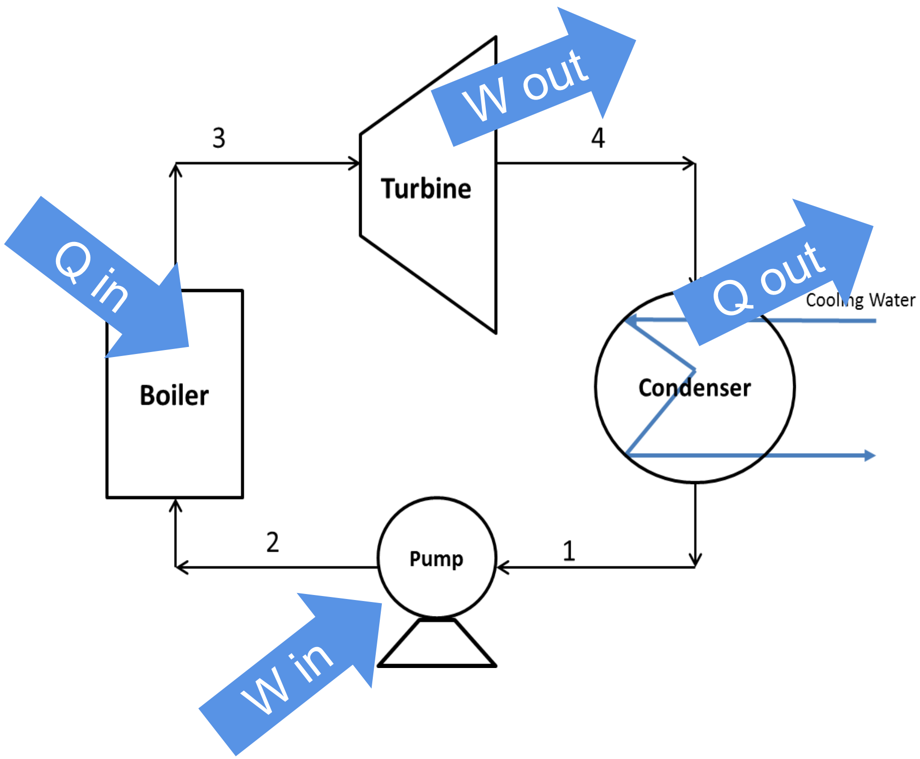
# Steam Turbine Technology

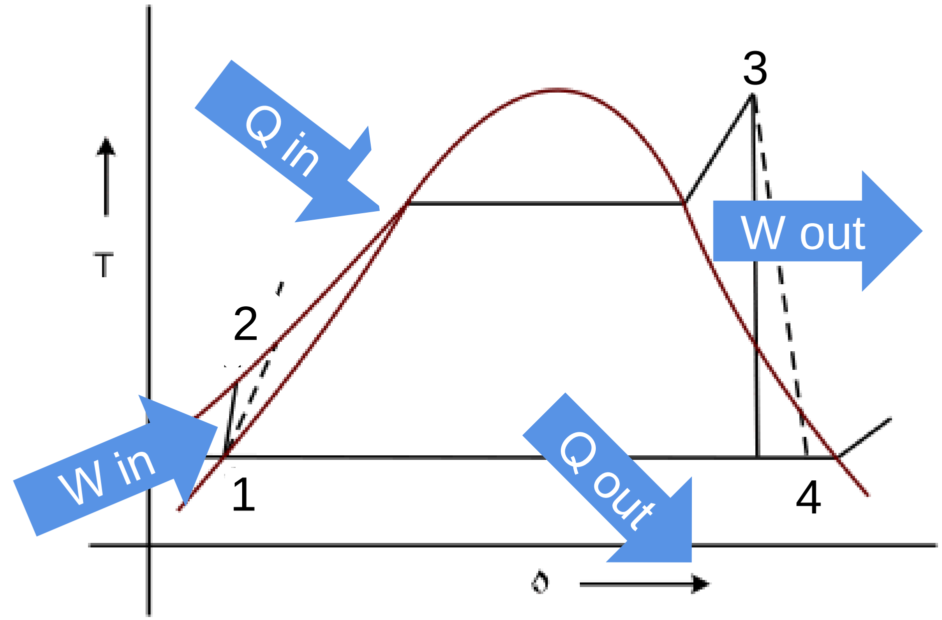
## Design aspects of major components

MONIKA TOPEL, PHD

*Based on: MARKUS JÖCKER, PHD, Siemens Industrial Turbomachinery*

# Rankine Cycle




1-2 Isentropic compression in a pump

2-3 Isobaric heat addition in a boiler

3-4 Isentropic expansion in a **turbine**

4-1 Isobaric heat rejection

# History – Significant milestones

**1850 Clausius-Rankine develops pratical process**

1883 First reaction turbine by **deLaval**

1884 First multi-stage reaction turbine by **Parsons**

1888 First impulse turbine by **deLaval** and first power station to produce electricity with a turbine (**Parsons**)

1894 The counter rotating **Ljungstrom** turbine (STAL)

1903 Turbine theory and calculation methods by **Stodola** and the **Mollier** diagram

1920+ 30 MW units with 20bar/325 degC **eff<0.18**

1934 First four flow LPT on a single shaft **eff=0.275**

1937 Steam turbines with 120 bar/500degC **eff=0.36**

1964 First combined cycle

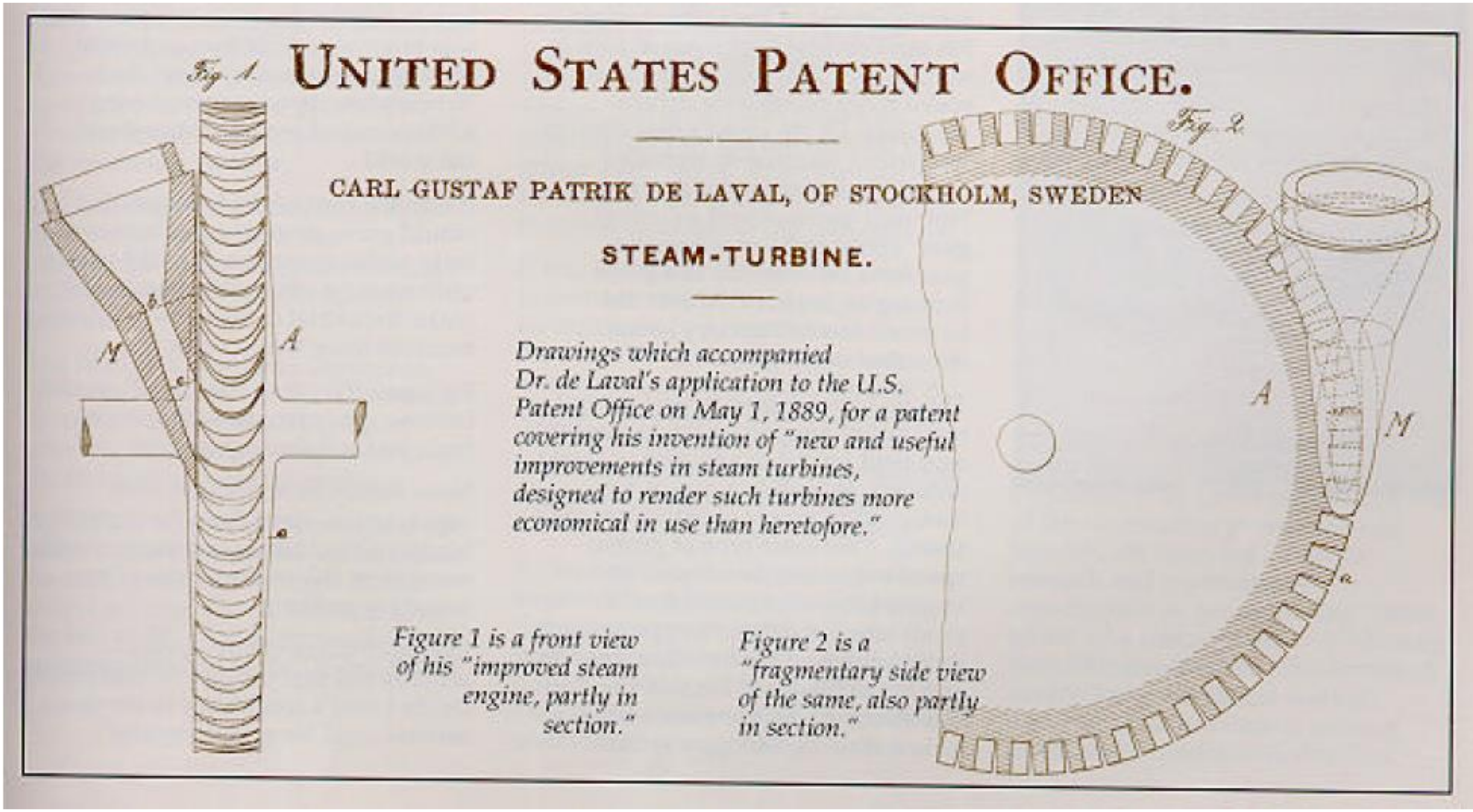
1965 250 MW units with reheat **eff=0.45**

First supercritical unit with double reheat **eff=0.48**

1970+ 500-900 MW coal fired units and 1400 MW nuclear

1988+ Combined cycle starts gaining popularity

# De Laval´s patent for impulse turbine from 1889



# Today: Challenges

Dominant worldwide!

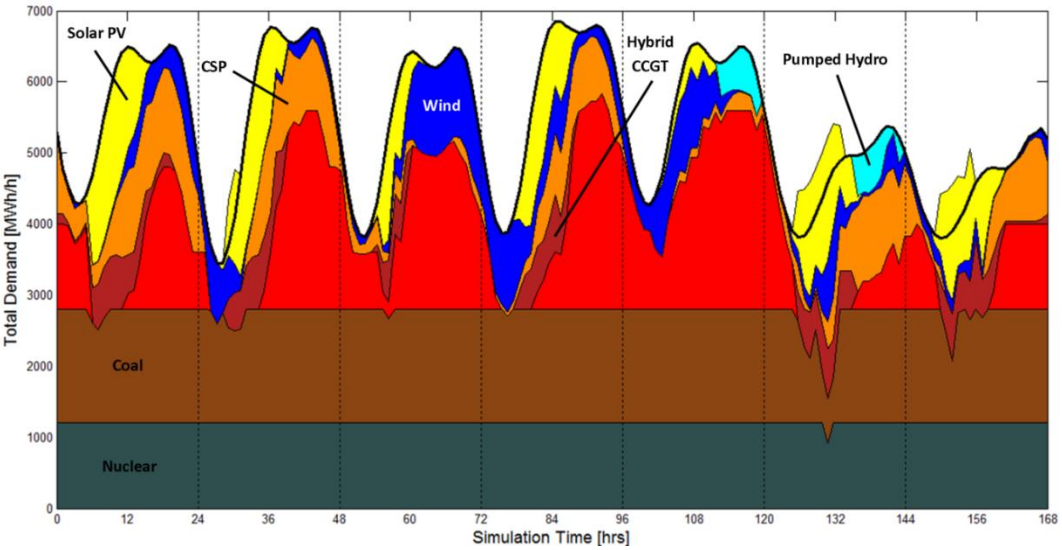
Intermittent renewables

Chase the best turbine efficiencies!

Effective combined cycle power plants

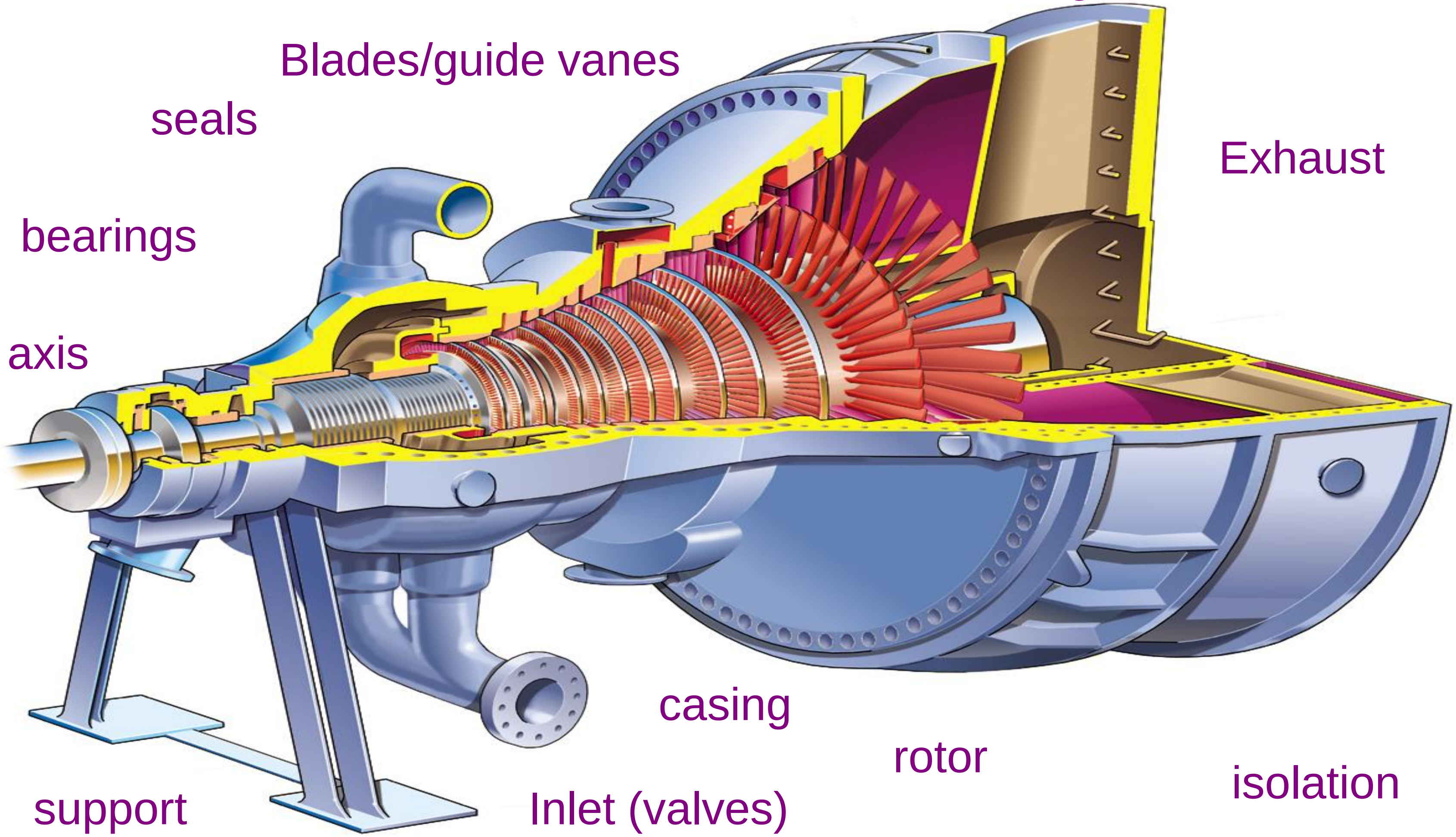
Highest efficiencies with district heating

Turbines for concentrating solar power

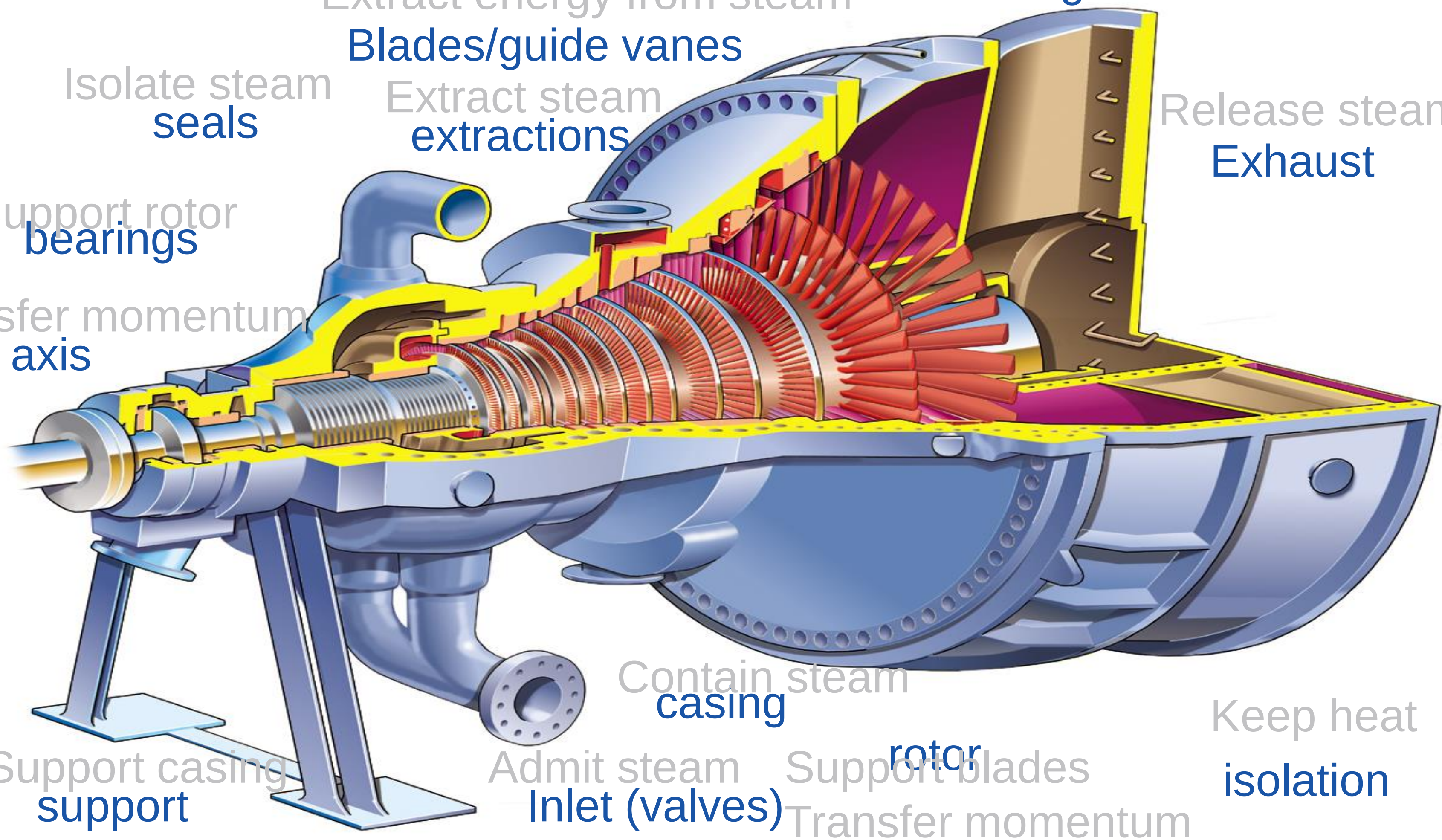



Gemasolar CSP plant

# What are the main parts of a steam turbine?

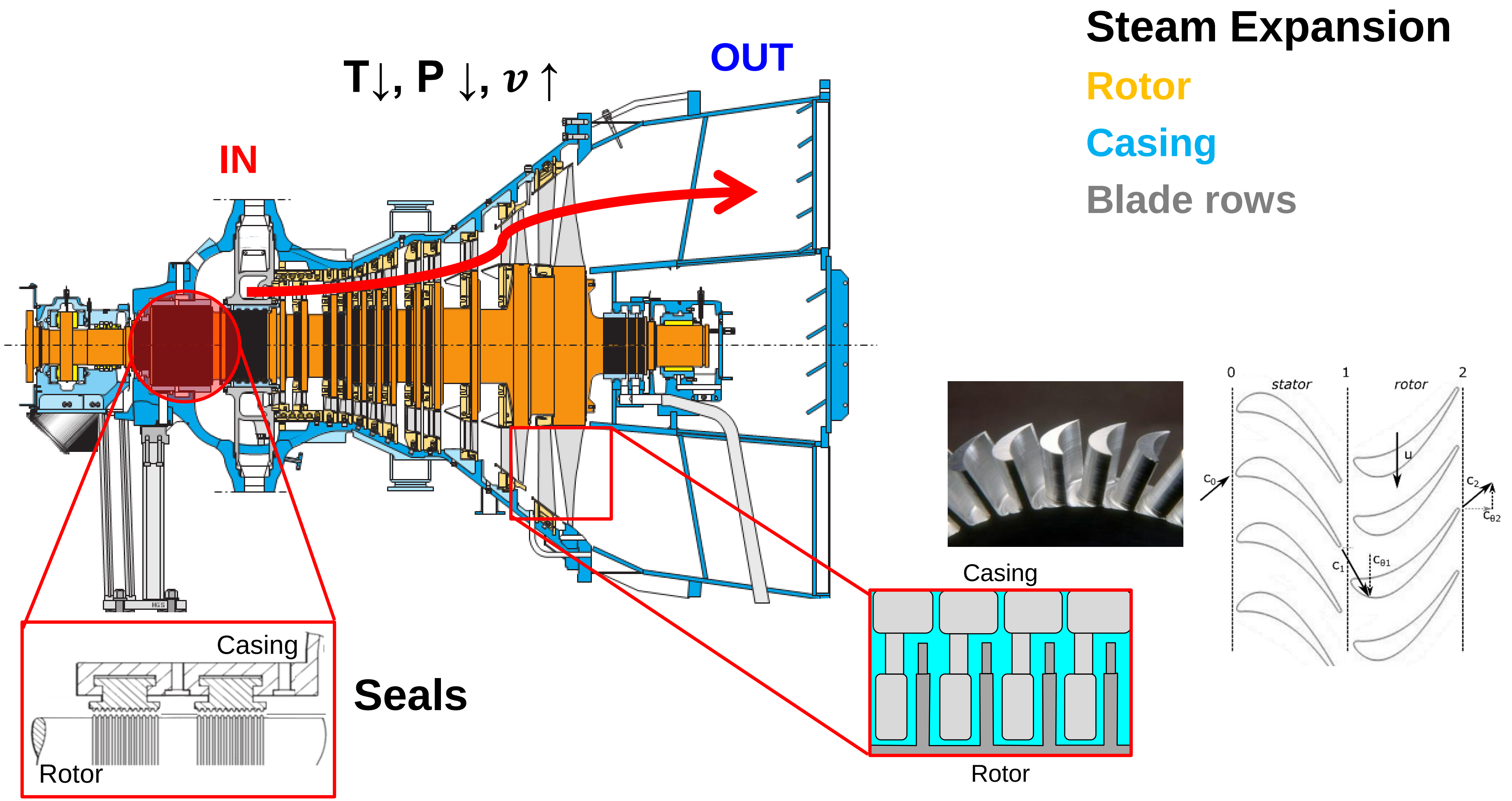


# Main Function of these parts?



# Steam Turbine – Overview

- Extract the thermal energy from steam,
- Shaft work → drive a generator.



# Today’s Lecture:

1. Blading
2. Control stages
3. Final stages
4. Seal technology
5. Inlets
6. Casings
7. Flexibility

**What are major design objectives?**

# Today's Lecture:

| | | |
|---|---|---|
| 1. | Blading | efficiency, integrity, costs |
| 2. | Control stages | efficiency, part load |
| 3. | Final stages | efficiency, integrity |
| 4. | Seal technology | performance, integrity |
| 5. | Inlets | low losses, costs |
| 6. | Casings | thickness, tightness, costs |
| 7. | Flexibility | fast response, lifetime |

## What are major design objectives?

**performance, reliability,**
**flexibility, costs**

# 1. BLADING

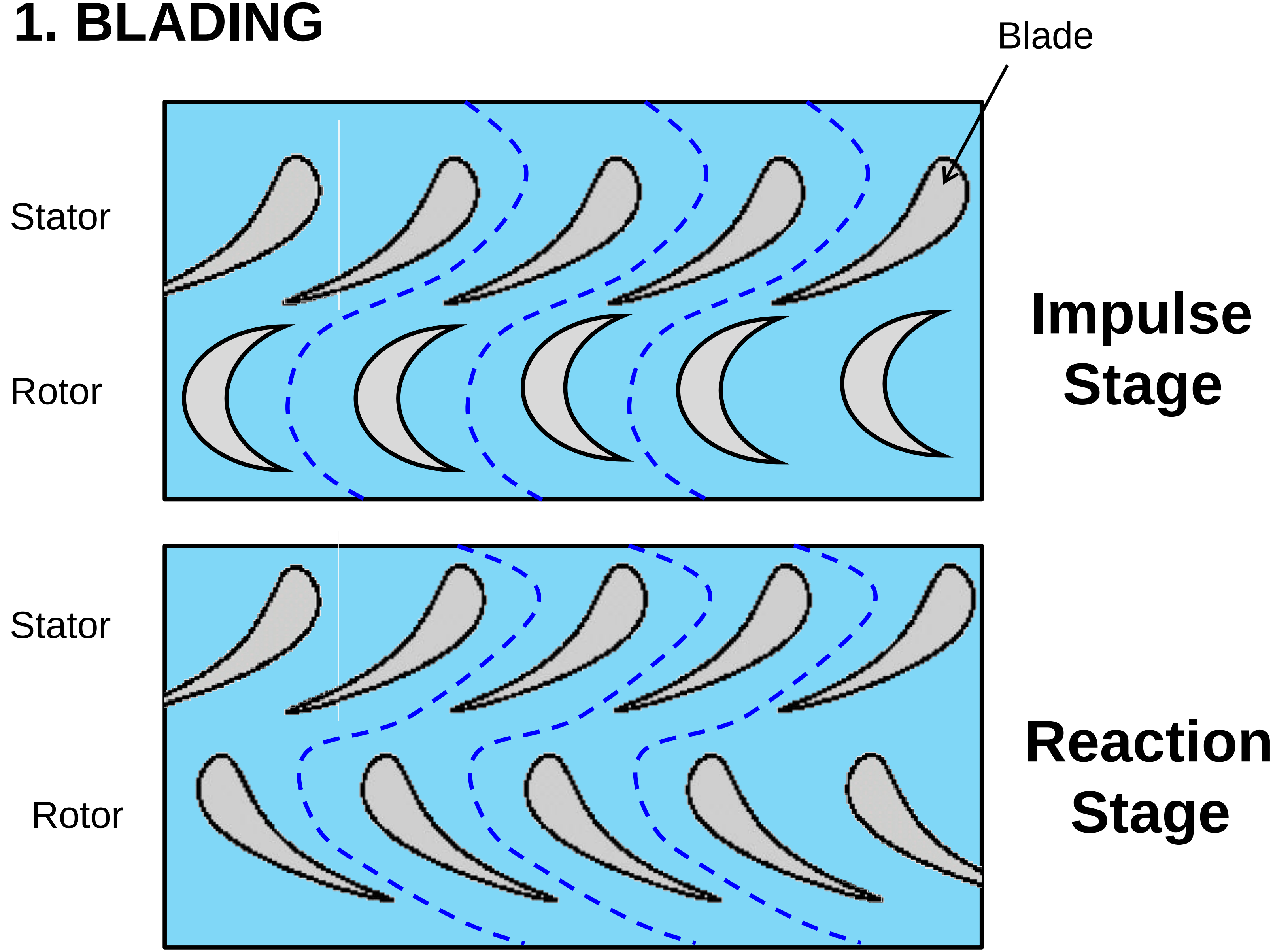
- Main function: Extract steam energy
  - High temperature and pressure at the inlet
  - Take that energy into shaft work

**Think of a hydro turbine !**

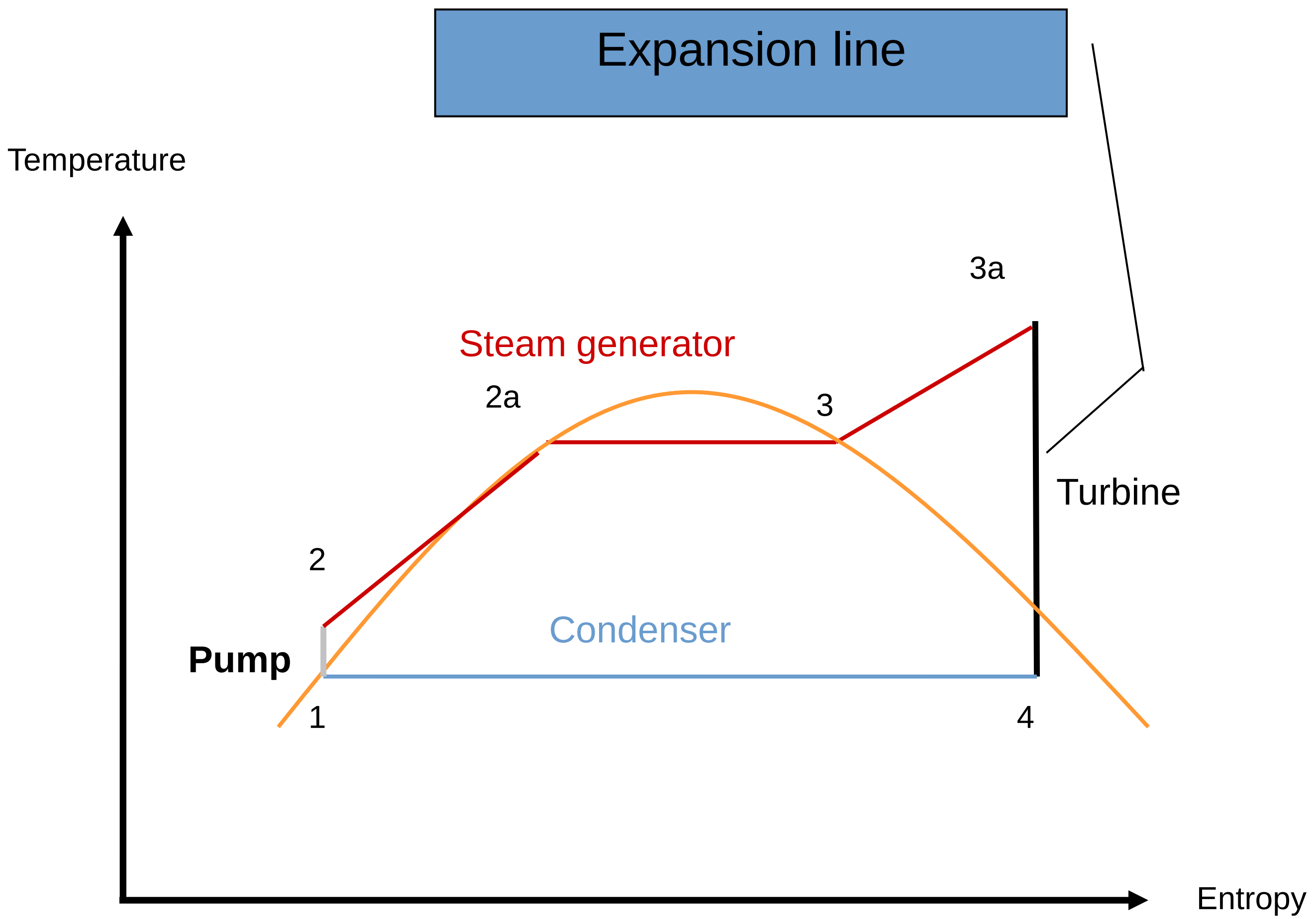
- Main principles of a steam turbine
  - Rotation
  - Deviation of the flow

- Blades deviate the flow
  - Impulse (low reaction)
  - Reaction

# 1. BLADING

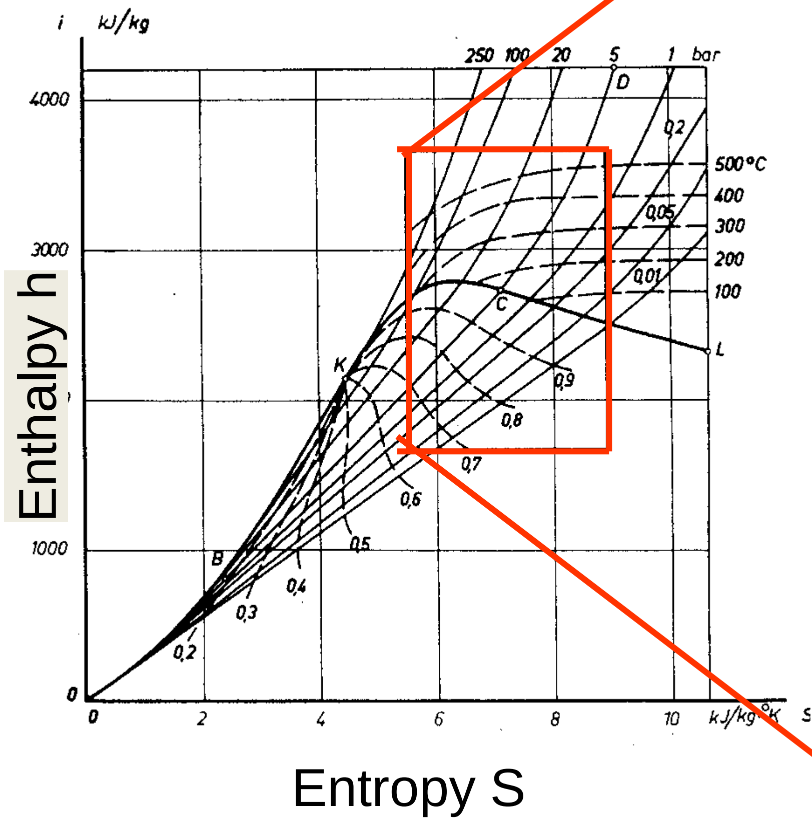

Blade
Stator
Rotor
Impulse Stage
Stator
Rotor
Reaction Stage

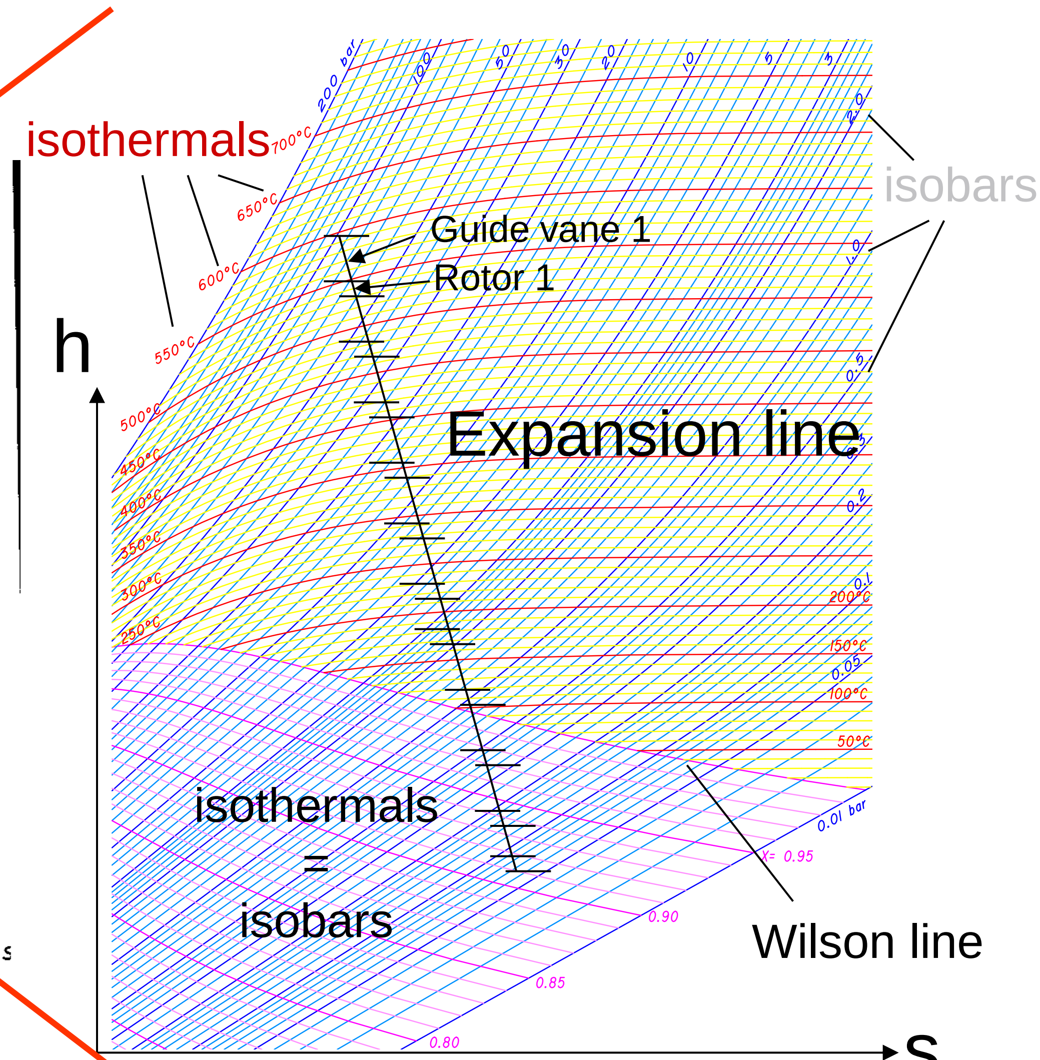
# Rankine Cycle



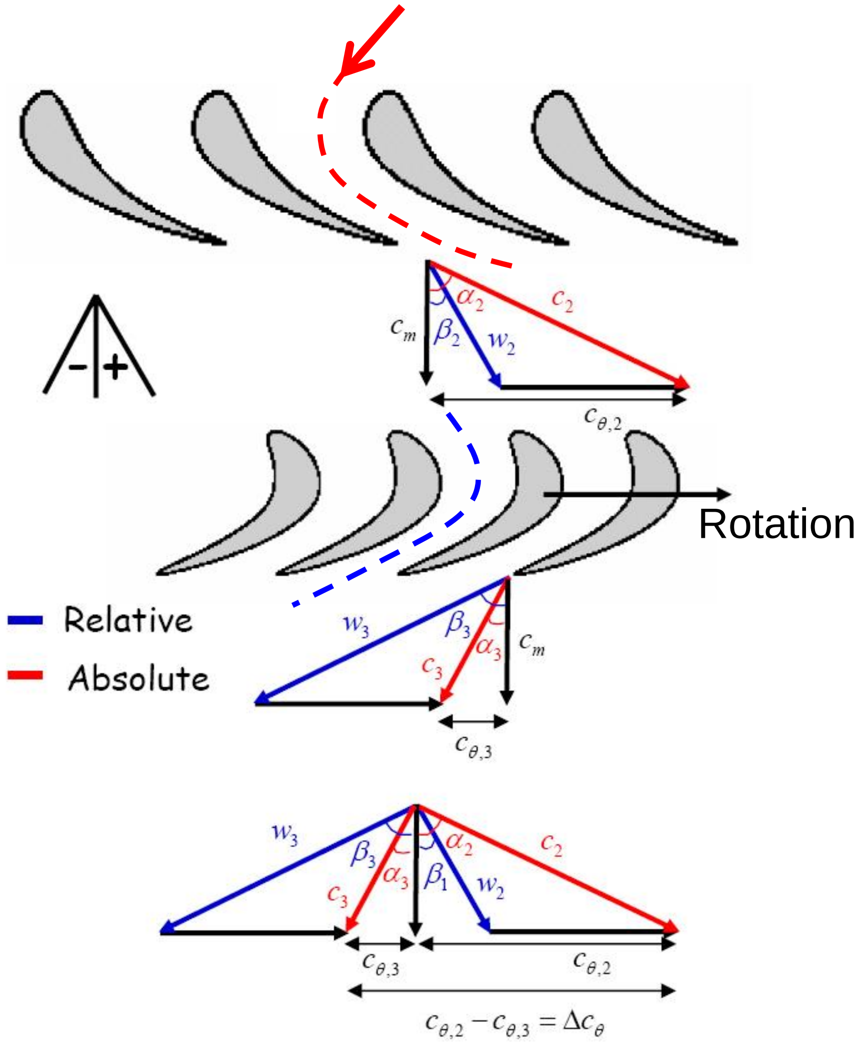
# Expansion Process

## Mollier Diagram



# Velocity triangles

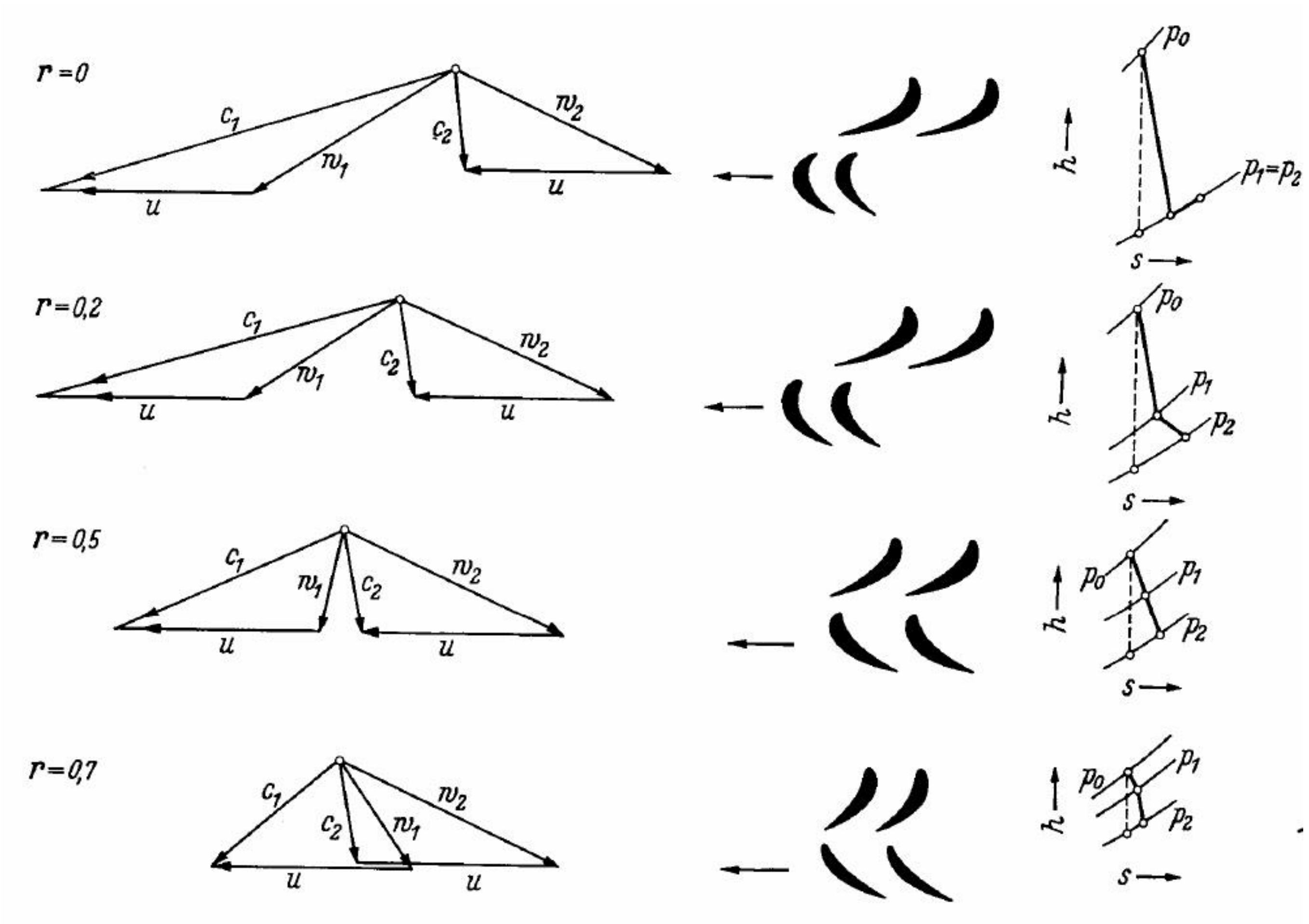



Stator row

Rotor row

$$\vec{C}_i = \vec{W}_i + \vec{U}$$

# Reaction




$$R = \frac{\Delta h_{is}\ Rotor}{\Delta h_{is}\ Stage}$$

$$R \sim \frac{\Delta p\ Rotor}{\Delta p\ Stage}$$

”Traupel”

# Euler’s turbine equation

- Conservation Principles
  - Mass
  - Momentum
  - Energy

$$w = \Delta h = u \times \Delta c_\theta$$

| | | |
|---|---|---|
| w | specific work | [J/kg] **[W/(kg/s)]** |
| h | enthalpy | [J/kg] |
| u | rotor blade velocity | [m/s] |
| $c_\theta$ | absolute swirl velocity | [m/s] |

# Smith diagram

Stage loading coefficient:

$$\psi = \frac{\Delta h_0}{u^2}$$

Flow coefficient:

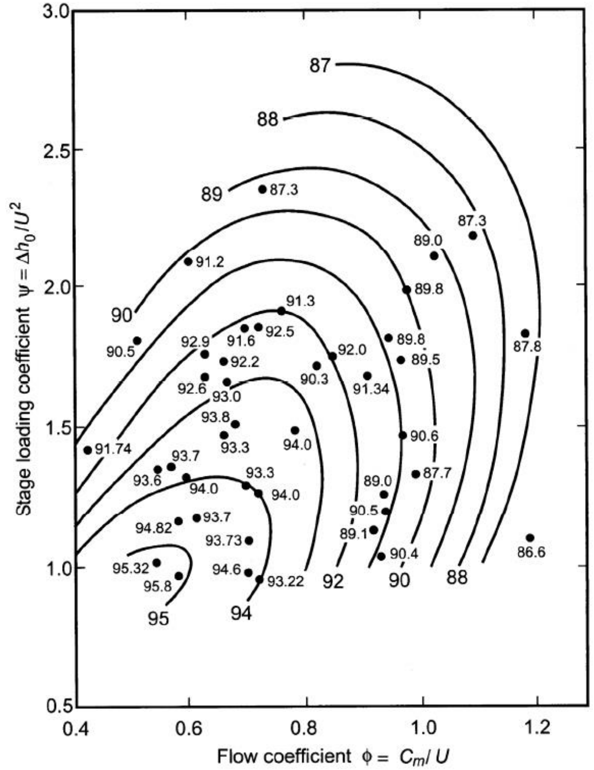
$$\phi = \frac{c_m}{u}$$

U: rotor velocity
Cm: axial flow velocity

Aero. loading

Number of stages

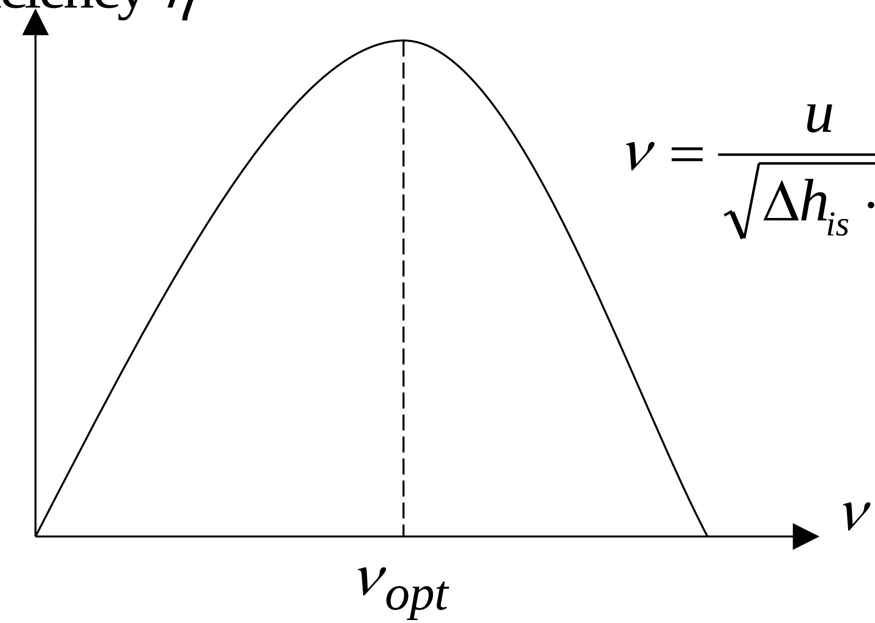
Eff, R




Flow

Size

# Velocity number




$$\eta = \frac{\Delta h_0}{\Delta h_{is}}$$

$$\nu = \frac{u}{\sqrt{\Delta h_{is} \cdot 2}}$$

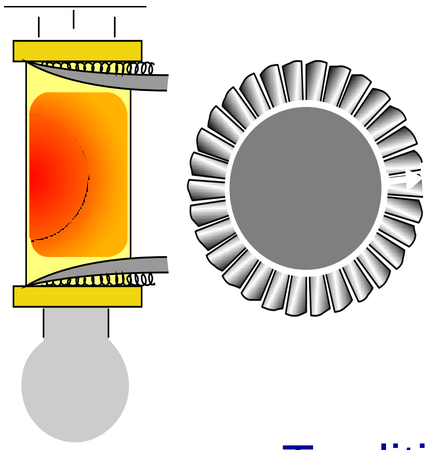
$u$ = rotor blade velocity $[m/s]$

$\Delta h_{is}$ = isentropic enthalpy drop $[J/kg]$

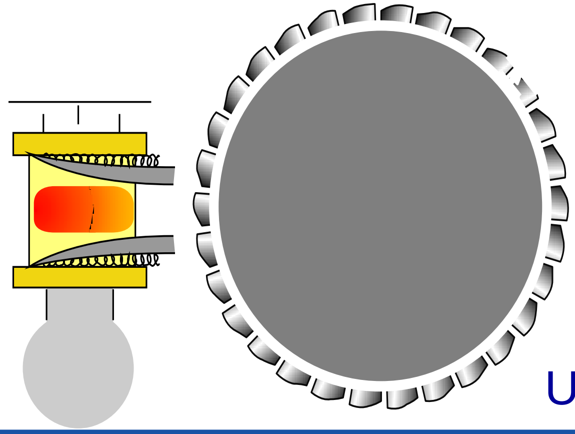
# BLADING – rotor speed

- High specific rotor speed enables use of long blades for improved efficiency
- Small tip leakage area due to small rotor diameter

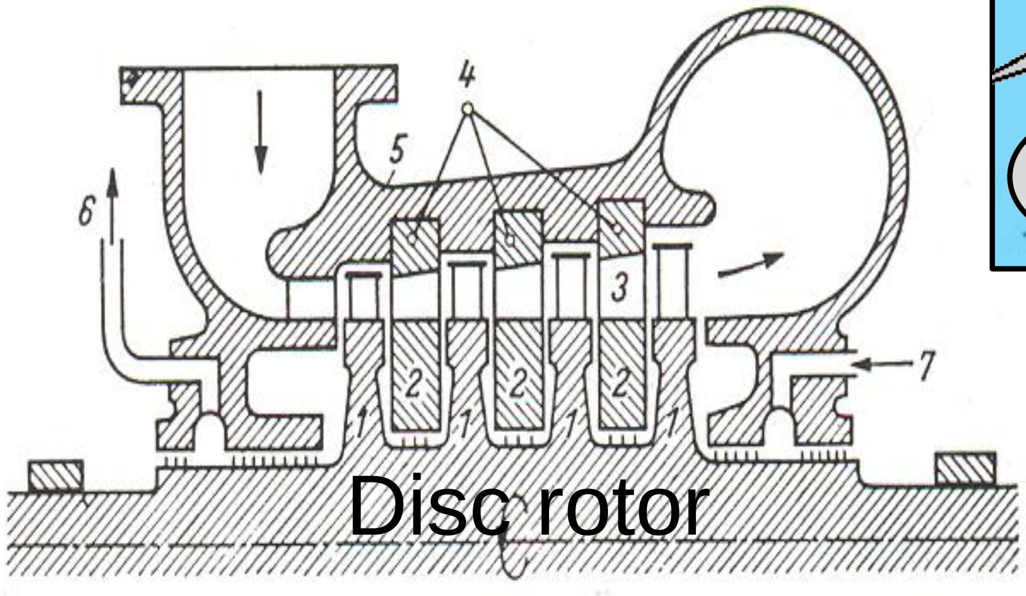
SST700 HP turbine

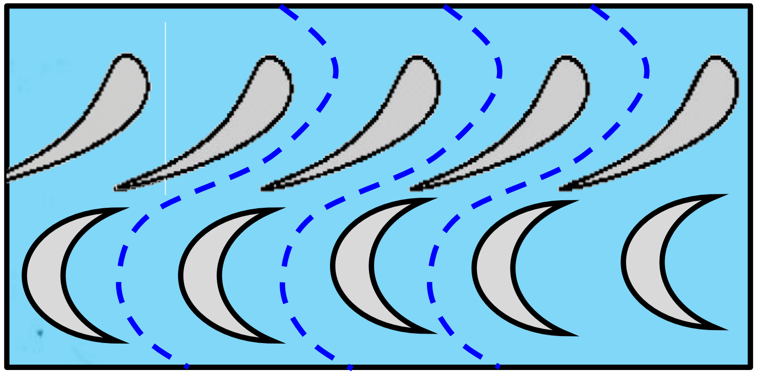



Traditional turbine



# 1. BLADING

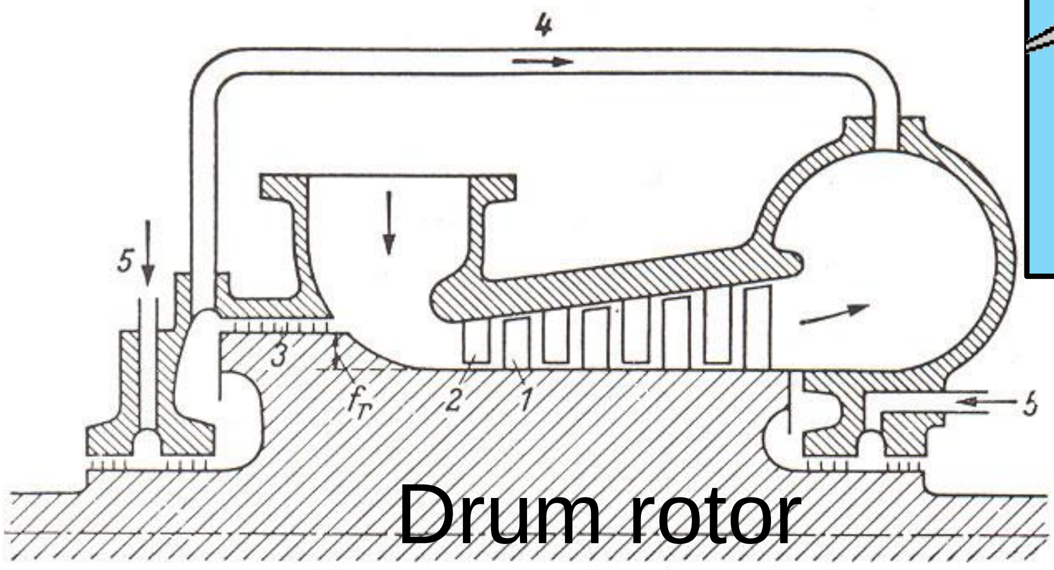


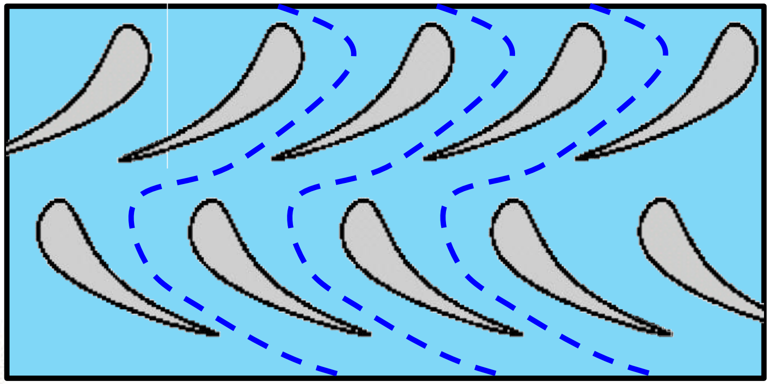



Impulse blading

Nearly no reaction
Small or no pressure drop over the rotor
High work output/stage (less stages)
Diaphragm design
Less leakage losses
More axial length/stage

# 1. BLADING



Reaction blading

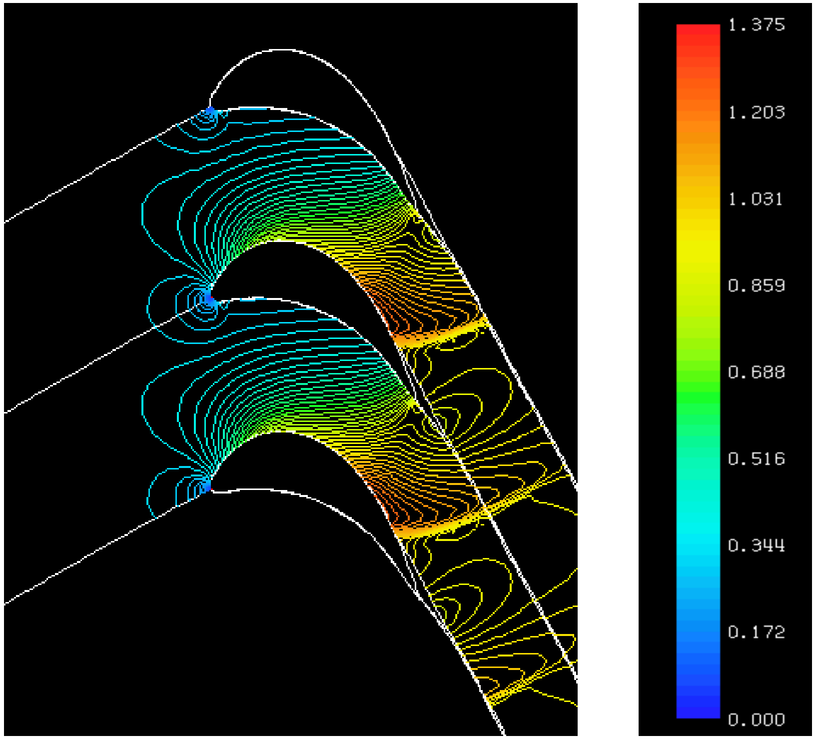
Reaction about 0.5
Pressure drop over rotor requires balance piston
Less work output /stage (more stages)
Better aerodynamics due to less turning

# 1. BLADING

Design aspects:

- Aerodynamics
- Integrity
- Roots
- Shroud Seals
- Manufacturing and assembly

# Profile losses

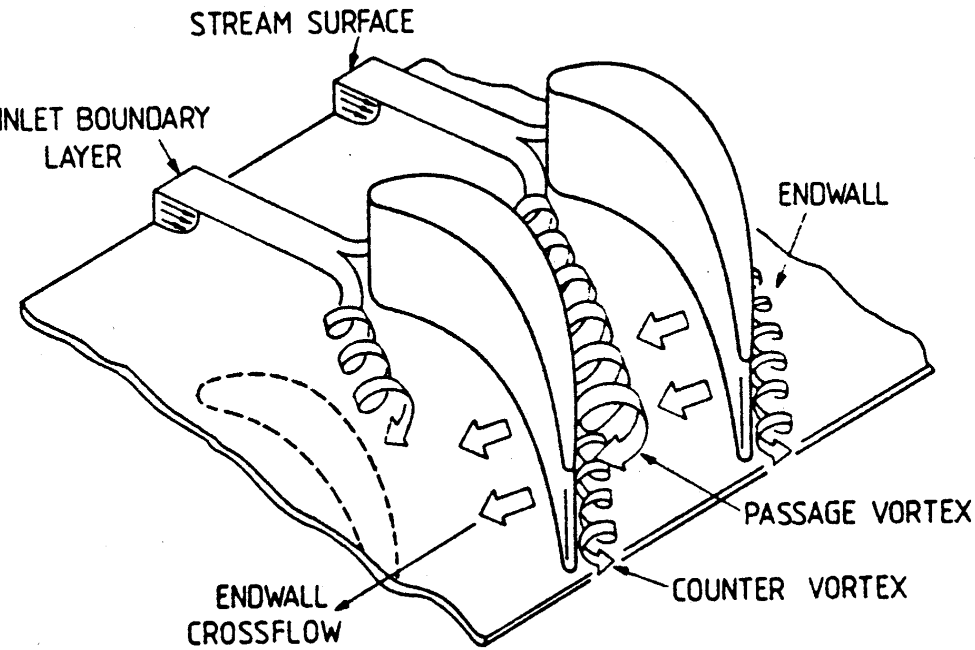



Mach Number in a rotor blading - transonic

- Friction losses
- Trailing edge losses
- Shock losses
- Separation losses

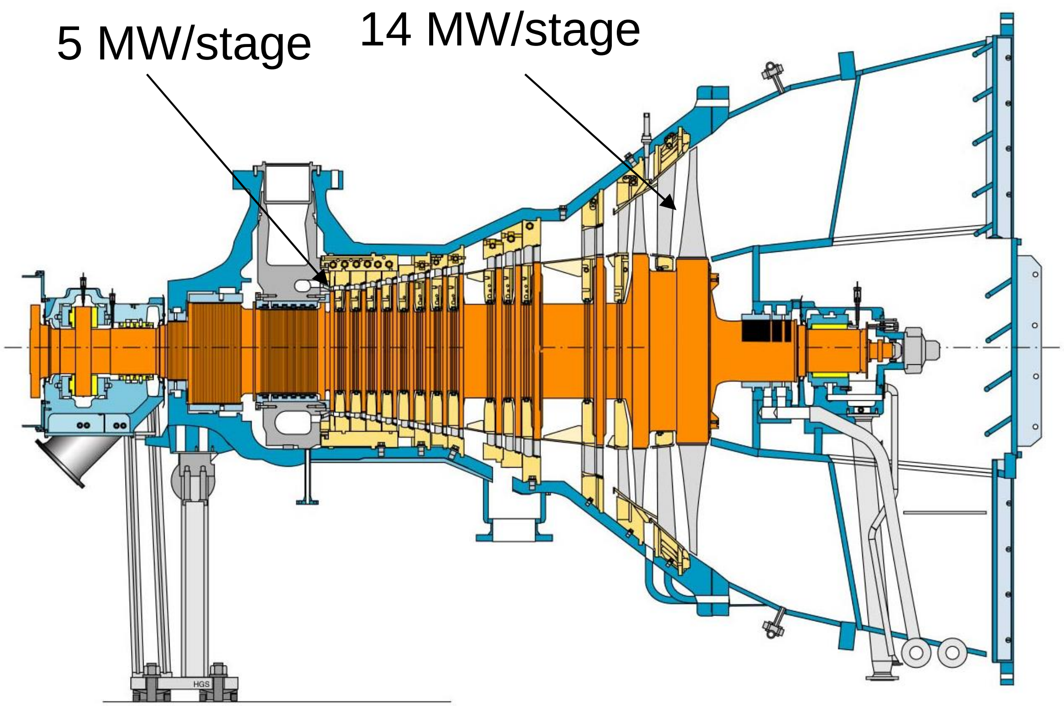
$$Ma = \frac{\text{velocity}}{\text{sound velocity}}$$

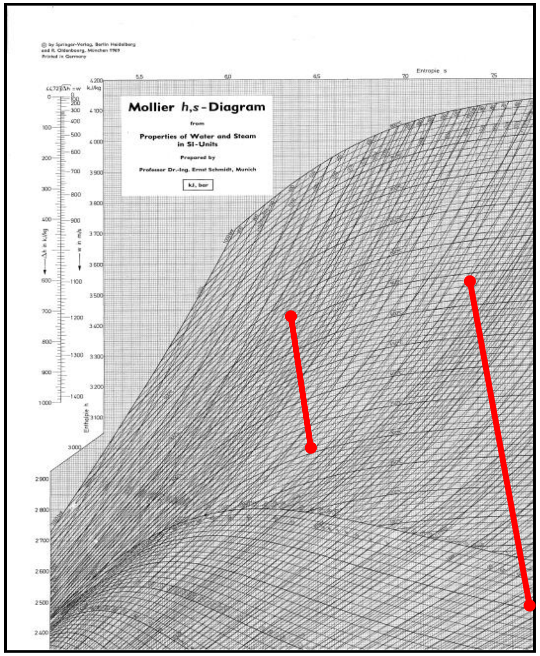
# Secondary flow




Endwall flow models by Klein and Langston

# 1. BLADING




Pressure ratio : 2000
Volume ratio:  700

Where are the challenges?

# 1. BLADING

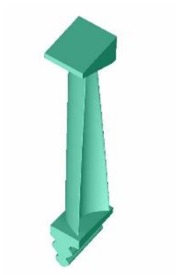
| | |
|---|---|
| Large centrifugal loads (static tension) | LP |
| Bending/torsion loads | LP |
| Large thermal loads (LCF, creep) | HP, IP |
| Unsteady steam loads (HCF) | HP, IP, LP |
| Stress concentration in notches | HP, IP, LP |
| Corrosion | LP |
| Erosion by particles | LP |
| Oxidation | IP, LP |

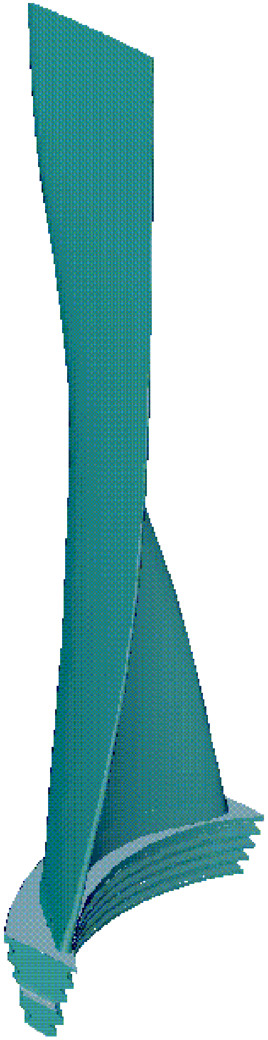
# 1. BLADING

Reduce thermodynamic losses!

- Profile losses
  - Secondary losses
  - Leakage losses
  - Axial gap losses
  - Moisture losses
  - Exhaust losses
  - Unnecessary losses

# 1. BLADING – typical blade data





| | | | HP | LP |
|---|---|---|---|---|
| Bladelength | l | [mm] | 34 | 866 |
| Length/Chord | L/C | [-] | 1.1 | 4.9 |
| Diameter ratio | $D_y/D_i$ | [-] | 1.2 | 2.2 |
| Blade velocity | u | m/s | 150 | 450 |
| Reynoldsnumber | Re | [-]*$10^5$ | 40 | 4 |
| Machumber | Ma | [-] | 0.2 | 1.3 |

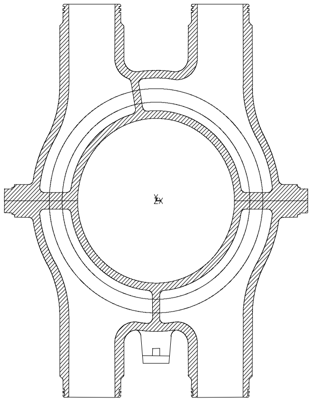
# 2. CONTROL STAGE

Partial admission
to control load

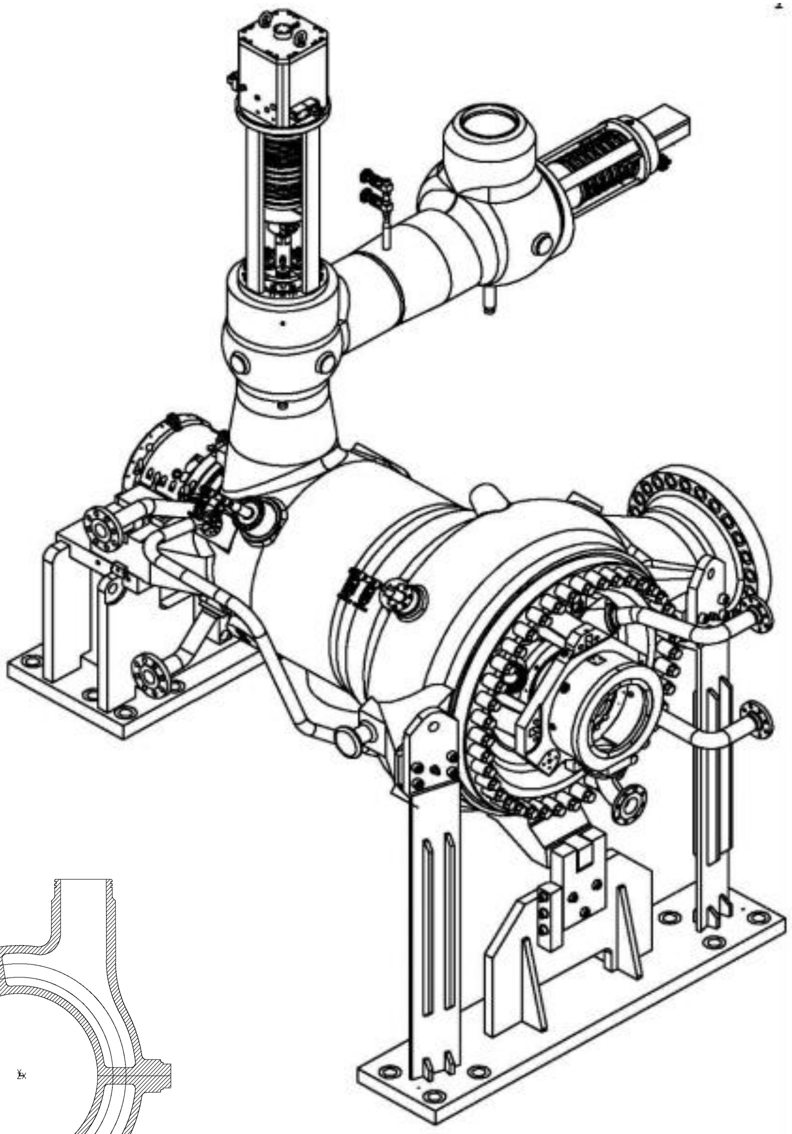
Several admission valves

Require zero reaction stage

High dynamic loads



Partial admission nozzle box



HP/turbine with control stage

# 2. CONTROL STAGE

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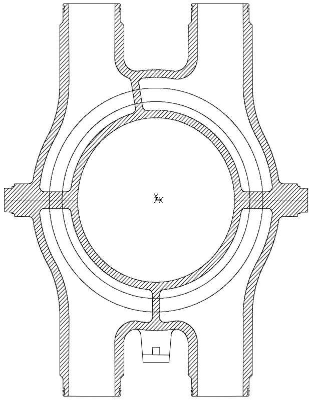
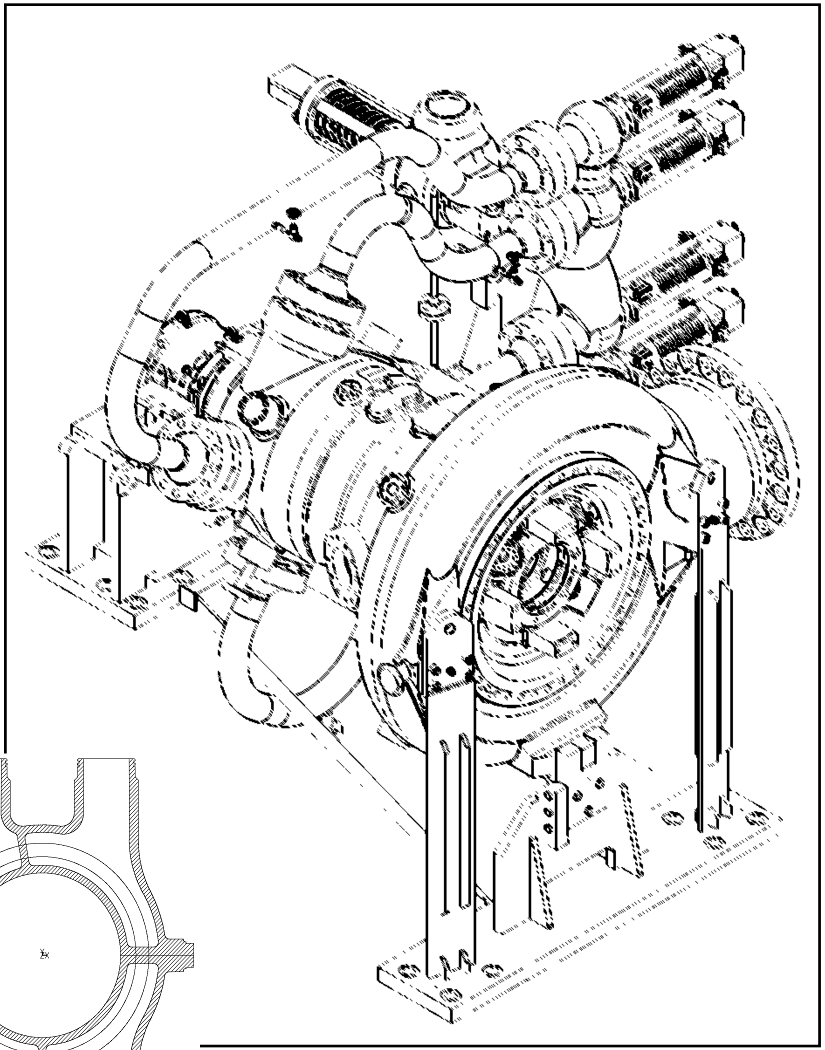
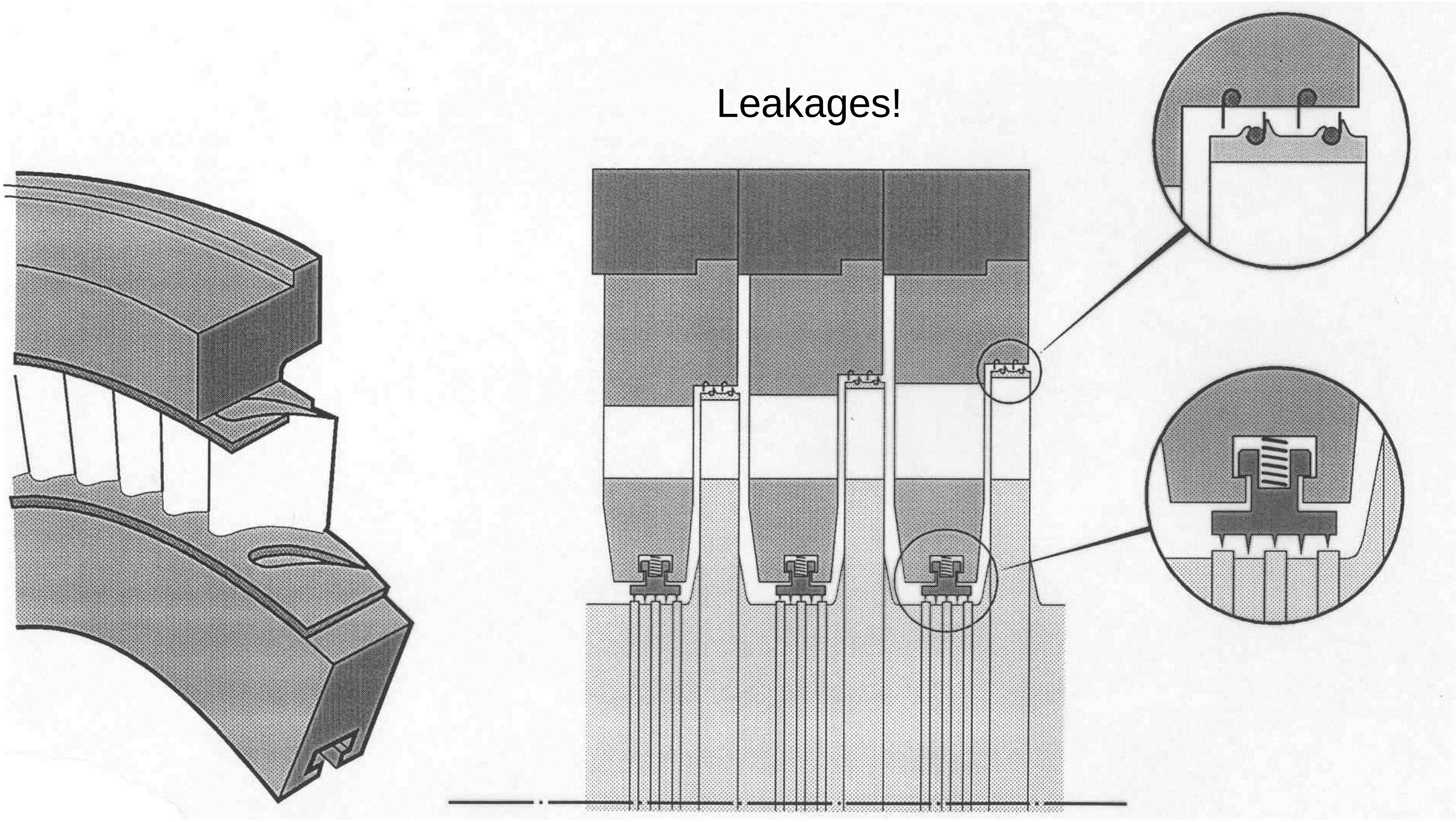


Partial admission nozzle box

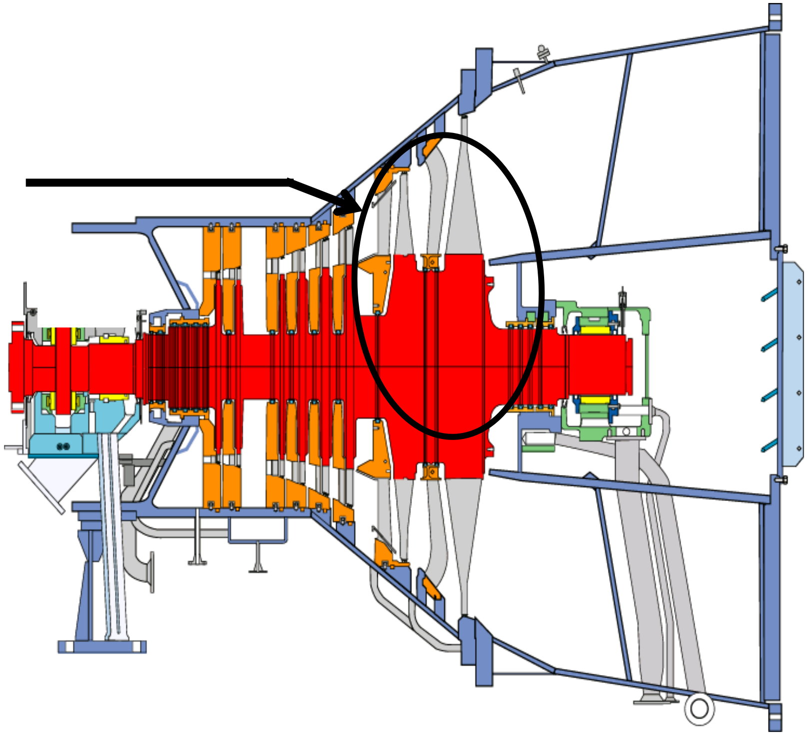


HP/turbine with control stage

# Diaphragms principle design

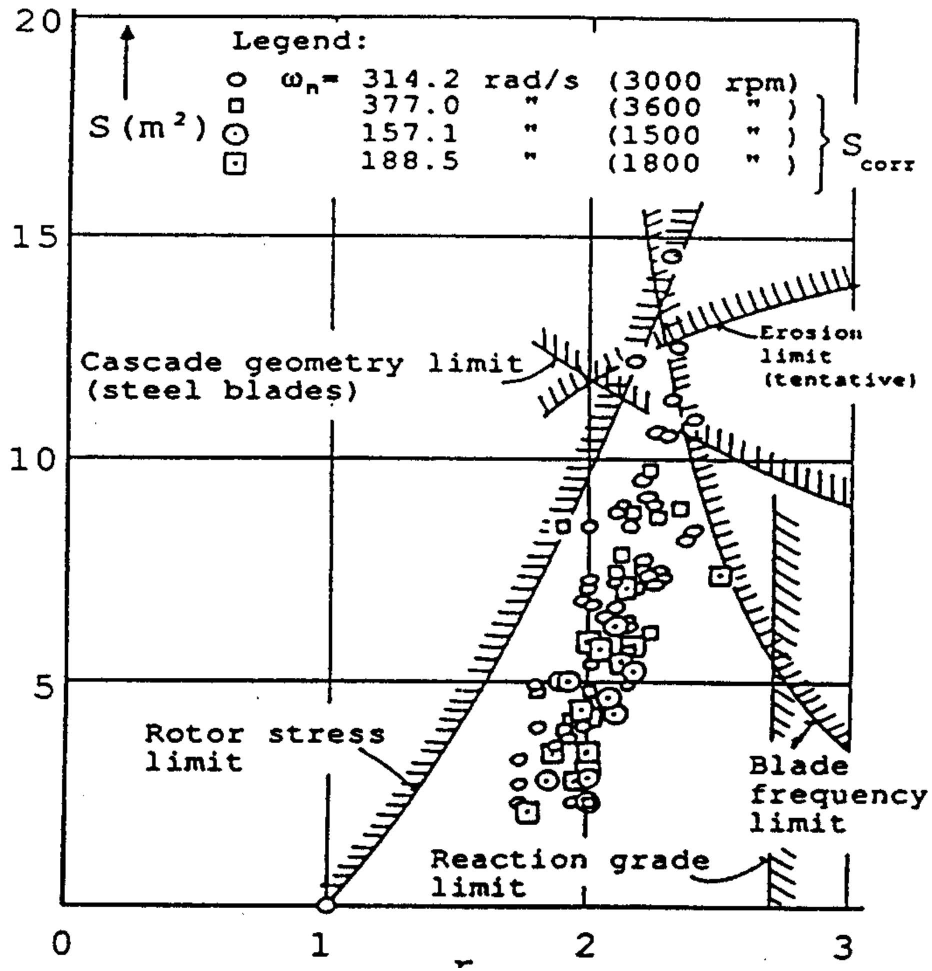


# 3. FINAL STAGES



Where are the challenges?

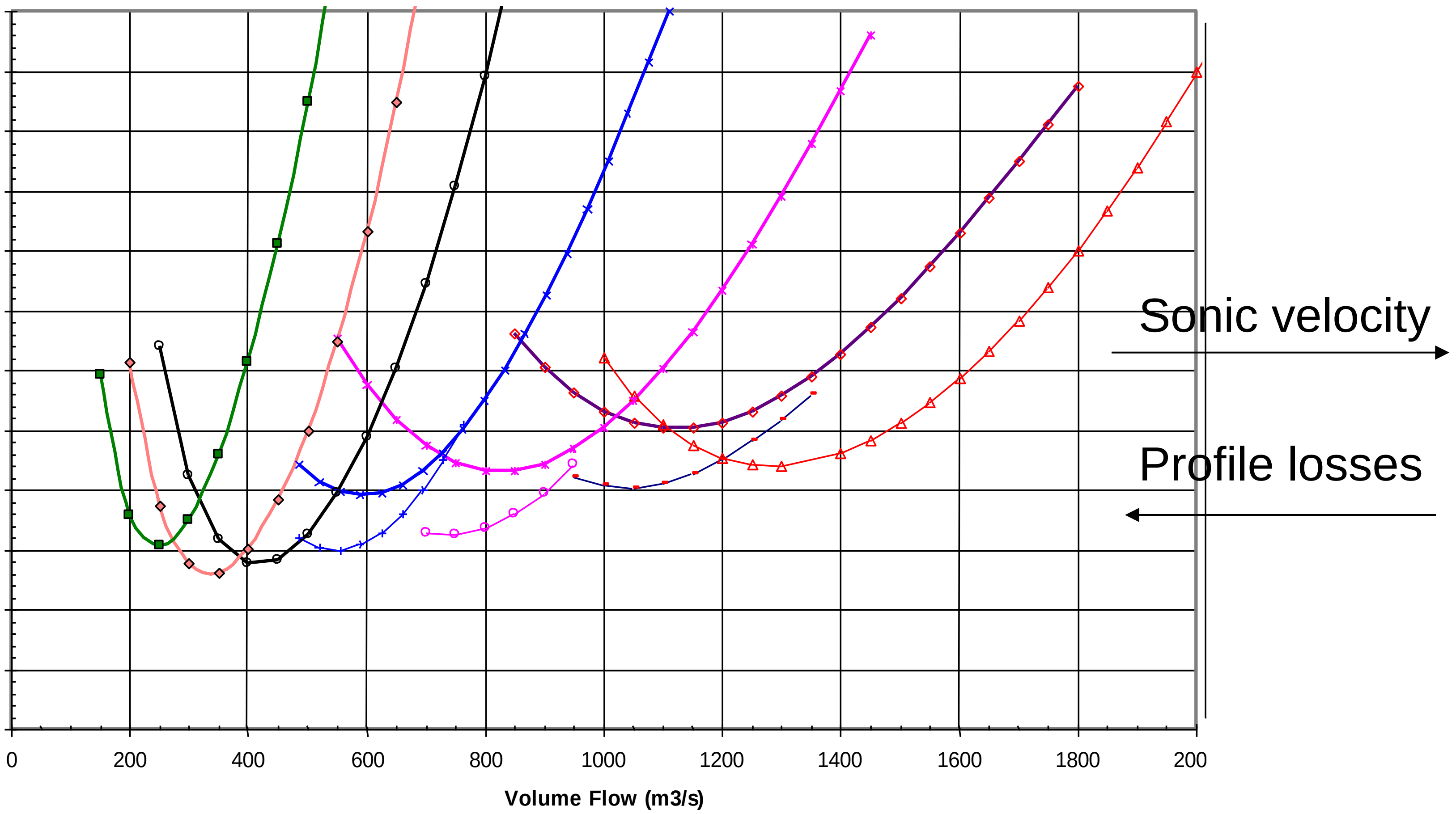
# 3. FINAL STAGES – limits




Rotor stress
Erosion
Cascade geometry
Blade frequency

”On the design limits of steam turbine stages”
Gyarmathi, Schlachter, 1988

# 3. FINAL STAGES – Exhaust losses



# 3. FINAL STAGES - roots

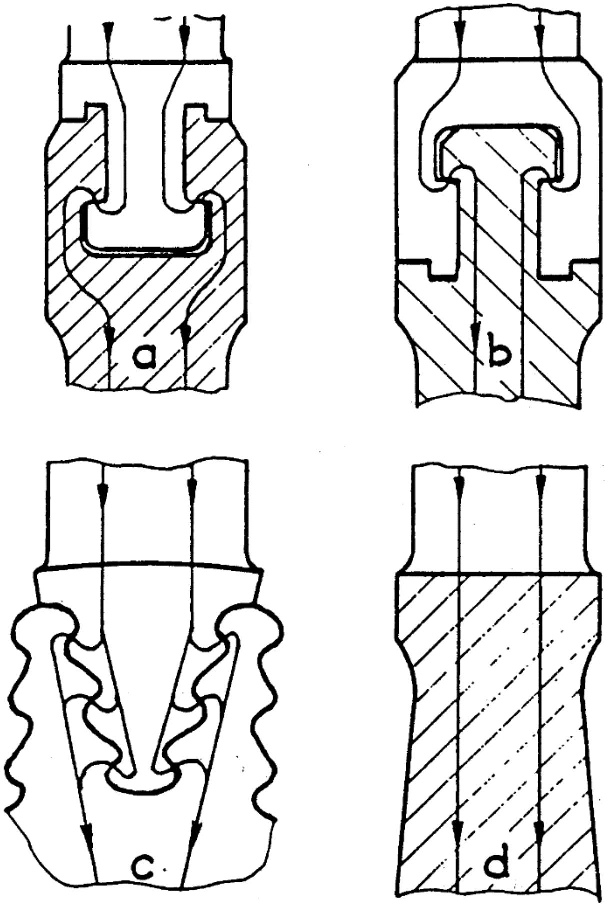



*Figure 6. Load Transfer for Various Roots. a) Circumferential Internal Groove, b) Straddled Root [3]. c) Axial Sawtooth Root, and d) Blade Integral With Rotor [7].*

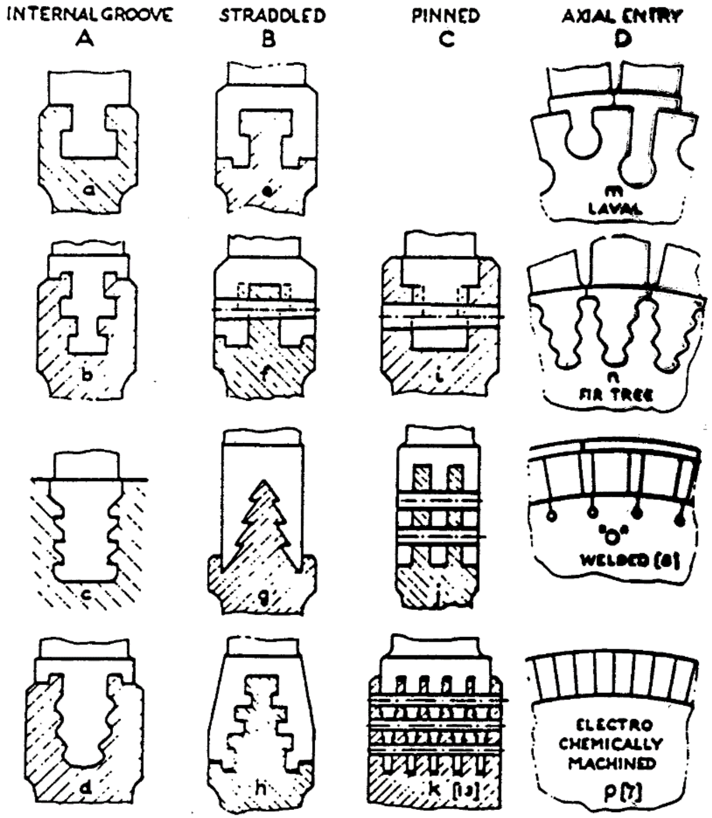
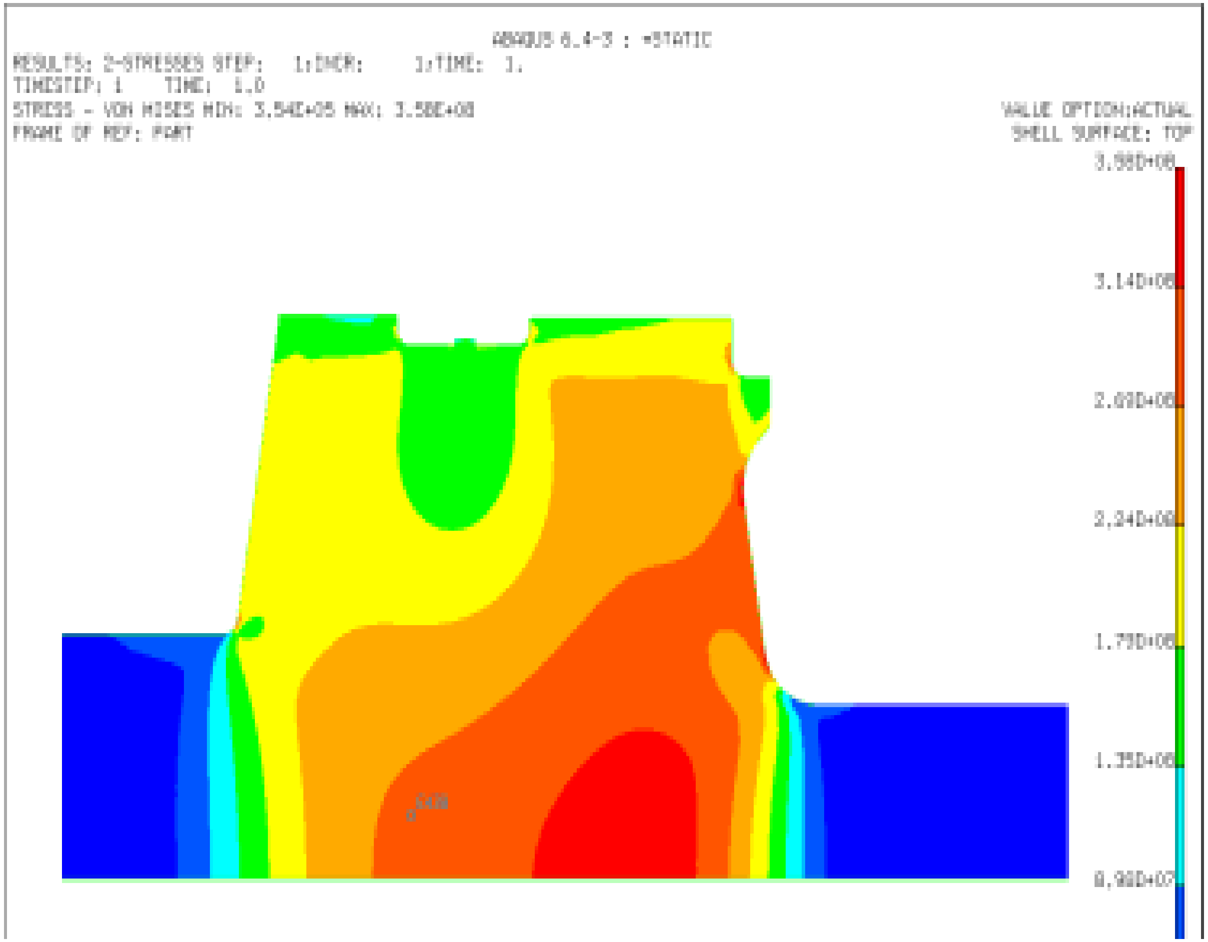
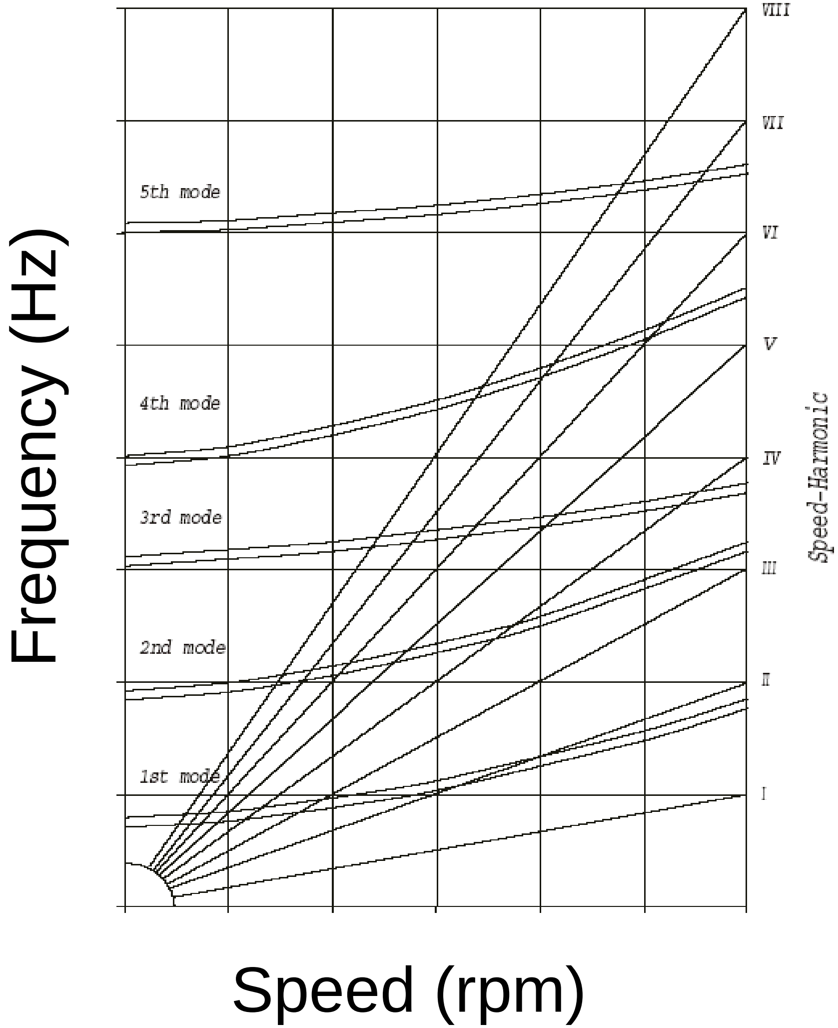



*Figure 7. Blade Fastenings.*

# 3. FINAL STAGES – example root stress analysis

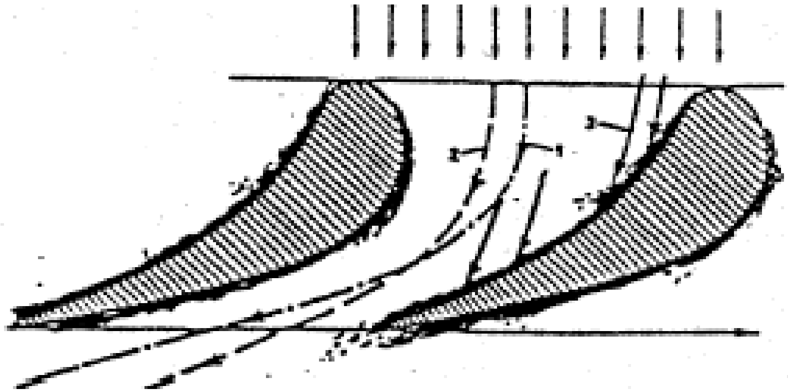


# 3. FINAL STAGES – blade vibration

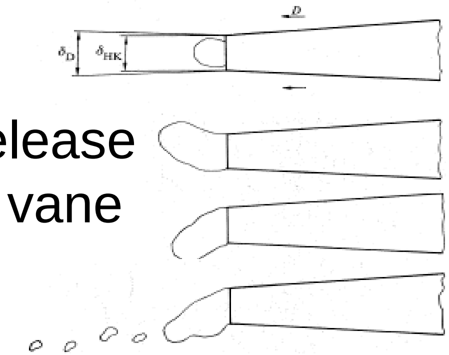


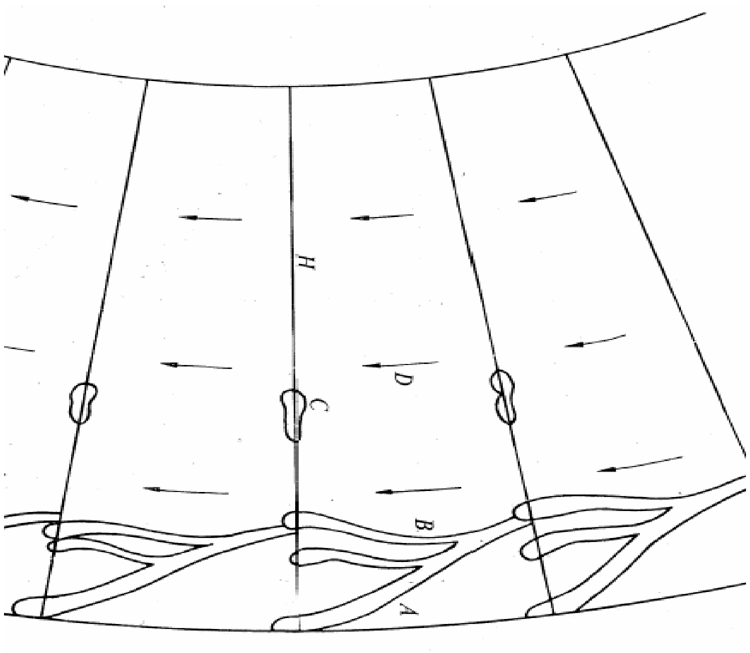

Campbell diagram

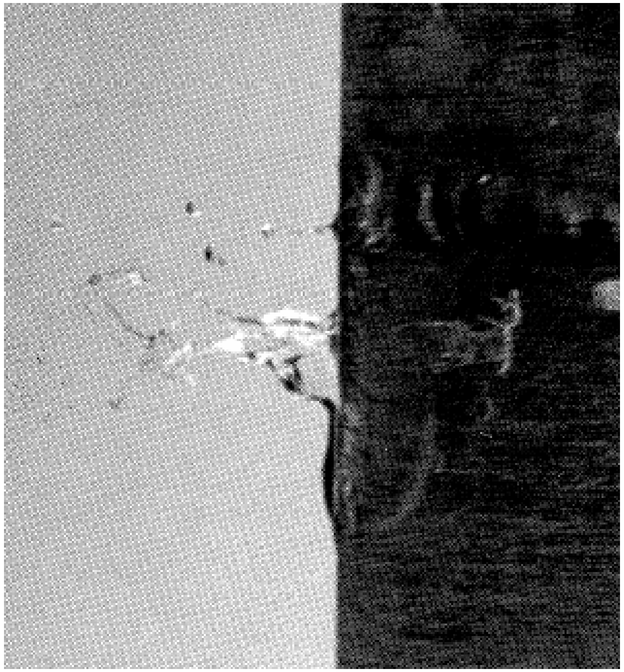
# 3. FINAL STAGES – moisture



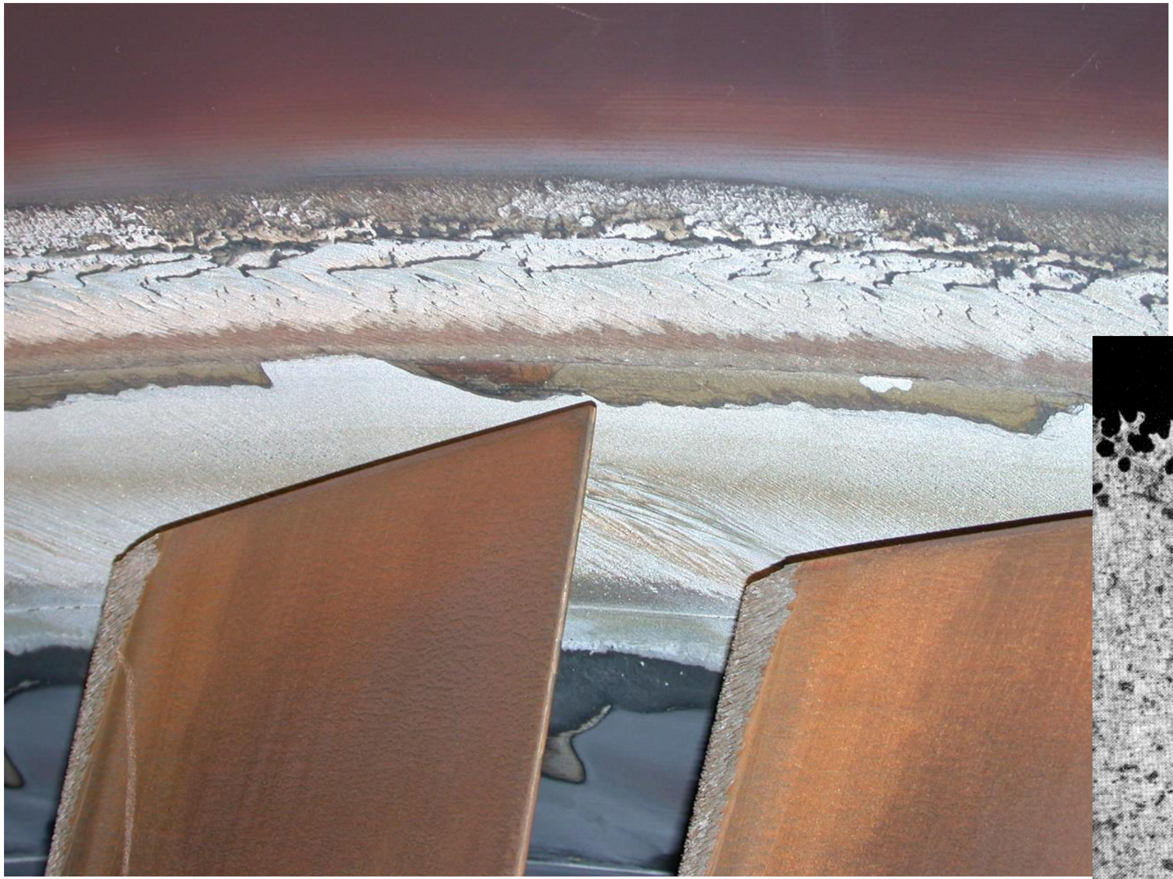
Collection and release of moisture from vane trailing edge



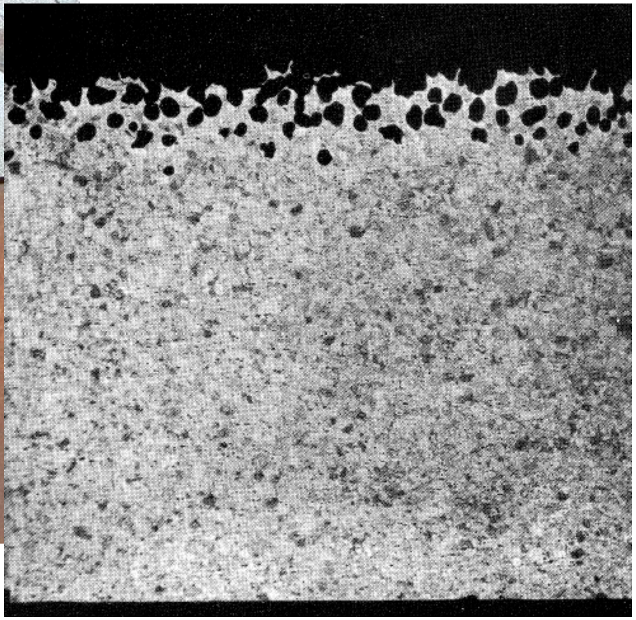


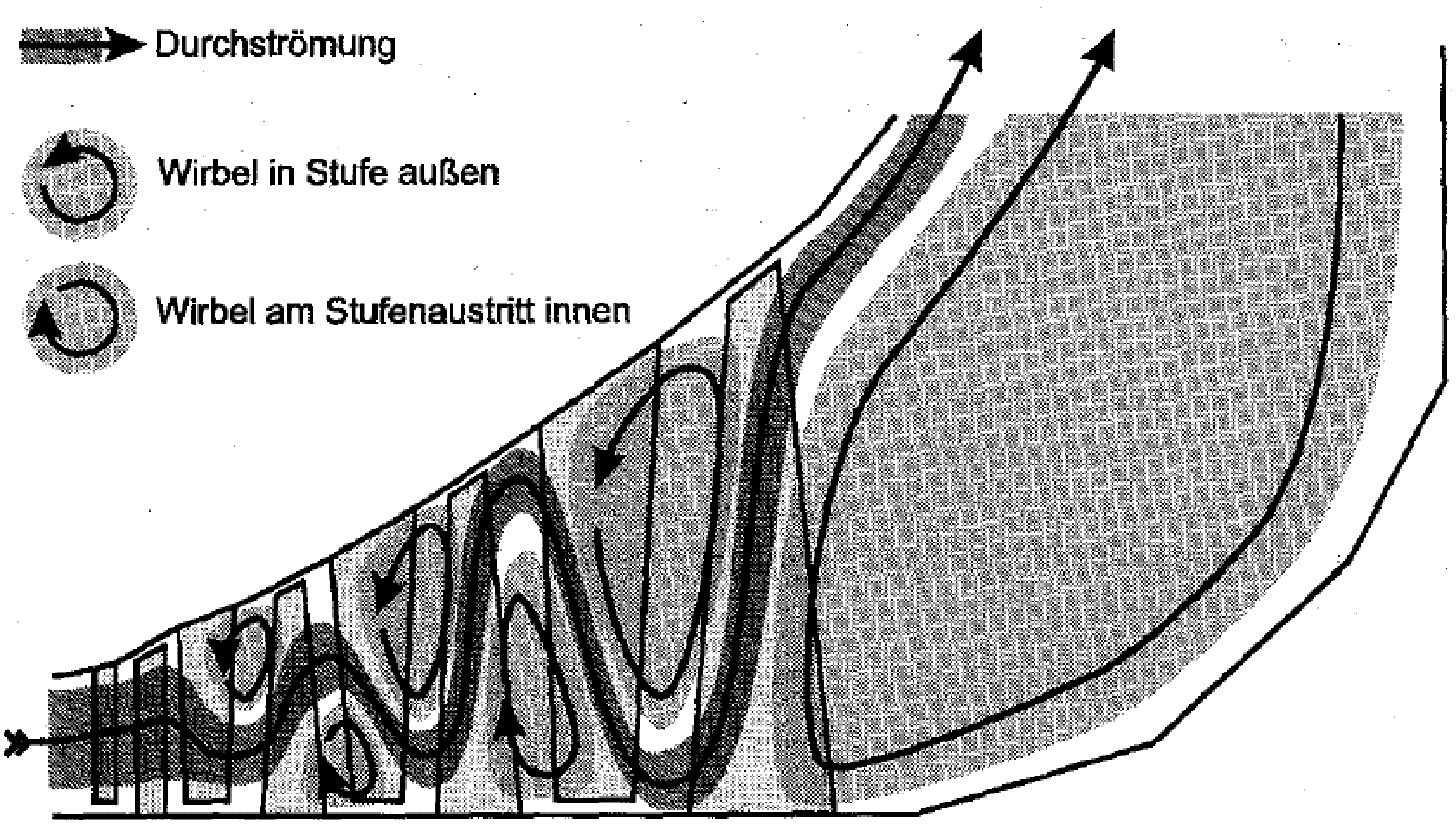
# 3. FINAL STAGES – Erosion damage on blades



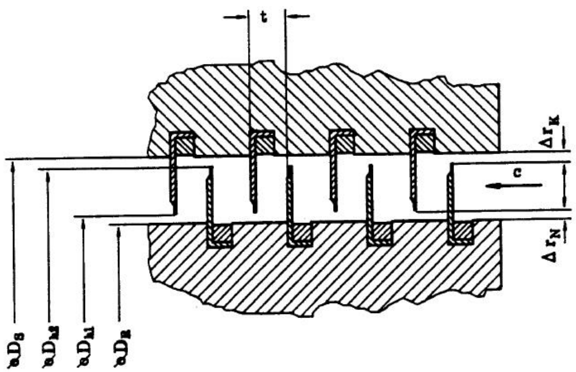
Cut through leading edge

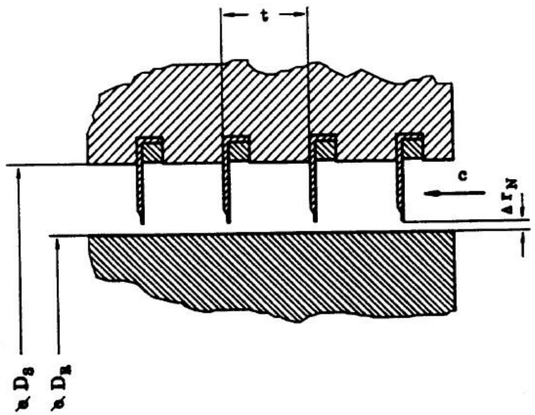


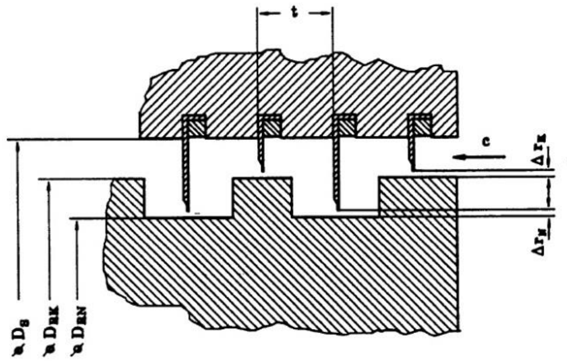
# 3. FINAL STAGES – low load limits



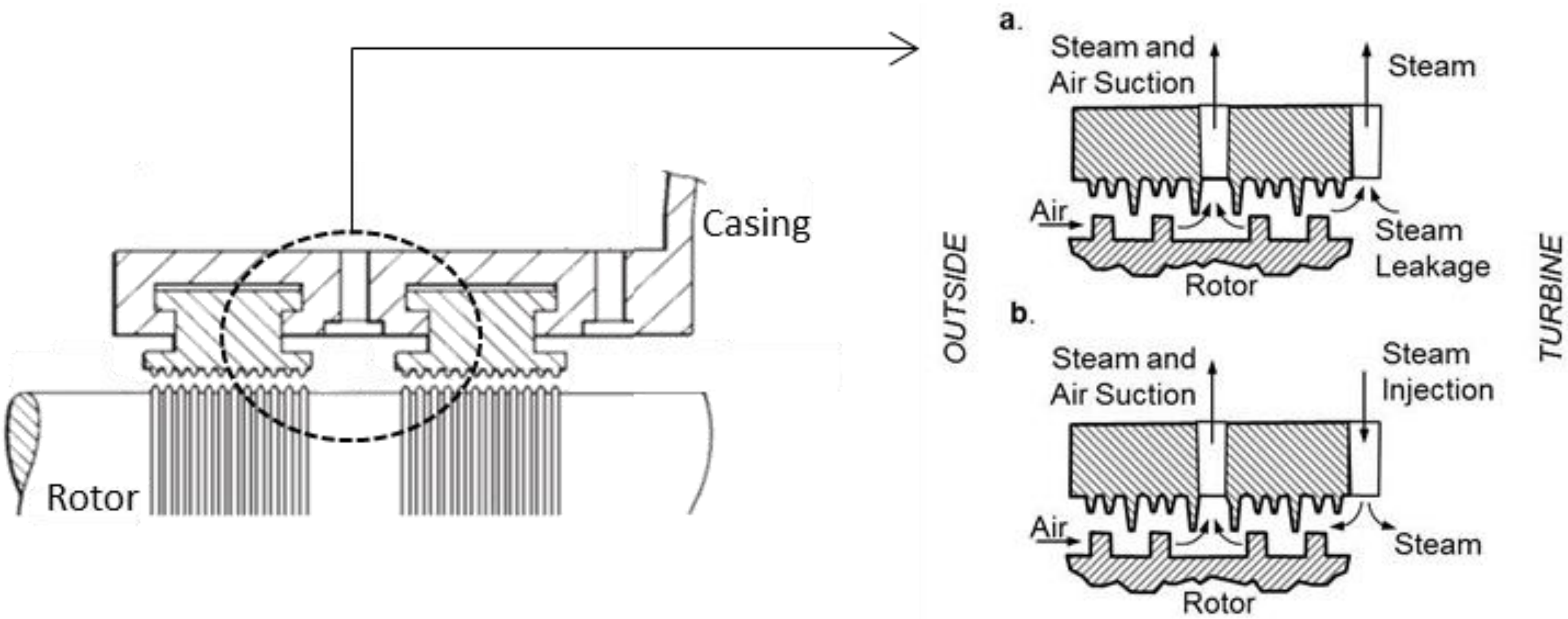
# 4. SEALS  Seal designs



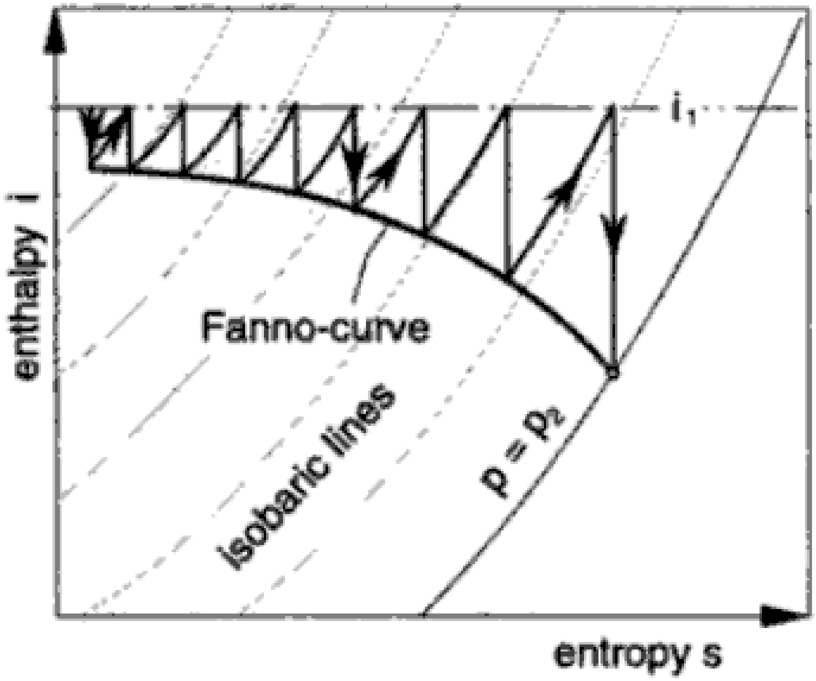



# 4. SEALS Operation

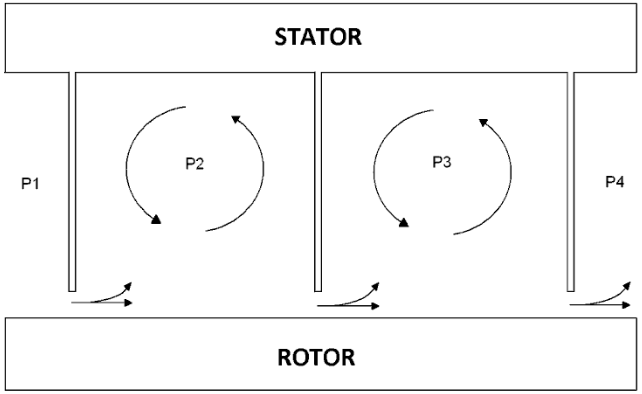


# 4. SEALS Theory

Fanno curve



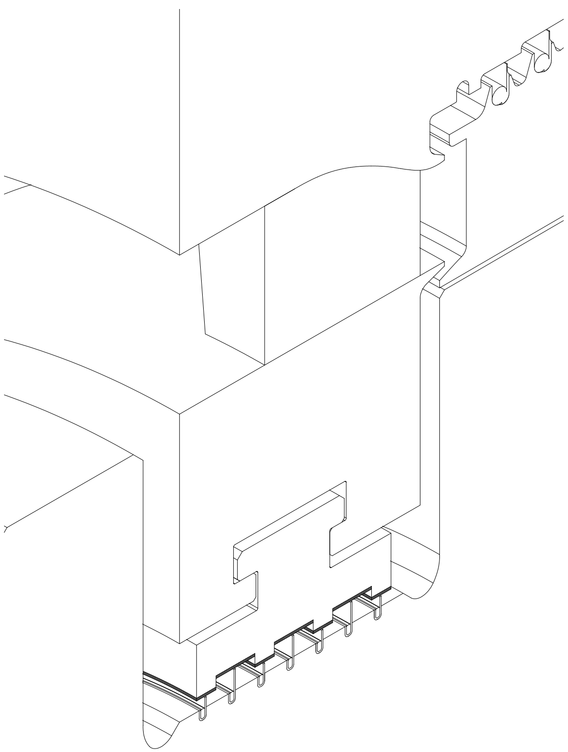

At clearance → high speed

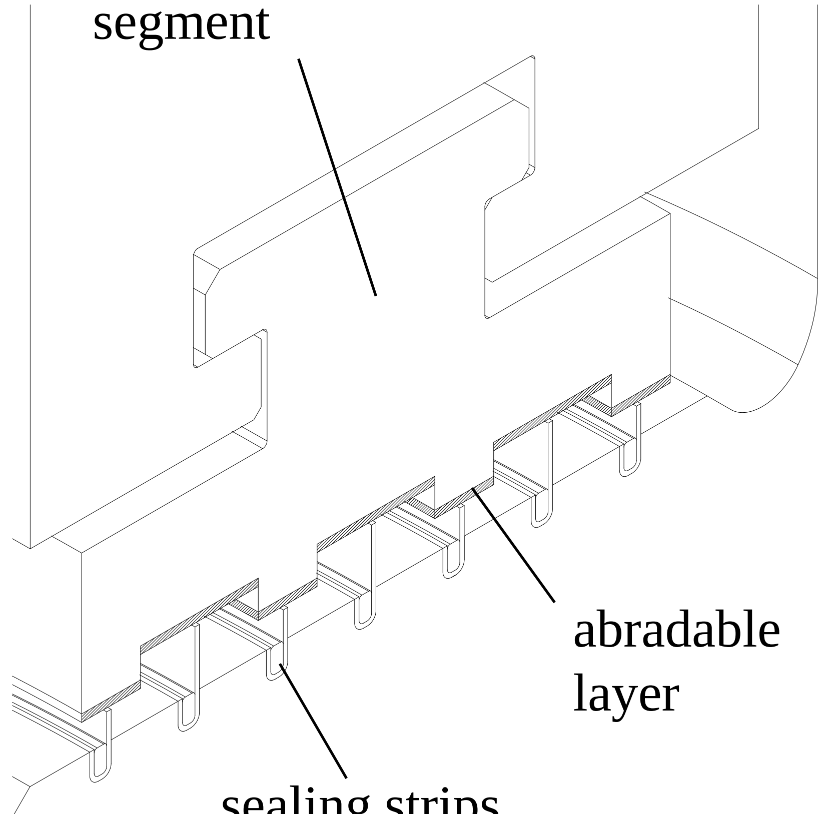



At cavity → dissipated + pressure decrease

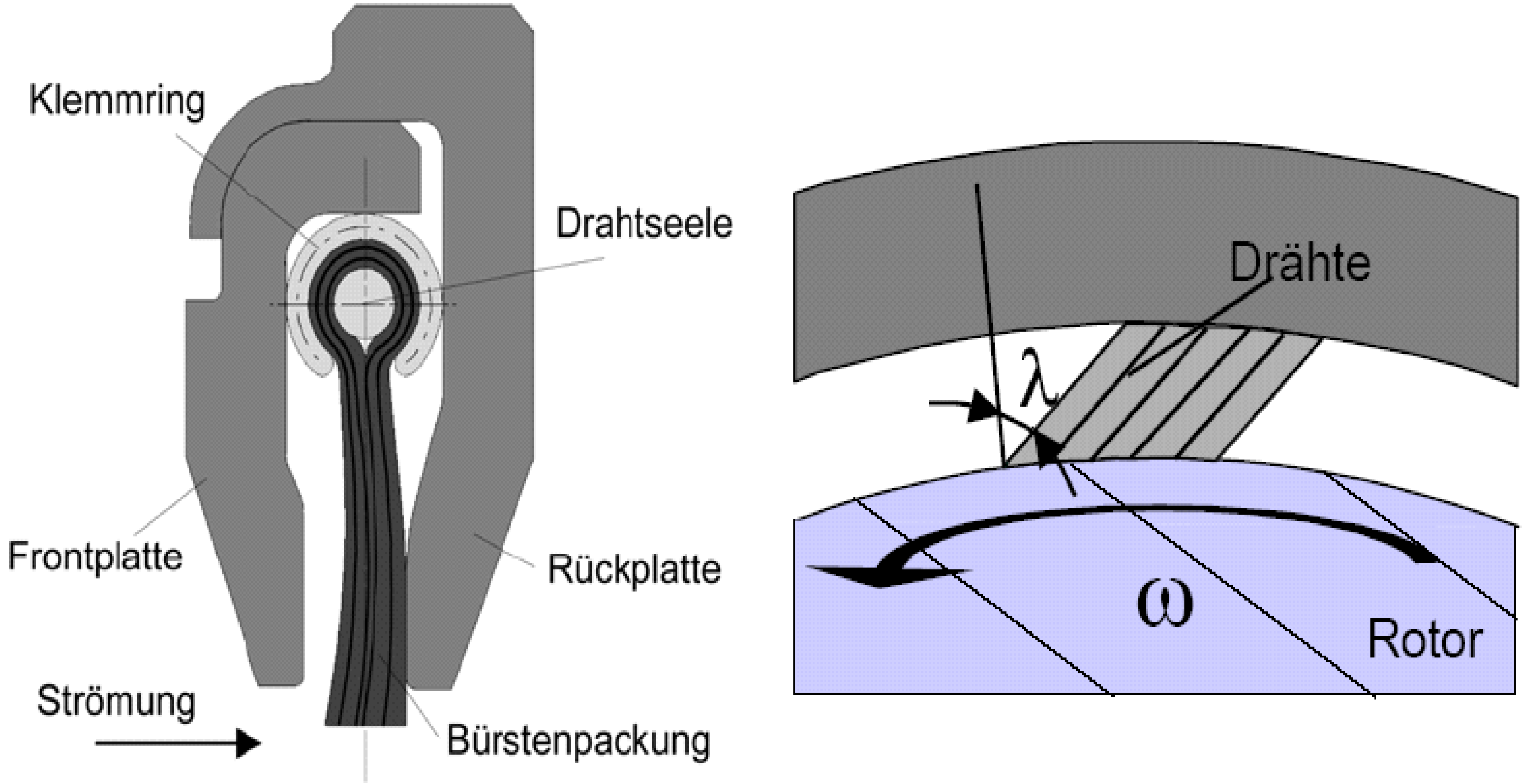
# 4. SEALS

## Abradable seals

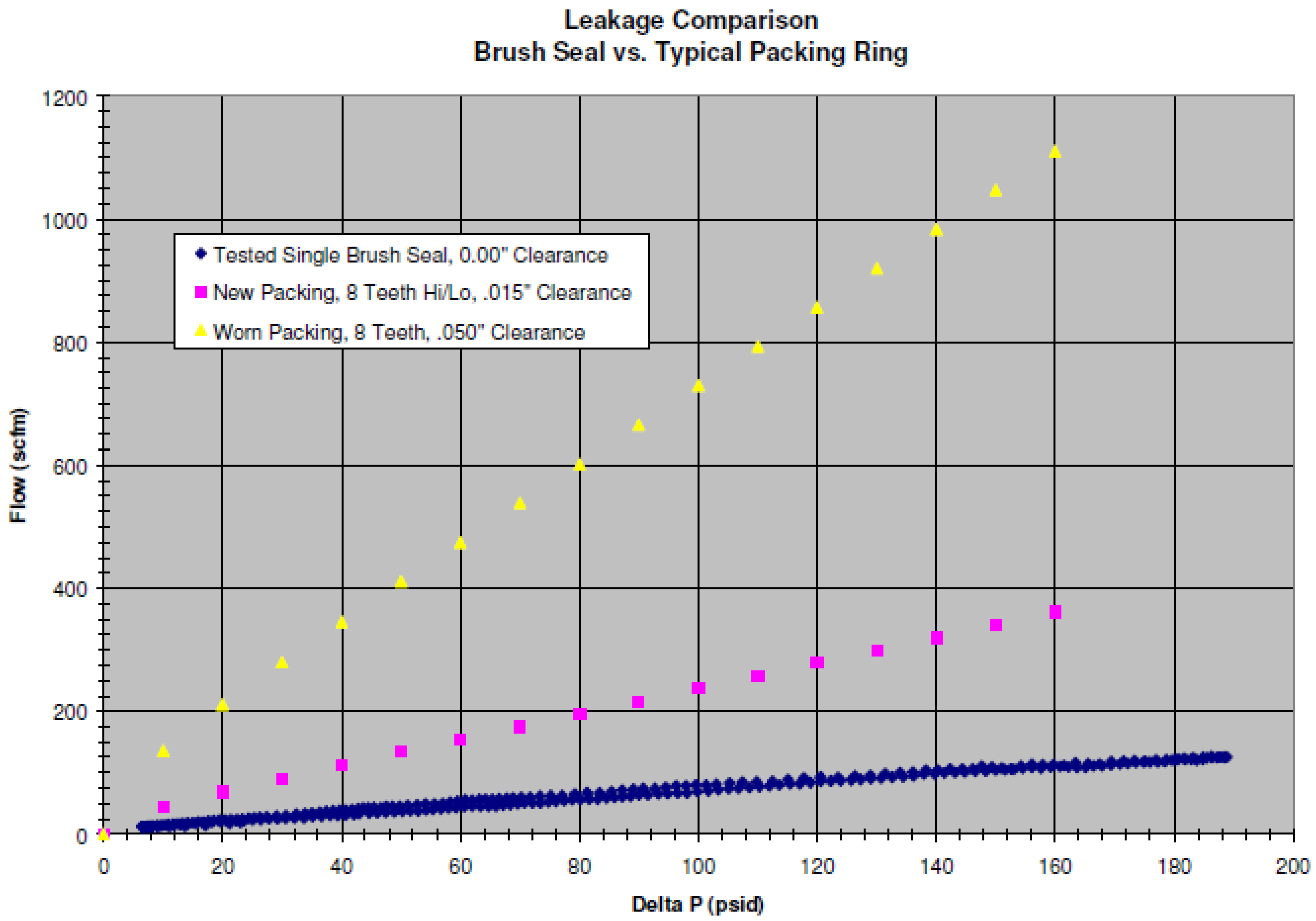




# 4. SEALS Brush seal



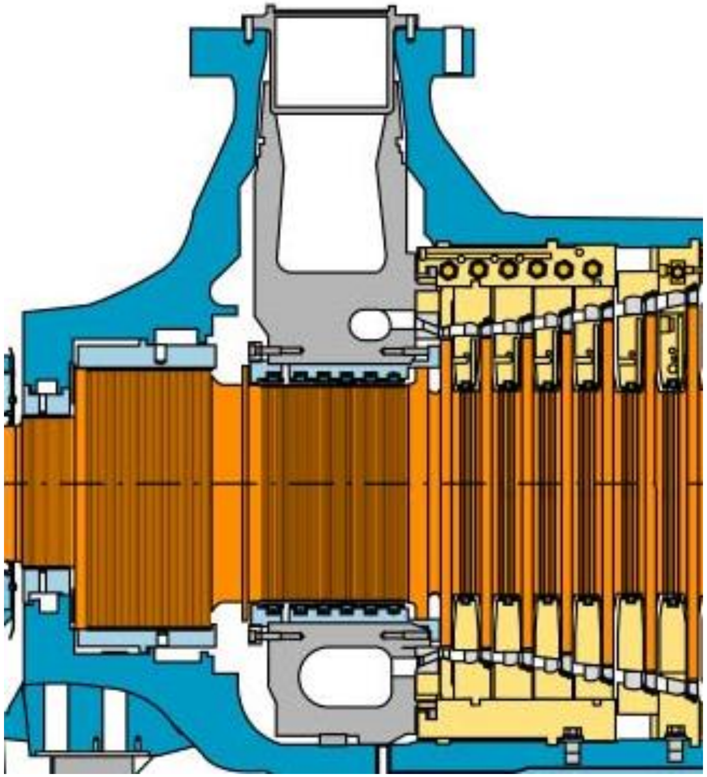
# Seals comparison

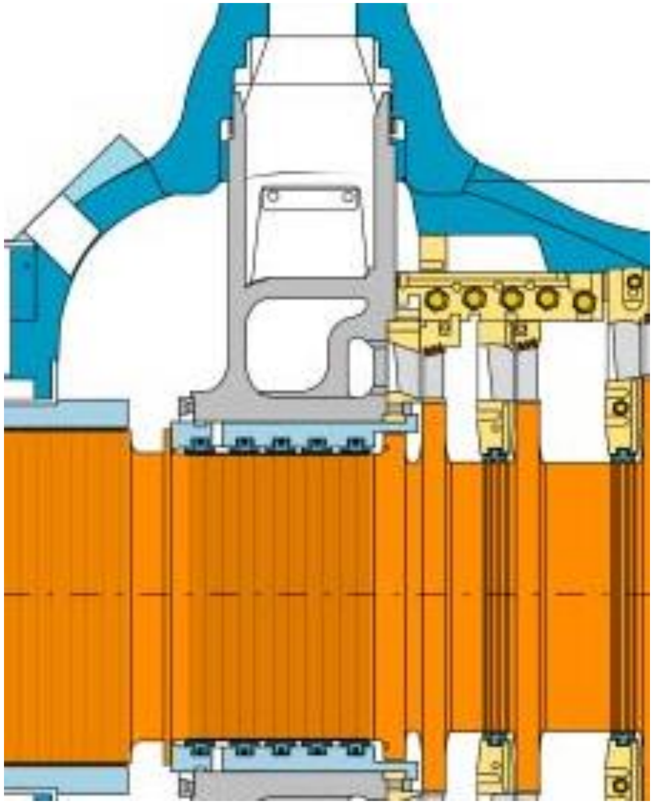



[Turbocare, Power Gen 2005]

# 5. INLETS

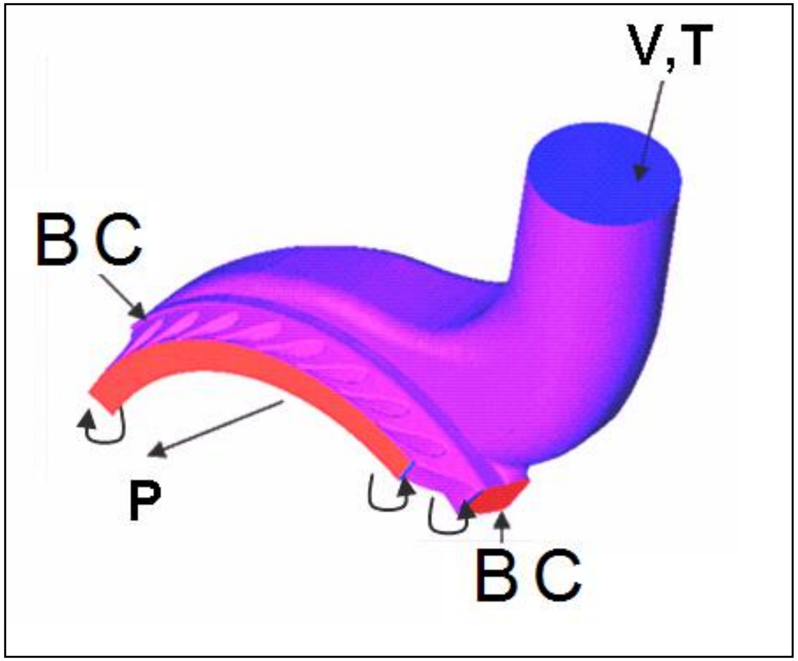
Main function: admit steam

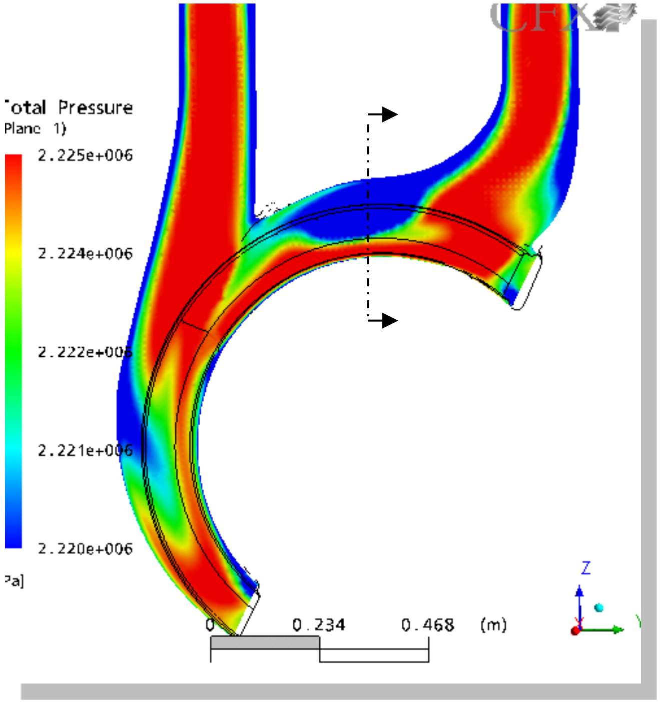




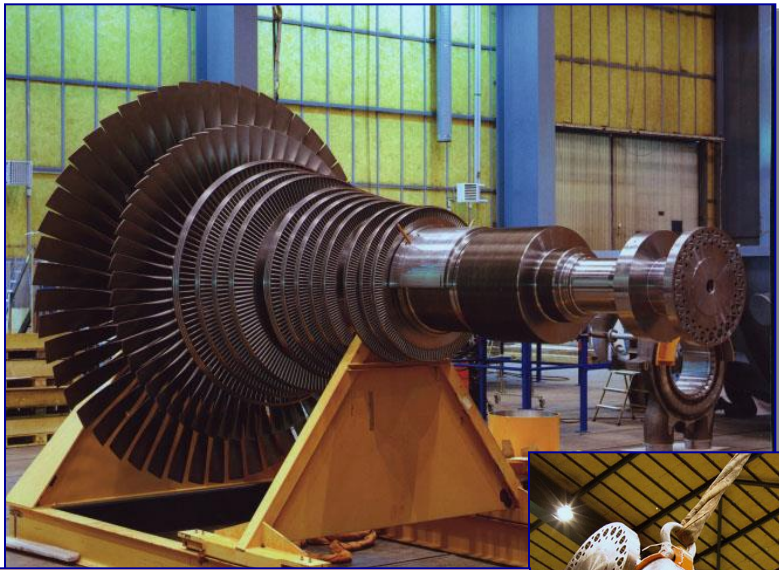
# Inlet pressure losses

Figure of volute and flow

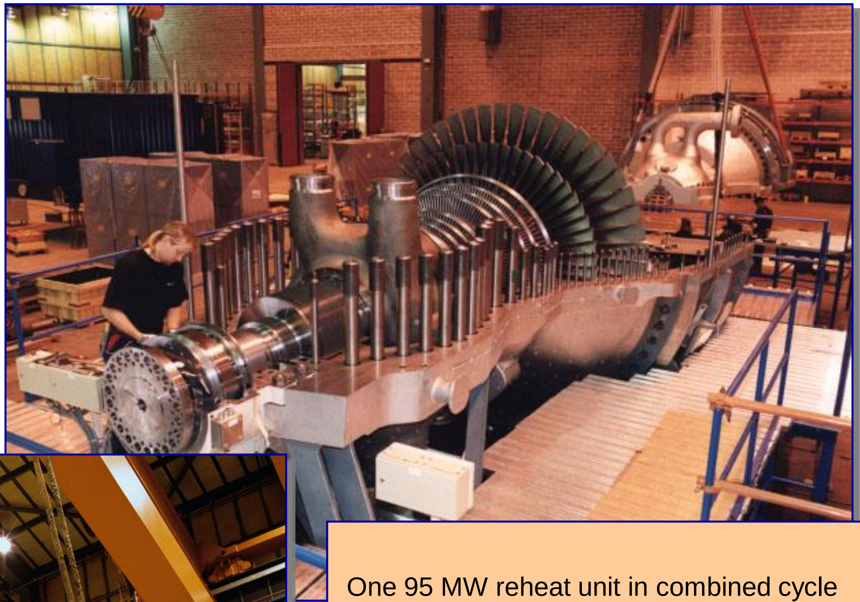


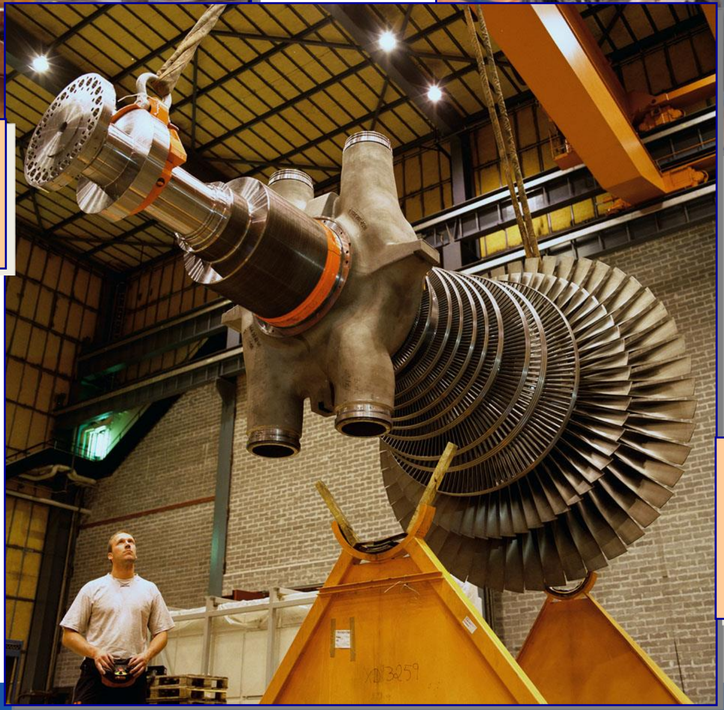
# Volute Assembly



One 114 MW reheat unit in combined cycle.
Inlet 148 bara/ 2150 psia, 565°C/1050°F,
with reheat to 565°C/1050°F.
Order spring 1999.



One 95 MW reheat unit in combined cycle
with a GE 7FA gas turbine.
Inlet 129 bar(a)/ 1871psia and 568°C/ 1054°F
Order March 2000.



Three 112.7 MW units in combined cycle
with W501F gas turbines. Inlet data
per unit 112.7 MW at 145 bar(a)/ 2103 psia and
561.3°C/1004 °F.
Order 1998.

# 6. CASINGS

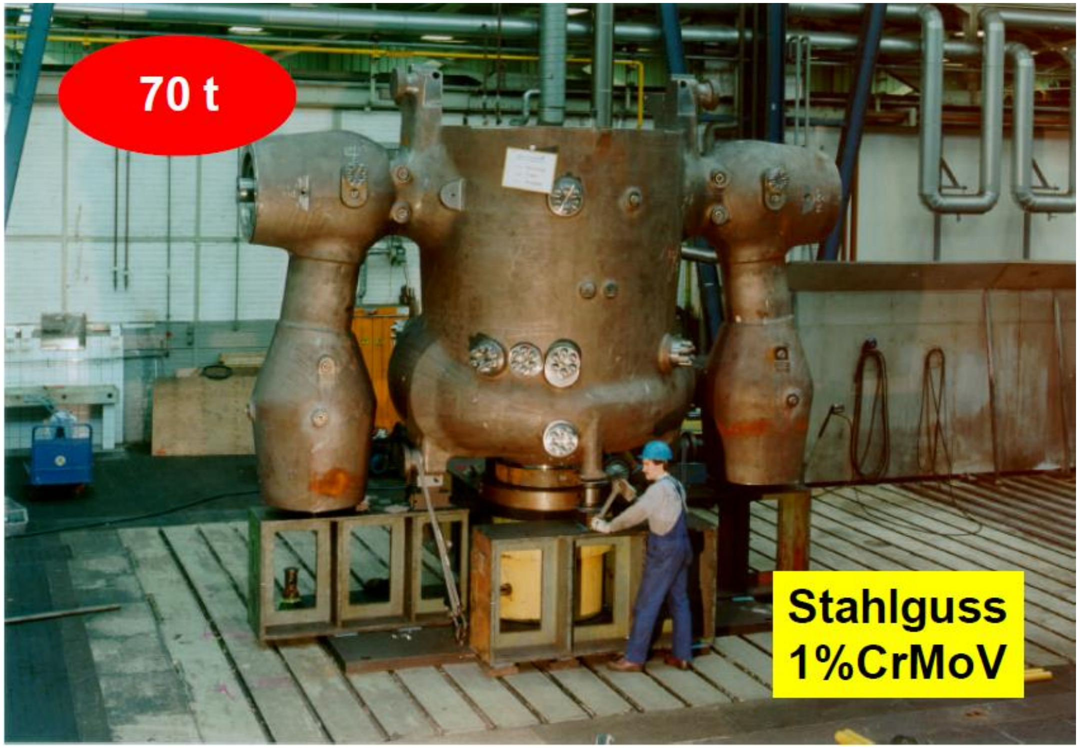
Main function: contain steam

Tightness
Mass
Thermal flexibility

# 6. CASINGS

## Main function: contain steam

Important parameters
-Tightness
- Mass
- Thermal flexibility



# 6. CASINGS

Large pressure loads
High temperatures (creep and LCF)

Welded designs and casted designs

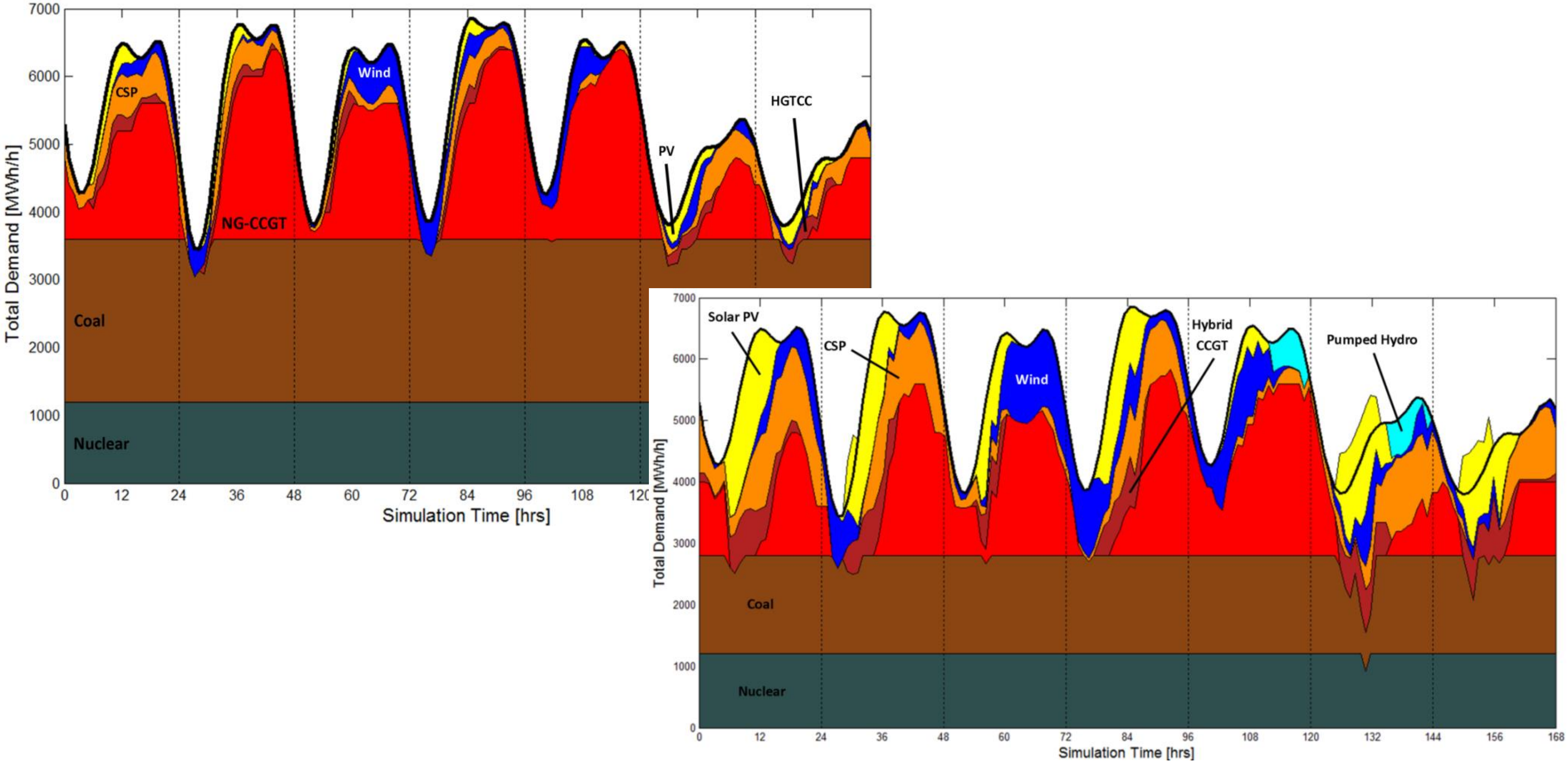
Modular design to adapt to applications necessary

# 7. FLEXIBILITY

***Steam turbines** have been available since the **19th century** and nowadays are the **dominant** technology in **electricity production**.*

↓

**Electricity Market Changes**



# The Start-up Process

1) Initial Conditions
- Overnight standstill
- Pressure kept in drum overnight
- Turbine in turning gear and sealed

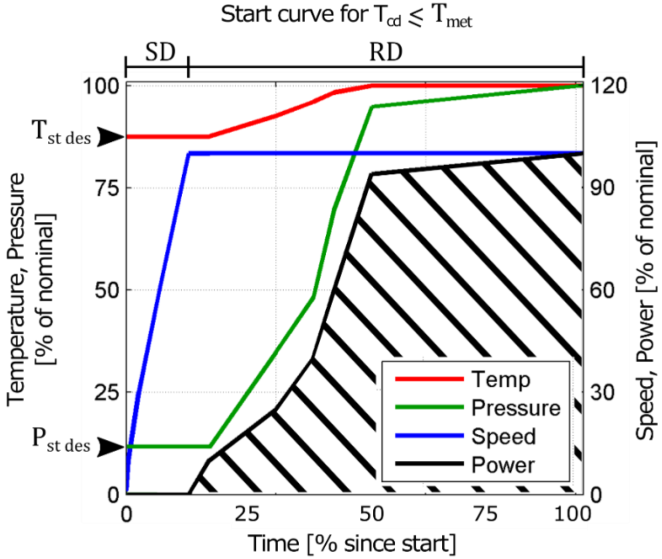
2) Boiler Start-up
- Recirculation to build pressure (mass flow)
- Steam conditions rising
- Allowed ramp rates $[\frac{K}{\text{min}}] = f(P)$

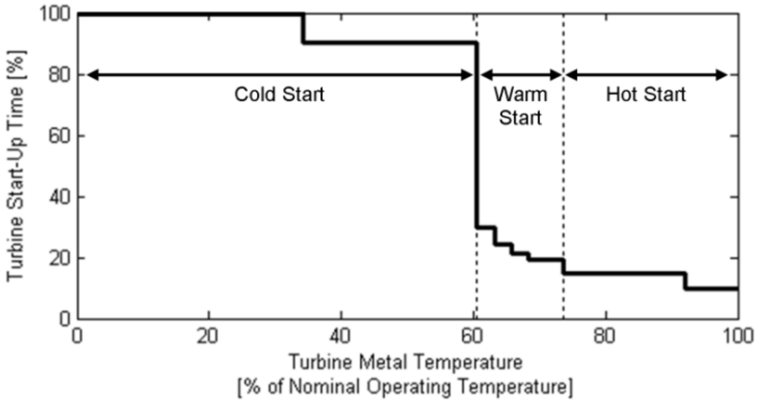
3) Preheating
- Main header to turbine
- Bypass to condenser

**4) Valve Opening**
- Steam matching turbine requirements
- Pressure, Temperature, Desired superheat

**5) Steam Turbine Start-up**
- Temperature rates controlled

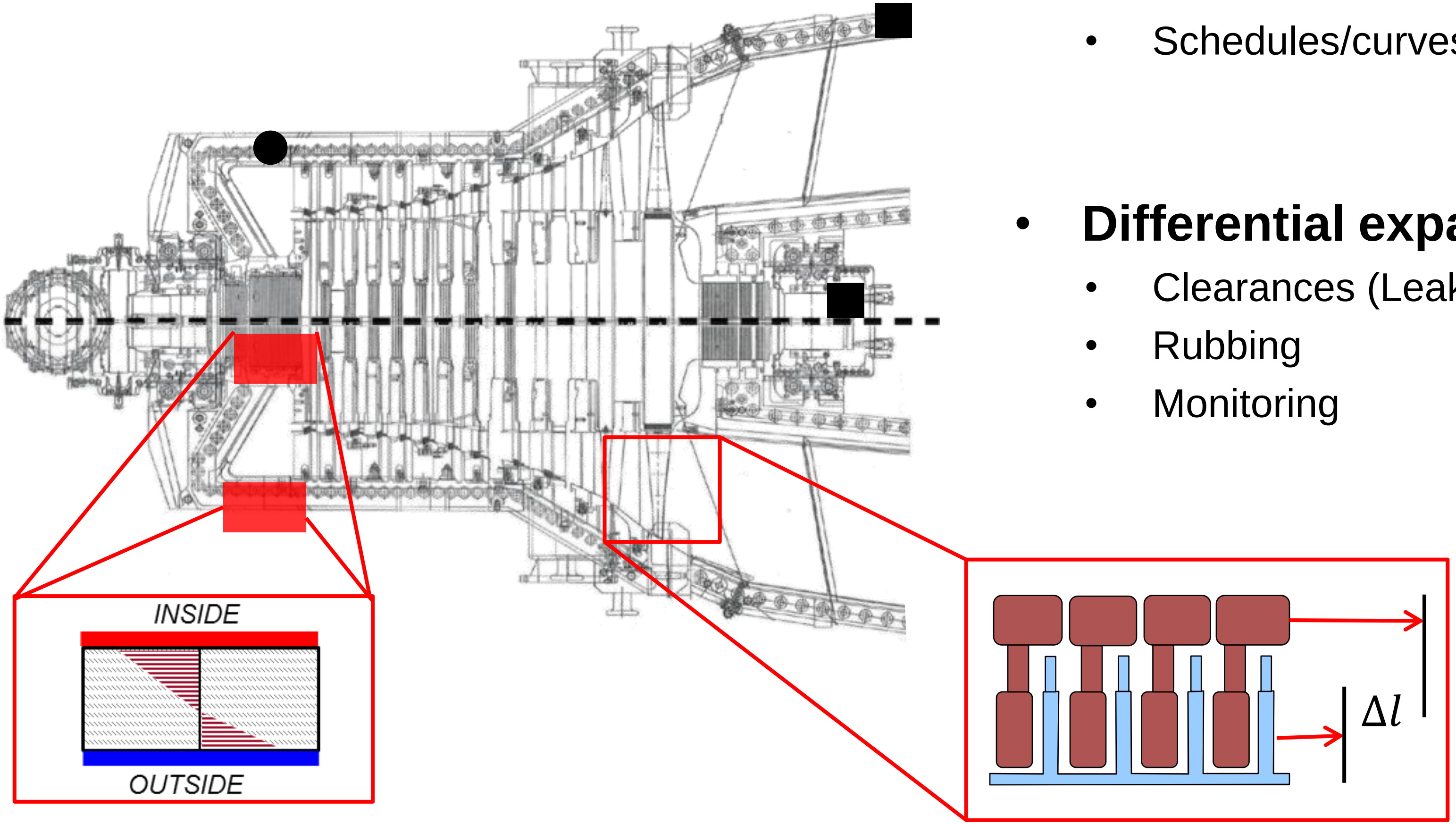
**6) Sync+Load**
- Rolling
- Loading



# Steam Turbine Start-up Operation

- Steam temperature(t)
- $T_{steam} - T_{metal}$



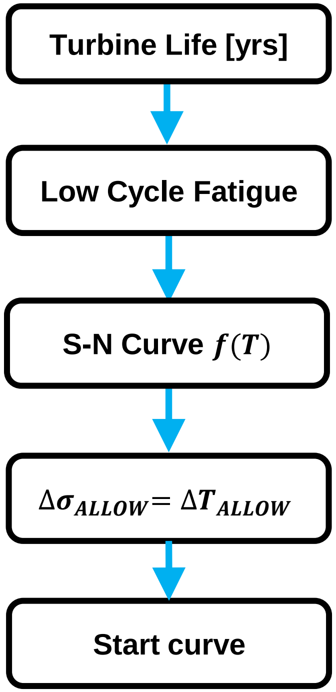

- **Thermal stress ●**
  - Thick-walled components
  - LCF Life
  - Allowed ΔT→ to last 40 yrs
  - Schedules/curves

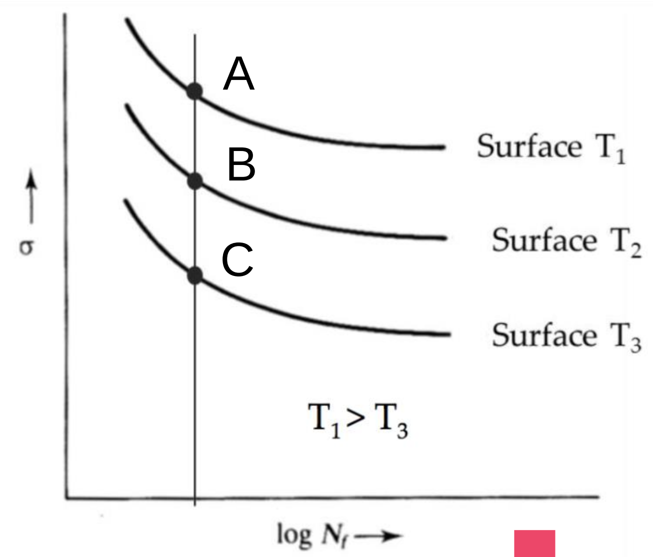
- **Differential expansion ■**
  - Clearances (Leakage)
  - Rubbing
  - Monitoring

# Thermal Stress and Life - Materials

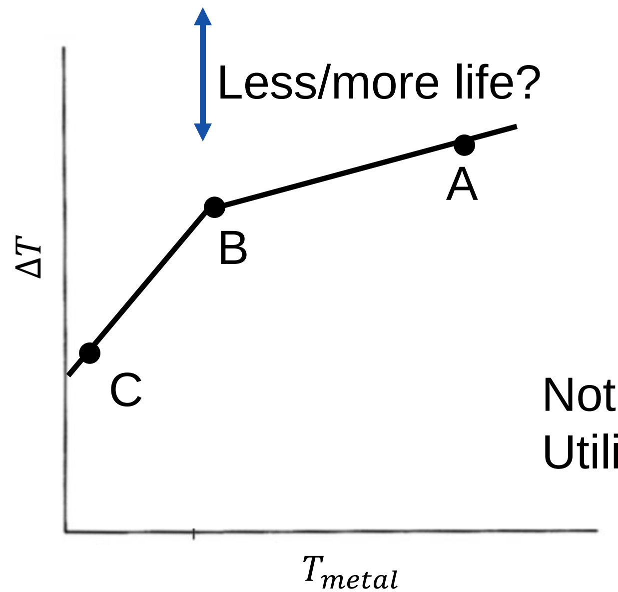
$$\sigma = \frac{E\beta_m \Delta T}{1-\nu}$$

$$\Delta T = T_s - \overline{T_m} = T_s - \frac{2}{R^2}\int_0^R rT(r)dr$$



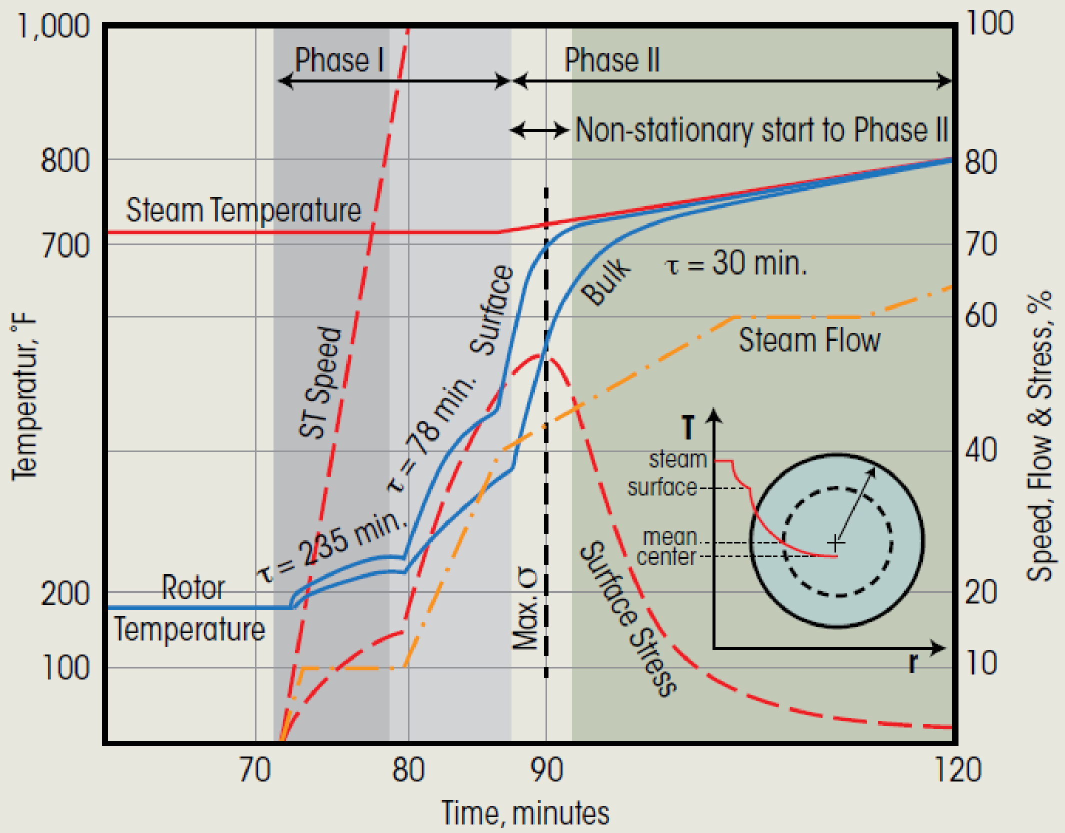




HS more life!




Notch factors!
Utilization Max

# Thermal Stress and Life - Transient



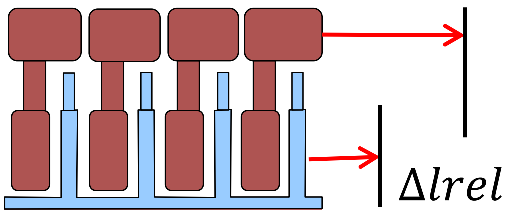

Typical ST roll via IP steam admission and the ensuing warm-up period [6]. Representative of a single-shaft GTCC cold start (total three hours). Note how the quasi-stationary Phase II is preceded by a short non-stationary period.

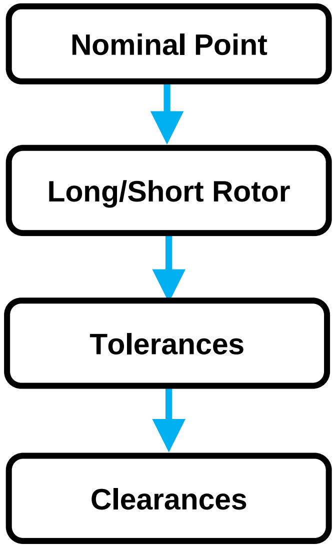
**Gülen ”Gas Turbine CC Fast Start: The physics behind the concept”*

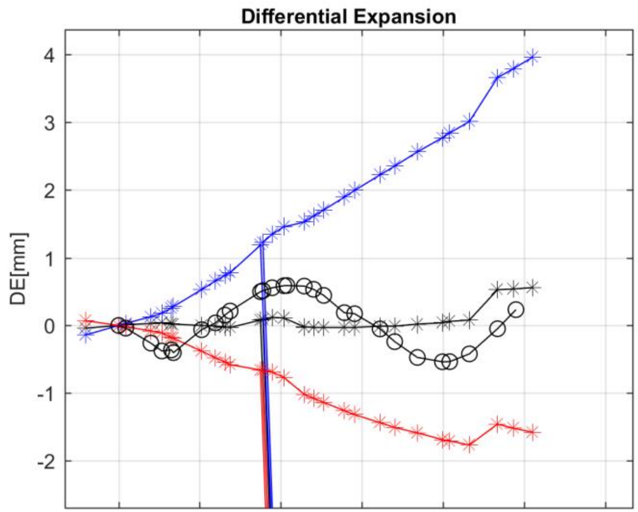
# Differential Expansion and Clearances

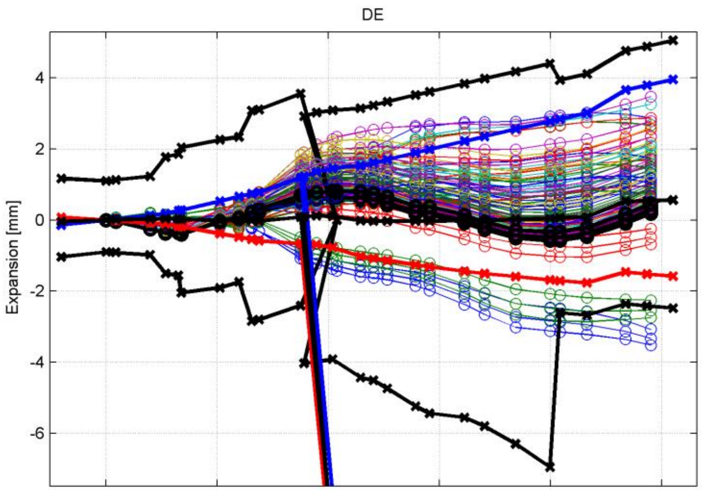
$$\Delta l = \beta_m l_i \cdot (T - T_i)$$

$$\Delta l_{rel} = \Delta l_{rot} - \Delta l_{cas}$$



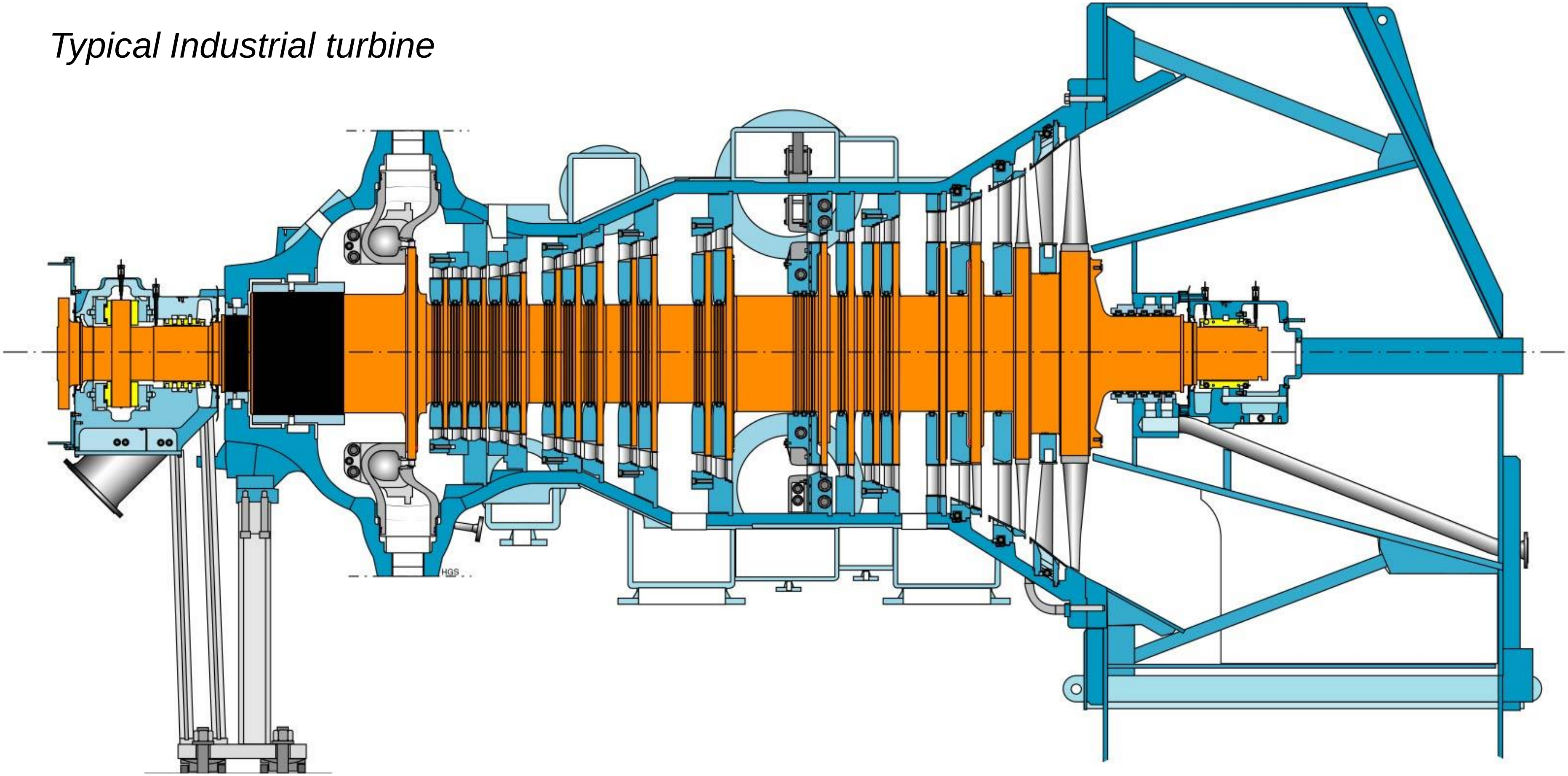



# Examples

Typical Turbine Layouts

# SST900-FN-34A-CE357

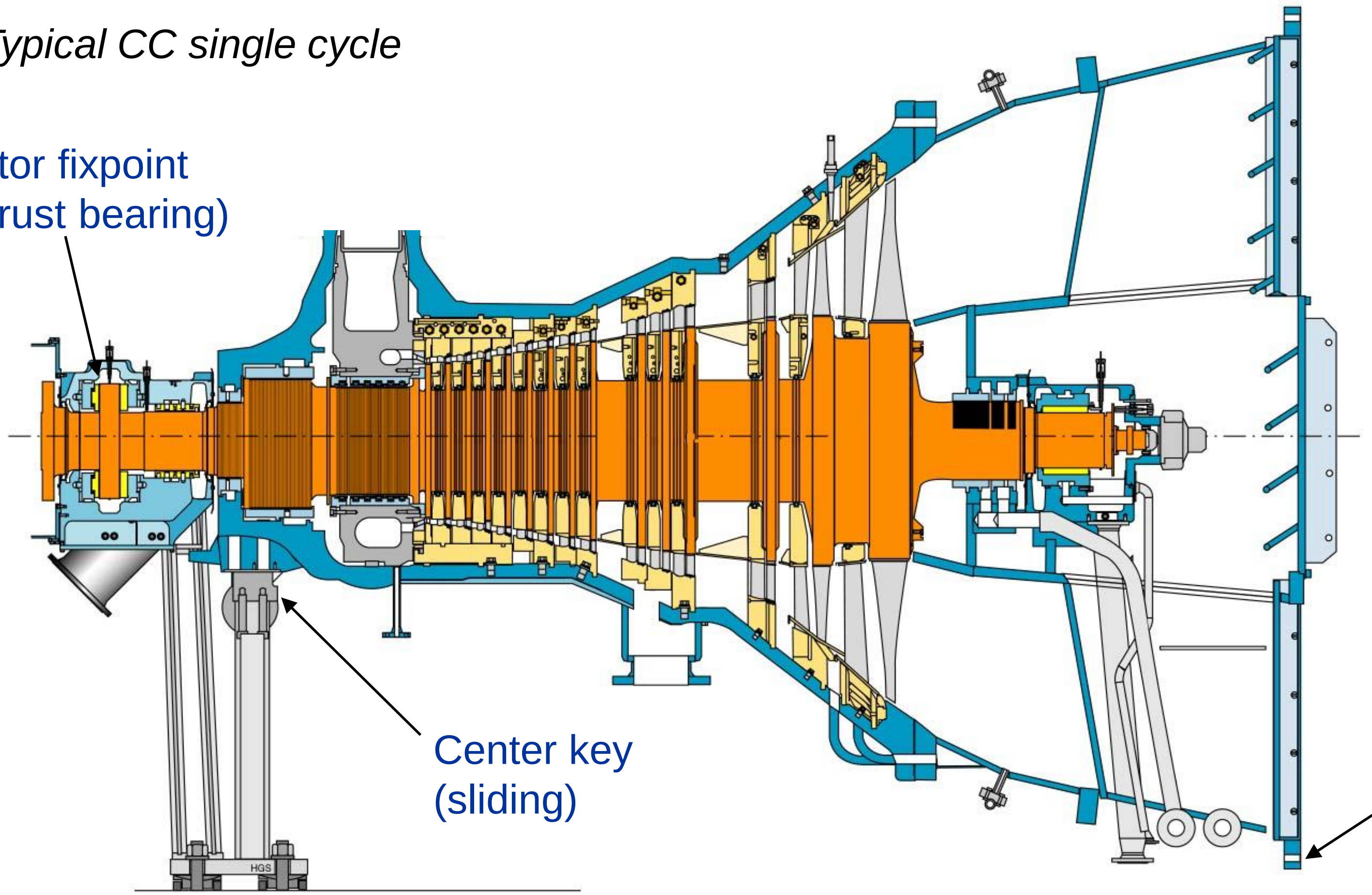
*Typical Industrial turbine*



# SST900-SV-2-C500

*Typical CC single cycle*

rotor fixpoint (thrust bearing)




Center key (sliding)

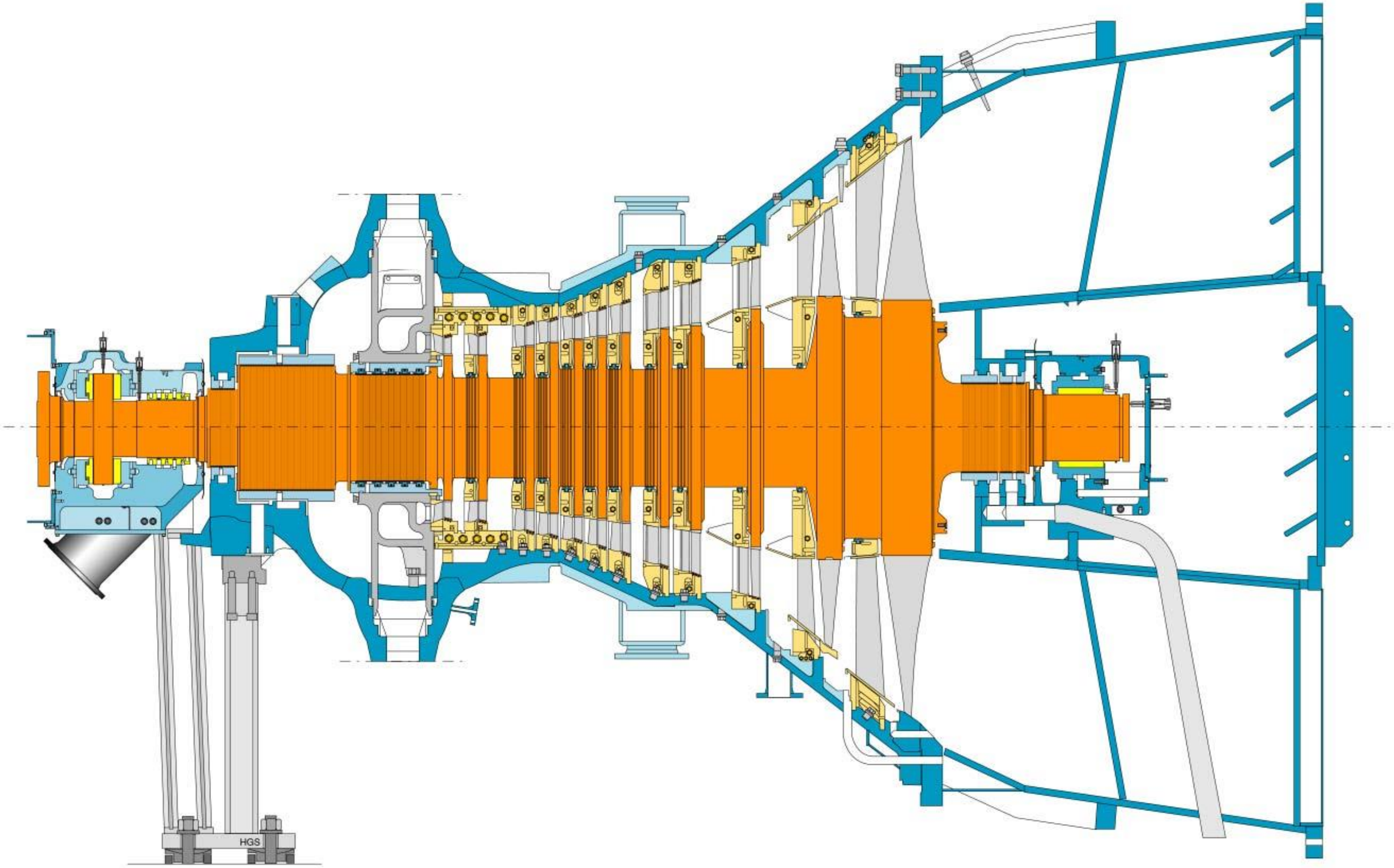
Flexible supports (no sliding elements)

casing fixpoint (600mm in to condenser)

- Minimised clearances in HP-part
- No majort sliding elements (maintenance)
- Cost effective
- High access for maintenance
- Compact
- Cost effective

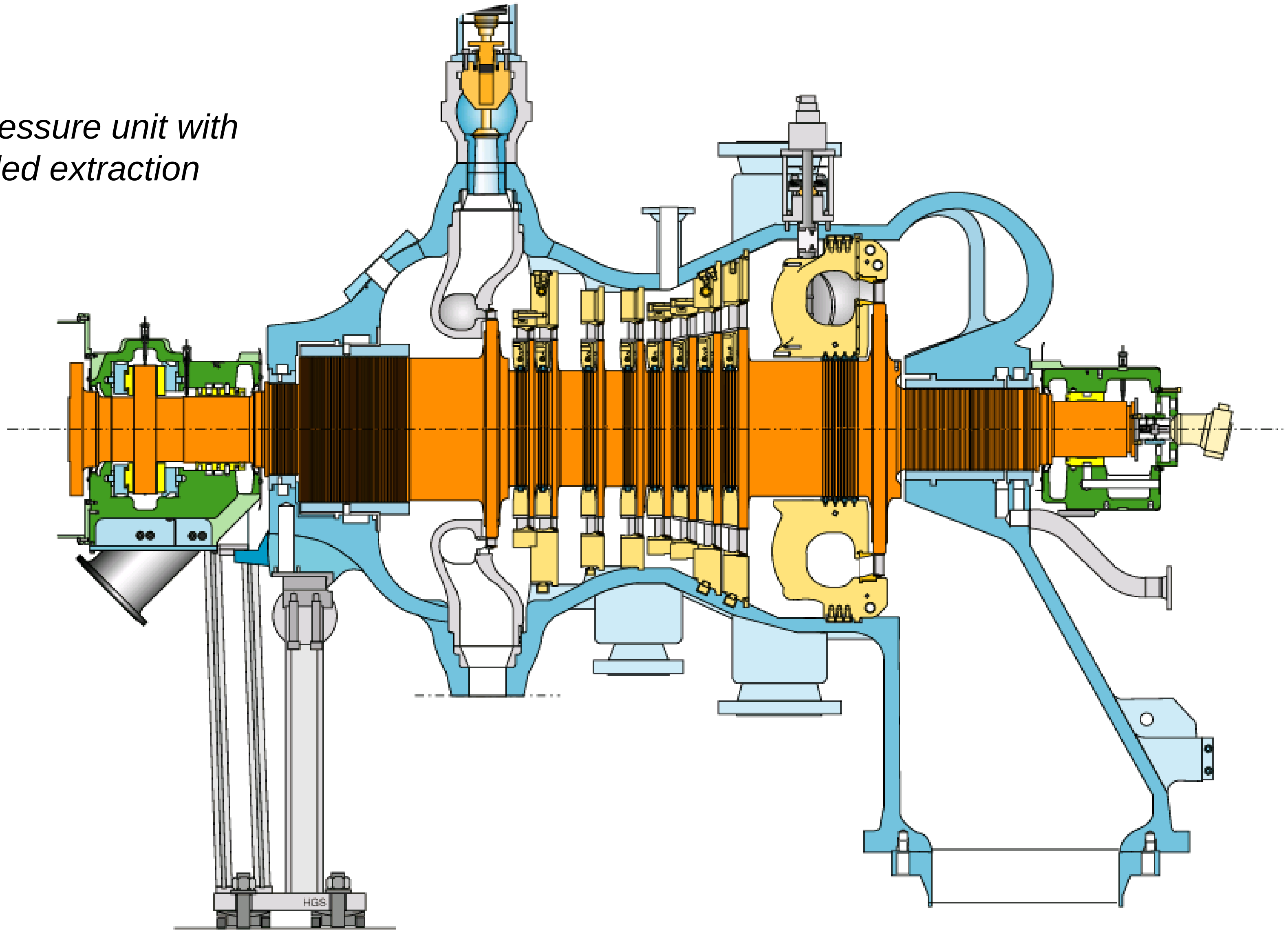
# SST900-FV-2-C620

*Typical IP for CC Reheat*



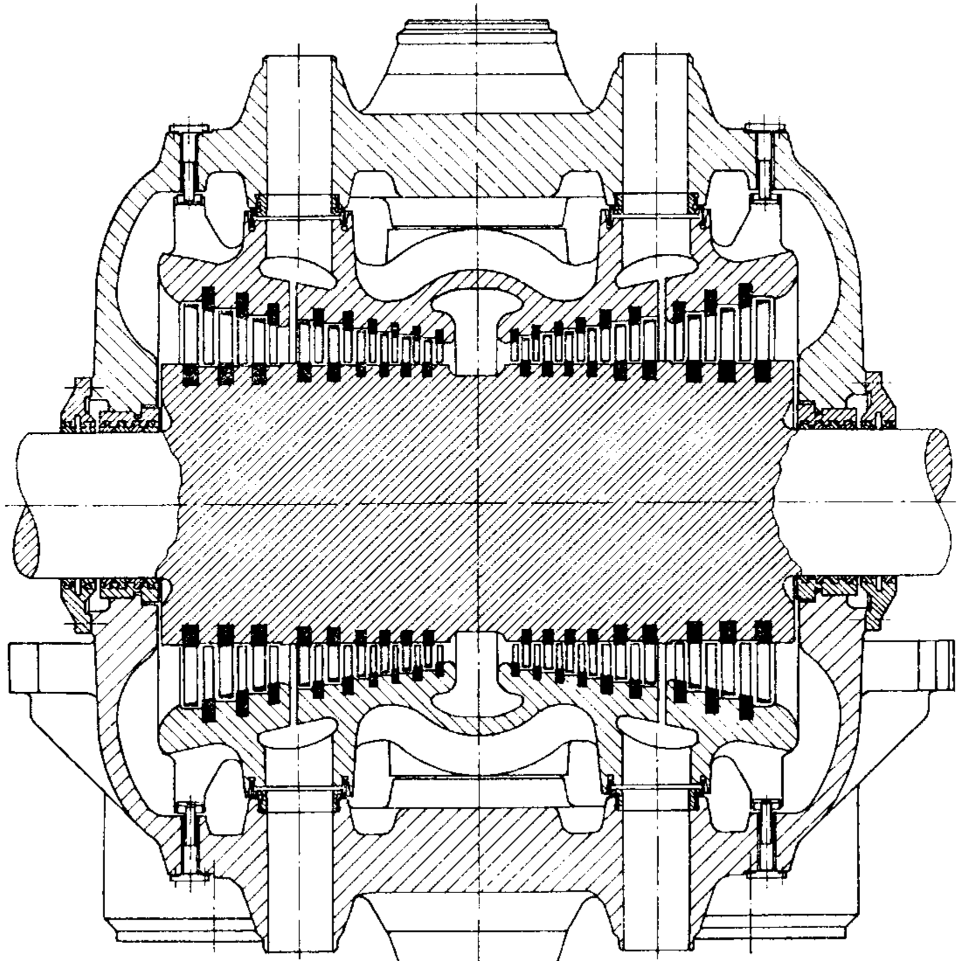
# SST900-FN-25B-BE(down)

*Backpressure unit with controlled extraction*

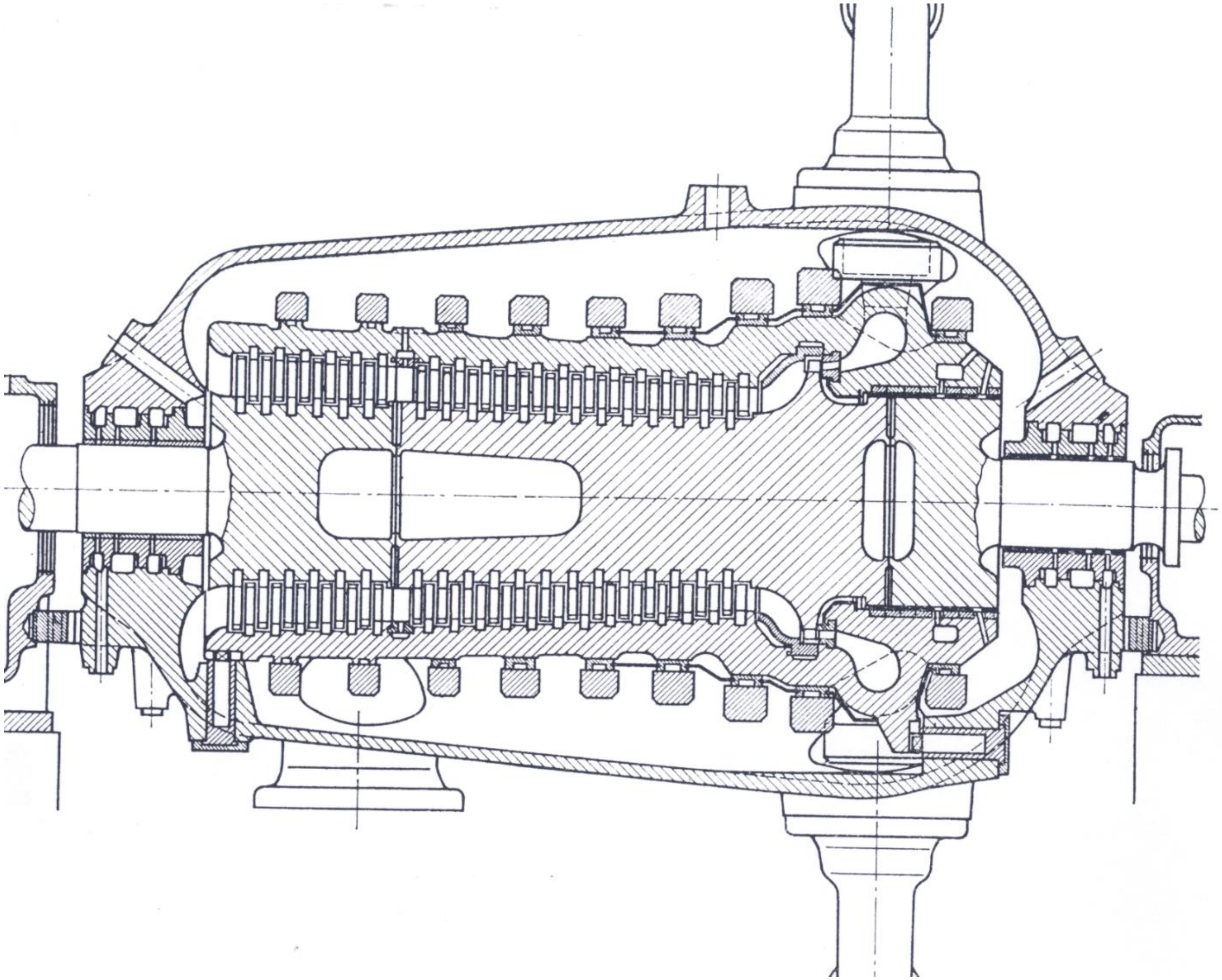


# Siemens SST 700 HP-turbine – barrel design

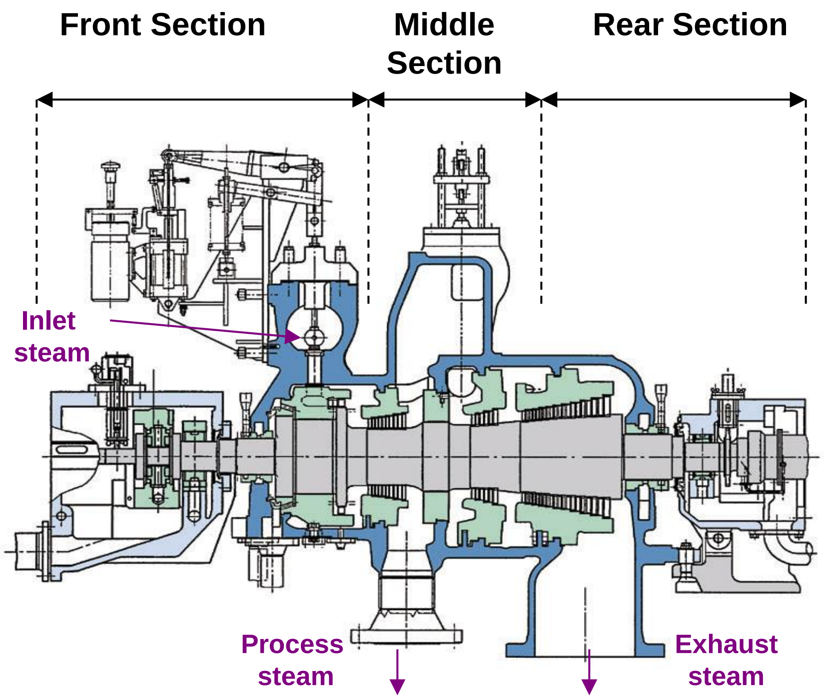
# Dual flow high pressure steam turbine



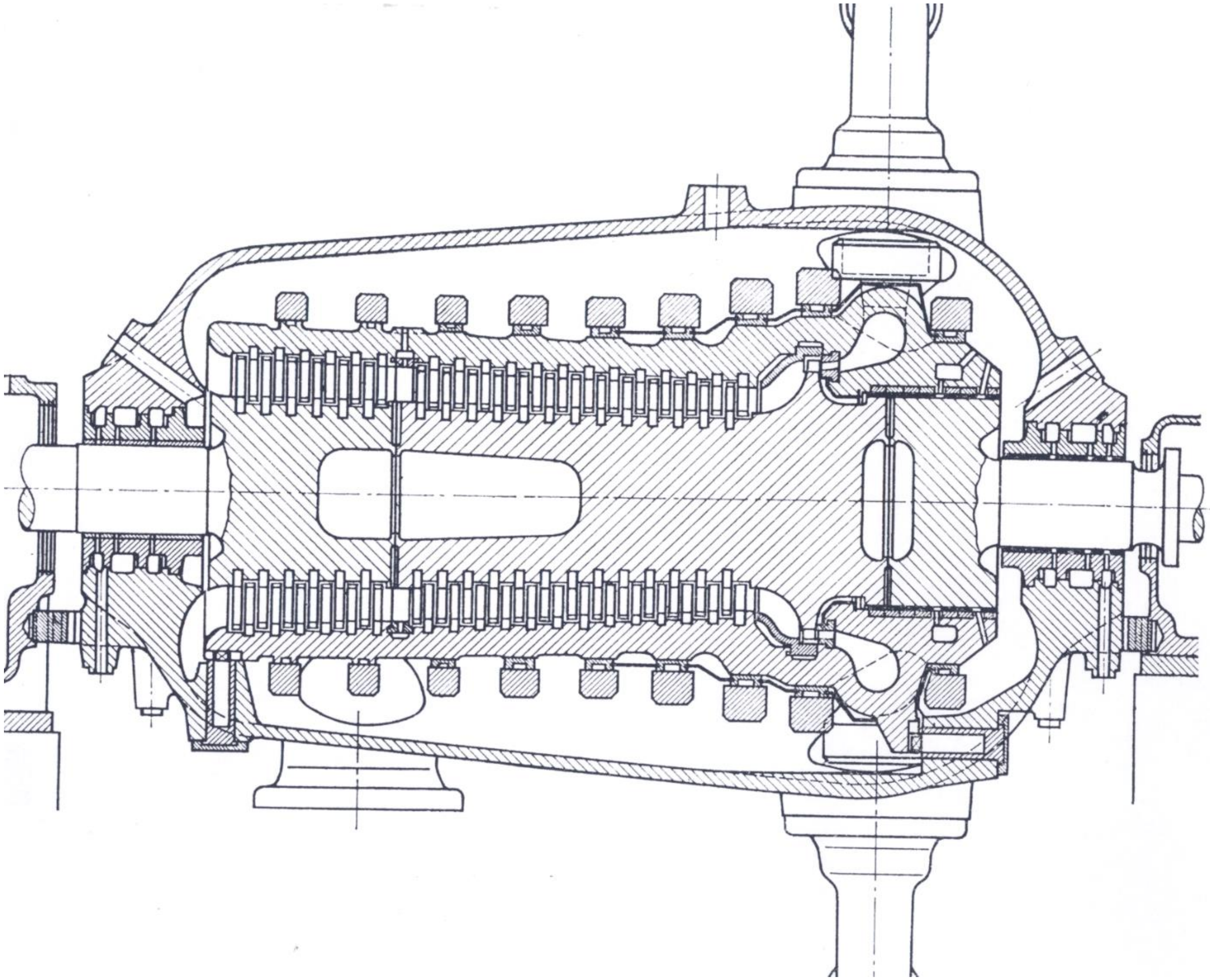
# High pressure steam turbine, drum rotor



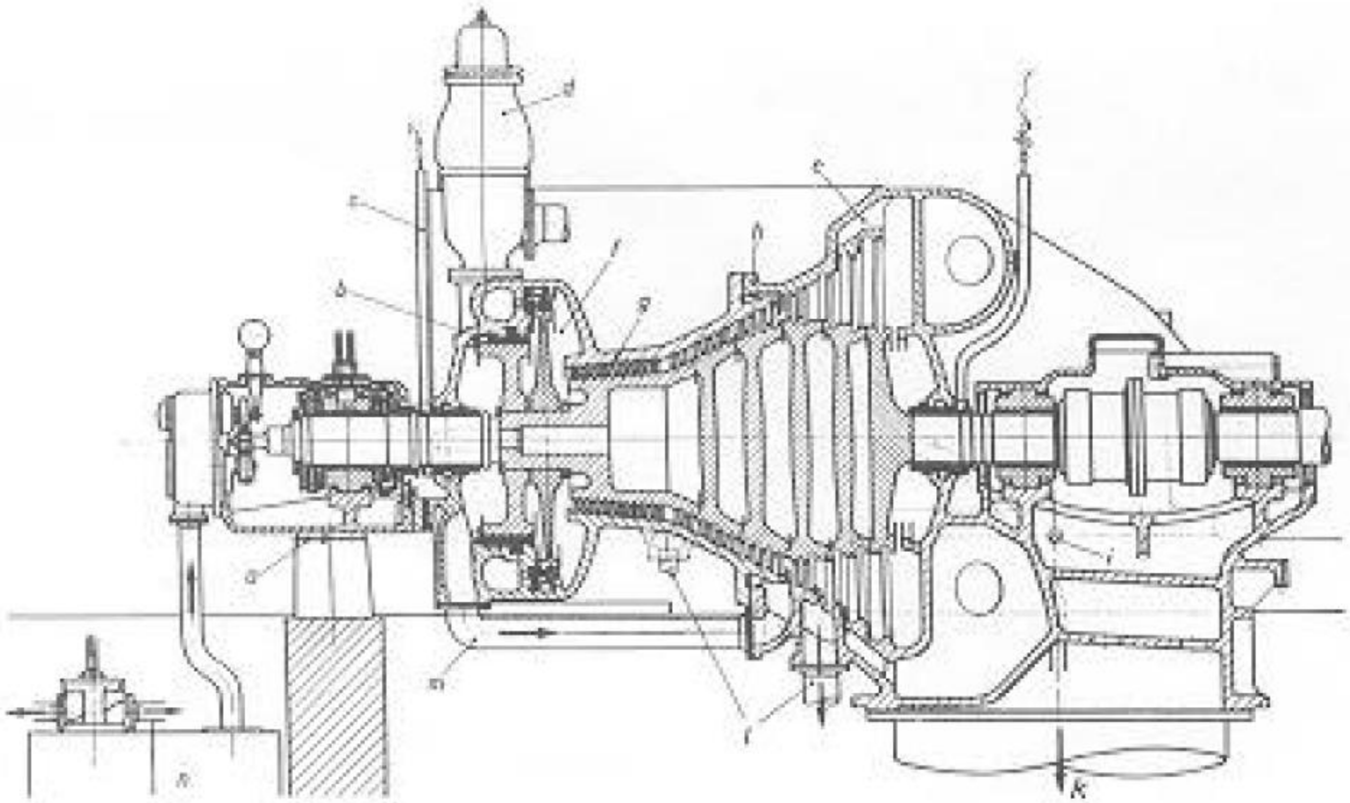
# Steam turbine with controlled extractions



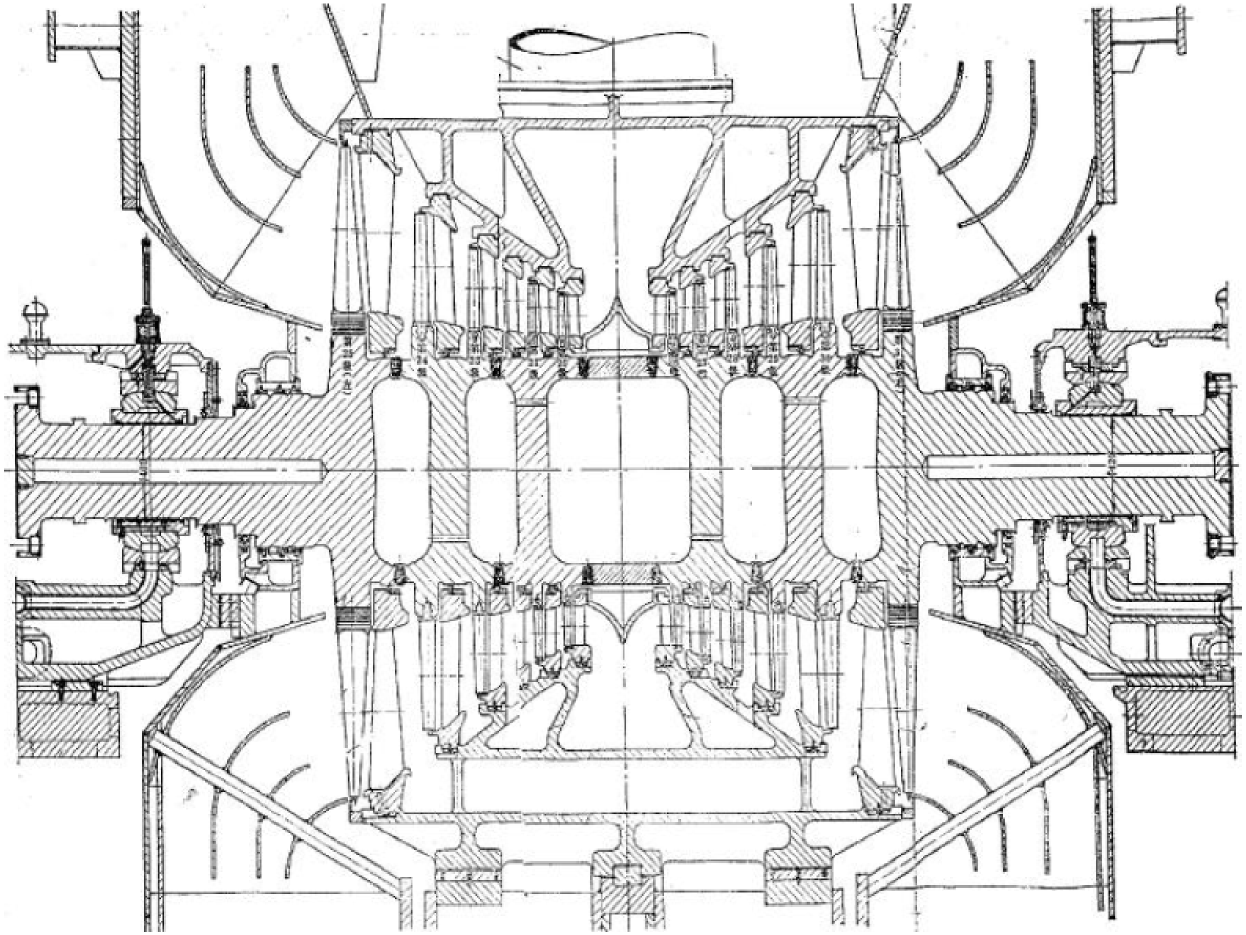

# High pressure reaction steam turbine with control stage



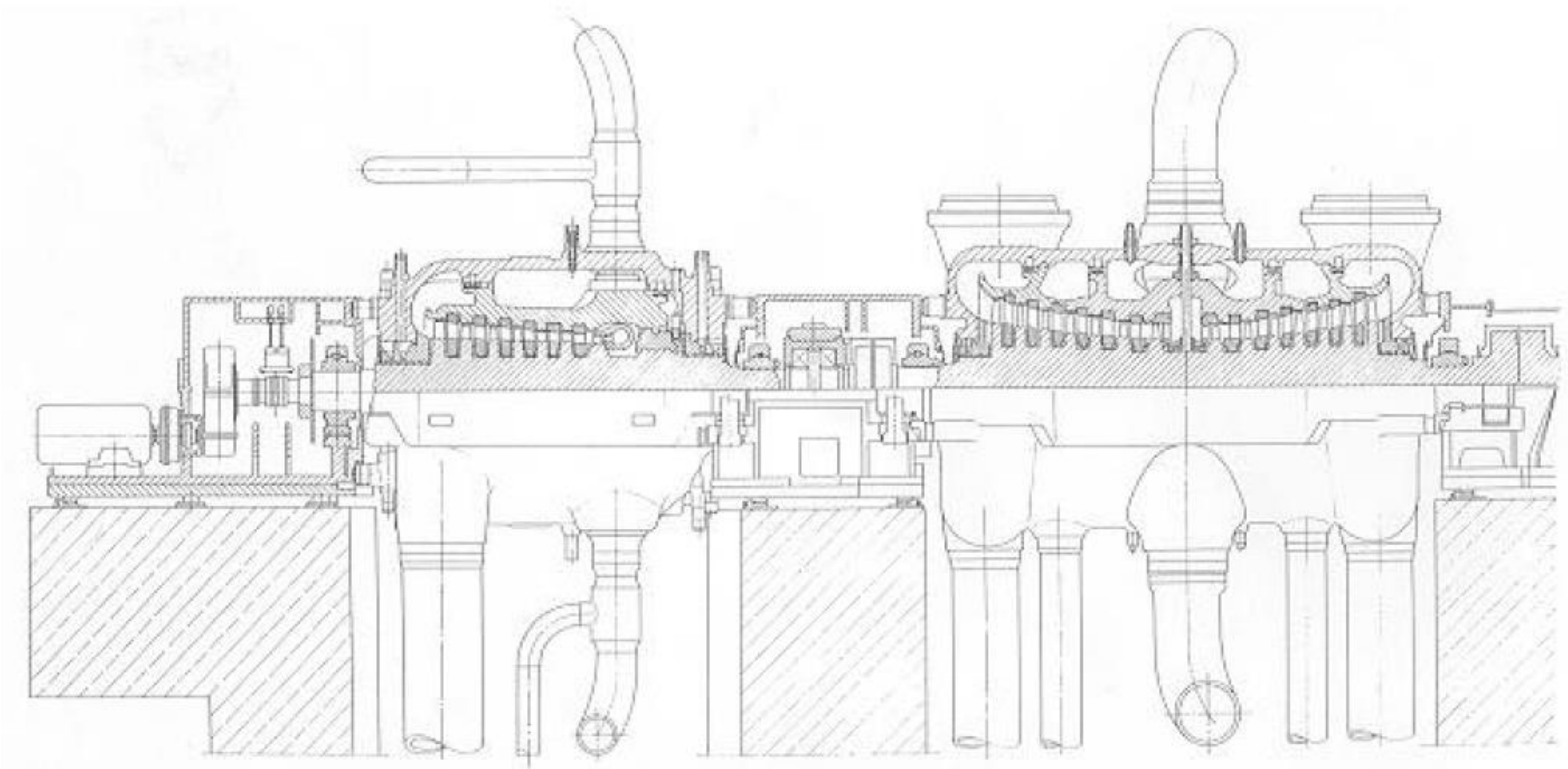
# Reaction steam turbine



# Low pressure impulse steam turbine from LMZ

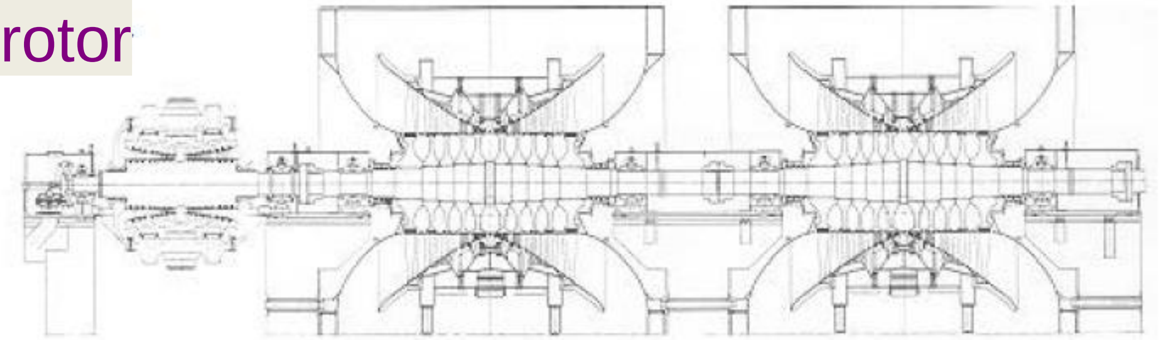


# High and intermediate pressure steam turbine with impulse blading

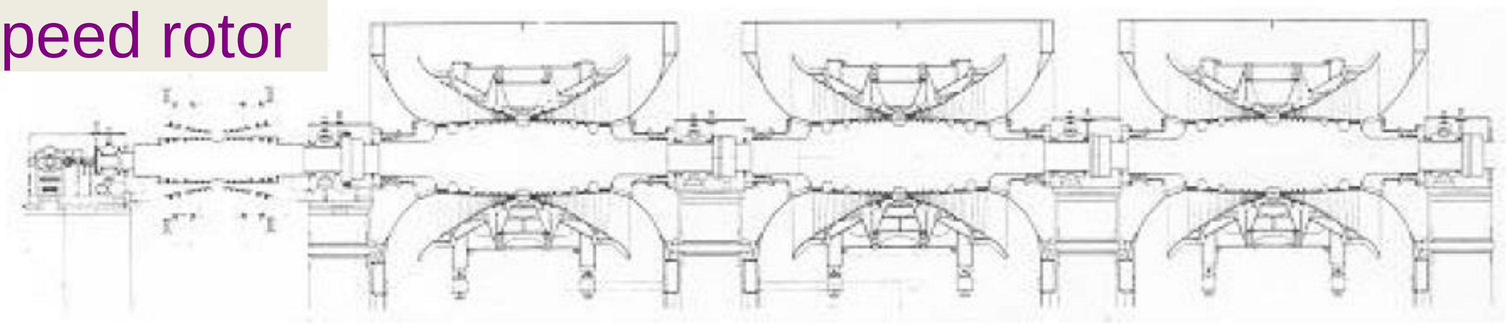


# Typical nuclear power steam turbine trains

Half speed rotor



Full speed rotor



End of Presentation

# Steam Turbine Technology

THANK YOU!