Hypersonic Flight: A Status Report

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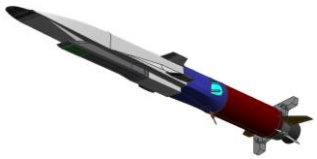
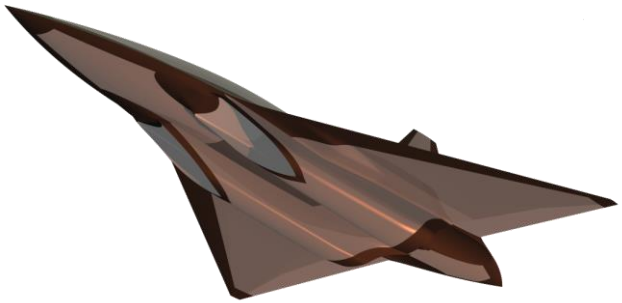
Hypersonics is More Than Weapons …but that's what we'll start with

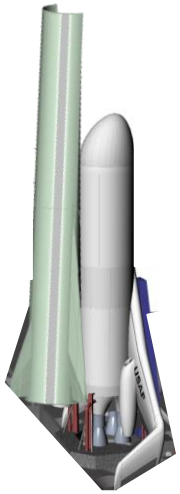


Weapons



Aircraft

Airbreathing Launchers

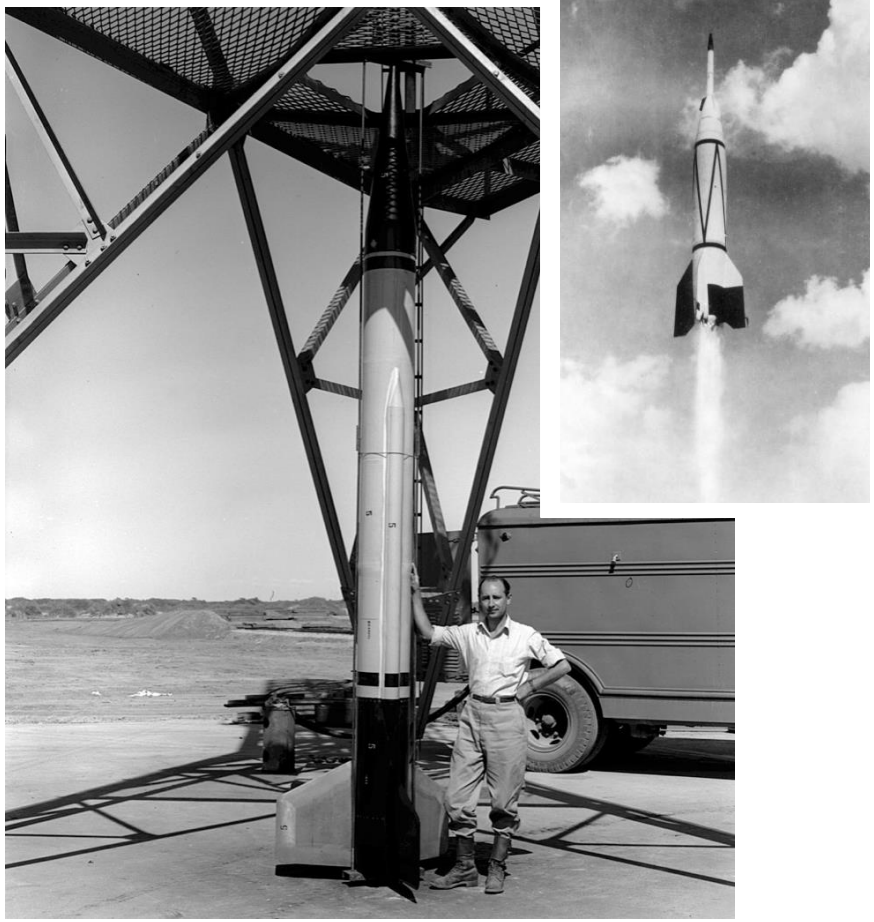


Entry Systems

Hypersonic Flight is Really Hard

- **Project Bumper: first hypersonic vehicle**
  - **WAC Corporal/V2 two-stage rocket**
  - **Program initiated Feb 1946, first flight May 1948**
  - **Flights 1-4 failed**
  - **Flight 6 failed**
  - **Flight 8 & 7 from the Cape**

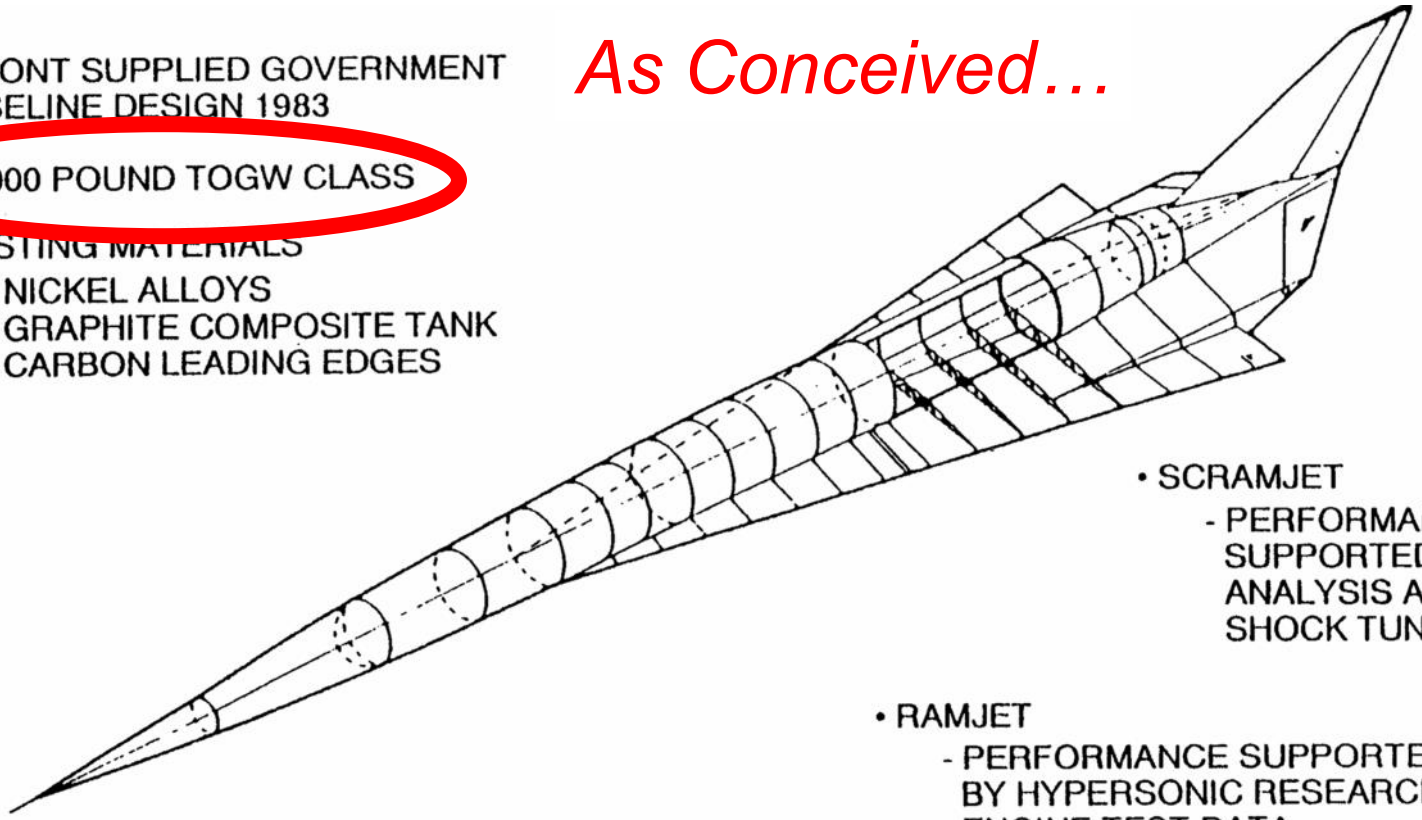
- **Flight 5: Mach 6.7 on February 1949, fifth flight**
- **50% flight success rate holds today**



And Sometimes We Made it Harder Than it Has to Be: X-30 NASP 1986

As Conceived…

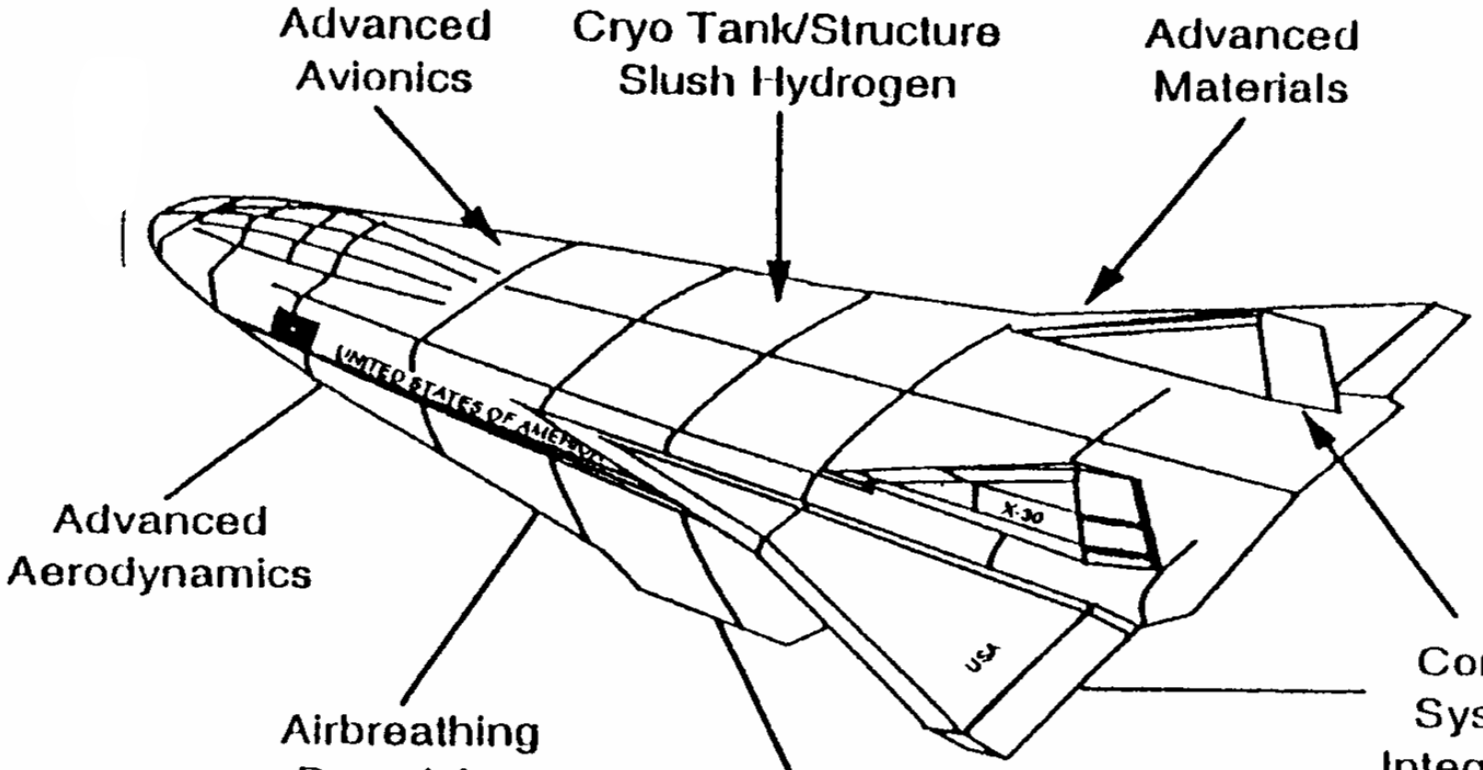
- duPONT SUPPLIED GOVERNMENT BASELINE DESIGN 1983
- 50,000 POUND TOGW CLASS
- EXISTING MATERIALS
  - NICKEL ALLOYS
  - GRAPHITE COMPOSITE TANK
  - CARBON LEADING EDGES



- SCRAMJET
  - PERFORMANCE SUPPORTED BY ANALYSIS AND SHOCK TUNNEL
- RAMJET
  - PERFORMANCE SUPPORTED BY HYPERSONIC RESEARCH ENGINE TEST DATA
- ACCELERATION ENGINE
  - U.S. PATENT ISSUED TO A. duPONT
  - PERFORMANCE VERIFIED BY GASL AND PW TESTS
- DRAG LEVEL VERIFIED
  - NASA WIND TUNNEL TESTS
  - BOEING SUPPLIED MODEL

And Sometimes We Made it Harder Than it Has to Be: X-30 NASP 1993

At program cancellation

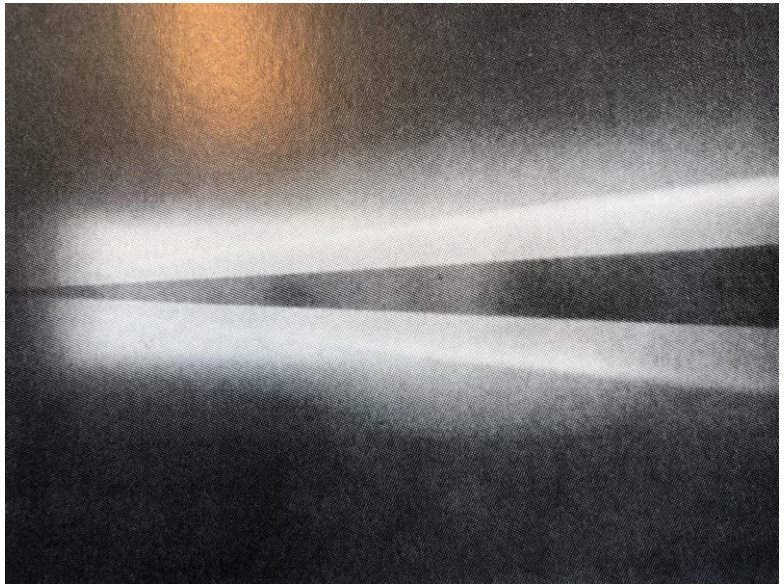


~450,000 lbs TOGW

NASA Dwg

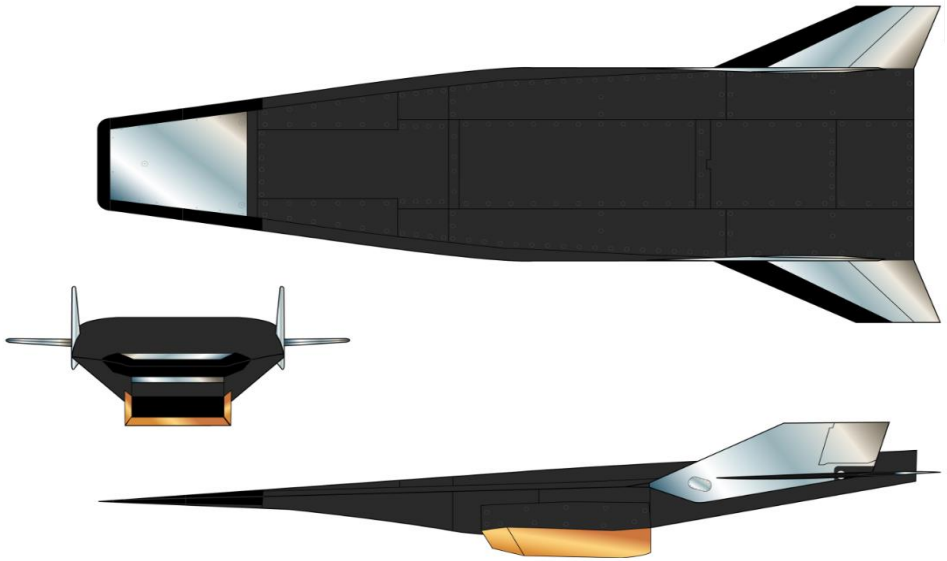
Hypersonic Flight is Also Often Easier Than We Thought

- **Development of hypersonic boundary layer theory (1950's)**
- **Lees, et. al. modeling as a complicated, merged thin shock & boundary layer**
- **Epiphany: the shockwave cannot be the top of the boundary layer, so there is a separate boundary layer**
- **Bertram and Blackstock, Chapman and Rubesin developed simple similarity approaches**



X-43A Proved Scramjets Work

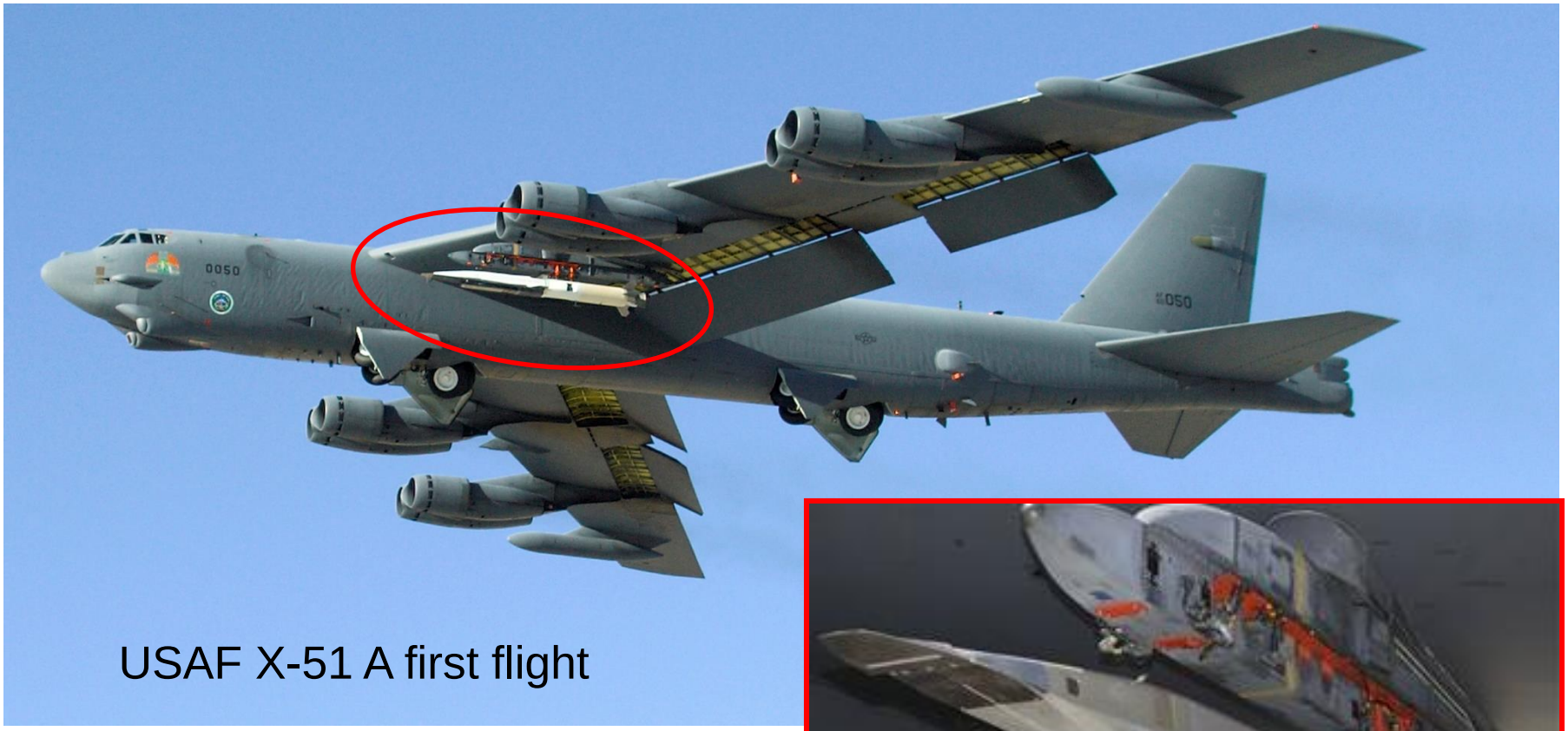
Cruiser length:	**145 inches**	**$230 million**
Weight:	**3000 lbs**	**10 second flights**
Fuel:	**hydrogen**	**Flew 2004**



"It's not that hard…"
Randy Voland, Nov 2004

SOURCE: NASA DRYDEN

First Scramjet flights: NASA X-43 and USAF X-51



USAF X-51 A first flight

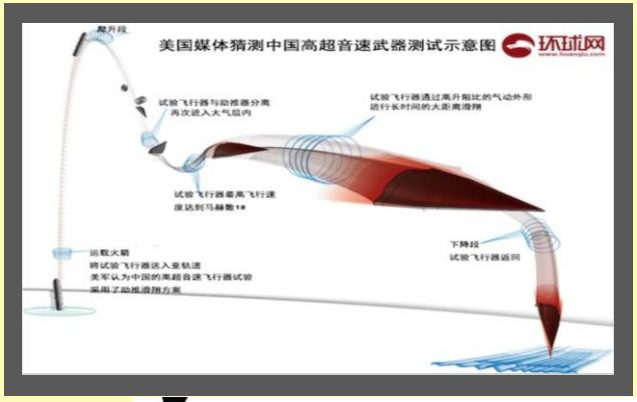
We Have Learned: Key Unknowns ca. 1989

- **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**
- **Aeroelasticity?**

Significant Progress Made ca. 2019

- **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)**
- **Aeroelasticity – progress, but ongoing**

“This Time It’s Different”



ASIA DEFENSE

China Tests New Weapon Capable of Breaching US Missile Defense Systems

Beijing has successfully tested a new hypersonic missile.

By Franz-Stefan Gady
April 28, 2016

766 Shares

Last week, China has yet again successfully tested the
elopmental DF-ZF (previously known as WU-14) hypersonic
e vehicle (HGV), Bill Gertz over at *The Washington Free Beacon*
eals.

test of the high-speed maneuvering warhead took place at the
zhai missile test center in central China’s Shanxi Province, some
miles (400 kilometers) southwest of Beijing.

e maneuvering glider, traveling at several thousand miles per hour,
osphere to an impact area in the western part of the country,” Gertz

Deputy PM Repeats Call For Hypersonic Bomber

MILITARY & INTELLIGENCE 18:00 27.08.2012 Get short URL

0 5 0 0

Russian Deputy Prime Minister Dmitry Rogozin repeated his appeal on Monday for Russia to develop a hypersonic aircraft for its PAK-DA long-range bomber requirement.

Russian Deputy Prime Minister Dmitry Rogozin repeated his appeal on Monday for Russia to develop a hypersonic aircraft for its PAK-DA long-range bomber requirement.

Weapon System

The superweapon travels at an eye-watering 7,000 miles an hour.

MILITARY — APR 26, 2016

Russia's Putting Hypersonic Missiles on Its Battlecruisers

The blisteringly fast Zircon missile will give old battlecruisers new striking power.

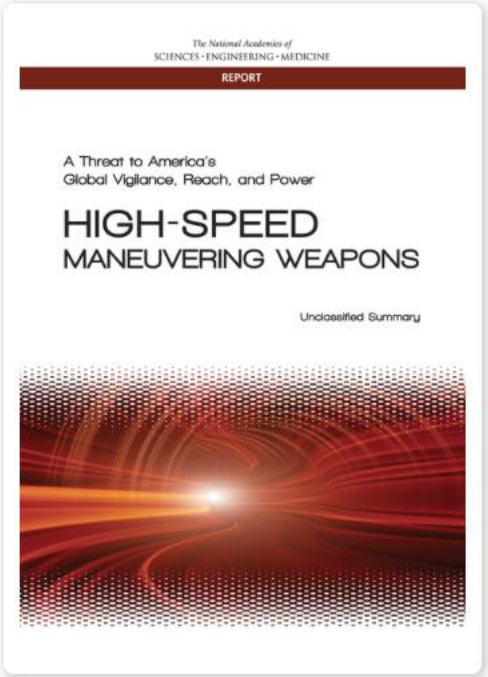
Our Competition

- Extensive efforts in both China and Russia

- Russia – building on Cold War legacy
  - Public statements emphasize defeat of MDA
  - Pushing to rapid operational systems
  - International partnerships (Europe, India)
  - Why???

- China – the rising newcomer
  - Investing in infrastructure (tunnels)
  - Experience in testing
  - Extensive foundational research effort with universities
  - Basic research portfolio covers a wide spectrum of topics (vs. U.S. focus on fluids)
  - Building on U.S. efforts
  - Fits clearly into Chinese doctrine

- Others: Australia, India, France, Germany



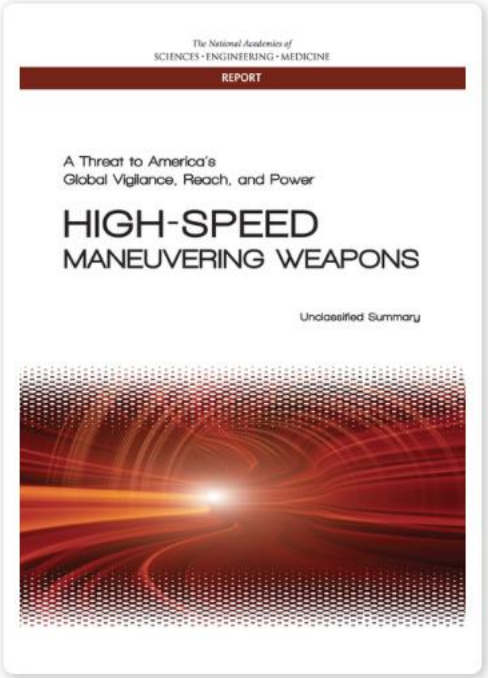
National Academy Dec 2016 report highlighted threats, need for defense, integrated approach

Key Takeaways from 2016 Academy Study

- Hypersonics is the combination of speed, maneuverability, and trajectory

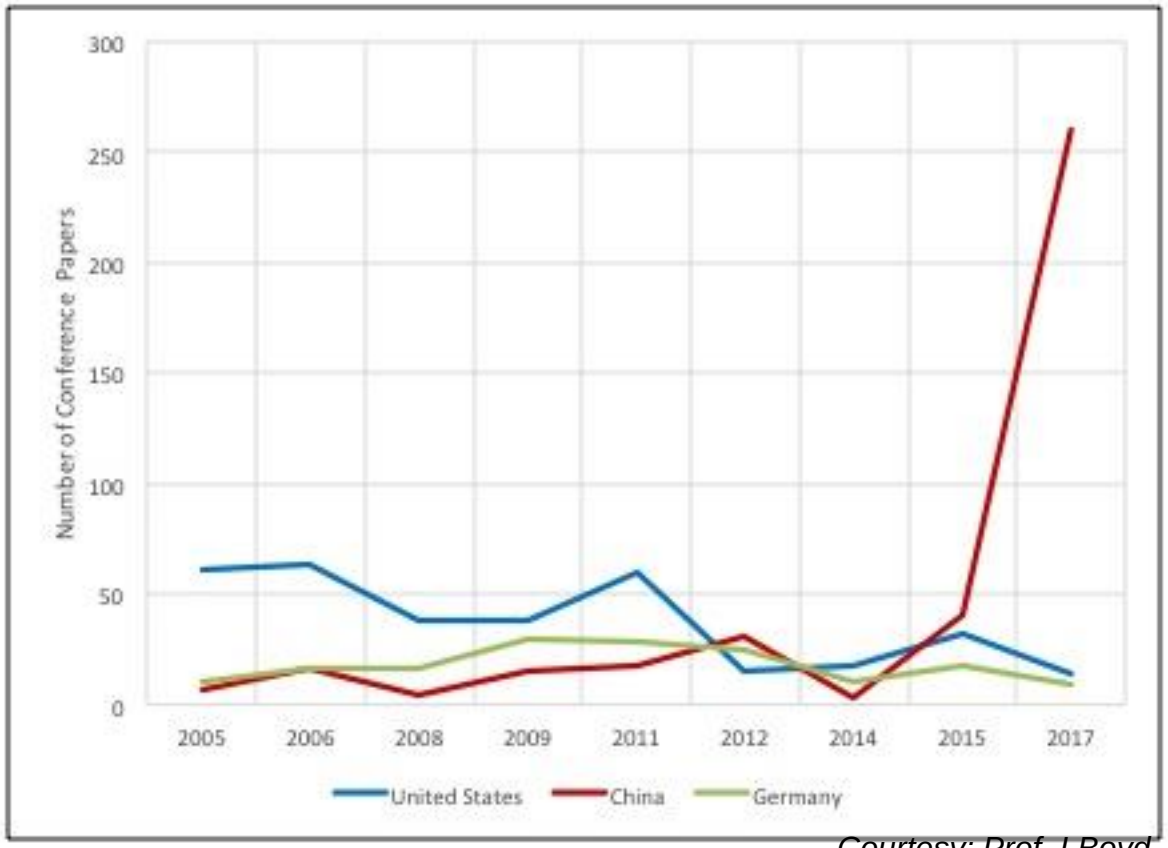
- Hypersonics is a threat to America's Global Vigilance, Reach, and Power
  - IC warnings are credible
  - A second-rate military with hypersonic systems can defeat a first-rate military
  - U.S. Navy, U.S. airbases especially at risk
  - This is a DOD-wide problem

- How to address?
  - Develop defensive measures (analogy to defending against kamikaze threat of WWII)
  - Detection and rapid response essential
  - Best defense may be a strong offense
  - Build an experimental capability (like space)
  - Coordinate efforts across the DOD



National Academy Dec 2016 report highlighted threats, need for defense, integrated approach

One Indication of the Competition: Papers Presented at the AIAA Hypersonics Conference



Courtesy: Prof. I Boyd

Another Indication of the Competition: YouTube Videos

Chinese researchers post about their research facilities

Meeting this Challenge: Plenty of Programs
but are they stovepiped or coordinated?

- **Conventional Prompt Strike (CPS)**
  - **Advanced Hypersonic Weapon (AHW)**
  - **FE-1 Navy variant**
- **DARPA Tactical Boost-Glide (TBG)/USAF Air-Launched Rapid Response Weapon (ARRW)**
- **USAF Hypersonic Conventional Strike weapon (HCSW)**

- **DARPA Hypersonic Airbreathing Weapon Concept (HAWC)**
- **AFOSR/ONR basic research**
- **US-Australia HIFiRE**
- **MDA defense-against portfolio**

Is the U.S. Losing Our Lead?

- **Snatching defeat from the jaws of victory**
  - **In 2004 NASA flew the first scramjet with T > D**
  - **In 2010 the USAF flew the first hydrocarbon scramjet**

Today we are further away from scramjet flight than we were 10 years ago, and not on a path to operational use

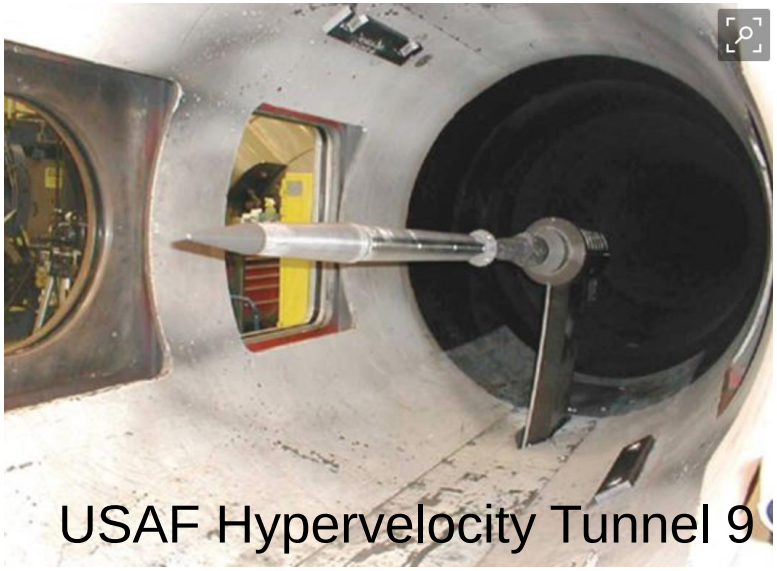
X-43; 15 years ago

- **Facilities at risk, little new investment**
  - **Only 2 U.S. engine test facilities**
  - **Quiet tunnels only at universities**
  - **Existing infrastructure is aging; we are closing tunnels.**
- **Limited workforce investment**

X-51: 9 years ago

What Are We Doing Wrong? Ground Test at Risk

- **Hypersonics depends on ground test, analysis, computation, and flight.**
  - **During the NASP program, some said computers would replace tunnels. NO!**
  - **After HTV-2 flight, program added significant tunnel tests.**
- **Ground test is still an essential part of our business, and will be into the future. Part of X-43, X-51 success**
- **We need test-class quiet tunnels**
- **More engine test capability- the U.S. only has two facilities currently**
- **More researcher access to facilities**



USAF Hypervelocity Tunnel 9

What Are We Doing Wrong?
Insufficient flight test opportunities

- **DARPA HTV-2**
  - **Two flights in 2010 and 2011**
  - **Achieved hypersonic speed but vehicles lost**

- **US Navy HyFly**
  - **Three flights, then terminated in January 2008**
  - **Never reached hypersonic flight**

- **USAF X-51**
  - **Four flights between 2010 and 2013**
  - **Two successful flights, though first had issues**

- **AHW**
  - **Two flights**
  - **One success (2011), one launch failure (2014)**
  - **FE1 followup success Fall 2017**

Some noble failures and some dumb failures

We Still Have Fundamental Research Topics

- **Systems and design**
  - **Rocket boost versus scramjet**
  - **Combined cycle systems**
- **Recovering and avoiding an engine unstart**
- **Active engine cooling**
  - **Design**
  - **Manufacturing/cost**
- **Advanced hydrocarbon fuels (endothermic, coking)**
- **Boundary layer transition and heating**
- **High L/D integrated aerodynamics for maneuverability**
- **Inlet design and performance across the Mach range**

Where Do We Go From Here?

- **The U.S. needs a coordinated national consensus including DOD and NASA**
  - **Investing in both near and short term, not just reactive**
  - **Leverage international partnerships (especially Australia)**

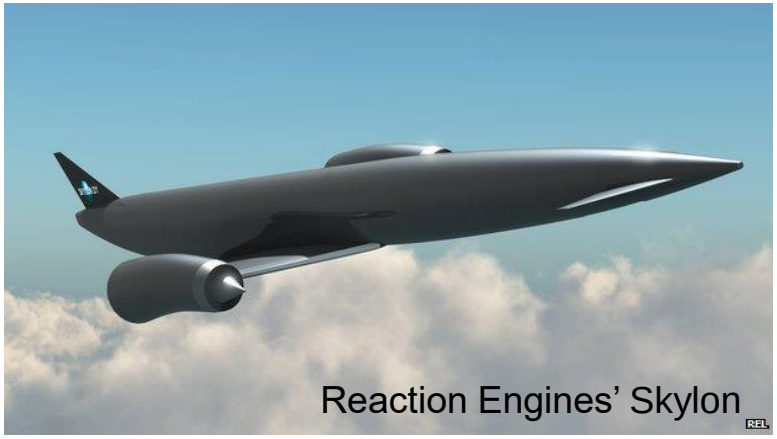
- **Maintain ground facilities and flight test capabilities, treat them as national assets**

- **Airbreathing must remain an option**
  - **Consider current programs**
  - **Wargamed results**

- **Workforce investments (universities)**
  - ***flying faster and higher***

- **Recoverable, or reusable testbed X-plane**
  - **Climb up the Mach scale**
  - **Scale up engines mass flow**
  - **Combined cycle systems**

- **Keeping long-term options on the table:**
  - **Aircraft – unmanned or manned**
  - **Access to space**



Reaction Engines' Skylon

Thank You!