AAE 538: Air-Breathing Propulsion

Lecture 22: Introduction to Supersonic Propulsion

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Overview of High-Speed AB Propulsion

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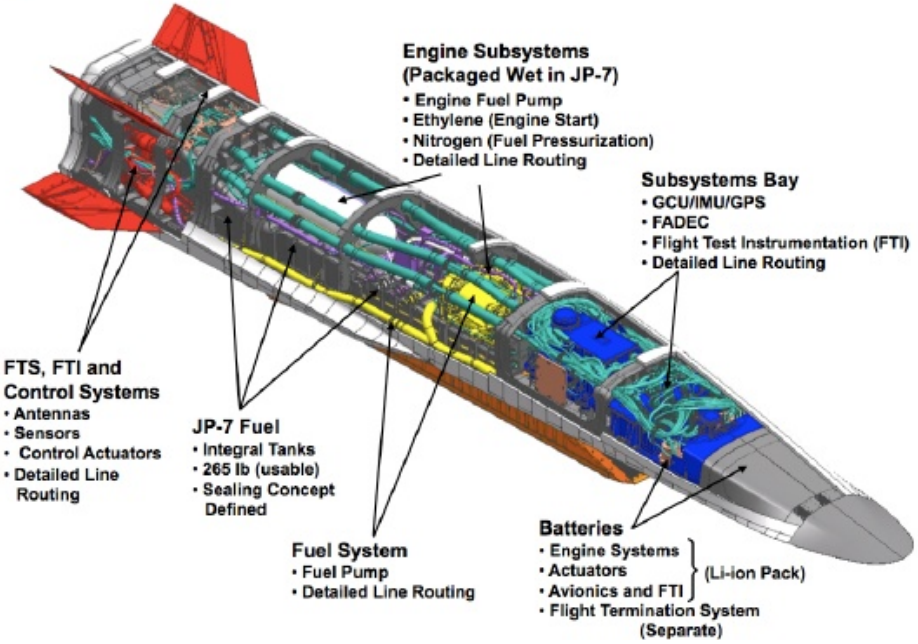
- The terms ‘supersonic’ and ‘hypersonic propulsion are generally delineated by the flight Mach number
  - Supersonic:
  - Hypersonic:
- The boundaries are somewhat loosely determined and some ‘traditional’ ramjet and turbojet engines find their way into both categories.
- Current/near-term applications:



Schematic diagram of the X-51a Waverider

Challenges of High-Speed Propulsion

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From a system-level perspective…

- Efficient and reliable operation over a wide range of operating conditions
  - Mach number could range from
- Stable, efficient mixing and combustion in a supersonic flow within a burner of a reasonable size
- Achieving sufficient structural integrity for a reusable system,
- Developing analytical tools that enable
- Engine/Airframe Integration
  - Traditional methods no longer viable

The X-51a required a booster rocket to achieve suitable conditions for scramjet operation.

Engine – Vehicle Integration

- Modern engineering of high-speed vehicles is

- Axisymmetric, hypersonic engines mounted to an airframe with a pylon or a strut removes all margin in the

- The integrated designs allows us to take advantage of the shape of the vehicle as part of the design process.

Engine – Vehicle Integration

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- There is a major change in the characteristic look of hypersonic aircraft from subsonic aircraft for this reason: the need for good aerodynamic integration.
- High speed vehicles tend to operate at very high altitudes in order to avoid the _____ that would result from hypersonic speeds.
  - The problem is that the air at these altitudes is also very rare, with densities _____ that at sea-level conditions.
  - Engines need a lot of air-flow to generate
  - One strategy to capture the required air-flow is to use the entire fore-body underneath the vehicle _____ .
  - Similarly, the entire after-body can be utilized as _____ .

Challenges of High-Speed Propulsion

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From a propulsion standpoint - everything is hot!

- Pulling 'free' oxidizer from the surrounding air-flow.
  - Engine inlet temperatures (T_2) are
- Fuel is used as a coolant and, usually, injected as a gas
  -
- Combustor typically operate near the stoichiometric condition to add any energy.
  -
  -
- Thermal expansion
  - $\alpha_{Ti} = 5\times10^{-6}\ /F$
  - Entry panels, drains, vents, etc.: cannot be accomplished by standard means.
  -
- Extremely high cooling requirements on turbomachinery
- High levels of compression create small internal passages
  -

Candidate Propulsion Systems

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Turbojet Engines

- **Strengths:**
  -
- **Weaknesses:**
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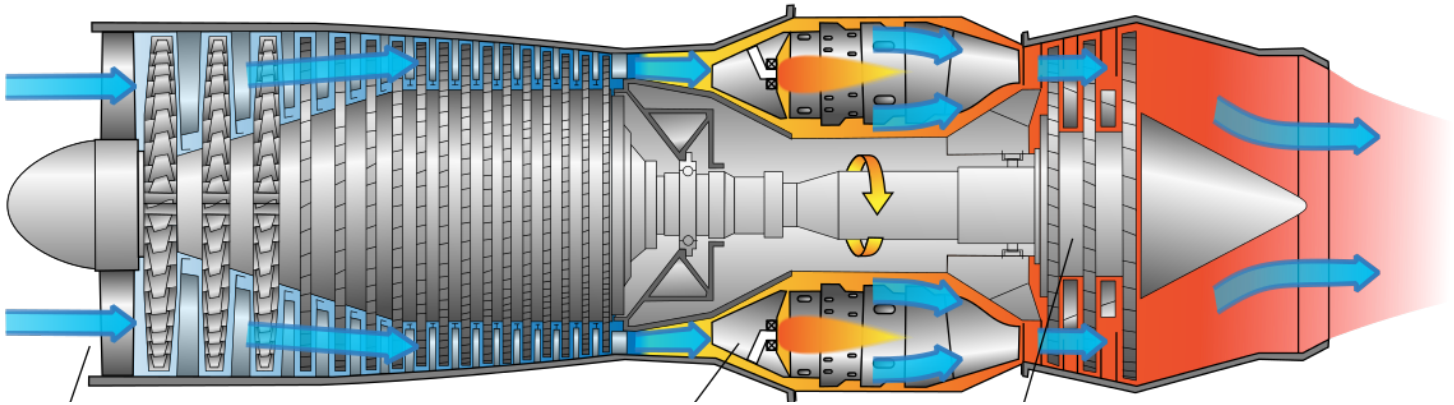
  -



Candidate Propulsion Systems

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Ramjet Engines

- **Strengths:**
  - Extremely simple
  - Highest specific impulse (I_{sp}) in the $M \approx$ range.
- **Weaknesses:**
  - I_{sp} drops rapidly around

Candidate Propulsion Systems

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Scramjet Engines

- **Strengths:**
  - Highest specific impulse (I_{sp}) in the $M \approx 4 - 10/15$ range.
- **Weaknesses:**
  - Long combustor required for high combustion efficiency

Candidate Propulsion Systems

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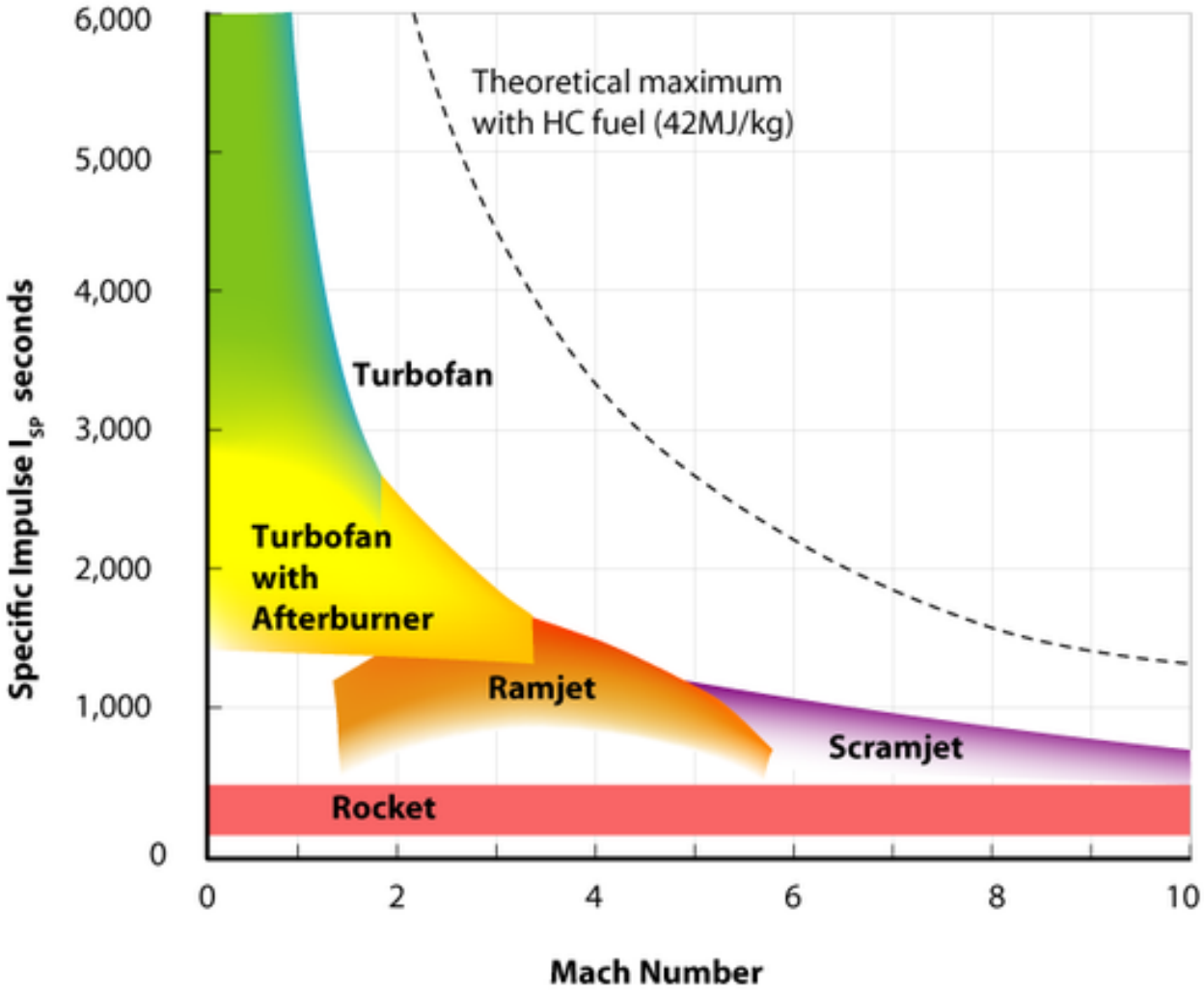
Rockets

- **Strengths:**
  - Highest specific impulse (I_{sp}) in the $M > 10/15$ range.
- **Weaknesses:**
  - Very (very) low I_{sp} compared to turbojets, ramjets, and scramjets at lower Mach number.

Candidate Propulsion Systems



Combined Cycle Concepts

- Composite propulsion systems (combined cycle) alternatives offer the best approach to maximizing the average I_{sp}.

Combined Cycle Concepts

1) Air Turbo-Rockets

- Expand hot gas from a rocket combustion chamber through a turbine to drive a fan.
  -
- Provide high _____and good performance at low speeds.
- Limited to _____flow through the engine
  - Shocks on the fan will reduce the efficiency and I_{sp}
  - Engine concept limited to modest Mach numbers, less than $\sim 3-5$

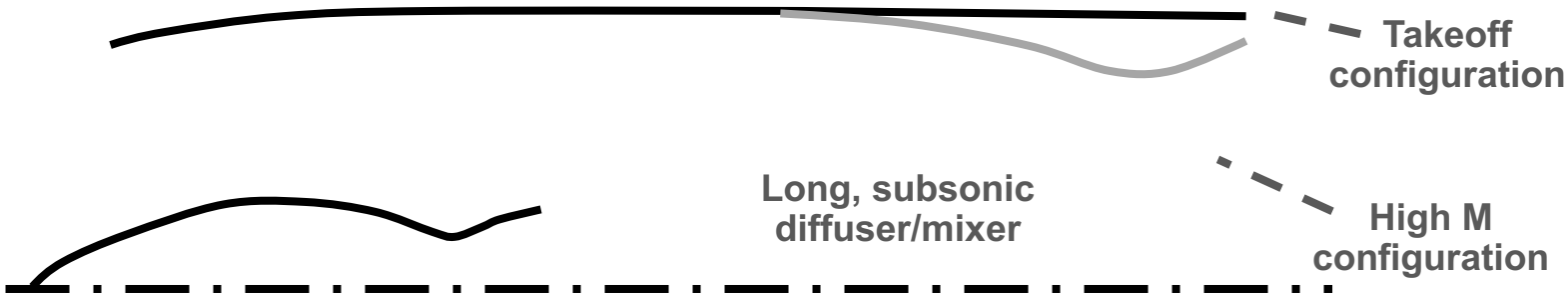
Combined Cycle Concepts

2a) Ducted Rocket

- Here, a rocket is used as an _____to pump a large air flow through the outer duct
  - The air mass-flow can be 5-9 times the rocket combustor to achieve the necessary static thrust
- Requires a long subsonic diffuser with small angles (3-5 deg)
- Often marketed for missile applications, this configuration has no real Mach limit.
  - As long as you still have air to 'breath' and enough nozzle/duct cooling.

Combined Cycle Concepts

2b) Integrated Rocket-Ramjet



- Very similar to the ducted rocket, but with augmented combustion using an afterburner.
  - Consuming the oxygen in the air duct flow, as well.
- Augmented thrust with minimal increase in complexity
- As with the ducted rocket, a variable geometry is necessary to achieve a large Mach number range.

Combined Cycle Concepts

2c) Liquid Air Cycle Engine

- Using the cooling capacity of the liquid H_2 to
- Use the liquid air in the combustor or pump it to a tank for later use
- Strength: minimize the tank/vehicle size to support the rocket combustor
- Weakness: This heat exchanger is really difficult to design
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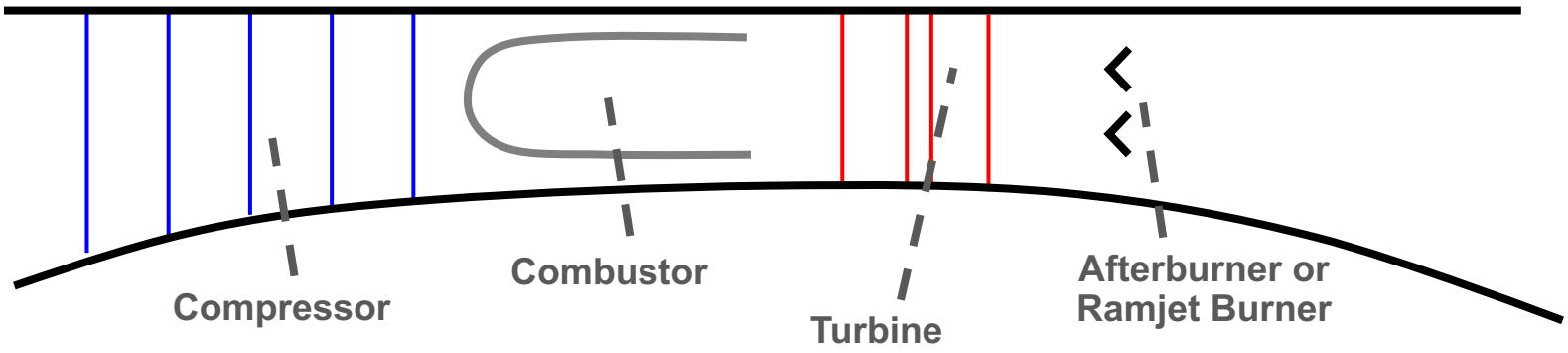
Combined Cycle Concepts

3) Turbo Ramjet

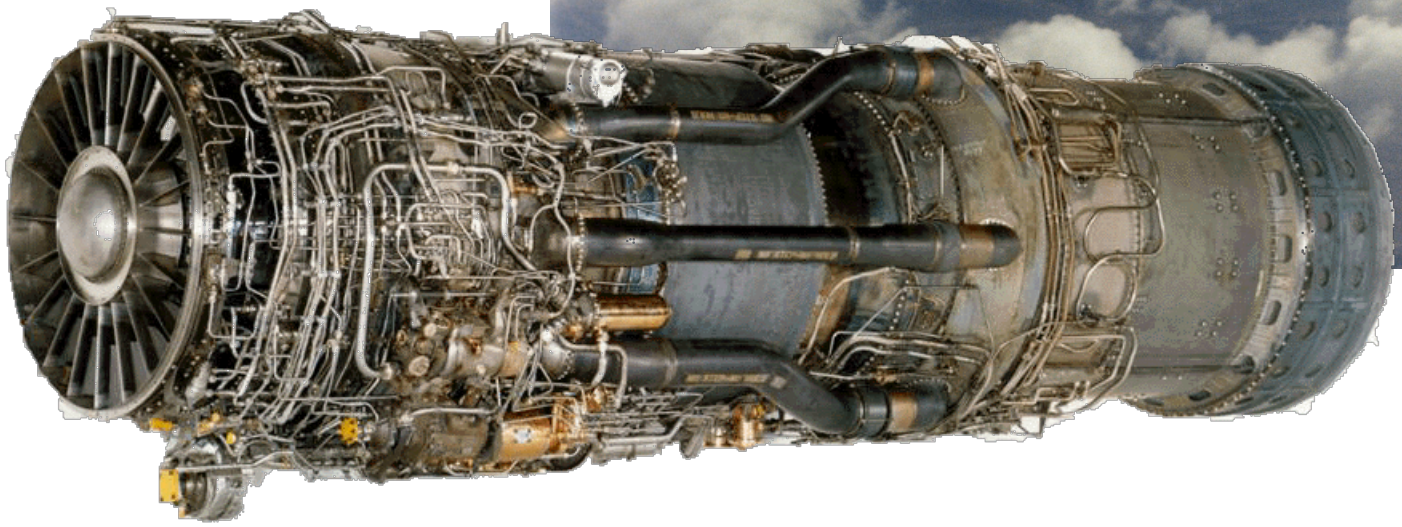


- At low Mach number, the engine operates as a normal Turbojet or Turbofan
- At high Mach number, the turbomachinery is bypassed by a large percentage of the total air mass-flow through the inlet and nozzle
  -
  -

Combined Cycle Concepts

3) Turbo Ramjet

- The Pratt and Whitney J-58 was able to power the SR-71 to achieve $M = 3.5$ with this design. Modest for a ramjet, but very respectable considering the turn-down capability.



Combined Cycle Concepts

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4) Turbo-Rocket-Ramjet

- The most complex, but also the most capable combined cycle

- This is a _____.
  - Effectively an Air-Turbo Rocket with an afterburner
- At low-speed, the first rocket combustor powers the turbine and
- Transition to Ramjet mode is accomplished by
- Final transition to pure-rocket operation with Rocket 2 for high-speed flight
-

Back to Integration

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A myriad of options exist…

- Can it all be fully-embedded?
- Is it worth the expense to do so?
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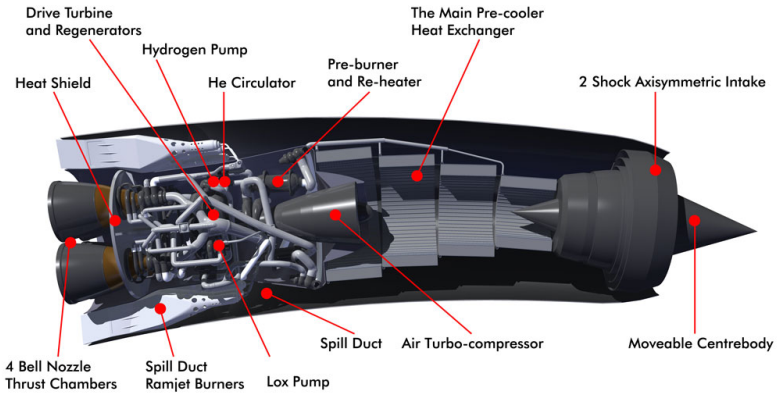
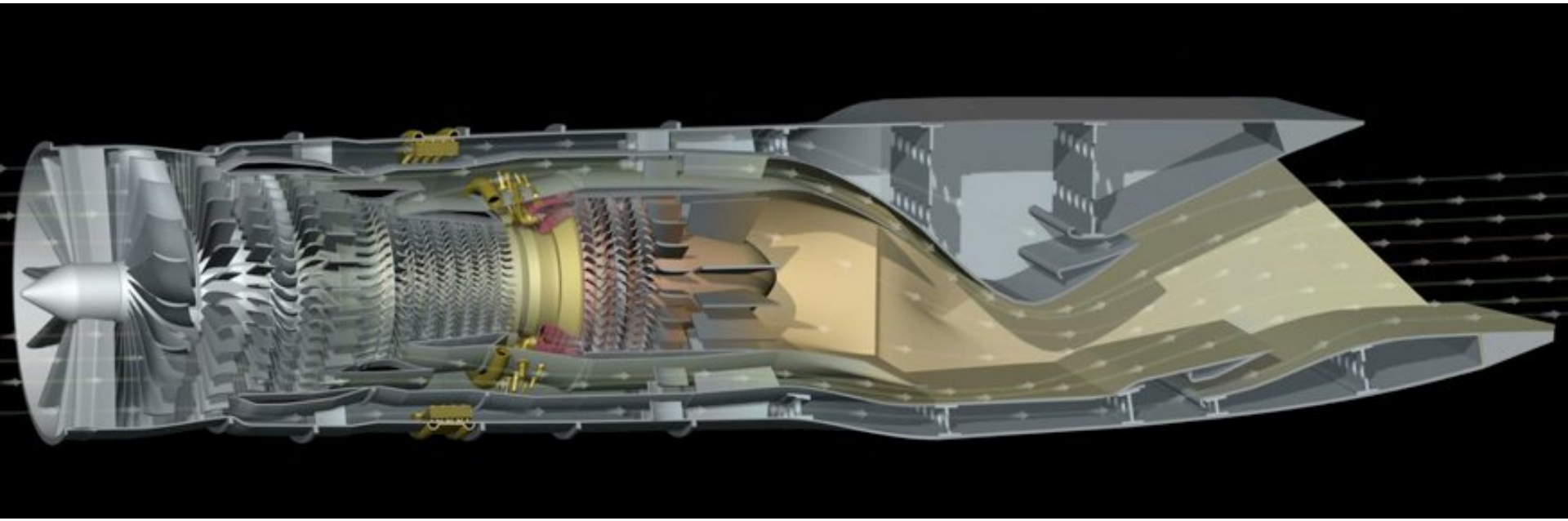
SABRE Engine Concept (Reaction Engines Ltd.)





The DoD VAATE program, ADVENT triple bypass design concept