AE 452 Aeronautical Engineering Design II

Air Intakes & Nozzles

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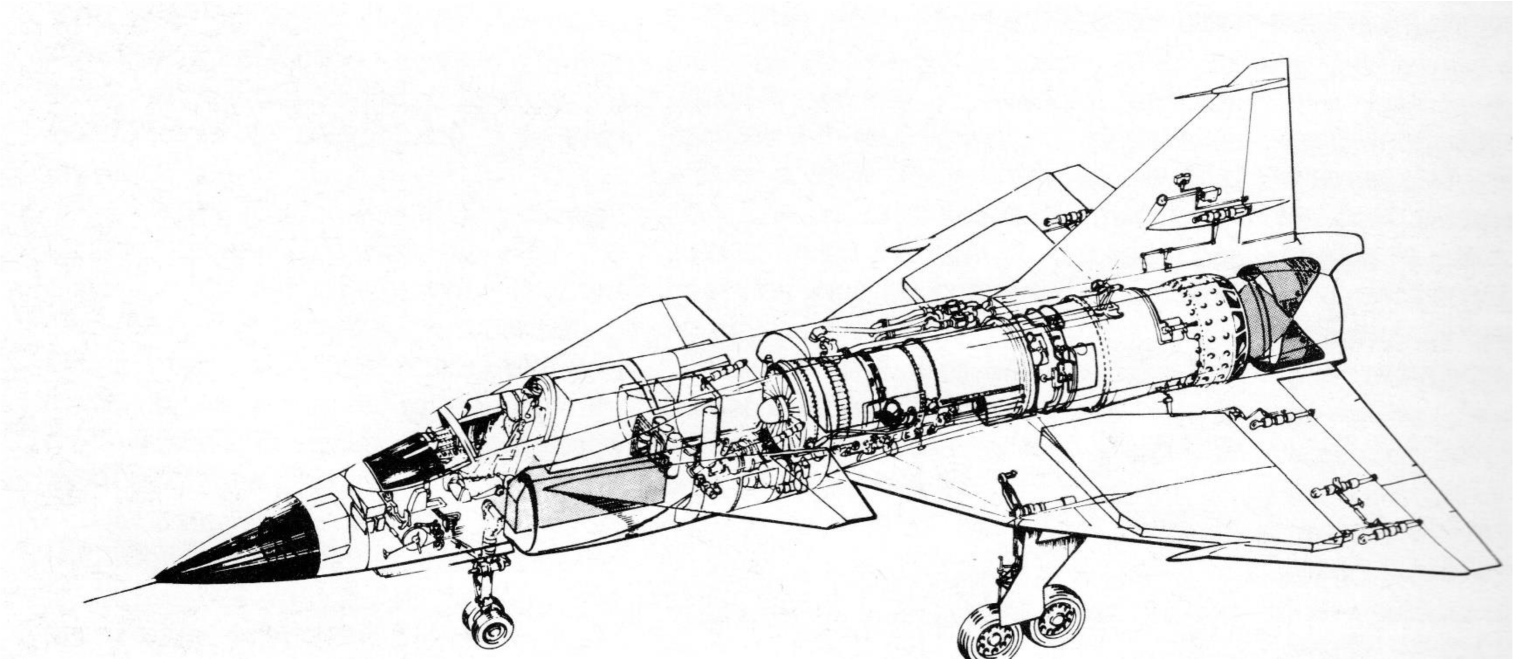
Outline

- Intake requirements
- Classification of air intakes
  - Normal shock diffuser
  - Oblique shock diffuser
  - Two dimensional intakes
- Exhaust nozzle
- Classification of nozzles
  - Convergent nozzles
  - Convergent-divergent nozzles
  - Ejector nozzles
  - Variable ejector nozzles
  - Iris nozzles
- Afterburning
- Reverse thrust

Intake requirements

- Combat aircraft have one or two engines, which are almost always **integral** with the fuselage.
- **Supplying the engines** with the **necessary quantity of air** for generating thrust takes place by specially designed inlets.
- The task of the inlet is to supply the engine with a **uniform, stable, low-loss flow.**
- The requirements for the inlet:
  - A **high pressure recovery** (1% loss in inlet pressure recovery results in 1.3% loss in thrust).
  - **Deceleration** so that the Mach # at the engine entrance is ≈0.4-0.5.
  - **Low drag**.

Integrated engine



Classification of air intakes

There are three basic types of air intakes:

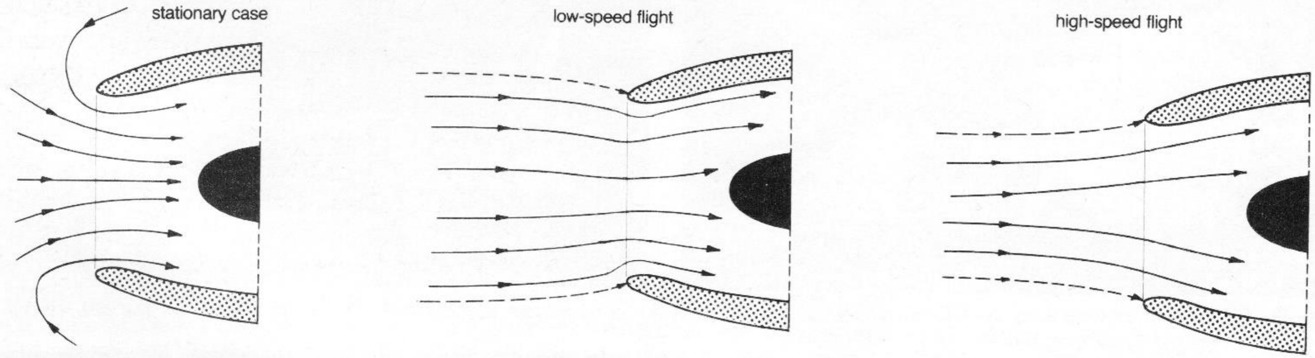
- Normal shock diffuser or pitot intake,
- Oblique shock diffuser (conical or spike inlet),
- Two-dimensional intake,
- Diverterless intake.

Normal-shock diffuser

Normal shock diffuser or pitot inlet: works well **subsonically** and fairly well at **low supersonic speeds**. However, the normal shock produced will reduce pressure recovery so it is not suitable for prolonged operation above M=1.4.

Normal-shock diffuser in subsonic flow

- The **air requirement of the engine** determines the **flow speed at the compressor face** and the **speed at the intake cross-section.**
- According to the flight speed, this results in a **contraction** (low speed) or **expansion** (high speed) of the **streamlines** entering the intake.

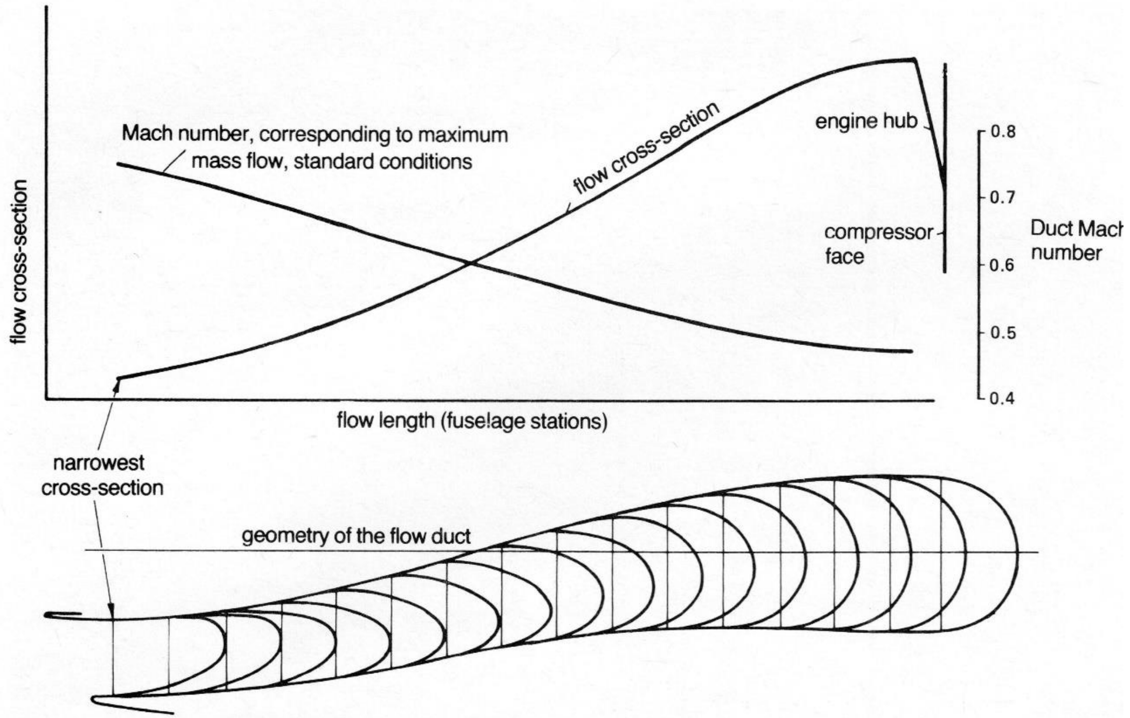


7-4 **Inlet flow at take-off, low-speed flight and high-speed flight (subsonic).**

Normal-shock diffuser in subsonic flow

- The exploitation of the kinetic flow energy to gain pressure continues in the inlet duct.
- The inlet duct is designed in such a way that the cross-section in the flow direction **expands gradually and steadily**.
- A **divergent air duct** with the capacity to **decelarate a subsonic flow** in this way and to **build-up pressure** is called a **diffuser.**

Normal-shock diffuser in subsonic flow

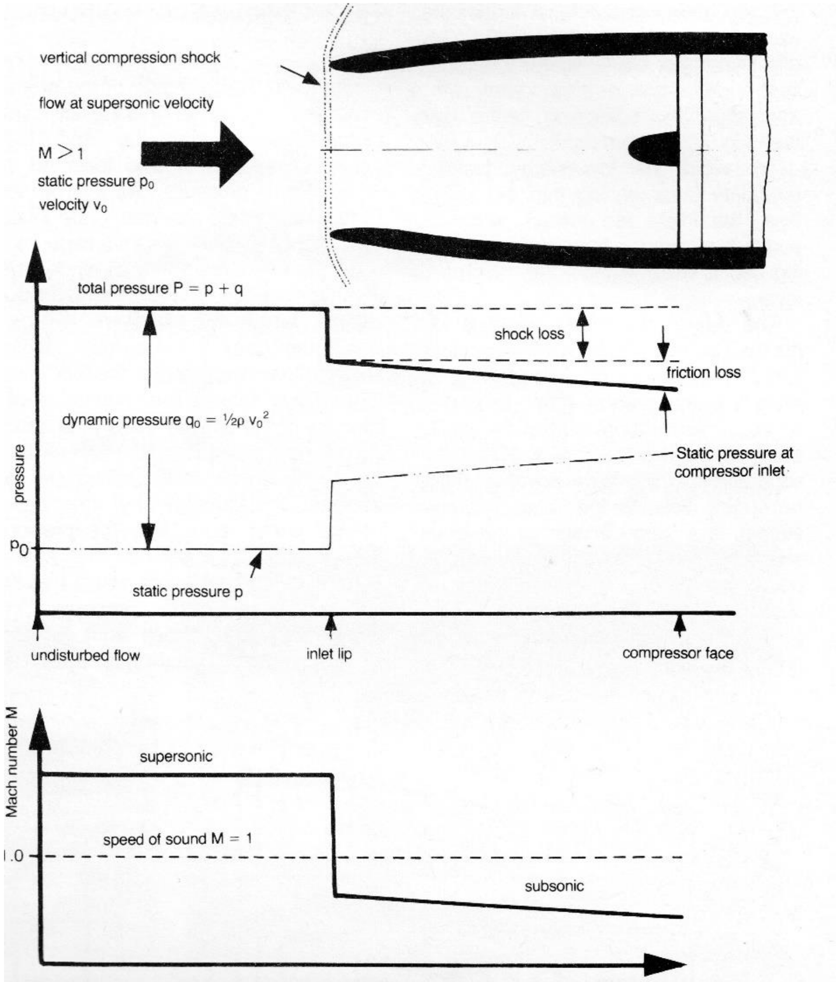


7-35 **Geometry of the F-16 duct.**
The gradual increase in cross-section makes an almost linear Mach-number drop possible between throat and compressor face.

Normal-shock diffuser in supersonic flow

- After exceeding the **speed of sound,** a **shock wave** forms in front of the intake.
- The shock wave **decelarates** the incoming flow instantaneously **from supersonic to subsonic speed** $\Rightarrow$ there is a rise of pressure and density $\Rightarrow$ **normal compression shock.**
- The kinetic energy taken away from the flow **is not completely regained** as pressure $\Rightarrow$ there is a loss increasing with flight Mach number.

Normal-shock diffuser in supersonic flow



7-5 Pressure changes of the air at a normal shock diffuser; supersonic flow.

Oblique-shock diffuser

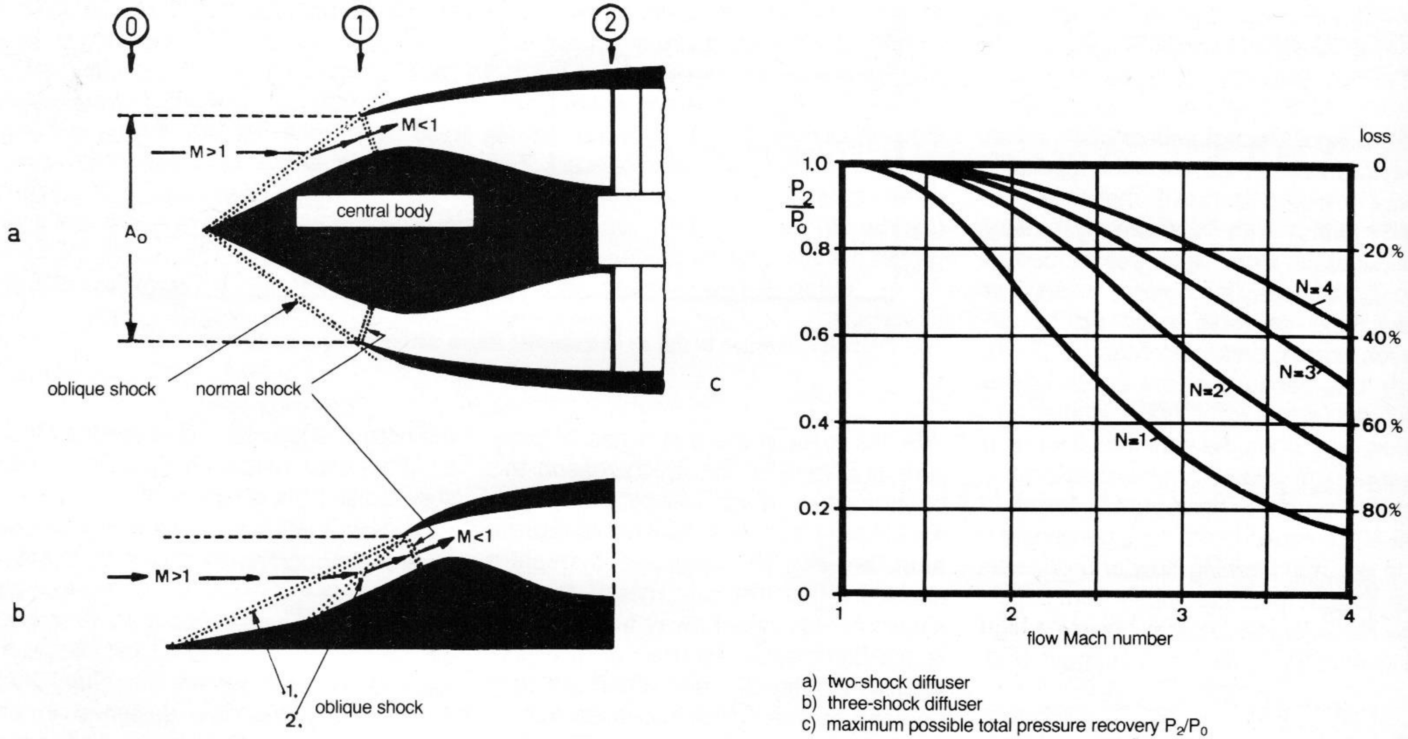
Oblique shock diffuser, spike or conical inlet: exploits **shock patterns** created by the supersonic flow over a cone. The spike inlet is lighter and has slightly better pressure recovery but has **higher cowl drag** and **mechanically more complex**. Suitable for $M>2.0$.

It **decelarates** the flow over one or several **oblique shocks,** which are relatively **low-loss** compared to normal shocks. The last shock in the intake is inevitably a normal shock, which decelarates the flow to **subsonic speed**.

The number of oblique shocks and their positions are determined by means of **kinks** on the center body.

Oblique shock diffuser

Oblique-shock diffuser in supersonic flow



7-6 **Oblique-shock diffuser.**

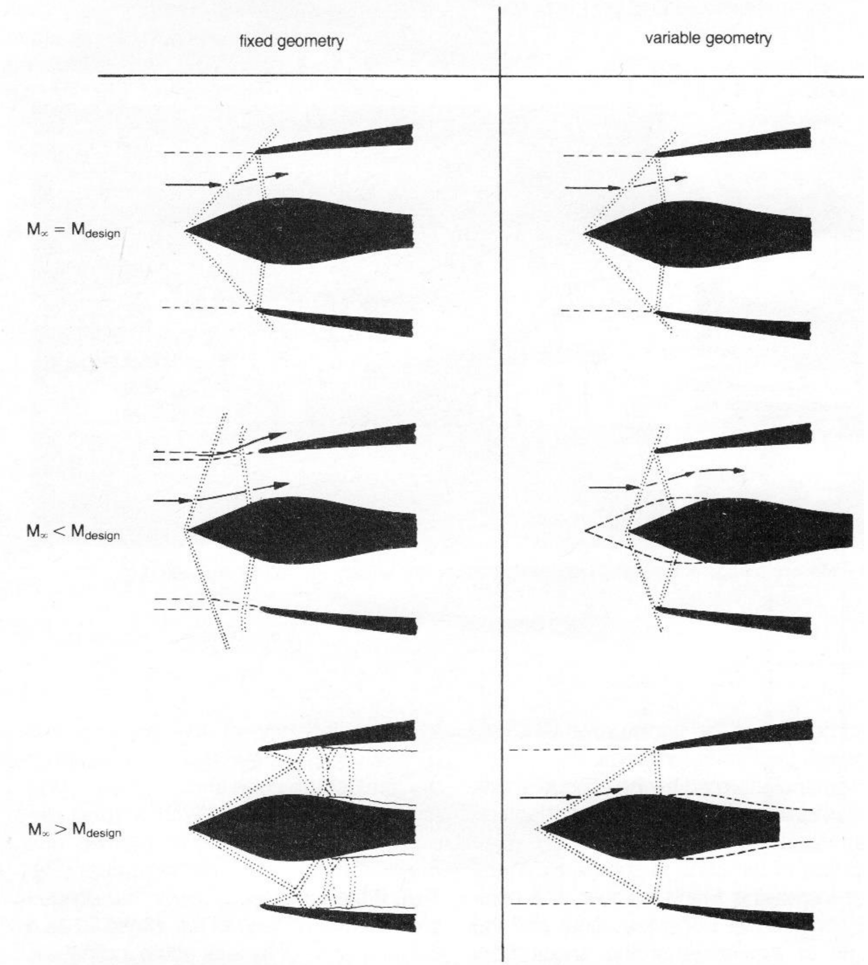
a) two-shock diffuser
b) three-shock diffuser
c) maximum possible total pressure recovery P_2/P_0

N = number of shocks

Oblique-shock diffuser in supersonic flow

- The **angle** formed by the oblique shock with the flow direction is dependent on the Mach number and the angle of deflection of the cone. With **increasing Mach number,** the conical shock wave becomes **acute**.
- The **efficiency of the inlet** requires that the **shock coming from the apex of the cone** should always pass **close to the inlet lip**.
- With a fixed geometry inlet this condition can be met only for one particular Mach number $\Rightarrow$ a **variable geometry inlet**.

Oblique-shock diffuser in supersonic flow



7-8 **Shock configurations in the case of a fixed geometry and variable geometry inlet.**

Two-dimensional inlet

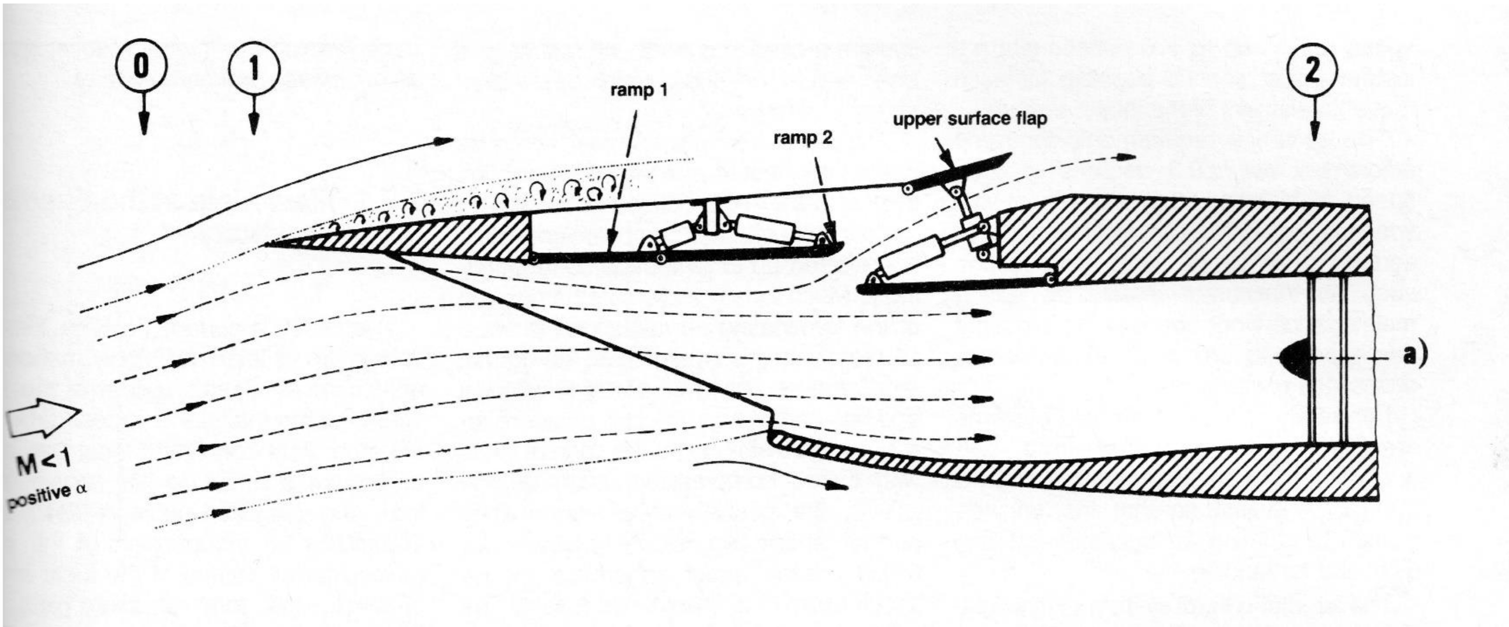
Two-dimensional or ramp inlet: Uses the **shock pattern** produced by a wedge. Suitable for M<2.0.

An oblique shock diffuser is optimum for pressure recovery but becomes unfavorable when the flow is not symmetrical to the axis of the cone but is at an angle to it. This occurs during maneuvering flight.

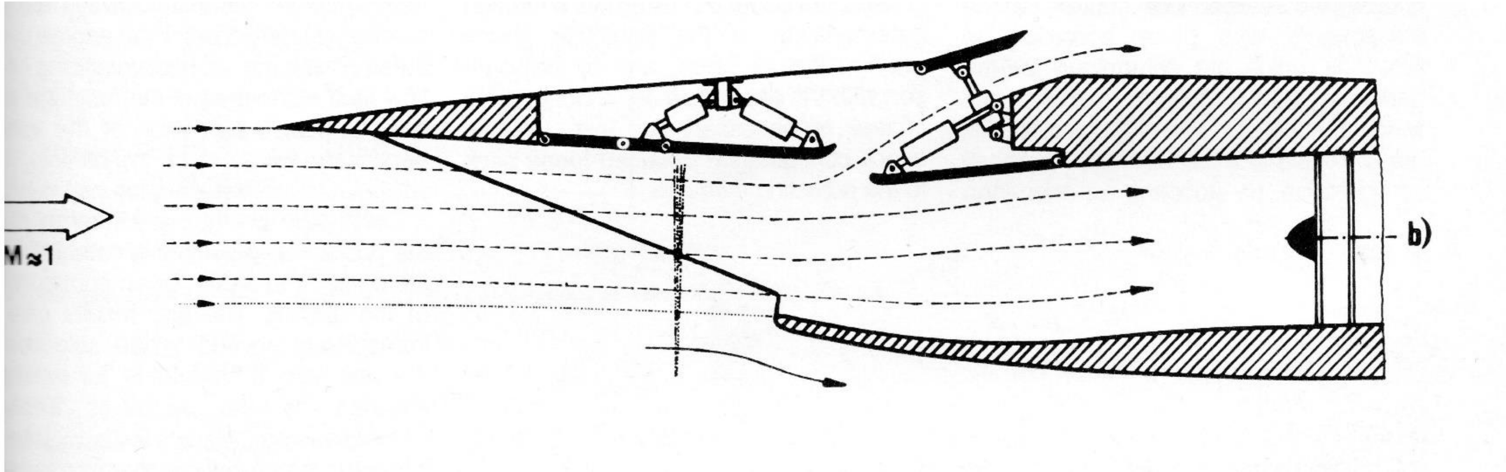
A **two-dimensional intake** reacts considerably less to oblique flow but the **pressure recovery is less favorable**.

Two-dimensional inlet

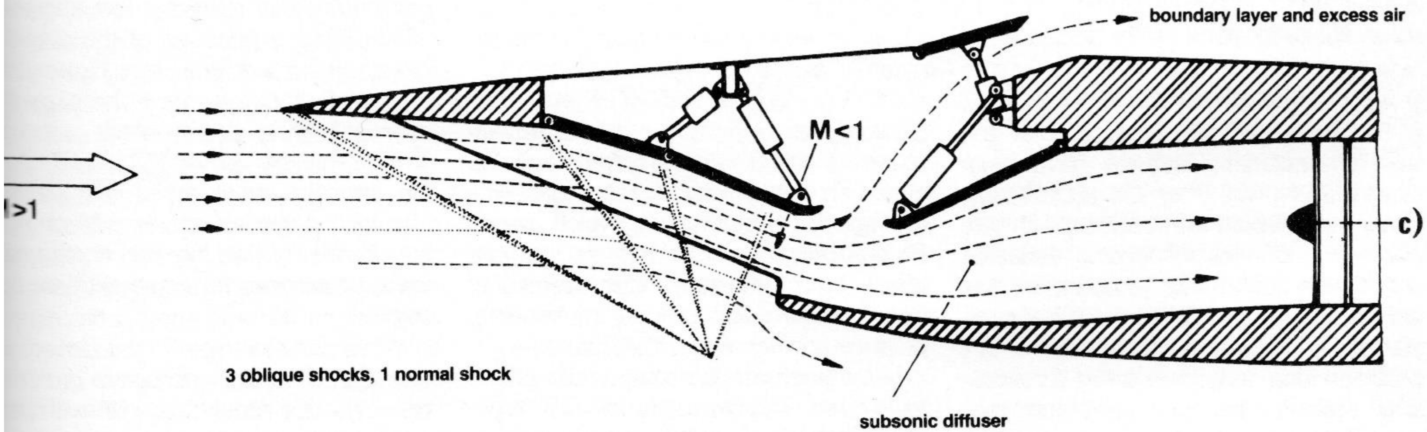
Two-dimensional inlet in subsonic flow



Two-dimensional inlet in transonic flow



Two-dimensional inlet in supersonic flow



26 **Inlet of the F-14**
Ramp positions and flow at various flight conditions: a) subsonic speed and high angle-of-attack (typical manoeuvre case); b) transonic flow; c) supersonic flow.

171

Diverterless intake

- A **diverterless supersonic inlet** (**DSI**) is a type of intake used by some modern combat aircraft consisting of a "**bump**" and a **forward-swept inlet cowl**, which work together to **divert boundary-layer away from the aircraft's engine**.
- This eliminates the need for a splitter plate, while compressing the air to slow it down from supersonic to subsonic speeds. The DSI can be used to replace conventional methods of controlling supersonic and boundary-layer airflow.

Diverterless intake

- The DSI bump functions as a compression surface and creates a pressure distribution that prevents the majority of the boundary layer air from entering the inlet at speeds up to Mach 2.
- Traditional aircraft inlets contain many heavy moving parts. In comparison, **DSI completely eliminates all moving parts**, which makes it far **less complex** and **more reliable** than earlier diverter-plate inlets. The removal of moving parts also **reduces the overall weight** of the aircraft.

Diverterless intake

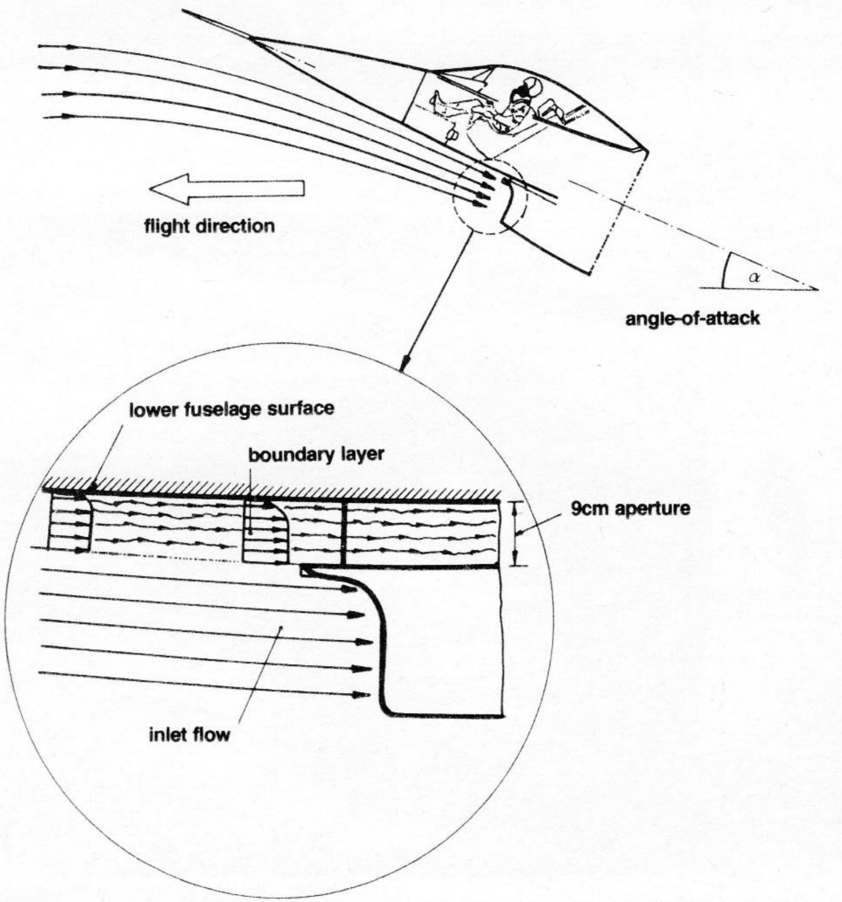
- DSIs also crucially **improve the aircraft's low-observable characteristics** (by eliminating radar reflections between the diverter and the aircraft's skin).
- Additionally, the "bump" surface **reduces the engine's exposure to radar**, significantly reducing a strong source of radar reflection because they provide an additional shielding of engine fans against radar waves.
- However, a diverterless intake **reacts considerably to oblique flow**, which is a disadvantage in maneuvering flight especially for two-engine aircraft.

Diverterless intake

Inlet configurations

- Inlet must not be placed where it can ingest a vortex off the fuselage, boundary-layer, or separated wake from the wing, the **inlet flow distortion** can stall the engine.
- The nose location offers the inlet a completely clean airflow, but requires a **very long internal duct**, which is heavy with high losses, requires high volume.
- The chin inlet has the advantage of a nose inlet with a shorter duct. It is particularly good at **high α** because the fuselage forebody helps to turn the flow into it.
- Nose landing gear must not be placed ahead of the inlet.
- Another problem is **foreign object ingestion**.

Inlet configurations



7-21 In the F-16 the boundary-layer diverter consists of a 25 cm-long (10 in) plate.

Exhaust nozzle

$$F = m\,(c_j - v_0) + m_f c_j + (p_j - p_0)\,A_j$$

- The thrust generated by an engine is directly proportional to the exit velocity, c_j.
- In order for accelaration to take place, there must be sufficiently large pressure at the nozzle entrance. In this way, it is possible to achieve **sonic** or even **supersonic flow at the nozzle exit.**
- Accelaration of the flow in the nozzle is also dependent on **temperature**. Hot gas has low density, so the gas molecules can easily be accelarated to high velocity.
- Pressure, density and temperature **decrease** through the nozzle. The pressure reaches the **atmospheric pressure** at the nozzle exit. The exiting jet is still hot, which is a **loss**.

Exhaust nozzle

- Velocity of sound, $a = \sqrt{\gamma R T}$.
- Mach number, $M = V/a$.
- As the temperature decreases in the nozzle, so does the speed of sound. However, the Mach number increases because:
  - The flow velocity increases,
  - The speed of sound decreases.
- If: $M < 1$: the gas flow is **subsonic**,

  $M = 1$: the gas flow is **sonic** or **critical,**

  $M > 1$: the gas flow is **supersonic.**

Exhaust nozzle

- Conservation of mass: $\dot{m} = \rho V A = constant$,
- Dependence of cross-section development as a function of Mach number:

$$\frac{dA}{dV} = -\frac{A}{V}(1 - M^2).$$

$dA > 0$: duct cross sectional area increasing,

$dA < 0$: duct cross sectional area decreasing,

$dV > 0$: flow accelarating,

$dV < 0$: flow decelarating.

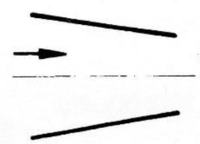
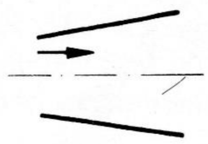
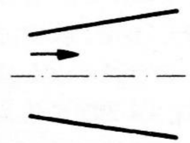
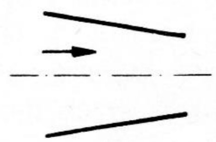
Convergent nozzle

- On entering the nozzle, flow is always **subsonic.**
- In accelarated flow ($dV > 0$), duct cross section must decrease: $dA < 0$.
- If the exit velocity need not exceed the speed of sound, a cross-section development of this kind is fully adequate.
- **The convergent nozzle,** is used in all jet-propelled **subsonic aircraft**. The highest velocity that can be reached at the exit is the speed of sound for this kind of nozzle.

Convergent-divergent nozzle

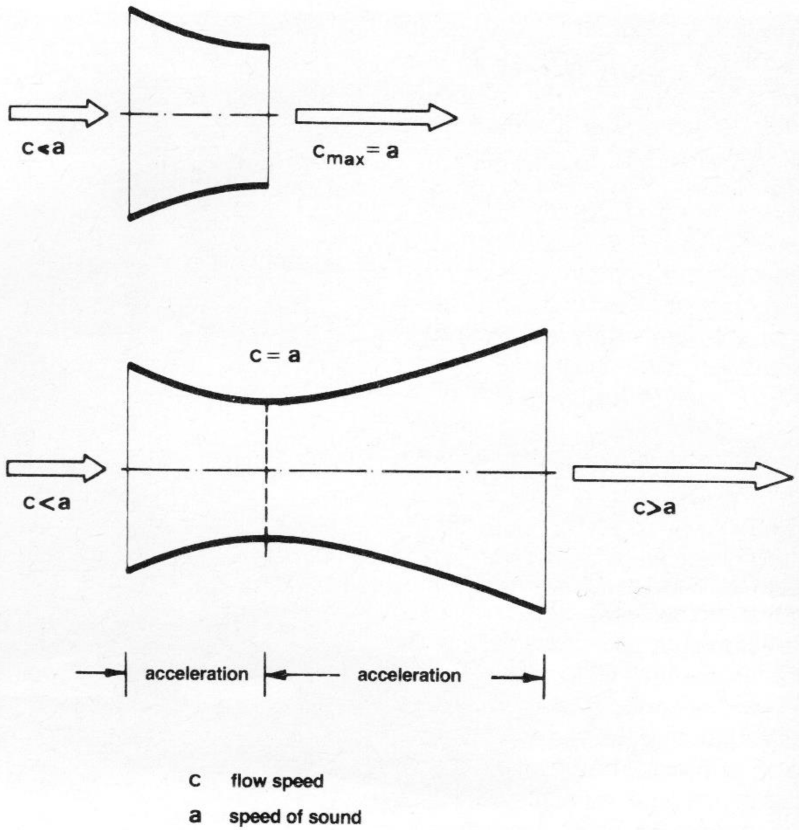
- If the velocity of sound or supersonic speed has already been reached in the nozzle ($M > 1$), for further accelaration ($dV > 0$), the cross section must increase ($dA > 0$).
- This the **divergent** part of the nozzle.
- The condition that in the cross-section exactly the speed of sound ($M = 1$) occurs is fulfilled by $dA = 0$.
- This is the narrowest cross-section, called the critical cross-section or the **throat**.
- Because of this, the flow in the supersonic nozzle is divided into two sections; **converging-diverging nozzle or Laval nozzle**.

Convergent and convergent-divergent nozzle

duct type	flow speed w	flow state in the duct	
		subsonic ($M < 1$)	supersonic ($M > 1$)
nozzle	w increases $dw > 0$ accelerated flow		
	example:	convergent exhaust nozzle	divergent section of a supersonic nozzle
diffuser	w decreases ($dw < 0$) decelerated flow		
	example:	inlet duct (subsonic diffuser)	cannot be realized

6-11 **The design of the duct system for nozzle and diffuser.**

Convergent and convergent-divergent nozzle



6-13 **Convergent and convergent-divergent nozzle.**

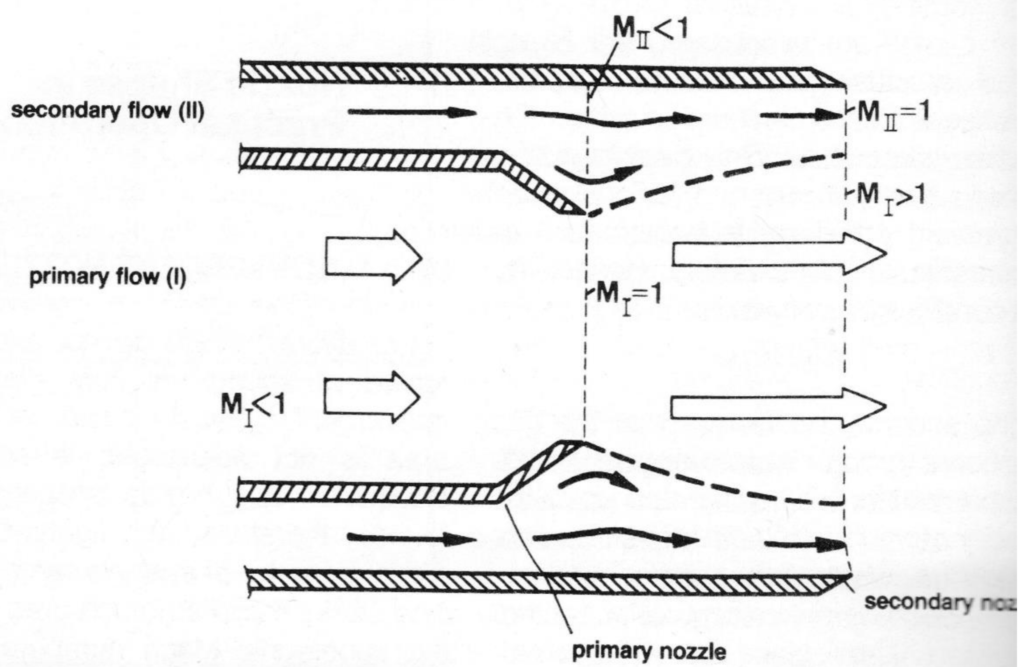
Ejector nozzles

- The **ejector nozzle** is the most frequently adapted form of the supersonic nozzle.
- It consists of a **convergent primary nozzle**, which is surrounded by a duct acting as a **secondary nozzle**.
- Without the secondary flow, the primary jet would abruptly expand to ambient pressure as result of the high pressure at the nozzle exit $\Rightarrow$ high losses, less thrust.
- The secondary flow has a **damping effect** on the primary jet and ensures **gradual expansion to supersonic velocity**.
- At the same time, it accelarates and reaches the speed of sound at the exit.

Ejector nozzles

- In an ejector nozzle, the divergent part of the Laval nozzle is replaced by the gaseous boundary walls of the secondary flow.
- The **secondary flow** ensures **cooling** of the walls.
- Advantages:
  - Low weight,
  - Uncomplicated construction.
- Disadvantages:
  - Convergent nozzle has limited performance at supersonic speeds
- Examples:
  - GE J85 in F-5 and T-38.

Adjustable, non-variable ejector nozzle



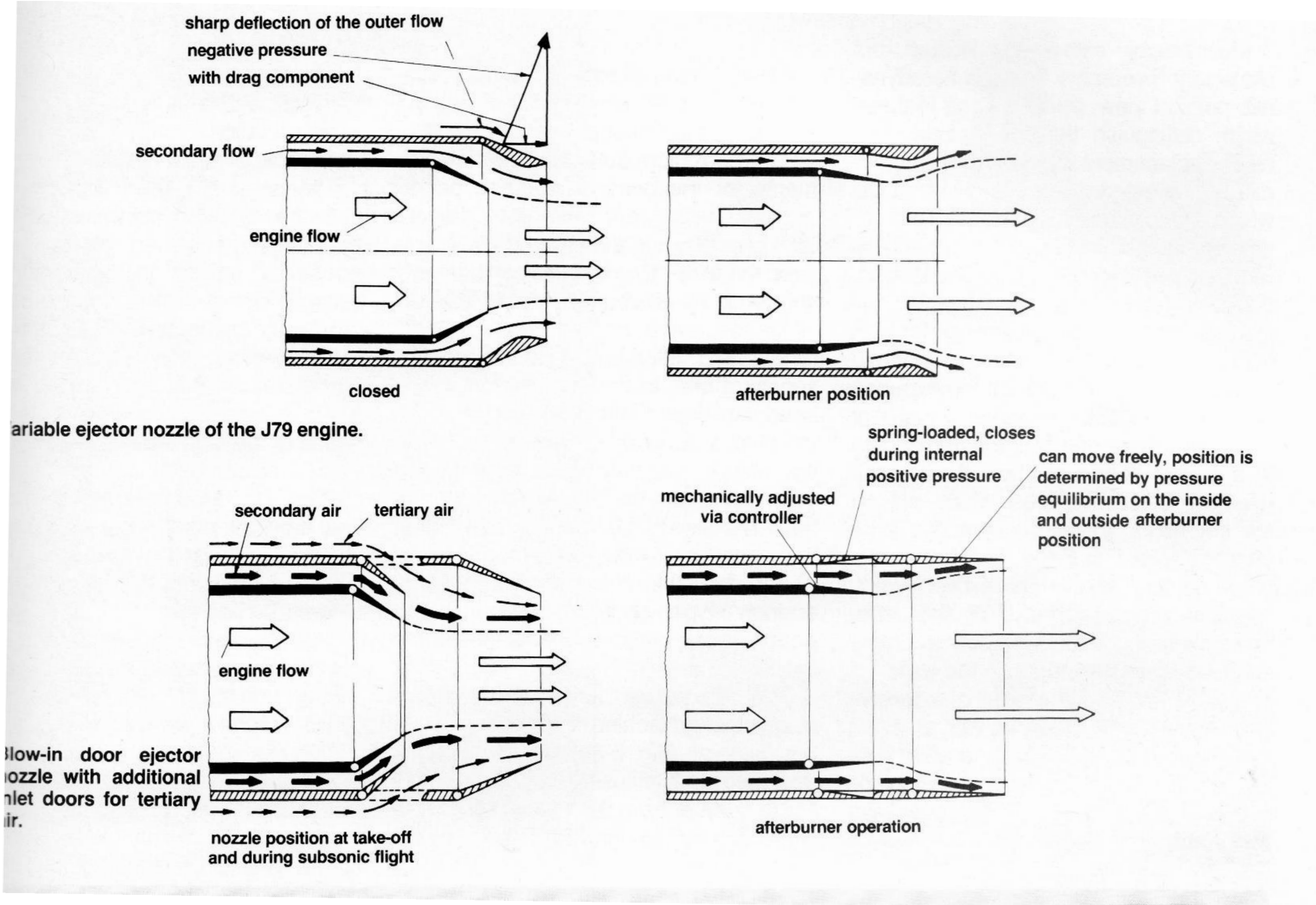
6-14 **Adjustable nozzle in non-variable ejector.**

Non-variable ejector nozzle, GE J85

Variable ejector nozzle

- A **variable ejector nozzle** has a more **complicated construction** but is also considerably **more effective**.
- The **convergent section** consists of a number of **overlapping segments**, while the **divergent section** is formed by the **secondary flow**.
- Advantages:
  - Due to combined action of **two adjustable nozzles**, the area ratio can be adapted to the particular flight condition in an ideal way.
- Disadvantages:
  - Complicated construction,
  - Increased weight,
  - Need for a lot of secondary air, increased drag.
- Examples:
  - GE J79 in F-4 and F-104.

Variable ejector nozzle



Variable ejector nozzle, GE J79

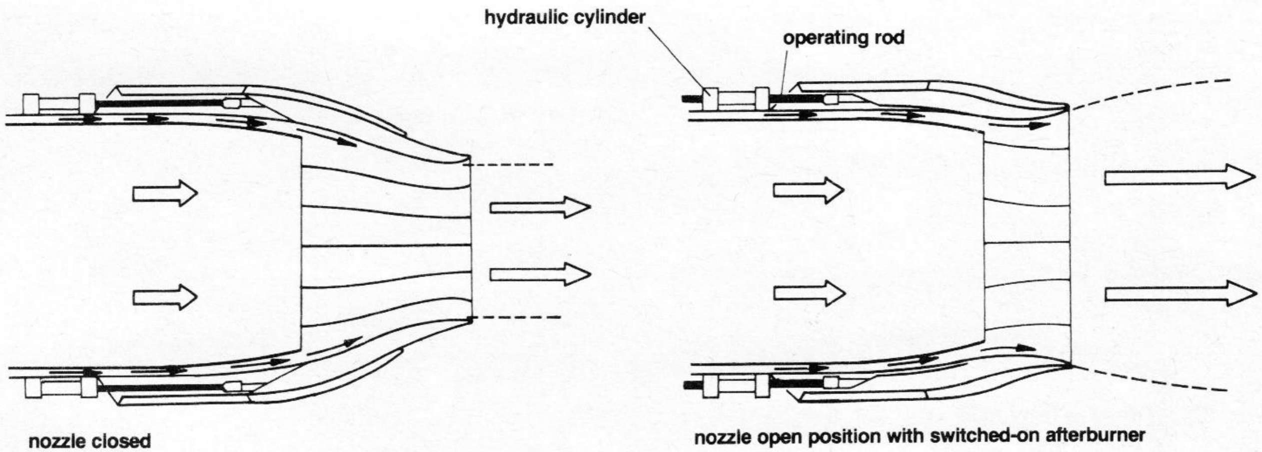
J79-8/15 Nozzle Interior

J79-10/17 Nozzle Interior

Iris nozzle

- **Iris nozzle** is **mechanically complicated** but is extremely **favorable** from an **aerodynamic** point of view.
- All nozzles designed for high Mach numbers generate **high drag** in **subsonic flight**.
- The outer shape of the iris nozzle avoids pressure distributions that create drag and conducts the flow smoothly and free of flow separation along the wall.
- Examples:
  - P&W TF30 in F-14.

Iris nozzle



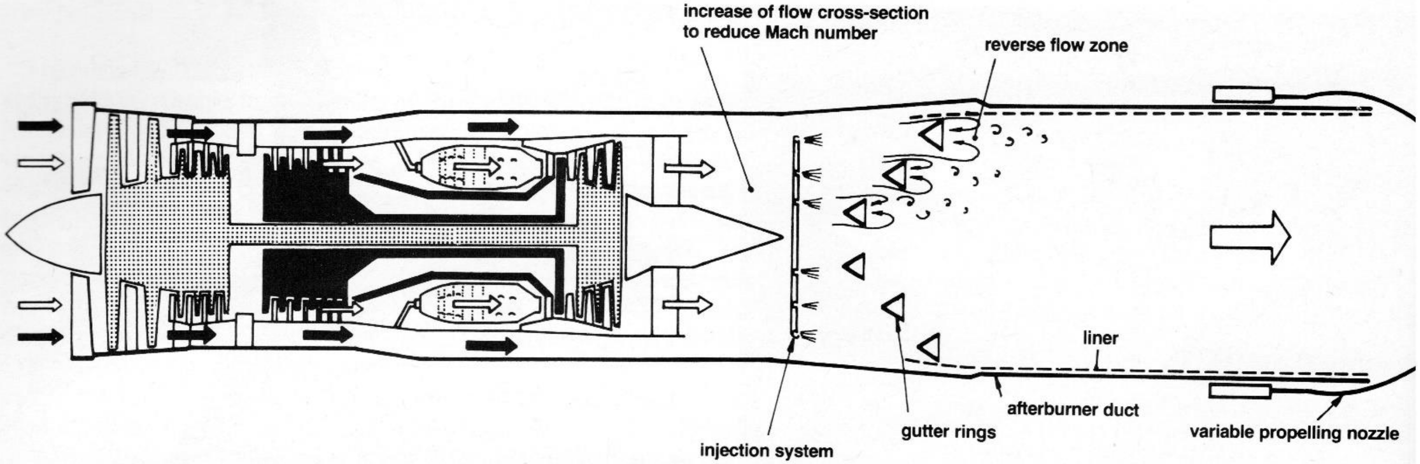
6-21 **Iris nozzle**

Iris nozzle, P&W TF30

Afterburner

- **Afterburning** or **reheat** (thrust augmentation) is an effective way of increasing the thrust of a jet engine.
- The aim is to raise the gas temperature.
- Increased thrust results in:
  - Improved maneouvre performance,
  - Shorter take-off distance,
  - Improved Accelaration.
- It consists of the following parts:
  - Afterburner duct,
  - Injection system,
  - Flameholder,
  - Variable exhaust nozzle.

Afterburner

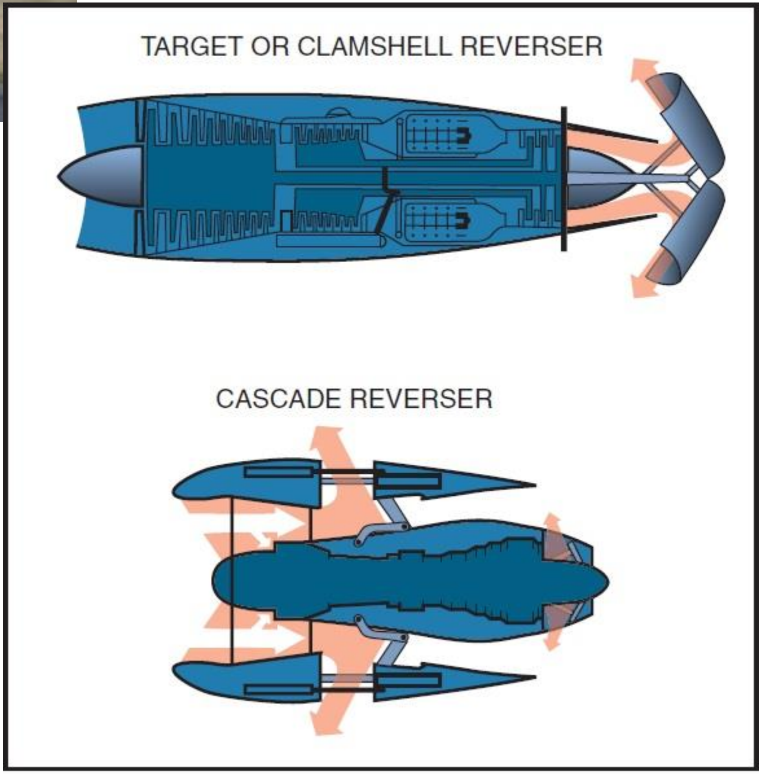


6-24 **The afterburner is a duct which is attached behind the engine (example: Volvo RM8).**

Reverse thrust

- Most aircraft require long runways to land and stop due to **high landing speed, weight and limited power of brakes.**
- The jet from the exhaust strikes baffle plates that can be swung into the flow path. The flow is diverted outwards with some forward deflection. The resulting **thrust component directed forward** provides a braking effect.
- Thrust reversers are a must for commercial aircraft, while they are **rare in combat aircraft** due to increased **weight, cost and complexity**.

Reverse thrust



Reverse thrust

https://www.instagram.com/p/B8ZEA6phQZt/?igshid=1nfy0zp4qk1bu