DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

UNIVERSITÀ DEGLI STUDI DI PADOVA

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The Lockheed SR-71 Blackbird Propulsion System

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List of Symbols

T= Absolute temperature;

p= Pressure;

ρ = Density;

μ= Dynamic viscosity;

a= Speed of sound;

M= Mach number.

INTRODUCTION: HISTORICAL CONTEXT AND THE BLACKBIRDS FAMILY

At the beginning of the cold war the USA was in need of a reconnaissance plane able to sustain supersonic speeds and high altitudes and entrusted Lockheed to come up with a solution

Lockheed then came up with the Blackbirds, a family of aircrafts which included(chronologically):

- The A-12(maiden flight in 1963);
- The YF-12(interceptor version of the A-12);
- The M-21(launcher for the D-21 drone);
- The SR-71(designed in 1964, took the place of the A-12 in 1968 when it finished its service).

Lockheed A-12 (1)

Back view of the Lockheed M-21 with Lockheed D-21 drone (2)

INTRODUCTION: THE SR-71 AND ITS MAIN FEATURES

The SR-71 was the last evolution of the A-12 and it's also the member of the blackbirds family who withstanded the most years of service. In fact it was operated by the U.S. Air Force from 1968 to 1989 and by NASA up until 1999(only research puroposes)

An SR-71 Blackbird operated by NASA (3)

MAIN FEATURES:

- •Wingspan: 16.94 m;
- •Length: 32.7 m;
- •Take-off max. weight: 78'000 kg;
- •Range without refueling: 5'400 km;
- •Crew: 2;
- •Primary Payload: optical/infrared imagery systems;
- •Cruise altitude: >80'000 ft ≈ 24'400 m;
- •Cruise speed: Mach 3.2.

Operational ambient: **Stratosphere**

ICAO Std. Atmosphere Parameters at 80'000 ft:

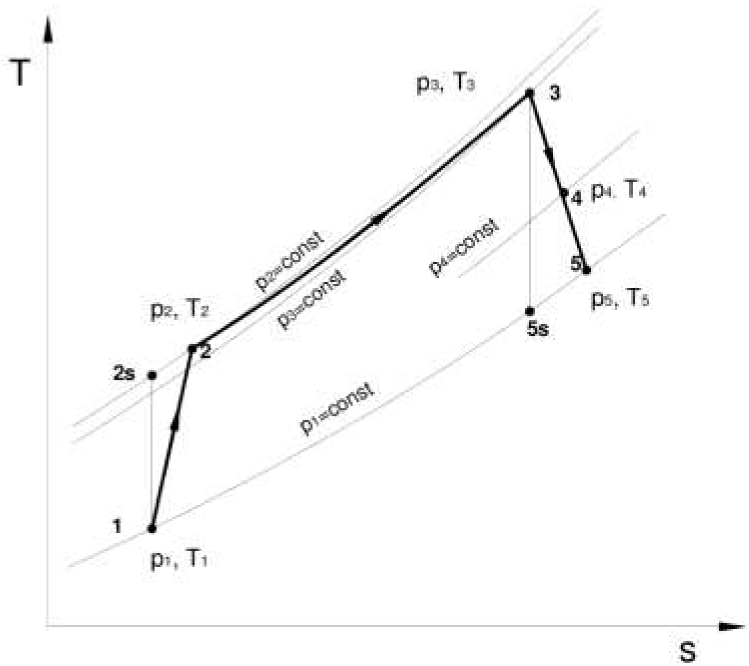
-**T**= 221.034 K; -**a**= 298.04 m/s;

-**p**= 2761.48 Pa; -**μ**= 0.0000145698 Pa s.

-**ρ**= 0.0435232 kg/m^3;

INTRODUCTION: AIR BREATHING JET ENGINES

All air breathing jet engines
feature the Brayton-Joule thermodynamic
cycle finalized to the production of thrust



Brayton-Joule diagram of a turbojet engine (4)

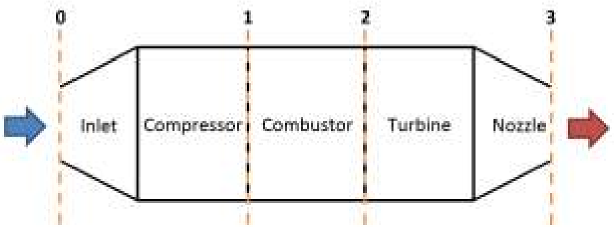
Tranformations:

- 1→2: Adiabatic compression;
- 2→3: Combustion;
- 3→4: Adiabatic expansion(gas turbine);
- 4→5: Adiabatic expansion(nozzle);
- 5→1: Isobaric cooling(in the atmosphere).

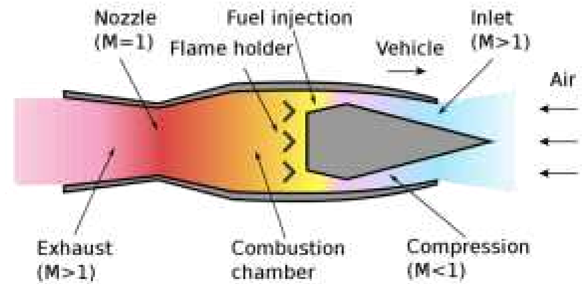
Main construction architectures:

- Turbojet/turbofan→axial compressor and turbine;
- Turboprop→production of power at the shaft;
- Ramjet→diffuser and nozzle.

INTRODUCTION: TURBINE BASED COMBINED CYCLE ENGINES (TBCC)



Turbojet Engine



Ramjet Engine

TBCC Engine

- Subsonic/transonic regime→turbojet;
- Superonic regime→ramjet.

- Better fuel efficiency at high speed;
- No compressor surges→higher max. speed of the aircraft.

SR-71 PROPULSION SYSTEM: OVERVIEW OF THE PRATT&WHITNEY J58 P-4 ENGINE

•Every SR-71 was fitted with two J58 engines; ⟶

-9 stages axial compressor;
-8 can combustor;
-2 stages axial turbine;
-Afterburner;
-Variable area output nozzle;
-Compression ratio at t/o: 8.8.

•First production implementation of a TBCC engine;

•Inlet assembly + bypass conducts + afterburner
→huge operational span;

•Nickel and titanium alloys construction for heat management
→temperatures up to 1470K;

•Purpose engineered low volatility JP7 fuel→burning characteristics+heat management;

•Static atferburner thrust at sea level: 150 kN.

A J-58 P-4 Engine (5)

SR-71 PROPULSION SYSTEM: ENGINE INLET AND INLET CONTROL SYSTEM

The inlet of the engine is made of a charcteristic traslating central spike(or centerbody) and a set of forward bypass doors.

Functions:
- Keep the pressure of the leading shockwave off of the engine;
- Compress the supersonic airflow by retaining the normal shockwave in the inlet vane;
- Slow the air flow to subsonic speed (when travelling supersonic);
- Provide correct amount of mass flow.

Control system

Analysed parameters:
- Flight Mach number;
- Angle of attack;
- Angle of sideslip;
- Normal acceleration
  →to account for frame deformation under high g-forces.

Iterations of the system:

1)Automatic Inlet Control System(AICS):
- -Analog system;
- -Fitted in A-12s and first SR-71s;

2)Digital Automatic Flight Inlet Control System(DAFICS):
- -Digital system;
- -Acted both as a flight control system and as an inlet control system.

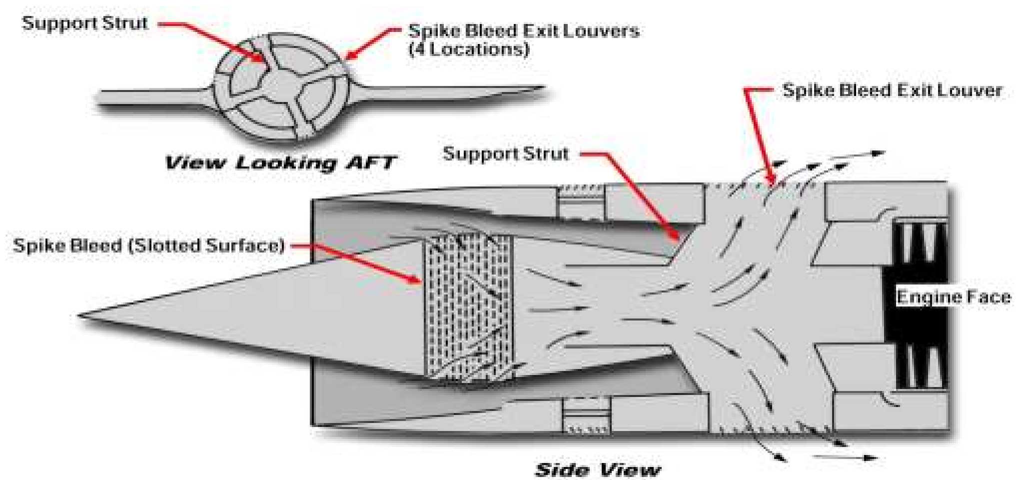
SR-71 PROPULSION SYSTEM: CENTERBODY BLEED AND SUCK-IN DOORS

Centerbody bleed:
a cave conduct connecting a series of slits on the surface of the spike to a series of louvres on the surface of the nacelle of the engine.

Low speed operation:
Lets more air enter the engine from the environment.

High speed operation:
Funnels the boundary layer on the surface of the spike to enhance the pressure recovery of the inlet system.

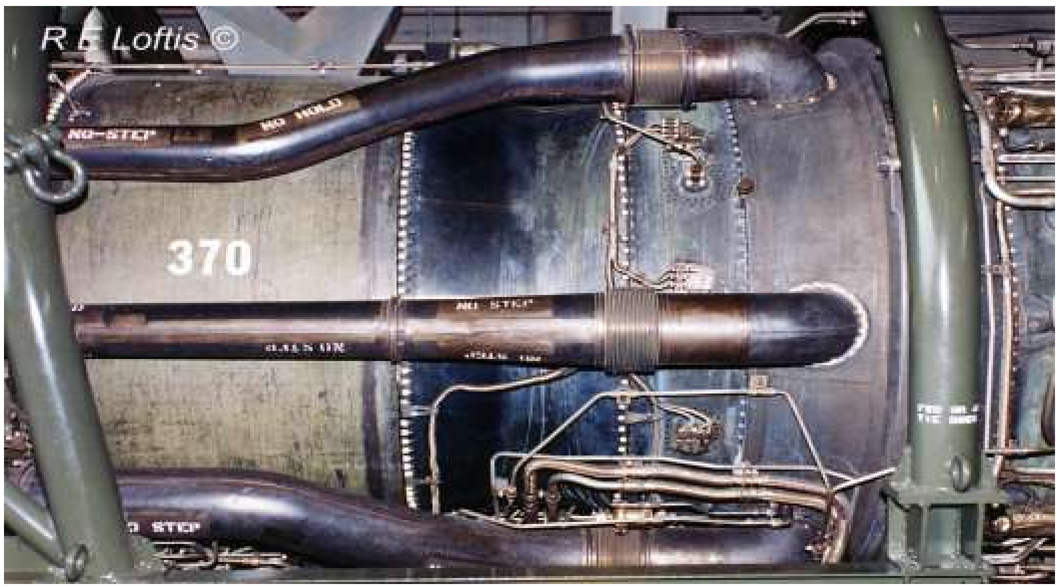
Suck-in doors:
Doors placed on the nacelle of the engine to feed more air to the afterburner during the take-off phase.



Centerbody bleed scheme at high speed regime (11)

SR-71 PROPULSION SYSTEM: AFT BYPASS DOORS AND AFT BYPASS CONDUCTS

Starting from Mach 2.2 → A part of the mass flow is spilled from the 4° stage of the compressor and taken directly to the afterburner→engine operates as a turbo-ramjet.



Detail of three bypass conducts (7)

The spilled flow enters 6 bypass conducts trough the 6 aft bypass doors and arrives to the afterburner directly→thrust production via ramjet effect.

The remaining flow that enters the 5° stage of the compressor keeps the turbomachinery in motion and also contributes to the thrust output.

SR-71 PROPULSION SYSTEM: STARTING AND RESTARTING PROCEDURES

ENGINE START ON THE GROUND:

1. External shaft(ICU starter or compressed air starter)sets the turbomachinery in motion;
2. Shot of triethylborane(TEB) directly in the combustor and in the afterburner chemically starts the engine and/or its afterburner.

TEB: -Highly toxic and unstable compound;
-Burns upon contact with air at T>268.15K;
-Needed to match the low volatility of the JP7 fuel.

ENGINE RESTART AFTER INLET UNSTART:

•8 TEB shots per engine available per flight;
•TEB shots-counter placed on the throttle lever of each engine;
•After inlet unstart the afterburner needed one shot of TEB.

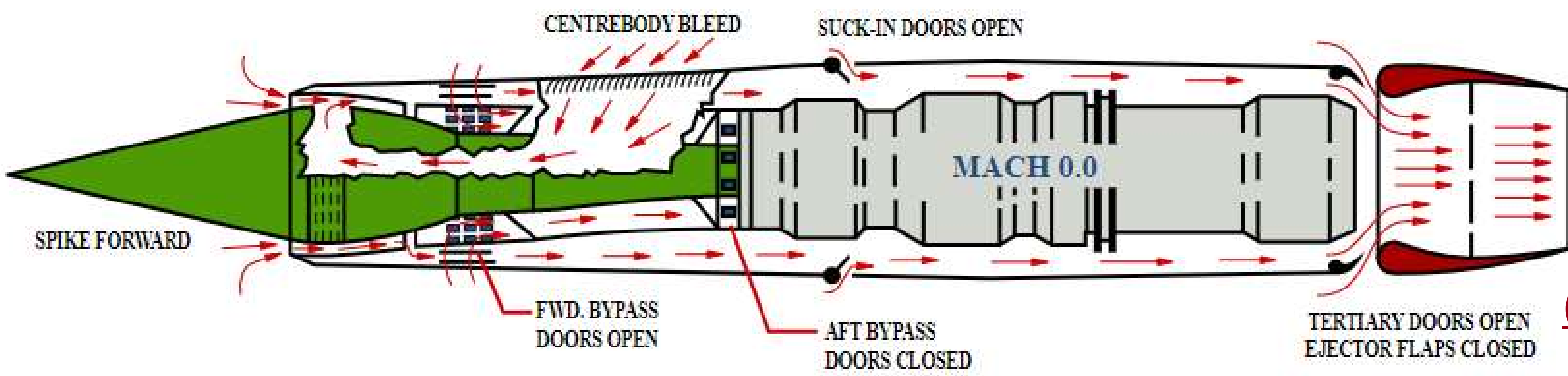
Inlet unstart: sudden process during which the normal shockwave exits the inlet and so there are insufficient pressure and air in it for correct engine operation.

Causes:
•Large air disturbances;
•Improper inlet control.

Consequences:
•Sudden loss of thrust;
•Violent pitching, yawing and rolling motions.

→ **Crashes**

SR-71 PROPULSION SYSTEM: TAKE-OFF REGIME



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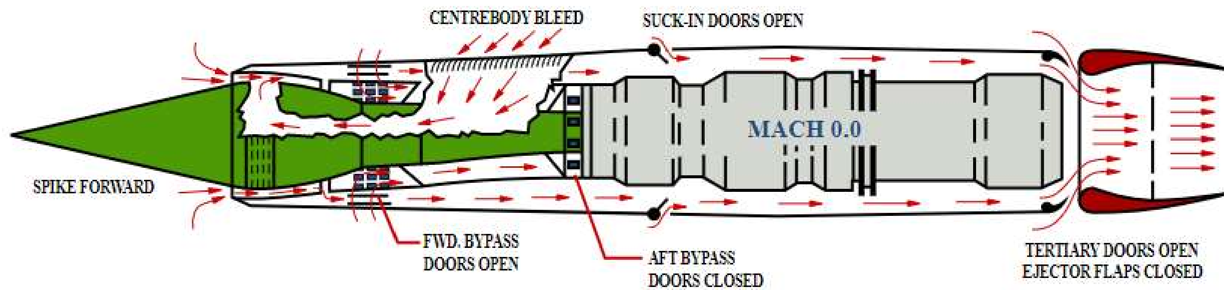
- Speed: 0→210 kt(108 m/s);
- Engine configuration: turbojet with full afterburners;
- Spike position: fully forward;
- Forward bypass doors: open to provide more airflow;
- Centerbody bleed doors provide more airflow;
- Aft bypass doors: closed;
- Suck-in doors: open;
- Thrust generated: maximum→150kN per engine.

SR-71 taking off (8)

SR-71 PROPULSION SYSTEM: AFTERBURNING IN THE BRAYTON-JOULE CYCLE



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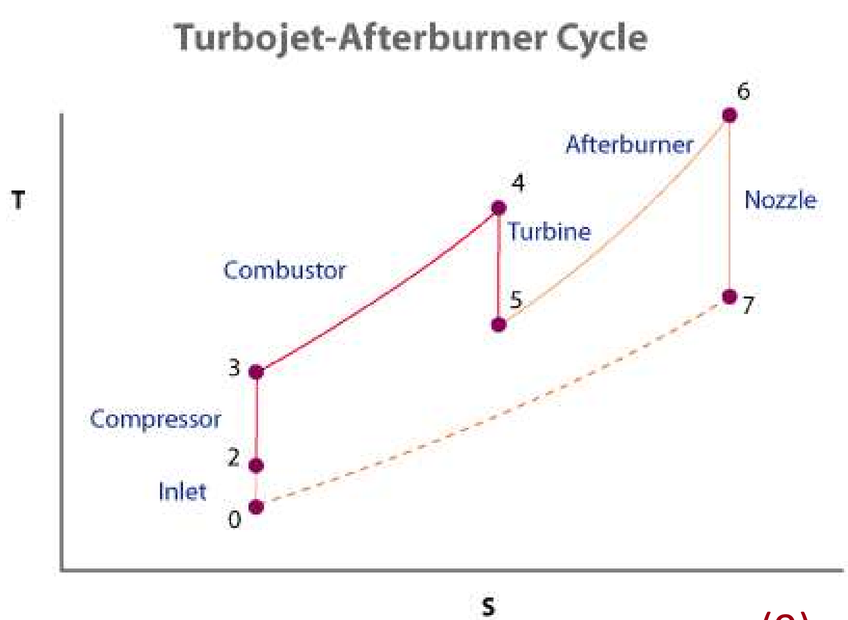

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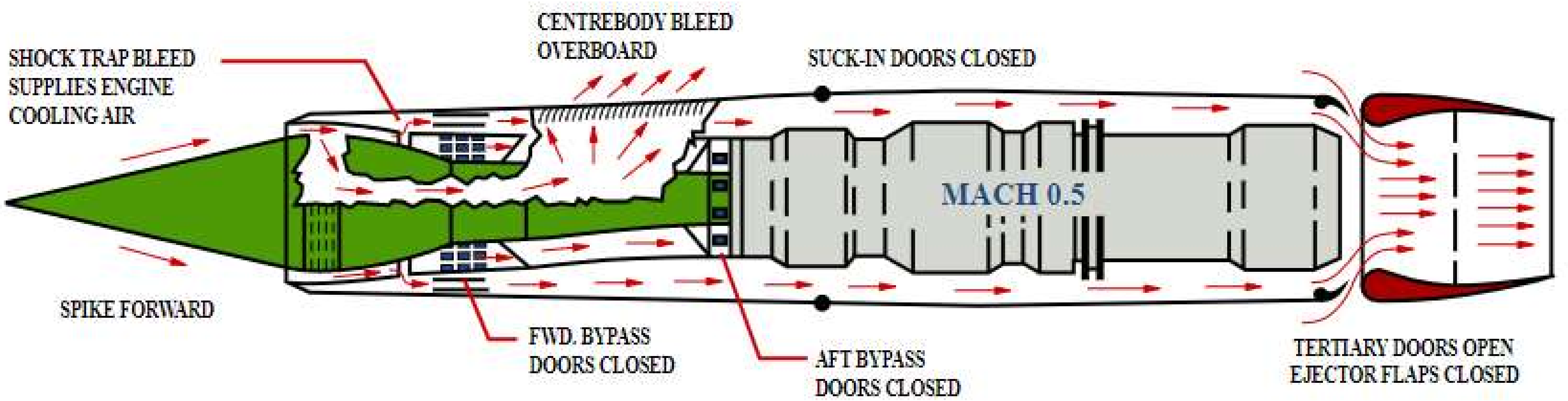
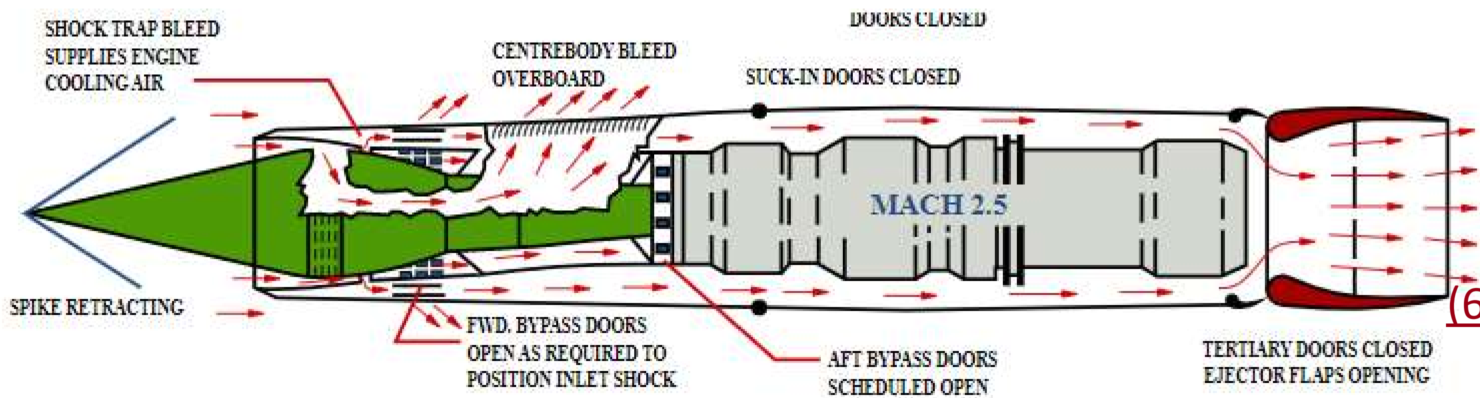
All the mass flow of air evolves as shown in the diagram during the take-off phase.

SR-71 PROPULSION SYSTEM: CLIMB REGIME



- Speed: 400-450 KEAS;
- Engine configuration: turbojet with afterburners;
- Spike position: fully forward;
- Forward bypass doors: closed upon gear retraction;
- Centerbody bleed wicks away the spike’s boundary layer;
- Aft bypass doors: closed.

SR-71 PROPULSION SYSTEM: ACCELERATION TO CRUISE SPEED REGIME



(6)

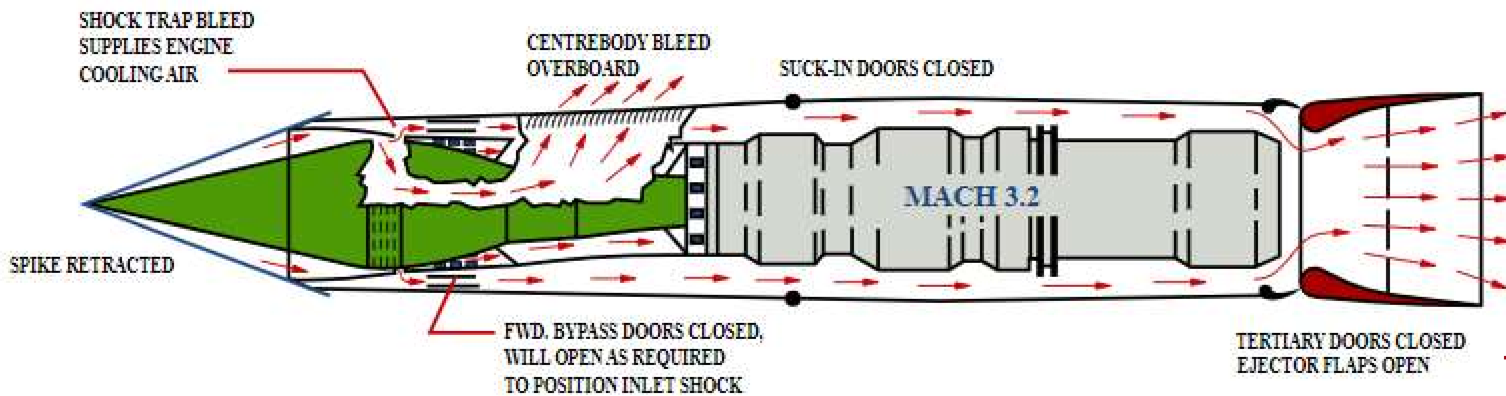
•From Mach 1.4-1.6→forward bypass doors and the spike are used and modulated to retain the normal shockwave in the optimal position within the inlet;
•Engine configuration: turbojet with afterburners until Mach 2.2, turbo-ramjet above Mach 2.2;
•Spike position: partially retracted;
•Forward bypass doors: open/closed;
•Centerbody bleed wicks away the spike’s boundary layer;
•Aft bypass doors: open above Mach 2.2.

% of total thrust generated at Mach 2.2:
•Inlet assembly: 13%;
•Engine: 73%;
•Afterburner ejector: 14%.

↓

Ramjet effect(inlet+AB effects): 27%

SR-71 PROPULSION SYSTEM: <u>CRUISE SPEED REGIME</u>



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•Engine configuration: turbo-ramjet with max. efficiency;
•Spike position: fully retracted→leading shockwave at the cowl;
•Forward bypass doors: open/closed to retain normal shockwave in the optimal position;
•Centerbody bleed wicks away the spike's boundary layer;
•Aft bypass doors: open;
•Inlet compression ratio: 40:1;
•Volumetric air flow: 2'831.7 m^3/s.

% of total thrust generated at Mach 3.2:
•Inlet assembly: 54%;
•Engine: 17%;
•Afterburner ejector: 29%.

↓

Ramjet effect: <u>83%</u>

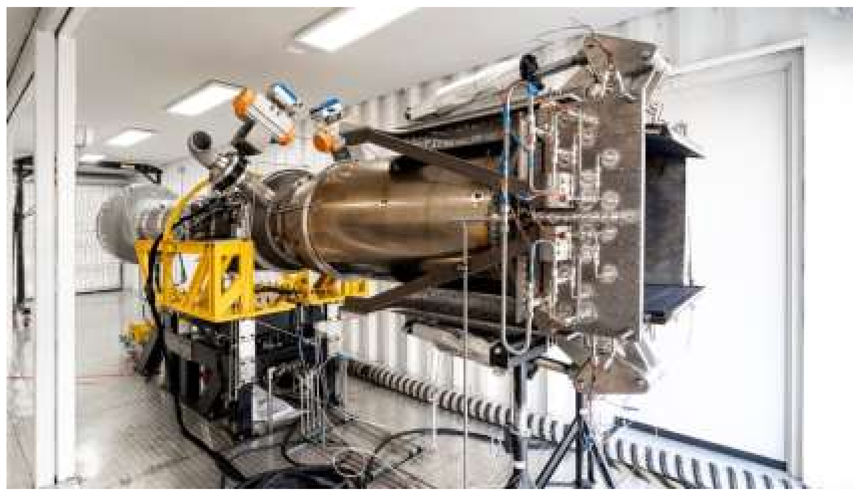
TBCC ENGINES: STATE OF THE ART AND FUTURE OF THE TECHNOLOGY

SOA: Hermeus "Chimera" engine → Designed to be fitted in an air breathing hypersonic(M>5) and reusable plane.

First ever transition from turbojet to ramjet (November 2022) → As opposed to SR-71's engines which always had a part of the flow passing through compressor and turbine.

TBCC engines' future applications: hypersonic atmospheric travel

- Military;
- Commercial;
- Hypersonic space launching platforms.



The "Chimera" Engine (10)

FINAL CONSIDERATIONS

- The J58 project pioneered the field of TBCC propulsion;

- TBCC engines are the key to having planes capable of a vast array of operational speeds;

- TBCC engines enable hypersonic flight to be operated by reusable and self-launching aircrafts;

- I personally expect the field of TBCC propulsion to grow massively in the next years due to the demand of hypersonic planes and hypersonic space-launching platforms.

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