



Steam Turbine Thermal Stress
Online Monitoring Technology
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1. Overview and Importance of Stress Analyzer/Consumed Life Monitoring Technology

Introduction

- The demand for operational flexibility of existing power plants has significantly increased over the last decade due to incentivized growth of power generation from renewables and CCPP.
- Thermal stress in steam turbine thick-walled elements (the steam turbine rotor in particular) is a major limit on the flexible operation of steam turbines

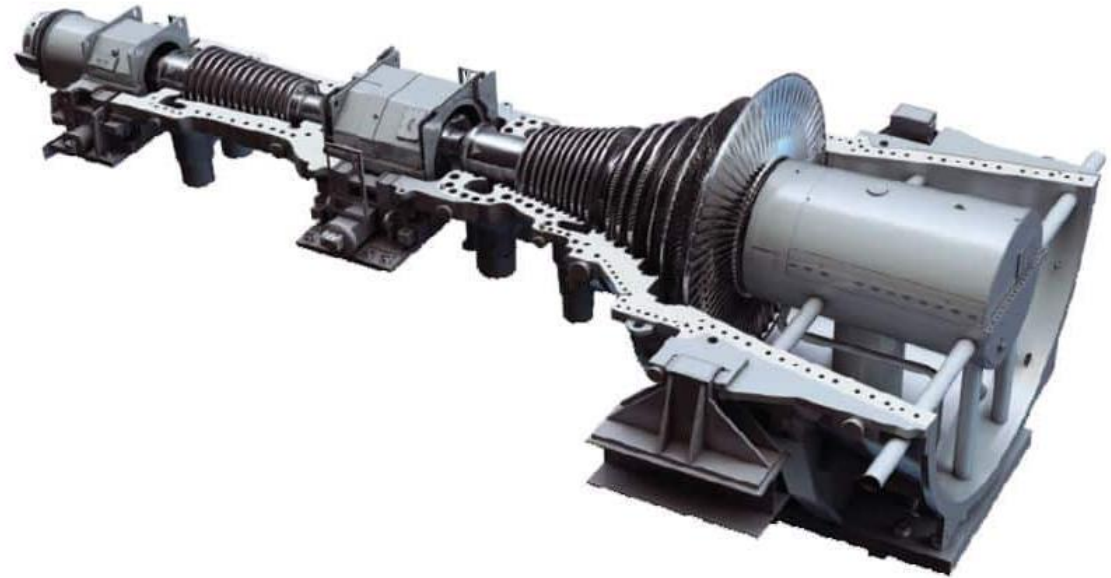


Fig. GE Steam Turbine for CCPP

<http://www.directindustry.com/prod/ge-steam-turbines/product-116289-1619774.html>

Importance of Stress Analyzer/Consumed Life Monitoring Technologies

Conflicting Requirements for CCPP Steam Turbine Design

- Accelerated starts
- Operation flexibility
(frequent start-up events)
- Long service life

Table. Typical start-up specification with P_n as nominal power (published by VDE, 2012)

Power Plant Technology		Hard Coal	Lignite-PP	CCPP
Load gradient	%P _n /min	1.5	1	2
Minimum load	%P _n	40	60	50
Hot startup (<8h standstill)	h	3	6	1.5
Cold startup (>48h standstill)	h	10	10	4

Design Lifetime vs. In-field Actual Operational Lifetime

- Lifetime design requirements are based on theoretical start-up curves
- **Actual start-up parameters usually differ from theoretical parameters**
 - Lifetime consumption must be corrected

Importance of Stress Analyzer/Consumed Life Monitoring Technologies

- The requirement of high operational flexibility in power plants and difference between theoretical and actual start-up operation data creates a need for utilization of online systems for monitoring and controlling the damage of critical components
- Such systems make use of different measurements and mathematical models enabling calculation of thermal stresses and their continuous control
- **Main purposes of online stress control:**
 - Assess the actual stress level in the steam turbine
 - Protect steam turbine from high thermal stress by monitoring steam temperature and flow during transient and steady state operation
 - Ensure the shortest possible steam turbine start up time for a guaranteed number of startups

Damage Mechanisms that Determine Component Life

Common damage mechanisms in the materials of turbine components:

- Fatigue (LCF, HCF)
- Creep
- Creep-Fatigue Interactions
- Corrosion
- Stress Corrosion Cracking (SCC)
- Mechanical Damage (erosion)
- Thermal Aging (carbide coarsening/inclusion growing)



Fig. SCC of a Steam Turbine Disk Dovetail

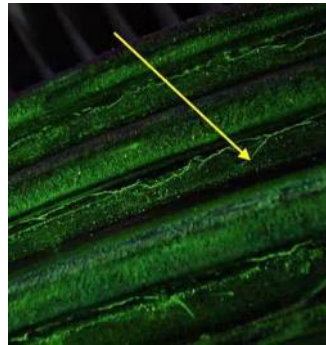


Fig. Damaged Steam Turbine Disk



Fig. Damage of Turbine Shaft

Damage Mechanisms that Determine Components Life

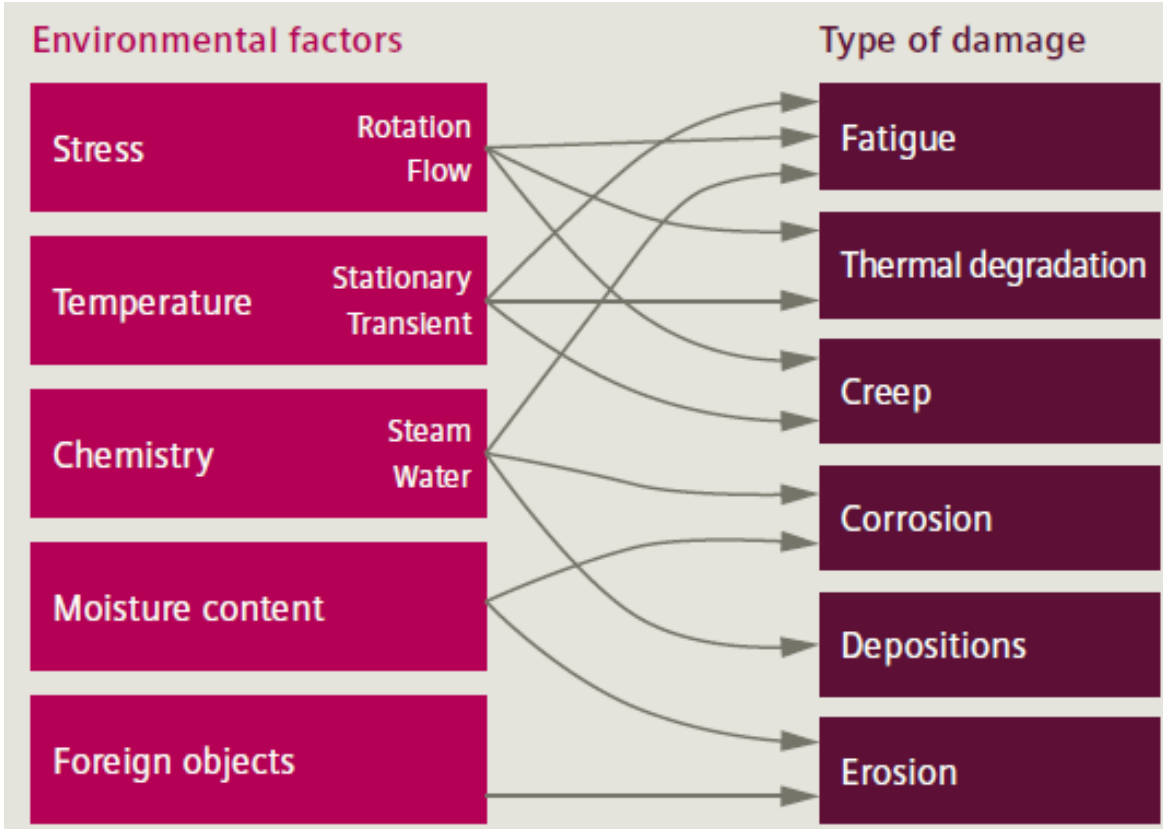


Fig. Broken Inlet Steam Pipe Due to Fatigue in a Position Exposed to High Temperature and a High Stress Level

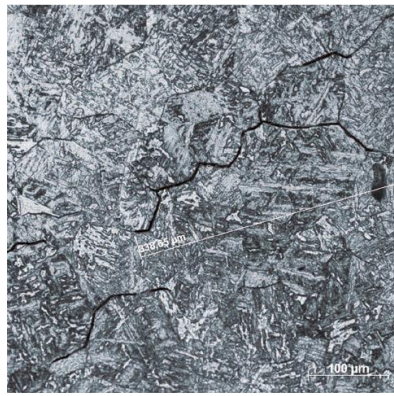


Fig. Creep Damages (micro cracks 400 μm - 2 mm)

Turbine Damages Caused by Transients

1. Thermal Fatigue of Thick-wall Turbine Design Elements

- Thick-wall turbine elements are prone to thermal fatigue caused by unsteady-state alternating thermal stresses arising at the transients
 - Rotors
 - Valve steam chests
 - Nozzle-boxes
 - Casings
 - Casing rings

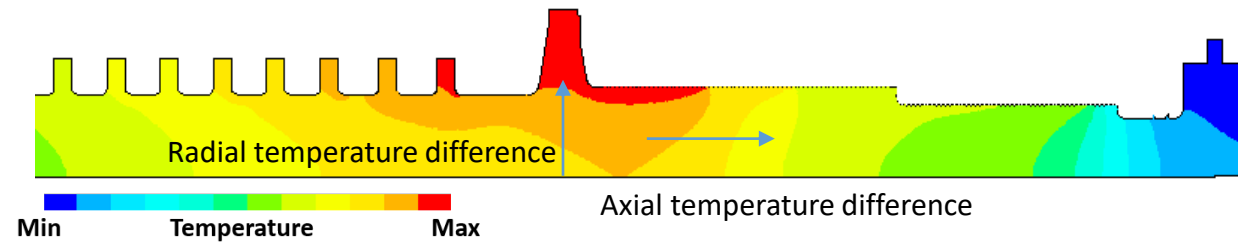


Fig. Temperature Difference in 300 MW Steam Turbine HP Rotor During CS

- Thermal stresses are caused by non-stationary temperature differences across the thickness of the element
- HP-IP rotors (critical elements for steam turbines)
- Radial temperature differences in rotor steam admission sections should be used as the leading indices of the turbine's temperature/thermal-stress
- Continuous monitoring of these temperature differences should be arranged by means of mathematical modeling of the rotor heating based on the measured heating steam temperatures

Turbine Damages Associated with Transients

2. Brittle Fracture of Rotors

- Most incidents happened during start-ups
- Caused by a gradual growth of hidden flaws in the rotor metal under combined action of the tensile centrifugal and thermal stresses
- Especially dangerous for large IP-LP rotors
- Rotor Failure examples:
 - 1) Medium-low pressure rotor (Tennessee, USA)
 - 2) 300-MW supercritical-pressure steam turbine of LMZ at the Kashira power plant

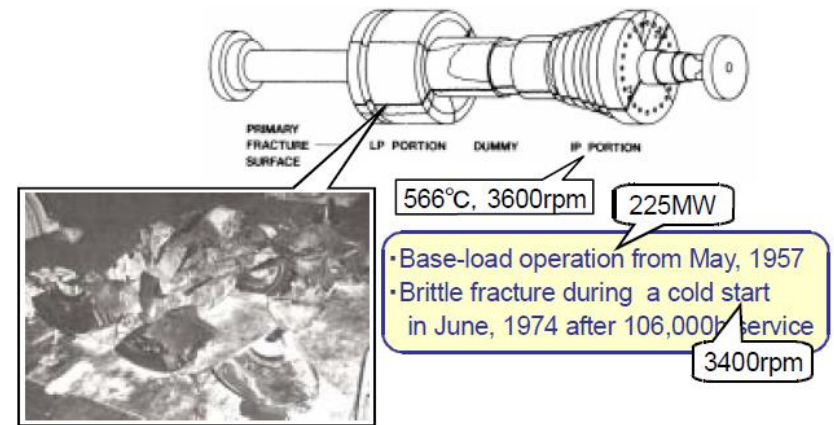


Fig. Failure of the Medium-Low-Pressure Rotor of a Steam Turbine (Gallatin, Tennessee, USA, 1974).

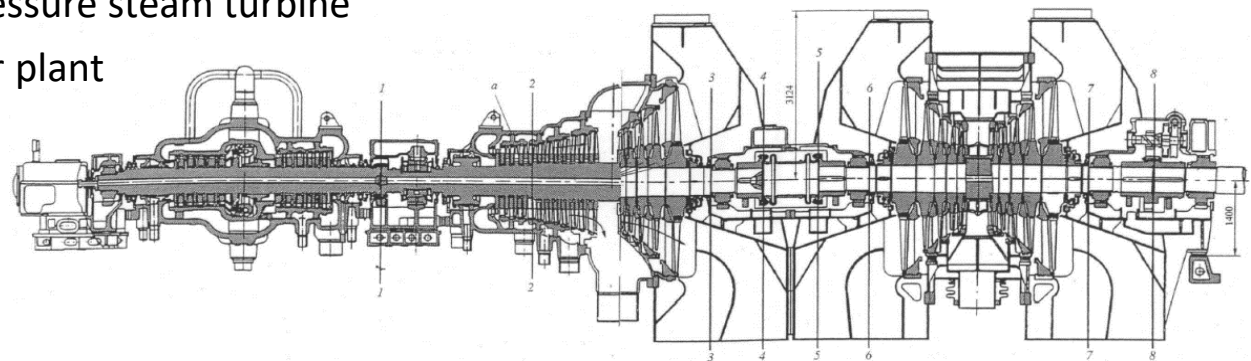


Fig. Shaft breakage sections (1-8) of the 300 MW steam turbine (Kashira power plant, 2002)

Turbine Damages Associated with the Transients

3. Stress Corrosion and Corrosion Fatigue Cracking

- Evident in the phase transition zone of the LP cylinders
- Main factor causing crack creation and propagation is anodal dissolving of metal in the crack root



Fig. Typical Locations of SCC Damages (LP turbine discs)

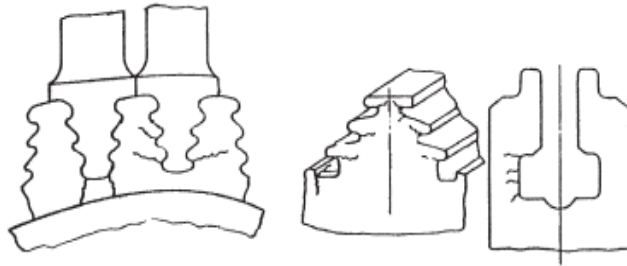


Fig. SCC at a Disc Rim in the Blade Attachment Zone

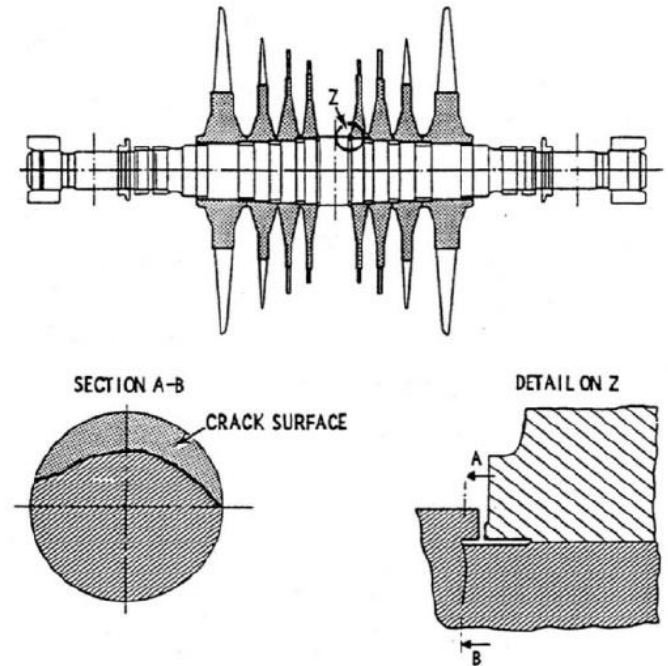


Fig. Crack Damage on the LP-1 rotor of AEG's 660-MW Wet-Steam Turbine at Würzburg

4. Solid-Particle Erosion

- Caused by oxide scale that exfoliates from high-temperature boiler surfaces, including superheater / reheater tubes, outlet headers, main / reheat steam-lines

Turbine Damages Associated with the Transients

5. Plastic Distortion of Casing and Other Stator Elements

- Great temperature unevenness lead to plastic deformation at the transients arising in:
 - HP-IP casings
 - Casing rings (HP-IP cylinders)
 - Diaphragms (HP-IP cylinders)
- Key factor - the quality of running the transients
- Also caused by metal creep with stationary temperature differences

6. Casing Deformations: Humping or thermal bend of the casing upward

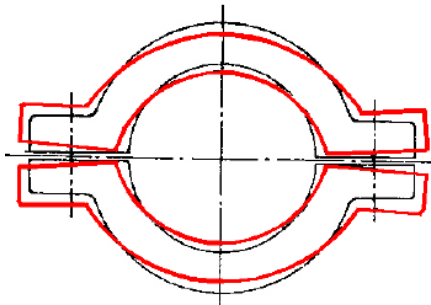


Fig. Transverse Deformation of Casing

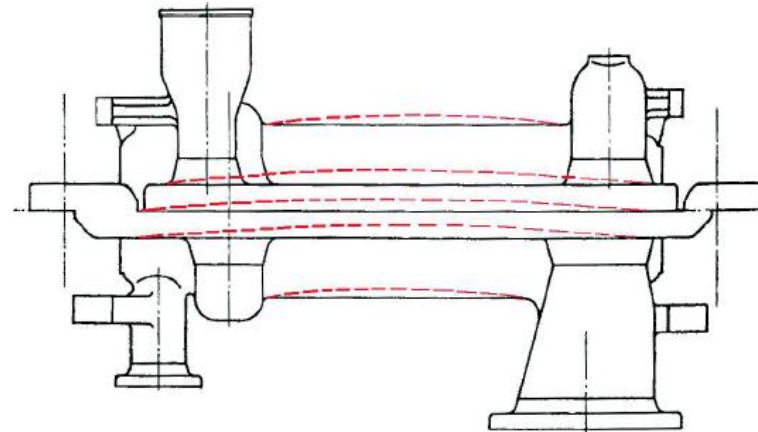
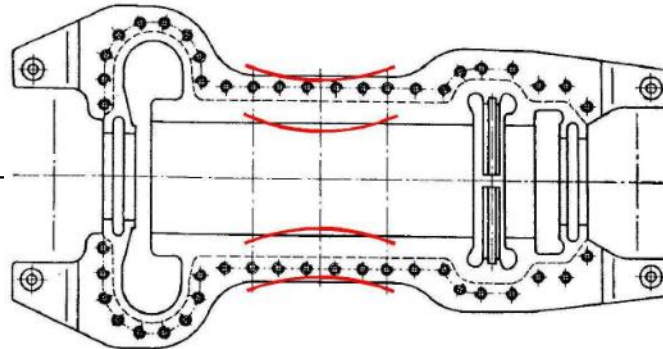


Fig. Bow of Casing Towards Top

Turbine Damages Associated with the Transients

7. Water Induction into Turbines

- Most frequent sources are:
 - Main and reheat steam-lines and their spray at temperatures
 - Can also descend from drainage lines of the main steam-lines, crossover pipes, and cylinder casings
 - Sometimes, water and/or cold steam enter turbines through the end gland seals

8. Overheating of Turbine Components Caused by Windage

- Regimes characterized with low flow and high rotation speed when turbine stages operate in compressor mode' - Ventilation effect
- - LP Blades
- LP Rotor
- LP Exhaust Hood

Fatigue of Major Steam Turbine Components

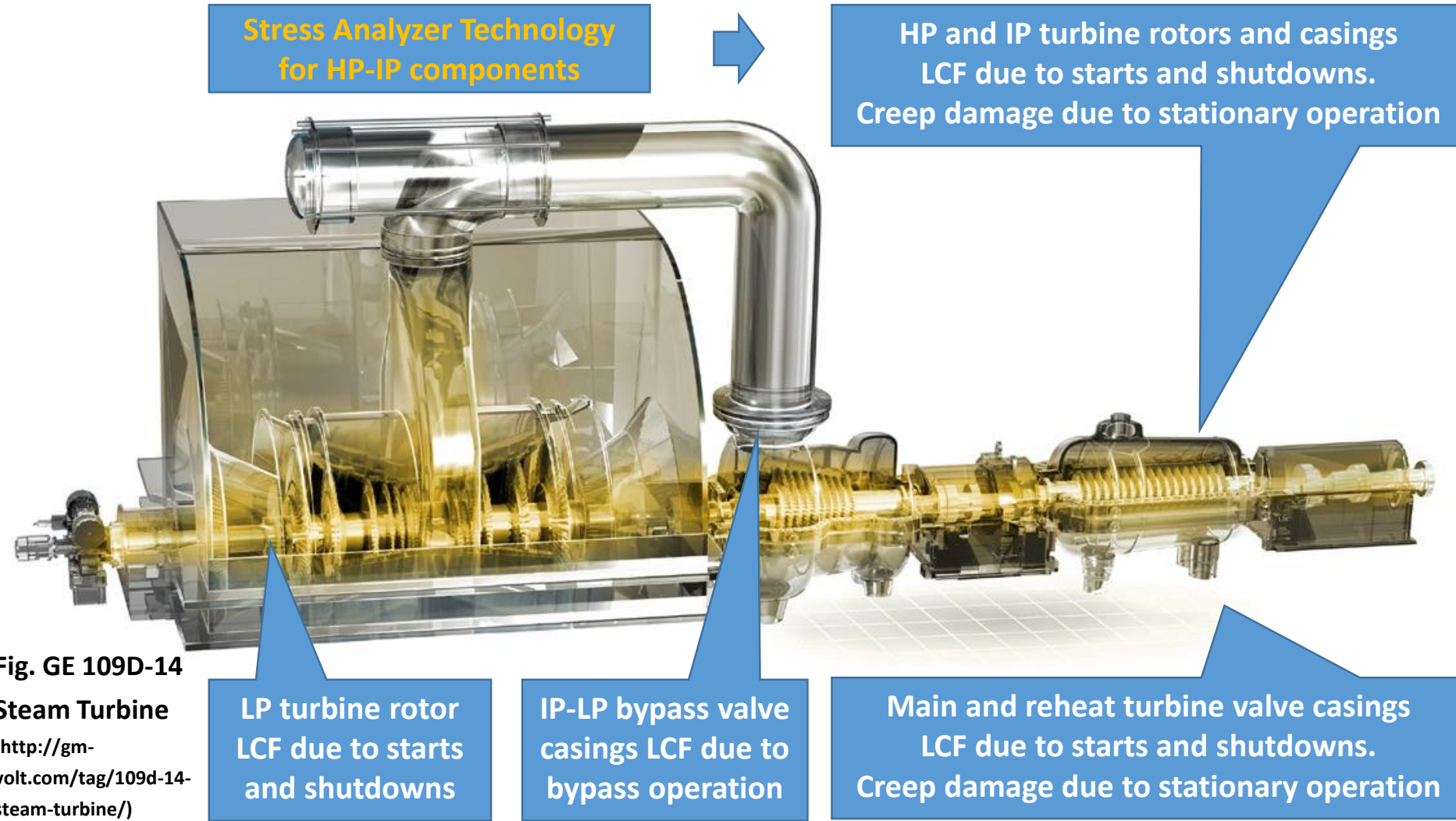


Fig. GE 109D-14 Steam Turbine
(<http://gm-volt.com/tag/109d-14-steam-turbine/>)



2. Steam Turbine Components Thermal Stress and Life Management in the Design Stage

Mathematical Modeling of the Heating up Process

- Methods

- The thermal state of the steam turbine's components during transients is a critical issue in thermo-stresses evaluation/monitoring
- **Methods:**
 - Heat conduction equation analytical/numerical solution
 - Simulation using analogous devices (electrical analogy)
 - Mathematical modelling:
 - Transfer functions
 - FDM
 - FEA
 - Experimental

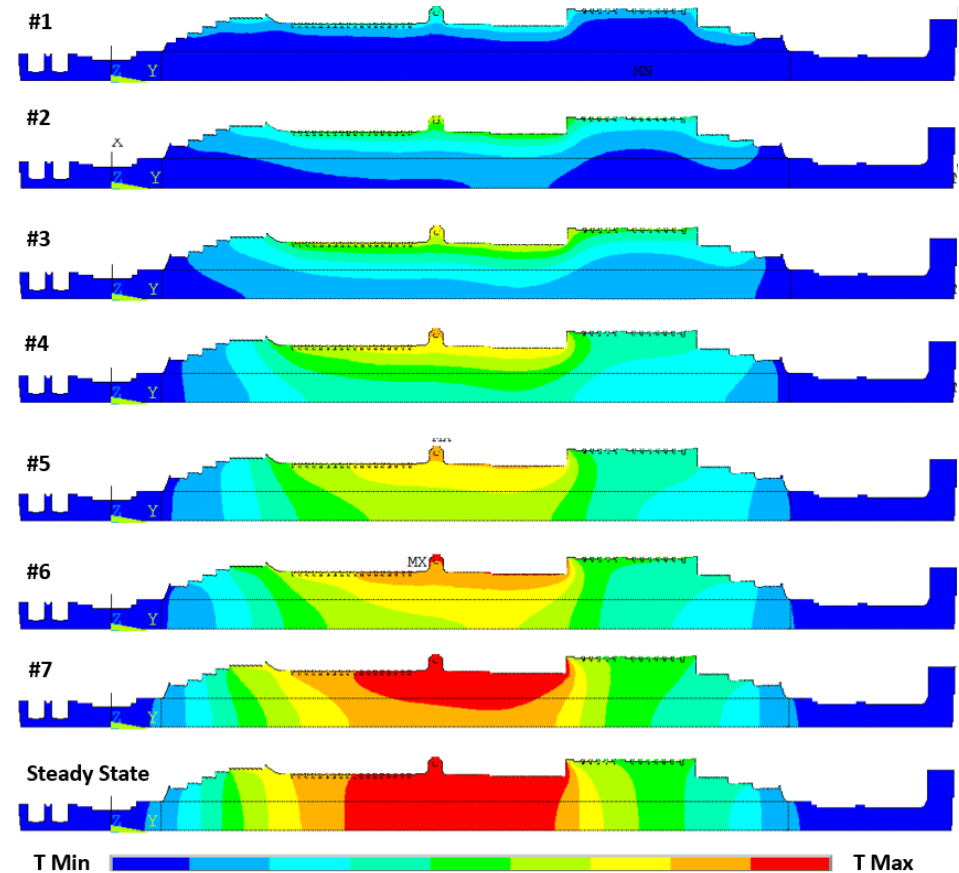


Fig. 40MW Steam Turbine HPIP Rotor Heating During Cold Start-up

Start-up Diagrams

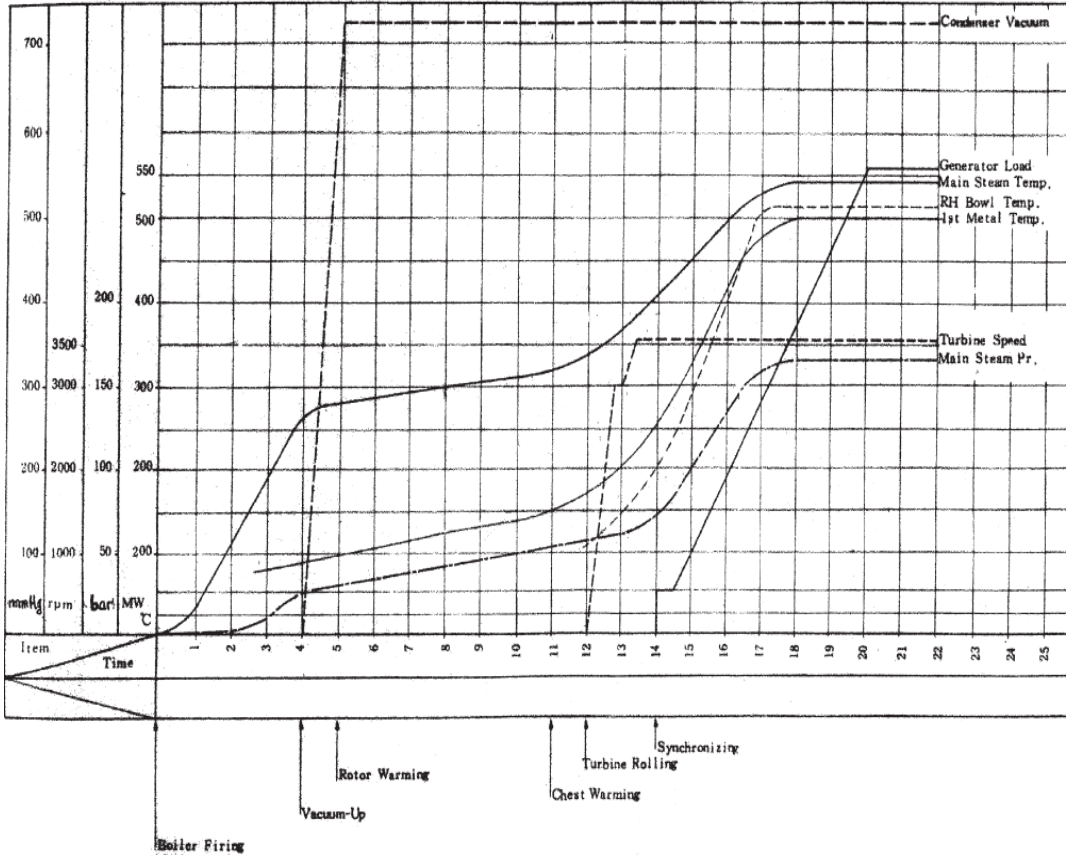


Fig. Cold Start-up Diagram for a 500MW Steam Turbine

Source: By courtesy of Doosan Heavy Industries and Construction

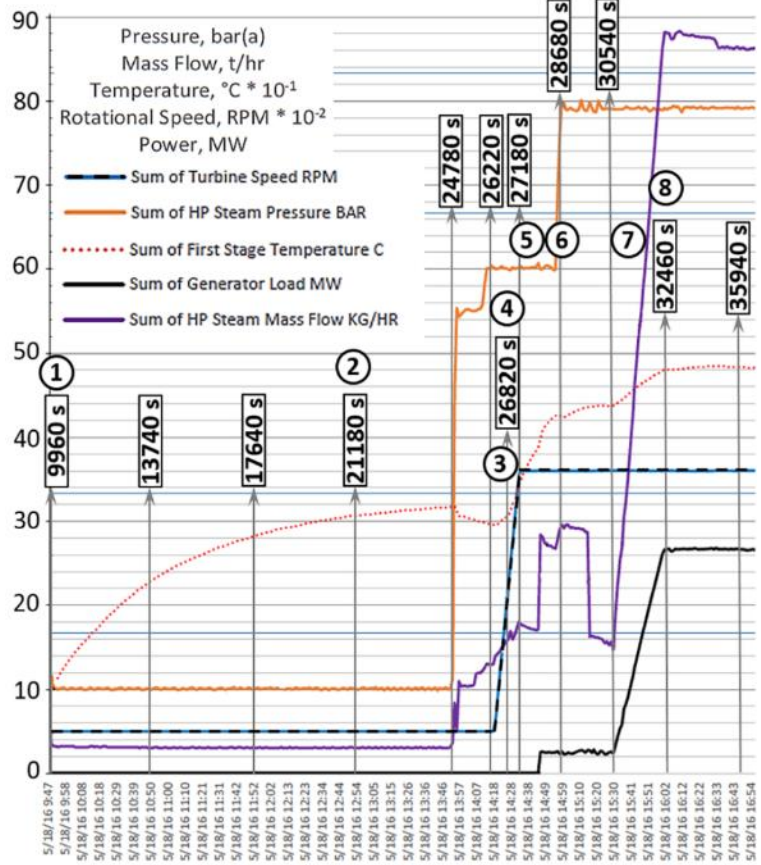


Fig. Actual Cold Start-up Curves for 40MW Steam Turbine

Mathematical Modeling of the Heating up Process

- Flow Parameters

Step 1. Flow parameters & steam properties:

- Based on measured results and determined by direct 1D/2D aero-thermo-dynamic solver
 - In the flow path
 - Rotor end seals/chambers
 - Inter-casing space

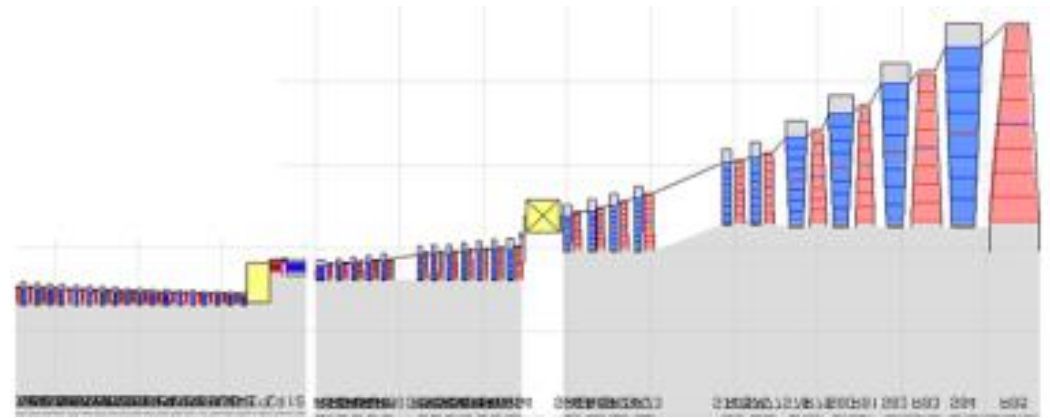


Fig. Steam Turbine Flow Path model in AxSTREAM®

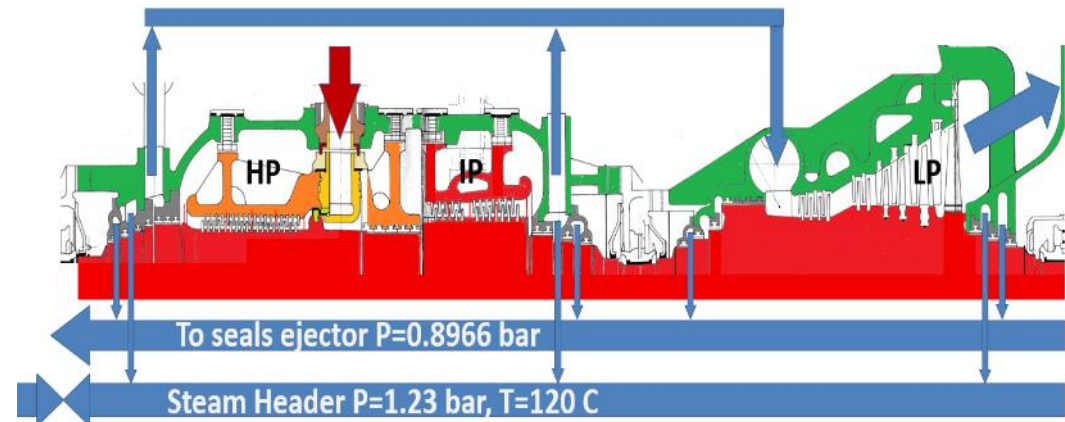


Fig. Turbine Flow Path Integrated with Rotor Seal System for 1D Aero/Thermodynamic Analysis

Mathematical Modeling of the Heating up Process

- HTC Simulation

- Heat transfer calculation for convection surfaces of rotors and casing components is based on the classical approach (Dittus-Boelter eq.) :

$$Nu = K \cdot Re^{0.8} \cdot Pr^{0.333}$$

$$HTC = Nu \cdot k / D_h$$

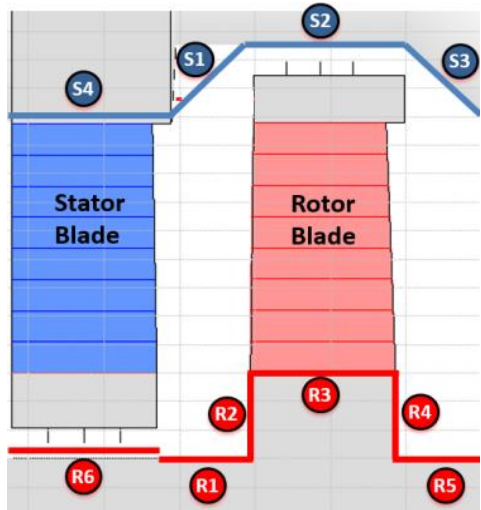


Fig. Typical Reaction Steam Turbine Stage with Thermal BC zones assignments

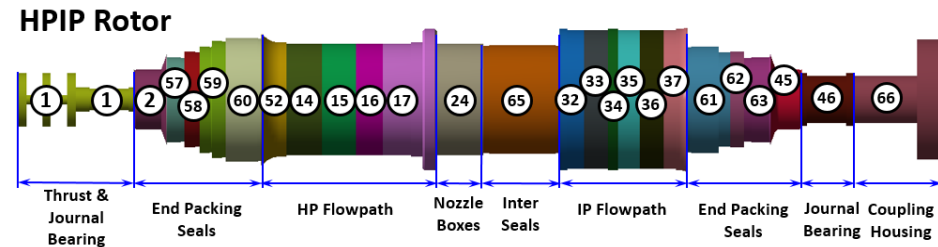
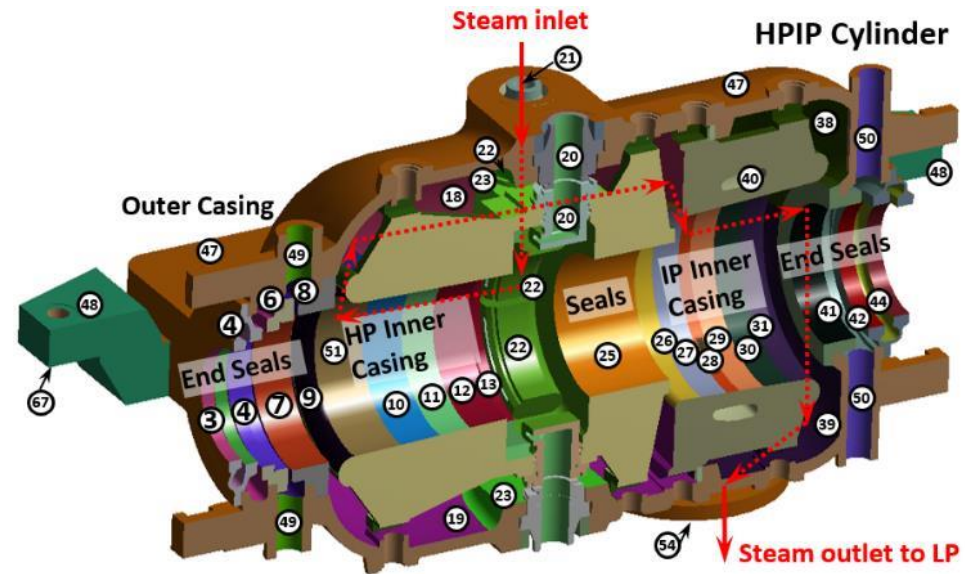


Fig. 40 MW Siemens Steam HPIP Turbine Heat Convection Zones Discretization Example for FE Thermal Analysis

Mathematical Modeling of the Heating up Process

- FEA Model Development

FEA Model and Mesh

- Casing components (3D models)
- Rotors (Axisymmetric 2D model):

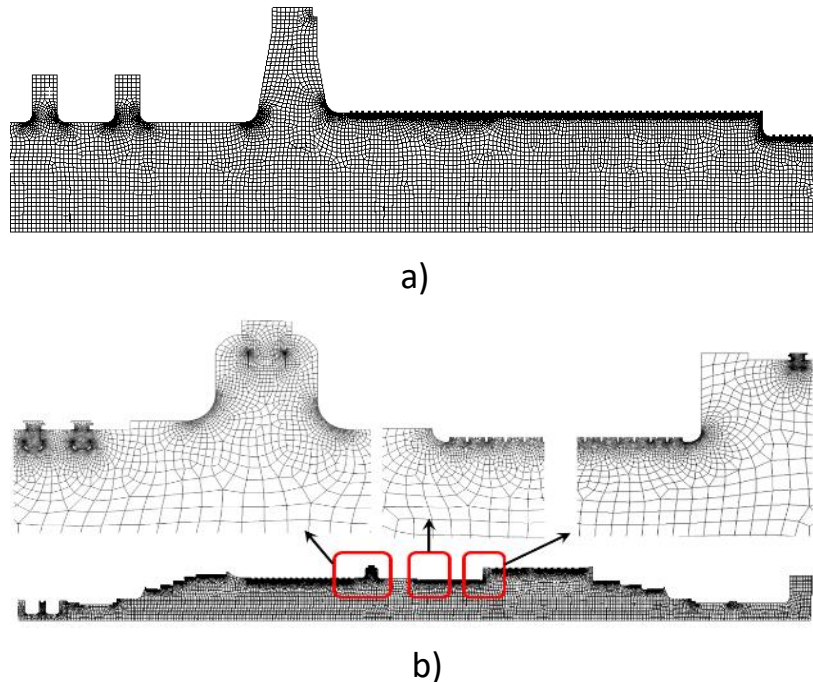


Fig. 2D Axisymmetric FEA Mechanical Models for Steam Turbines Rotors: a) 300 MW, b) 40 MW

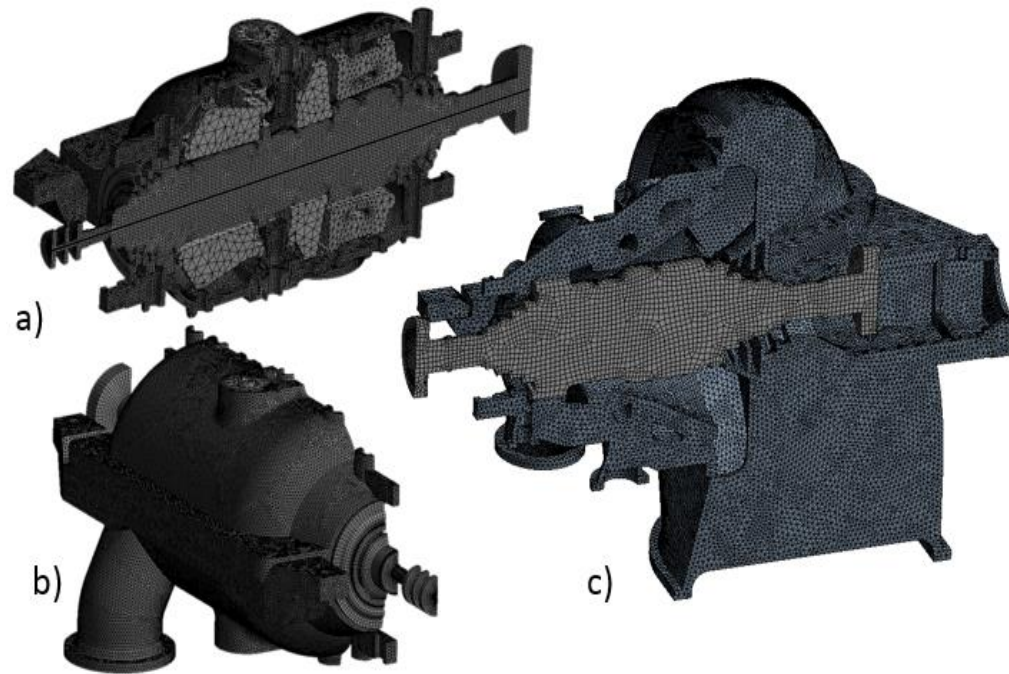


Fig. FEA Models for 40 MW Steam Turbine Casing Components and Rotor (3D)

Mathematical Modeling of the Heating up Process

- FEA Model Development

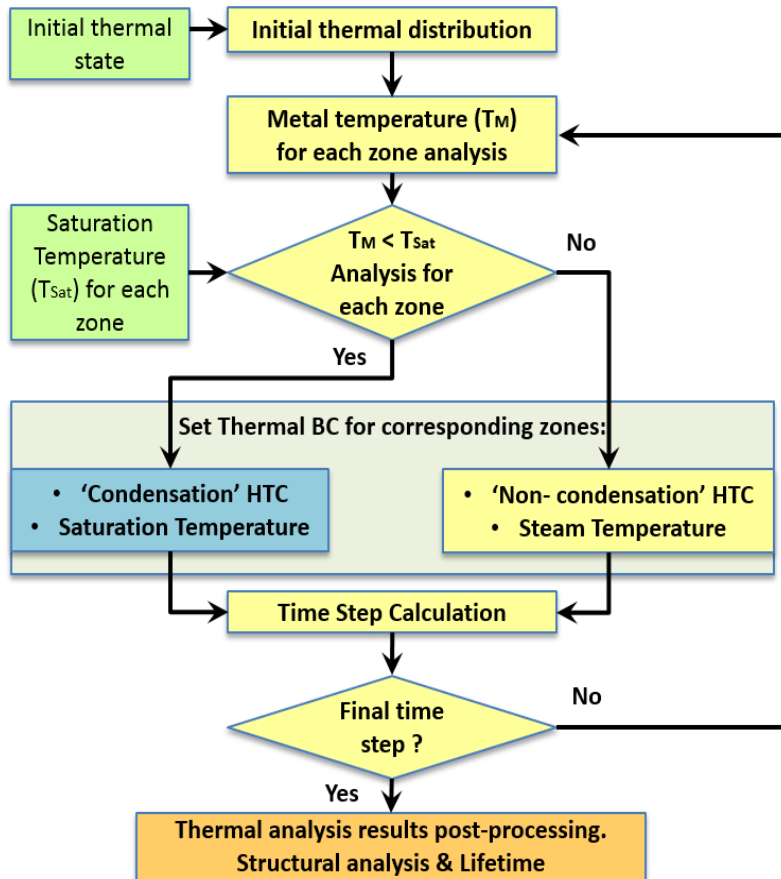


Fig. Transient Thermal Analysis Improved Algorithm (Allows user to account for condensation effect)

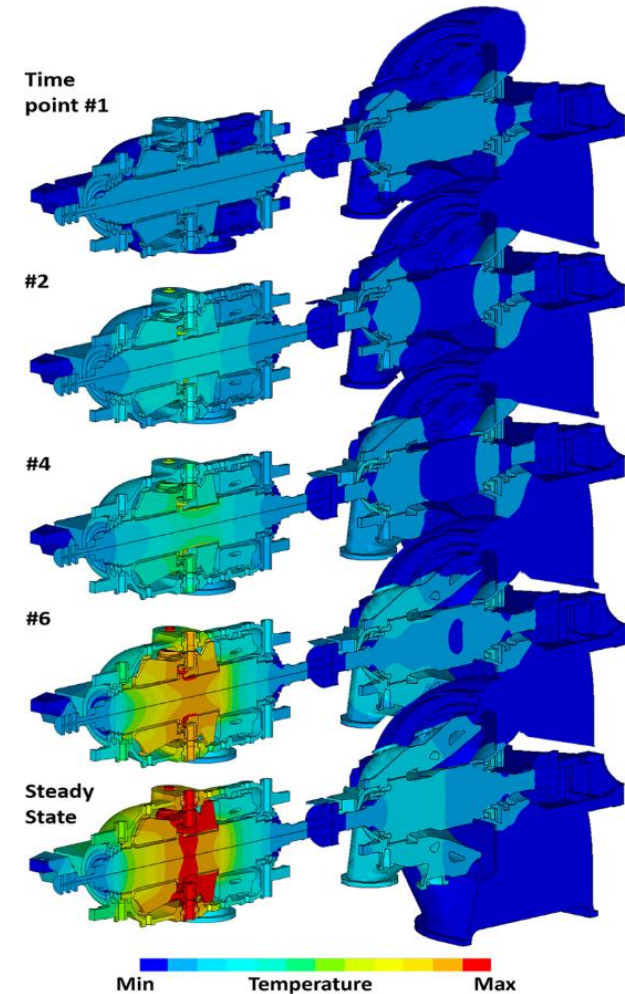


Fig. 40MW Steam Turbine Thermal State during Cold Start-up

Steam Turbine Component Stresses During Transients

- The stresses in the rotor are produced by:
 - Temperature gradients in the material (Thermal Stress)
 - The centrifugal force
 - The pressure
- Thermal Stress (the main contributor) makes up roughly 95% of the overall stress during start up transient

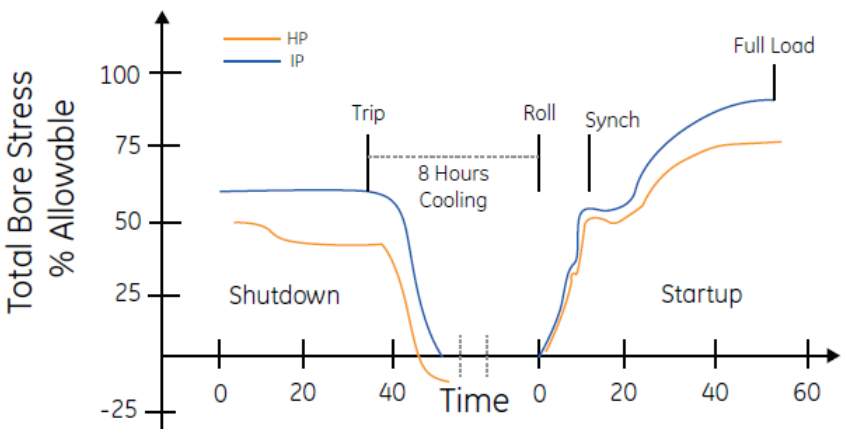


Fig. Peak HP-IP Bore Stress During Startup- Shutdown Cycle

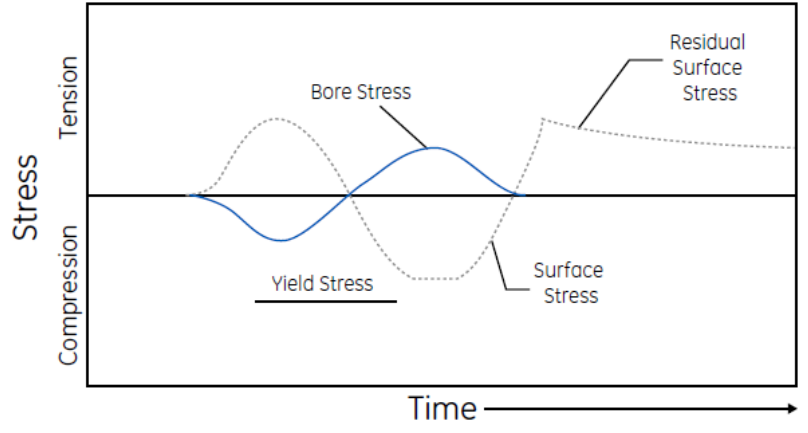
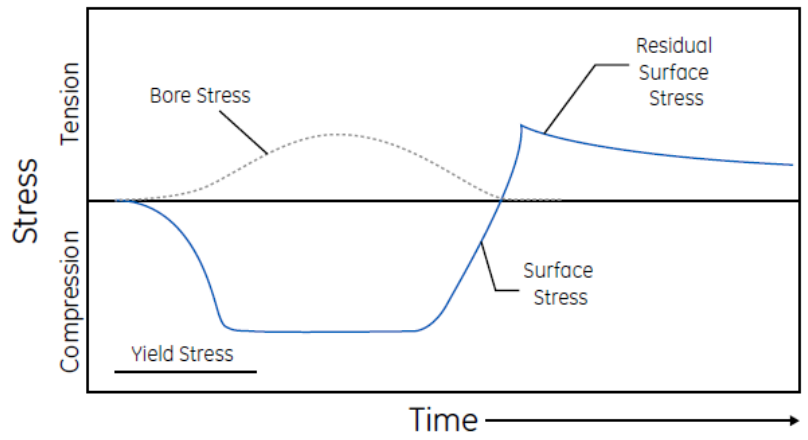


Fig. Typical Steam Turbine HPIP Rotor Stresses at Cold and Hot Start-up

Critical Elements and Regions with Potential Structural Integrity Problems

- **HP-IP Rotors:**
 - 1st, 2nd, 3rd stage blade grooves
 - Disks fillets at steam inlet region
 - Grooves
 - Bore
- **LP rotors**
 - Bore (last stages)
- **Casings**
 - Hot inlet parts of HP-IP turbine shells
- **Valve steam chests**
 - Stop valve
 - Control valve
 - Reheat and intercept valves
- **Nozzle-boxes**

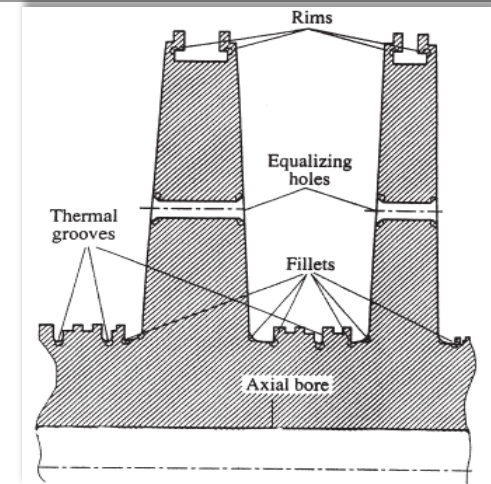


Fig. Scheme of Critical Zones for Forged High-Temperature Rotors (Impulse-Type Turbines)

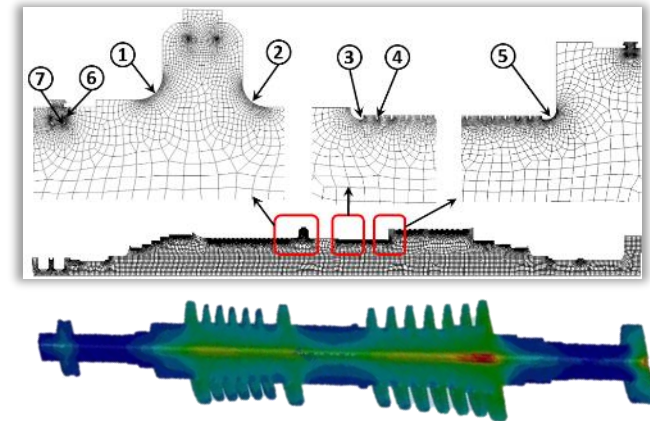


Fig. HPIP Rotor Critical Zones

Steam Turbine Components Stress Analysis

Example 40MW Steam Turbine HPIP Rotor

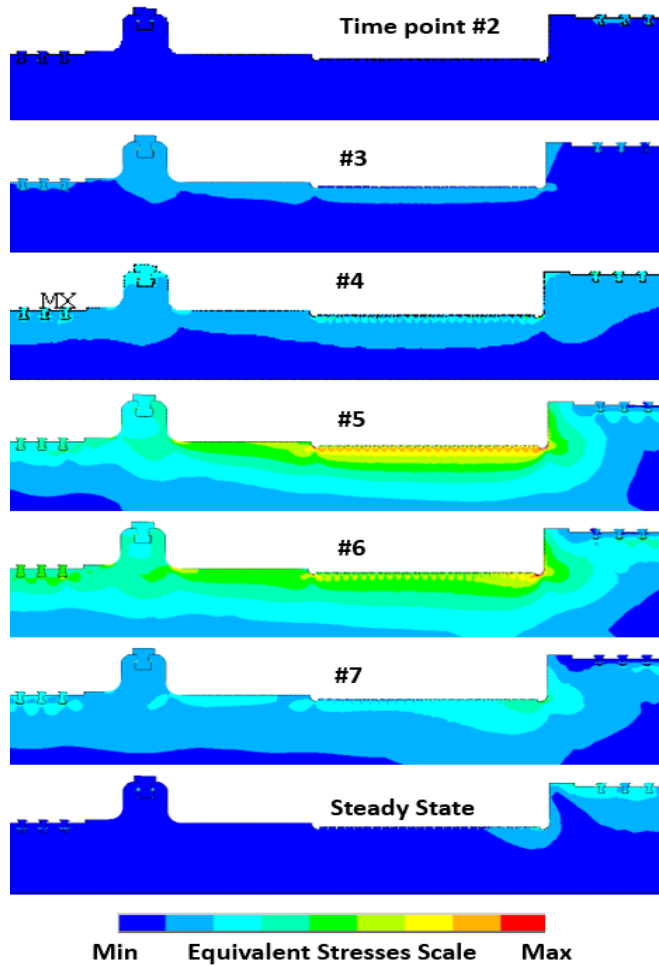


Fig. Stress Distribution in HPIP Rotor During CS

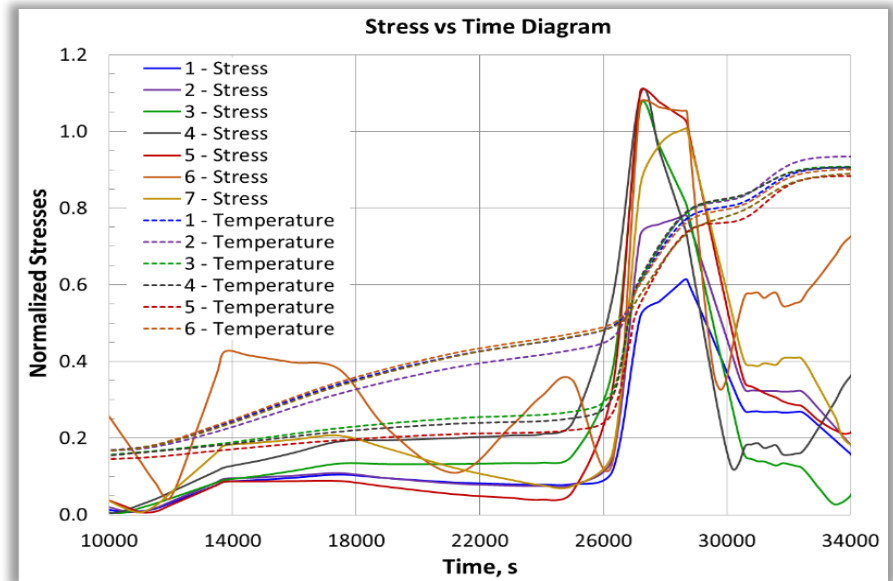
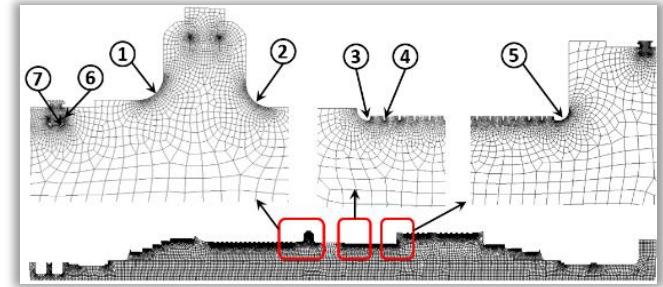


Fig. Normalized Equivalent Stresses in Critical Zones of HPIP Rotor During CS

Steam Turbine Components Stress Analysis

Example 300MW Steam Turbine HP Rotor

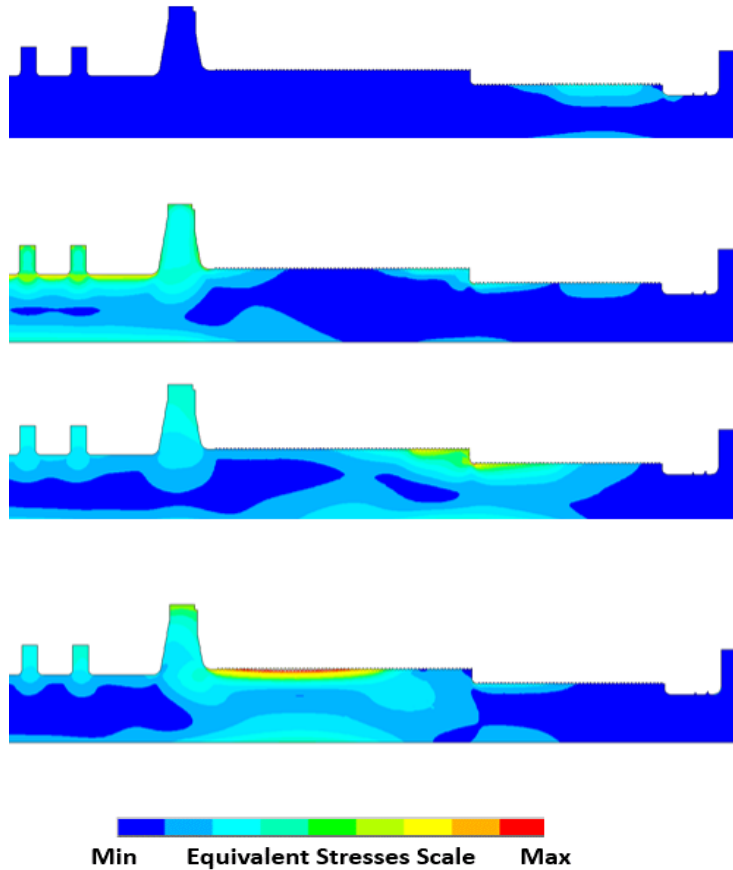


Fig. Stress Distribution in HP Rotor During CS

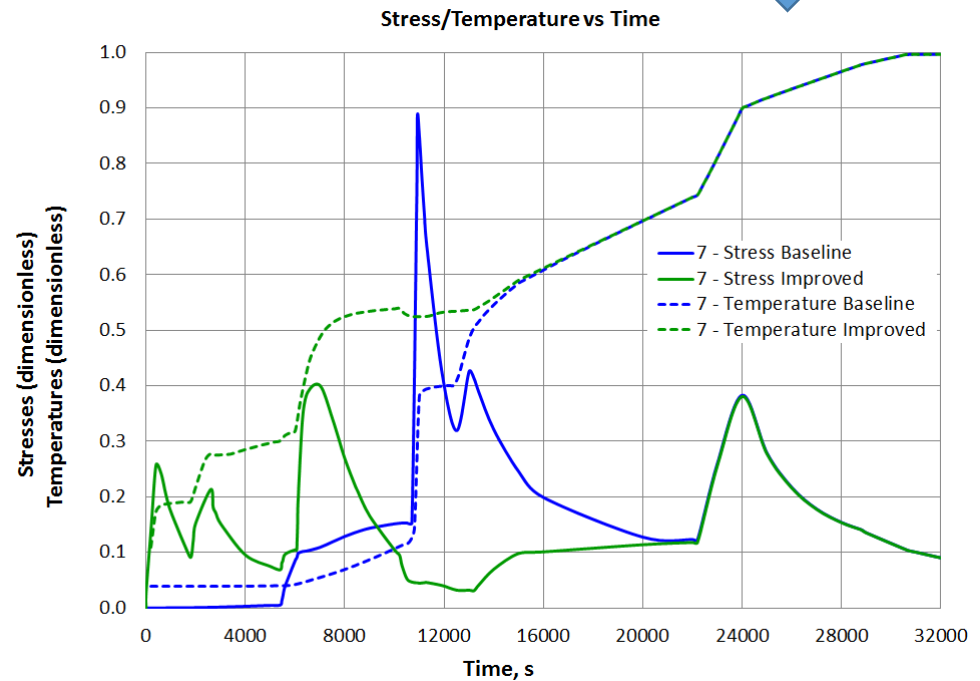


Fig. Normalized Equivalent Stresses in Critical Zones of HP Rotor during CS

Life Consumption Analysis

- The accumulation of **creep and fatigue damage over time** are two principal degradation mechanisms which eventually lead to crack initiation in critical high temperature steam turbine components
- **Fatigue:** material weakens due to repeatedly applied loads, and when a material is subject to cyclic loading, localized cracks initiate and grow by the action of repeated stress
- **LCF is associated with localized plastic behavior in metals**
- LCF consists of at least two parts
 - 1) Repetitive centrifugal loading
 - 2) Thermal transients
- Strain-based parameter is used for fatigue life prediction
- LCF is a function of the applied strain range and the mean stress

LCF Analysis

➤ Start-up / Shut down cycle simulation has to be considered:

- **3D FE Analysis**
- **Life consuming process**

➤ FEA Formulations:

- Linear (elastic) formulation + Neuberization
- Nonlinear (elastoplastic) formulation

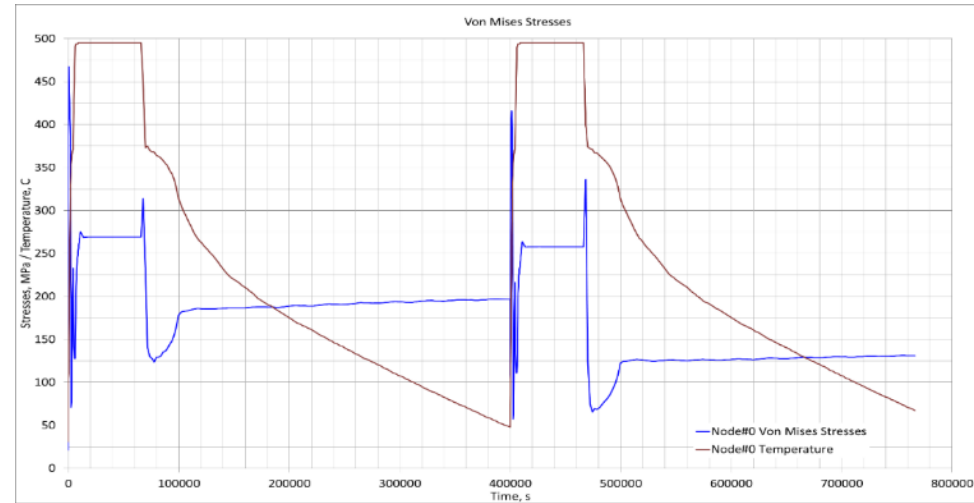


Fig. Equivalent Stresses on 1st Stage Disk Fillet for 40 MW HPIP Steam Turbine Rotor During 2 Cycles of Cold Start-Up/Shut Down

➤ Following aspects should be taken into the account:

- Cyclically hardened / softened material
- Plasticity model
- Bauschinger effect + geom. non-linearity
- Actual material stress-strain curves
- 2 cycles of start-up - steady state - shut down are modelled to reach stabilized stress-strain hysteresis loop
- Experimental strain-life (ϵ -N) curves

LCF Analysis Methodology

➤ Effective strain range ($\Delta\varepsilon_{eff}^{tot}$) is calculated for critical zones to determine the rotor LCF lifetime based on transient stress analysis results calculated for cycle of operation

Effective total strain range formula: $\Delta\varepsilon_{eff}^{tot} = \Delta\varepsilon_{eff}^{el} + \Delta\varepsilon_{eff}^{pl}$,

$\Delta\varepsilon_{ij}^{el/pl} = \varepsilon_{ij\ MAX}^{el/pl} - \varepsilon_{ij\ MIN}^{el/pl}$, $\varepsilon_{ij}^{el}, \varepsilon_{ij}^{pl}, \gamma_{ij}^{el}, \gamma_{ij}^{pl}$ - elastic/plastic strain components

Correction for non-symmetrical stress cycle: $\Delta\varepsilon'_{eff}{}^{tot} = \frac{\Delta\varepsilon_{eff}{}^{tot}}{1 - \frac{\sigma_{avr}}{\sigma_{ult}}}$,

where σ_{ult} - ultimate strength, σ_{avr} - average stresses in a cycle.

Safety factors: $N = \min\{N_{aN}, N_{a\varepsilon}\}$, $N_{aN} = \frac{N(\varepsilon_a)}{K_N}$; $N_{a\varepsilon} = N(\varepsilon_a K_\varepsilon)$;

where ε_a - strain amplitude, K_N, K_ε - safety factors, $N(\varepsilon_a), N(\varepsilon_a K_\varepsilon)$ - number of cycles to failure

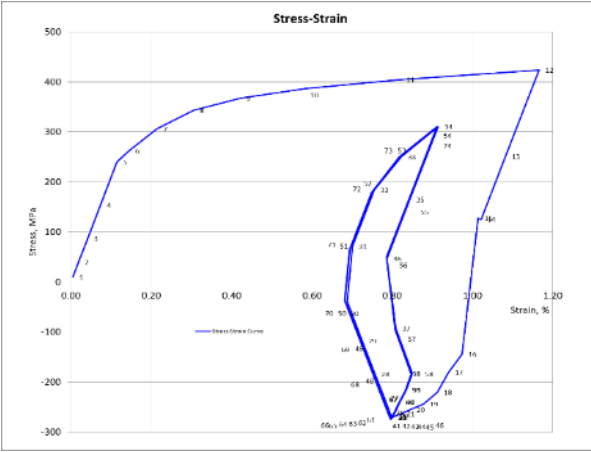


Fig. Stabilized Stress-Strain Loop for LCF Estimation

LCF Analysis Results

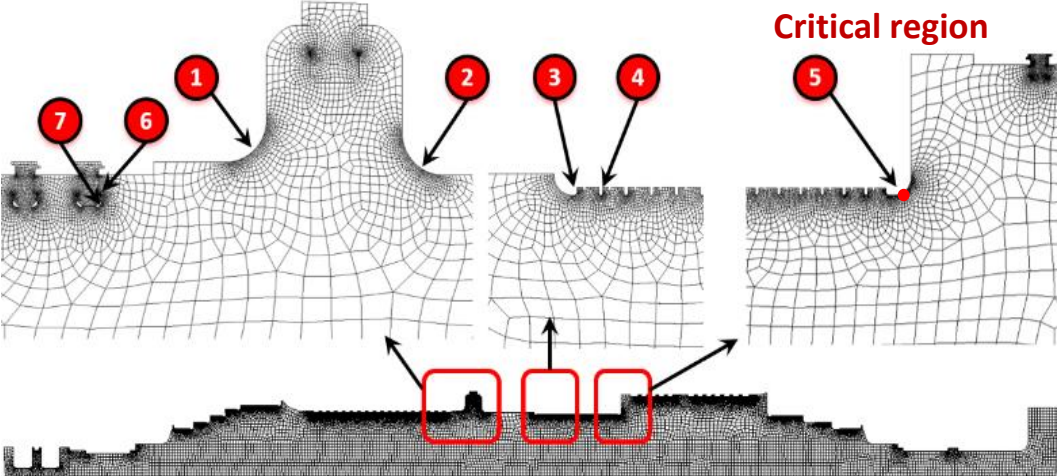


Fig. 40 MW Steam Turbine Rotor FE Model and Critical Zones with Regards to Strength and LCF Life

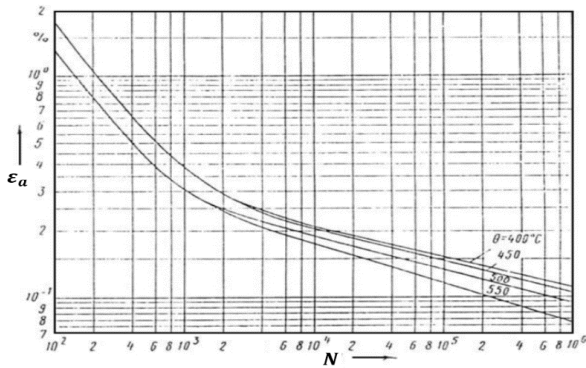
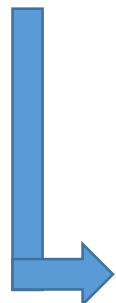


Fig. Rotor Material Strain-Life Curve



Table. Allowable Number of Start-Ups

Critical Zone # (from Fig. 11)	Equivalent Total Strain Range, %	Allowable number of CS
1	0.12%	> 50000
2	0.17%	> 50000
3	0.30%	15000
4	0.49%	1100
5	0.34%	6000
6	0.58%	900
7	0.22%	> 50000

Life Prediction for Creep

Creep

- Time-dependent deformation under a certain applied load
- Generally occurs at high temperature (thermal creep)
- The material undergoes a time dependent increase in length, which could be dangerous while in service
- Creep in service is usually affected by changing conditions of loading and temperature

- Creep for metal is described by the Larson Miller parameter (LMP)

$$LMP = T \frac{\text{Log}(N_C) + 20}{1000}$$

T – temperature, K deg., N_c - time to creep rupture, h. C=20

- Predicts rupture lives given certain temperature and stress
- First used by General Electric in the 50's to perform research on turbine blades

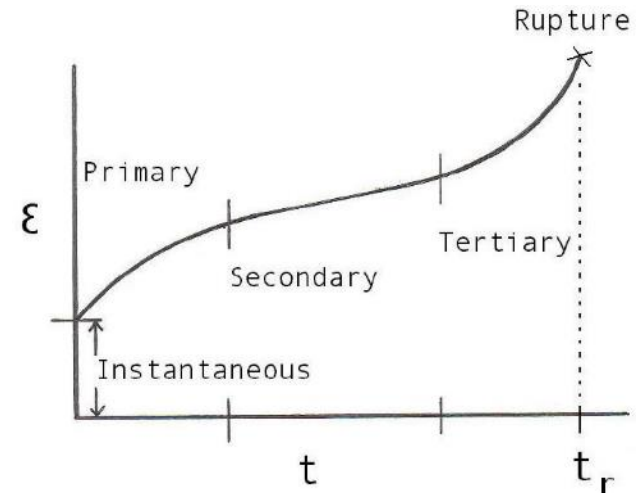


Fig. Classical Creep Curve

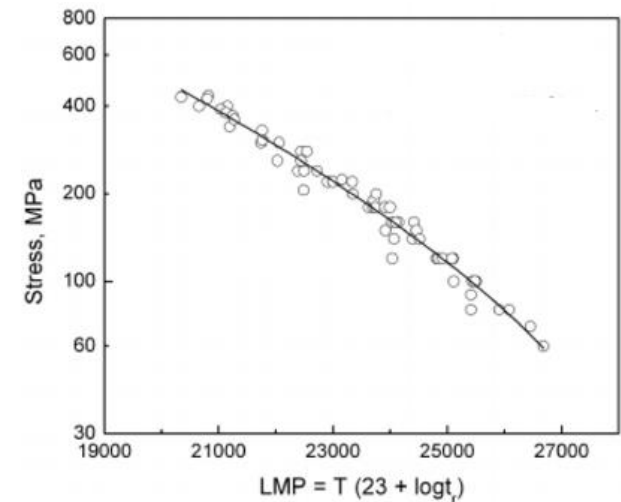


Fig. LMP Curve

Model for Fatigue-Creep Interaction

- Steam turbine components exposed to the combination of environment impact and degradation mechanisms:
 - High temperature creep
 - Cyclic loading fatigue
 - Corrosive environment embrittlement
- **Fracture Criterion for Creep-Fatigue:** Combine Palmgren-Miner (P-M) rule for fatigue life with Robinson's (R) rule for creep life under various $\sigma - T$ combinations

$$\sum \frac{N_i}{N_{fi}} + \sum \frac{t_i}{t_{fi}} = 1$$

N_i – number of cycles at stress amplitude σ

N_{fi} – number of cycles to failure at stress amplitude σ

t_i – time spent at stress-temperature combination

t_{fi} – creep fracture life

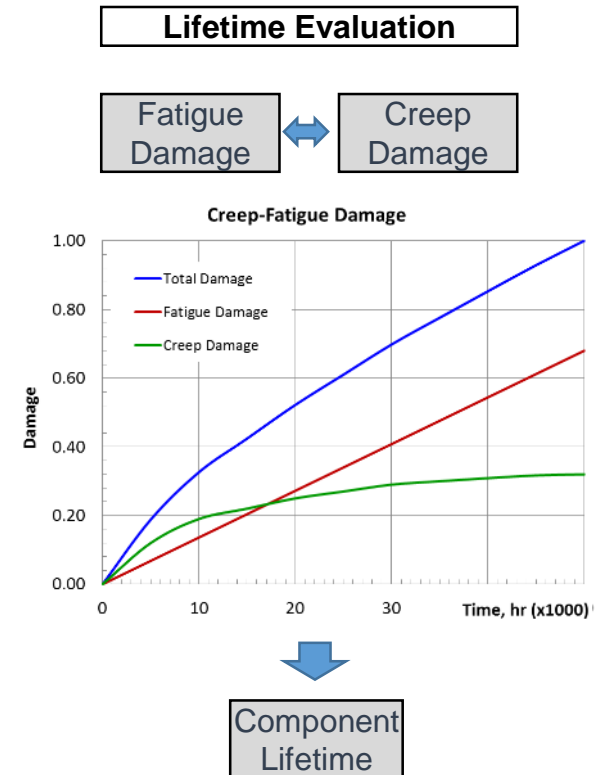


Fig. Creep-Fatigue Lifetime Evaluation

3. Sensors/Instrumentation Technology

Measurement of Pressure - Liquid Columns

Pressure Measuring Devices

- Liquid columns
- Expansion elements
- Electrical

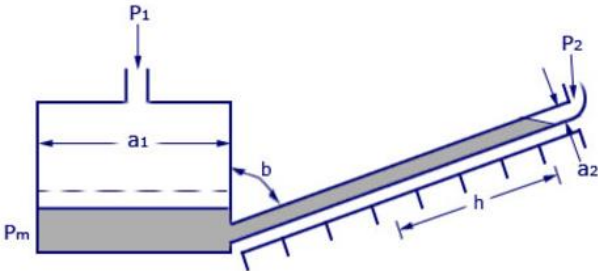


Fig. Inclined Manometer

Liquid Columns

- Low range pressure measurement
- Could be U-tube type, incline or well-type

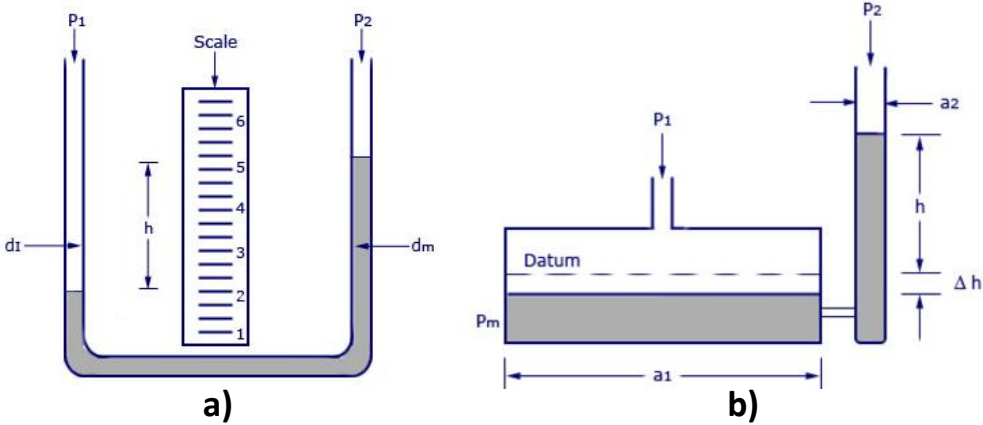


Fig. Manometer: (a) U-Tube-Type, (b) Well-type

Measurement of Pressure - Expansion Elements

- Used in modern power plants
- Its movement indicates the pressure (Metallic)
- Either directly coupled with mechanical linkages or indirectly by an electrical transducer connected to a read out device

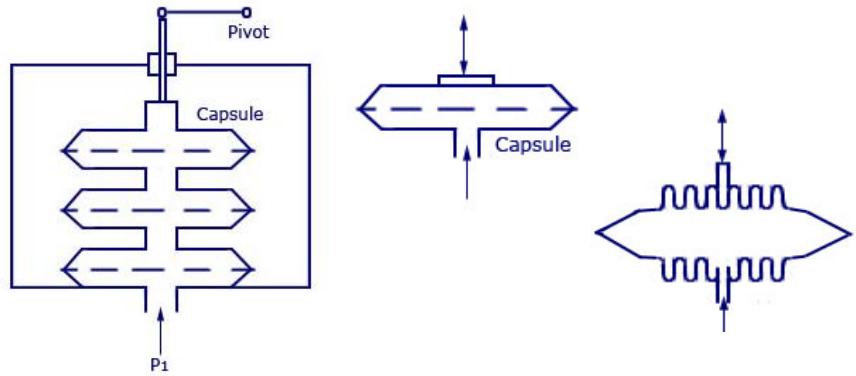


Fig. Diaphragms

- **Diaphragms**
 - Corrugated types
 - Capsule element (increase the deflection capabilities)

- **Bellows**
 - Manufactured from brass alloys stainless steel
 - Used for low pressure measurement
 - Connected with spring - for high pressure measurement

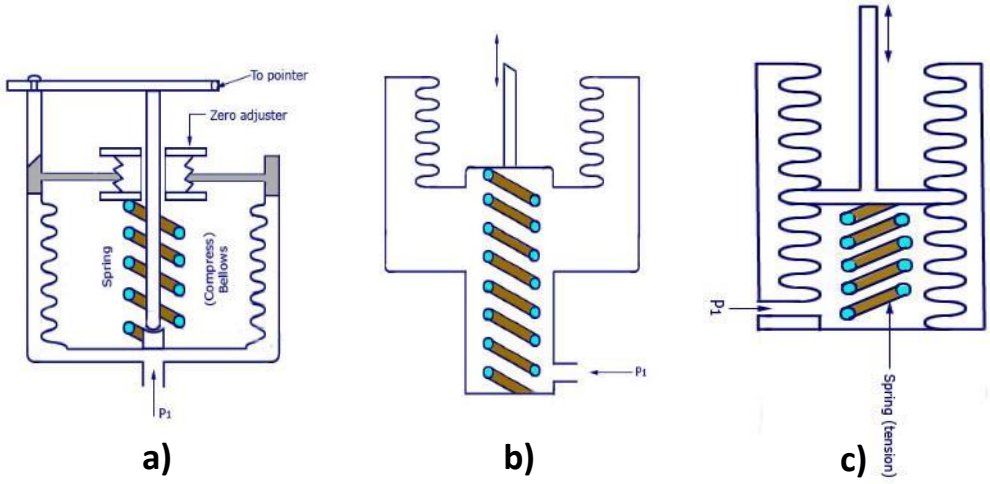


Fig. Bellows: (a) Compressed Type, (b) Expanded Type Spring, (c) Opposed

Measurement of Temperature

- The most important parameter in a thermal power plant is temperature and its measurement plays a vital role in safe operation
- Rise of temperature in a substance is due to the resultant increase in molecular activity of the substance on application of heat (which increases the internal energy of the material)
- The efficiency of generation also depends on the temperature measurement

$$\eta = 1 - T_2/T_1$$

T₂ – Temperature inside the condenser, T₁ – Super heater temperature

Measurement of Temperature

Expansion Thermometer

- Two dissimilar metal tubes having different expansion coefficients are attached end to end
- For the same temperature change difference in the lengths are compared and calibrated for unknown temperature measurement
- Variation in length is slight and has to be magnified

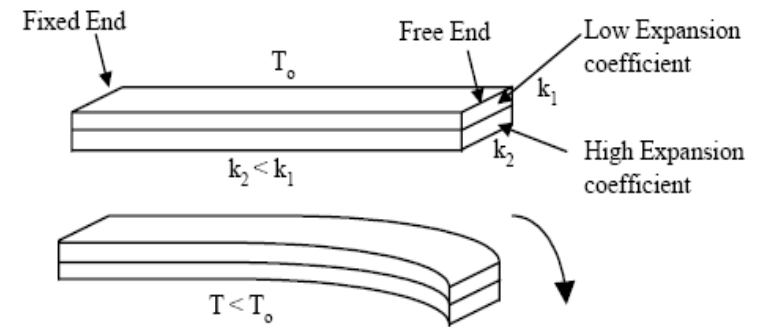


Fig. Expansion Thermometer

Thermoelectric Thermometry

- Based on SEEBACK and PELTIER effect
- Comprise of two junctions at different temperature. Then the emf is induced in the circuit due to the flow of electrons
- The actual value depends upon the material used and on temperature differences between the junctions

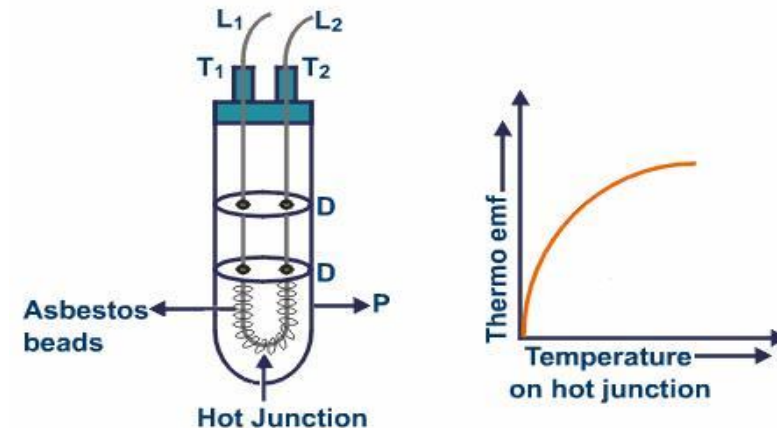


Fig. Thermoelectric Thermometry

Measurement of Temperature

Resistance Thermometry

- Suggested by Siemens (1871)
- Not satisfactory when used for high temperature
- Today RTD is given by H.L. Calender (1891)
- PROPERTY-The resistance of the conductor changes when its temperature is changed
- Platinum, nickel or nickel alloys are commonly used
- Tungsten is used for high temperature applications

METAL	MIN. TEMP.	MAX.TEMP.	MELTING
PLATINUM	-260 °C	110°C	1773°C
COPPER	0 °C	180°C	1083°C
NICKEL	-220°C	300°C	1435°C
UNGSTEN	-200°C	1000°C	3370°C

Ultraviolet Sensor

- This device is used in the furnace and it measures the intensity of ultraviolet rays in accordance with the wave generated, which directly indicates the temperature in the furnace

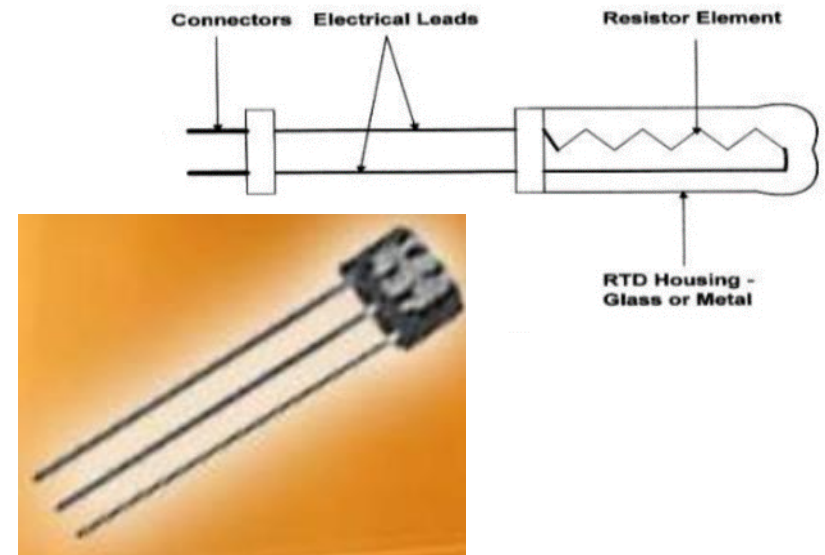


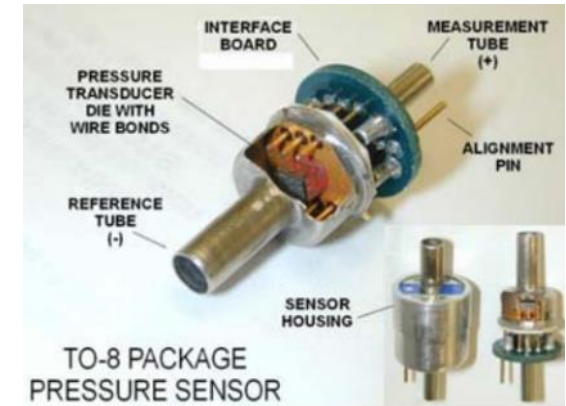
Fig. Ultraviolet Sensor

Sensors for Equipment Online Diagnostic

Pressure Sensor

➤ Typical performance specification

- Measurement Range 0psi – 120psi
- Sensitivity $\pm 15\%$
- Max Pressure 500psi - 4kpsi
- Type Compression



Intelligent Pressure Scanners

➤ Typical Performance Specification

- Measurement Range 15 psi to 10,000 psi
- Sensitivity $\pm 0.10\%$



Sensors for Equipment Online Diagnostic

Temperature Sensor

➤ Typical performance specification

- Measurement Range 500 °C – 932 °C
- Sensitivity $\pm 1\%$
- Max Pressure 932 °C
- Type Thermocouple



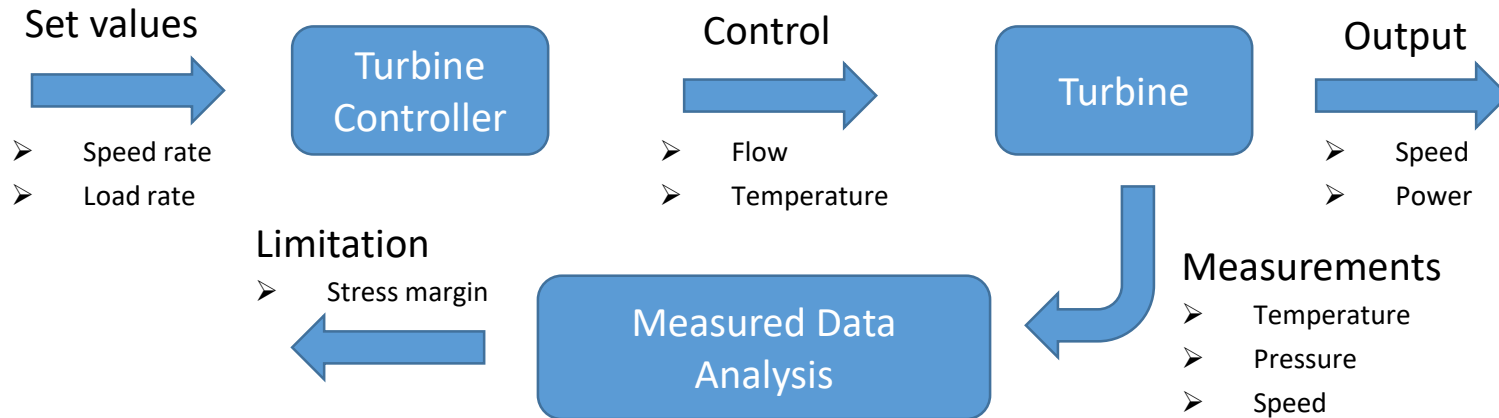
Intelligent Temperature Scanners

➤ Typical performance specification

- Measurement Range 15 psi to 10,000 psi
- Sensitivity $\pm 0.25^\circ\text{C}$



Measured Data Analysis/Post-Process



- Extensive post-processing of the measured data is needed to retrieve relevant information and compare it with permissible levels of stresses and fatigue limitations
- Accurate analysis will:
 - Prevent unexpected structural failures
 - Identify fatigue consumption
 - Provide insight in deviations of predicted lifetime consumption
 - Increase safety by monitoring lifetime consumption
 - Undertake rational measures to limit excessive lifetime consumption
 - Justify lifetime extension
 - Provide operational feedback for future design

4. Online Monitoring of Turbine Temperature and Thermal-Stress States

History of Thermal Stress Monitoring - Physical Modelling

- Monitoring the thermal-stress states of the turbine components first occurred in the **1960s** to prevent the rotors of newly designed large power steam turbines from cracking from cyclic thermal stresses (at transients)
- Physical modeling - introduced by Brown Boveri
- Similar devices were employed by other turbine producers
- Rotors were supervised using start-up probes which were thermo-physical models of turbine rotors
- Thermo-physical startup probe measures temperature:
 - On steam turbine rotor surface
 - Mean rotor temperature
- Stresses are calculated based on temperature difference

History of Thermal Stress Monitoring - Mathematical Modelling

- **Mathematical models (Introduced in the 1970s)**
 - **Better accuracy:** replacing the measured average temperature with a mathematical model
- Further development of thermal stress supervision systems consisted in complete resignation from the temperature probe and **modeling thermal stresses based on the standard process measurements**
- Rusin (2005): method of thermal stress modeling in turbine rotors employing **Green's functions and Duhamel's integral**, as well as steam temperature measurement at critical locations
- The Green's functions and Duhamel's integral have been used for many years in fatigue life-monitoring of nuclear plants equipment by companies such as GE, EDF and EPRI
- Recent developments include **artificial neural networks**

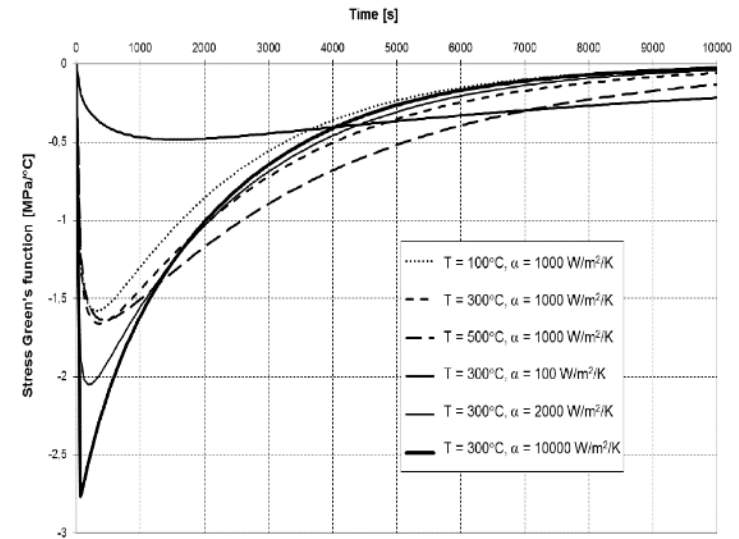


Fig. Green's Function, G , for Axial Stress at Cylinder Surface at Various Temperatures and Heat Transfer Coefficients

History of Thermal Stress Monitoring - Analogous Modelling

- Analogous device for modeling the rotor thermal-stress states was developed and applied to the HP-IP rotors of LMZ turbines K-300-240
- Based on the method of **approximate transfer functions**, taking into account variation of heat transfer conditions on the rotor surface with the steam flow through the turbine

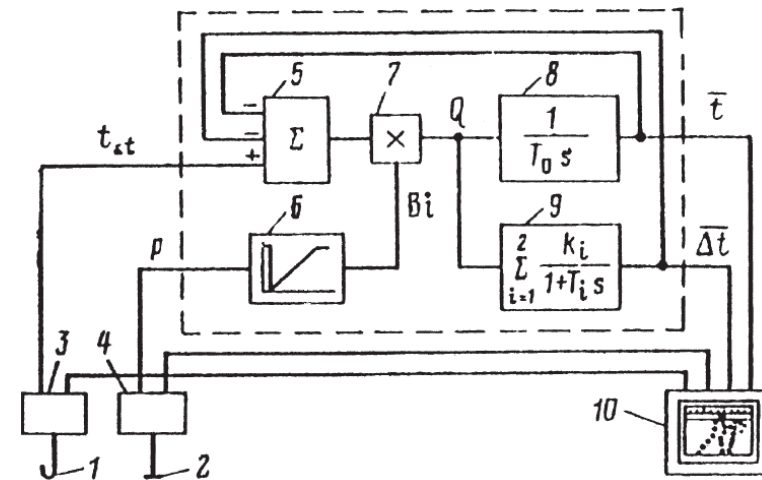


Fig. Analogous Model for Monitoring the Thermal-Stress States of a Rotor

- (1- heating steam temperature sensor,
 2 – steam pressure sensor,
 3,4 – normalizing converters,
 5- inlet summer,
 6 –non-linear converters,
 7 – multiplier,
 8– integrator,
 9 –non-periodic element,
 10 – multipoint recorder)

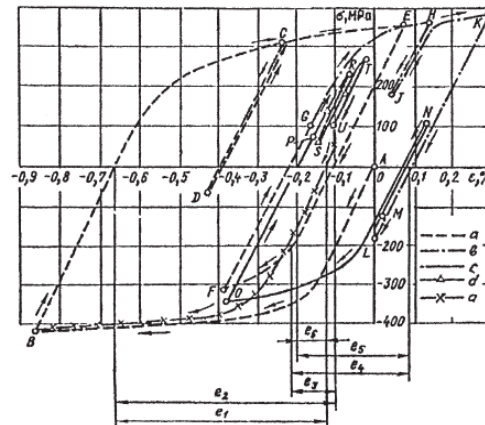
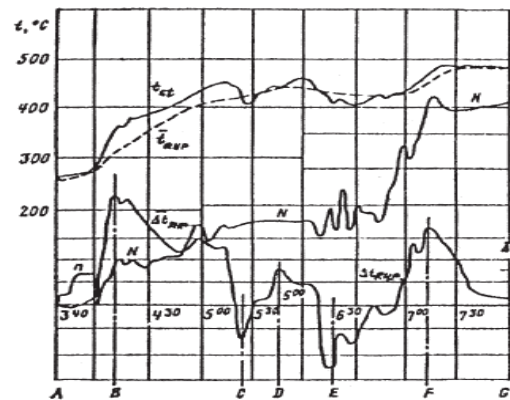


Fig. Thermal State Variations and Cyclic Stress-Strain Diagram for the HP Rotor of 300MW Steam Turbine at Warm Start-up

History of Thermal Stress Monitoring - Microprocessor-Based Controllers

- Microprocessor-Based Controllers:
 - Considers the dependence of the metal thermal conduction on temperature
 - Influence of the turbine rotation speed
 - Axial heat flux to the front seal and bearing
- In the 1980s the principle of physical modeling was partially replaced with mathematical modeling
- Finite-Difference method
- Raise accuracy of modeling: error approximation 10-15%:
 - 1) HPIP rotors
 - 2) LP rotors (heating up/cooling down during outages)
 - 3) Stator elements (if poorly suitable for accurate temperature measurements)
 - 4) Thick-wall components of boilers



Fig. Microprocessor-Based Controller

(source: www.siemensvakfi.org/i/content/3855_1_R3C_Istanbul-2008_e_V1-0.pdf)

History of Thermal Stress Monitoring - Microprocessor-Based Controllers

- Example: algorithmic module “CONTUR”
 - Supercritical-pressure turbines 250, 300, 500, and 800 MW
 - Calculates the temperature and thermal-stress state for HP-IP rotors
 - Models the heating up of the HP stop-valve steam-chests,
 - Temperature state indices as applied to other stator elements on the basis of their measured metal temperatures
 - Post-operating evaluation of the LCF
- Great variety of the applied solutions:
 - Tensomax
 - Tensomarg
 - Turbomax
 - Turbomax 7+

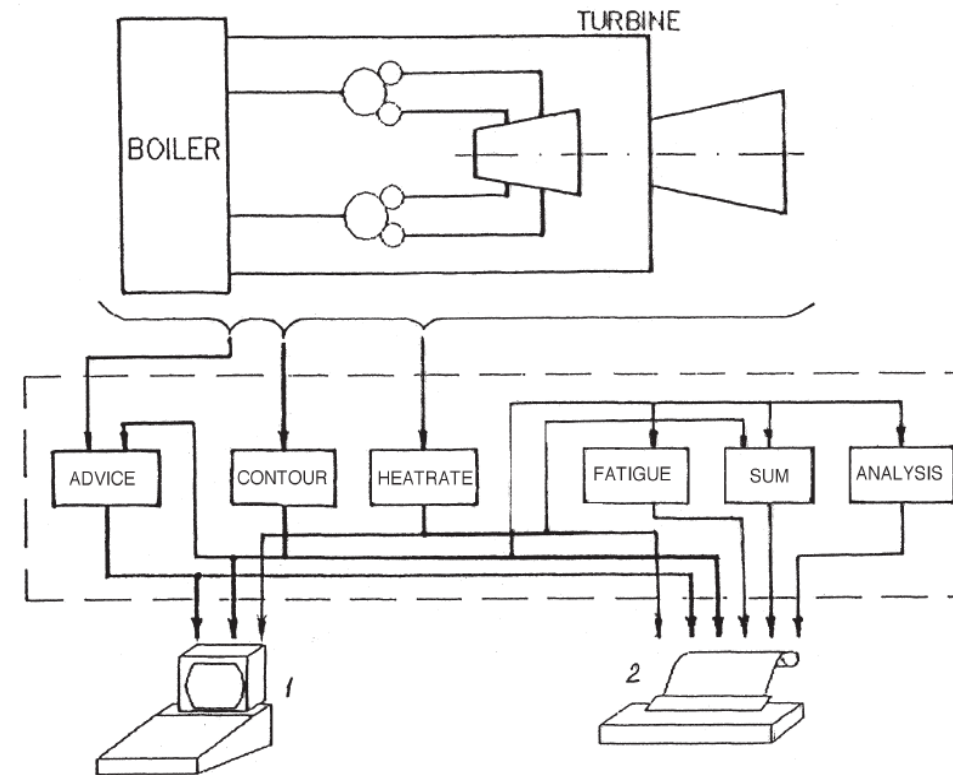
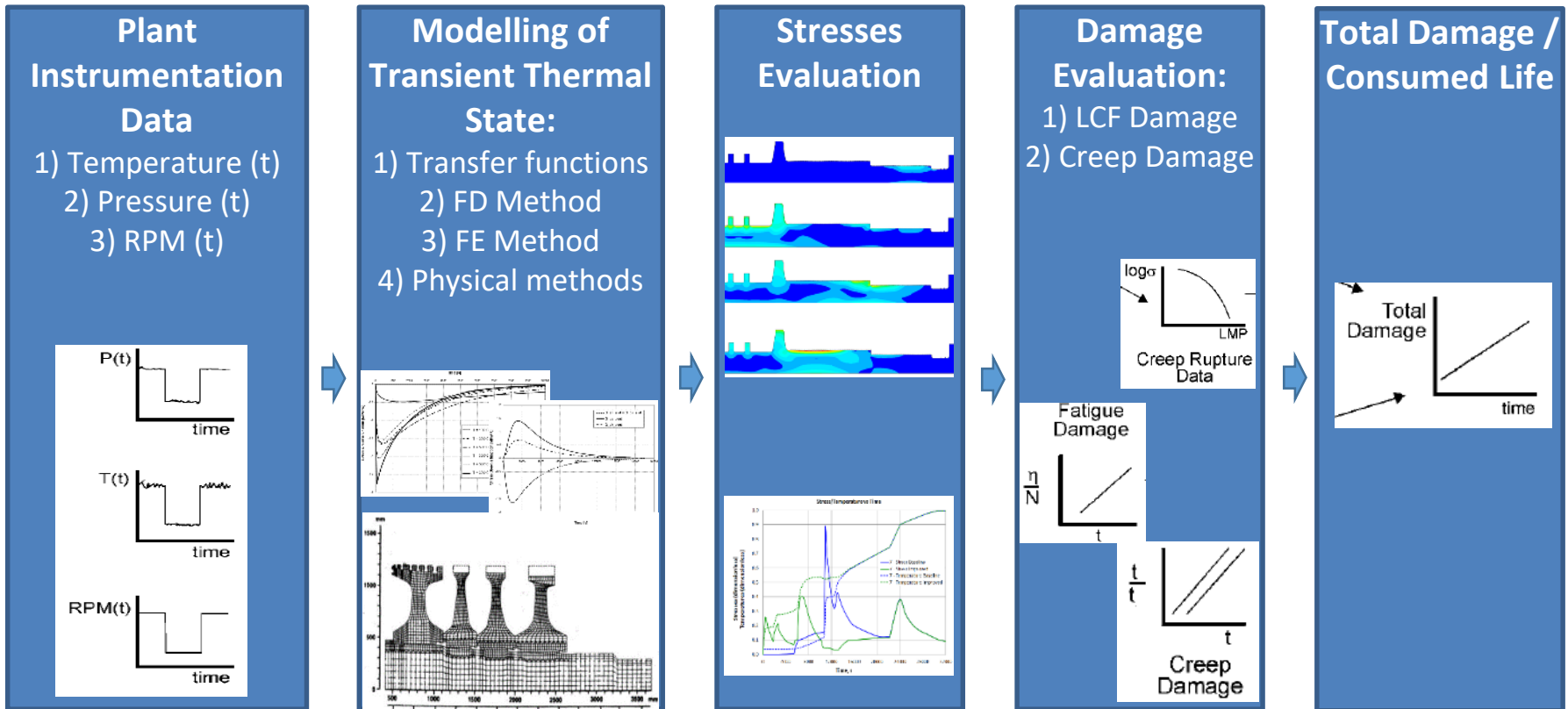


Fig. Set of Algorithms and Information Flows of Local Subsystem of Diagnostic Monitoring of the Turbine

General Scheme of Stress Monitoring / Consumed Life Evaluating Approach



Cutting Edge Systems for Thermal Stress Monitoring - ABB Group TURBOMAX

ABB-Alstom Turbomax® Thermal Stress Calculator

- The history of TURBOMAX began in 1957
- Performs thermal stress simulation
- Developed in the frame of automatic control module
- Limits the load if thermal stresses of the turbine rotor exceed the permissible limits

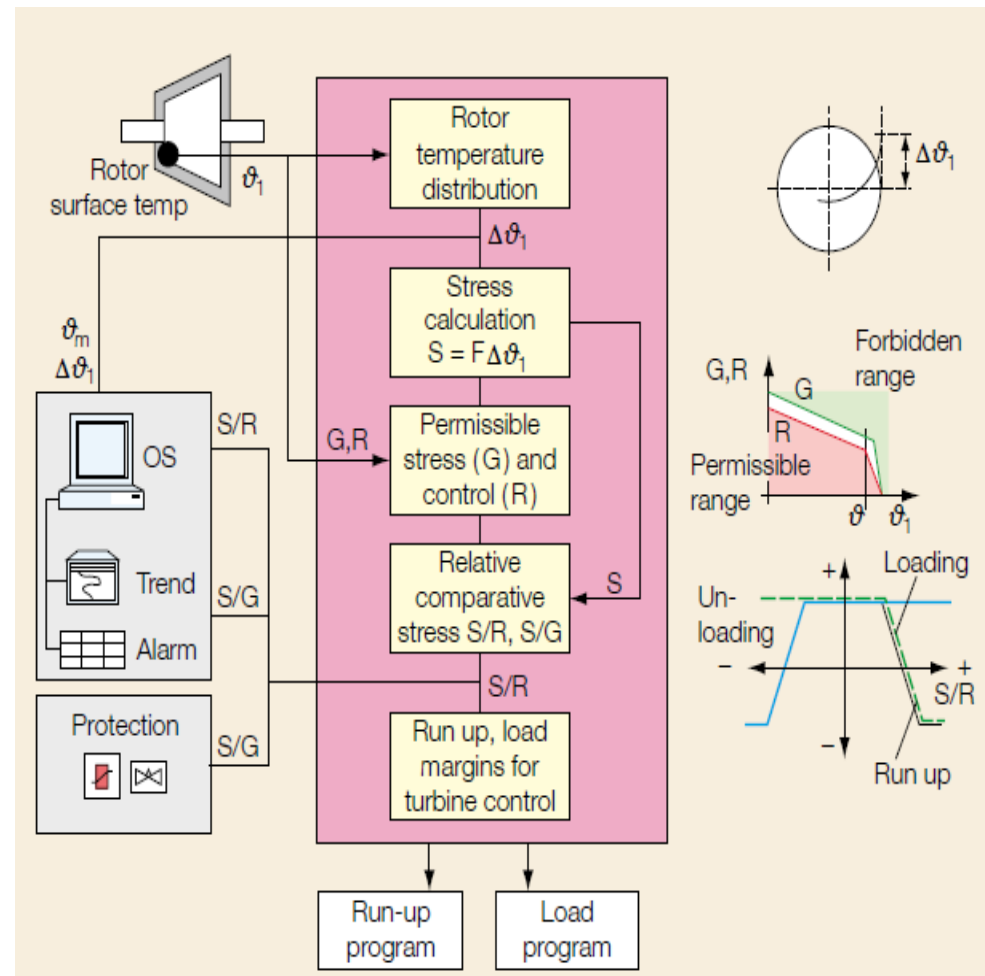


Fig. Block Diagram of the ABB Turbomax Thermal Stress Calculator

Cutting Edge Systems for Thermal Stress Monitoring - Alstom (GE) TURBOMAX 7 / 7+

- Protects the HP and IP rotors and the HP and IP valve chests
- Mathematical models:
 - HP-IP rotors: cylinder models (based on startup probe temperature measurements located in HP and IP inner casings at the steam path inlet)
 - HP-IP valve chests: Duhamel's integral (based on steam temperature measurement before the protected valve chest and metal temperature measurement of the protected chest)
- Stress limits are related to the stress responsible for cumulative LCF damage
- The stress limiter participates in the control and protection system through control and protective signal exchange

Cutting Edge Systems for Thermal Stress Monitoring - Alstom (GE) TURBOMAX 7 / 7+

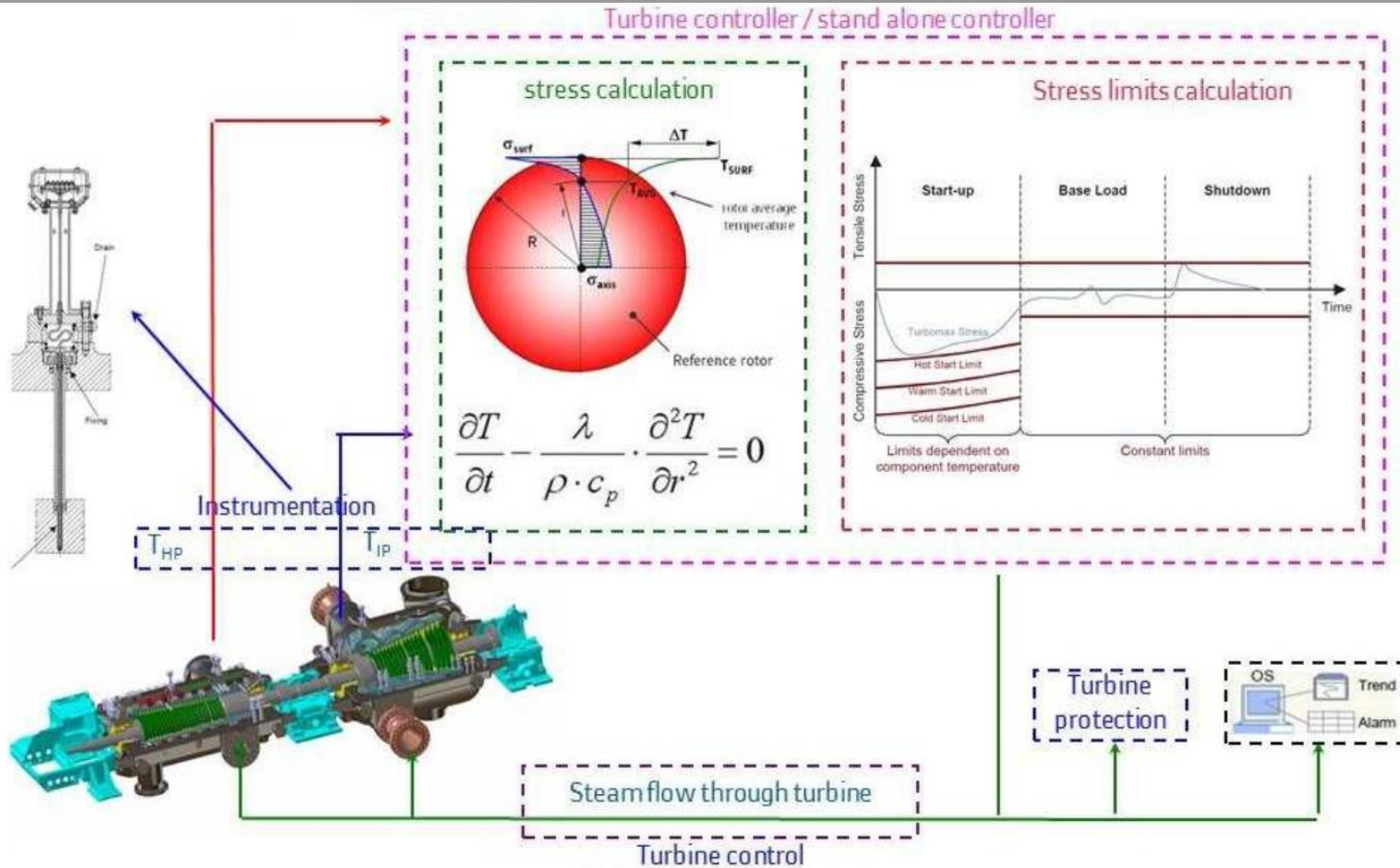


Fig. Idea of TURBOMAX 7

(reference: Dominiczak K., Radulski W., Banaszkiwicz M., Mróz K., Bondyra R. Thermal stress limiter for 13K215 steam turbine retrofit in Połaniec Power Plant, Poland Journal of Power Technologies 96 (4) (2016) 285–294)

Cutting Edge Systems for Thermal Stress Monitoring - Siemens SPPA-R3000 Control System (2006)

Siemens SPPA-R3000

- Thermal stress control and supervision
- SPPA-R3000: Direct influence of thermal stress on different operating conditions:
 - Gradients
 - Cold, warm, hot start-up and load changes
 - Protection, critical speed ranges
- Application: steam turbines 1-1600 MW
- Advanced stress monitoring algorithm which can be fully integrated into the turbine governor for optimal exploitation of the stress limits. Leader in:
 - Fastest start-up
 - Fuel savings
 - Higher load output
 - Lowest lifetime consumption

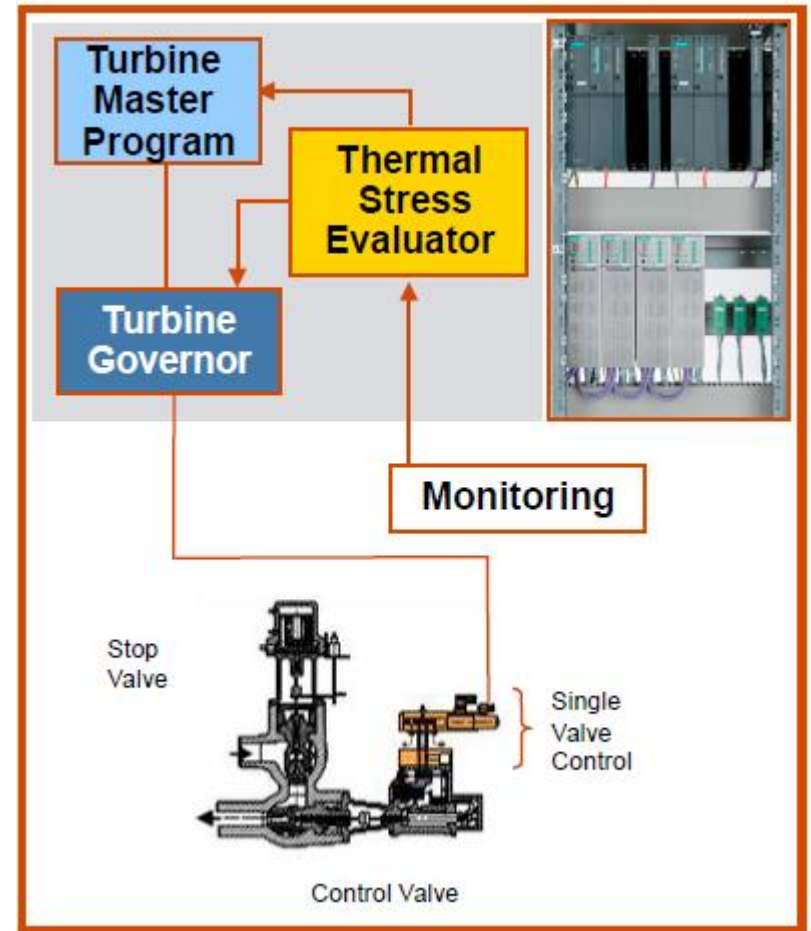


Fig. Siemens Thermal Stress Evaluator in the Frame of Steam Turbine Control System

(source: www.siemensvakfi.org/i/content/3855_1_R3C_Istanbul-2008_e_V1-0.pdf)

Turbine Stress Controller of Siemens

- Example: Turbine Stress Controller of Siemens
 - Measured temperature on the heated surface of the probe (into the cylinder casing) is considered to be representative for the rotor
 - Temperature difference characterizing the rotor's thermal-stress state is calculated based on this temperature

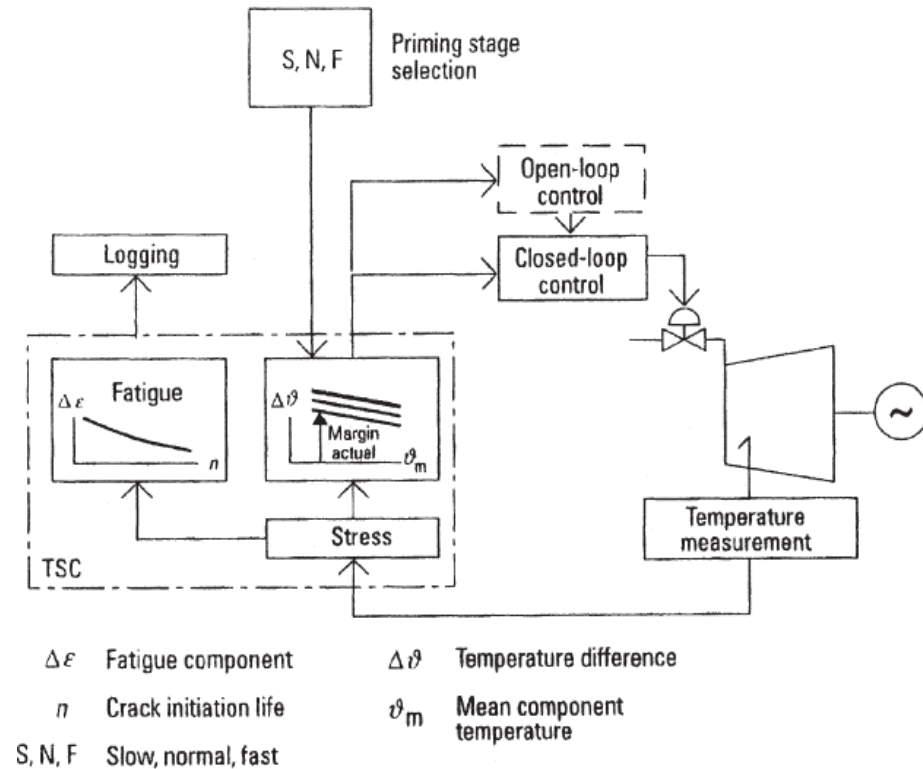


Fig. Configuration of Turbine Stress Controller of Siemens

(Source: Sill U. and W. Zörner. Steam Turbine Generators Process Control and Diagnostics, Erlangen: Publicis MCD Verlag, 1996)

Cutting Edge Systems for Thermal Stress Monitoring - BHEL Turbine Stress Evaluator (TSE)

- Compares thermal stress in the monitored components with the permissible limits to generate margins
- Derives start up criteria for automatic turbine run-up system
- Components Monitored:
 - Emergency stop valve
 - HP control valve
 - HP casing
 - HP shaft
 - IP shaft
- Measuring Points:
 - Surface and mid wall temperatures of ESV (T_i & T_m)
 - Surface and mid wall temperatures of HPCV
 - Surface and mid wall temperatures of HP casing
 - Derived value for HP and IP shaft temperatures from specified locations

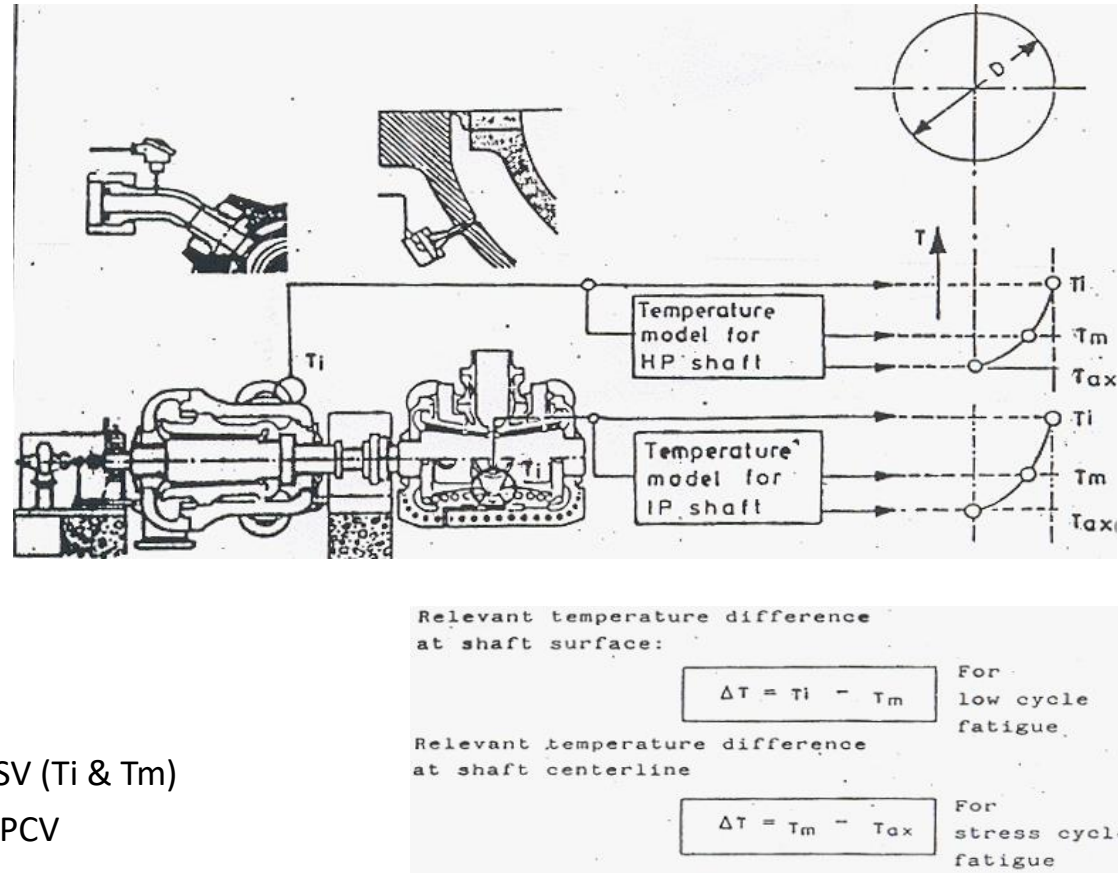


Fig. Determination of Representative Temperatures for Shaft Stresses

Cutting Edge Systems for Thermal Stress Monitoring - BHEL Turbine Stress Evaluator (TSE)

Margins:

- For any component, the difference of $T_i - T_m$ represents the actual thermal stresses
- The permissible value of thermal stress is determined by the value of T_m and operating mode
- From the difference of the permissible stress and prevailing actual stress, the margin is derived
- The margins of different components are provided in the bar graph form in the TSE monitor
- The reference variable derived from the minimum margin acts directly on the turbine control system

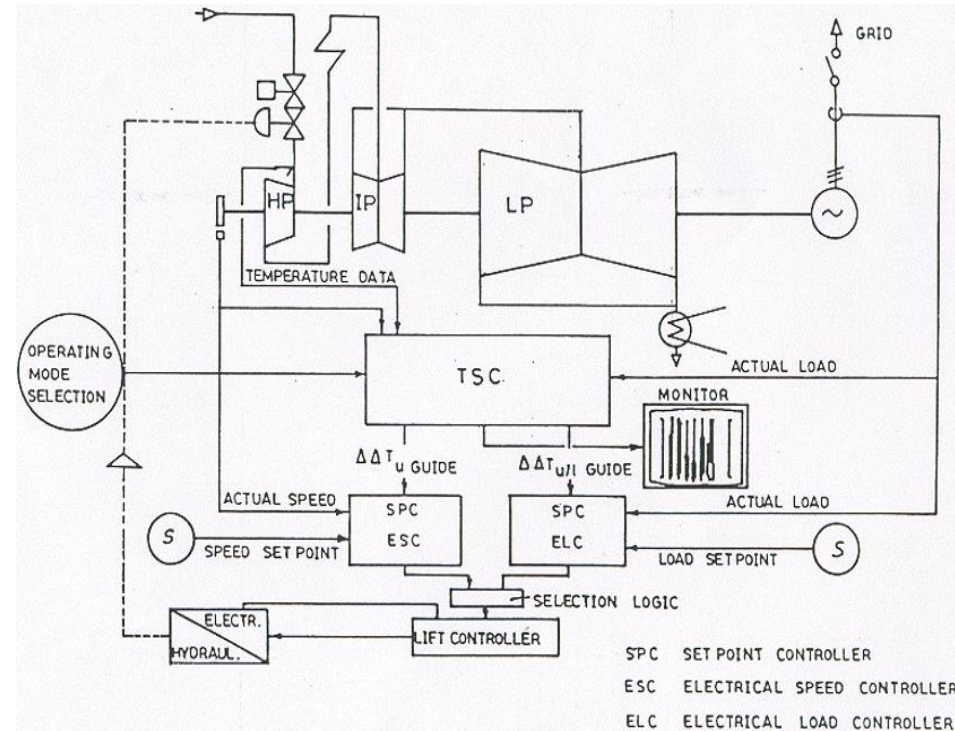


Fig. Action of TSE on Turbine Control System

Recommended Steam Turbine Monitoring Parameters by Turbine Size/Type

Steam Turbine Parameters to be Monitored Continuously	Small Single Stage Units 0.5-2 MW	Medium Size Multi-stage Units 1.5-10 MW	Admission/ Extraction and Non-Reheat Units <100 MW	Combined Cycle Reheat Units	Large Reheat Subcritical and Super-critical Units
Speed (RPM)	X	X	X	X	X
Power (MW or SHP)	X	X	X	X	X
Steam Turbine Inlet Pressure	X	X	X	X	X
Steam Turbine Inlet Temperature	X	X	X	X	X
Steam Turbine 1st Stage Pressure		X	X	X	X
HP Turbine Outlet, IP Turbine Inlet, IP Turbine Outlet/LP Turbine Inlet Pressures and Temperatures				X	X
Admission Steam Inlet Pressure and Temperature (As Applicable)			X	X	
Extraction Steam Outlet Pressure and Temperature (As Applicable)			X		
Turbine Exhaust Steam Pressure	X	X	X	X	X
Turbine Exhaust Steam Temperature			X	X	X
Sealing Steam Pressures	X	X	X	X	X
Sealing Seal Exhauster Vacuum		X	X	X	X
HP and IP Turbine Shell/Steam Chest Temperatures/Differentials			X	X	X
Rotor/Shell Differential Expansions			X	X	X
Rotor Eccentricity			X	X	X
HP and IP Stress					X
Extraction Line and Drain Line Thermocouples			X	X	X
Lube Oil Supply Pressure	X	X	X	X	X
Lube Oil Supply Temperature		X	X	X	X
Lube Oil Sump Level			X	X	X
Bearing Metal or Drain Temperatures		X	X	X	X
Bearing Vibration (Seismic, Shaft) Rider, or Proximity Measurements		X	X	X	X
Thrust Bearing Wear/Tear		X	X	X	X
Hydraulic Fluid Pressures and Temperatures		X	X	X	X
Cooling Water Supply Pressures and Temperatures for Lube Oil and Hydraulic Fluid Heat Exchangers	X	X	X	X	X
Water and Steam Purity Monitoring		X	X	X	X
Control Valve Position (%) Indication		X	X	X	X
Admission and Extraction Valve Position (%) Indication			X	X	

Initial Data for Stress Evaluator from the Field

Standard Power Plant Measurements:

- Rotor speed (rpm)
- Power (MW)
- Flow rate
- Steam temperature (inlet and 1st stage)
- Steam pressure (inlet and 1st stage)
- Steam turbine shell and steam chest temperatures
- HP turbine outlet, IP turbine inlet, and IP turbine outlet/LP turbine inlet (or crossover) pressures and temperatures
- Steam turbine rotor/shell differential expansions (for large turbines)

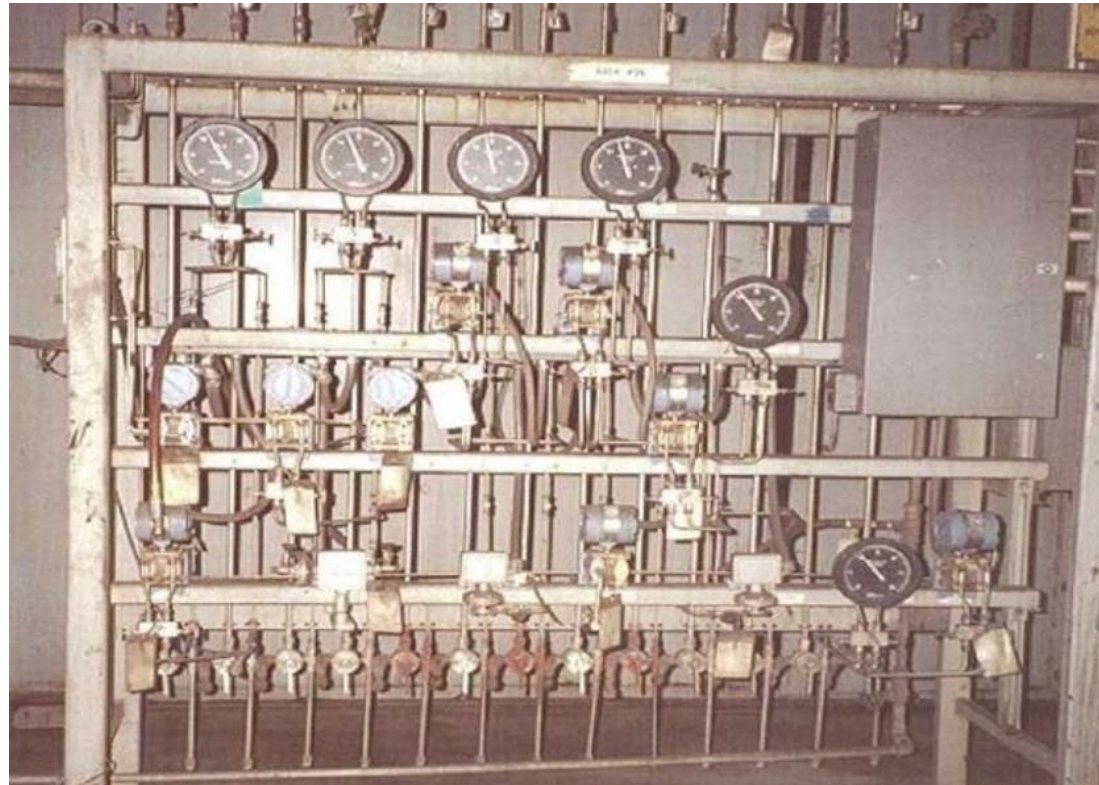


Fig. Instrument Panel for Typical 1000 MW Power Station

Scope of Temperature Measurements

- Scope: All major turbine elements
- It is desirable to minimize the number of temperature measurements
- Sufficient to control data for the most thermally stressed (critical) elements
 - High-temperature rotors (HP, IP)
 - Cylinder casings
 - Valve steam chests

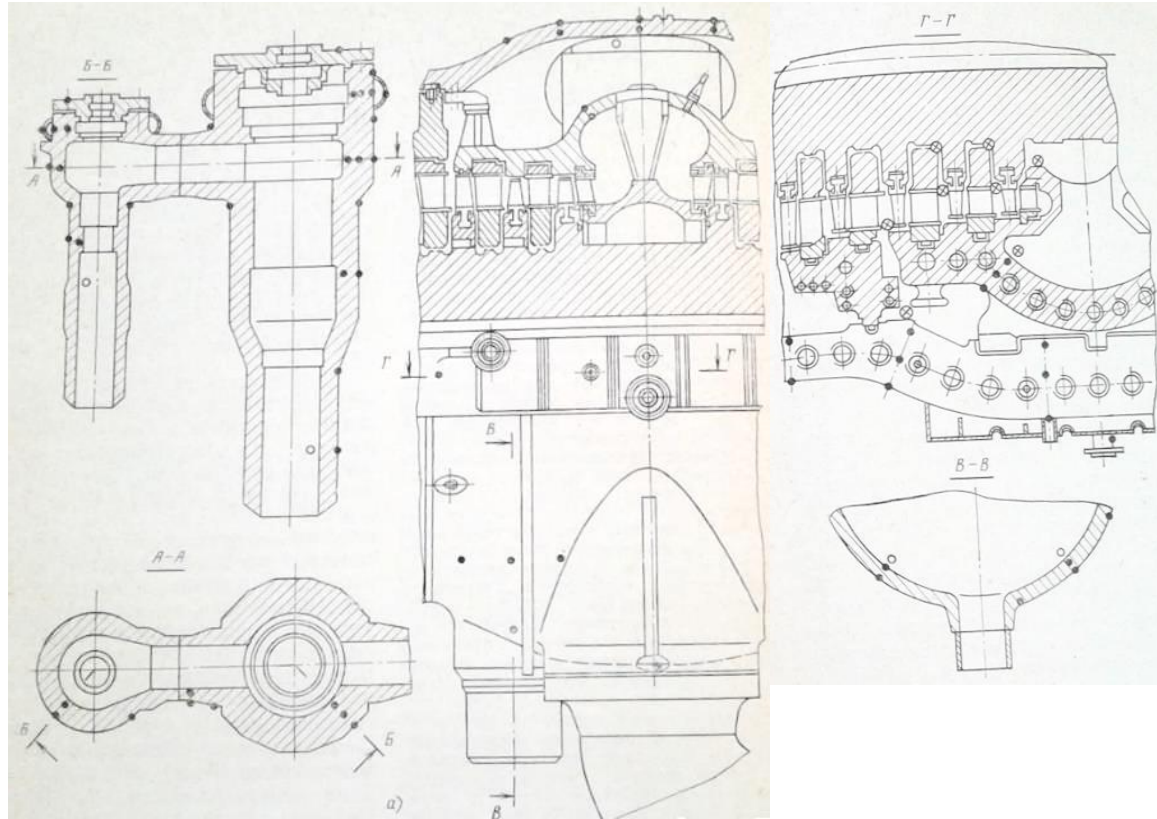


Fig. Thermocouples Installation Scheme for Valve Chest and HP Casing for 800 MW Steam Turbine

Steam Turbine Temperature Measurement - Location

Casing Temperatures

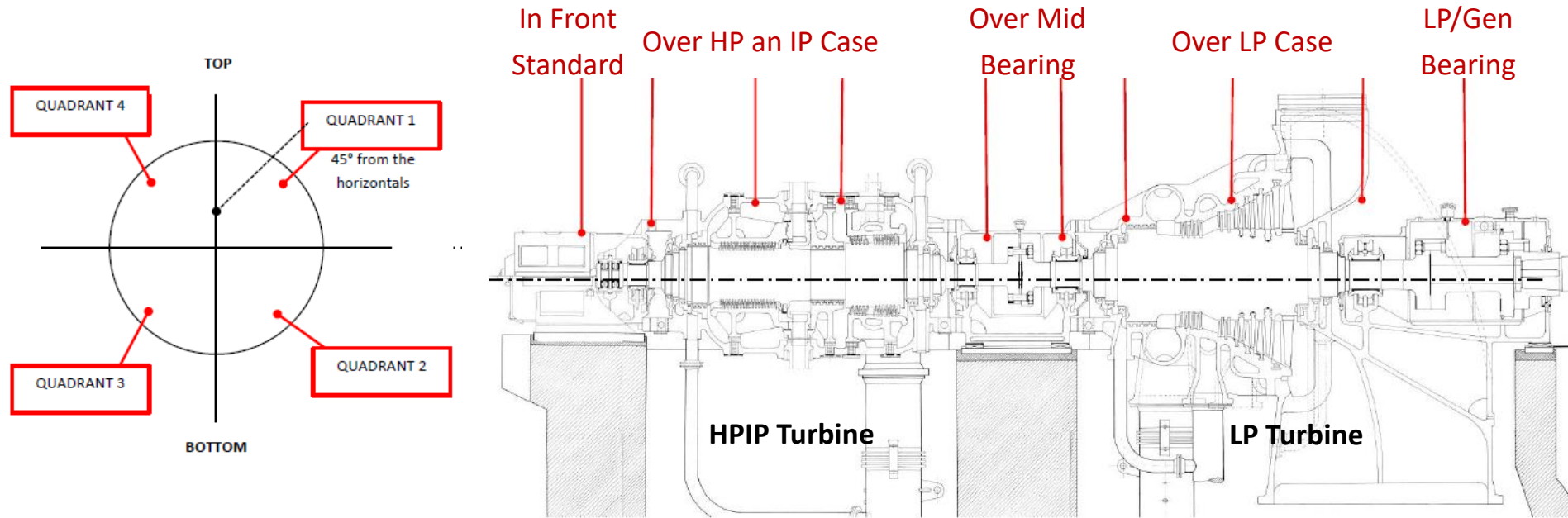


Fig. Thermocouples Installation Scheme for Typical 40 MW Steam Turbine

Other Locations

- Flange joint
 - Monitor and limit the temperature differences
- Flange-bolt temperature difference proportional to the temperature difference across the flange width
- Top-bottom temperature difference to prevent humping and thermal bend of the casing upward
- Number of metal temperature measurements (for high-temperature casings) can significantly vary

Temperature Measurements - HP-IP Rotors

- Heating conditions influenced by the steam flow
- Thermal stresses are determined by means of online mathematical modeling of the heating up process for the rotor based on the measured heating steam temperature
- Δt - radial temperature difference
- t - average integral temperature
- **Δt and t can be calculated based on the measured heating steam temperature at the first HP stage**

- Highest thermal stress (maximum radial temperature differences):
 - First stage disc's fillet
 - Thermal grooves at the inlet

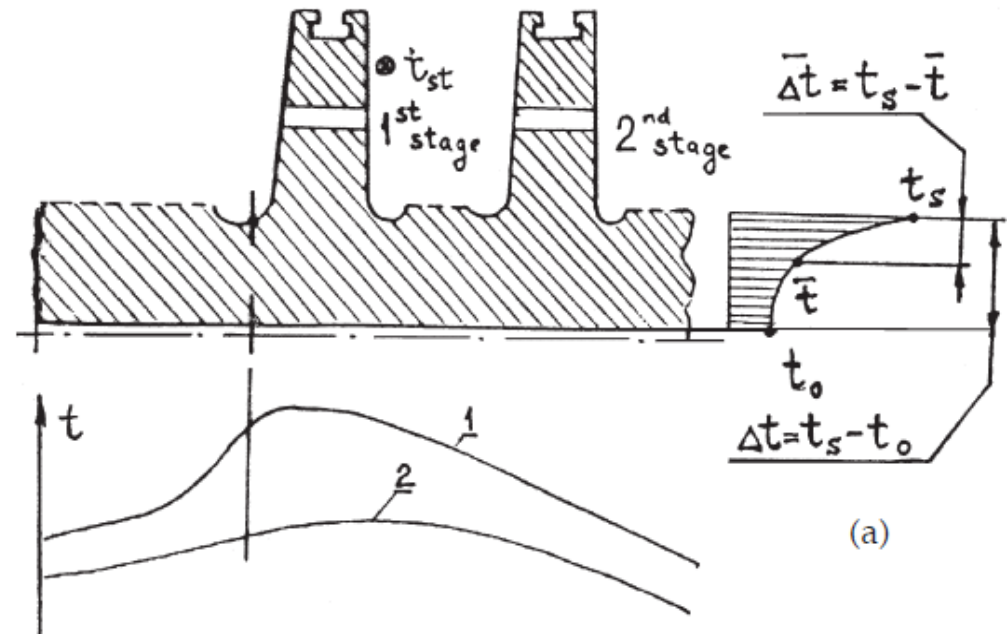


Fig. Temperature Distribution Along the External and Bore Surfaces for a Typical Forged HP Rotor of an Impulse-Type Turbine

Temperature Measurements - HP-IP Rotors

- HP Rotors – Steam Temperature:
 - After the valves
 - Input of a calculated correction
 - Errors by crossover pipes between the HP valve steam chests and cylinder
- IP rotors – Steam Temperature:
 - After the intercept values
 - In the steam admission chamber
 - Calculated corrections
- Rotors with artificial steam cooling
 - The effect should be taken into the account



Fig. GE Energy HP Turbine Rotor

http://images.pennnet.com/articles/pe/cap/cap_gephoto.jpg

Temperature Measurements - LP Rotors

- LP rotors for large steam turbines
 - Great steam flow amounts
 - Increased steam temperatures downstream from the IP cylinder
 - The most dangerous stresses are tensile (centrifugal and thermal stress in the metal depth)
 - On the surface of the central bore
 - At the rotor axis in the steam admission section vicinity
- This thermal stress can be taken in proportion to the entire metal temperature difference Δt (between the metal temperatures on the heated and bore surfaces)
- Steam temperature for the monitoring of LP rotors: measured in the LP crossover pipes



Fig. GE Energy LP Turbine Rotor

http://www.cleveland.com/business/index.ssf/2013/04/firstenergy_corps_perry_nuclea.html

Temperature Measurements - Casing Components

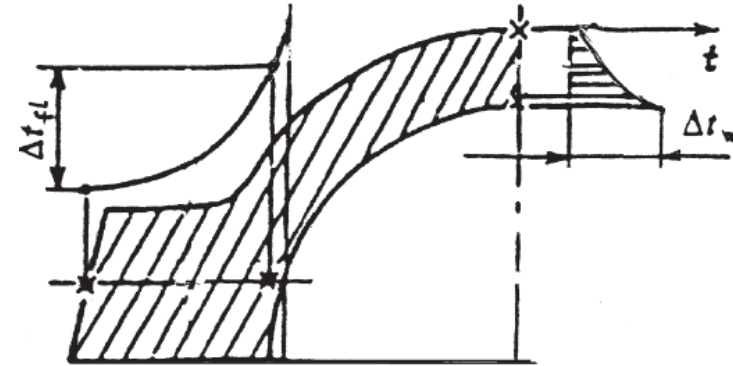
1. Casing Component Wall Thickness and Flange Width

- Monitoring an 'effective' temperature difference

$$\sigma_t = \sum_{i=1}^n (a_i \times \Delta t_i), \quad a_i (i = 1, 2, \dots, n) - \text{influential factors}$$

- 'Effective' temperature difference for dominant temperature Δt_1 to be in proportion to σ_t

$$\overline{\Delta t_1} = \Delta t_1 + \sum_{i=2}^n \left(\frac{a_i}{a_1} \times \Delta t_i \right).$$



2. Temperature difference lengthwise the wall determines the bending thermal stresses

$$\Delta t_z = \frac{t_{w0} - t_{w1}}{\Delta l_1} - \frac{t_{w1} - t_{w2}}{\Delta l_2}$$

Δt_w – temperature difference across the wall thickness

- Correction for the distance from the measured point to the heated surface

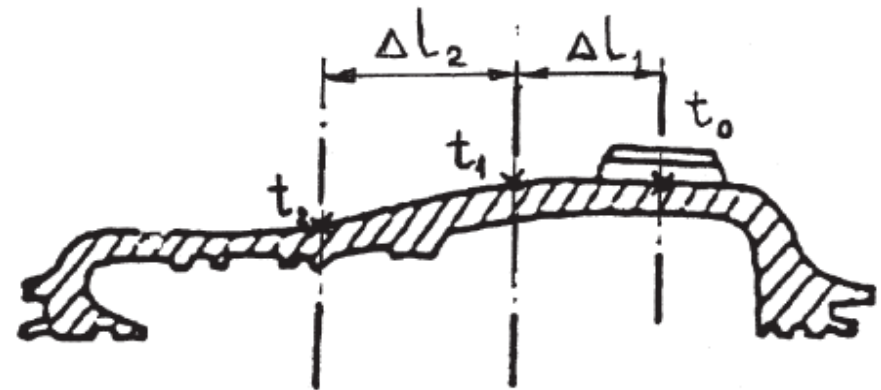


Fig. Metal Temperature Differences in a Turbine Casing Characterizing its Thermal Stress State

Steam Turbine Temperature Measurement Locations

Casing Wall

Casing Wall Temperature Measurement

- Thermocouple installation for online stress evaluation

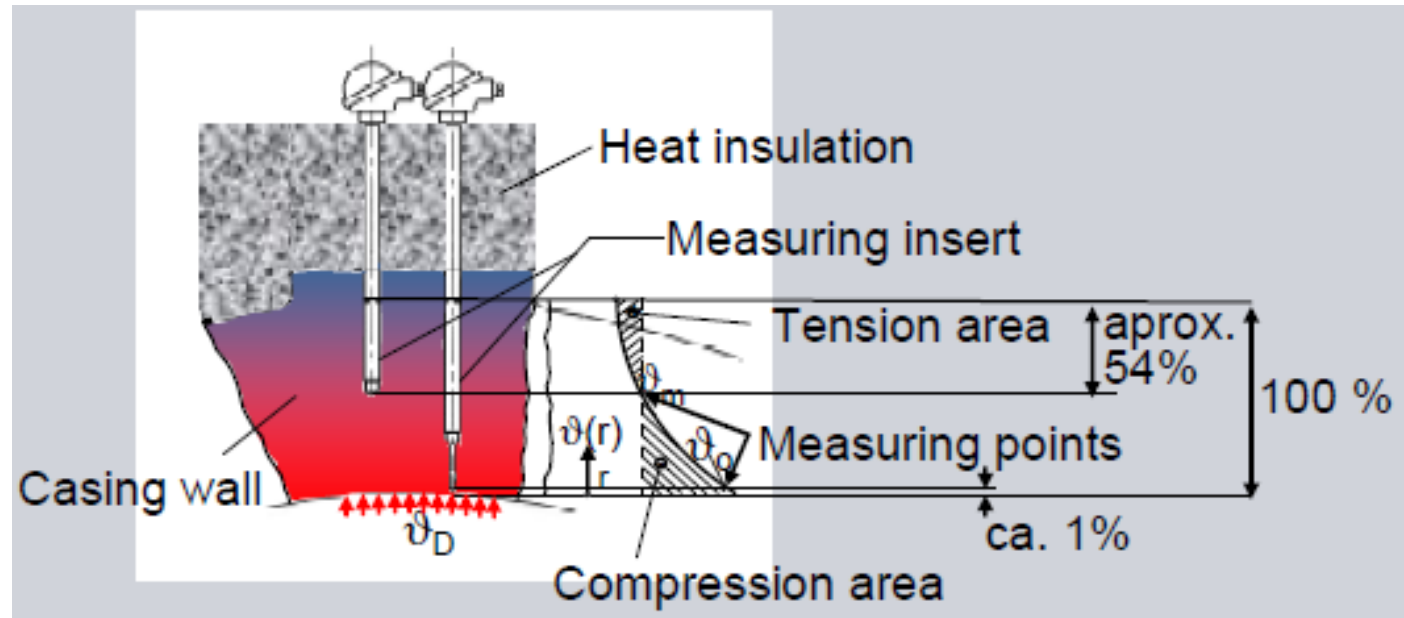


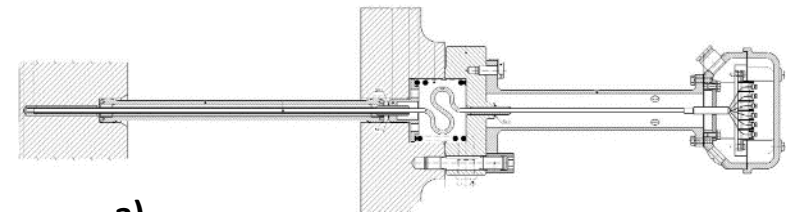
Fig. Steam Turbine Casing Wall Temperature Measurements

(source: www.siemensvakfi.org/i/content/3855_1_R3C_Istanbul-2008_e_V1-0.pdf)

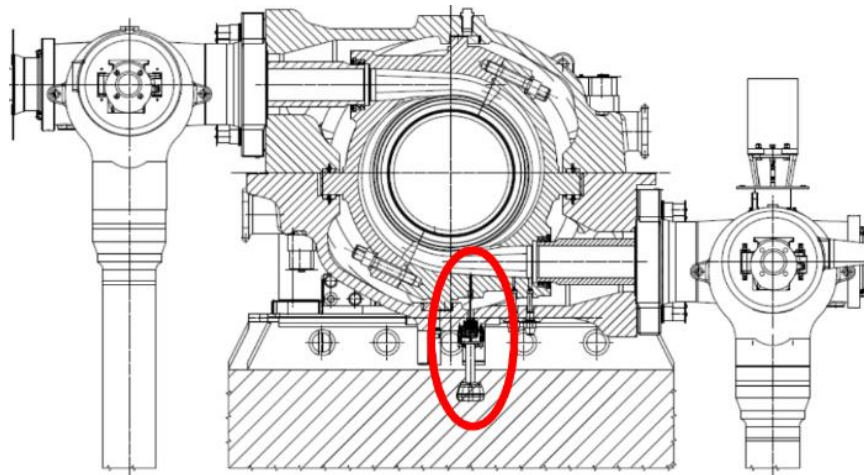
Steam Turbine Temperature Measurement Locations

Steam Temperature

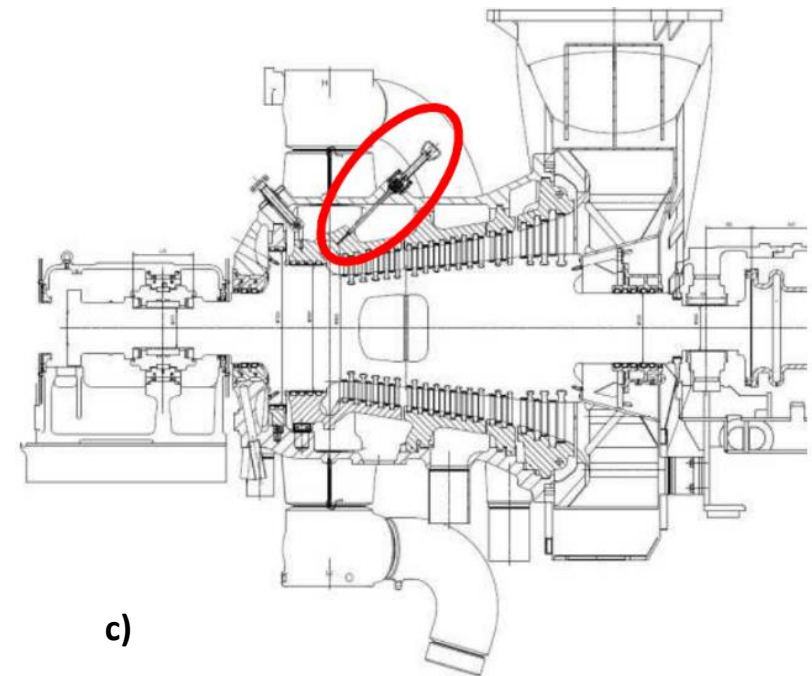
- Temperature in a critical location of the protected rotor is simulated by a **startup probe** [*]
- Measures temperature in the inner casing in front of the steam path
- The depth of temperature measurement by the startup probe as well as the inner casing boss in the vicinity of the startup probe provides appropriate modeling of the critical location of the protected rotor



a)



b)



c)

Fig. Startup probe (a), Installed in Steam Turbine Casing HP (b), IP (c)

(reference: Dominiczak K., Radulski W., Banaszkiwicz M., Mróz K., Bondyra R. Thermal stress limiter for 13K215 steam turbine retrofit in Połaniec Power Plant, Poland Journal of Power Technologies 96 (4) (2016) 285–294)

Models for Monitoring Thermal-Stress States

- **Casing Components and Valve Steam Chests** - Direct thermometry can be applied
- **Turbine Rotors:** Direct thermometry is too complex and unreliable.
Indirect methods of physical or mathematical modeling can be utilized



Physical models

Mathematical models

1) Imitates the shape of the rotor sector, swept by steam of the same temperature as the rotor near its most stressed section

Limitations:

- 1) Settling the probe within the turbine cylinder in the proper place involves serious design difficulties
- 2) HTC's from steam to the probe head and the rotor surface are significantly distinct from each other
- 3) Hardly removed heat flows on the side probe surfaces cause errors in modeling

1) Materialized on the basis of analogs or digital computing techniques

2) Reliable computing resources

3) Diverse calculation schemes:

- Finite elements
- Finite differences
- Approximate transfer functions

Post-Operative Analysis of the Turbine's Operating Conditions

- The measured and calculated data of online diagnostic monitoring should be recorded and stored to be analyzed offline by plant engineers and supervisors
- The main goals of this analysis is evaluation of:
 - Equipment's state
 - Quality of its service
- The resultant comprehension of the equipment state provides the basis for scheduling maintenance—inspections, current repairs, and overhauls
- Together with results of maintenance diagnostics at the stopped unit, this analysis is used for planning replacement of individual equipment elements or more general upgrades
- Evaluation of the operation quality is basic to teaching and training the operational personnel to prevent repetition of the revealed characteristic operating errors. All these measures are necessary to keep and improve the unit's efficiency, reliability, and flexibility
- Effectiveness of this offline analysis depends on the opportunity to access the stored results, their completeness and representativeness, and the possibility of processing them

Online Operative Support for Turbine Operators at Transients

- Support the operational personnel in observing the state of equipment:
 - Information about equipment condition during operating
 - Assistance in alarming or ambiguous situations, relying on the properly processed measured data

- Example: Nuclear Power Plant Control Complex with Advanced Man-Machine Interface 90 (NUCAMM-90), developed by Hitachi in the mid-1990s



Fig. Main Control Board of NUCAMM-90 for the 1356MW Kashiwazaki- Kariwa Unit 7

5. Heat Transfer / Stress Analysis Model Optimization for Field Applications

Basic Idea of Steam Turbine Thermal Stress Analyzer

- Stress measurements for steam turbine components are extremely difficult due to the:
 - High operating temperature
 - Life limiting location accessibility
 - Rotation in the case of the steam turbine rotor
- Indirect methods of stress assessment are currently used
- Stress in supervised steam turbine components is estimated by thermal stress analyzers - monitoring systems which assess on-line current stress and allowable stress in components
- Due to real time calculation limitations, stresses are not assessed in the whole supervised component but only in a life limiting location
- The main goal of the thermal stress limiter is to limit stress amplitude in the supervised steam turbine component in order to fully achieve the required number of cycles

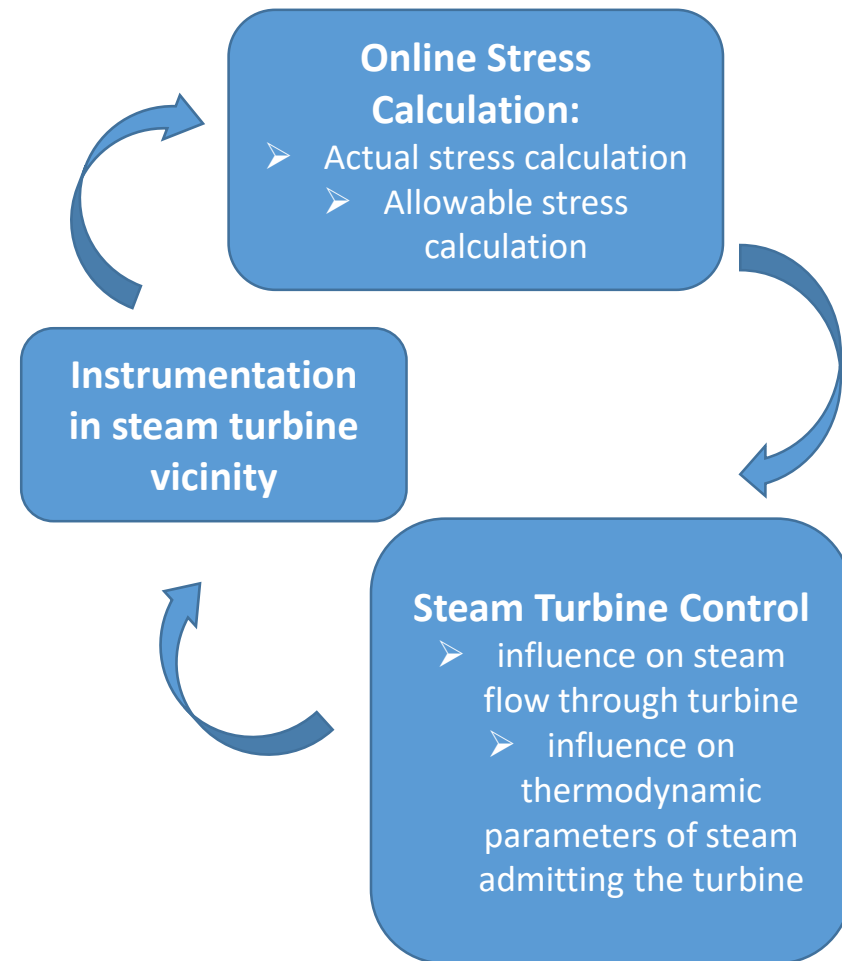


Fig. Idea of Steam Turbine Thermal Stress Limiter

Turbine Stress Evaluator

- 1 – rotation speed and load limiters of the turbine's electrohydraulic system
- 2, 3, 4 – computing device, indicator, and multipoint recorder
- 5, 6, 7 – detectors of temperature differences in HP valve steam-chests, HP and IP rotors
- 8 – HP combined unit of stop/control valves
- 9 – rotation speed sensor
- 10, 11, 12 – HP, IP, LP turbine cylinders
- 13 – electric output sensor

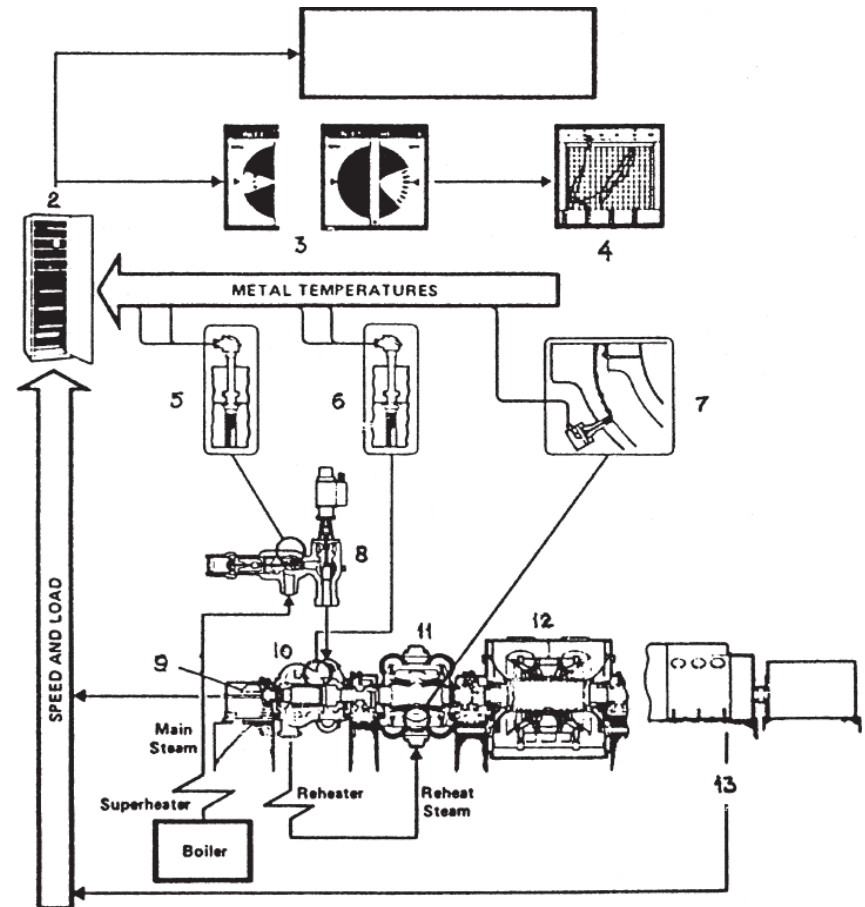


Fig. Turbine Stress Evaluator of Siemens

(Source: Hoerster B., W. Gorzegno, and H. Termuehlen. "Two-Shift Handley Station Units 4 and 5— Experience with 2000 Starts," Proc. of the American Power Conference 47, Chicago, 1985, 62-71.)

Analysis Model Optimization for Field Applications

Thermo-structural analysis models have to be optimized for the field application to provide:

- High speed of simulation
- Results accuracy
- Simplicity and reliability of the models and methods
- To be able to continuously calculate the actual conditions of the turbine components that are subjected to high material stresses, not only must the turbine characteristics be known (i.e., its geometrical, thermodynamic flow and material-specific characteristics), but also a large number of measured values and logical quantities must be taken into account.
- The combination of known and measured information is the basis for program initialization and for determining the actual operating states of the running turbine

Calculation Models

Calculation Models:

- Thermodynamics
- Temperature
- Stress Simulation

Thermodynamic Calculation Model

- Considers the turbine through which steam is flowing as a multiple orifice system
- The steam parameters pressure, temperature and heat transfer for the shaft cross-sectional area under investigation are obtained by iteration (always taking into account the valve characteristics and the power efficiency of the turbine stages)
- The physical material characteristics are determined on the basis of a steam characteristics table
 - In the cooling and heating phases, the turbine casing temperature is used as the reference for all further calculation.

HP-IP Valve Chests Stresses Calculation

- Based on equivalent stress (mechanical & thermal)
- Mechanical stresses are based of measured pressure:
 - HP valve chests live steam
 - IP valve chests reheat steam
- Thermal stresses are determined by Duhamel's integral:

$$\sigma^T = \int_0^t \frac{dT_P(\tau)}{d\tau} f(t - \tau) d\tau$$

- Input signals for thermal stress calculations are online measured temperatures:
 - 1) HP valve chest: live steam temperature and valve casing temperature
 - 2) IP valve chest: reheated steam temperature and valve casing temperature

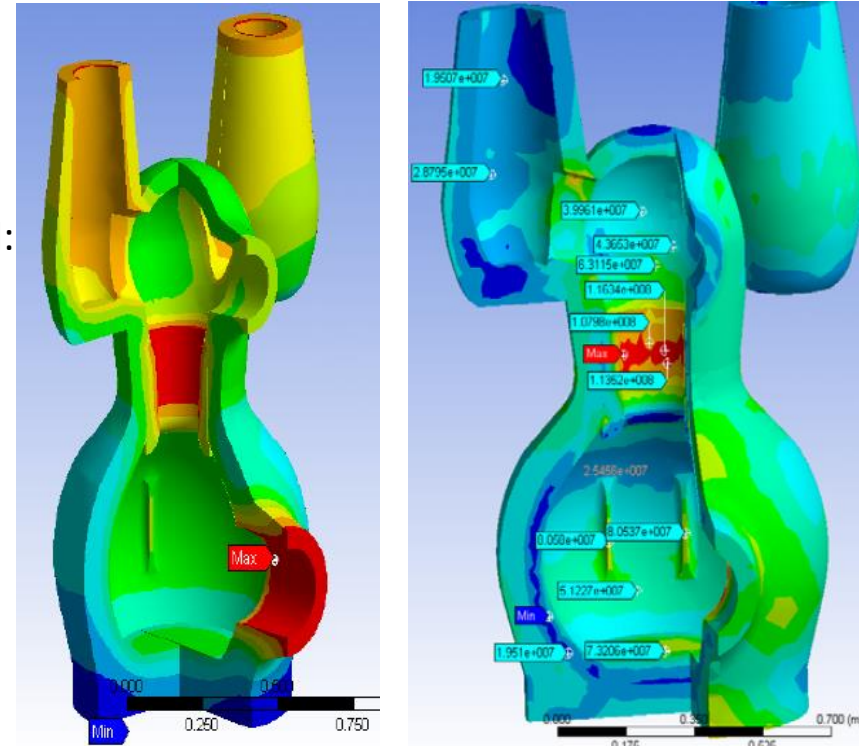


Fig. Example Results of Temperature and Stress Calculations of the 200 MW Steam Turbine Valve chest

(source: Chernousenko O. Yu, Summarizing and analysis of results of calculation study on individual service life of HPC&MPC cases and rotors of 200MW K-200-130 turbine // Energy and thermal processes and equipment., NTU«KhPI», Kharkiv,2008. N6.)

HP-IP Rotors Stresses Calculation - Smooth Cylinder Model

- Mathematical model for online rotor stresses estimation - smooth cylinder
- Stress attained maximum at the heated surface
- Stresses are proportional to the surface-mean temperature difference:

$$\sigma^T = -\frac{E\beta}{1-\nu}(T_p - T_{sr})$$

E – Young modulus,

β – thermal expansion coeff.,

ν – Poisson coefficient,

T_p – surface temperature,

T_{sr} – mean temperature

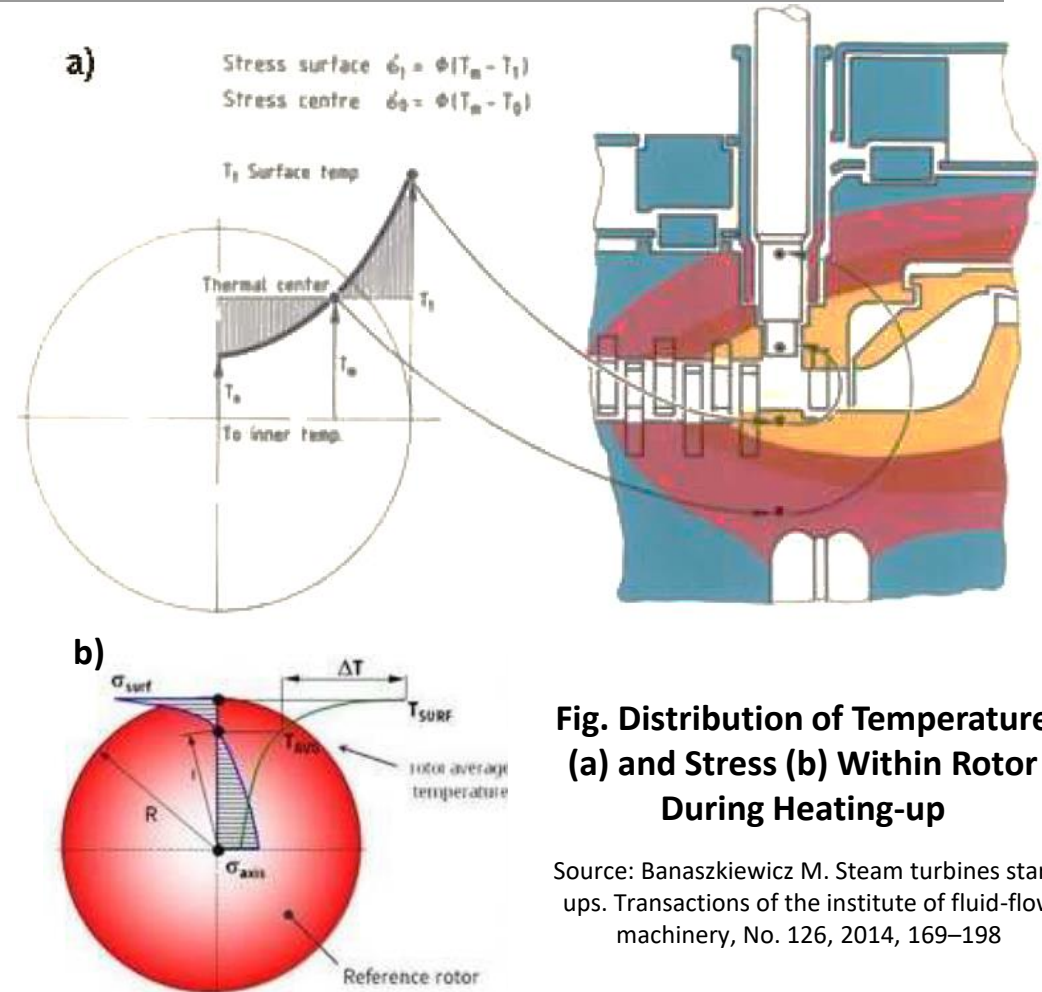


Fig. Distribution of Temperature (a) and Stress (b) Within Rotor During Heating-up

Source: Banaszkiwicz M. Steam turbines start-ups. Transactions of the institute of fluid-flow machinery, No. 126, 2014, 169–198

Stress Concentration Accounting

- On rotor surface, stress concentrates at locations of sudden change in geometry, such as wheel roots or labyrinth seals, therefore the solid cylinder approximation described above cannot be used without modification.
- The obtained axial stress is multiplied by the stress concentration factor k_c (1.6÷2.0):

$$\sigma_z = -k_c \frac{E\alpha\Delta T}{1-\nu}$$

E – Young modulus,

α – thermal expansion coeff.,

ν – Poisson coefficient,

$\Delta T = T_p - T_{sr}$ – temperature difference

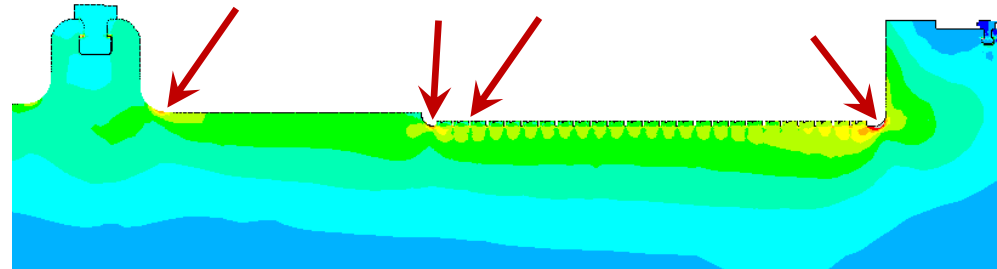


Fig. Stress Concentration in 40 MW Steam Turbine HPIP Rotor

HP-IP Rotors Stresses Calculation - 2D Axisymmetric FEA Model

- Detailed FEA 2D/3D models are used in modern stress analyzers based on life steam and hot reheat steam parameters
- 2 meshed models are required:
 - Vicinity of the probe and the surface temperature sensor is modelled by a 2D or 3D structure with planar symmetry
 - Full rotor is modelled by a 2D FE model with axial symmetry
- The heat transfer coefficients are calculated from the steam mass flows and local steam pressure and temperatures

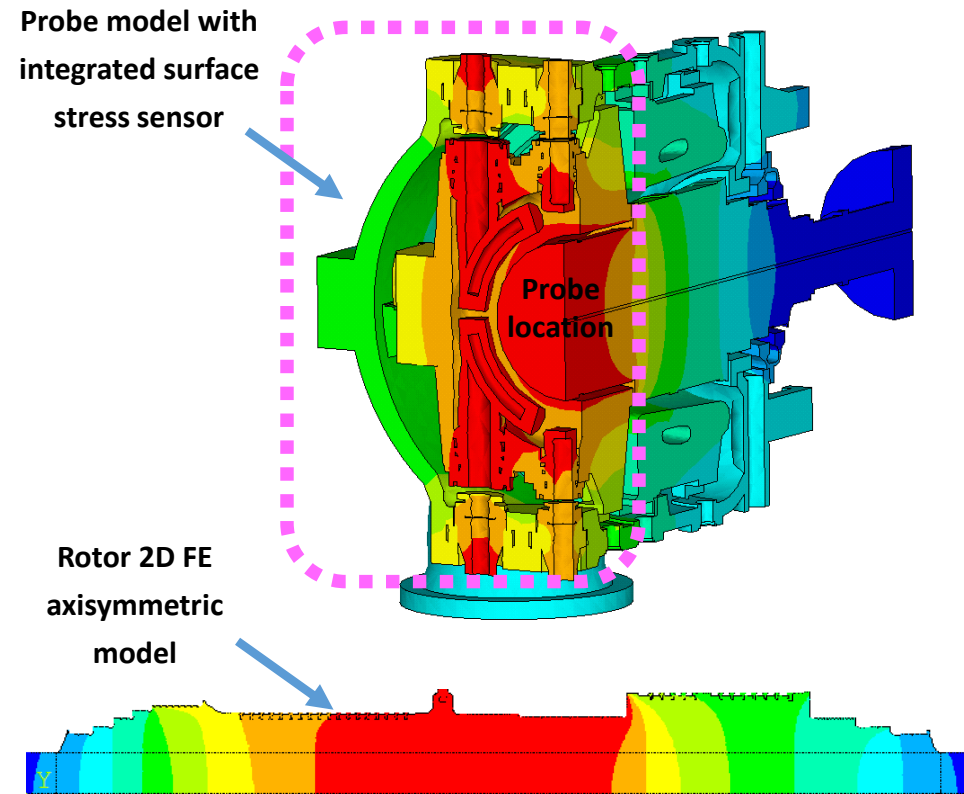
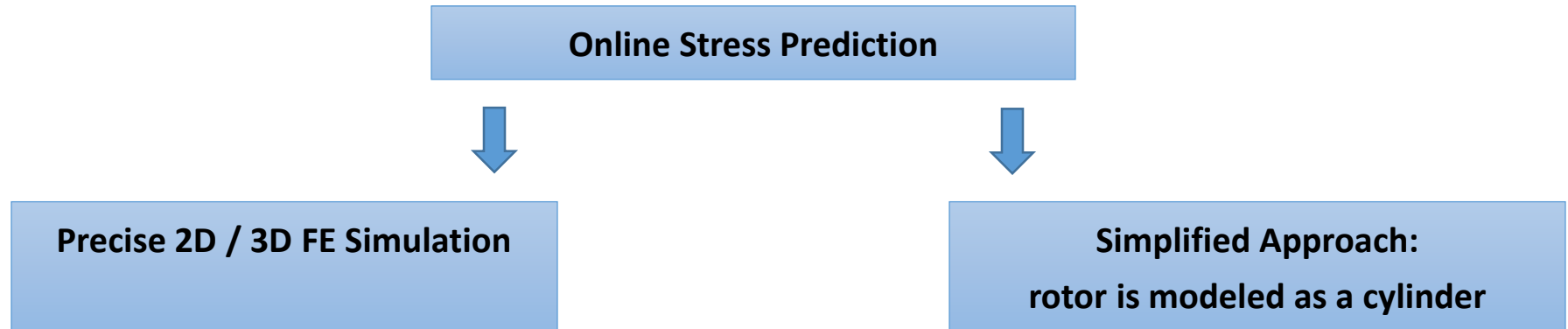


Fig. FE Models for Probe Vicinity and for Rotor are Required to Improve the Precision Simulation

Modern vs. Old-Fashioned Online Stress Calculation



- High accuracy of results
- High performance computational resources are needed
- **Modern turbine protections rely on precise 2D/3D FE calculations**

- Moderate or low accuracy of results
- Computational resources is not an issue
- Simplified approaches are used:
 - Rotor is modelled as a simple cylinder (2D)
 - Transfer function are widely used

6. Challenges

Bad Sensors Problem

- Sensors going bad are very common issues
- Wrong readings are a dangerous phenomenon, as they can result in the wrong diagnoses
- Bad sensors make more than 70 % of all detections made, and a sensor which has impact on a protection logic could cause a major issue. Therefore, the focus of continuous monitoring lies on persistently evaluating all aspects of the plant and on cooperating with the customer to maintain the sensors and other equipment of the plant at the highest level possible

Main challenges for future

- To decrease sensitivity to shock and vibration
- To increase sustainability to aggressive environment
- To decrease fragility
- To increase sensitivity
- Long-term stability

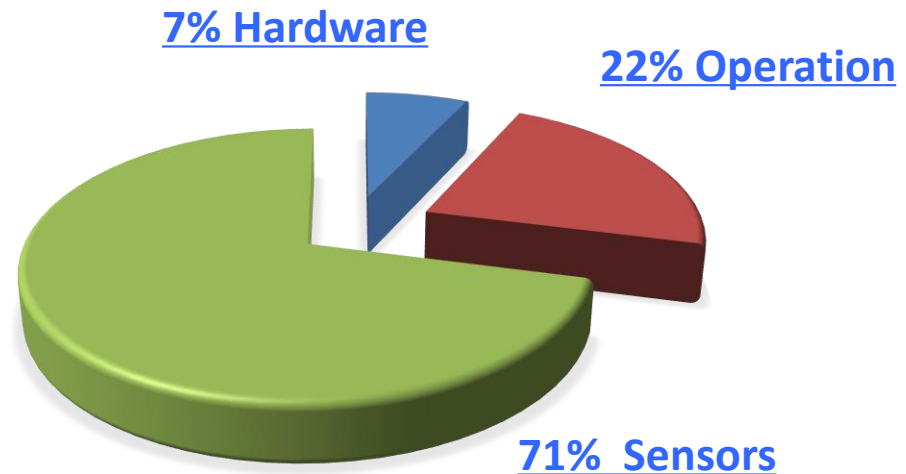


Fig. Power Plant Failure Statistics

Accuracy of Thermal Stresses Prediction

- Limited Field Data
 - The information and amount of thermal/pressure probes available are often very limited
 - Rotor metal temperature measurements are nearly impossible to take
- Simplified calculation models and methods can be applied due to hardware limitations
 - Such models do not represent the actual component behavior accurately
- Applied models don't consider advanced physical effects such as:
 - "Condensation" phenomena which takes place in the early stages of cold start-up
 - "Windage" effect at regimes characterized by low flow and high rotation speed when turbine operates at compressor mode
- No backup solution, often calculations stop after several years and results are lost
- Possible measurement deviations due to replacement of measurement equipment can lead to wrong calculation results
- **Modern methods which are based on FEA Simulation on-line should be developed to predict stresses and lifetime with highest accuracy**



Thank You for Your Attention!

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