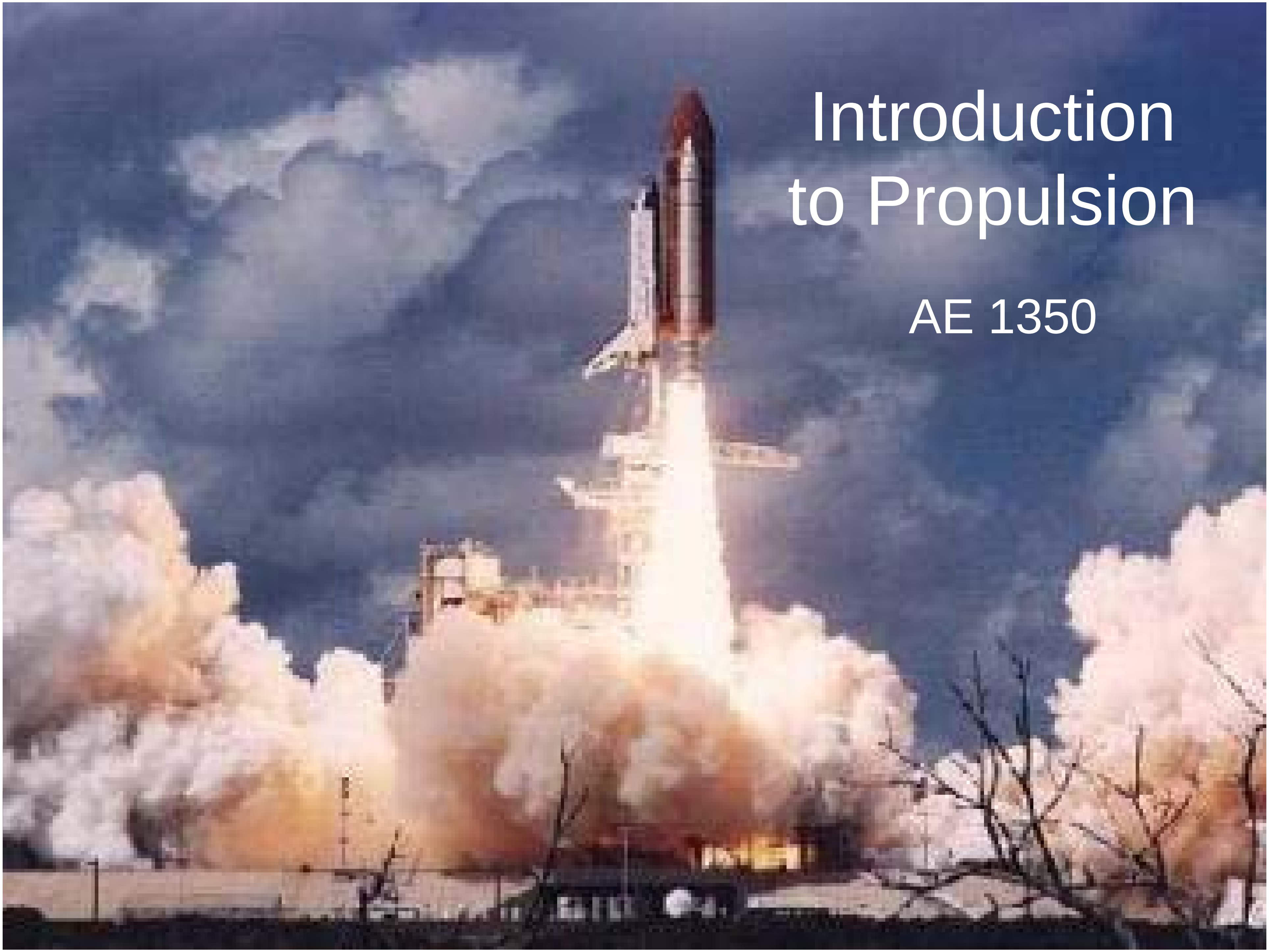
Introduction to Propulsion

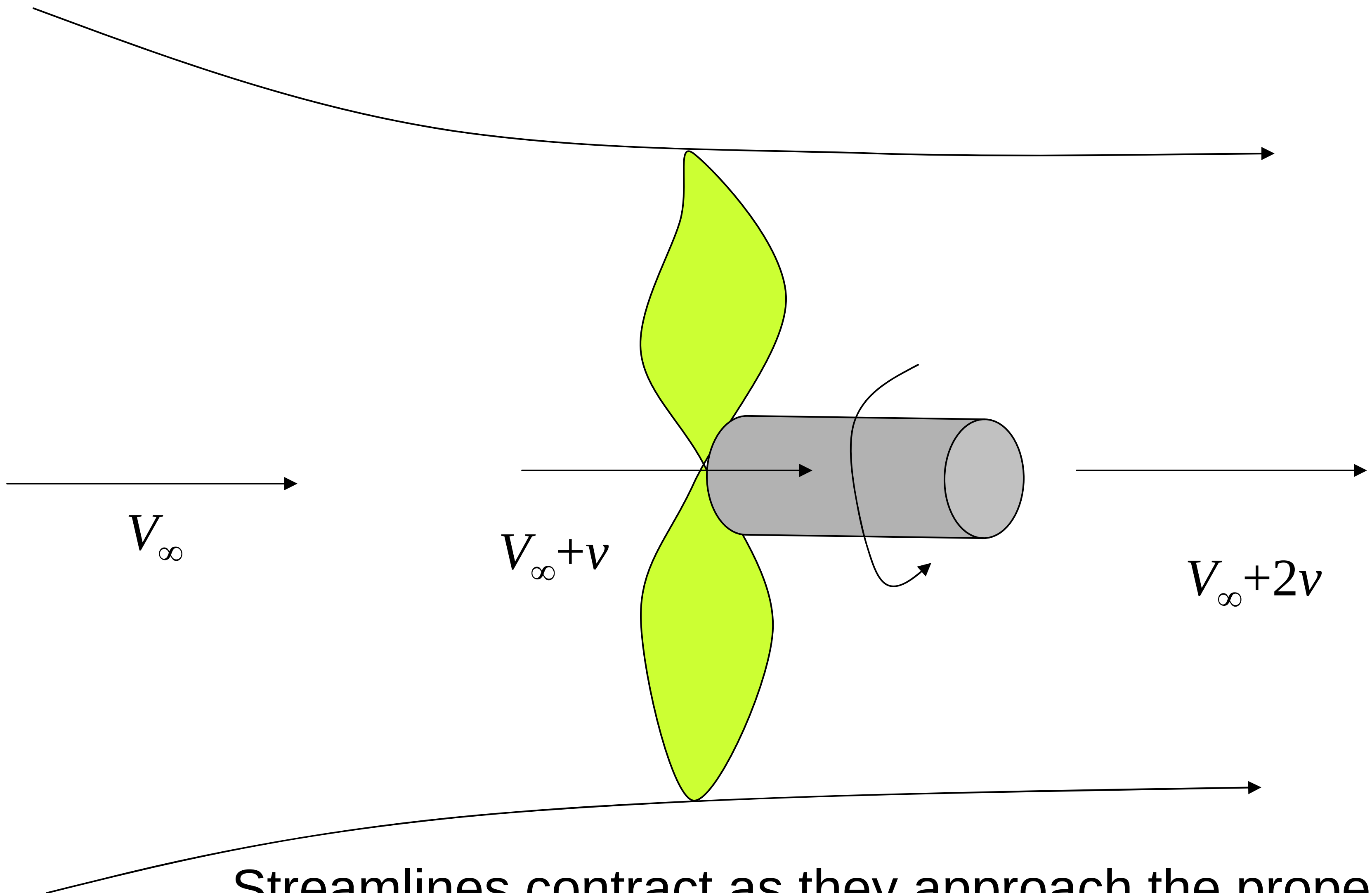
AE 1350



How does a propeller work?

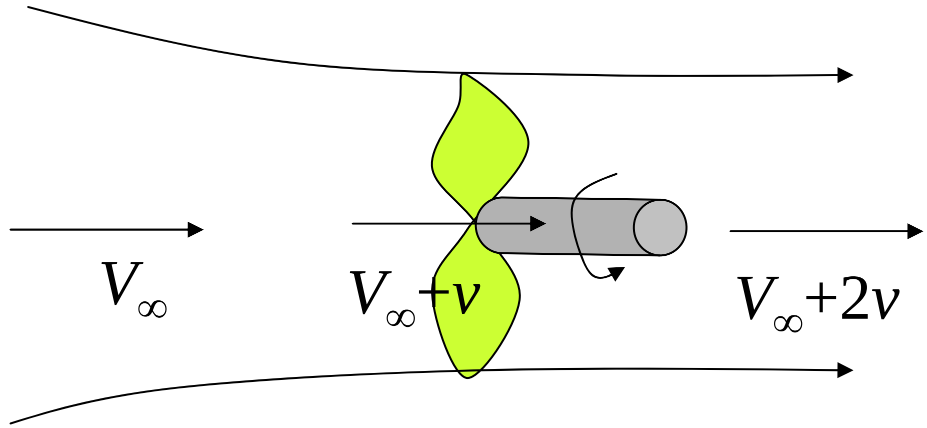
- Air approaches the propeller with low velocity, leaves with higher velocity, and energy
- This change in momentum of the particles is caused by the force exerted by the propeller on the particles
- There is an equal and opposite reaction - the particles exert a forward force on the propeller, called <u>thrust</u>

As the propeller turns…



Streamlines contract as they approach the propeller, Velocity of the particles increases

Thrust

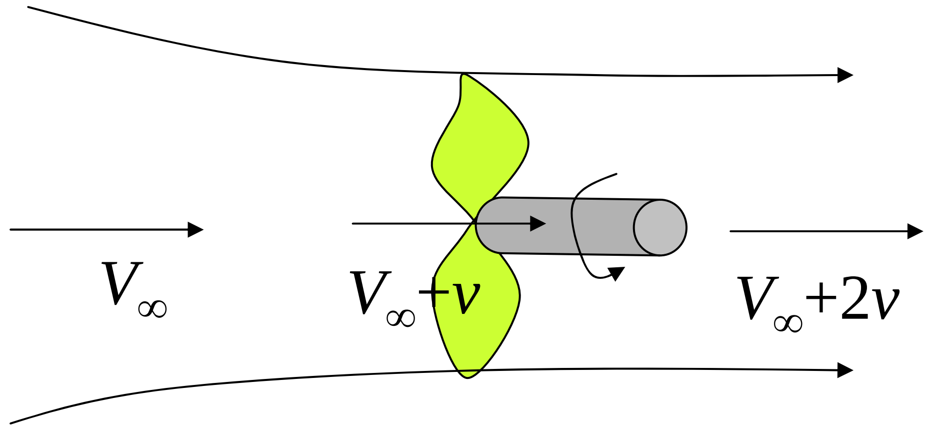


Mass flow rate = $\rho A\ (V+v)$ where A is the propeller disk area
Momentum flow rate = mass flow rate times velocity
Thrust = Rate at which Momentum flows out-
Rate at which momentum flows in

$$T = \rho A(V_\infty + v)\ (V_\infty + 2v) - \rho A\ (V_\infty + v)\ V_\infty = 2\rho A(V_\infty + v)v$$

Thrust is increased if the disk area A is large, and/or if the excess velocity v is large

Power



Mass flow rate = $\rho A (V+v)$ where A is the propeller disk area
Energy flow rate = 1/2 (mass flow rate) times (velocity squared)
Rate at which energy is added to the fluid (<u>power</u>) =

Energy rate out – energy rate in

$= 1/2\rho A(V_\infty + v)(V_\infty + 2v)^2 - 1/2\,\rho A\,(V_\infty + v)\,V_\infty^2$

$= 2\,\rho A(V_\infty + v)^2\,v = T(V_\infty + v)$

Notice that power consumed will be high for a given thrust T and forward velocity V_∞, if v is high

Propeller Thrust vs. Power Consumed

$$T = 2\rho A (V_\infty + v)v$$
$$P = T(V_\infty + v) = TV_\infty + Tv$$

- The first term (TV_∞) is useful work done by the propeller to overcome drag (Power = Force x Velocity)
- The second term (Tv) called induced power, represents excess energy we dump into the wake, as the propeller accelerates the flow to a higher velocity
- To minimize this wasted power, this should be kept small
- Propulsive efficiency = Useful Power/Total Power $= TV_\infty /(TV_\infty + Tv) = V_\infty /(V_\infty + v)$
- Rule of Thumb for propellers: Keep disk area A as large as possible, this minimizes v at a given thrust
- Or, the bigger the prop, the lower the power required (within limits…)

There is a limit to the Disk Area

- If we make the disk area large, the blade radius and diameter will be high
- Tip of prop will be traveling at a high speed
- If cruise speed is also high, shocks will form on the blades (critical Mach number!)
- Additional power will be needed to overcome the wave drag on the blades caused by the shock waves
- Noise will also go up
- These factors have limited the use of propellers to aircraft that have relatively low subsonic cruise speeds (say, Mach < 0.6)
- A related issue is getting the RPM low enough

Tu-95 Bear

How is the propeller or fan turned?

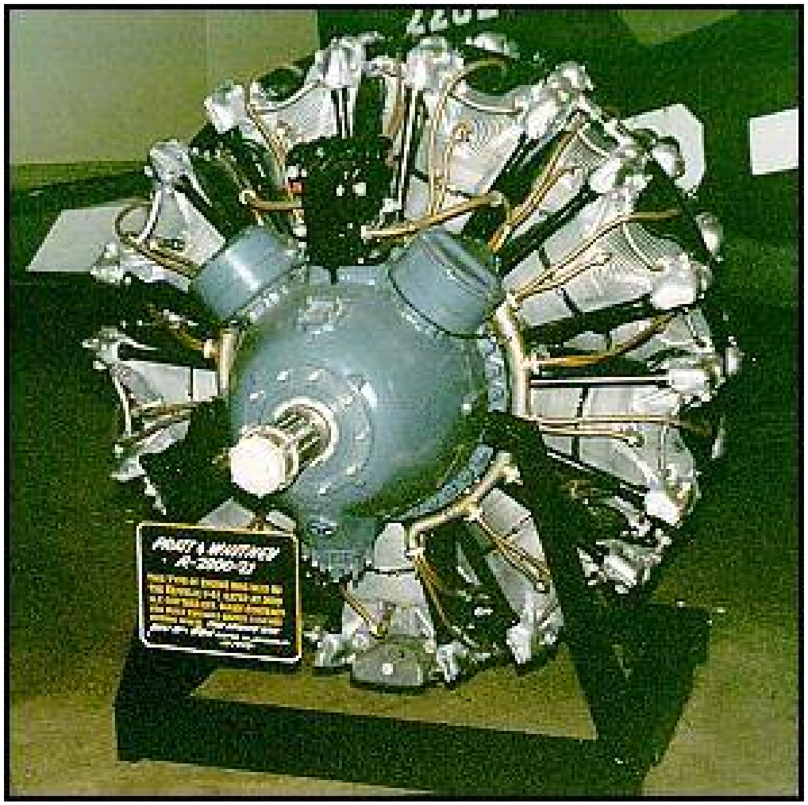
- With a
  - piston engine (as in a typical car)

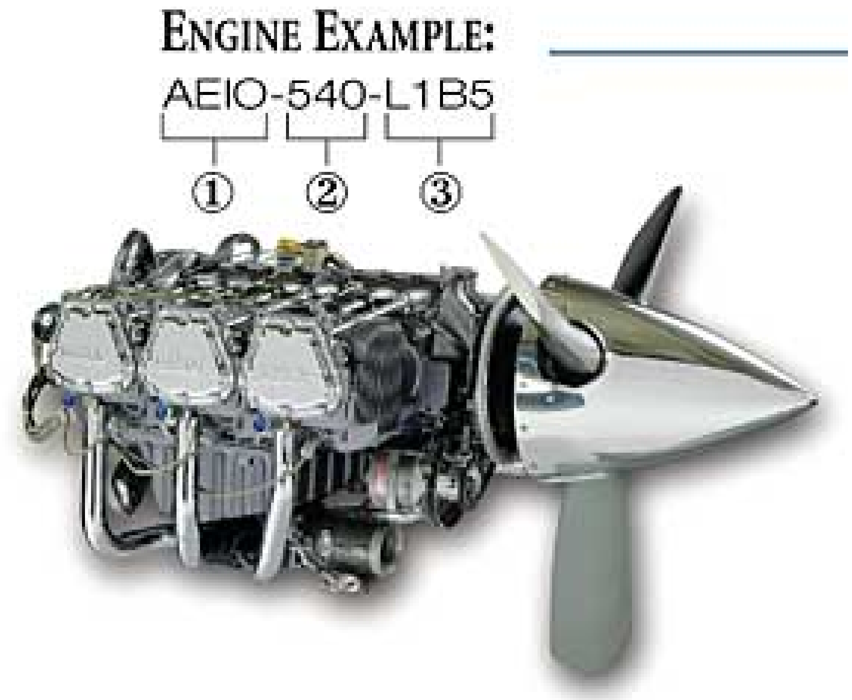
    or a

  - gas turbine engine

- Typical engine:
  - Compress air
  - Add fuel
  - Burn it to add energy to flow
  - Use energy in flow to do work

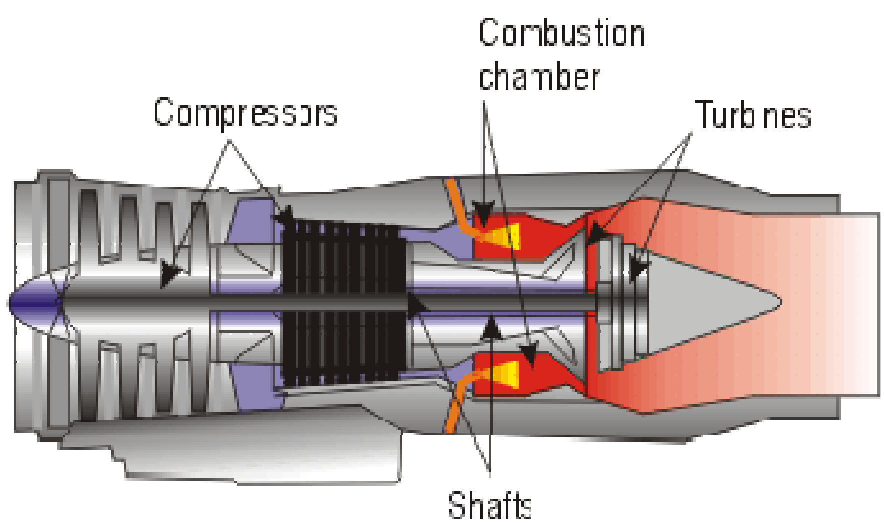
Piston Engines



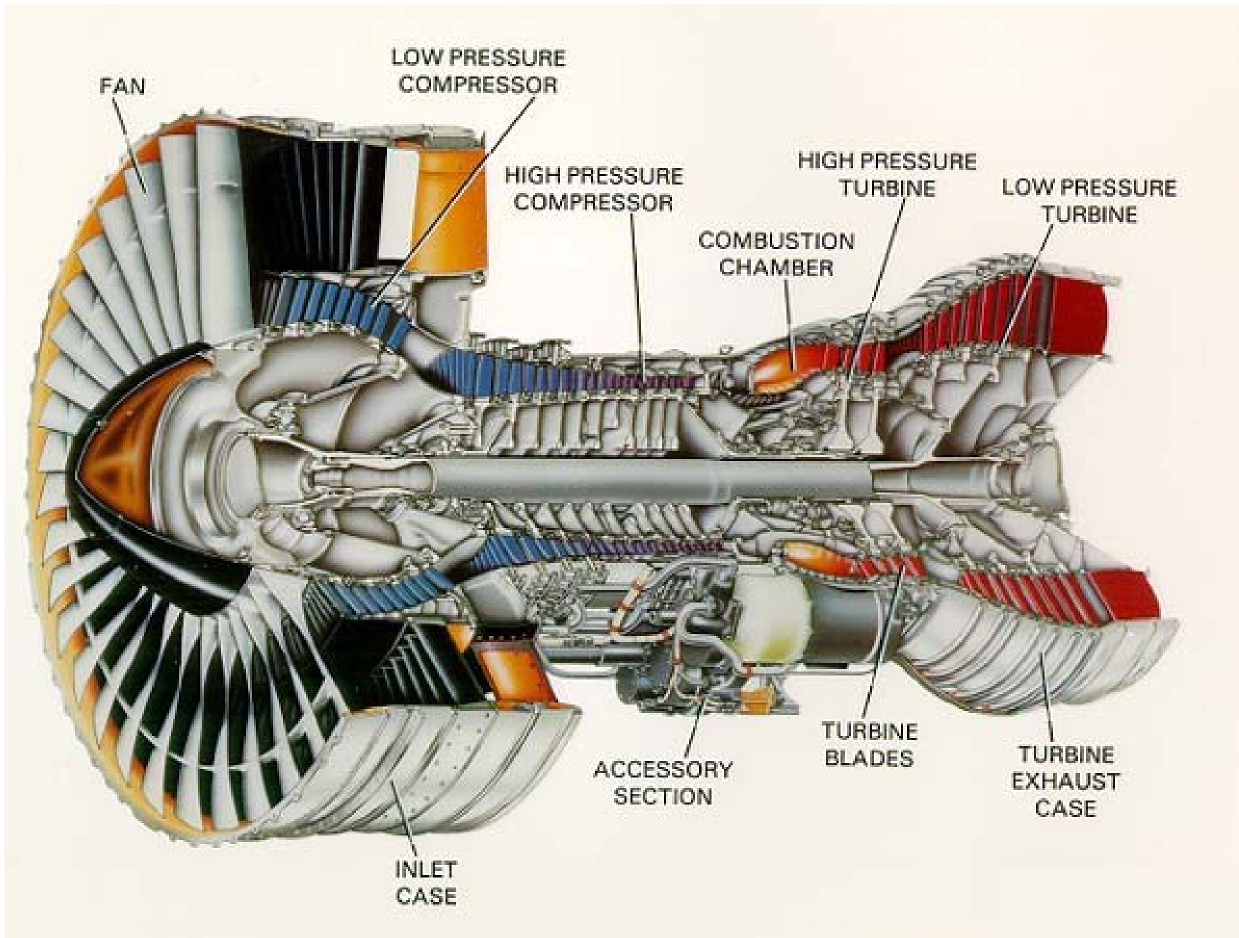


Gas Turbine Engines

- Compressor — draws in outside air and increases the pressure of the air
- Combustor — mixes fuel with the air, ignites mixture
- Turbine — extracts energy from the heated air to turn the compressor and possibly other components



Turbofan



Turbine turns a fan, where the majority of the air does not go through the combustor/turbine (it is bypass flow) - The fan acts like a ducted propeller, provides the majority of thrust

Low Bypass Ratio Turbofan

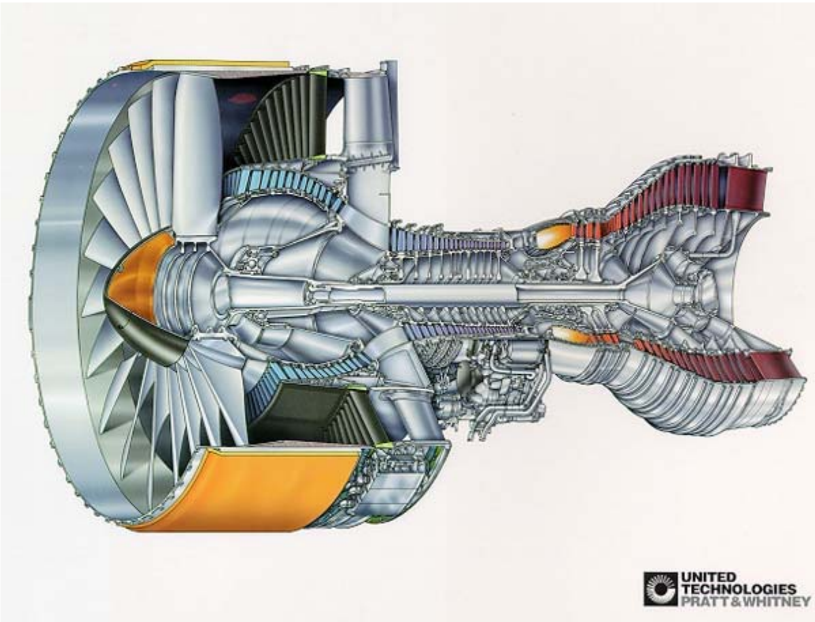
Fan tip diameter: *54.0 inches*
Length, flange to flange: *168.6 inches*
Takeoff thrust: *21,000 pounds of thrust*

Bypass ratio: *1.74-to-1*
Overall pressure ratio: *18.2 to 19.4*
Fan pressure ratio: *1.91*

Engine Models
JT8D-standard
JT8D-217/219

Planes Powered by JT8D
Boeing 727
Boeing 737-100/-200
McDonnell Douglas DC-9
Boeing MD-80

High Bypass Ratio Turbofan



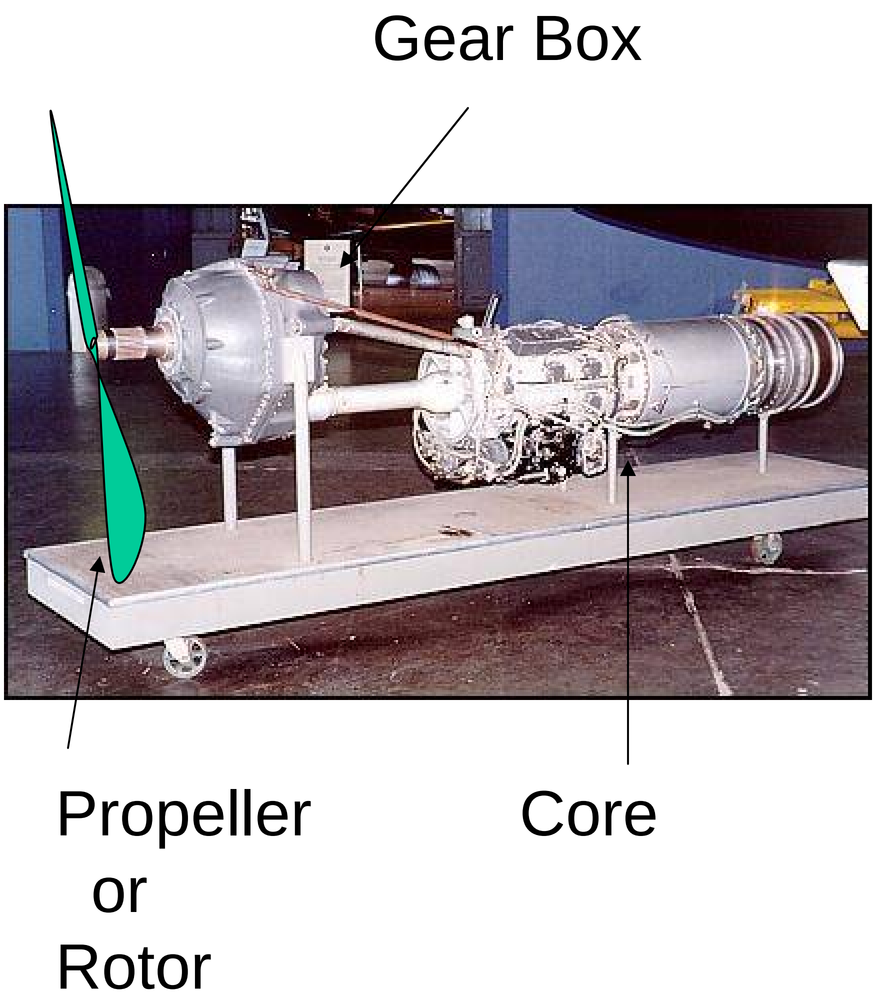
Fan tip diameter: *112 inches*
Length, flange to flange: *191.7 inches*
Takeoff thrust: *86,760 - 98,000 pounds*

Bypass ratio: *5.8-to-1 to 6.4-to-1*
Overall pressure ratio: *34.2 - 42.8*
Fan pressure ratio: *1.70 - 1.80*

Engine Models
PW4084
PW4090
PW4098

Planes Powered by PW4000
Boeing 777-200/-300

Turboshaft Engines (Turboprop)

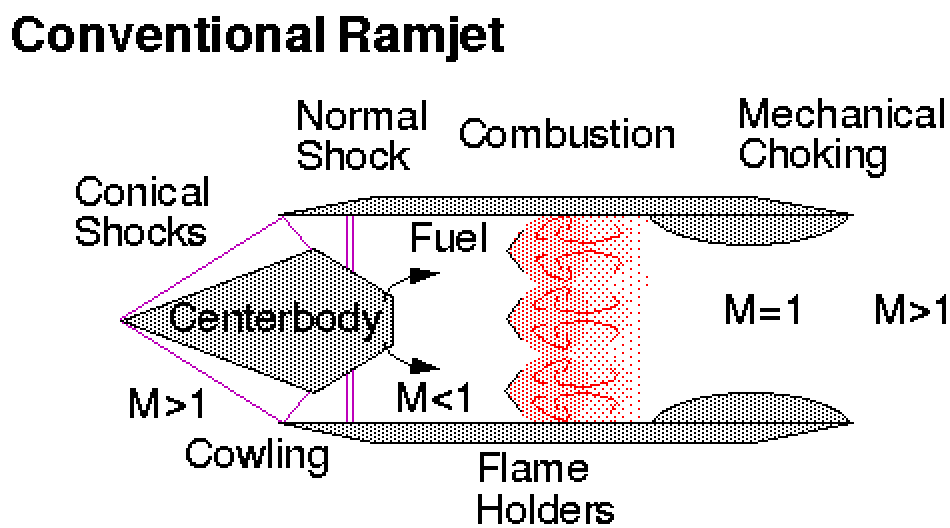


Through a gear box, the power from the engine shaft may be used to spin:

a propeller (turboprop),

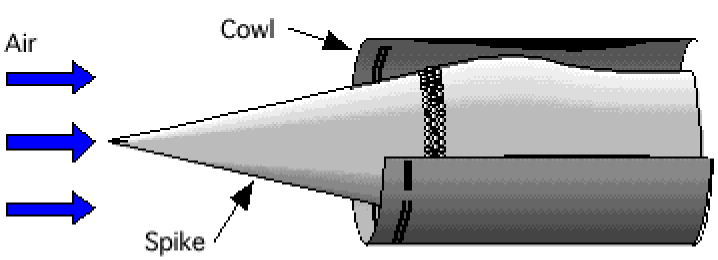
or helicopter rotor (turboshaft)

Ram Jet Engines



- Only work above about Mach 3
- Dramatic pressure rise from slowing flow from supersonic to subsonic (through shock waves) increases pressure for combustion

Supersonic Combustion Ram Jet
SCRAMJET Engines



Shock waves in front of the aircraft and inside the inlet slow down the flow and increase the pressure

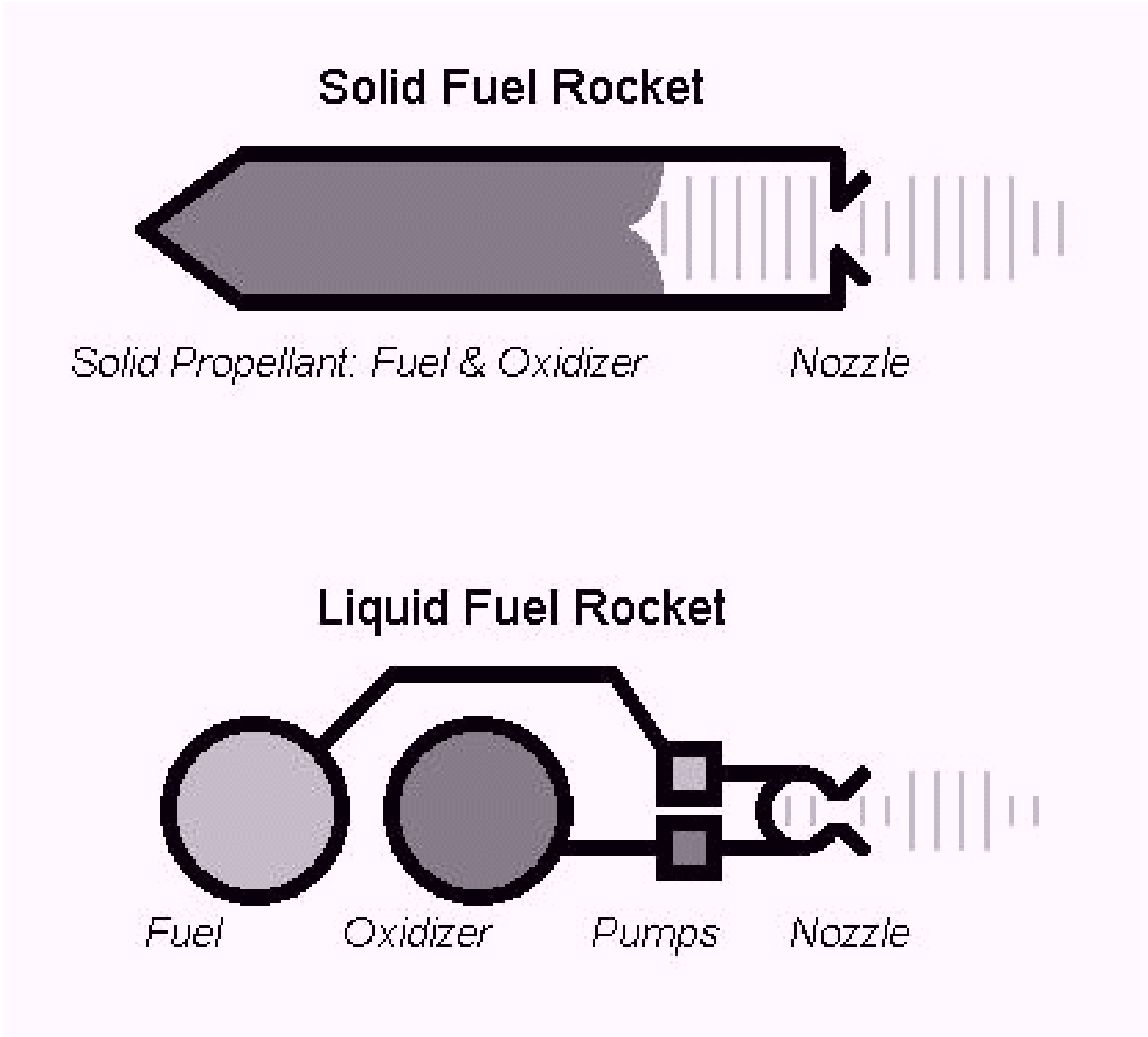
The flow inside the entire engine, including the compressor, is supersonic (Mach > 1)

When you want to go very fast…

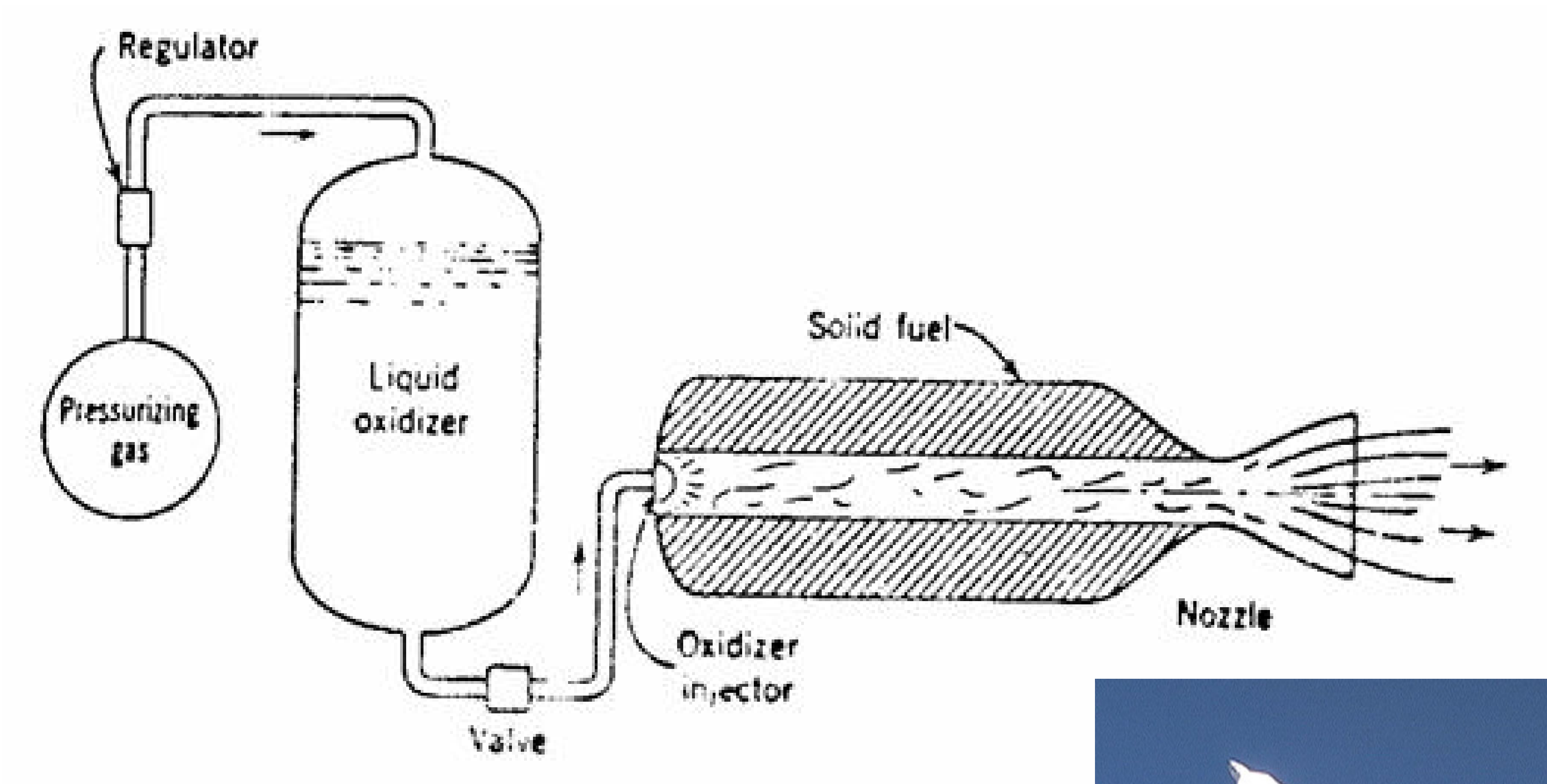
Jet Engines and Piston Engines Need Air...

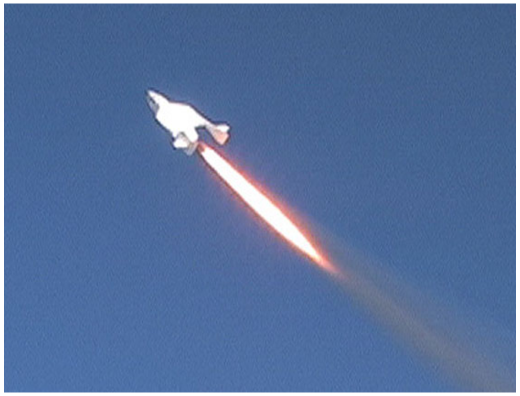
- They need air (or oxidizer) for combustion of the fuel and generation of energy
- For this reason, these are called “air-breathing” engines
- Jet and piston engine aircraft carry only the fuel
- Advantage: They don’t have to carry the oxidizer around with them
- Disadvantage: These devices stop working outside the atmosphere…

Solid vs. Liquid Fuel Rocket Motors



Hybrid Rocket Motor (Combo!)

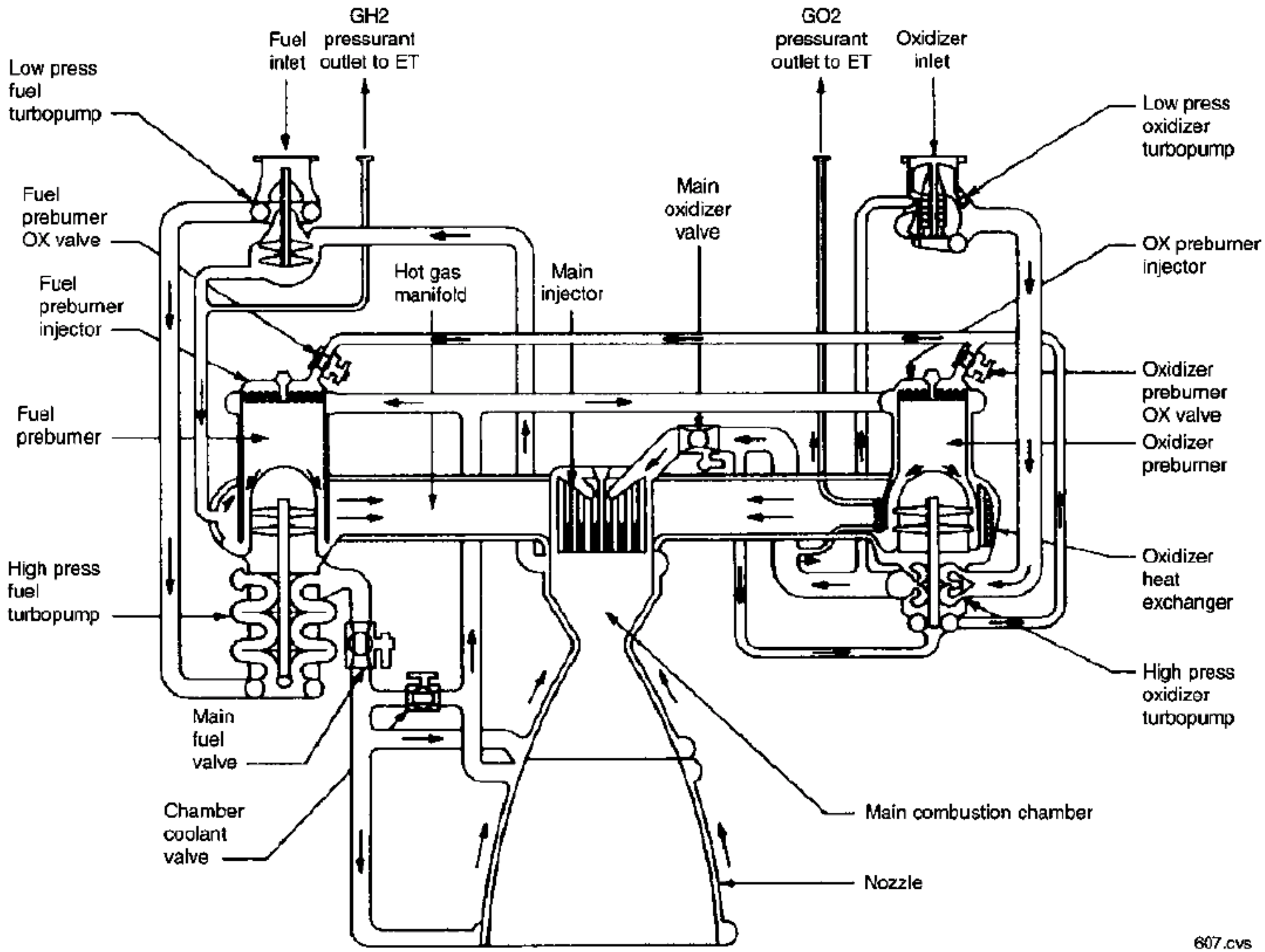




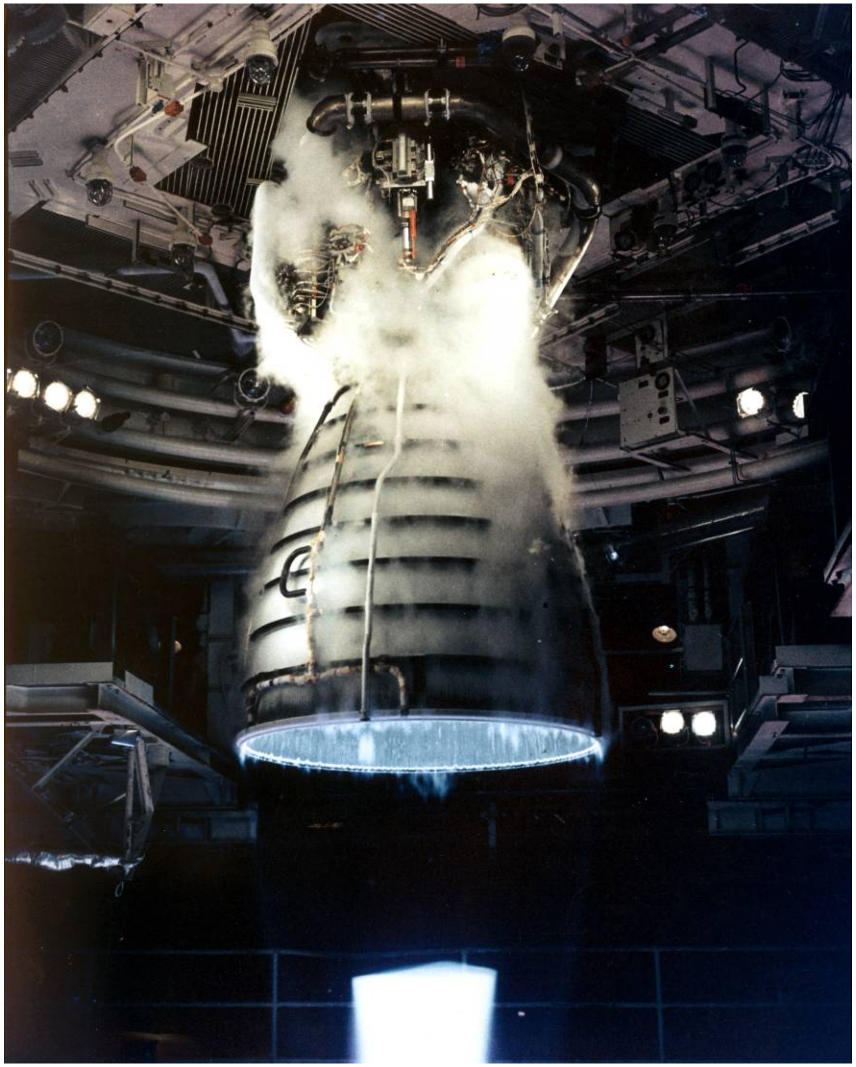
Liquid Fuel Rocket Motor

- Uses separate liquid fuel and oxidizer, which are combined only at the moment of combustion
- Pumps are required to get the fuel & oxidizer to the motor quickly enough to develop desired thrust, and at enough pressure for desired efficiency (turbopumps)
- This makes liquid fuel rockets more complicated
- Liquid fuel rockets can be turned off and then turned on again relatively easily
- Many can be throttled for more or less thrust

Space Shuttle Main Engine (SSME)

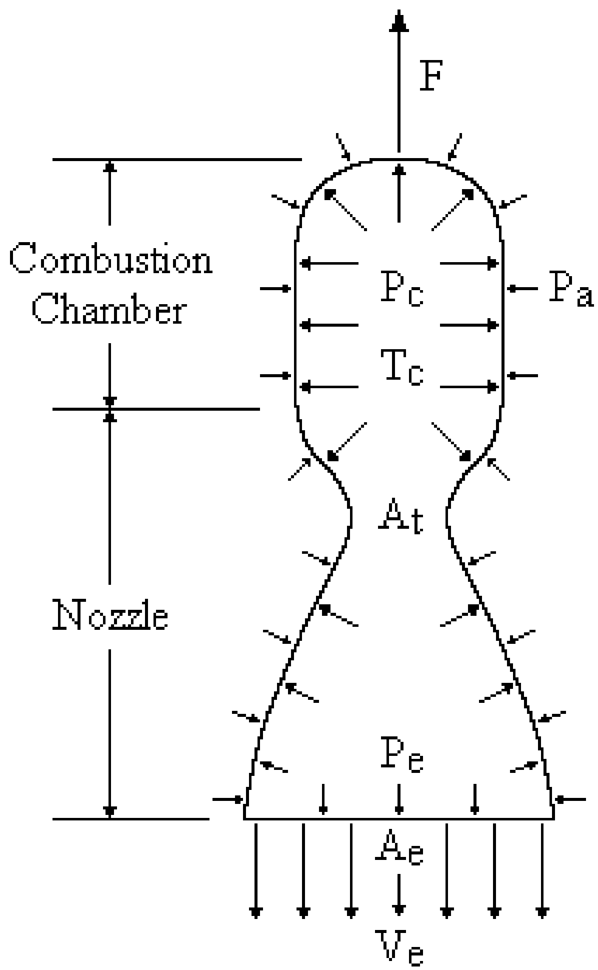


Space Shuttle Main Engine (SSME)



400,000 pounds Thrust

Rocket Motor Thrust



Thrust = (Mass Flow Rate) * V_{jet}

+ $(p_{exit} - p_{\infty})\, A_{exit}$

Specific Impulse

- Specific Impulse is how long a pound of fuel can develop a pound of thrust

$$F_{\mathrm{thrust}} = I_{\mathrm{sp}} \cdot \frac{\Delta m}{\Delta t} \cdot g_0$$

- Thrust is Specific Impulse, multiplied by the mass flow rate of propellants and the acceleration of gravity
- A very good chemical rocket in terms of Specific Impulse is the Space Shuttle main engine, at about 453 seconds
- Air breathing engines can do better if there is air (and we’re going slow enough), due to the fact they do not have to count the oxidizer

Specific Impulse