Reusable Hypersonic Aircraft Challenges: Opportunities for Materials and Manufacturing

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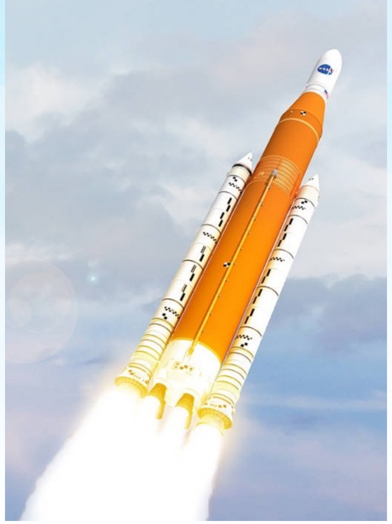
  - What are desired/"wish list" mfg. advancements?
- Summary

NASA's Interests in Hypersonics

hypersonic technology project

HYPERSONICS

- **Blunt Body Re-entry**
- **Launch**
- **Unpowered <u>Atmospheric</u> Flight**
- **Powered <u>Atmospheric</u> Flight**

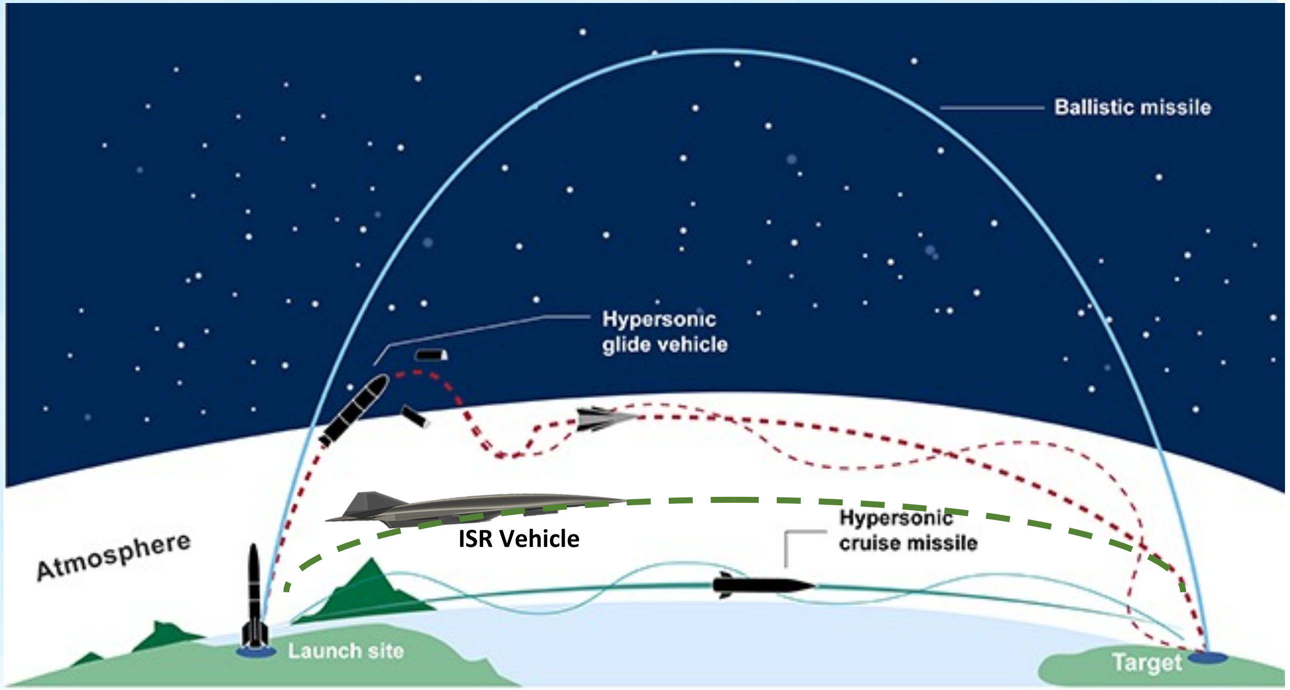


Hypersonics: Speeds of Mach 5 (5000 ft/sec) or greater

Multiple NASA applications require mastery of hypersonic flight

What is allure of atmospheric hypersonic flight ?

- Military:
  - Reach target quickly
  - Extraordinary speed→ difficult to defend against (“stopping a bullet with a bullet”)
  - Fly unpredictable trajectories → heat tolerant airframe can maneuver in the environment unlike standard ballistic missiles with predictable parabolic trajectories
  - Type of missions:
    - Offensive (single use)
    - ISR: Intelligence, Surveillance, Reconnaissance (re-usable)
    - Movement of high value assets quickly - personnel or hardware (re-usable)
    - Space Access (re-usable)



Source: GAO analysis of Department of Defense data from GAO-21-378. Figure not drawn to scale.

- Commercial Re-usable Hypersonics
  - “Shrink the World”
  - Mach 5 flight: Travel Los Angeles to Tokyo (5000 nm) in <2 hr vs current flight times of 12 hrs
    - Challenges: long range flight requires light weight structures; high efficiency propulsion systems, and overcoming significant safety and regulatory issues

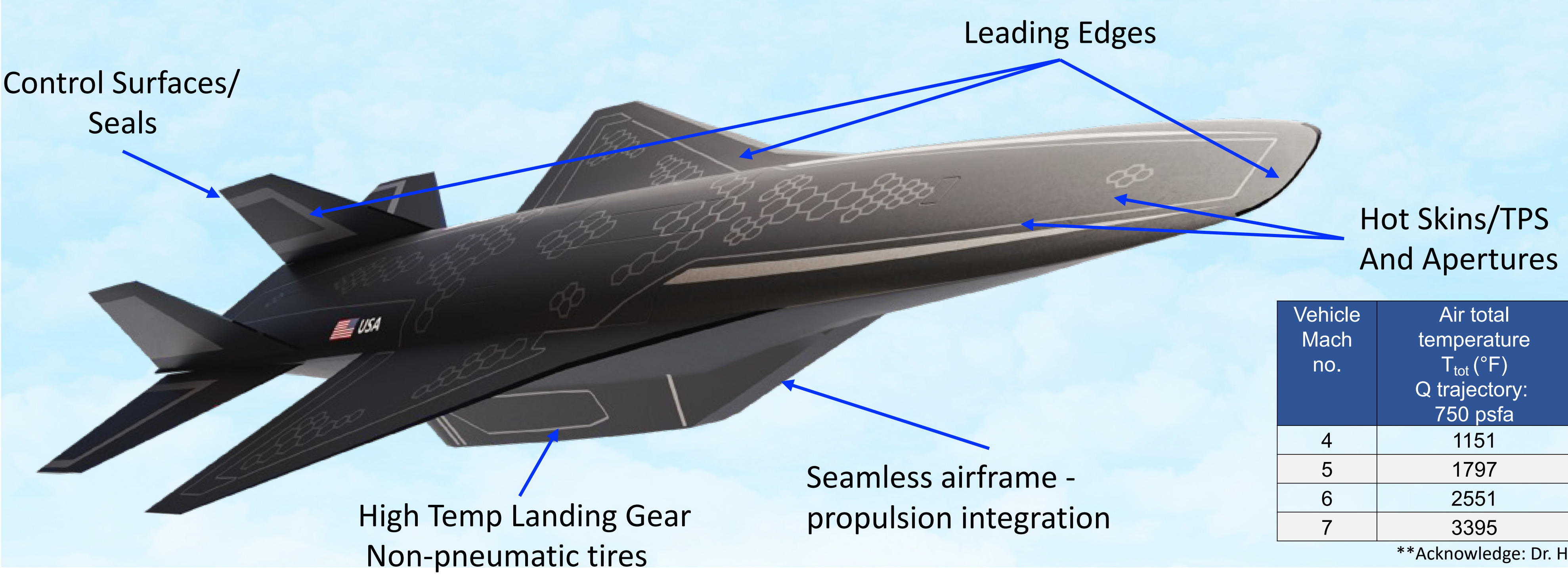
What are unique challenges of reusable hypersonics vs rocket access-to-space?

- Extreme temperatures: Mn 5: 1800F; Mn 6 2550F stagnation temperatures require novel application of advanced materials

- Time at Temperature
  - Access to space/Re-entry: travels at hypersonics speed
    - To orbit: **8 minutes**; Re-entry: **10s' of minutes** → where maximum heating is sustained
  - Hypersonics: sustained high speed flight for **hours** results in high "integrated heat load"
- Combined extreme temps/time-at-temp challenges thermal management:
  - Where to dump the heat so internal systems stay within allowable temperatures??
- Highly integrated airframe and propulsion system
  - Eliminate boundary between airframe/propulsion → increases challenge for manufacturing, joining, sealing
  - Smooth streamline transition: eliminate gaps/steps
- Sharp edges on vehicle nose, wing, and control surface leading edges that need to remain sharp, with no or limited recession for efficient aerodynamics
- Lightweight airframe structures made of heat resistant materials capable of holding sufficient fuel for the long-range high-Mach mission → No steps or gaps
- Efficient airbreathing propulsion systems → able to accelerate aircraft quickly through transonic (~Mn 1→Mn 2) and have sufficient fuel for lengthy cruise at high altitude (>70 kft)

What are example propulsion/airframe challenges?

Example Technology Challenges/Needs: Vehicle

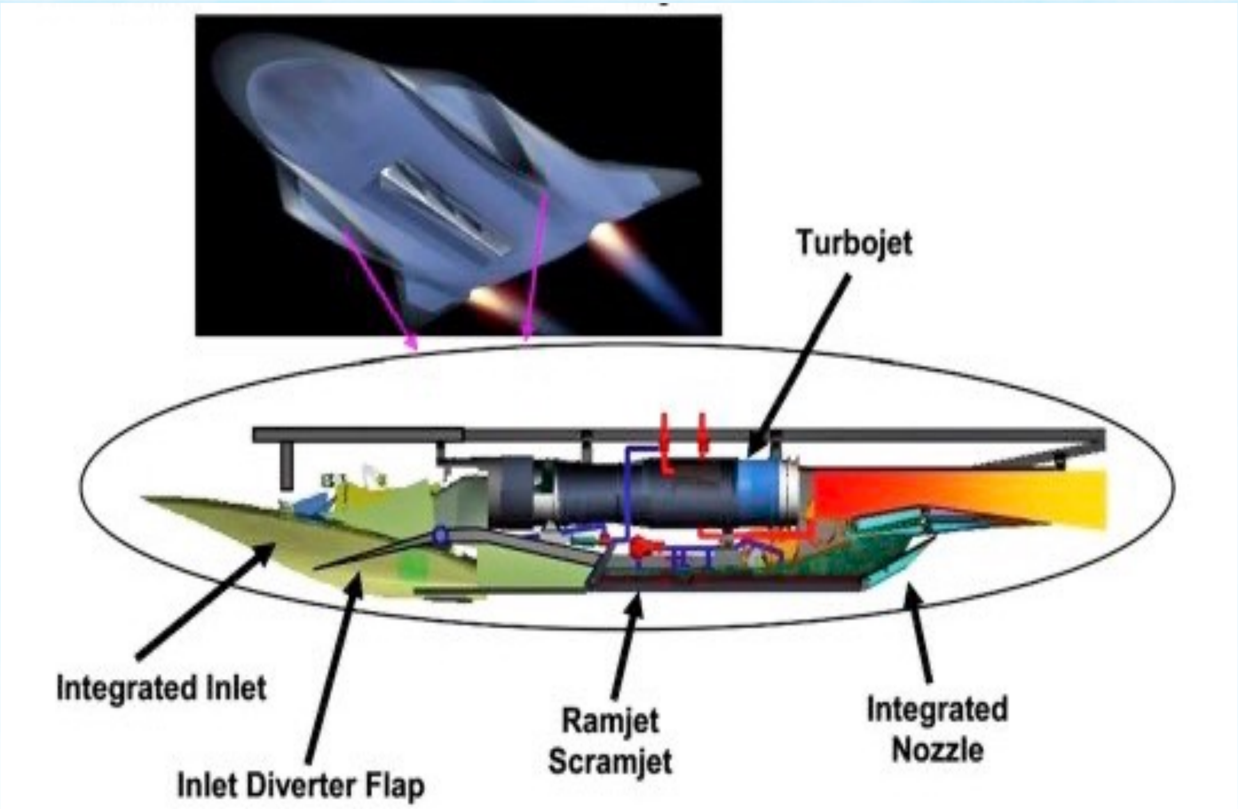


Vehicle Mach no.	Air total temperature T_{tot} (°F) Q trajectory: 750 psfa	Adiabatic wall temperature T_{aw} (°F)	Vehicle radiation equilibrium temperature T_{rad} (°F) Emissivity = 0.8 Turbulent (x= 5 ft)
4	1151	1037	762
5	1797	1627	970
6	2551	2316	1128
7	3395	3067	1249

**Acknowledge: Dr. Heath Reising, NASA Glenn Research Center

- Integrated shape stable leading edges and joining techniques capable of high stagnation temperatures (Mn 5 1800°F; Mn 6 2550°F)
- Lightweight, durable, high temperature acreage thermal protection (TPS) hot structures with stable joining techniques that prevent gaps/steps during flight
- High temperature control surfaces, seals, and apertures
- Airframe-Propulsion Integration: seamless engine/airframe attachment w/minimal thermo-structural deflection
- High temperature landing gear
- Design-Oriented Thermo-Structural Analysis & Optimization Validated Methods (FTSI)
- Limited ground test facilities to test vehicle structures under representative thermal/acoustic conditions

Example Technology Challenges/Needs: Propulsion



- High temp., efficient turbomachinery for Turboramjets (TRJ) and high thrust Dual Mode Ramjets (DMRJ)
- Large, variable geometry, lightweight 2-D airframe-integrated inlet(s) able to sustain high total temperatures (Mn 5 1800°F, Mn 6 2550°F)
- High temperature actuators, pumps, seals, bearings, power generation and thermal management systems
- Management of both primary and secondary flows throughout the Mn range (high temperature bypass ducts)
- Extreme temperature ramburner and nozzle liners to accommodate extreme temp, high acoustic exhaust flows
- Limited ground test facilities to test engine structures under representative thermal/acoustic conditions

Manufacturing Considerations

What are current/near term mfg technologies?

Metals:

- Additive Mfg (A/M) conformal heat exchangers (propulsion and airframe) and fuel injection systems (superalloy)
- A/M Leading edges with internal cooling passages made of high entropy superalloys (e.g. GRX-810)
- A/M propulsion flow path liners, seals, spring preloaders, and other components for high temperature service made of high entropy superalloys (e.g. GRX-810)

Ceramics/Ceramic Matrix Composites (CMCs):

- Melt Infiltration (MI) SiC/SiC - high temp first stage shrouds, nozzles, combustor liners; other
- Chemical Vapor Infiltration (CVI) C/SiC flow path liners, leading edges; other
- Oxide/Oxide (Ox/Ox) or (MI) SiC/SiC duct systems
- Ultra-High Temperature Ceramics (e.g. $ZrBr_2$, other) Leading edges
- Other

Inconel 625 additively manufactured heat exchanger developed by UTC and partners

Fuel nozzle for land-based industrial gas turbines for power generation applications with reduced parts: 4 (A/M) vs 17 Components (Conv) Collins

(MI) SiC/SiC - high temp first stage shrouds, nozzles, combustor liners (GE)

CMC Leading Edge Arc Jet Tests

What are desired/"wish list" mfg advancements?

- Large format (10's ft) A/M printers for internal metal airframe structures
  - Stiff stable structure with limited joints improves vehicle performance at hypersonic speed
  - Tooling cost savings
  - Minimize waste of hard-to-source, long-lead advanced alloys (e.g high temperature titanium alloys)
  - Limited production runs amenable to A/M
- A/M of ceramic matrix composites
  - High temperature structural materials for external skins, wings, control surfaces
- Hybrid "Graded" A/M of external hot structure (e.g. ceramics) graded to internal "warm" metallic structure
- Integrated A/M and non-destructive evaluation → part is ready for service or next processing step immediately after printing
- A/M of fine feature systems (e.g. HX, high temperature spring preloaders, seals, etc)
- High throughput (multi-head?) systems to speed production to meet demand signal

A/M: Additive Mfg

Summary

- Hypersonic flight poses significant materials challenges
- Advanced materials (e.g. CMCs, ODS/High entropy alloys) opportunities are key in allowing the nation to embrace reusable atmospheric hypersonic flight
  - Materials are needed to contend with the high enthalpy hypersonic flow, maximize engine performance, and meet durability goals
- Current and future trends in additive manufacturing will be enabling for hypersonics
  - Allow faster, more efficient development cycles facilitating product evolution with "lessons leaned" from testing with minimal tooling costs
- University involvement key to
  - Fostering innovation
  - Providing necessary workforce

Questions?

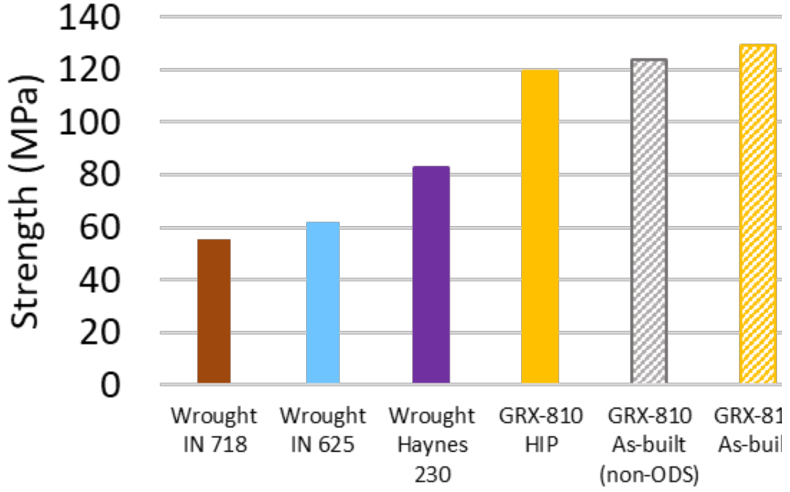
Appendix

NASA Glenn GRX-810 is Success Story for A/M

- A/M completely changes value proposition for alloys previously deemed “too expensive to conventionally fabricate” such as Oxide Dispersion Strengthened (ODS) Superalloys
- NASA alloy GRX-810 is an example of what can be achieved when a matrix is designed for optimum printing and solid solution strengthening then combined with dispersion strengthening (yttria) for high temperature stability

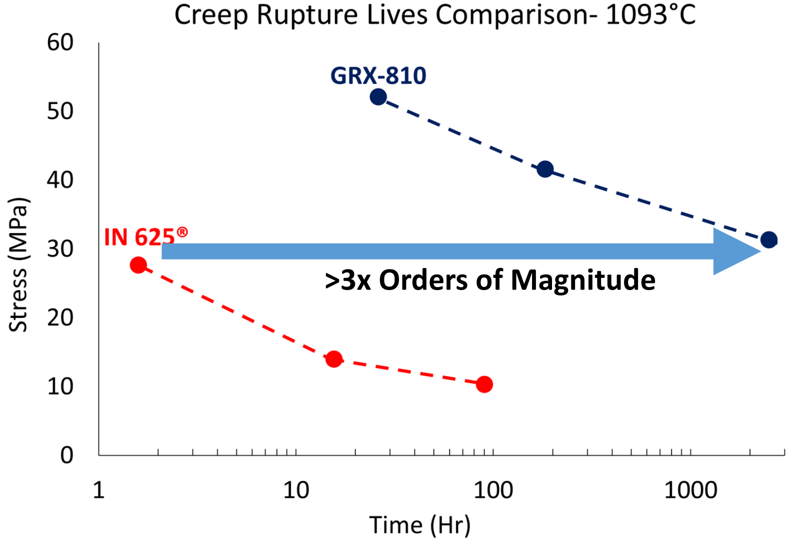
Turbine engine combustor (fuel-air mixer) 3-D printed from GRX-810

Better Tensile Strength

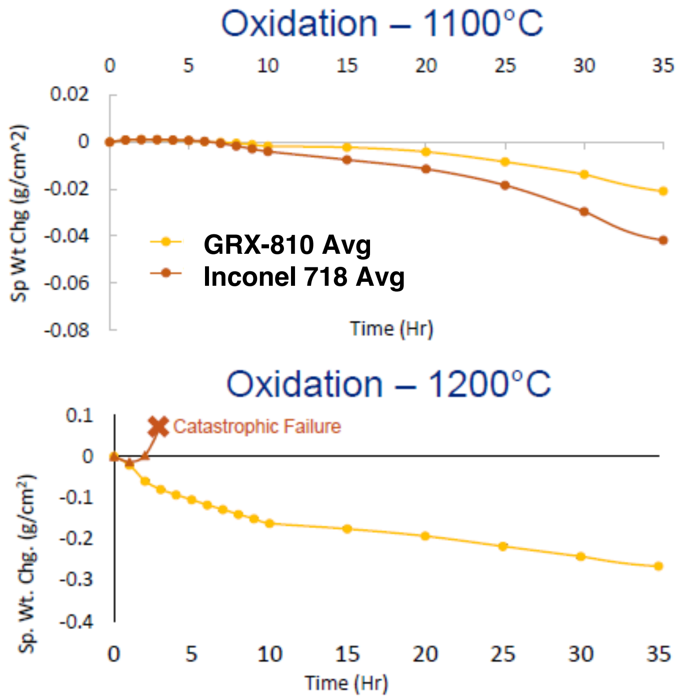


SIGNIFICANTLY Better Creep

1093 C / 31 MPa



Better Oxidation Resistance



Dream Chaser Composite Monocoque Structure

- 30’ long by 15’ wide carbon fiber reinforced polymer composite structure autoclaved in furnace at Ft Worth
  - Built by Lockheed Martin Ft Worth under subcontract to Sierra Space

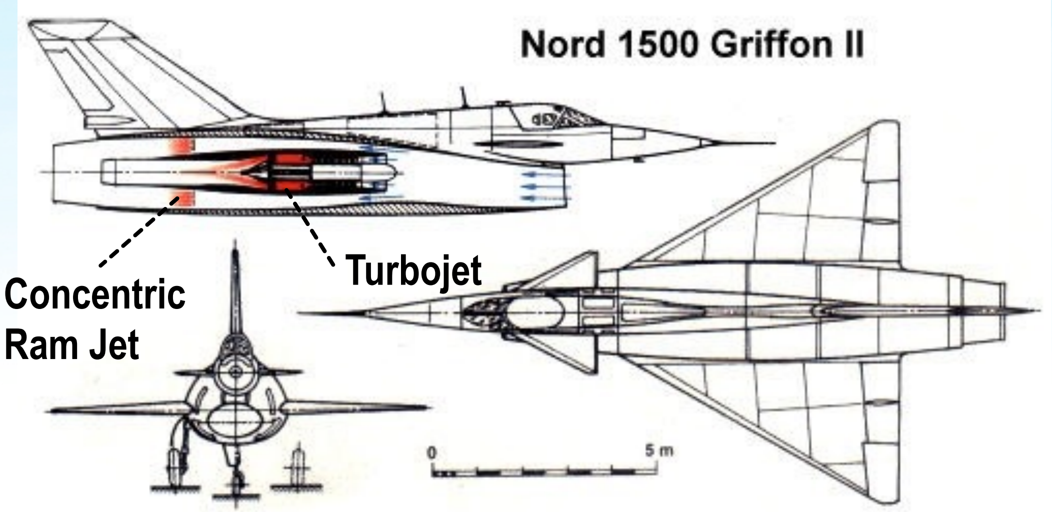
Sciaky Large Format Electron Beam Ti Printing (8ft Diameter)

https://www.sciaky.com/news/press-releases/sciaky-to-deliver-large-industrial-scale-metal-3d-printer-to-airbus

Turboramjets: A Brief Historical Look

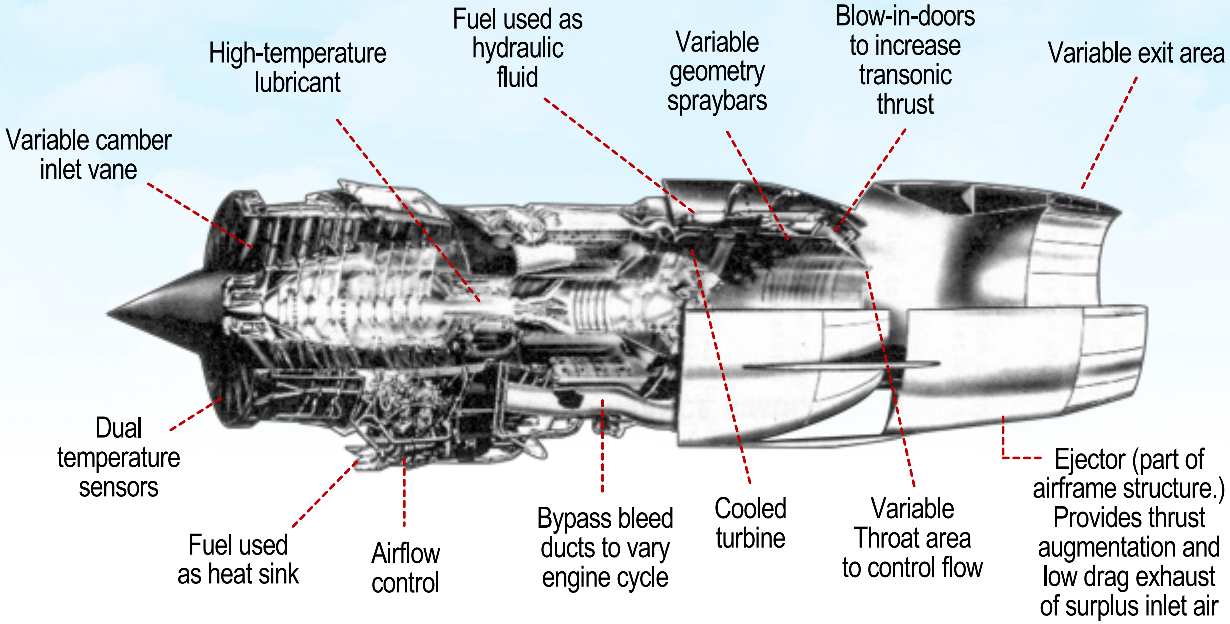
Nord 1500 Griffon II

https://en.wikipedia.org/wiki/Nord_1500_Griffon



Gaillard, P., ***Les oublies du Salon de l'Aeronautique (5): les experimentaux***
(The Forgotten Ones of the Paris Air Show, Part 5: The Experimental Ones)

SR-71/J-58



Law, P., ***SR-71 Propulsion System: P&W J58 Engine (JT11D-20)***,
the 10th Annual Aircraft Engine Historical Society (AEHS) Convention

NASA Technology Readiness Levels

From
https://www.gao.gov/assets/gao-20-48g.pdf

Technology readiness level (TRL)		Description
1	Basic principles observed and reported	Scientific research begins to be translated into applied research and development. Examples include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively low fidelity compared with the eventual system. Examples include integration of ad hoc hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include high fidelity laboratory integration of components.
6	System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in its relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
7	System prototype demonstration in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requirement demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, a vehicle, or space).
8	Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system proven through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Source: GAO analysis of agency documents. \| GAO-20-48G

NASA Mfg Readiness Levels

Manufacturing Readiness Level (MRL)

Phase	MRL	State of Development
Phase 3: Production Implementation	9	Full production process qualified for full range of parts and full metrics achieved
	8	Full production process qualified for full range of parts
	7	Capability and rate confirmed
Phase 2: Pre production	6	Process optimised for production rate on production equipment
	5	Basic capability demonstrated
Phase 1: Technology assessment and proving	4	Production validated in lab environment
	3	Experimental proof of concept completed
	2	Application and validity of concept validated or demonstrated
	1	Concept proposed with scientific validation