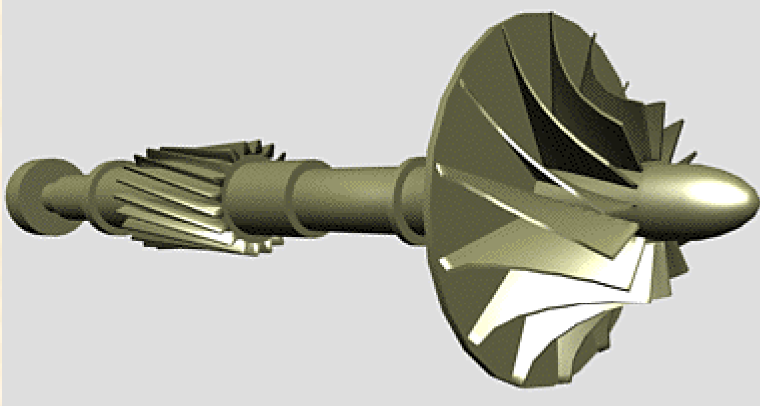
August 2020



Introduction to tribology, rotordynamics & lubricated elements

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Tribology?

What is it for?

…

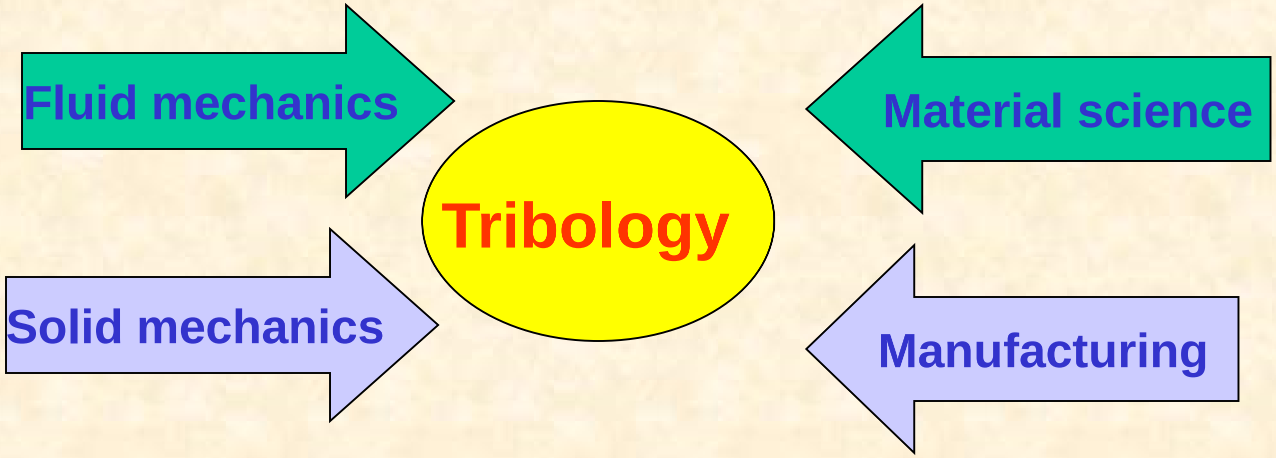
Will I ever use it?

Tribology embodies the study of

friction, lubrication and wear.

and involves mechanical processes (motion & deformation).

A tribologist performs engineering work to predict and improve the performance (how much) and reliability (for how long) of a mechanical system.



Tribology – Some Applications Today

Exo-skeletons & sports equipment

compliant, durable, tough, better performance (less friction and less wear)

→ Surface engineering, materials.

Medicine:

Hip-joint replacements,
miniature pumps for fluid injection/removal,
heart pumps and implants,
1 MRPM dental hand drills

→ Surface engineering, materials, 3D print
Solid lubricants.

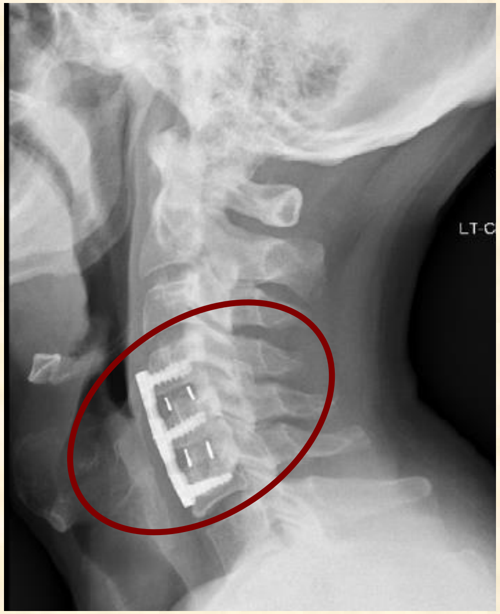
→ Gas hydrodynamics

Ultra-hard drilling equipment:

no wear and tear, i.e. infinite life

→ Solid lubricants (coatings)
Surface engineering

Dr. San Andres moves **from being**



a pain in the neck

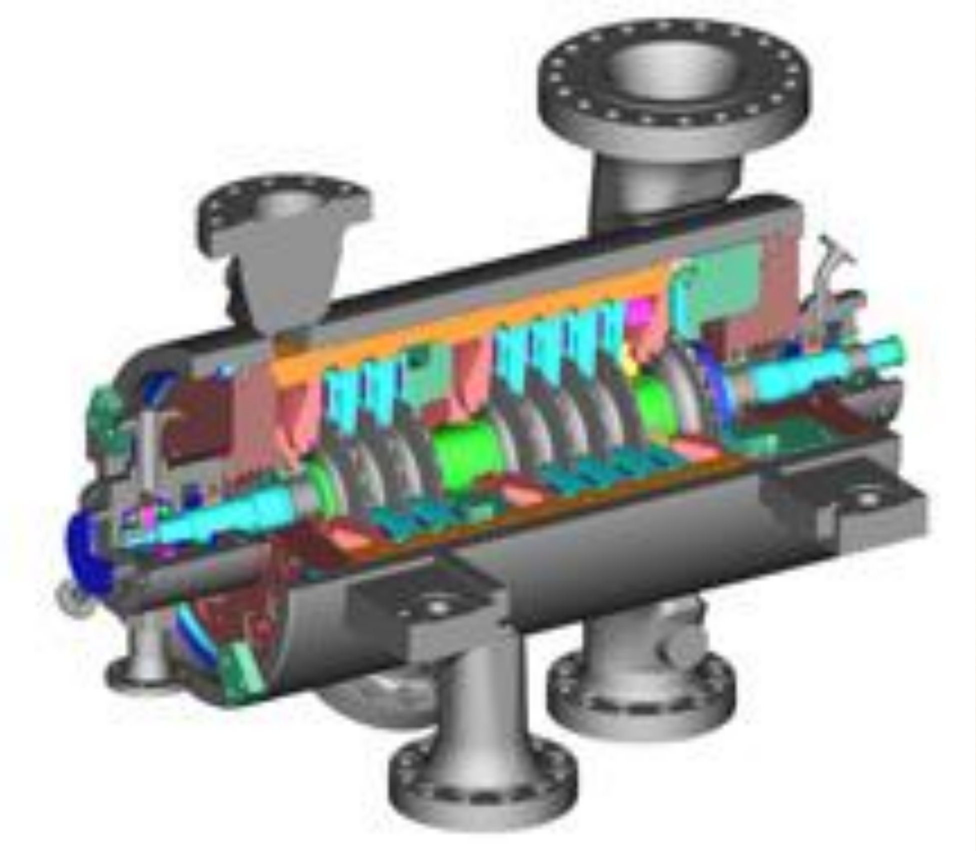
… to being screwed

… to being crushed

Friction, lubrication & wear

Is the order important?

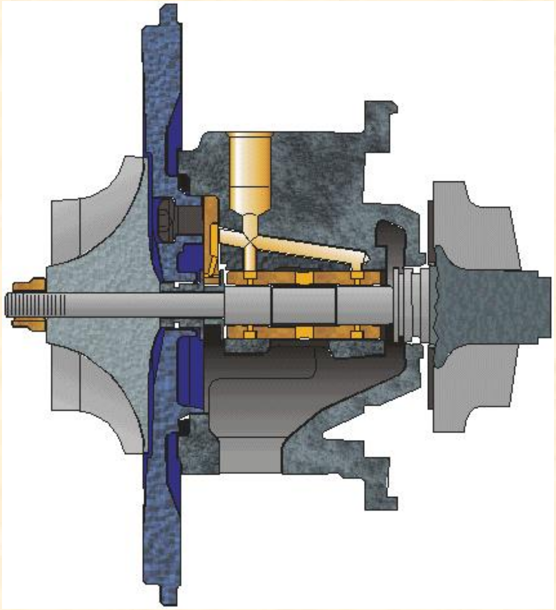
Turbomachinery



today
& tomorrow

Turbomachinery

A rotating structure where the load or the driver handles a process fluid from which power is extracted or delivered to.



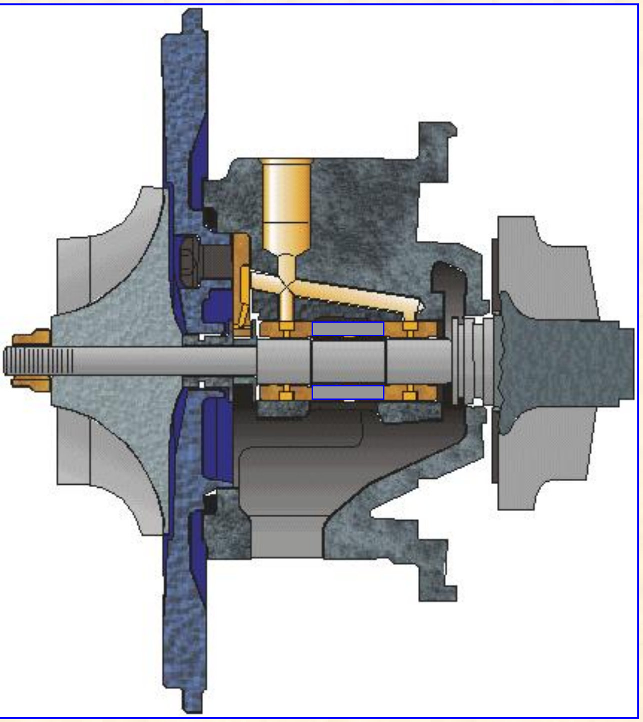
Fluid film bearings (typically oil lubricated) support rotating machinery, providing stiffness and damping for vibration control and stability.

In a pump or a compressor, neck ring seals and inter stage seals and balance pistons also react with dynamic forces. Impellers also act to impose static and dynamic hydraulic forces.

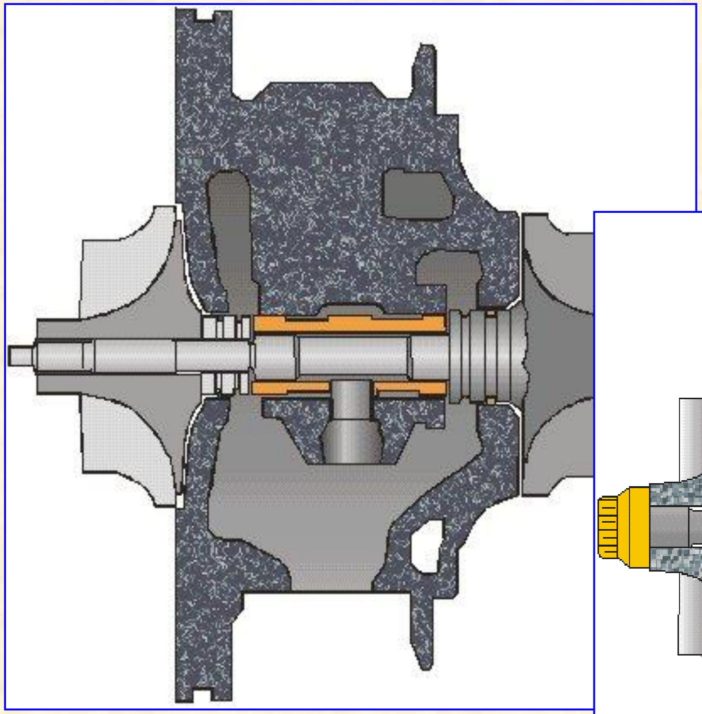
Acceptable rotordynamic operation of turbomachinery:

Ability to tolerate normal (even abnormal transient) vibrations levels without affecting TM overall performance (reliability and efficiency)

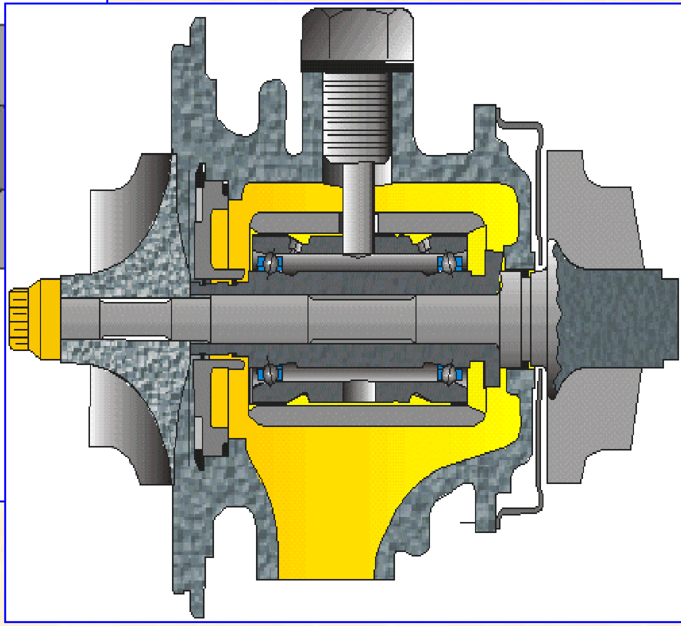
PV/CV turbochargers



w/
Fully Floating Bearing



w/
Semi Floating Bearing

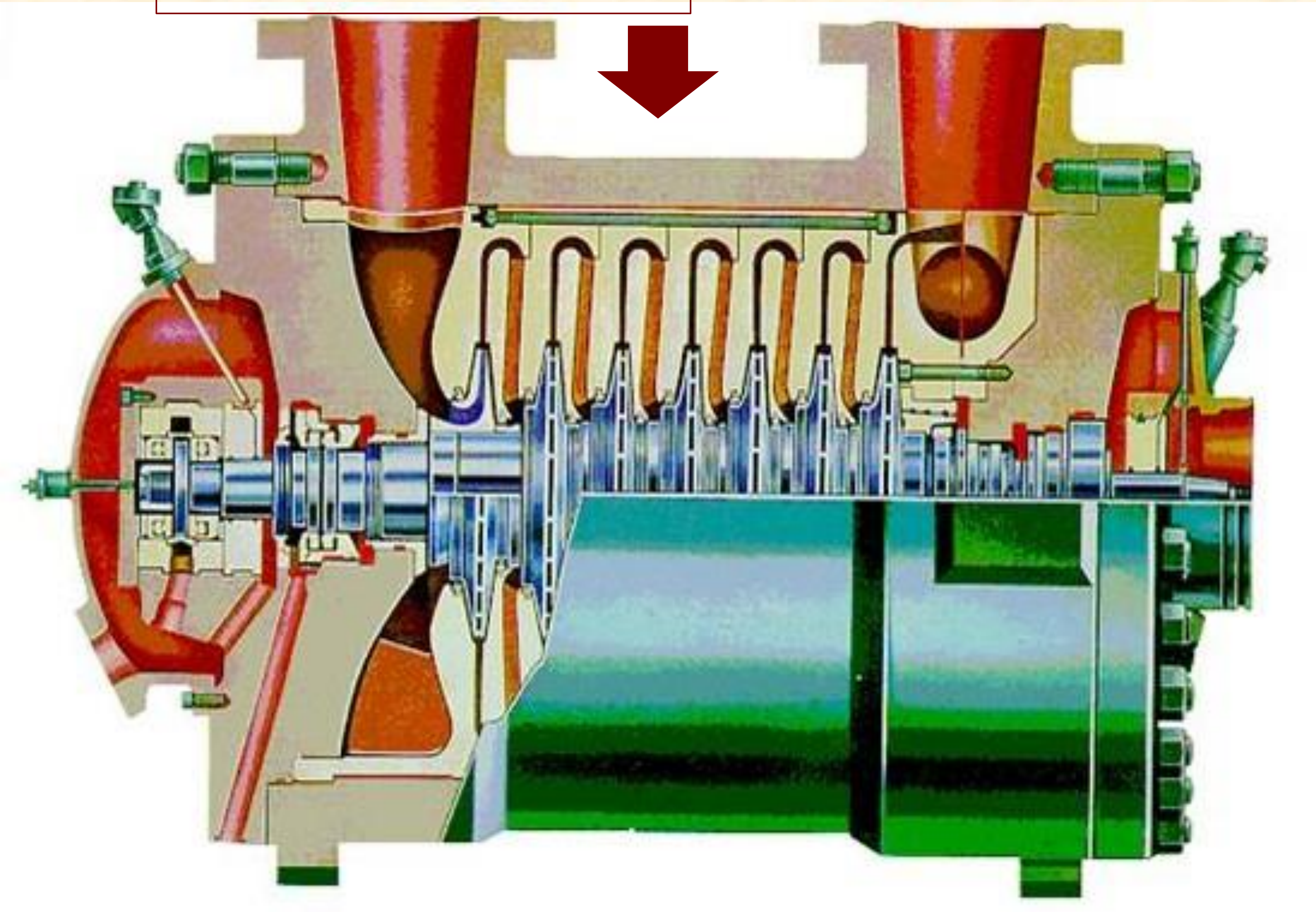


w/
Ball Bearing

The future today

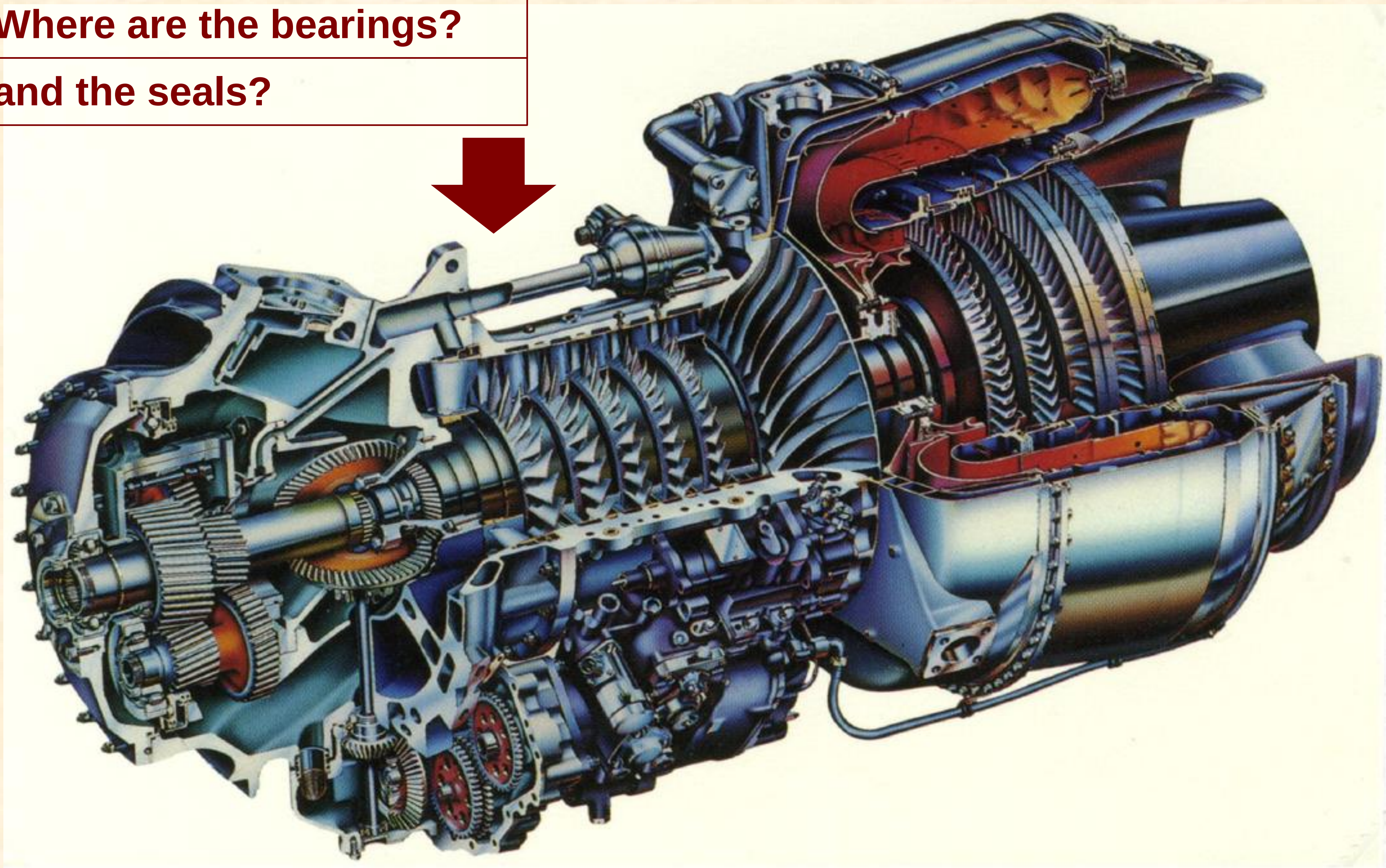
Centrifugal compressor

Where are the bearings?
and the seals?



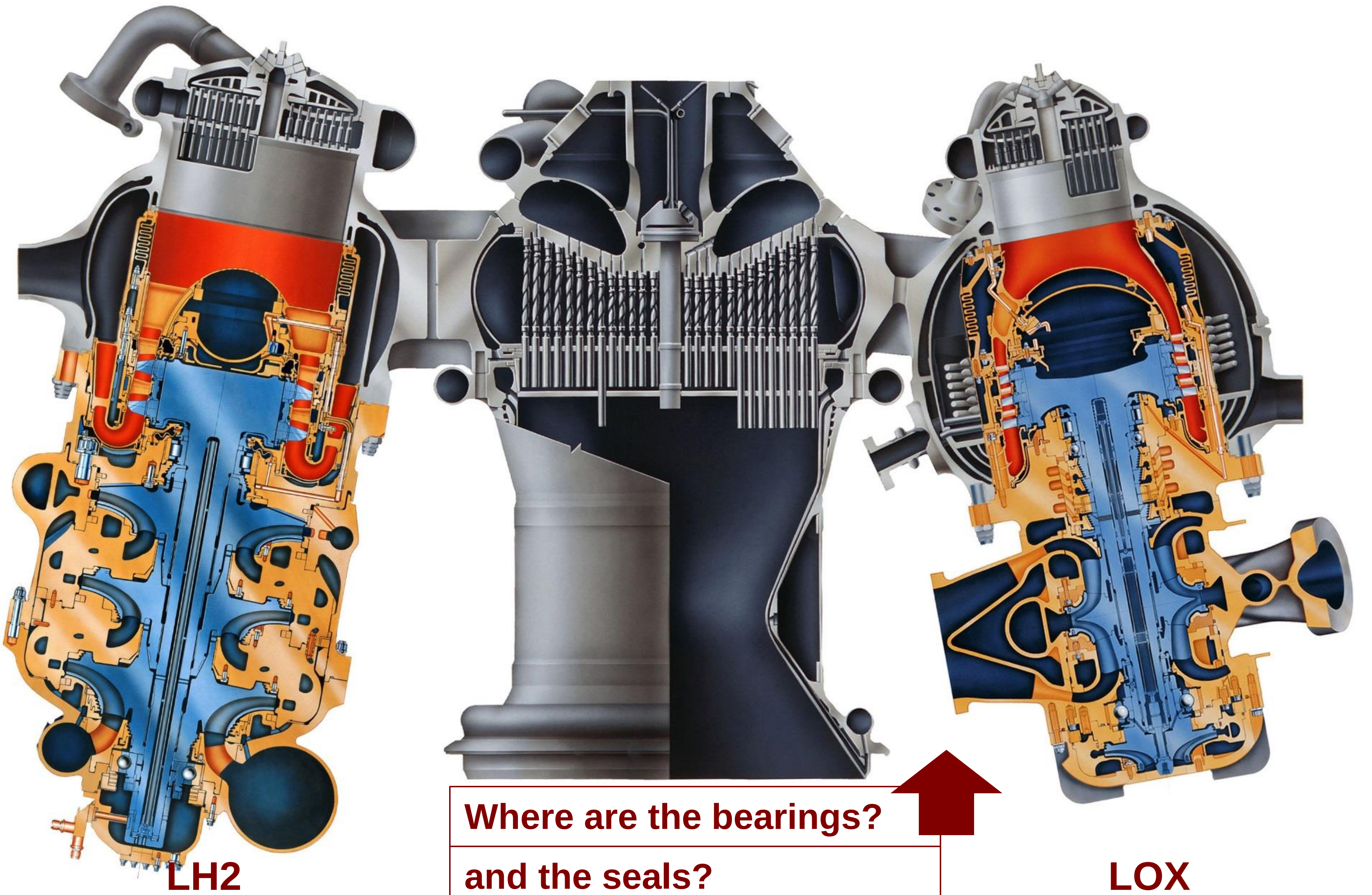
Gas turbine

Where are the bearings?
and the seals?



Source: Avco Lycoming

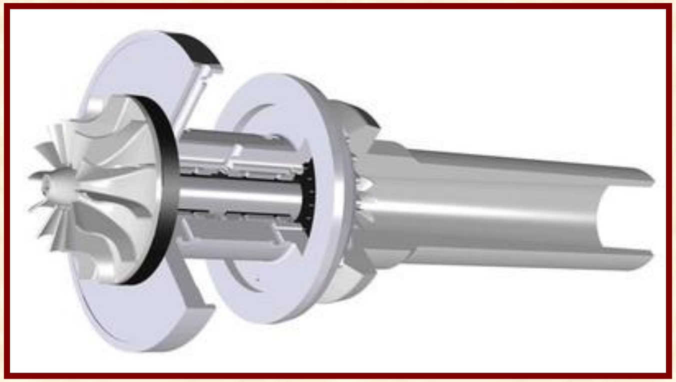
SSME turbopumps



Where are the bearings?

and the seals?

21st century turbomachinery



21^{st} century turbomachinery

Ultra-performance (reinjection) compressors: > 15,000 psi (1,000 bar) → **Rotordynamics, materials, seals, extreme environments**

Combined cycle turbines (gas/steam):
Concentrated solar power: sCO2

efficiency > 60% → **composite materials, coatings, extreme environments**

Aircraft: Larger high-bypass geared turbofans (GR>5)

Electric distributed propulsion systems
GTs → batteries → electric fans for thrust

Larger efficiency & lower noise. Braking regenerative power → **Rotordynamics, Electronics, Materials & Coatings, SFDs**

Unmanned Aerial Vehicles (Drones):

war at a distance &w/o casualties,
surveillance, parcel mail delivery, crop fumigation, archeology → **E-motors, materials, 3D printing, controls and electronics.**

Smart engines and structures:
control of surge and stall in compressors,
elimination of Noise & Vibes with configuration changes → **Materials, 3D printing rotordynamics**

Reusable rocket engines:

LH_2 and LO_x with fluid film bearings

Subsea pumping & compression

High pressures & extreme temperatures

Subsea Engineering or SURF –

- **<u>S</u>ubsea**
- **<u>U</u>mbilicals**
- **<u>R</u>isers)**
- **<u>F</u>lowlines**

***Wet* compression systems must be reliable (5 y operation)**

Meso-micro turbomachinery:
portable packs (5 kW), 1 million rpm → **Rotordynamics, 3D printing, materials**

Oil-free gas turbines and generators:
(mid size to 0.5 MW): foil gas bearings, damper seals. → **coatings: solid lubes gas lubrication & rotordynamics**

Microturbomachinery needs & hurdles

Largest power to weight ratio
Compact & low # of parts

Reliability and efficiency
Low maintenance

Extreme temperature and pressure – multiple phases

Environmentally safe (low emissions)

Lower lifecycle cost ($ kW)

High speed

Rotordynamics &
(Oil-free) Bearings & Sealing

Materials

Coatings: for low friction and wear
Ceramic rotors and components

Manufacturing

Automated agile processes
Additive manufacturing: $ & #

Processes & Cycles

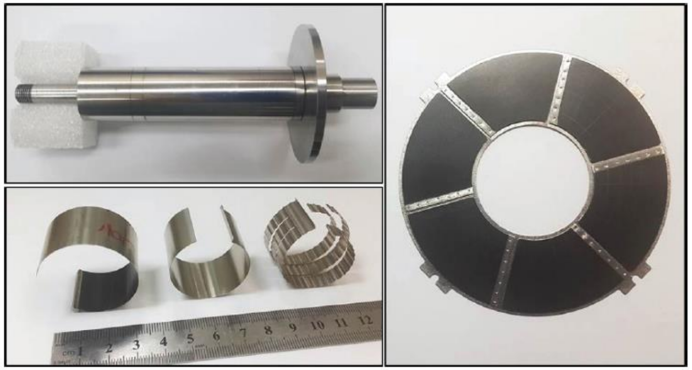
Low-NOx combustors for liquid & gas fuels. Scaling to low Reynolds #

Fuels

Best if free (bio-fuels)

H2 Fuel Cell Electrical Vehicles

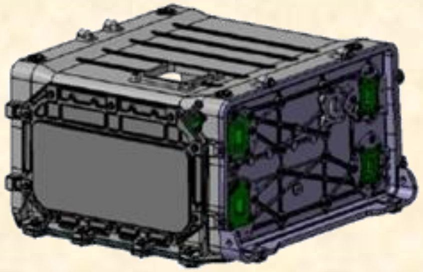
Oil-free system offers higher efficiency and power density.



Rotor supported on gas bearings

Air compressor

Compressed air blows into Fuel Cell stack



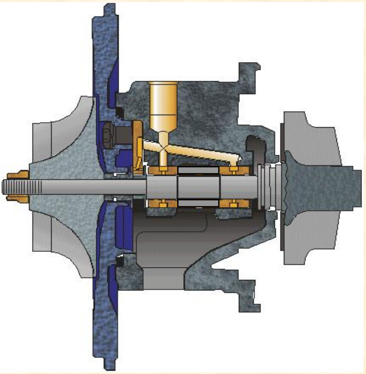
Fuel cell stack

Efficient FCEV!!

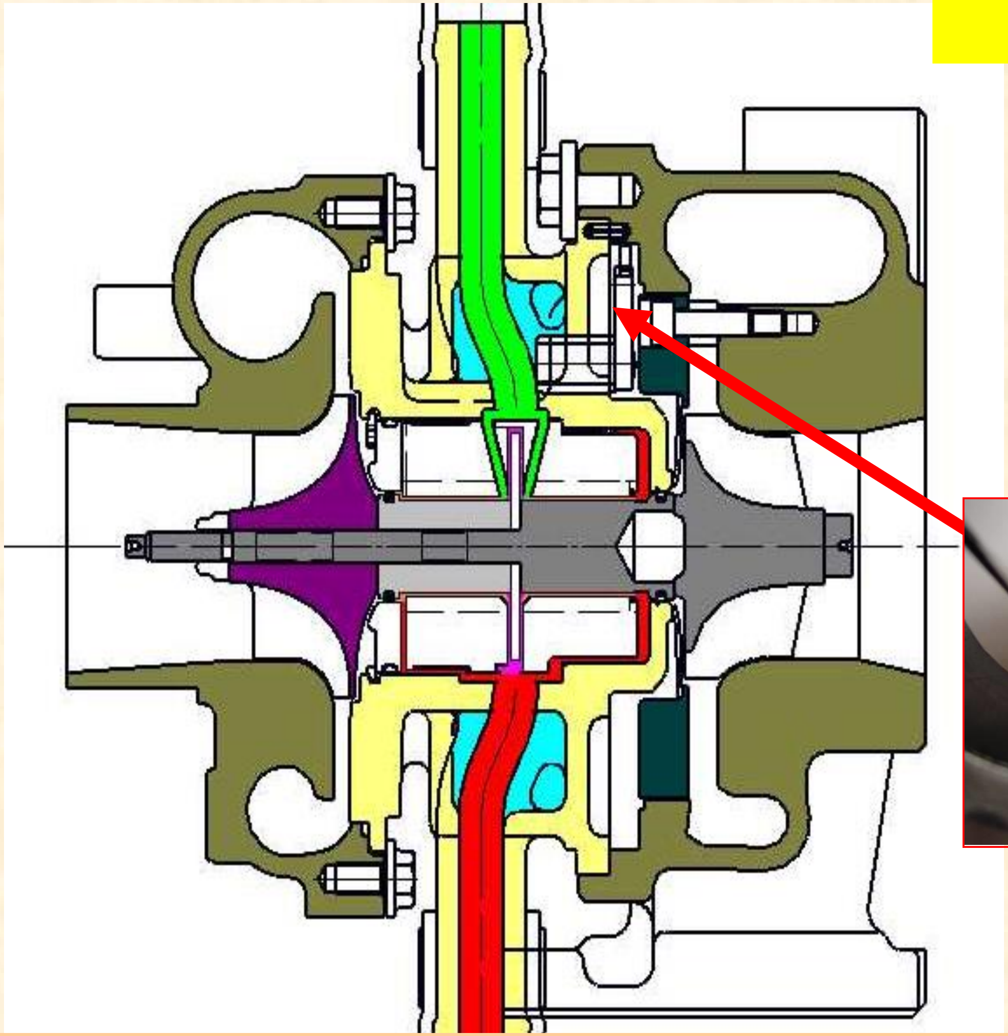
***Photos from SAE Int. J. Alt. Power 2016 and EHEC 2018**

PV turbocharger system

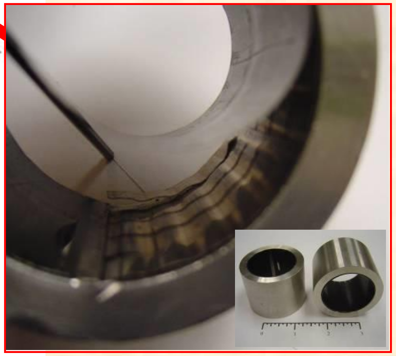
Honeywell (2007)
Borg & Warner (2012)



conventional Oil-Bearing

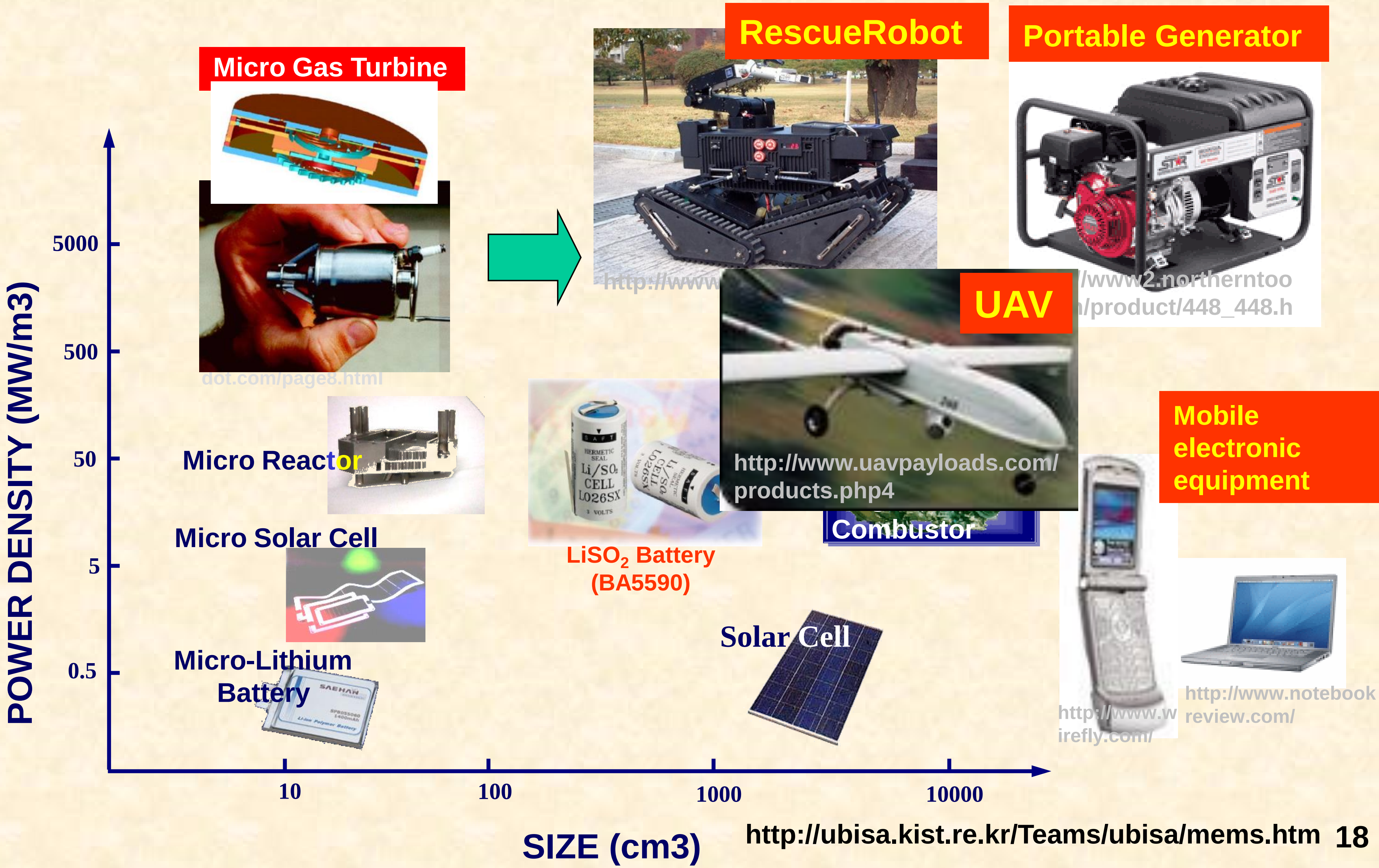


Foil Bearings chosen

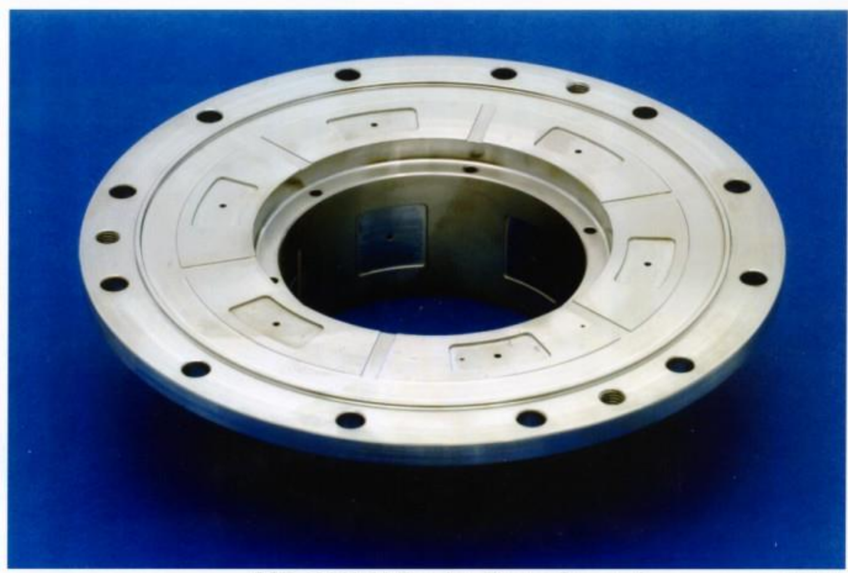


Hybrid vehicles: 50 miles/gal & 0 NOx → fuel cells.
Issues are high temperature, materials and NL rotordynamics

Application of Meso/MEMS MTM



Fluid Film Bearings



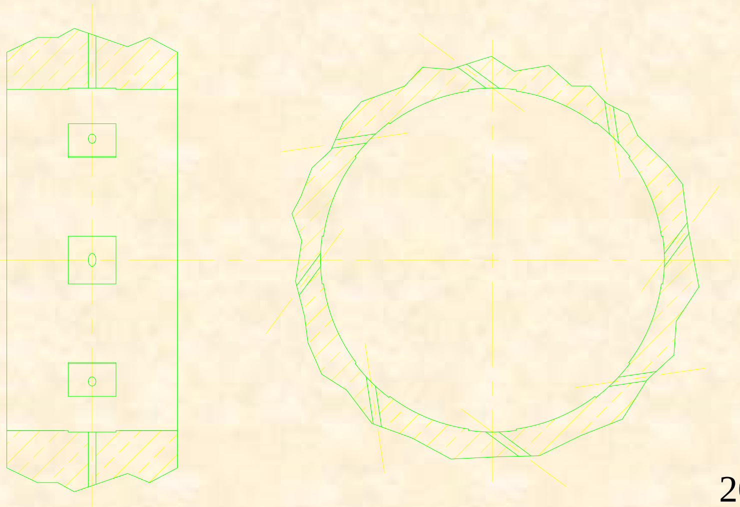
Fluid Film Bearings

Fluid film bearings produce low friction between solid surfaces in relative motion and generate a load support for mechanical components.

The lubricant or fluid between the surfaces may be a liquid, a gas or even a solid (coating).

Fluid film bearings, if well designed, support static and dynamic loads, affecting the dynamic performance of rotating machinery.

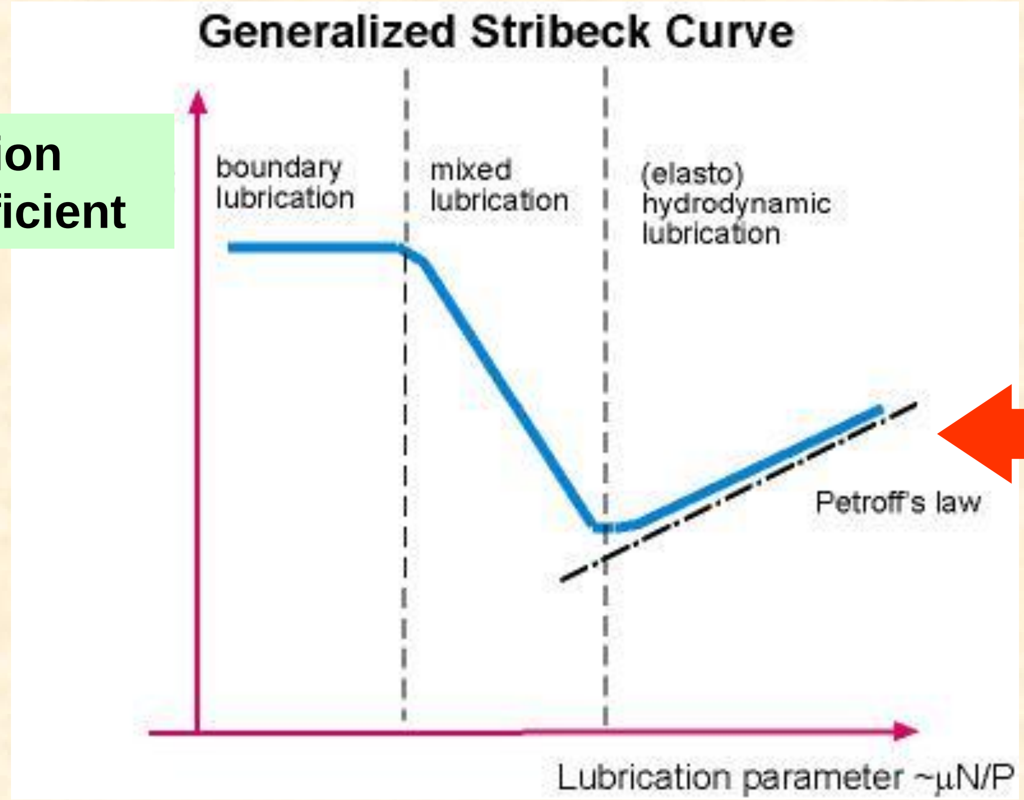
Basic operational principles are hydrodynamic, hydrostatic or hybrid (a combination of the former two).



Bearings: Friction and Lubrication

Bearings enable smooth (low friction) motion between solid surfaces in relative motion and, if well designed, support static and dynamic loads. Bearings affect the dynamic performance of machinery (reliability and availability).

Friction coefficient



Full film lubrication

$$\frac{\textbf{Surface velocity x viscosity}}{\textbf{Specific pressure}}$$

Hydrodynamic Bearings

Hydrodynamic pressure generated by relative motion between two mechanical surfaces with a particular "wedge like" shape

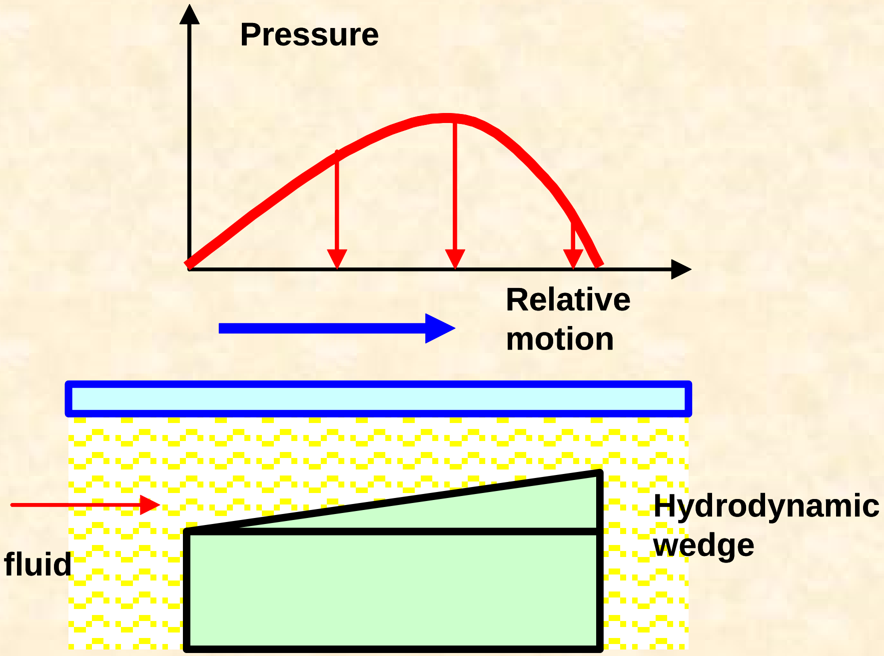
Advantages

Do not require external source of pressure. Fluid flow is dragged into the convergent gap in the direction of the surface relative motion.

Support heavy loads. The load support is a function of the lubricant viscosity, surface speed, surface area, film thickness and geometry of the bearing.

Long life (infinite in theory) without wear of surfaces.

Provide stiffness and damping coefficients of large magnitude.



Slider bearing

Schematic view of hydrodynamic (self-acting) fluid film bearing

Hydrodynamic Bearings

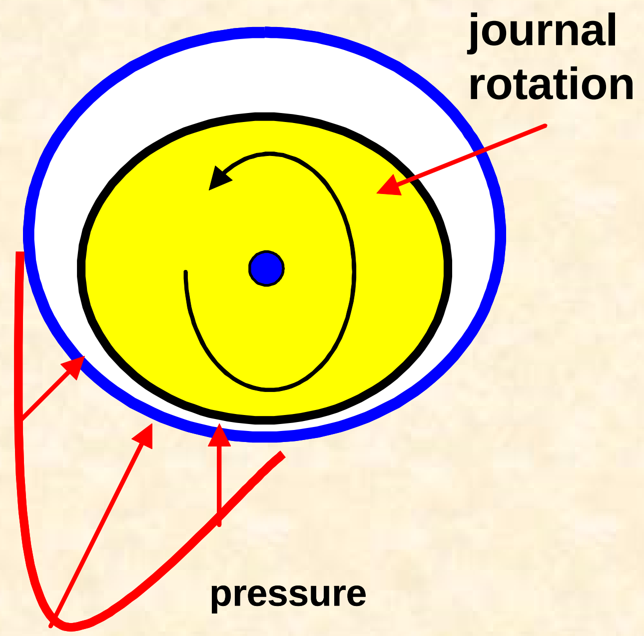
Disadvantages

Thermal effects affect performance if film thickness is too small or available flow rate is too low.

Require of surfaces' relative motion to generate load support.

Induce large drag torque (power losses) and potential surface damage at start-up (before lift-off) and touch down.

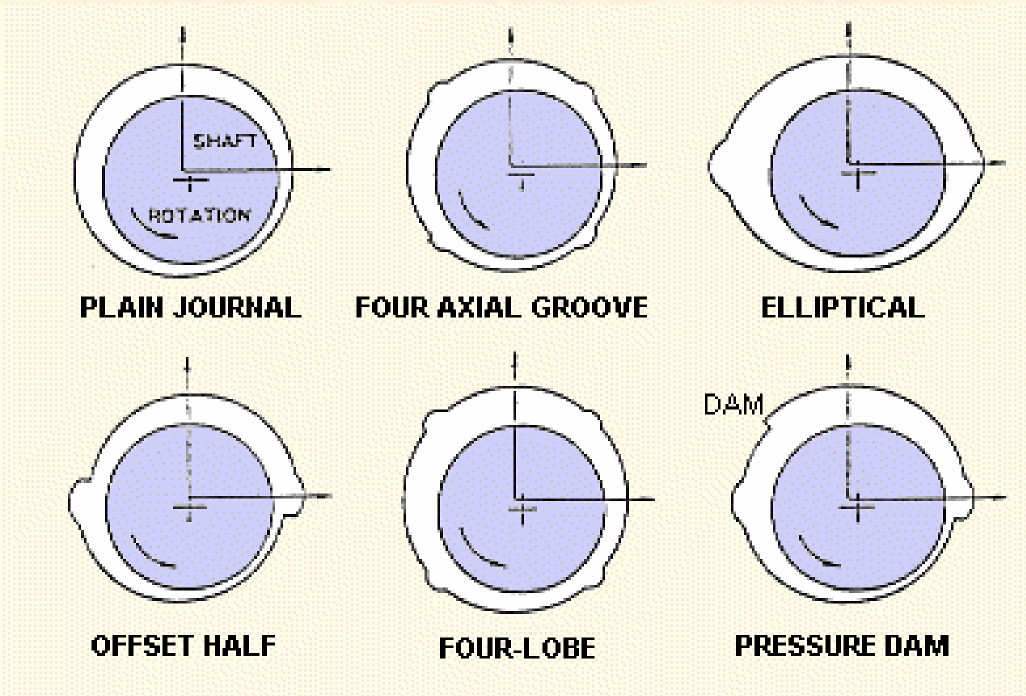
Potential to induce hydrodynamic instability, i.e. loss of effective damping for operation well above critical speed of rotor-bearing system

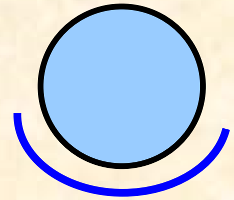


Plain journal bearing

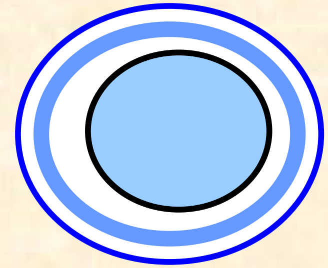
Schematic view of hydrodynamic (self-acting) journal bearing

Examples of hydrodynamic bearings

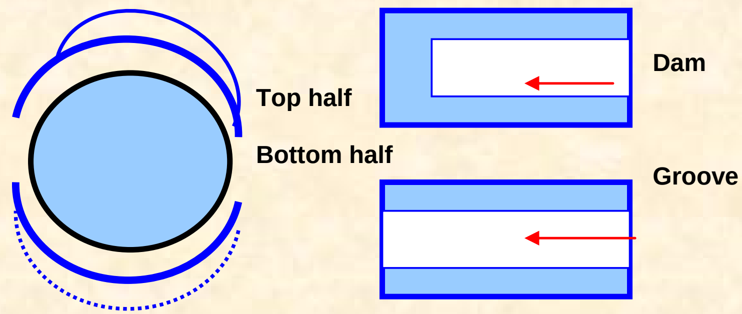




PARTIAL ARC JOURNAL BEARING

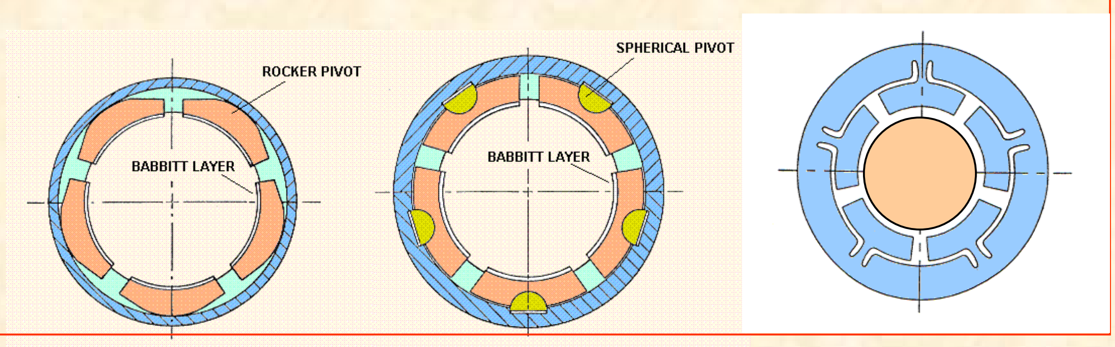


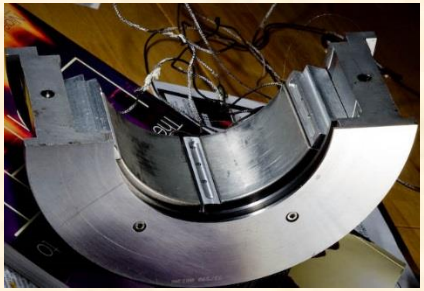
FLOATING RING JOURNAL



PRESSURE DAM JOURNAL BEARING

Tilting pad bearings





Typical cylindrical journal bearings

Hydrostatic Bearings

External source of pressurized fluid forces lubricant to flow between two surfaces, thus enabling their separation and the ability to support a load without contact.

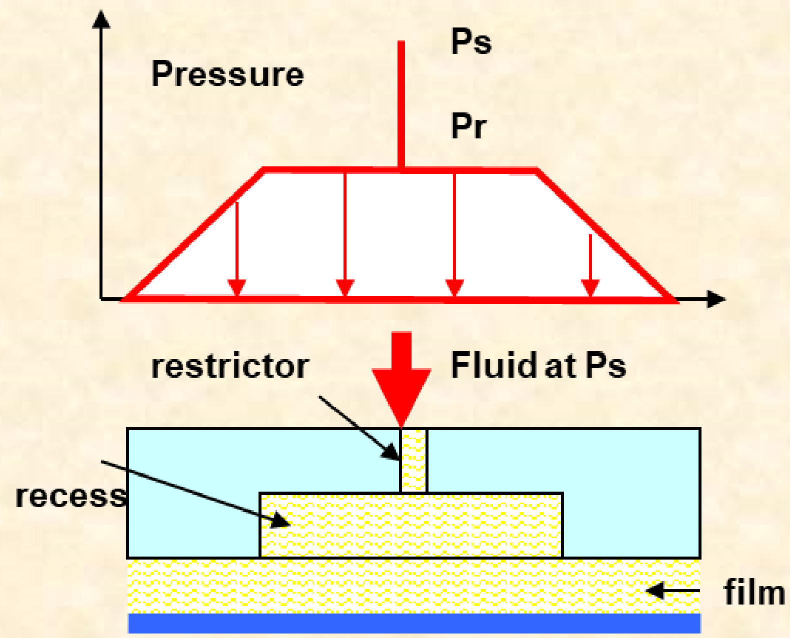
Advantages

Support very large loads. The load support is a function of the pressure drop across the bearing and the area of fluid pressure action.

Load does not depend on film thickness or lubricant viscosity.

Long life (infinite in theory) without wear of surfaces

Provide stiffness and damping coefficients of very large magnitude. Excellent for exact positioning and control.



Schematic view of hydrostatic/ hydrodynamic journal bearing

Hydrostatic Bearings

Disadvantages

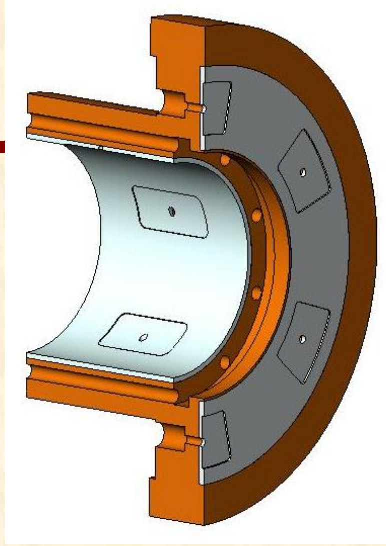
Require ancillary equipment. Larger installation and maintenance costs.
Need of fluid filtration equipment. Loss of performance with fluid contamination.

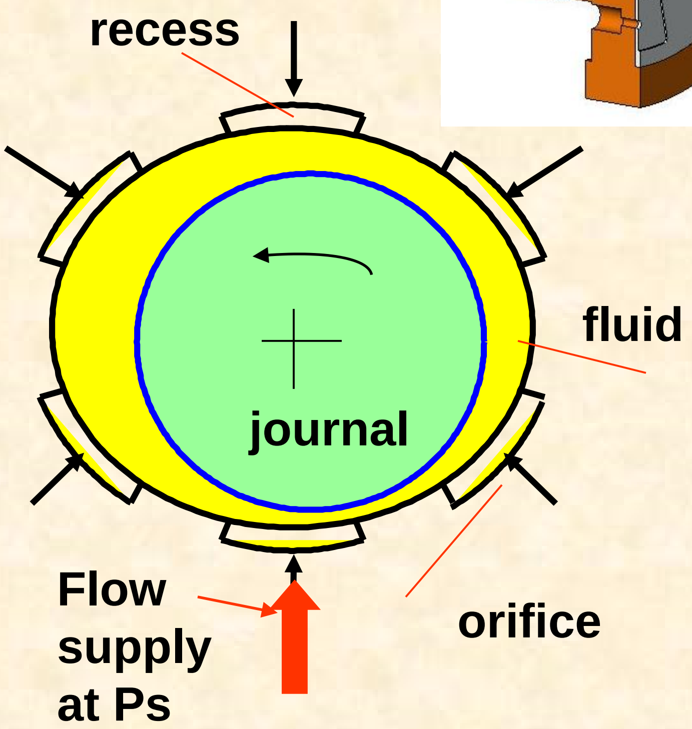
Penalty in power consumption: pumping losses.

Limited LOAD CAPACITY ~ f(P_{supply})

Potential to induce hydrodynamic instability in hybrid mode operation.

Potential to show pneumatic hammer instability with compressible fluids, i.e. loss of damping at low and high frequencies of operation due to compliance and time lag of trapped fluid volumes





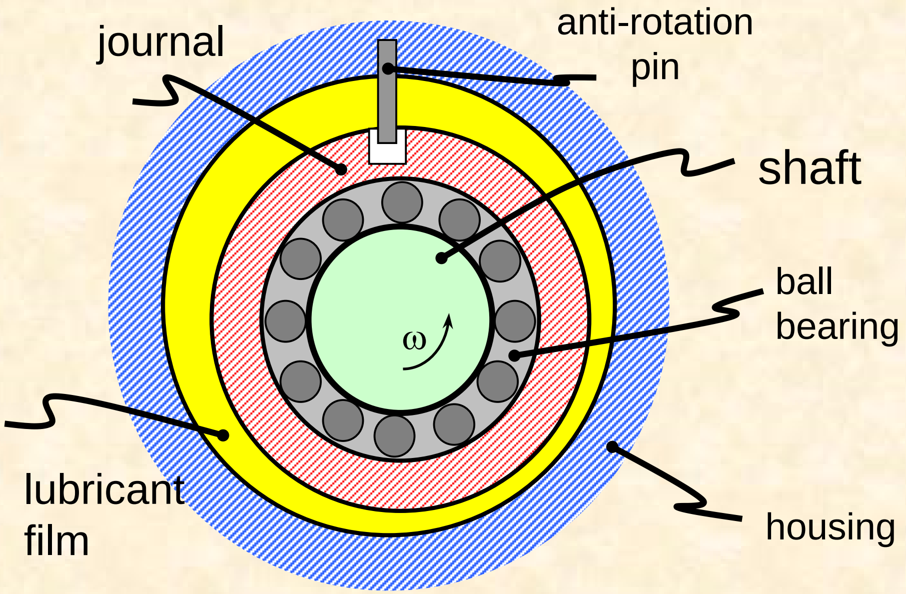
Schematic view of hydrostatic/ hydrodynamic journal bearing

Squeeze Film Dampers

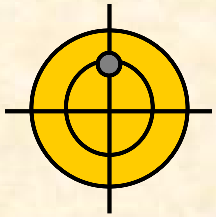
Normal surface motions can also generate hydrodynamic pressures in the thin film separating two surfaces.

The squeeze film action works effectively only for compressive loads, i.e. those forcing the approach of one surface to the other.

Squeeze film dampers are routinely used to reduce vibration amplitudes and isolate structural components in gas jet engines, high performance compressors, and occasionally in water pumps.

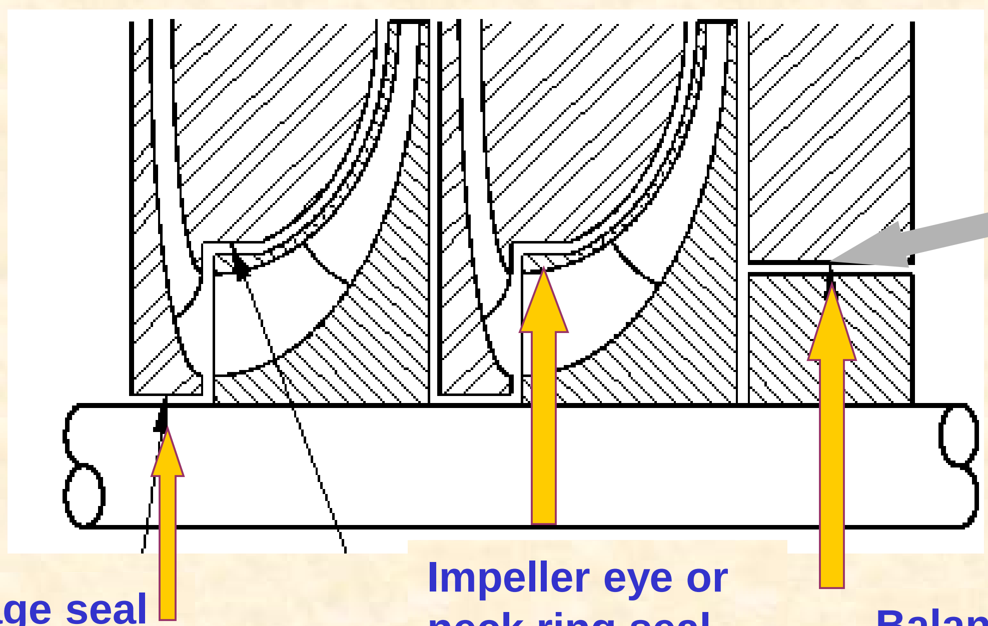


Typical squeeze film damper (SFD) configuration

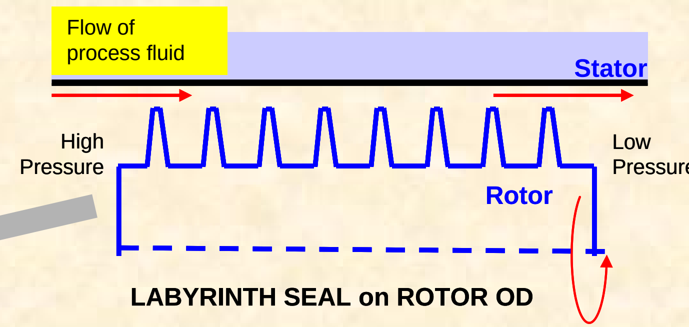


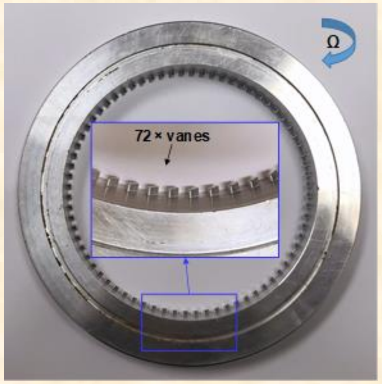
Annular Pressure Seals

Seals (annular smooth, labyrinth or honeycomb) separate regions of high pressure and low pressure and their principal function is to minimize the leakage (secondary flow); thus improving the overall efficiency of a TM extracting or delivering power to a fluid. Seals have larger clearances than load carrying bearings.

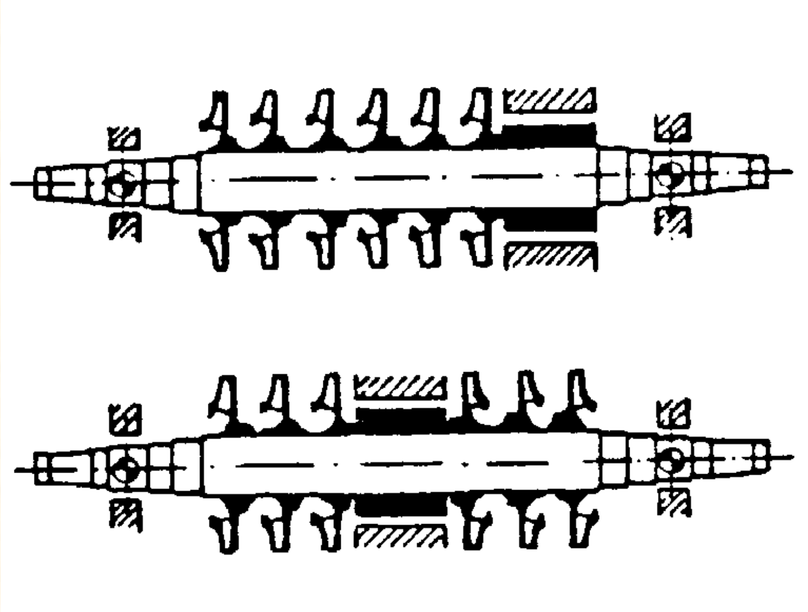


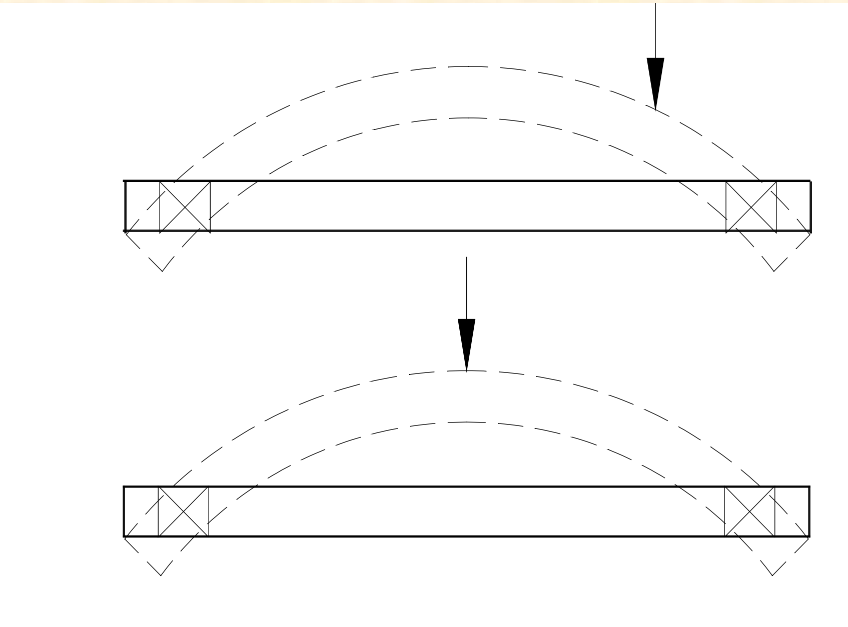
Seals in a Multistage Centrifugal Pump or Compressor





Annular Pressure Seals

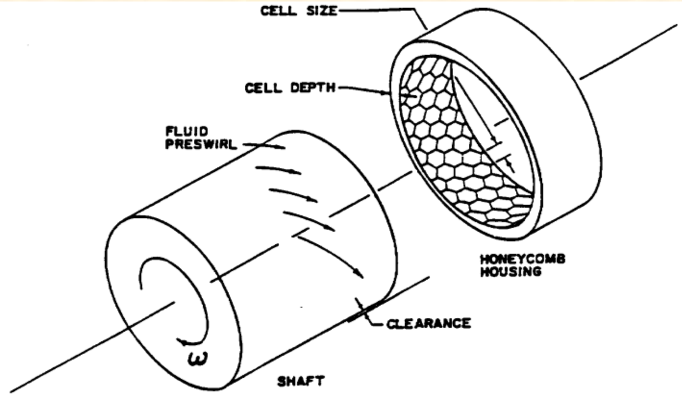




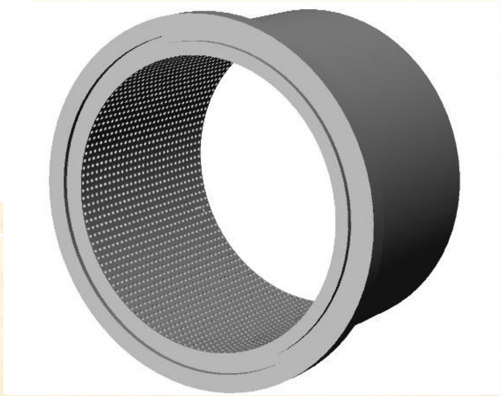
Straight-Through and Back-to-back Compressor Configurations and 1st Mode Shapes

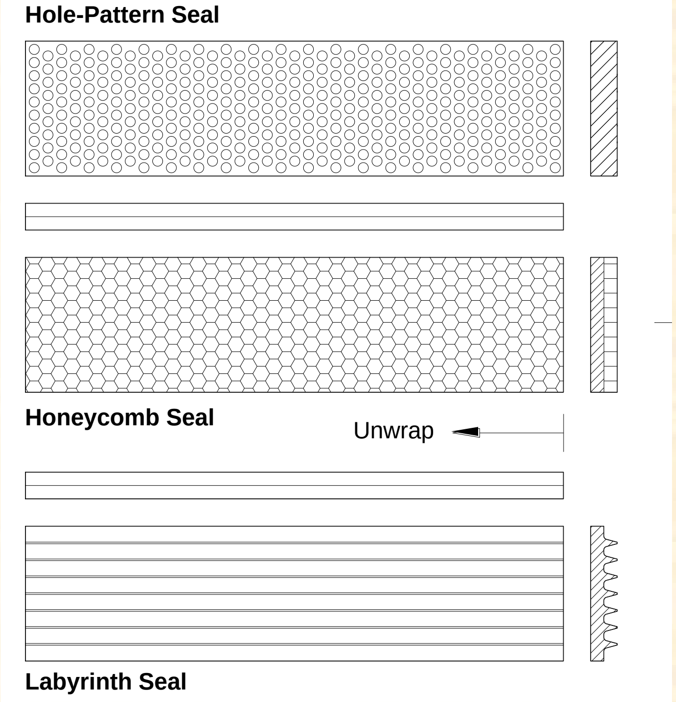
Due to their relative position within a rotor-bearing system, seals modify sensibly the system dynamic behavior. Seals typically "see" large amplitude rotor motions. This is particularly important on back-to-back compressors and long-flexible multiple stage pumps.

Damper Seals



Round hole-pattern seal





Surface textured seals for turbopumps

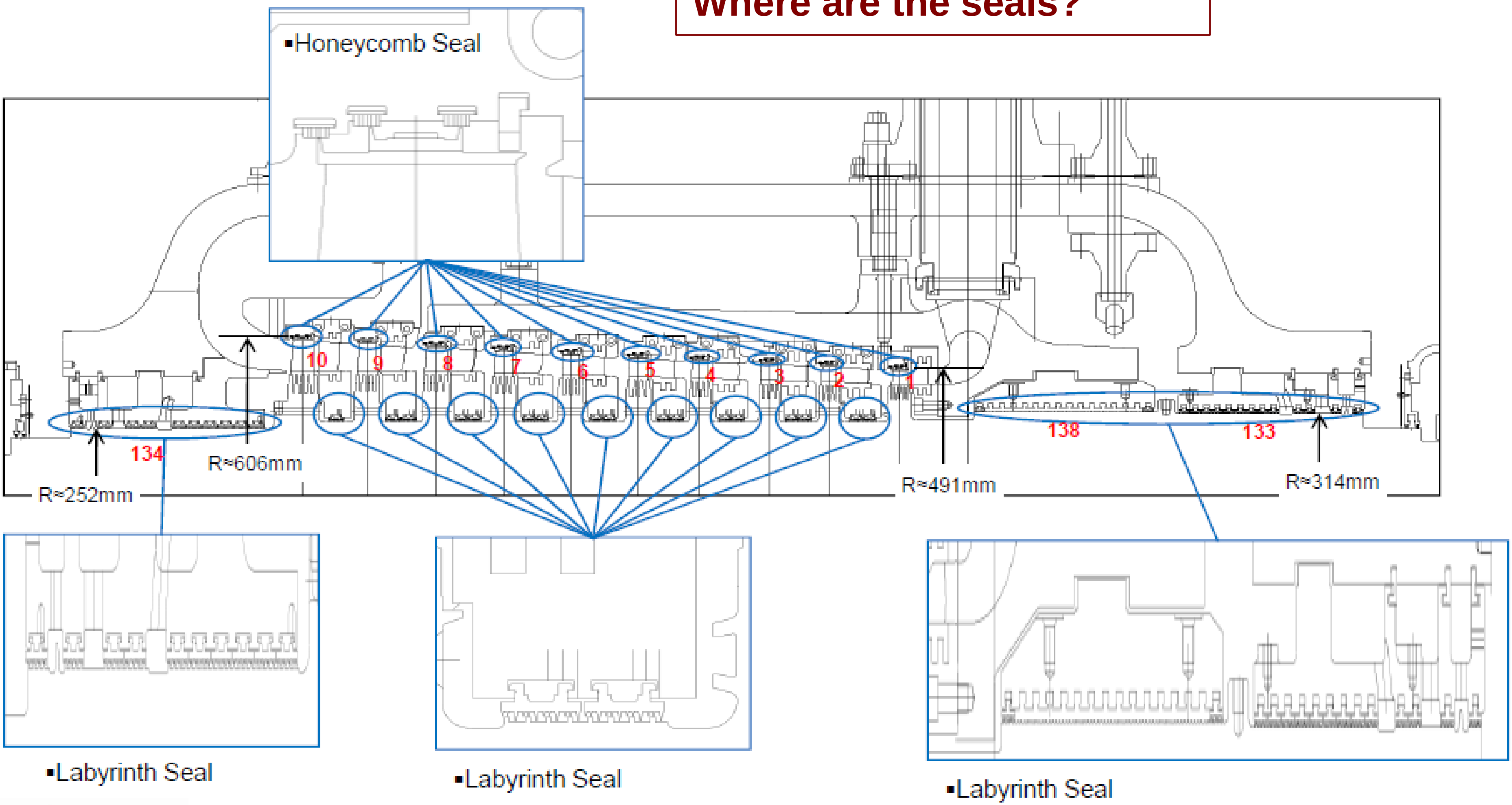
Intentionally roughened stator surfaces (macro texturing) reduce the impact of undesirable cross-coupled dynamic forces and improve seal stability.

Annular seals acting as Lomakin bearings could be support elements (damping bearings) for cryogenic turbopumps as well in process fluid pumps & high pressure compressors

Seals in a high pressure steam turbine

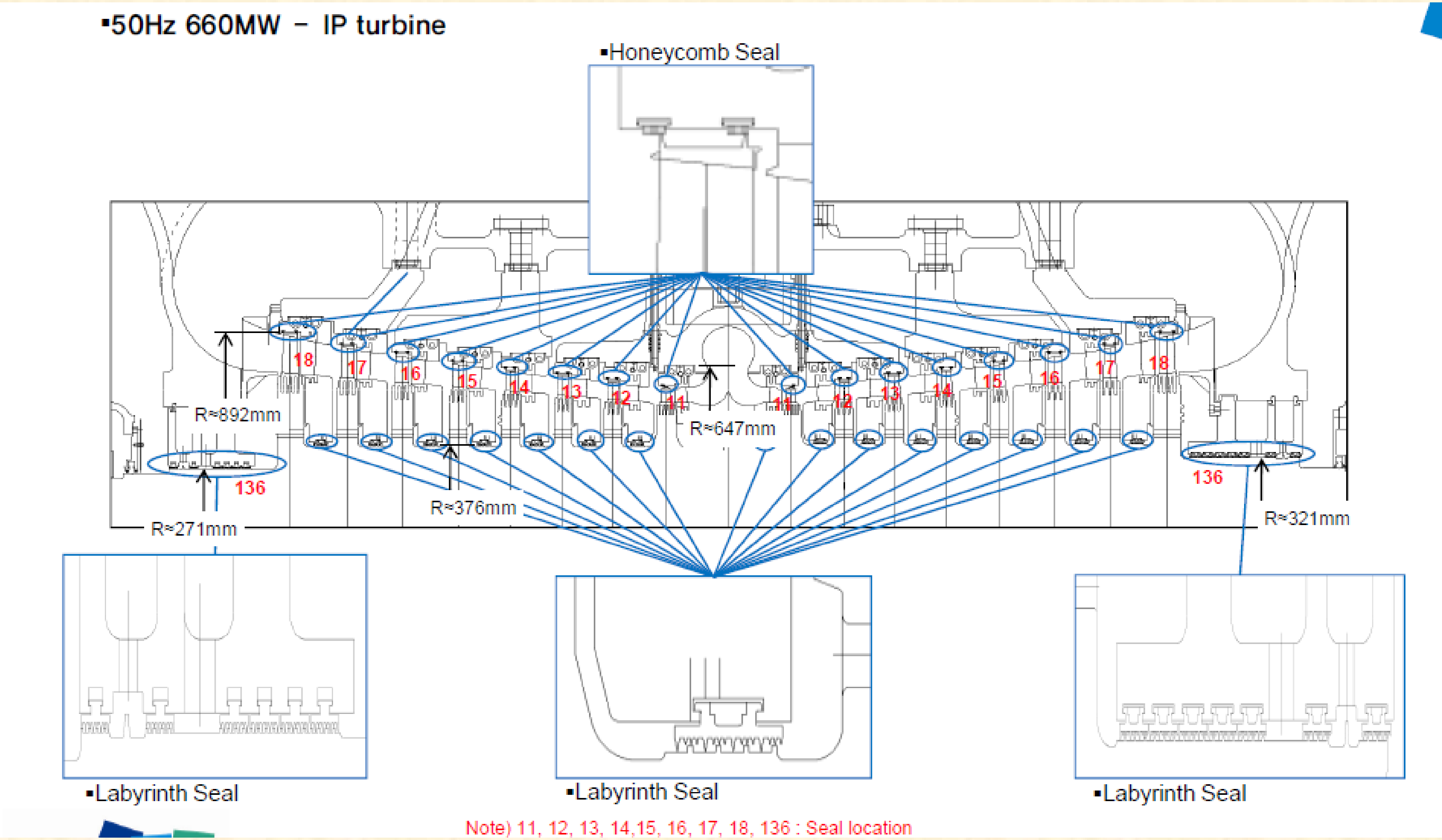
▪50Hz 660MW – HP turbine

Where are the seals?



Note) 1, 2, 3, 4, 5, 6, 7, 8, 133, 134, 138 : Seal location

Seals in an Intermediate pressure steam turbine



ME626 Course Objectives

1. To learn about the physical concepts and mathematical models for the analysis and design of fluid film bearings and seals.

2. To acquire knowledge based on the detailed review of the literature on fluid film lubrication and rotordynamics.

3. To identify the mechanical effects of importance on the static and dynamic forced performance of fluid film bearings.

4. To learn about the effects of fluid film bearings on the rotordynamics of turbomachinery.

5. To identify the future trends in applications of bearing and seal technologies and the needs for further research.

6. To provide the basics of efficient computational skills for the prediction of the static and dynamic forced performance of fluid film bearings.

LEARN MORE AT **http://rotorlab.tamu.edu**

Questions (?)

TURBOMACHINERY LABORATORY
TEXAS A&M ENGINEERING EXPERIMENT STATION