to Hypersonics



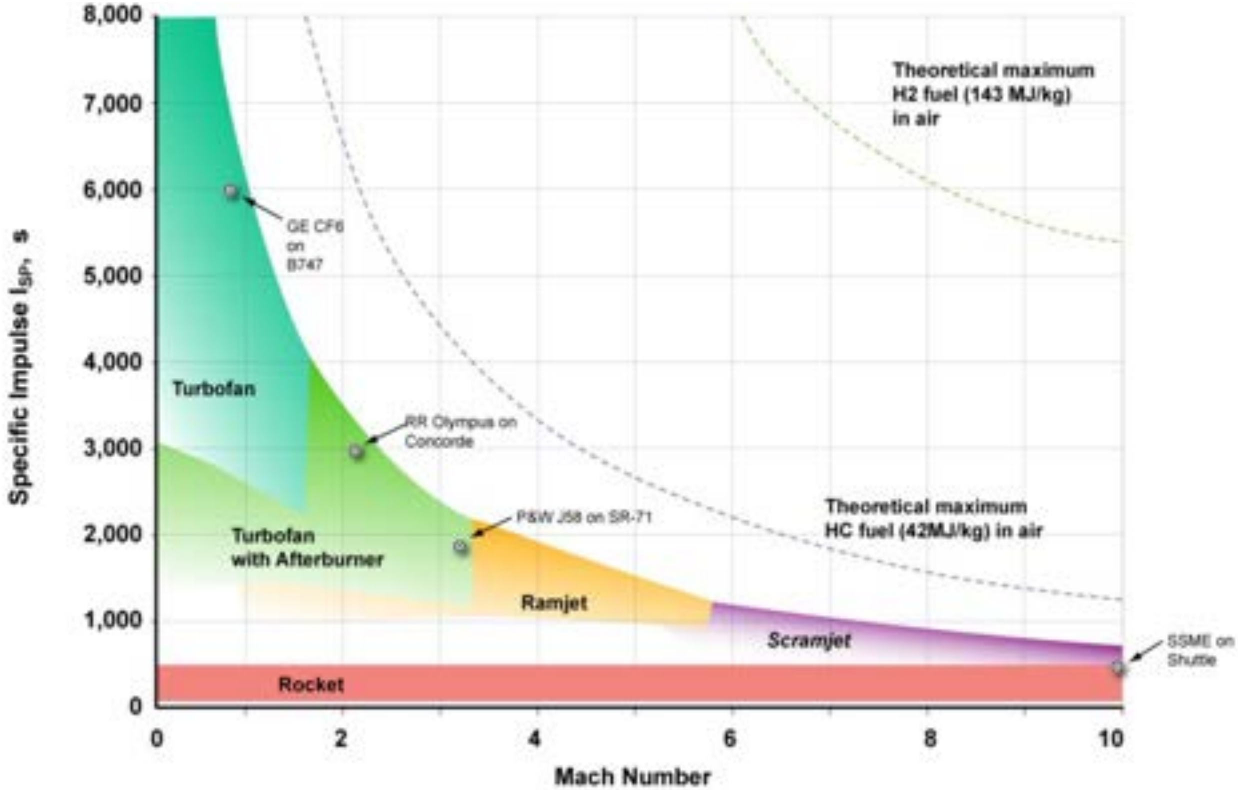
Airbreathing

Rocket Boost-Glide

Both technologies have value

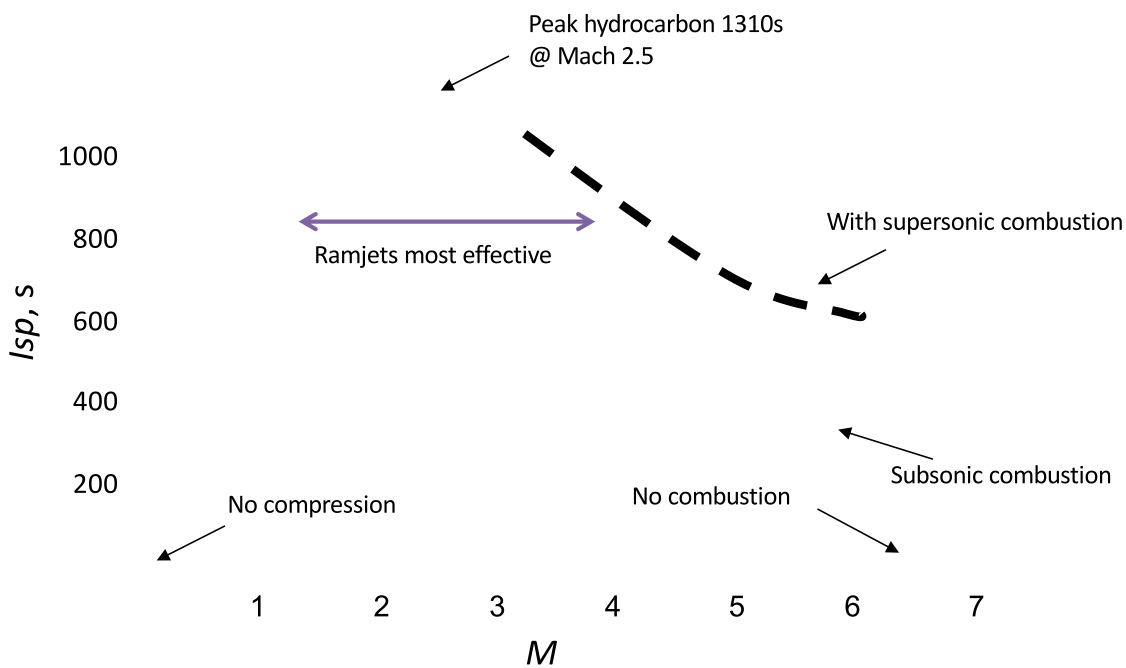
SOURCE: NASA DRYDEN

Airbreathing vs. Rockets



The "Tom Curran" curve 1986

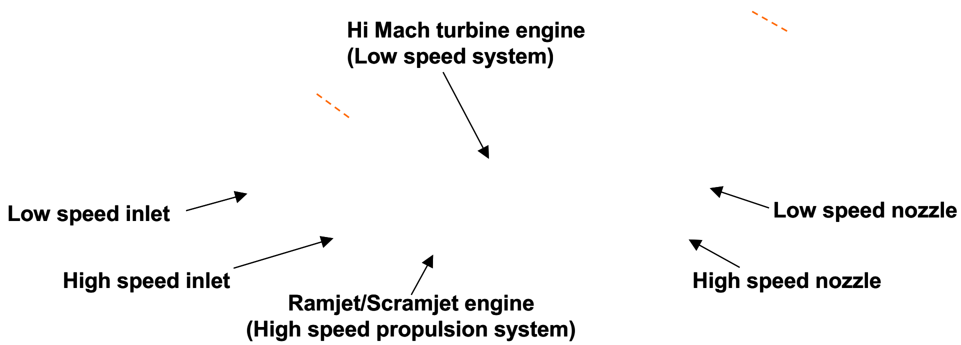
The ”Classic” Ramjet Curve



from Kerrebrock, *Aircraft Engines and Gas Turbines, 1992*

Combined Cycle Engine Technology

From Takeoff to Transonic to Hypersonic (and Back)

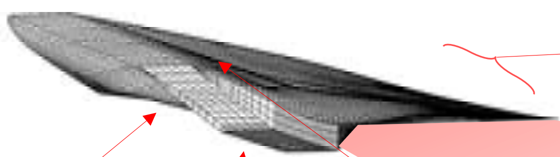


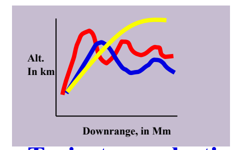
Scramjets
Turbines
Complex integration

Technical Challenges

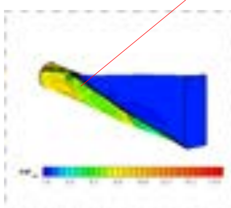
- **Ram/Scramjet operation from Mach 2+ to Mach 6**
- **Mach 4 turbine for acceleration to Ram/Scramjet takeover / overlap**
- **Inlet / exhaust flowpath integration and hypersonic engine operability**
- **Materials and structural components for thermal management**

High Mach Vehicle Design Challenges





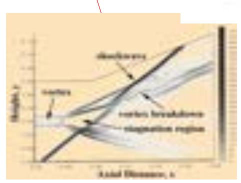
Trajectory selection
Periodic cruise
Multi-staging
Off-design optimization
Transonic drag
Landing/takeoff
Stage and store separation
Guidance and Control



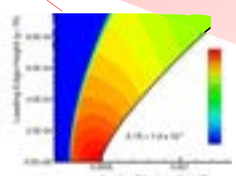
Engine/airframe integration
High efficiency inlet
Starting/unstarting
Unsteady flows

CH4+3/2 CO2->CO+ 2H2O
CO+1/2O2 ->CO2
Kf=1.2x10e10 Kb=5x10e8
SiH4 +5O2 -> SiO2 +
4H2O

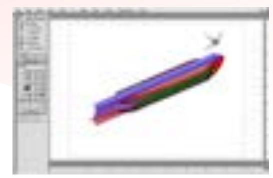
Finite-rate chemistry
Fuel selection and handling
Piloting and enhancers
Nozzle reactions
Engine/attitude coupling



Engines, combined cycles
Internal flows
Fuel injection and mixing
Multimode operation
Plasmadynamics/MHD



Leading edge physics
Shock location
Off-design aerodynamics
Sharp leading edge heating/cooling
Advanced materials/TPS
Plasma and telemetry
Sensing and communication
Navigation and guidance



Coupled Optimization
Base closure
Targeting and communication
Sensing
Operability
Aeroelasticity
Health monitoring
Testing and Evaluation

Circa 2002

Key Unknowns In Hypersonics ca. 1988

NDIA EMERGING TECHNOLOGIES INSTITUTE

- Scramjet operation at any Mach number, up to 18-25
- Surviving an engine unstart
- Fuel injection and mixing up the Mach scale
- Leading edge heating including shock-shock interactions
- Boundary layer transition and heating
- Inlet distortion and efficiency
- Controllability with integrated propulsion
- High L/D integrated aerodynamics
- Inlet design and performance, 2-D vs 3-D

Significant Progress – Status in 2023

NDIA EMERGING TECHNOLOGIES INSTITUTE

•Scramjet operation at any Mach number, up to 18-25 (yes to Mach 10)

•Surviving an engine unstart (yes, done it)

•Fuel injection and mixing up the Mach scale (yes, done it)

•Leading edge heating including shock-shock interactions (yes)

•Boundary layer transition and heating (work in progress)

•Inlet distortion and efficiency (yes, more to do)

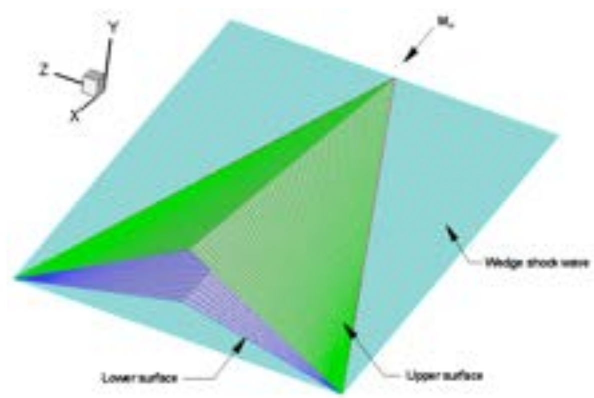
•Controllability with integrated propulsion (yes, done it)

•High L/D integrated aerodynamics (yes, but always more to do)

•Inlet design and performance, 2-D vs 3-D (yes, 3-D)

Slender Hypersonic Shapes: Waveriders

- **Bow shockwave attached to the leading edge along the vehicle**
  - High pressure retained at the lower surface
  - High L/D configurations
  - Good for inlet matching
- **Concept introduced for reentry vehicles by Nonweiler, 1959, fully developed by Rasmussen, others**
- **Explored extensively throughout the 90’s and 00’s**
- **Many generating techniques**



Hypersonic Scramjets: NACA-NASA Legacy

1958

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

TECHNICAL NOTE 4386

AN ANALYSIS OF RAMJET ENGINES USING
SUPERSONIC COMBUSTION

Richard .J. Weber and John. S. McKay

Lewis Flight Propulsion Laboratory

Cleveland, Ohio

September 1958

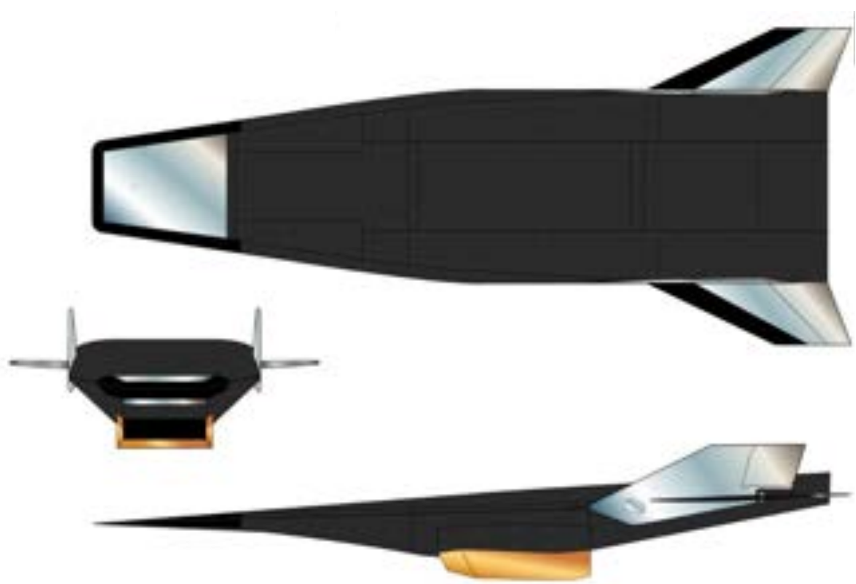
"…the possibility of replacing the conventional ramjet inlet and combustor by a combustor having supersonic inlet velocity is thus suggested…"

2004

- **Flight 1: 2 June 2002, Fin Failure**
  Loss unrelated to hypersonic systems
- **Flight 2: 27 March 2004, Mach 6.8 (!)**
- **Flight 3: 16 Nov. 2004, Mach 9.7 (!!!)**

X-43A Proved Scramjets Work

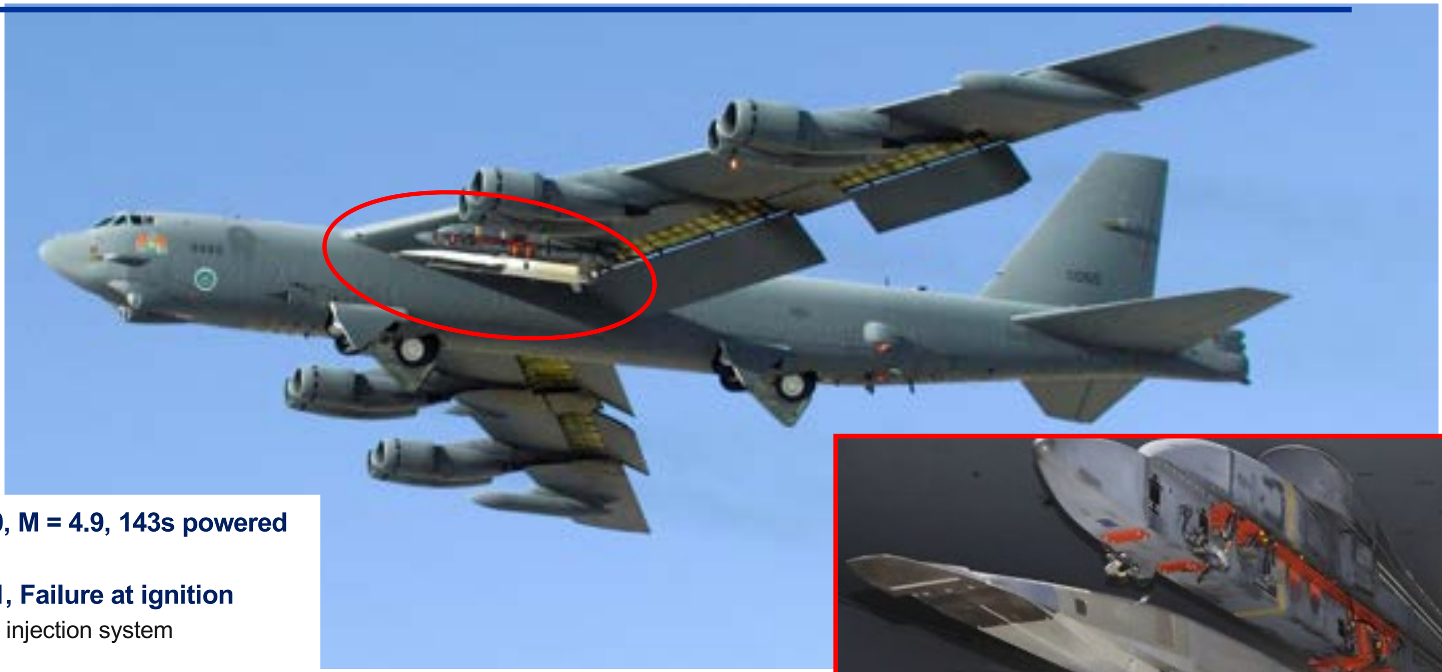
Cruiser length:	**145 inches**	**$230 million**
Weight:	**3000 lbs**	**10 second flights**
Fuel:	**hydrogen**	**Flew 2004**



Derived from the Langley Dual Fuel Vehicle

SOURCE: NASA DRYDEN

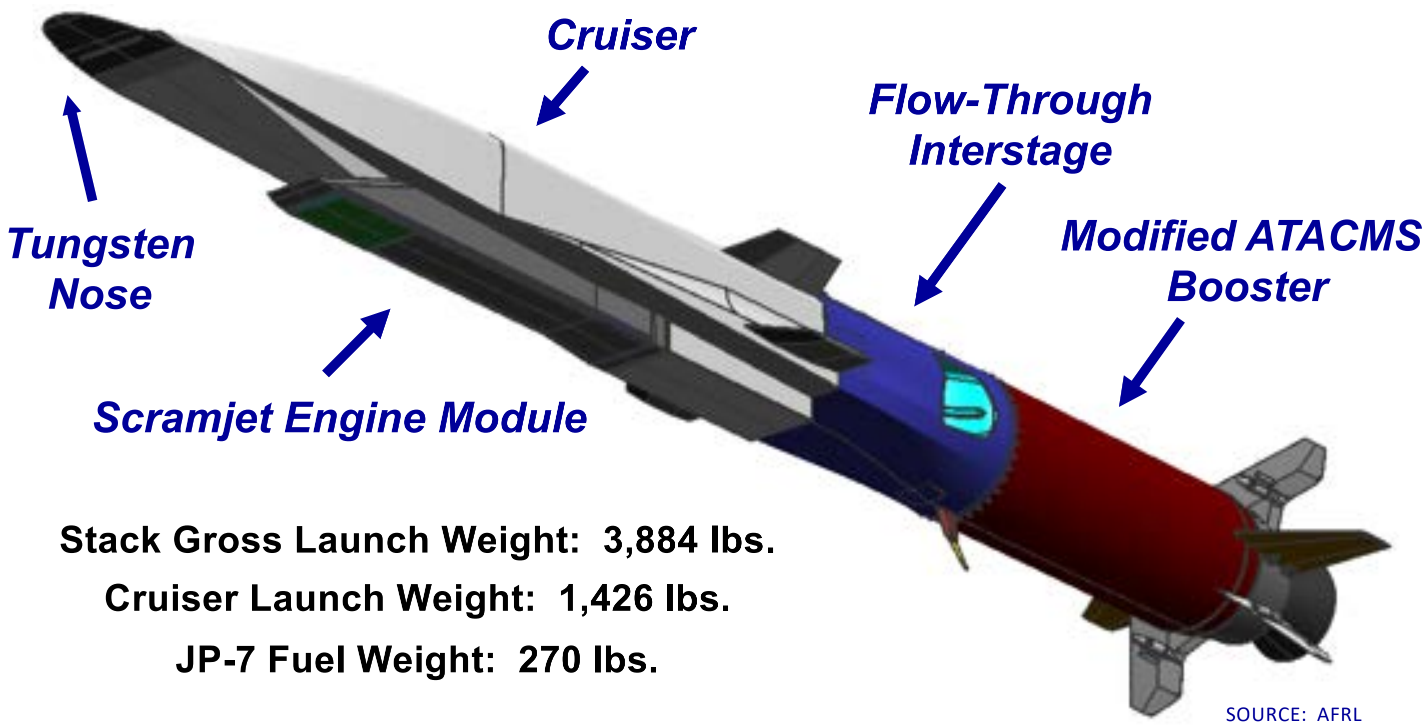
Eliminating Doubt: X-51



- **Flight 1: 26 May 2010, M = 4.9, 143s powered**
- **Flight 2: 13 June 2011, Failure at ignition**
  Resulted in refined fuel injection system
- **Flight 3: 14 Aug 2012, Fin failure at boost**
  Loss unrelated to hypersonic technology
- **Flight 4: 1 May 2013, M = 5.1, 209s powered**

X-51A Proved Scramjets Practical

Cruiser length:	168 inches	$299 million
Overall Stack length:	301 inches	5 minute flights
Cruiser max width:	23 inches	Flew 2010-2013



Stack Gross Launch Weight: 3,884 lbs.

Cruiser Launch Weight: 1,426 lbs.

JP-7 Fuel Weight: 270 lbs.

SOURCE: AFRL

Raytheon/Northrop HAWC

- **First flight 2021**
- **Baseline for primary USAF program, HACM 2023**

SOURCE: AFRL

Tough Love

- Inconsistent funding is bad policy (15-year cycle)
  - Impacts workforce
  - Constantly relearning
  - Loss of infrastructure (ie. Wind tunnels, etc.)
- Oversold concepts (Aerospace Plane, NASP, Blackswift)
- Poor program choices (e.g. boost glide versus airbreathing)
- Hubris (HTV-2 “we don’t need no wind tunnels…”)
- Insufficient flight testing (unit numbers and frequency)
  - ~50% failure rate
  - Dumb mistakes – lack of systems thinking
  - Risk aversion, failure leads to over-introspection
  - Poorly designed experiments increase risk unnecessarily
  - We seem to have forgotten how to design solid rocket boosters or fins that remain attached
- Failure to follow through on success (X-43, X-51)
- “Next-program-itis” – (11 years between X-51 and HAWC successes)

An Interesting Development: Investments from Outside Government

Stratolaunch: repeatable, reusable hypersonic flight test

NineTwelve Hypersonic Ground Test Center

Where Do We Go From Here?

- Continue Hypersonics at Scale

- Reusable systems
  - Aircraft – unmanned or manned
  - Combined cycle engines
  - Alternative propulsion flowpaths

- Spinoff to Commercial

- Access to space

Reaction Engines' Skylon

Questions?