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Major Steam Turbine Plant Components

Older Turbine-Generators

Maintaining
Modernizing
Purchasing New Units

Jurek Ferleger
Sargent & Lundy, L.L.C.

Stephen Rashid
Advanced Turbomachine, LLC

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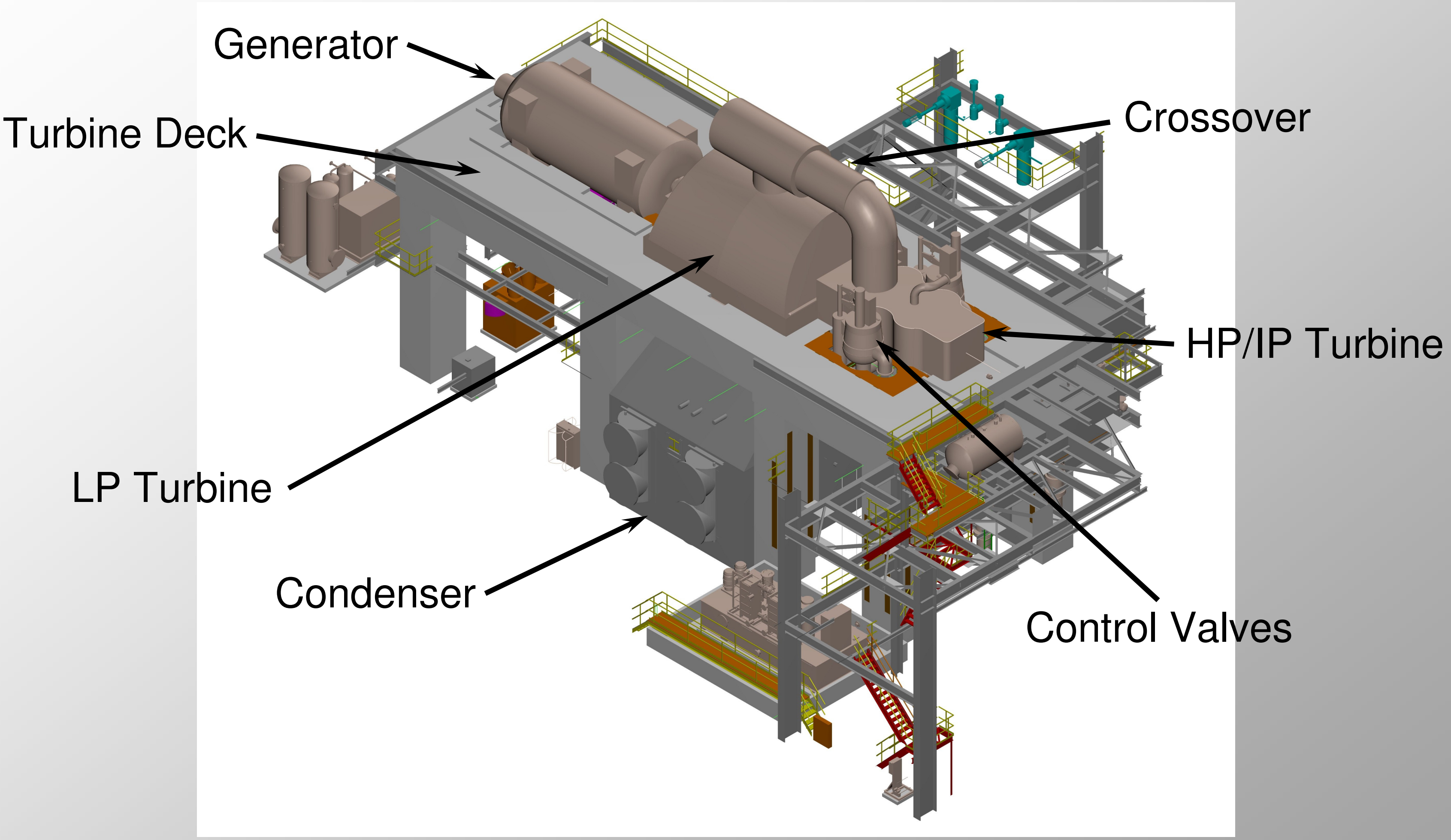
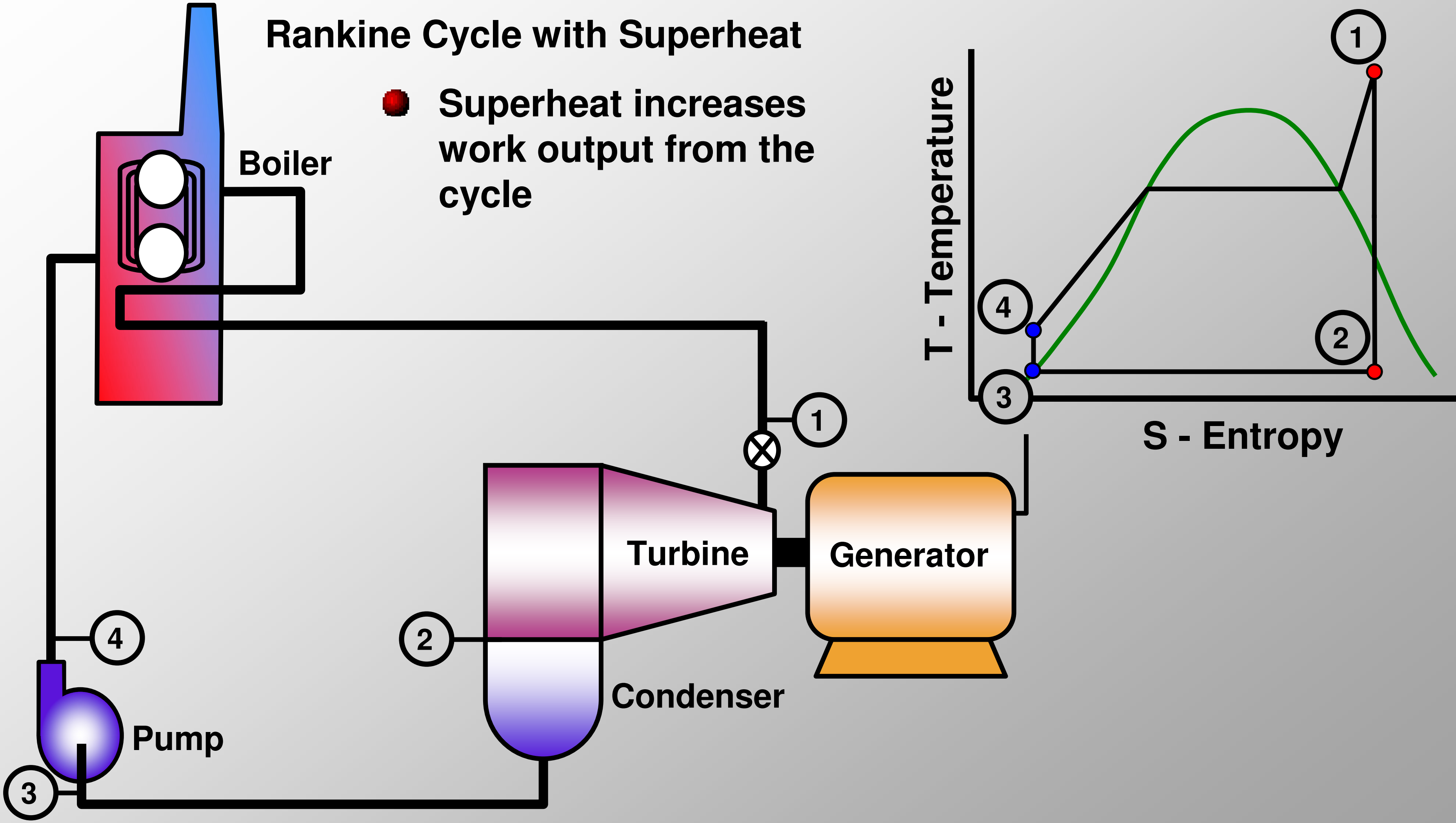
Major Steam Turbine Plant Components



Rankine Cycle Variations

Rankine Cycle with Superheat

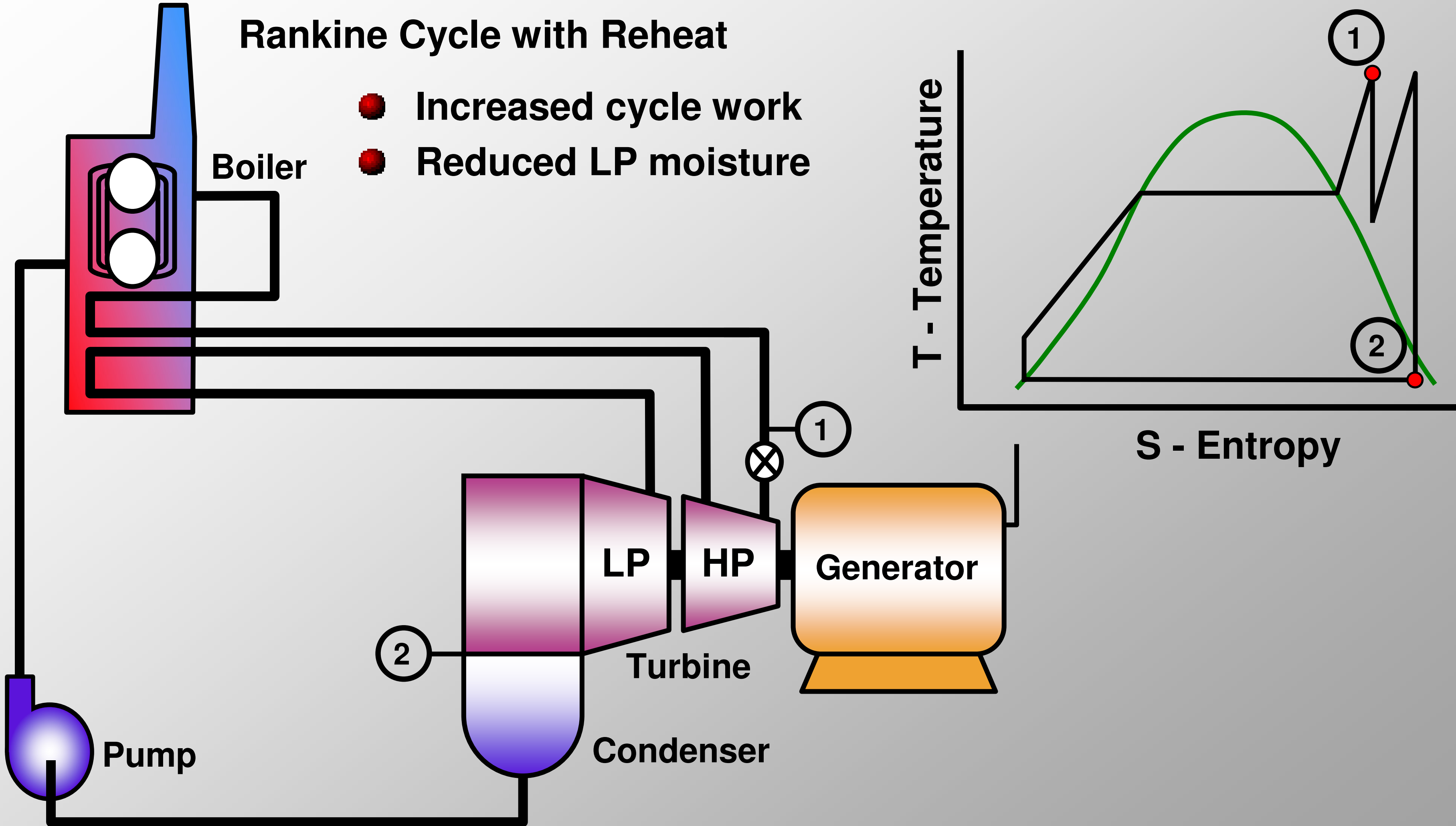
- Superheat increases work output from the cycle



Rankine Cycle Variations

Rankine Cycle with Reheat

- Increased cycle work
- Reduced LP moisture



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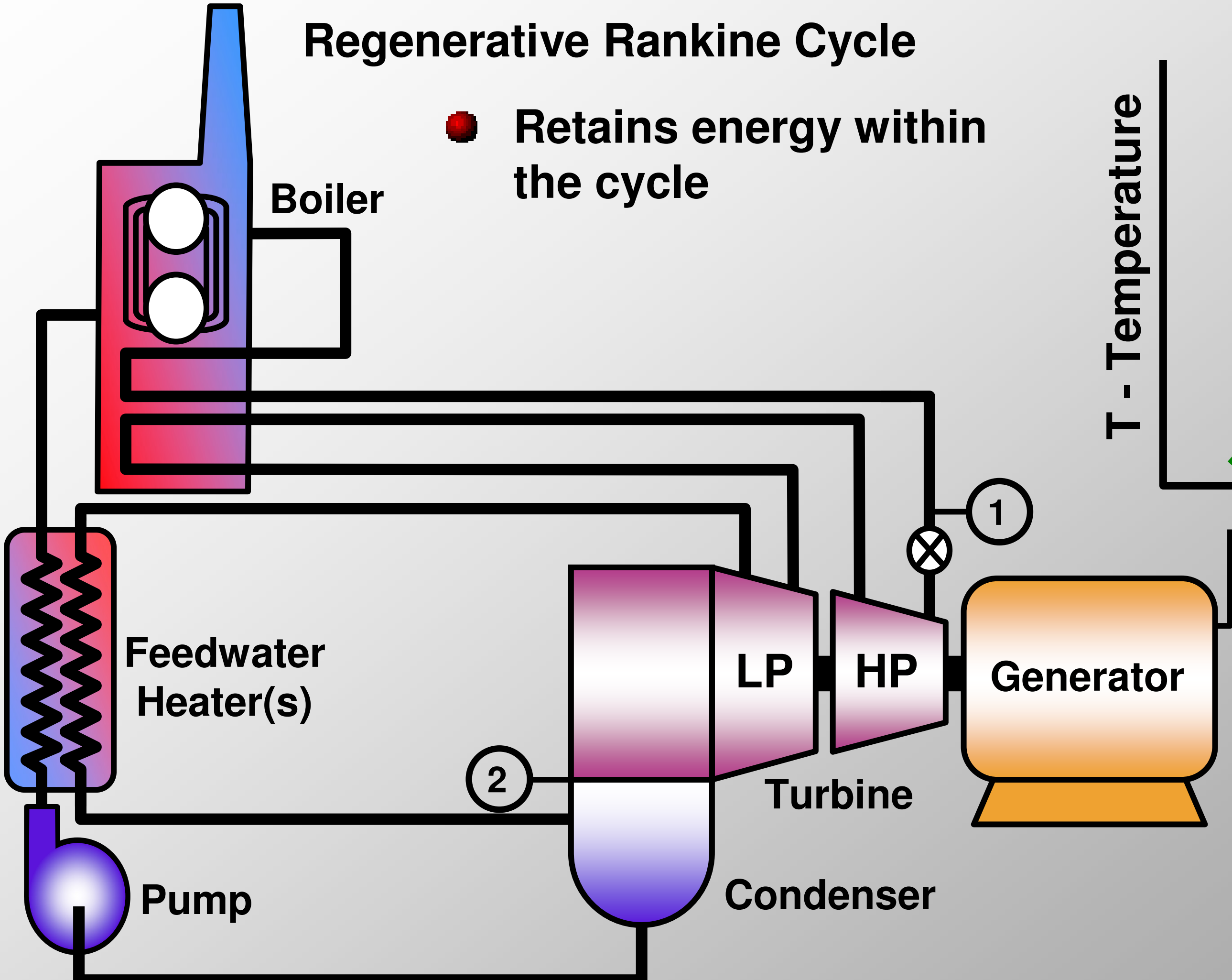
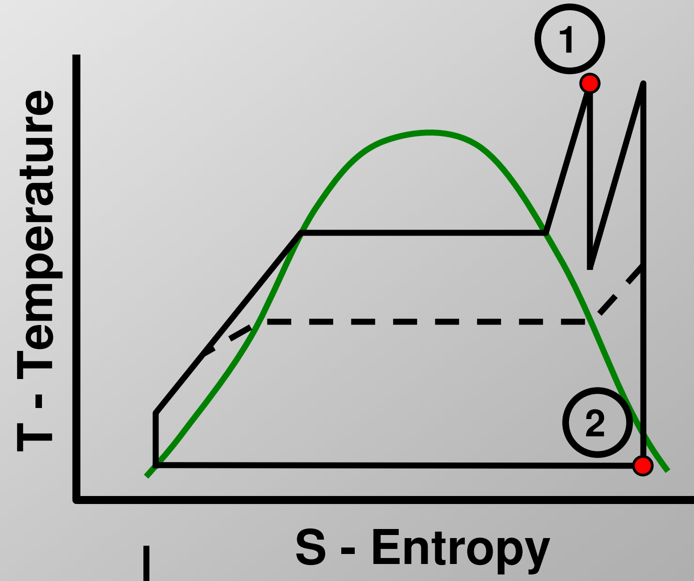
Rankine Cycle Variations

Regenerative Rankine Cycle

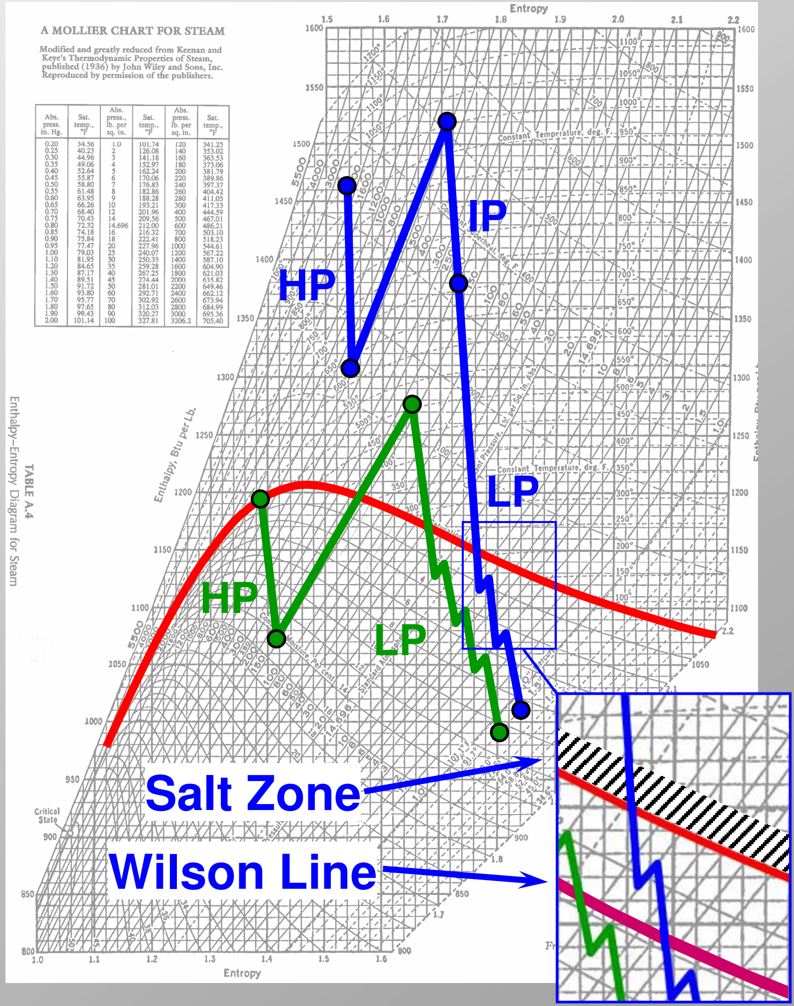
- Retains energy within the cycle





Typical Steam Turbine Expansion Lines

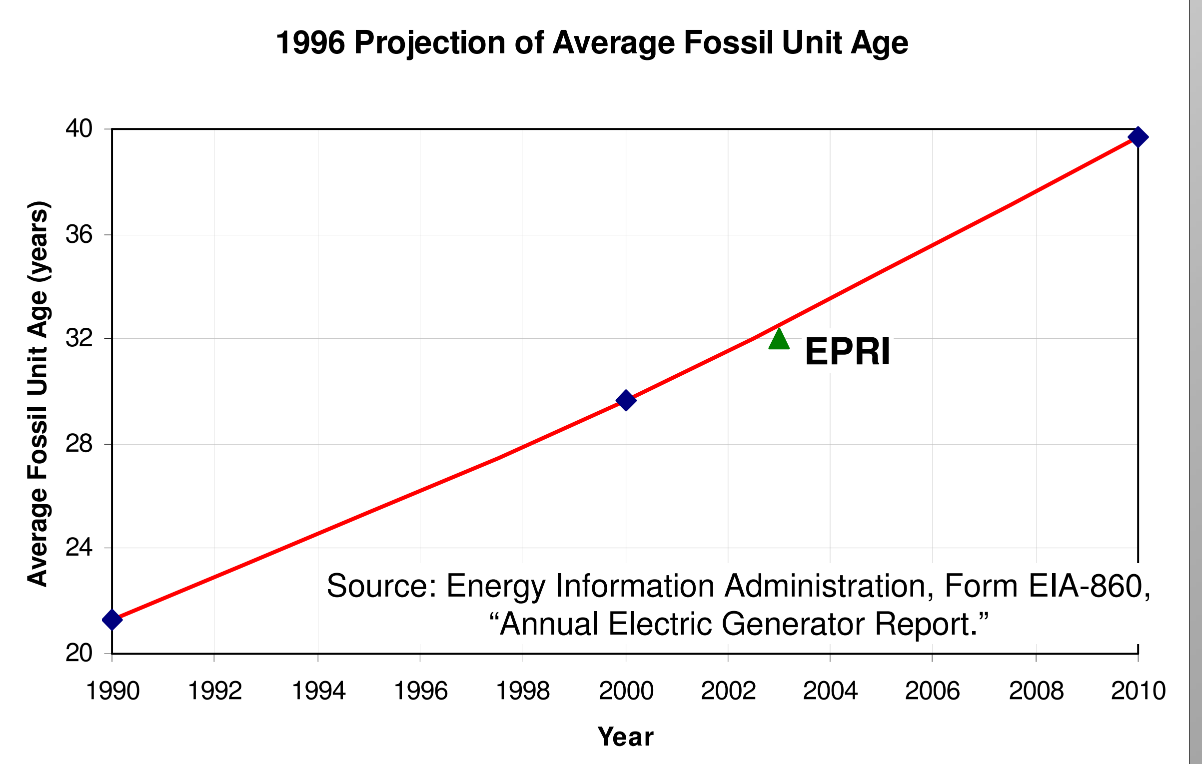
- **Fossil**
  - Typical turbine inlet conditions:
    - 2400 PSIA
    - 1000° F
  - 3600 (60 Hz) or 3000 (50 Hz) RPM
    - 2 pole generator
  - Higher available cycle energy
- **Nuclear**
  - Typical turbine inlet conditions:
    - ≈1000 PSIA
    - Dry & Saturated
  - 1800 (60 Hz) or 1500 (50 Hz) RPM
    - 4 pole generator
  - Very high steam flow rates
  - Very large blades and diameters
  - BWR (single loop), PWR (2 loops)



Increasing Average Unit Age

- Due to fewer new units coming online, the average unit age is increasing…

EPRI T-G Age Data	
Age (Years)	Active T-G Units
0-5	0
5-10	13
10-15	77
15-20	90
20-25	261
25-30	297
30-40	714
Over 40	1329



Source: Energy Information Administration, Form EIA-860, "Annual Electric Generator Report."

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Common NDE Methods

- Liquid Penetrant (PT), colored/fluorescent liquid used to detect surface cracks
  - Requires a clean surface, and time for liquid to penetrate
- Mag Particle (MT), (sub)surface crack detected by magnetic particles
  - Requires a part material that can be magnetized
  - Can be affected by surface condition
  - A high level of skill is necessary to detect subsurface crack
- Eddy Current (ET), magnetic field created by electromagnetic induction
  - Surface and subsurface cracks are detected by changes in magnetic field
  - Sensitive to small cracks, but directionally biased
- Ultrasonic Testing (UT), cracks found by reflection of high frequency sound
  - Detects surface and subsurface cracks
  - Some coarse grained materials are difficult to inspect
  - Requires a high level of skill
- X-ray Radiography (RT), x-rays used to detect internal discontinuities
  - Used to inspect welds for cracks, inclusions, voids, and porosity

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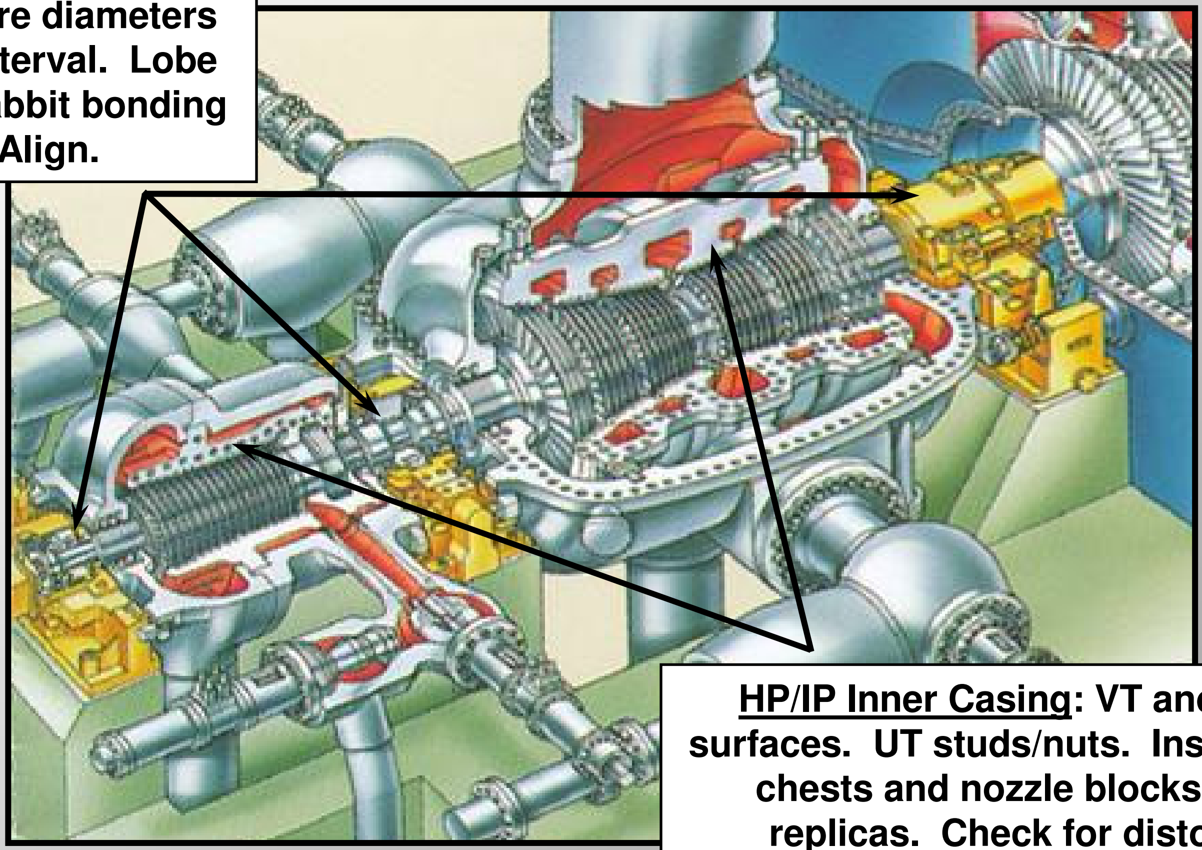
HP/IP Turbine Components

<u>HP & IP Bearings</u>: PT/MT journals. Measure diameters 90° apart at 1” interval. Lobe check. UT/PT babbit bonding on pads. Align.



<u>HP/IP Inner Casing</u>: VT and MT all surfaces. UT studs/nuts. Inspect valve chests and nozzle blocks. Take replicas. Check for distortion.

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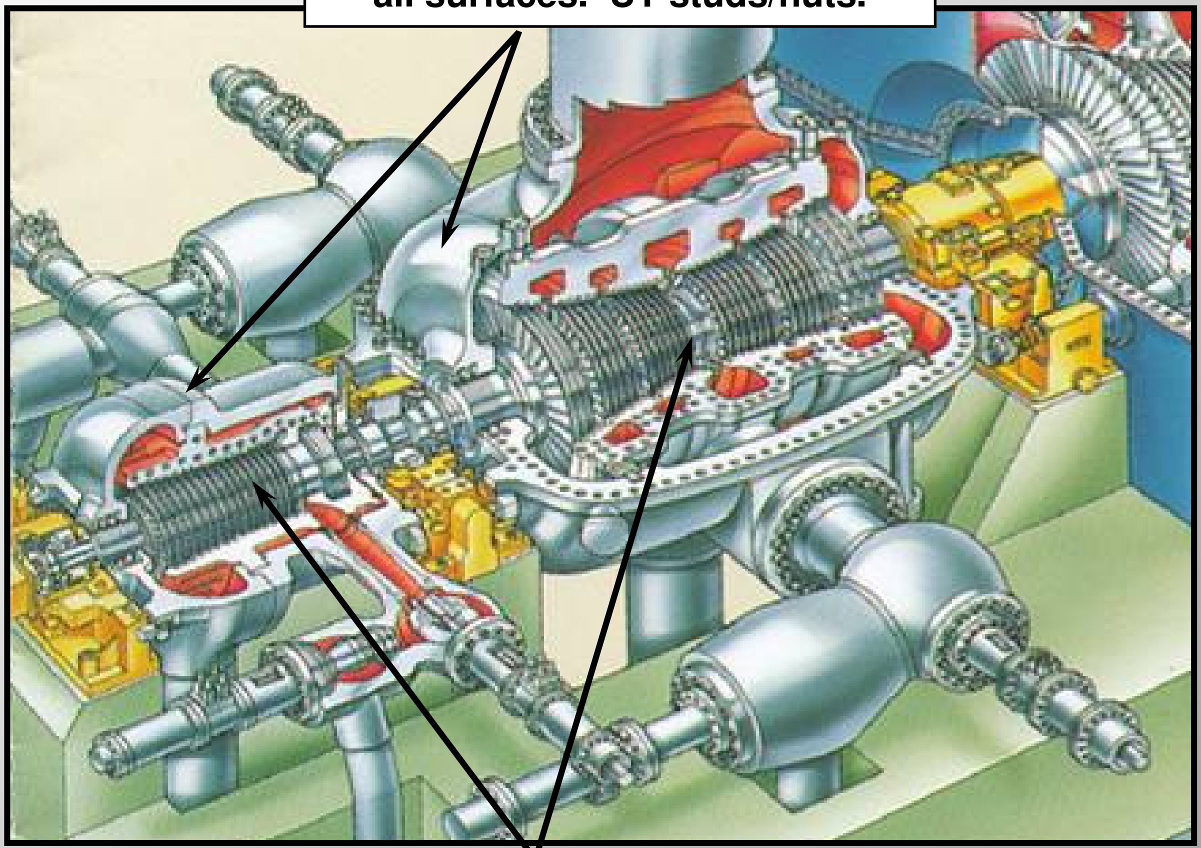
HP/IP Turbine Components

<u>HP/IP Outer Casing</u>: VT and MT all surfaces. UT studs/nuts.



<u>HP/IP Rotor</u>: UT peripherally/axially. Measure TIR. Check bow. Inspect steam balance holes and balance plugs. Take replicas.

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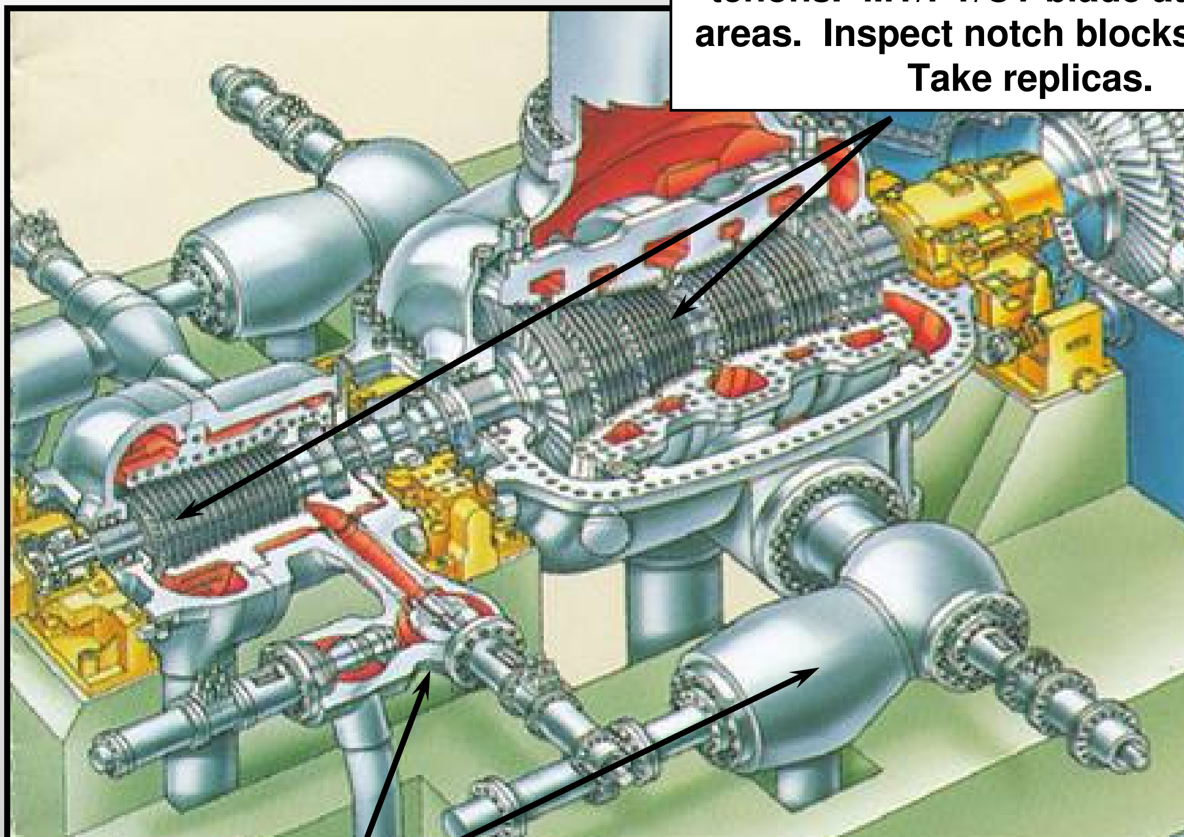
HP/IP Turbine Components

HP/IP Blades: Check for SPE. UT tenons. MT/PT/UT blade attachment areas. Inspect notch blocks and pins. Take replicas.



Valves and Steam Chest: VT, PT & MT valve seats. UT valve body. MT all internal surfaces of the steam chest and assembly welds.

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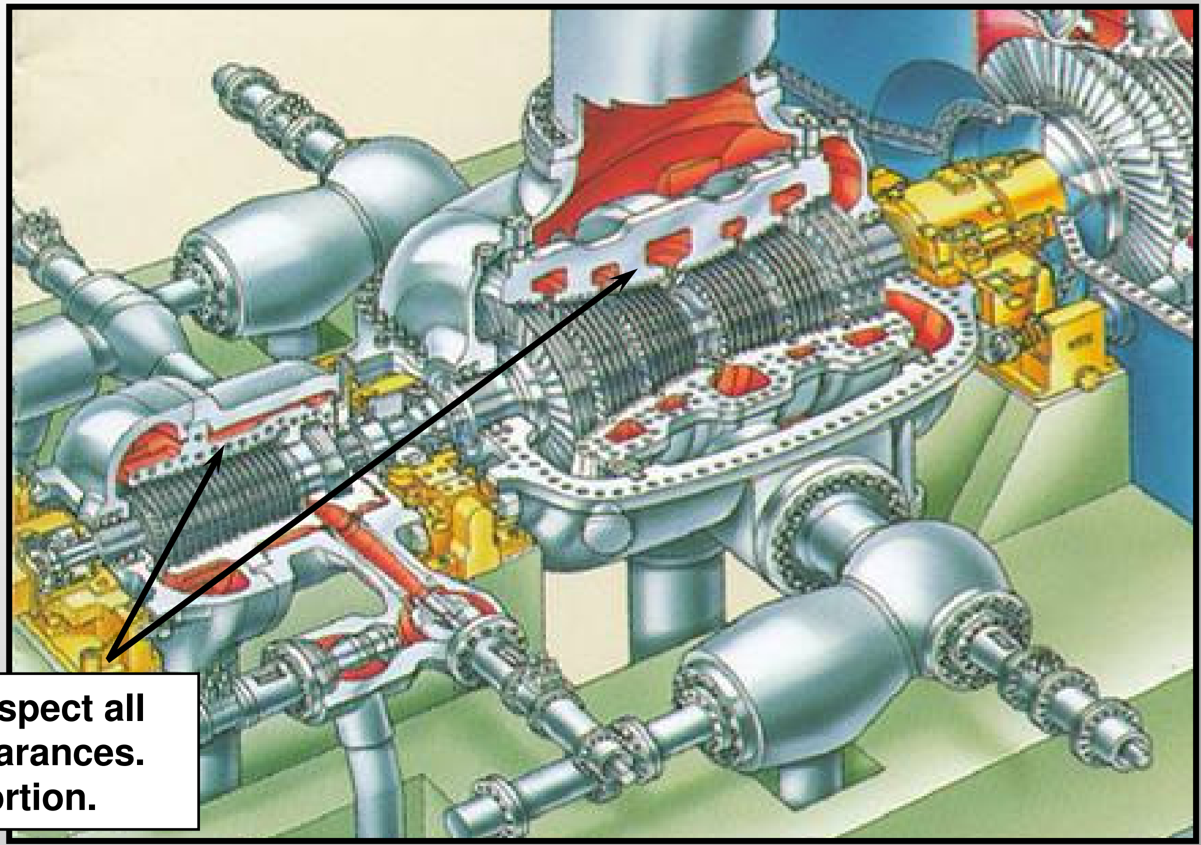
HP/IP Turbine Components



<u>Blade Carriers</u>: Inspect all welds. Check clearances. Check for distortion.

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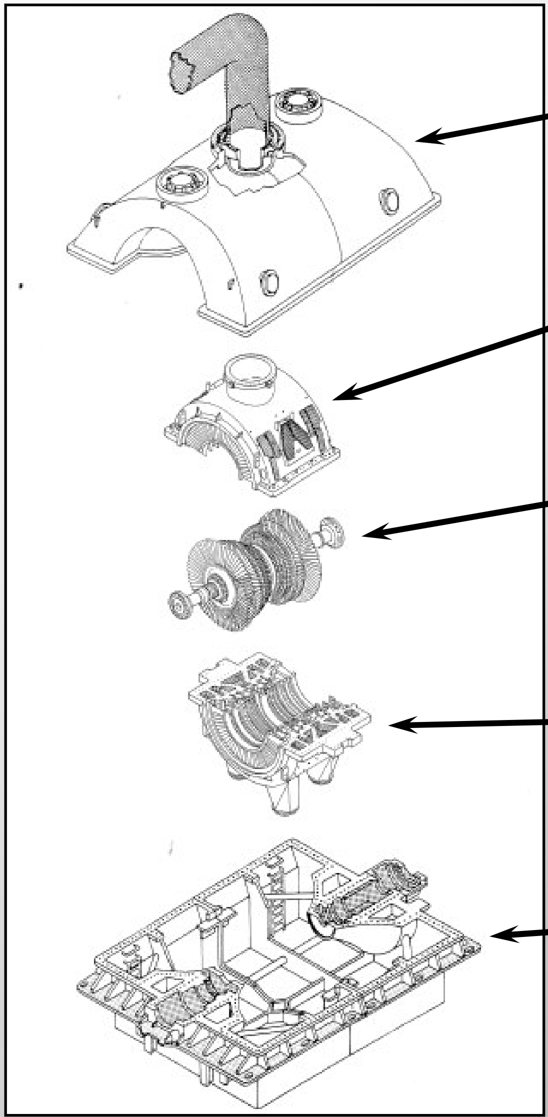
LP Turbine Components



Outer Casing: Inspect crossover/PT expansion joints. Check breakable diaphragms. MT casing and welds.

Inner Casing: MT inner surfaces. Assess distortion. Check horizontal joint. UT staybars.

Rotor: UT axially/peripherally. PT/UT bearings and babbit bonding. MT/PT/UT blade attachments. UT tenons. Inspect notch groups. Check rabbet fits. MT/UT couplings. MT/PT journals. Check TIR. Inspect for erosion.

Inner Casing: MT selected welds. MT stationary vane welds. Check flatness of horizontal joint.

Outer Casing: Examine bearing housings. UT exhaust hood welds. Check flatness of horizontal joint.

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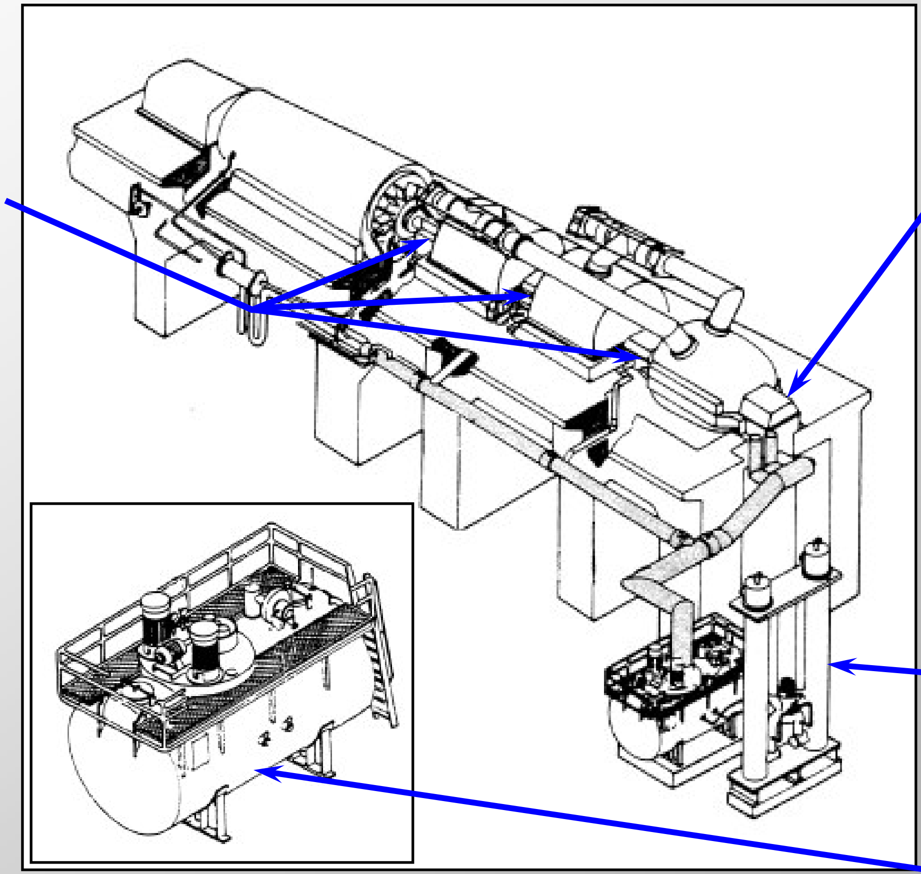
Lube Oil System - Components

<u>Bearing Housing</u>: Check oil deflectors



<u>Shaft Driven Oil Pump</u> (some OEMs): Check valves, bearings, clearances; check for leaks and vibration

<u>Oil Coolers</u>: Must be cleaned periodically, reverse flush if possible

<u>Lube Oil Reservoir</u>: Drain and examine, remove any sludge

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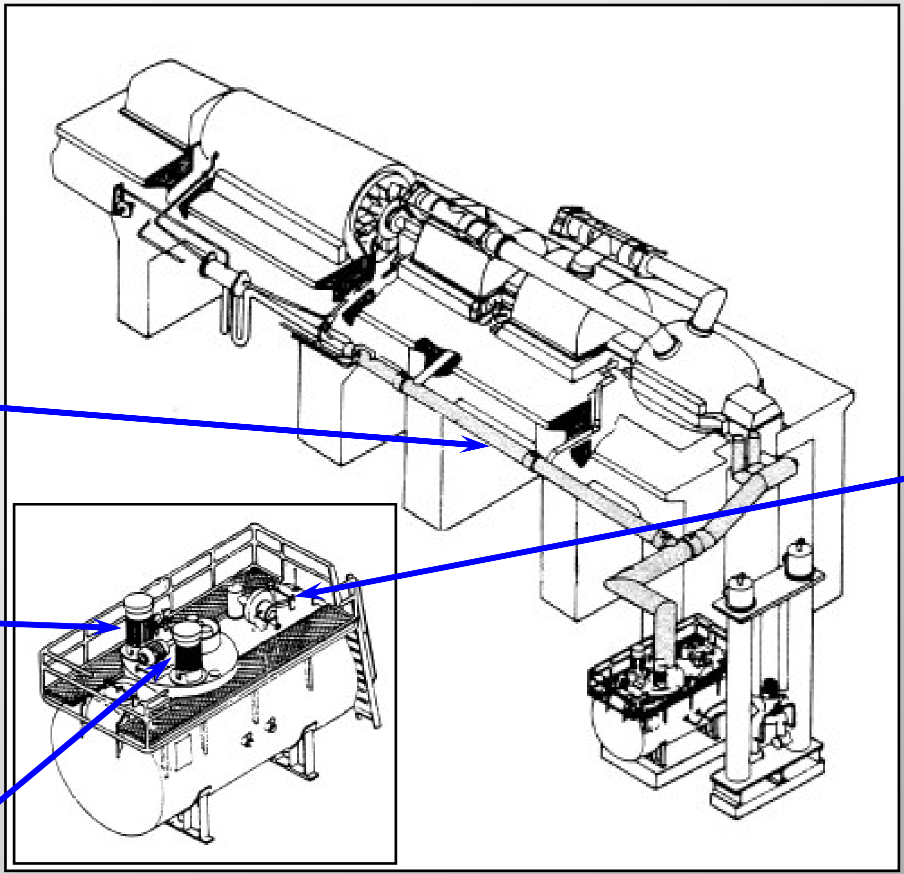
Lube Oil System - Components



Turbine Drain Piping: Check for leaks, corrosion, sagging, broken/missing supports

DC Motor Oil Pump

AC Motor Oil Pump: Check valves, bearings, clearances; check for leaks and vibration

Lube Oil Extractor: Check fan, lubricate bearings on vapor extractor

Steam Turbine Deterioration Mechanisms

Mechanism	Symptom	Likely Location
High Cycle Fatigue	Cracking	High stress areas of blades, rotors
Thermal Fatigue	Cracking	Cylinder inlet
Low Cycle Fatigue	Cracking, Local deformation	LSB
Creep	Cracking, Deformation	HP/IP blades and vanes, tenons, rotors, stationary components
Embrittlement	Brittle fracture	HP cylinder

Mechanism	Symptom	Likely Location
Corrosion	Stress corrosion cracking	Low pressure rotor
Hard Particle Erosion	Loss of material, Performance degradation	HP inlet (blades, vanes, and casings)
Moisture Erosion	Loss of material, Performance degradation	LSB leading edge deterioration
Stress Corrosion	Cracking	Blade attachments in LP element
Fretting	Cracking	Blade attachment

Steam Turbine Life Assessment

- **Life assessment of an older steam turbine is based on boresonic rotor inspection, NDE inspection of blades, valves, high pressure casing, etc.**

  - **Remaining creep life may be calculated using Robinson's rule:**

$$D_t = \sum \left(\frac{t_1}{T_1} + \frac{t_2}{T_2} + \frac{t_3}{T_3} \ldots \right) \leq 1$$

t_i = operating time in a creep range; T_i = time to rupture

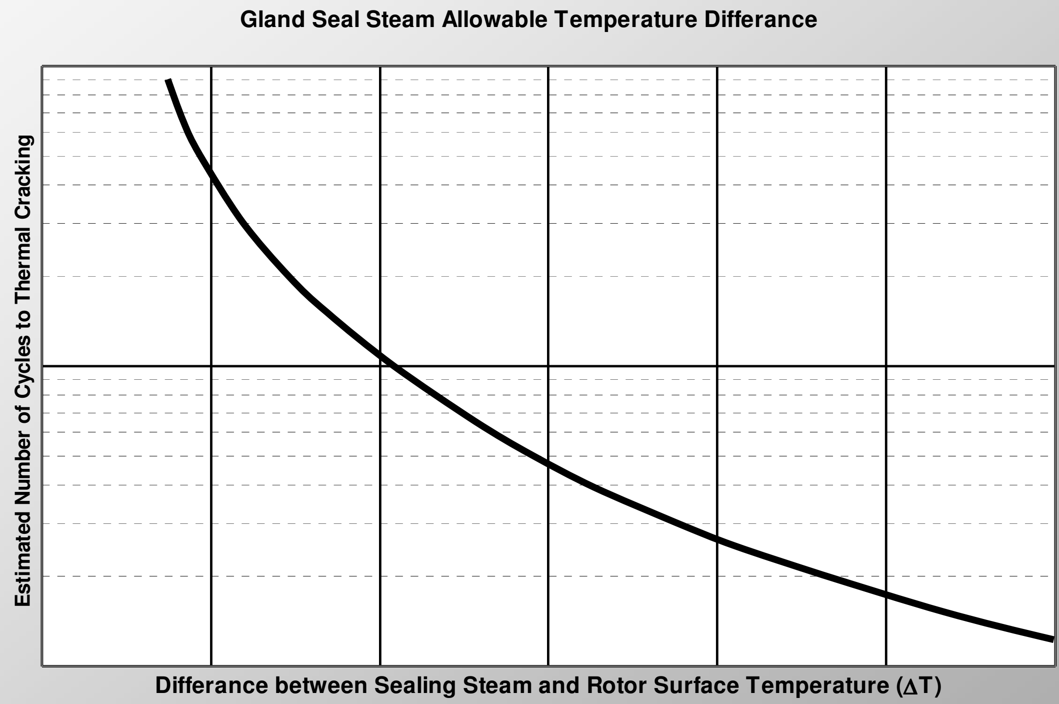
  - **Remaining fatigue life is estimated using Palmgren-Miner's rule:**

$$D_n = \sum \left(\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} \ldots \right) \leq 1$$

n_i = number of cycles in a strain range; N_i = cycles to crack initiation

Thermal Cracking

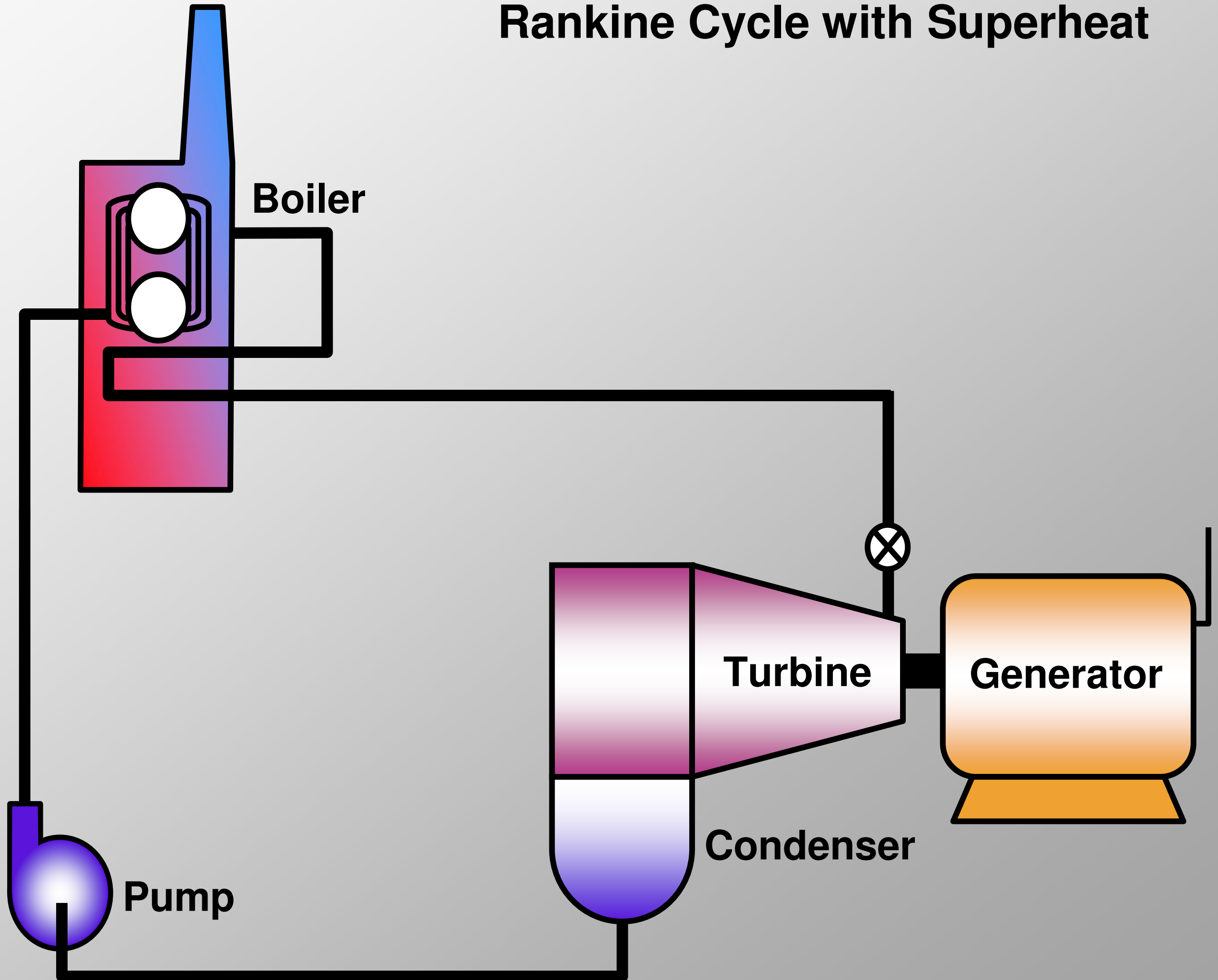
- **Thermal cracking occurs due to the difference between steam and rotor temperatures.**



$$Percentage\ of\ life\ used = \sum \frac{Number\ of\ occurances\ at\ \Delta T}{Estimated\ cycles\ to\ cracking\ at\ \Delta T}\ X\ 100$$

Repowering Options

Rankine Cycle with Superheat



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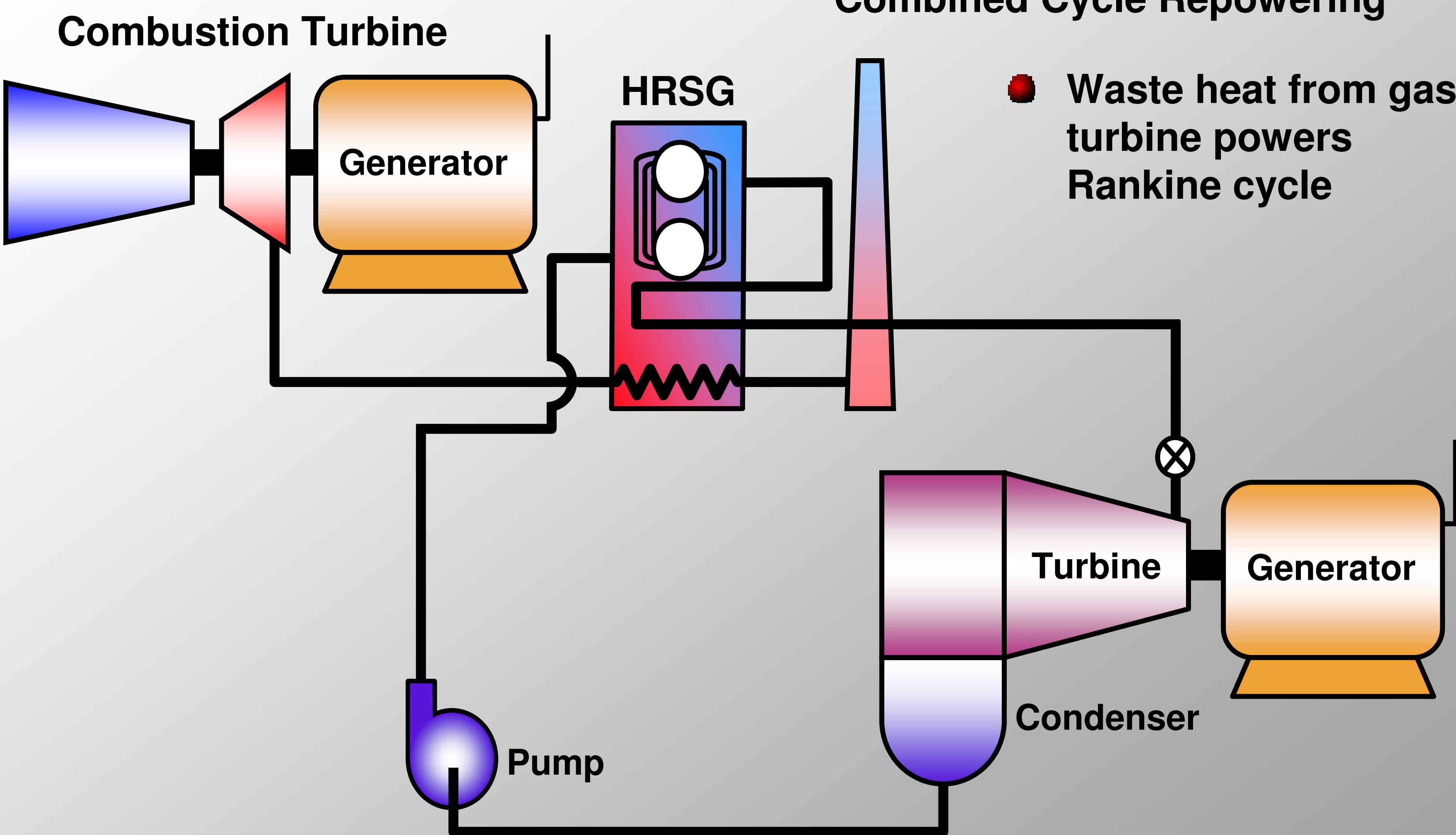
Repowering Options

Combined Cycle Repowering

- Waste heat from gas turbine powers Rankine cycle



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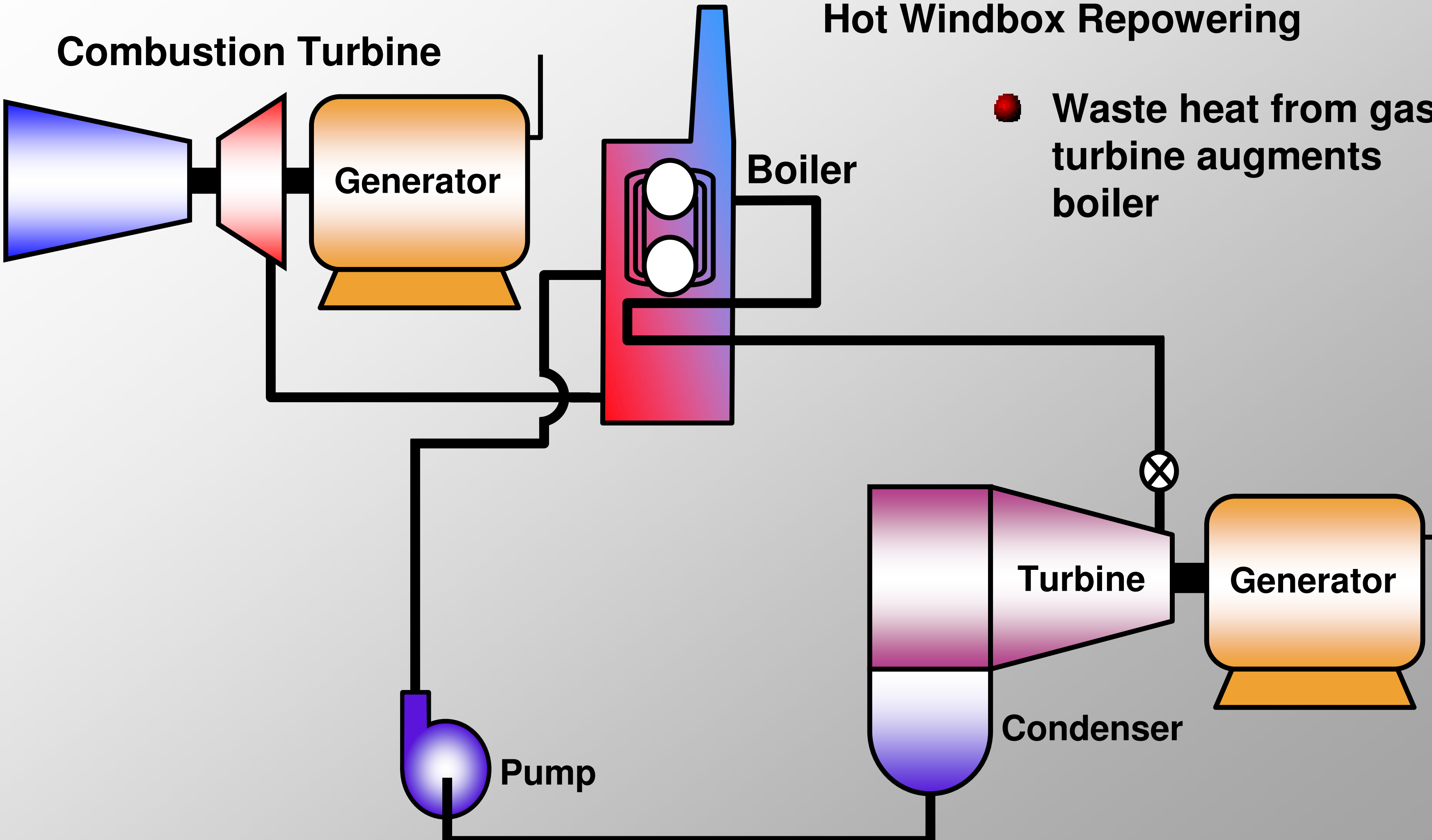
Repowering Options

Hot Windbox Repowering

- Waste heat from gas turbine augments boiler



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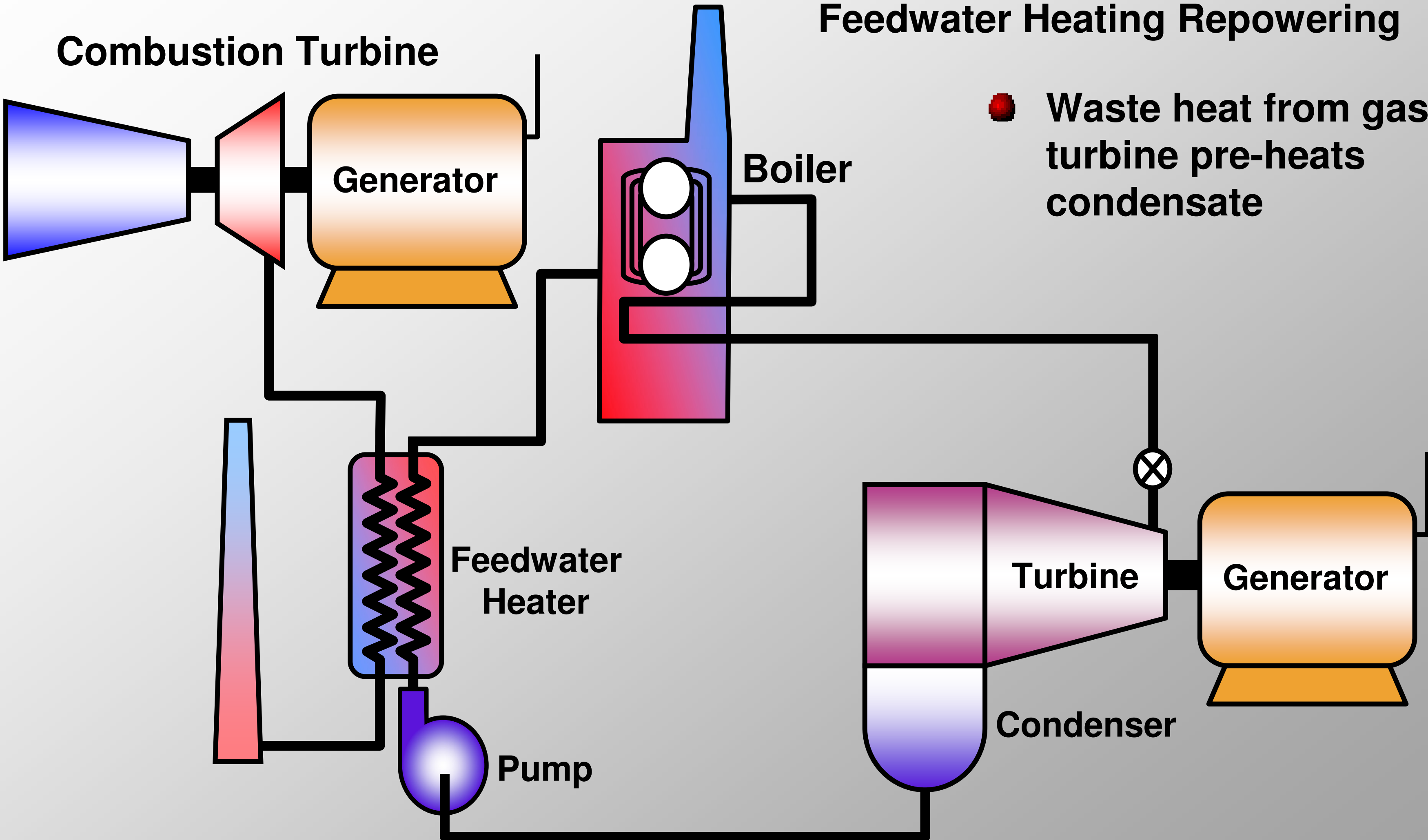
Repowering Options

Feedwater Heating Repowering

- Waste heat from gas turbine pre-heats condensate



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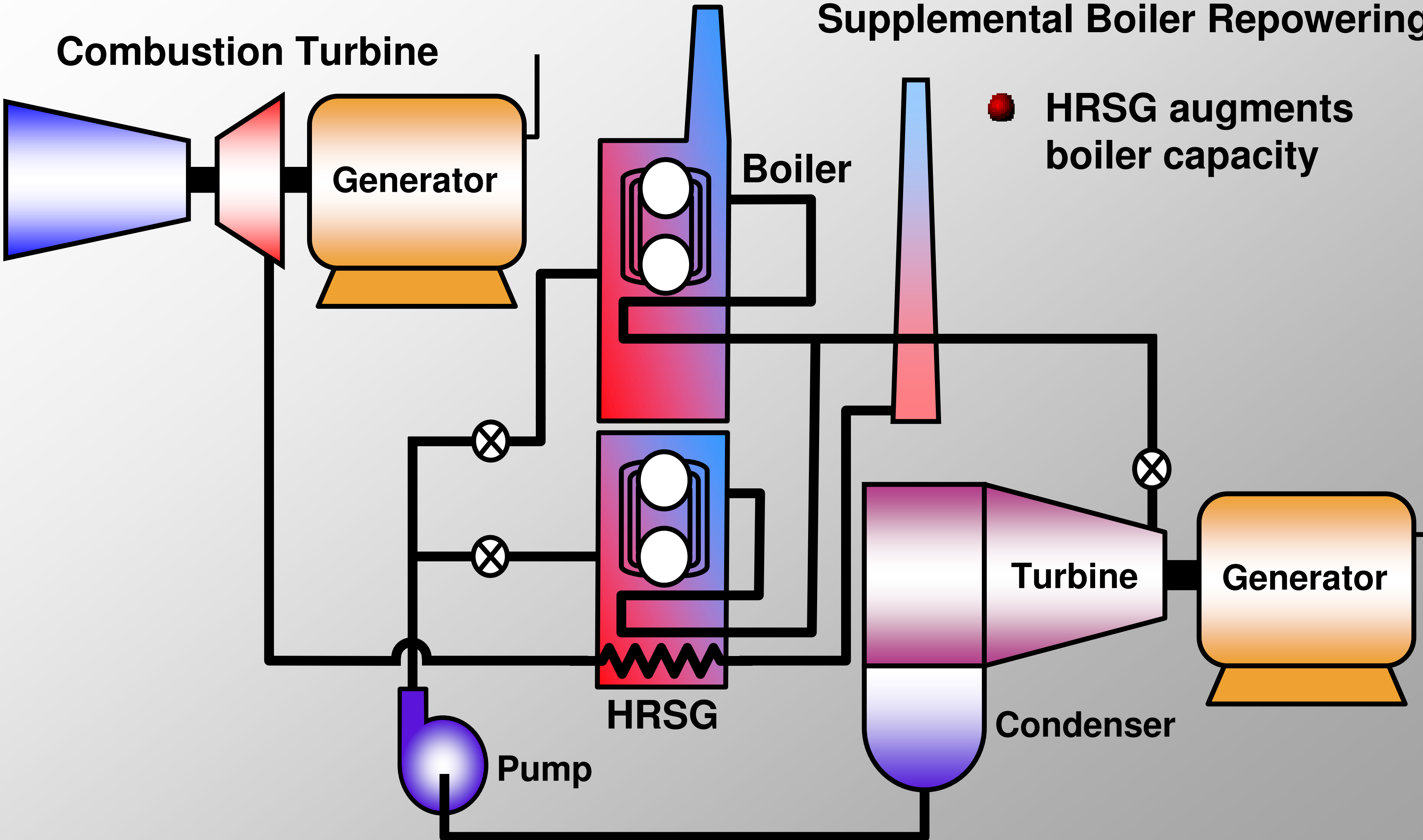
Repowering Options

Supplemental Boiler Repowering

- HRSG augments boiler capacity

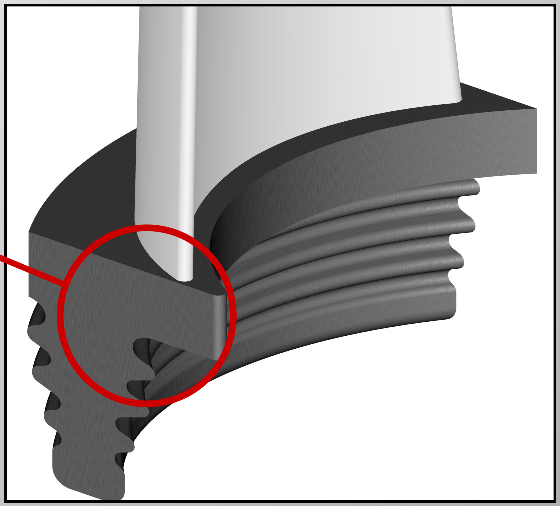


Steam Turbine Repowering Considerations

- **Determine new loading conditions, evaluate for:**
  - Increased steam flow
  - Change in pressure drop
  - Change in temperature in steam path
  - Change in moisture content
- **Evaluate impact on casing**
  - Nozzle chamber
  - Steam chest
  - Blade rings
  - Bolting
- **Evaluate impact on rotor**
  - Operating temperature
  - Creep
  - Thermal cycling
  - Review differential expansions
  - Review thrust bearing load
  - Check couplings

Steam Turbine Repowering Considerations

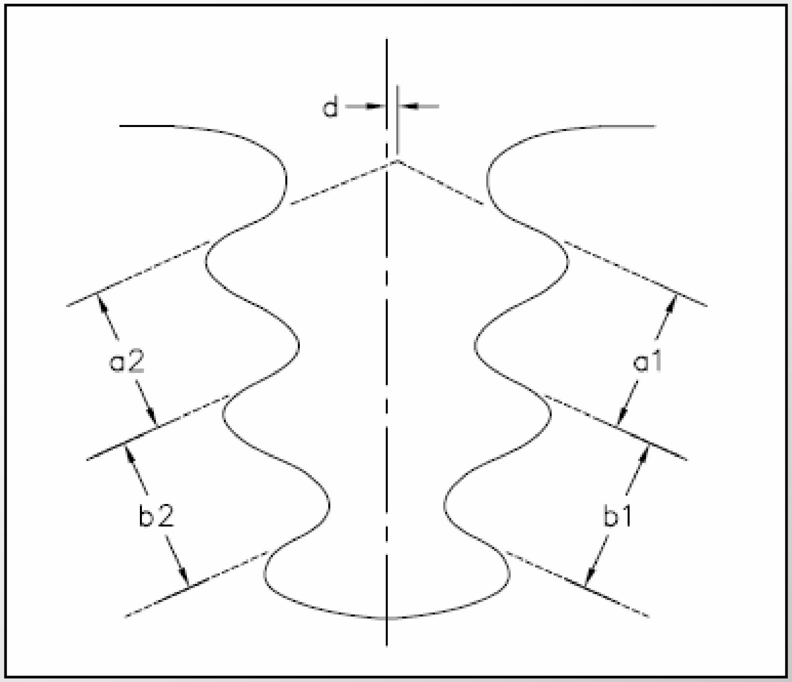
- Determine acceptability of steam path components
  - Rotating blades
  - Load cycling capability of LSB
  - Stationary vanes
  - Seals



- Design steam turbine drains/cap extractions
  - Capped extractions must be designed to minimize likelihood of water induction as outlined by the ASME TDP-1.
- Evaluate impact on valves
- Check crossover pipe pressure & temperature
- Check gland seal system
- Review start up procedures
- Calculate the efficiency of the modified steam turbine

Attachment Considerations When Re-Blading

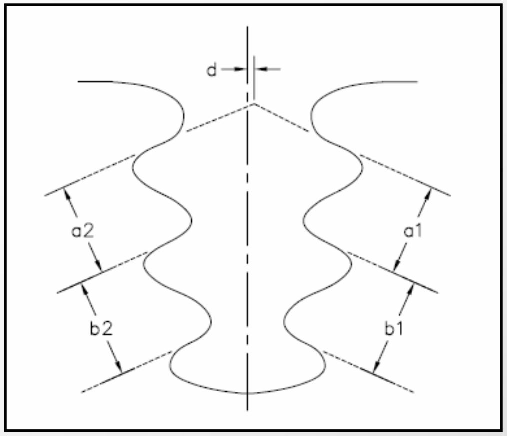
- **Re-blading an existing disc can present certain challenges…**

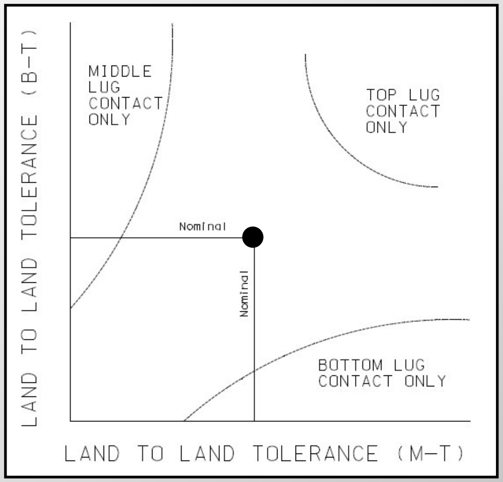


- **Root & Groove are similar - some controlled clearances are necessary**
- **Symmetric load improves stress distribution**
- **Design assumes a certain load distribution between different lugs (usually top lug must contact)**

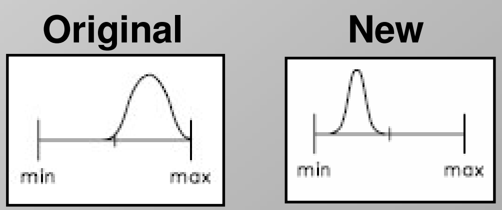
Attachment Considerations When Re-Blading

- **Re-blading an existing disc can present certain challenges…**





- **Symmetry and lug to lug tolerance affect peak stress. Can be result from root or groove tolerances**
- **Manufacturing process results in some deviations from nominal geometry**
- **A replacement blade fits the same groove but is made with new manufacturing capability, as shown:**



- **In spite of improved manufacturing capability, an asymmetric root to groove contact or non-optimal lug load distribution may result.**

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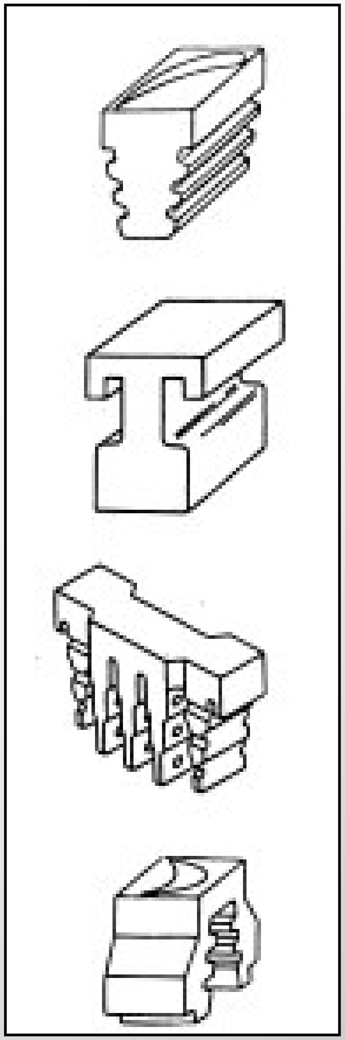
Typical Blade Attachments



- **Fir Type Side Entry Root (straight, skewed or curved); high load carrying capability, simple blade replacement, but...**
  - **Bottom of groove forms stress concentration**
  - **Sensitive to tolerances when used with mid size blades**
  - **Expensive to manufacture**
  - **Source of leakage, important in HP turbine**
- **Tee Root (recessed, straddle or double tee); grooves cut on a lathe, no tangential stress risers, but…**
  - **Complex closing blade geometry**
  - **Proportionally high stress concentration at root and groove fillets**
  - **Single tee limited in load carrying capability, double tee complex to manufacture**
- **Finger Dovetail (flat or nested); high load carrying capability, minimal radial stress risers caused by root to airfoil mismatch, but…**
  - **Complex to manufacture**
  - **Highly stressed pins susceptible to SCC**
- **Fir Type Straddle Tangential Entry; rotor machined on a lathe, no tangential stress risers, but…**
  - **Complex notch blade/block assembly**
  - **Limited load carrying capability**

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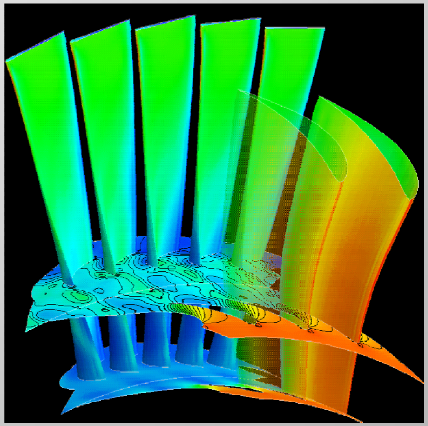
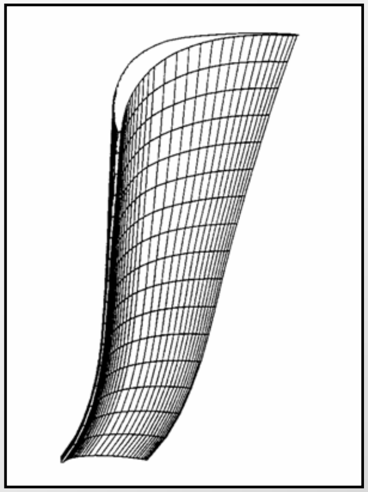
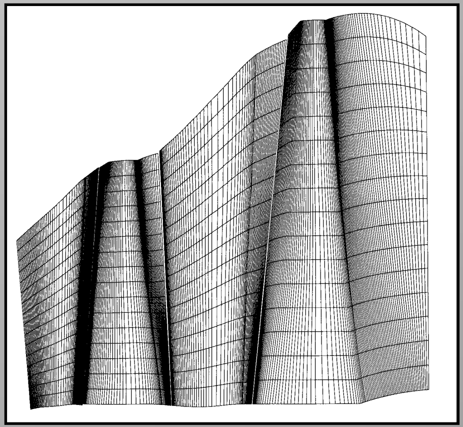
Technology Improvements

- **Improved design methods result in more sophisticated airfoil designs and increased LP efficiency through reduced profile, secondary flow, leakage, and shock losses.**





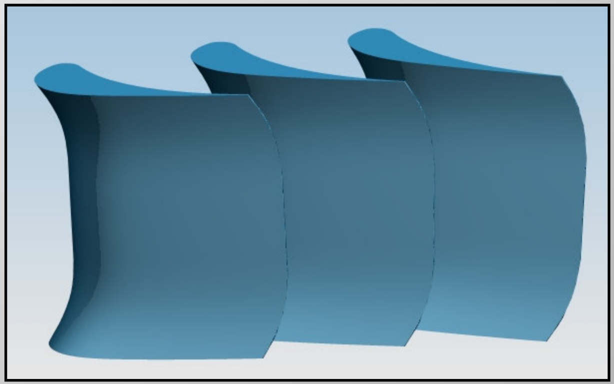
- **Bowed vane design increases stage reaction and reduces the risk of back flow at the hub of the last LP stage.**

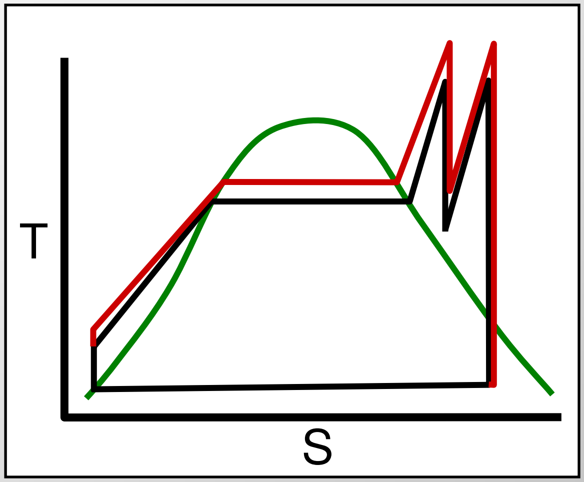


- **Longer last row blades reduce turbine leaving losses which are proportional to the square of blade exit velocity.**

Technology Improvements

- **Bowed airfoils improve turbine efficiency. Largest benefit for low aspect ratio airfoils (e.g. HP turbine).**

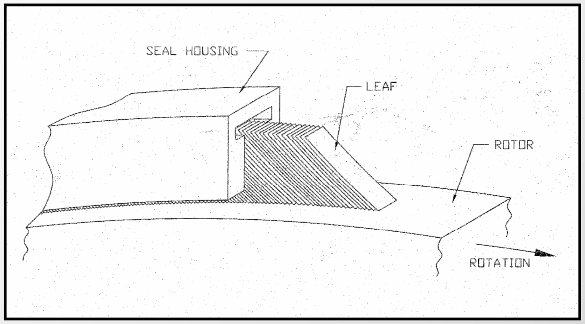




- **Improved materials allow increased inlet temperature and pressure which results in more available energy.**

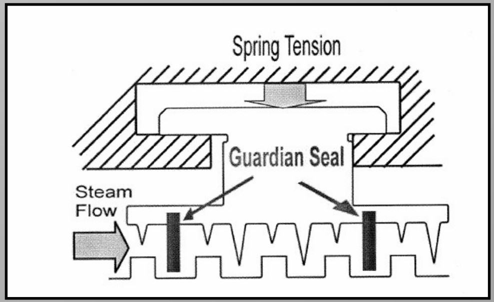
Technology Improvements - Seals

- **Retractable® and Active Clearance Control seals use springs to open the seal clearance at low power/start up, pressure forces close the seal clearances at higher power levels. (Photo courtesy of Siemens)**

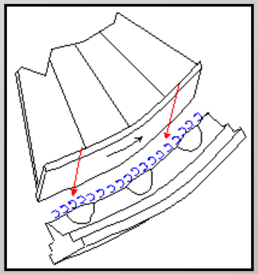


- **Leaf seals are comprised of a series of leaned thin metal plates nested together. The windage effect lifts the leaves preventing contact, but maintaining a negligibly small clearance. Used in the gland area.**

- **Guardian® seals use low friction seal elements at the beginning and end of each segment. These are set to tighter clearances and act as bumpers to prevent rub damage to the rest of the seal. (Figure courtesy of Hitachi)**



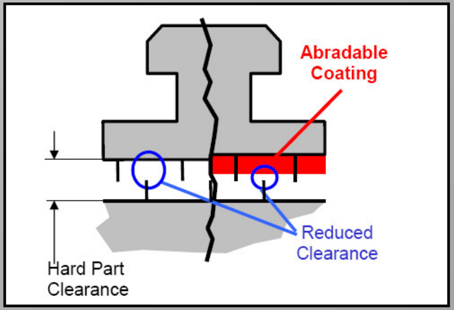
Technology Improvements - Seals



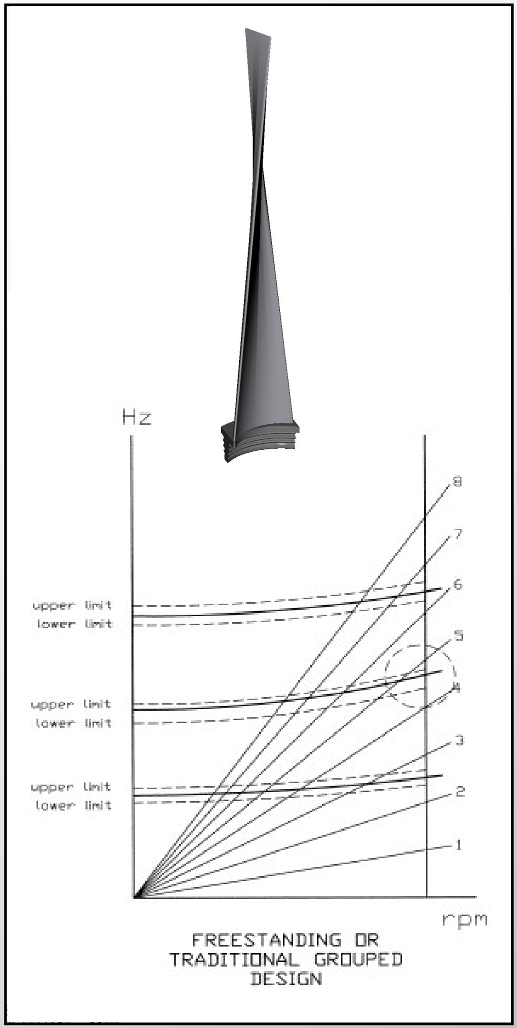
- Vortex Shedder seal leg features a dimpled seal inner surface. The interrupted sealing surface causes series of vortices which inhibit leakage flow. (Figure courtesy of Hitachi)

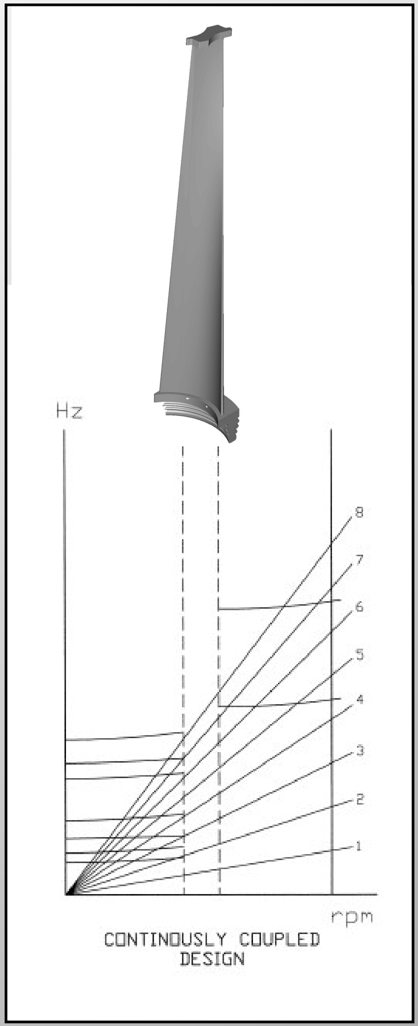
- Brush seals use a brush type seal segment installed between remaining seal strips. The bristles are installed slanted and adjust to a radial orientation with increasing load, thus reducing clearance. (Photo courtesy of Siemens)

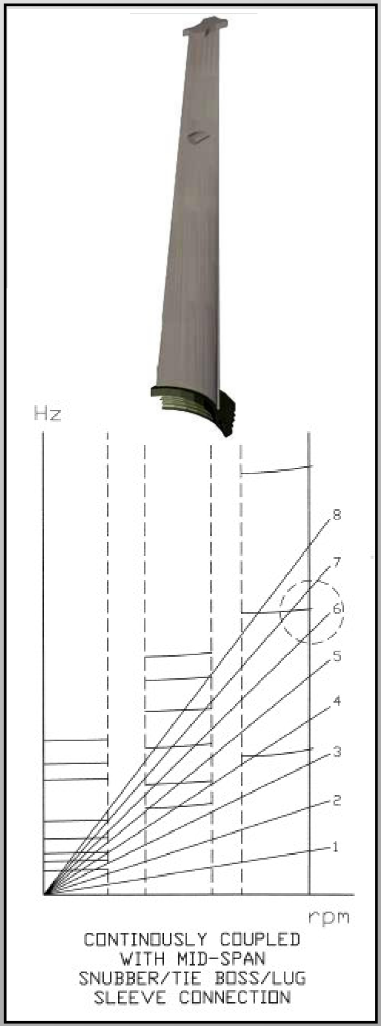
- Seal with Abradable Coating uses a soft coating sprayed between standard seal strips. The coating reduces clearance. During rub, rotor seals, made of harder material, are not damaged. (Figure courtesy of Siemens)



Campbell Diagrams







These diagrams are conceptual and do not represent any particular design.

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Campbell Diagrams

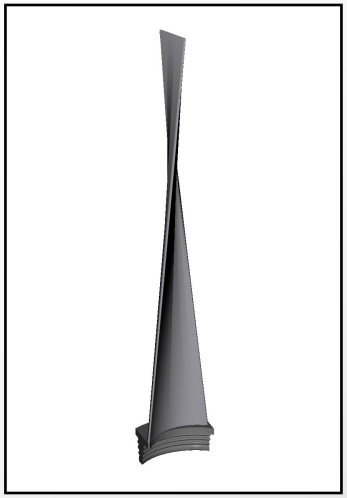
Freestanding Blades or Traditionally Grouped Construction

- Linear system
  - Rotating frequency = Stationary frequency + Rotating rise
  - Rotating rise can be calculated
  - Stationary frequency limits, needed for QA inspection, can be determined from prototype rotating test

Continuously Coupled Blades

- Non-linear system
  - Frequencies in the “free standing” speed range are different than frequencies when the shrouds and/or snubbers/tie bosses are locked
    - An intermediate condition may exist if both snubber/tie boss and Z-lock shroud are used
  - Stationary frequency limits cannot be directly correlated with full speed frequencies
    - Transition ranges result when snubbers/tie bosses and/or shrouds initiate contact
    - Frequencies depend on contact forces

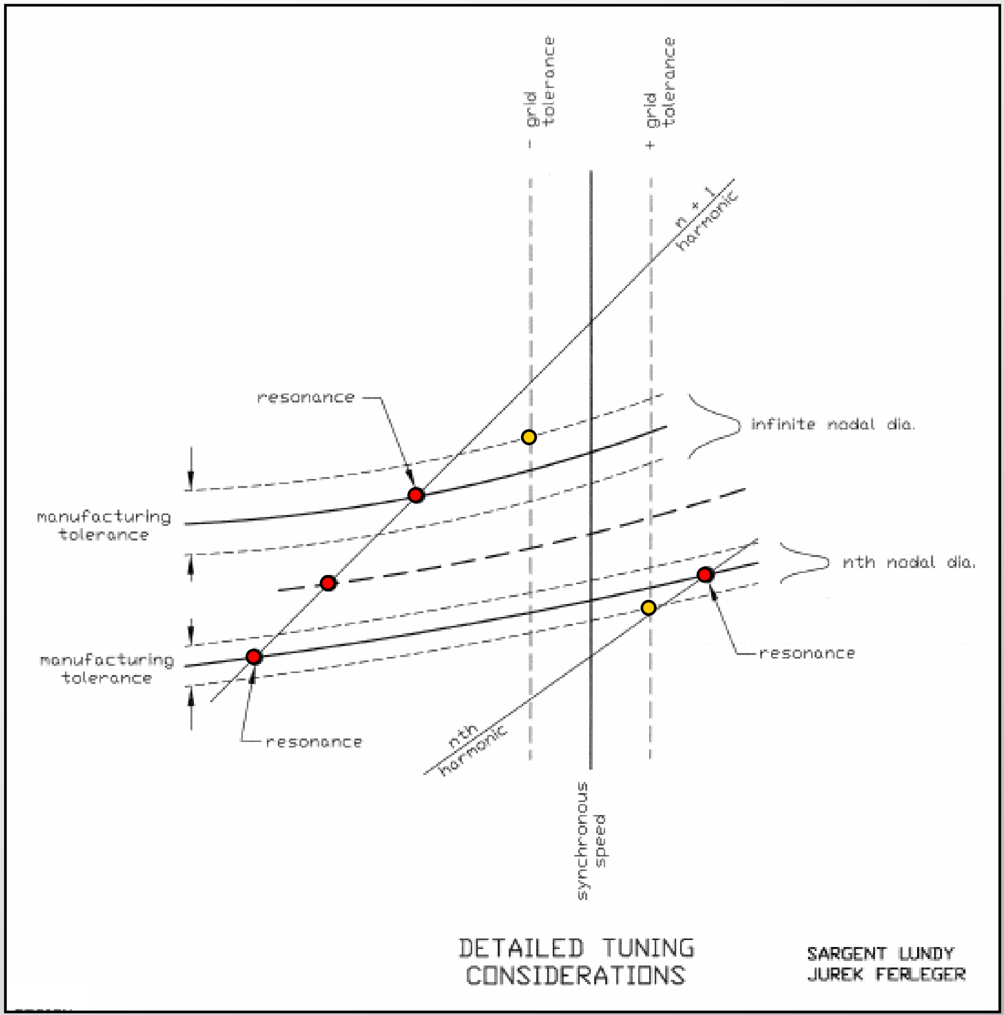
Campbell Diagrams



- Freestanding Blades; developed in 1960s, dynamic behavior can be predicted with simple analytical methods, but…
  - Blades are very wide at the base, increasing rotor span and weight
  - More susceptible to non-synchronous excitation
  - Increased tip leakage

- Continuously Coupled Blades; disc type vibratory pattern results in stiffer structure allowing thinner airfoils which improve performance, reduced bearing span and rotor weight, but…
  - Complex dynamic behavior makes predicting the effects of tolerances on wheel frequency more difficult
  - Individual blade replacement may be difficult
  - Wear at contact areas may be a concern
  - Mid-span snubber/tie boss affects performance

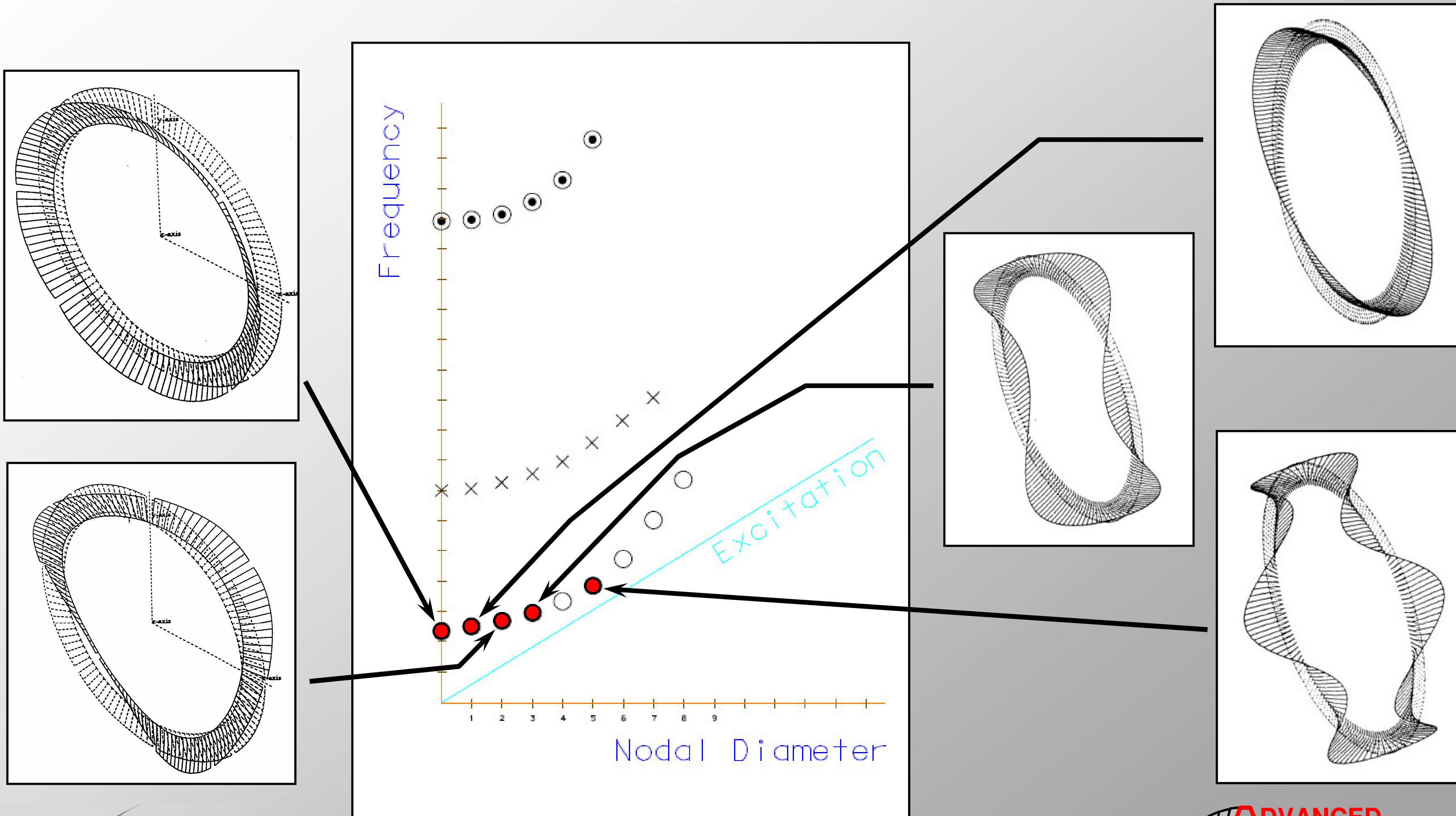
Campbell Diagram - Enlarged



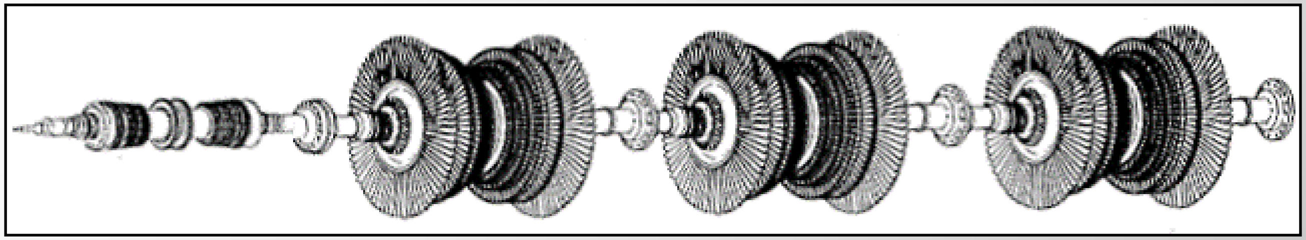
- Family of modes must be considered
- Grid frequency tolerance must be considered
- Manufacturing tolerance must be considered
- On a prototype design, calculation uncertainty must be considered

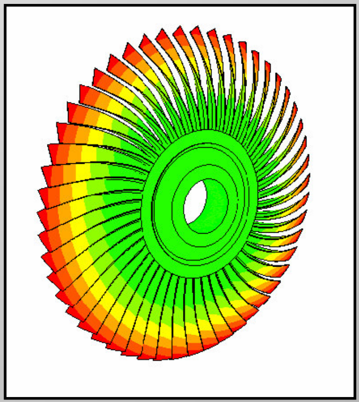
This diagram is conceptual and does not represent any particular design.

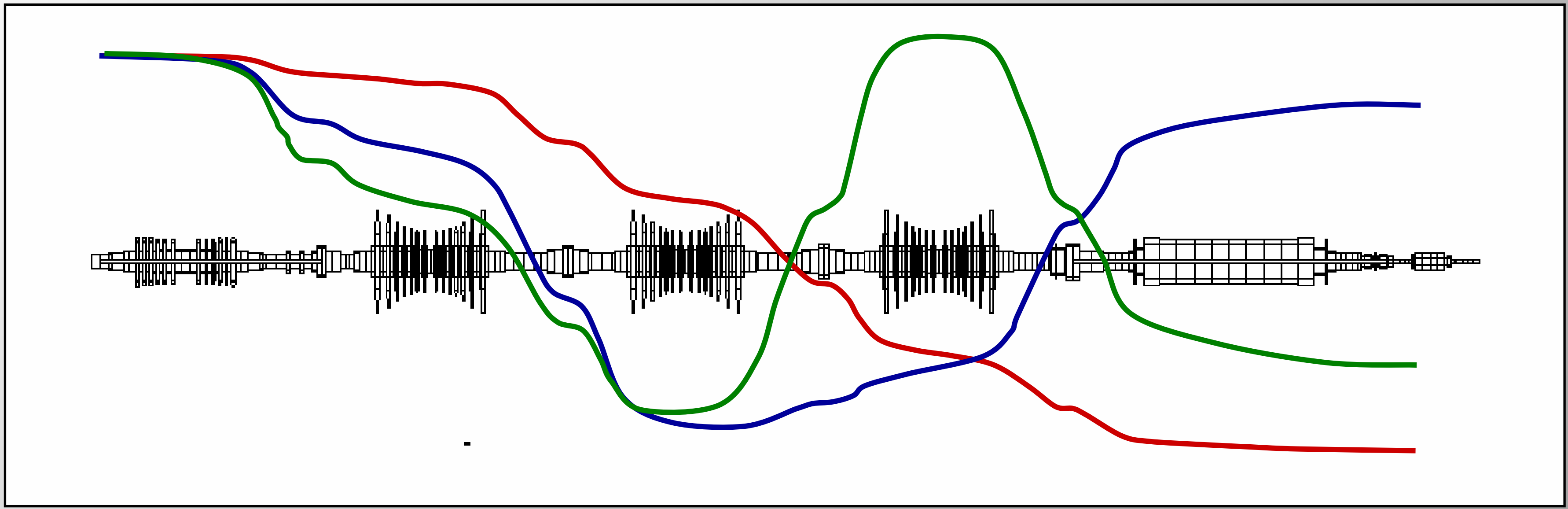
Interference Diagram



Torsional Vibrations







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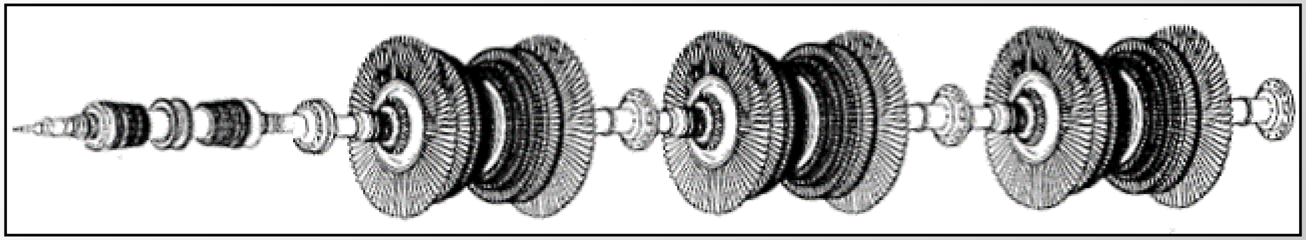
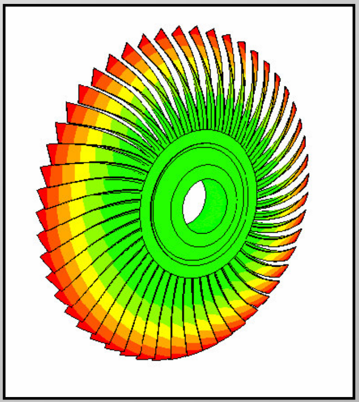
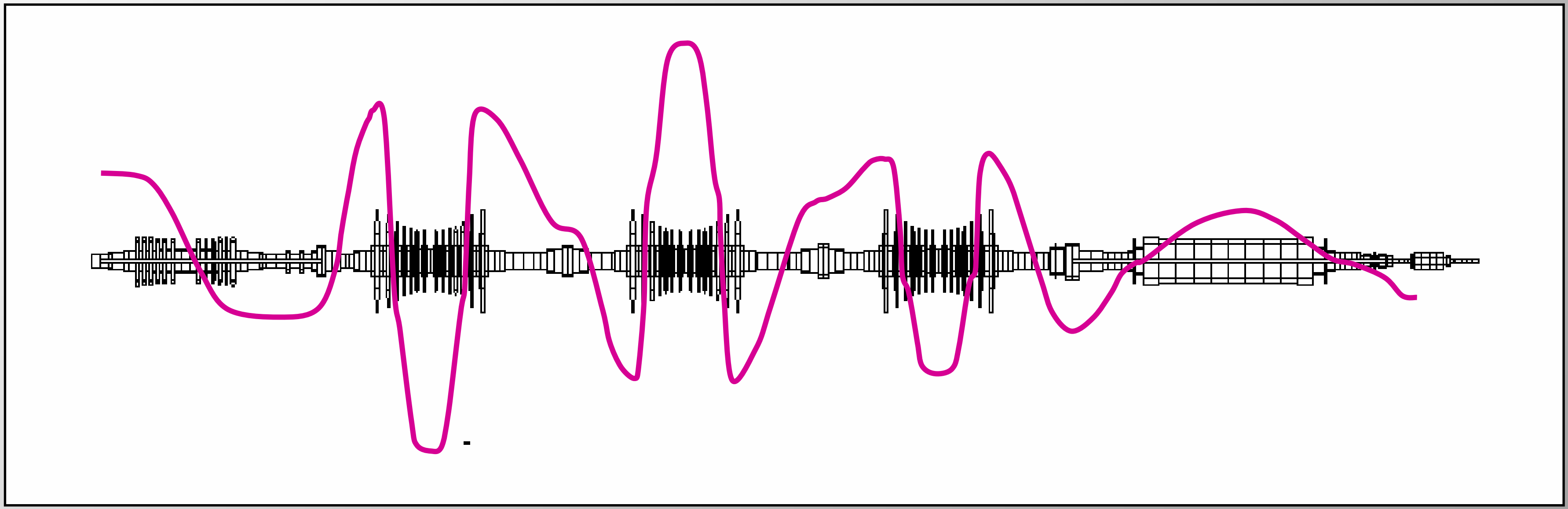
Torsional Vibrations







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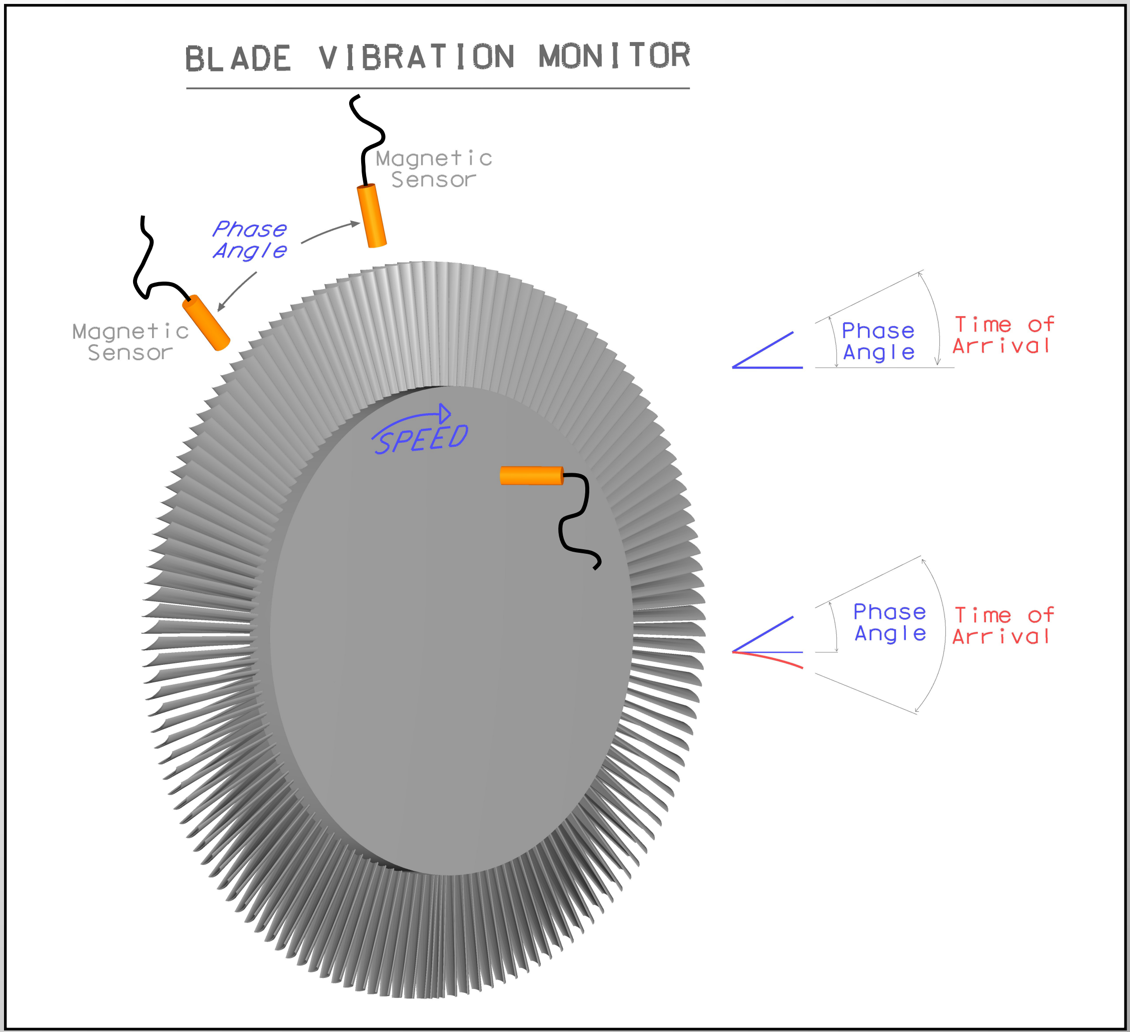
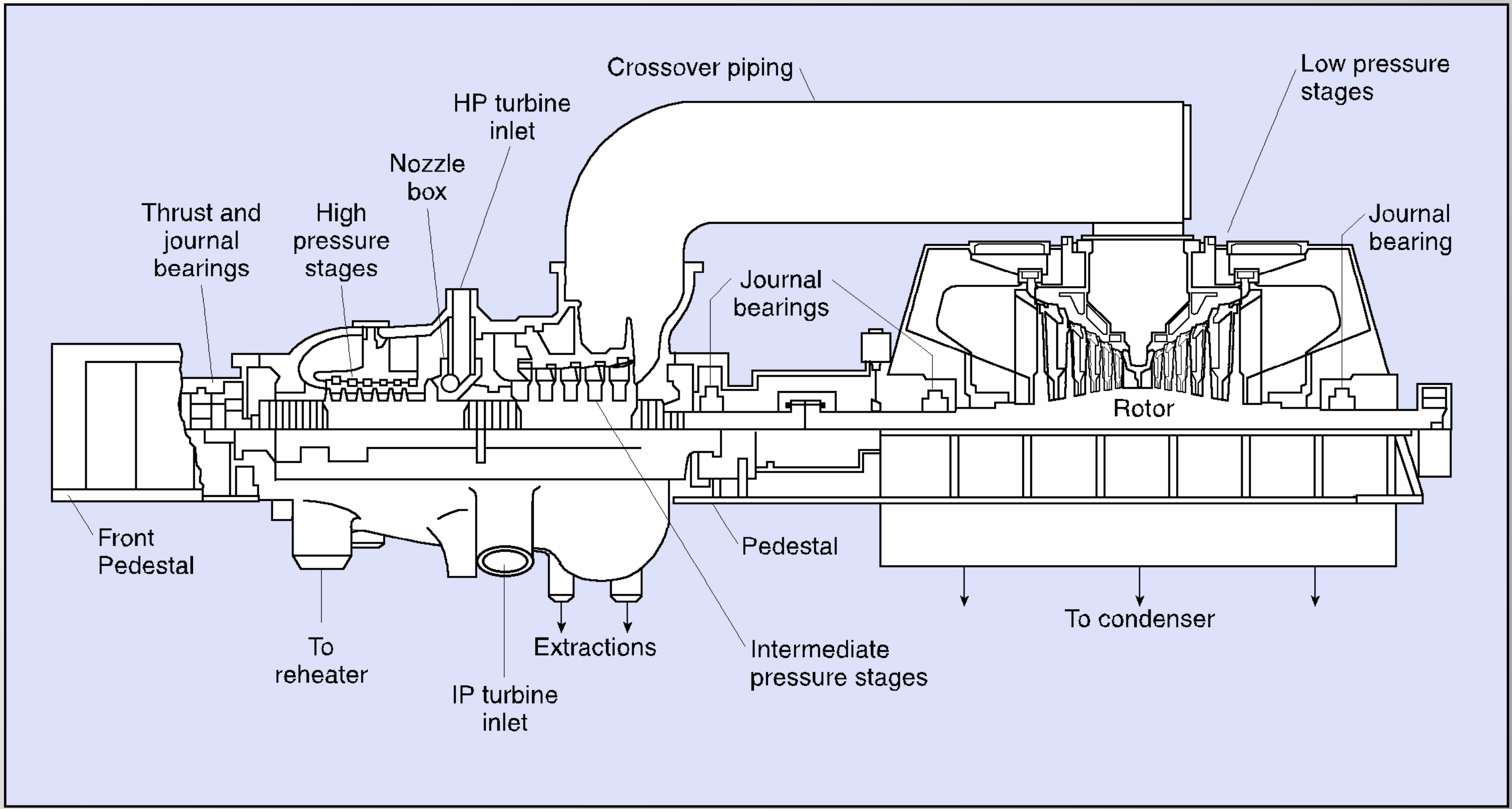
Blade Vibration Monitor



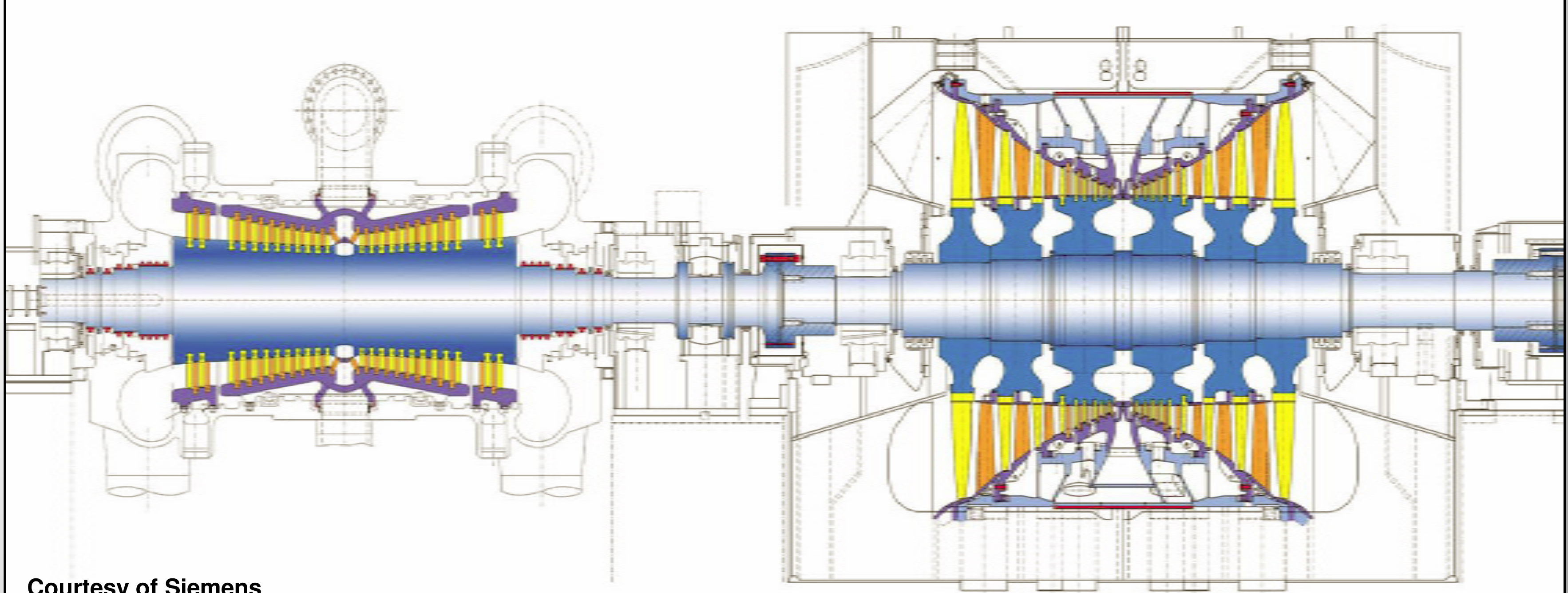
Modern Fossil Turbine

- **Condensing, Reheat, Regenerative Heating**



Modern Nuclear Turbine

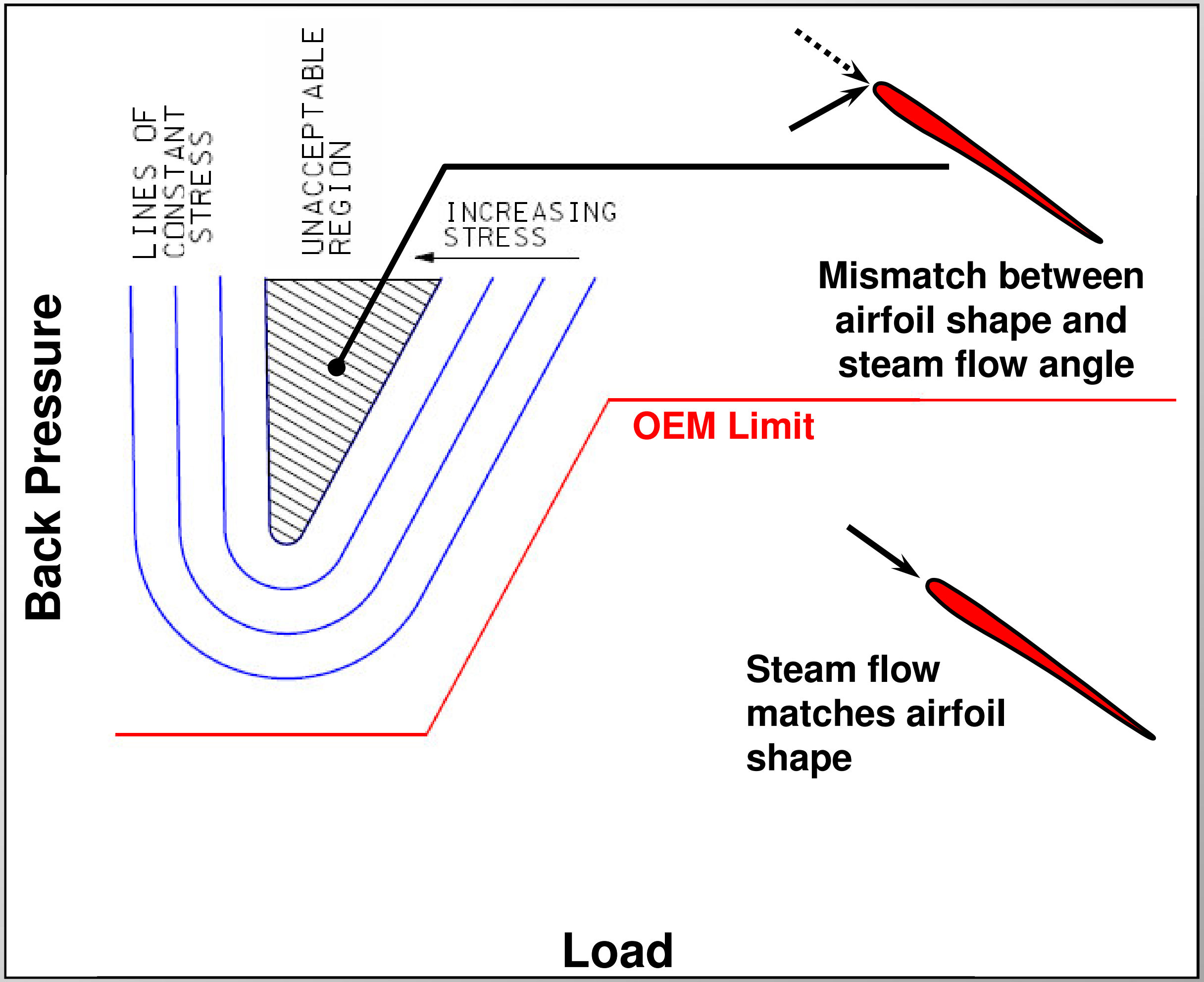
- Dry and saturated HP inlet, superheated LP inlet.



Courtesy of Siemens

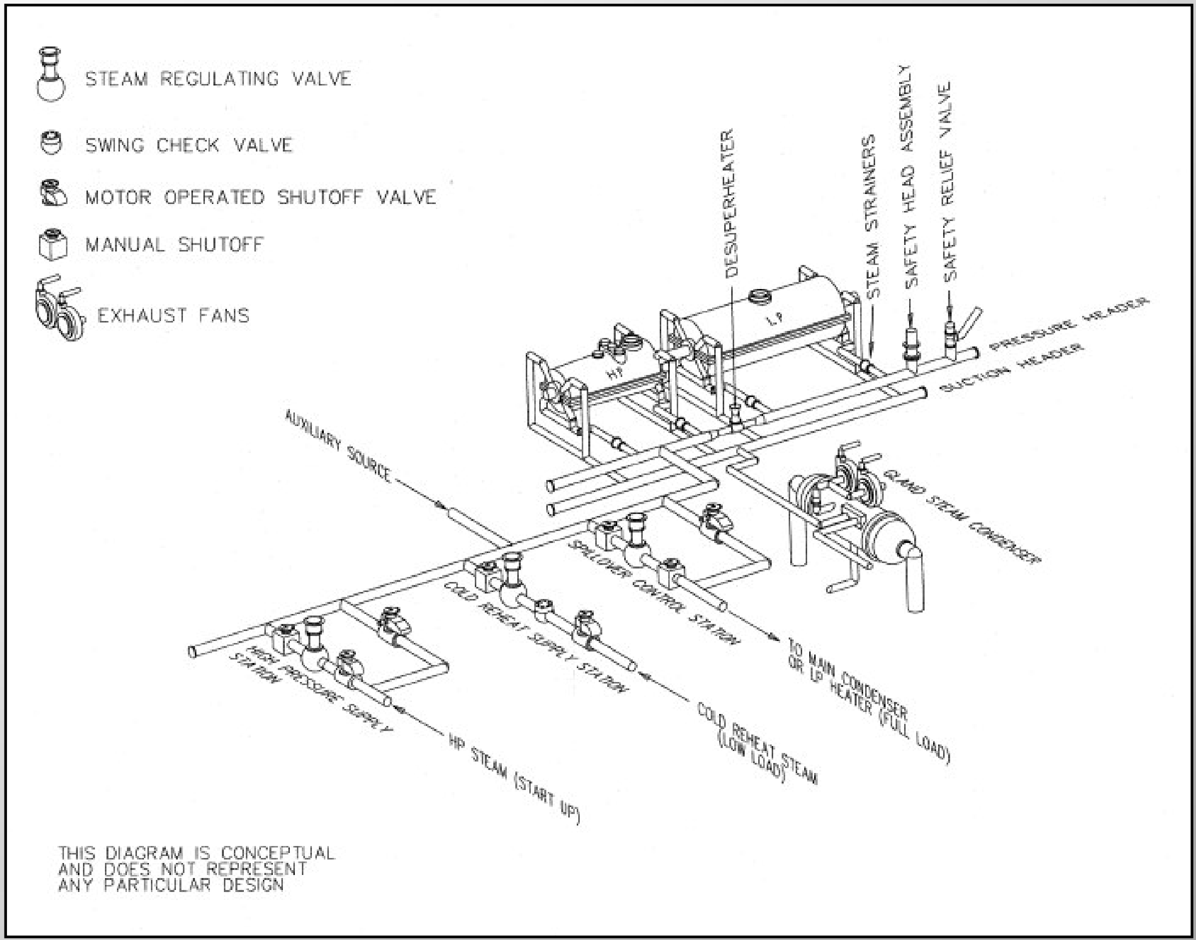
Back Pressure Curve

- Flutter is caused by aero-elastic excitation of the blade.



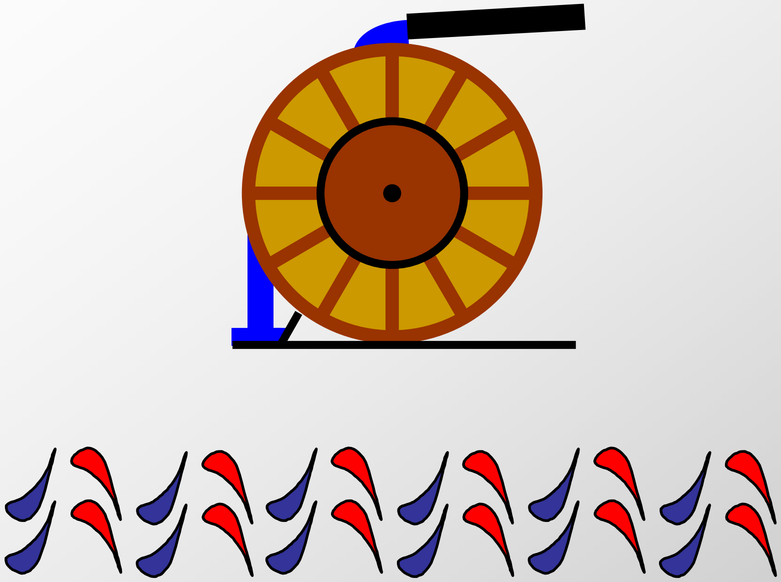
Gland Seal System

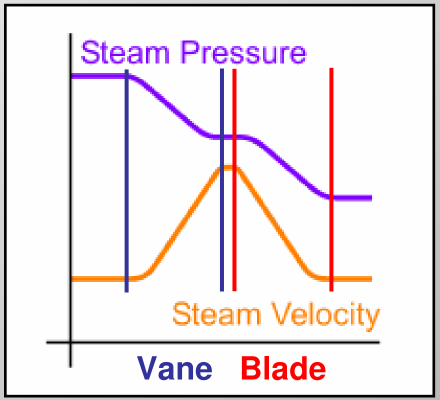
- **Gland seal systems recycle leakage flow and seal the flowpath. When modernizing the capability of the gland seal system must be considered.**



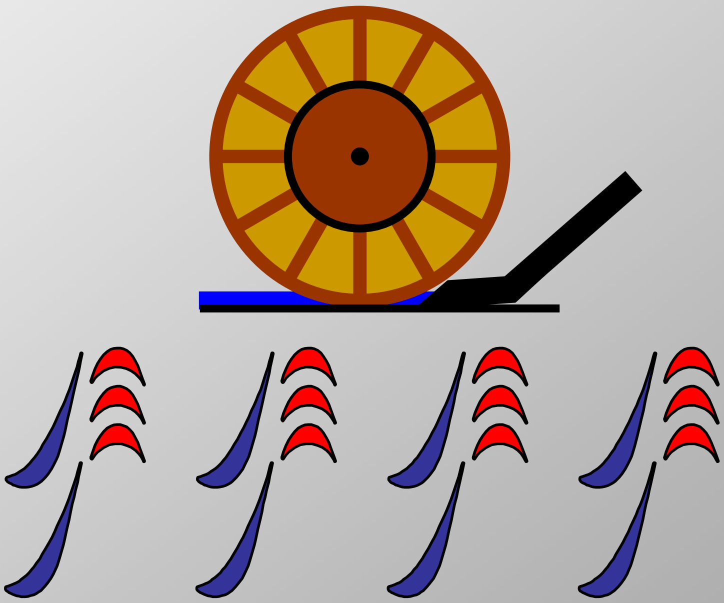
Reaction vs. Impulse

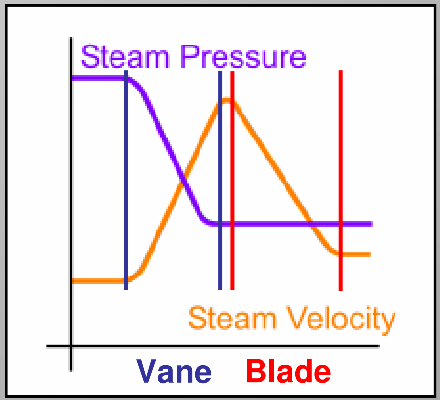
Reaction





Impulse





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Reaction vs. Impulse

Reaction

- Stator and rotor share the conversion of pressure to velocity
- Requires more stages
- Higher aerodynamic efficiency
- Efficiency is dependent on effective rotor sealing
- Efficiency less dependent on diaphragm sealing
- Wider efficiency band
- Not recommended for partial admission operation
- No steam balance holes

Impulse

- Stator accelerates fluid, rotor redirects fluid
- High stage work, fewer stages
- Moderate aerodynamic efficiency
- Efficiency is insensitive to rotor sealing
- Efficiency more sensitive to diaphragm sealing
- Moderate efficiency band
- Partial admission operation
- Steam balance holes are typically used

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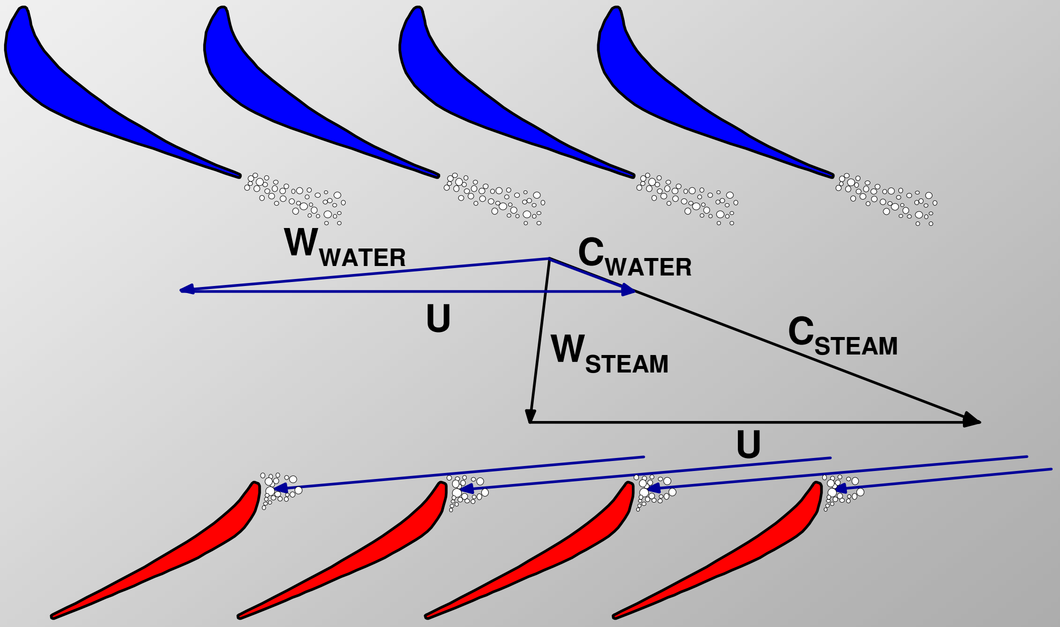
Erosion and Moisture Removal

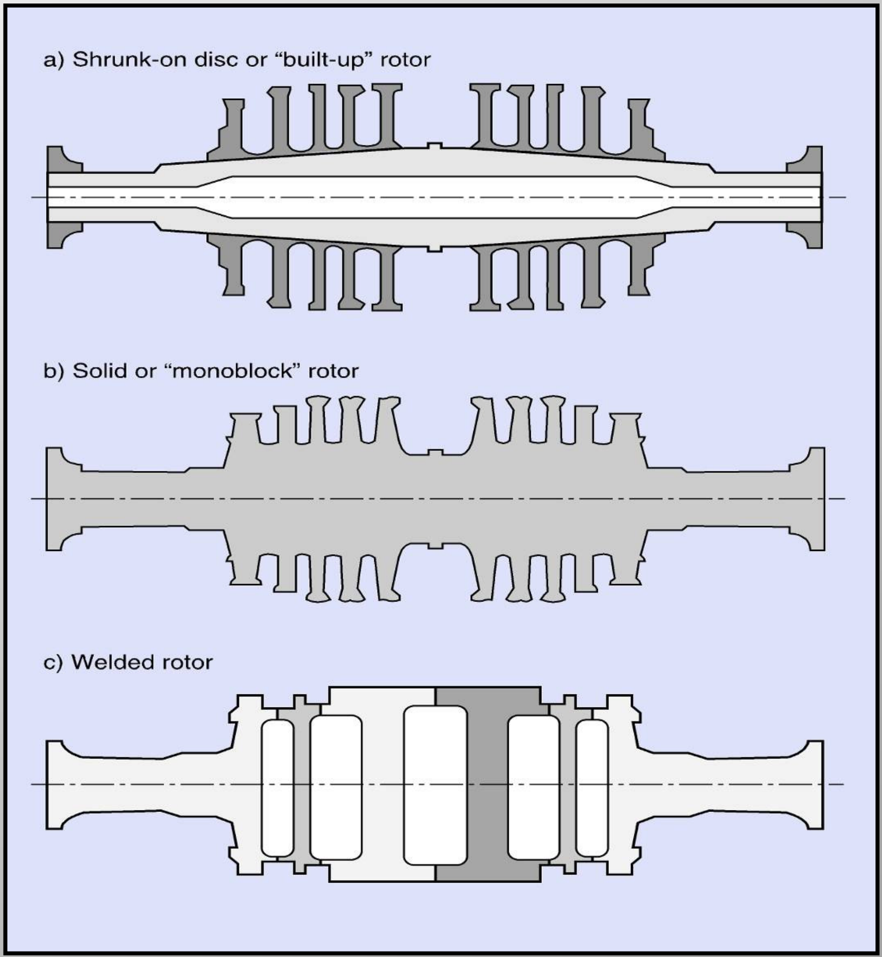
- Erosion is the result of low velocity water droplets leaving the vane trailing edge and impacting the rotor leading edge.
  - Hardened LSB leading edges are required.
- Erosion increases with higher moisture level, wheel speed, and lower pressure.



- Improved moisture removal can reduce erosion damage:
  - Improved moisture traps
  - Hollow vanes
  - Grooved vanes and blades
  - Vane coating (research by EPRI)

Rotor Design

- Older rotors have a bore and require periodic boresonic inspections.
- Shrunk-on discs are susceptible to SCC, but discs can be replaced. Couplings need to be removable.
- Monoblock rotors reduce susceptibility to SCC but require long lead times. Forging quality has improved substantially.
- Welded rotors have low incidence of SCC and can use different materials for different discs optimizing mechanical needs and minimizing SCC.
- To reduce high temperature corrosion in supercritical applications, 9Cr and 12Cr material is welded to conventional CrMoV rotor.



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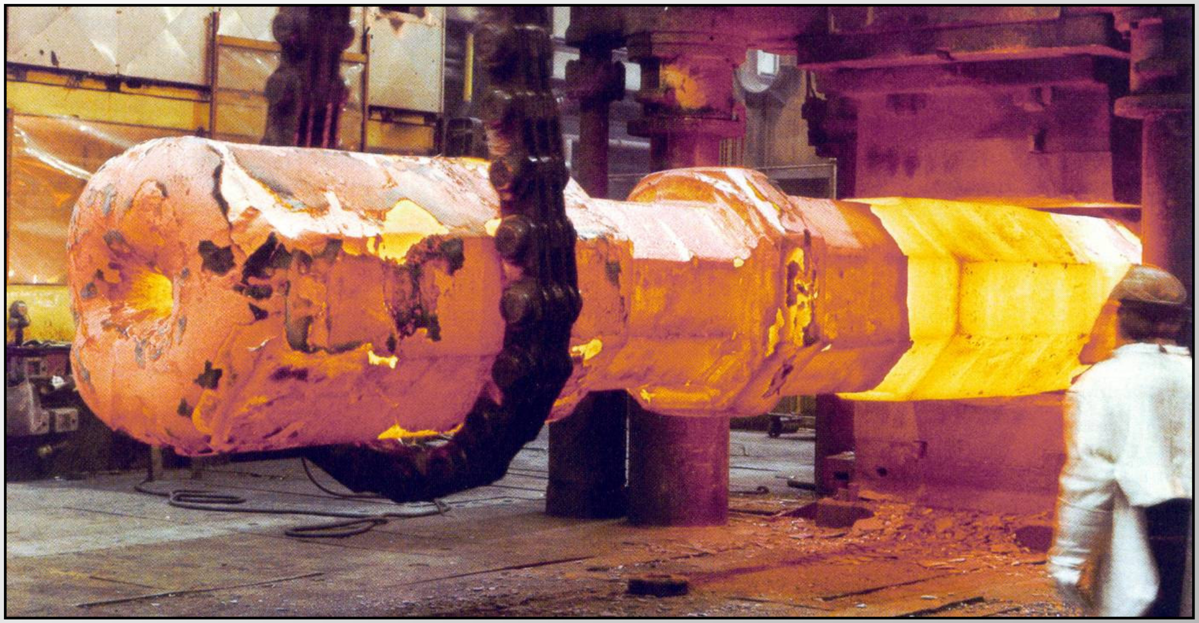
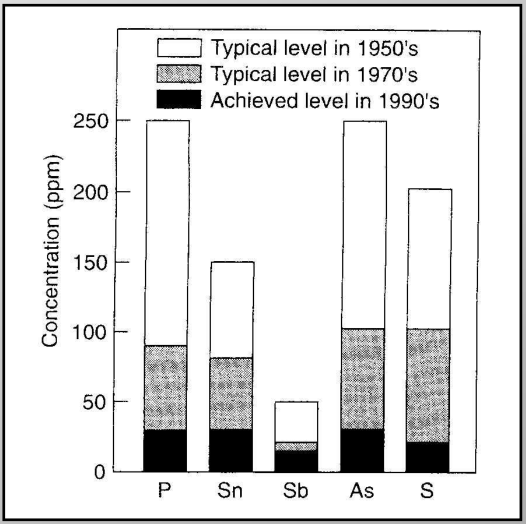
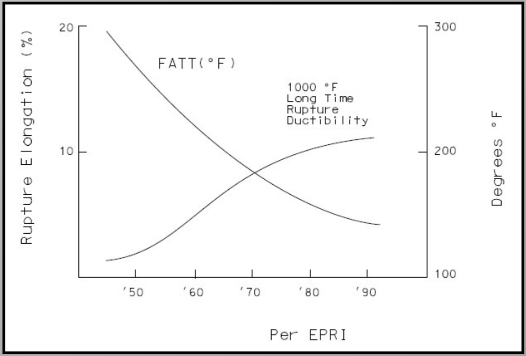
Improvements in Rotor Manufacturing Technologies

- **Steam turbine rotor manufacturing technology has improved substantially…**

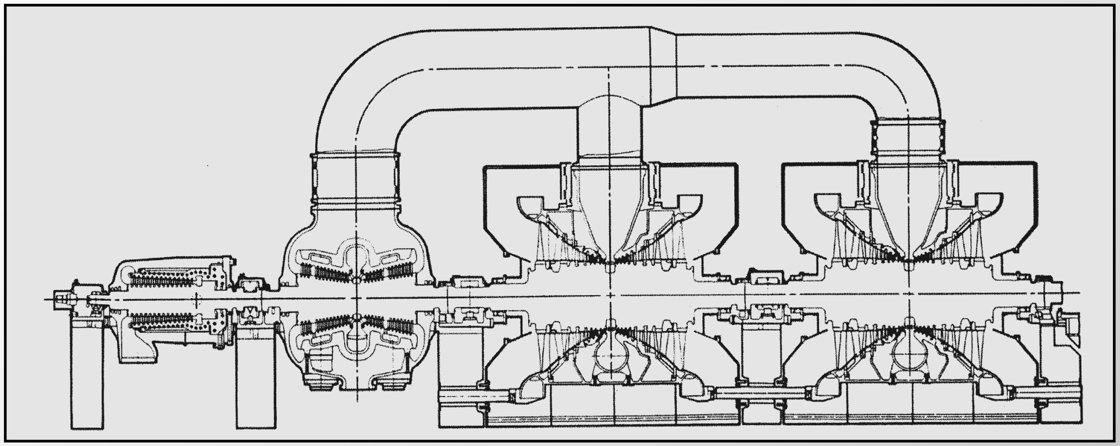






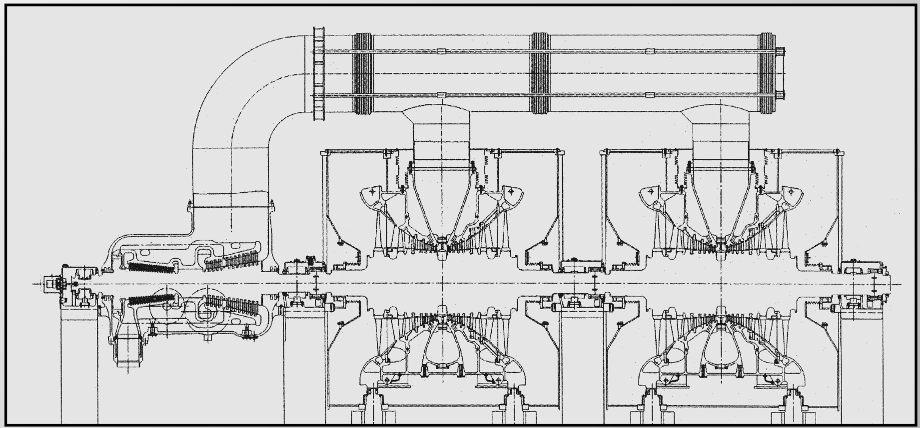
Cylinders and Casings

- **Separate HP and IP casings**



- Reduced potential for thermal stress
- Lower impact on differential expansions
- Preferred on large units
- Can accommodate more stages
- Used for split flow design

- **Combined HP/IP casing**



- Lower cost
- Reduced length
- Lower weight
- Reduced maintenance

Areas to Consider Before Steam Turbine Purchase

- Purchase proven technology. OEM must demonstrate prior experience.
- Develop a detailed spec that outlines all the relevant requirements. Compare and measure different suppliers against those requirements. Review all exceptions.
- Exercise caution when mixing EOMs. If different suppliers are involved, clearly identify responsibilities.
- Give an OEM a number of different conditions, including steam bypass, to evaluate.
- If performance test is planned, define clearly the basis for the test (e.g. ASME PTC 6), be very specific on the test conditions (e.g. based on average annual temperature), obtain all the correction curves from the OEM.
- Verify redundancy in the oil lube system (including loss of AC power). Also, verify redundancy in the auxiliary systems (e.g. two exhausters in the gland steam system, a DC power supply for turning gear, etc).

Areas to Consider Before Steam Turbine Purchase

- Require design review and/or design finalization meeting with OEM.
- Review OEM QA records. Request records of all manufacturing non-conformances and their resolutions.
- Request and review tolerance stack up analyses (e.g. root & groove, area check).
- Evaluate frequency of scheduled maintenance and replacement recommendations. Carefully review maintainability of the proposed design. Request turbine NDE inspection ports where practical (HP/IP inlet).
- Verify sufficient verification testing is planned/has been performed.
- Define the critical dimensions and the location of the interface points. Verify mechanical requirements are met.
- Evaluate impact of the new/modernized unit on balance of plant.
- Verify adequate interface between the turbine control and the plant DCS system.
- To know the drawbacks of the proposed design, contact the competition.

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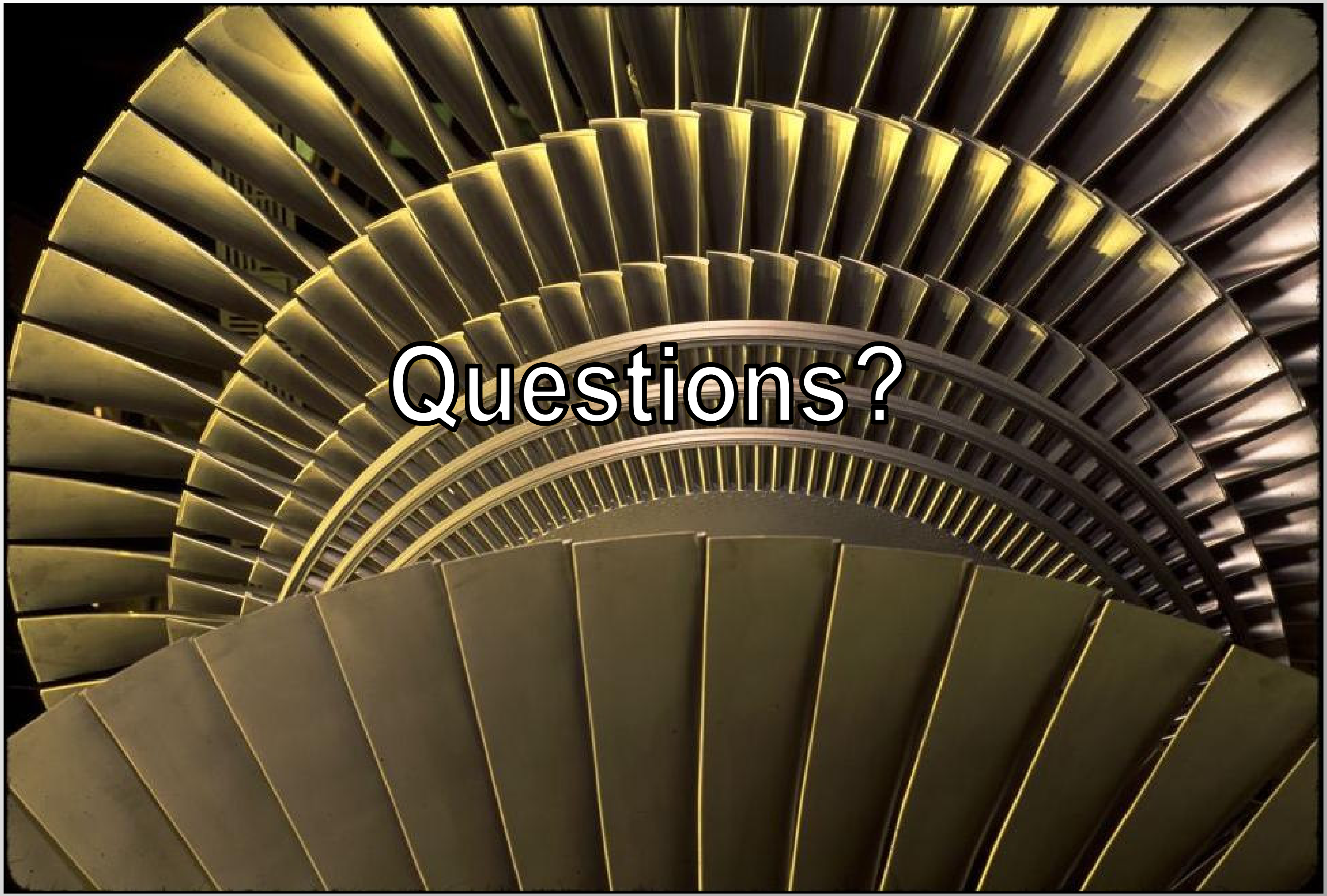

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