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Flexibilization of Conventional Power Plants – Indian Experience

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National seminar on "Reducing Net Heat Rate – for Thermal Power Plants, 25 – 26 April. 2022, Goa

Corrosion and Water Management Consultants

"Improving Plant Performance, Availability & Reliability by Chemical Interventions"

About Myself

Name: Ashwini K. Sinha (Retired as Addl. GM (NETRA), NTPC in July 2012)

Qualifications: M.Sc (Electrochemistry)
P.G. Dip. In Corrosion Science & Technology, Univ. of Ferrara (Italy)

Affiliations: Member NACE International, Life Fellow Member SAEST, IAAPC
Core Member of CII-Avantha Corrosion Management Committee

Experience: 44+ years experience in Corrosion Analysis, Monitoring and Control in Power Plants. 5 Years BHEL (R&D), Hyderabad. 30 years with NTPC (R&D) (now "NTPC Energy Technology Research Alliance **(NETRA). Free Lance Consultant in the areas of Corrosion & Water Management (since 2012).**

Specialization: Corrosion Assessment, Failure Investigations, Corrosion Monitoring, Corrosion Audit, Design of Cathodic Protection Systems for Underground Pipelines; Condenser Water Boxes; RCC Structures such as Cooling Towers**; etc, Selection of Anticorrosive Coatings, Development & Implementation of Cooling Water Treatments, Waste Water Recycling & Treatment, Chemical Cleaning of** Condensers; Boilers; Pipelines; PVC Film Type Fill Packs of Cooling Towers**; etc, Material Selection, Water Management, etc.** Research Studies on **Extraction of Moisture from Flue Gases, Ash Mineralization by Flue Gas, etc. (For details please Visit https://www.cwmcindia.com)**

About Myself

Corrosion and Water Management - International,

1.Plants under O&M by NOMAC –

- **USC Plant (Coal & Gas Based, Seawater Cooled), Dubai, and Desalination plants at Umm Al Quwain, IWP, Taweelah IWP, UAE**
- **CCPP (Coastal, Air Cooled), Salalah, Oman;**
- **Tanger Wind Farms (Coastal), Morocco,**
- **Boujdour PV, Layuoune PV, NOOR 1 CSP, NOOR 4 PV; Morocco,**
- **Sohar3 CCPP (Seawater Cooled), IBRI CCPP (Air Cooled) & PV; Barka IWPP; Oman;**
- **Vin Hao 6 PV (Coastal, Salt Pan), Vietnam,**
- **Egypt Energy PV; Benban Egypt for Solar Energy PV; Nile Energy PV; Egypt,**
- **Shuaibh IWPP (Seawater Cooled CCPP), Jeddah;**
- **DEWA PV and Noor Energy 1 CSP, Dubai; UAE**
- **Sardarya CCGT, (Snow area), Uzbekistan;**
- **Al Dur 2, IWPP (Seawater Cooled CCPP), Bahrain**
- **Bokpoort CSP, South Africa**

2. Sembcorp IWPP (Seawater Cooled CCPP), Salalah, Oman

3. Failure of SS Tubes at Oman Food Products, Salalah, Oman

4. Condenser tubes and Boiler Tube Failures at CCPPs (3 No.), Iran

About Myself

Corrosion and Water Management - National

1.NTPC and NTPC Subsidiary Companies (almost all stations till 2012, Meja)
2.Adani Power- Mundra (Seawater), Tiroda, Kawai, Udupi (Seawater), Raipur,
3.Sembcorp (Seawater), Nellore
4.Rajasthan RVUNL - Kalisindh, Dholpur CCPP, Kota Thermal, Chhabra (TPP & SC), Suratgarh
5.Mahagenco – Chandrapur STPS, Koradi (SC), Bhusawal, Khaparkheda
6.CLP Jhajjar (SC) and Paguthan CCPP
7.Haldia Energy Limited, Haldia, Dhariwal Infrastructure Ltd., Chandrapur
8.Vedanta Limited, CPP & IPP, Jharsuguda, TSPL Bhatinda and Balco, Korba
9.GSECL Sikka TPS (Seawater), Jamnagar
10.Essar Sallaya Project (Seawater), Jamnagar
11.NABHA Power, Rajpura, Punjab
12.IOCL Refinery - Dibrugarh, Guwahati, Panipat
13.Lanco Kondapally, Gurugram, Udupi (now with Adani Power)
14.HMEL Refinery, Bhatinda, Punjab
15.Reliance Power - Rosa Power, Shajahanpur, Sasan UMPP
16.Jindal Power, Raigarh; JSPL, Odisha
17.Neyveli Lignite Corp. and NTPL, Neyveli, TN
18.Hindalco – Mahan, Sambalpur
19.Pipavav CCPP (Seawater), Gujarat
20.Tuticorin TPP (Seawater), Panipat Thermal Power Plant

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Introduction, Installed Capacity

Cycling Units

Cycling

Cycling is a load following operation. The unit load fluctuates with system demand, with the unit synchronized at very low loads during low-demand periods. A typical load variation for cycling units might range from 30% to 100% of design capacity.

Peaking is a form of cycling in which the unit is operated only during peak power demand periods. At off-peak hours the unit is on hot or cold standby, depending upon the estimated time between restarts. Two-shift operation is typical of peaking units, which generally furnish power for the morning and evening high demand hours.

Ref.: Cycling, Startup, Shutdown, and, Layup Fossil Plant Cycle Chemistry Guidelines for Operators and Chemists – TR 107754, EPRI

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Flexible Operation

Flexibility: The term was first introduced in IEA (2008) as: "…The ability to operate reliably with significant shares of variable renewable electricity." A more specific definition was put forward in IEA (2011): "**Flexibility expresses the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise**." IEA (2014) introduced a distinction between a broader concept of flexibility and a narrower concept of ramping flexibility: "**In a narrower sense, the flexibility of a power system refers to the extent to which generation or demand can be increased or reduced over a timescale ranging from a few minutes to several hours**."

RES: Unless mentioned otherwise, the term RES or Renewable Energy Sources has been used to represent Solar and Wind power. Biomass and Small Hydro have been mentioned separately whenever required.

Minimum Load: **The minimum load is the lowest possible net load a generating unit can deliver under stable operating conditions**. It is measured as a percentage of normal load or the rated capacity of the unit.

Flexible Operation

Start-up time: **The start-up time is defined as the period from starting plant operation till reaching minimum load**. The start-up time of different generation technologies varies greatly. The other factors influencing the start-up time are, down time (period when the power plant is out of operation) & the cooling rate.

Ramp rate: The ramp rate describes how fast a power plant can change its net power during operation.
Mathematically, it can be described as a change in net power, ΔP, per change in time, Δt. Normally the ramp rate is specified in MW per minute (MW/min), or in the percentage of rated load per minute (% P/min). In general, ramp rates greatly depend on the generation technology.

Minimum Thermal load (MTL): The MTL is the ratio of actual minimum load on the prime mover of a thermal power station and its rated capacity. E.g. if a 200 MW plant runs at minimum load of 120 MW during a day, then the MTL for that plant is 120/200 i.e. 60%.

Source: **FLEXIBLE OPERATION OF THERMAL POWER PLANT FOR INTEGRATION OF RENEWABLE GENERATION, CEA, 2019**

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ALL INDIA INSTALLED CAPACITY (IN MW) OF POWER STATIONS

(As on 30.04.2021)

(UTILITIES)

Power Sector at a Glance ALL INDIA

1.Total Installed Capacity (As on 28.02.2021) - Source : Ministry of Power (MoP) (As on 22-04-2021)

Sector	**MW**	**% of Total**
Central Sector	98,327	24.9%
State Sector	1,05,314	26.7%
Private Sector	1,91,434	48.5%
Total	**3,95,075**	100.0%

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ALL INDIA INSTALLED CAPACITY (IN MW) OF POWER STATIONS

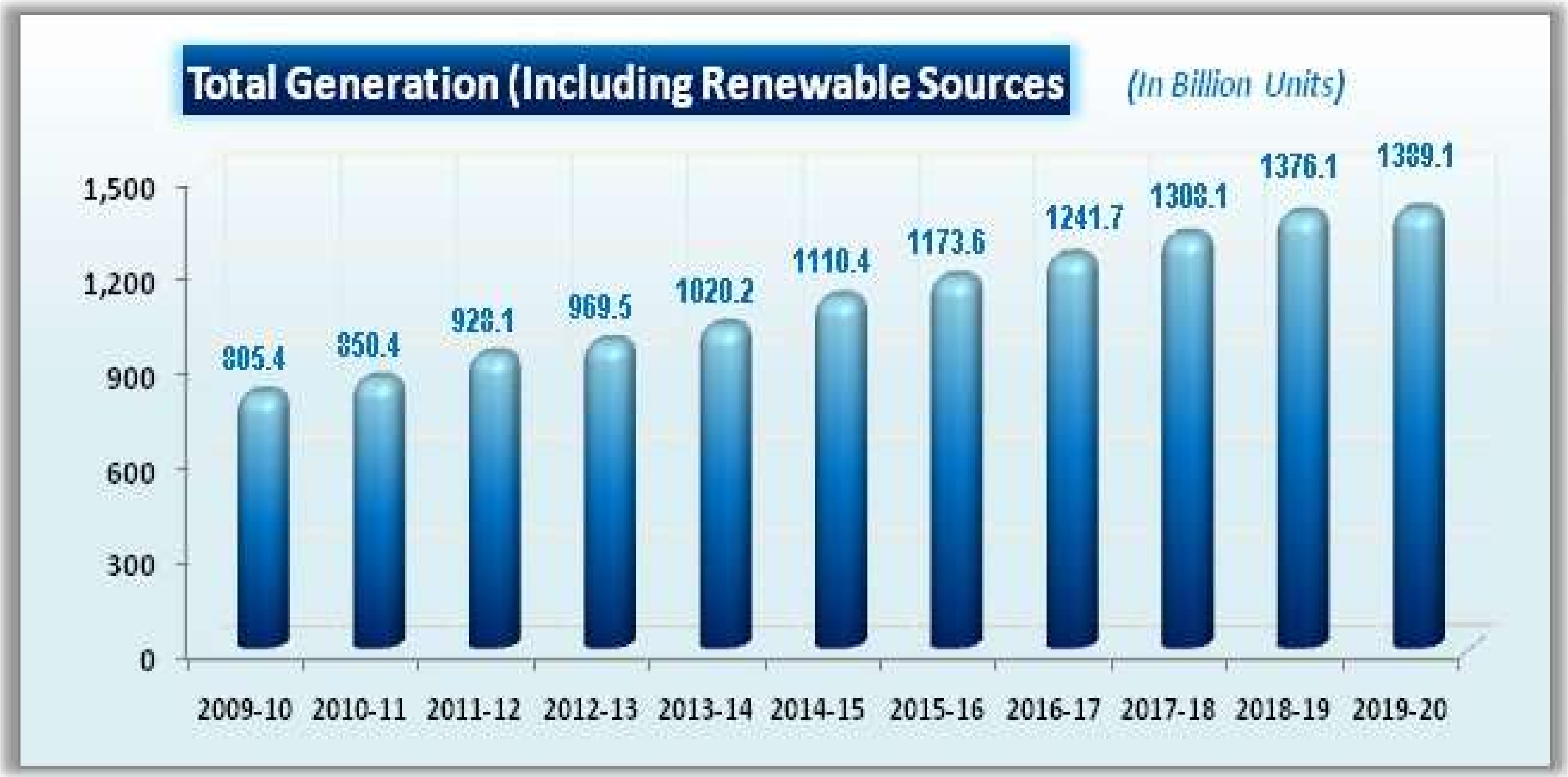
(As on 30.04.2021)

(UTILITIES)

Installed GENERATION CAPACITY(FUELWISE) AS ON 31.01.2022		
CATAGORY	**INSTALLED GENERATION CAPACITY(MW)**	**% of SHARE IN Total**
Fossil Fuel		
Coal	2,03,900	51.6%
Lignite	6,620	1.7%
Gas	24,900	6.3%
Diesel	510	0.1%
Total Fossil Fuel	**2,35,929**	**59.7%**
Non-Fossil Fuel		
RES (Incl. Hydro)	**1,52,366**	38.5%
Hydro	**46,512**	**11.8 %**
Wind, Solar & Other RE	**1,05,854**	26.8 %
Wind	40,101	10.2 %
Solar	50,304	12.7 %
BM Power/Cogen	10,176	2.6 %
Waste to Energy	434	0.1 %
Small Hydro Power	4,840	1.2 %
Nuclear	6,780	1.7%
Total Non-Fossil Fuel	**1,59,146**	40.3%
Total Installed Capacity (Fossil Fuel & Non-Fossil Fuel)	**3,95,075**	**100%**

CWMC Generation Growth (%):- * Upto February 2021 (Provisional), Source : CEA

Generation (Billion Units)



Generation Growth (%):- * Upto February 2021 (Provisional), Source : CEA

Generation Growth

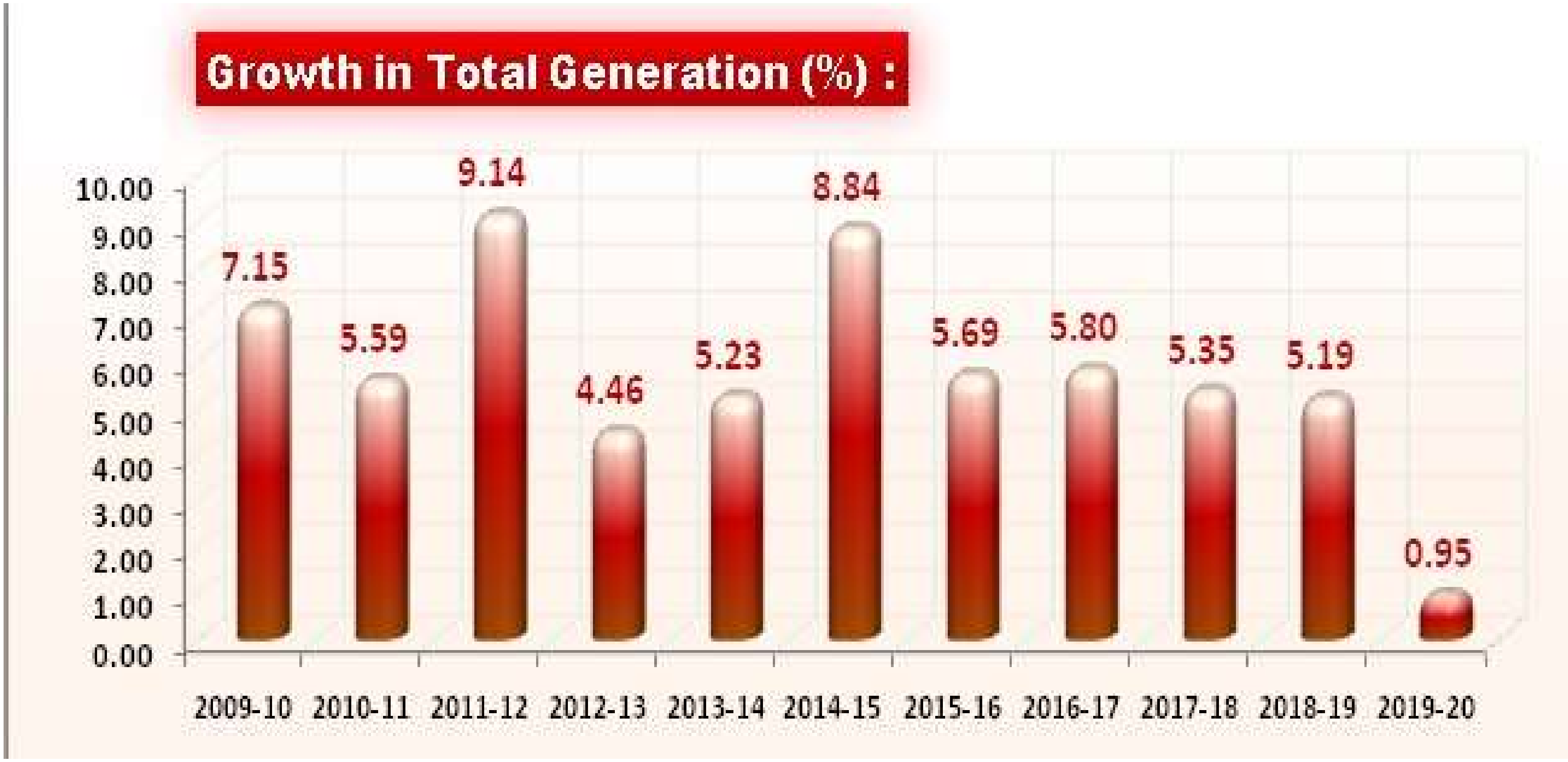


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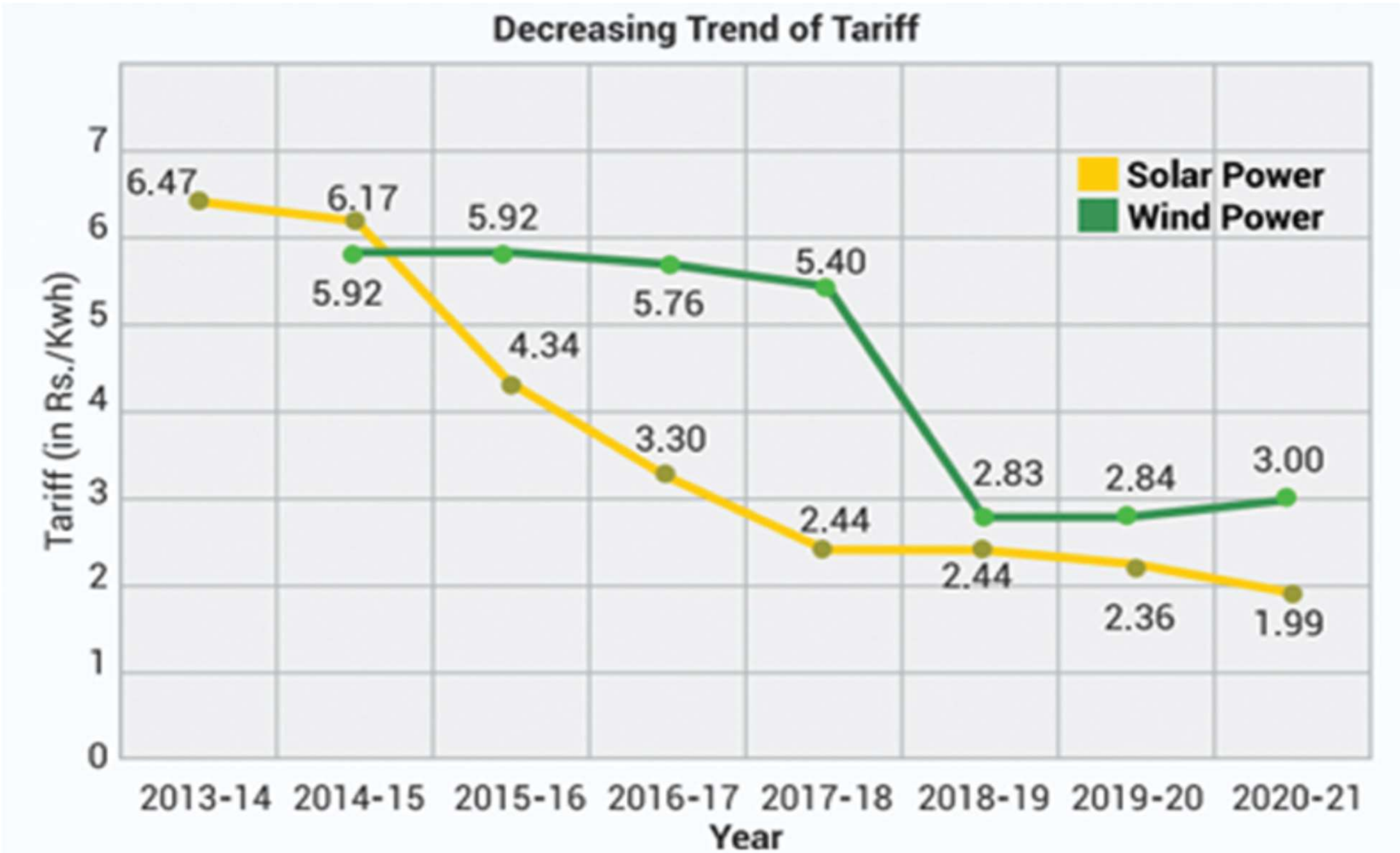
Table 1.1: India's RE Sector at a Glance

Year	Installed RE Capacity (in GW)	% Share of RE in total Installed Capacity	Generation from Renewable Sources (in BU)	Total Generation from all sources (in BU)	% Share of RE in Generation
2014-15	**39.55**	**14.36**	61.78	1110.18	**5.56**
2015-16	46.58	15.23	65.78	1172.98	5.60
2016-17	57.90	17.68	81.54	1241.38	6.56
2017-18	69.77	20.24	101.83	1303.37	7.81
2018-19	78.31	21.95	126.76	1375.96	9.21
2019-20	87.07	23.52	138.32	1390.93	9.95
2020-21	**92.54**	**24.53**	111.92	1017.81	**11.00**
	(Up to Jan,	(Up to Jan,	(Up to Dec,	(Up to Dec,	(Up to Dec,
	2021)	2021)	2020)	2020)	2020)

Table 1.1: India’s RE Sector at a Glance



Covid Effect (Source IEA Report on Energy Outlook)

Covid-19 will leave lasting scars

Prior to the global pandemic, India's energy demand was projected to increase by almost **50%** between 2019 and 2030, but growth over this per iod is now closer to **35%** in the STEPS, and **25%** in the Delayed Recovery Scenario

India's primary energy demand falling **5% from 2019 levels**, with coal and oil expected to take the largest hit due to far-reaching restrictions on mobility and a reduction in economic activity. Natural gas demand has been resilient, as low prices have offset some of the forces driving down demand. **Re newables have also fared relatively well, with generation from wind a nd solar growing by 15%.**

Even though the pandemic and its aftermath could temporarily suppress emissi ons,as coal and oil bear the brunt of the reduction in demand, it does not move India any closer to its long-term sustainable development goals.

Flexible Operation

***How Do Operating State Changes Influence Damage**?*

Market deregulation, changing market rules, growing capacity due to additions of new gas-fired capacity, environmental policy changes, and more recently, renewable generation, have caused the power industry to operate power plants differently. A major change in the operation pattern of existing fossil generation has been increased cycling, or *flexible operation*.

Generation flexibility encompasses many possible operating modes. Some of the possible objectives of flexible operation include the following:

- Grid stabilization (fast load changes, reserve capacity)
- Reliable, efficient, low-cost, low-emissions-producing part-load capacity
- Fast, reliable startups that avoid component damage
- Layups that avoid component damage at minimal cost

Flexible Operation

***How Do Operating State Changes Influence Damage**?*

Most existing steam generating coal- or gas-fired plants were not specifically designed for this flexible operation, but were instead intended to provide **steady baseload generation**.

When fossil-fueled generators cycle on and off or ramp down to minimum generation, the component thermal and pressure transients can lead to fatigue, creep, and creep fatigue interaction damage, which results in increased maintenance, repair, and capital expenditures.

Flexible Operation

Some Common Boiler Damage Mechanisms associated with Flexible Operations

- Economizer inlet header, steam drum, mud drum borehole, or tube- or downcomer/riser
- nozzle-to-header connection corrosion fatigue damage.
- SH or RH header borehole or tube-to-header connection creep fatigue damage.
- Water wall tube corrosion fatigue.
- Water wall tube circumferential thermal fatigue in coal-fired units.
- Tube rubbing.
- DMW failures.
- Fatigue of tubing supports.
- Control valve seat damage and leakage.
- Long-term overheat creep of SH or RH tubes.
- Ash corrosion of water walls.
- Ash erosion.

Flexible Operation

Damage-influencing Factors

When a unit's flexible operation characteristics change, the static and cyclic loads and the fuel and fluid-side service environments that must be tolerated by the boiler components will inevitably change.

Boiler component damage is generally influenced or controlled by some combination of the following:

- Sustained and cyclic loads, reaction forces, and moments
- The fluid-side environment (cycle chemistry, steam quality, deposit or oxide scale buildup, condensate steam flow blockage, oxide exfoliation, time and spatial variations in fluid pressure, temperature, and flow heat transfer)
- The fuel-side environment (slagging and fouling, sustained and transient temperature and heat flux magnitudes and spatial variations, the local gas chemistry, and the mass flow and ash burden for coal-fuel fired boilers)

The frequency and severity of these damage-influencing factors is strongly correlated with the flexible operating characteristics of the unit.

Flexible Operation

***How Do Operating State Changes Influence Damage**?*

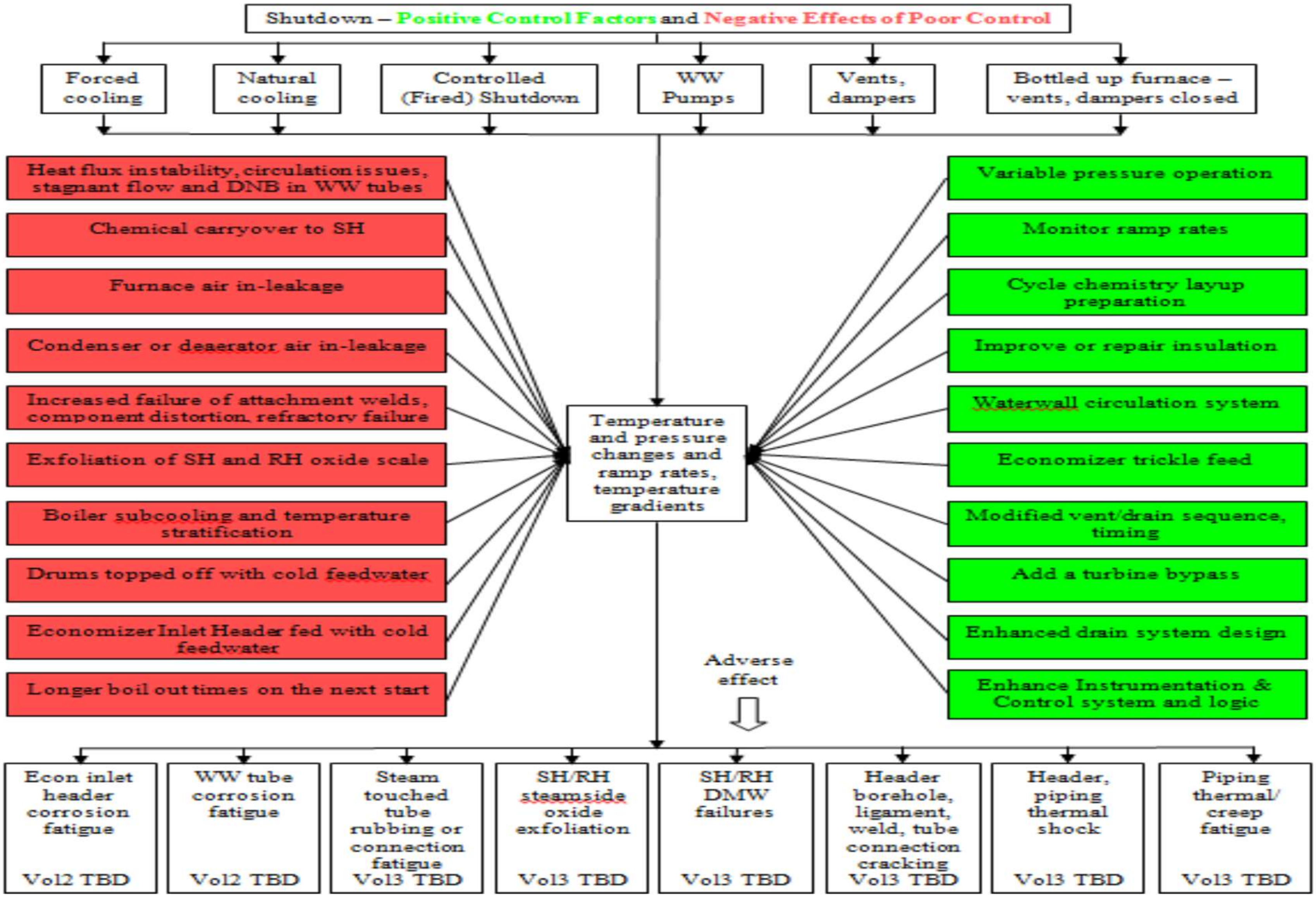
Flexible operation involves extensive operation at transient conditions and loads that were not necessarily envisioned by the designers. Although flexible operation may have an adverse effect on particular boiler component/damage mechanism combinations, it may also have a beneficial effect on other component/damage mechanism combinations.

The effects of flexible operation on boiler component/damage mechanisms has been categorized into five aspects of flexible operation:

- Shutdown (including layup)
- Startup
- Load cycles
- Low-load operation
- Cycle chemistry

Flexible Operation

How Do Operating State Changes Influence Damage?



The effect of shutdown control

Flexible Operation

How Do Operating State Changes Influence Damage?

The effect of startup control

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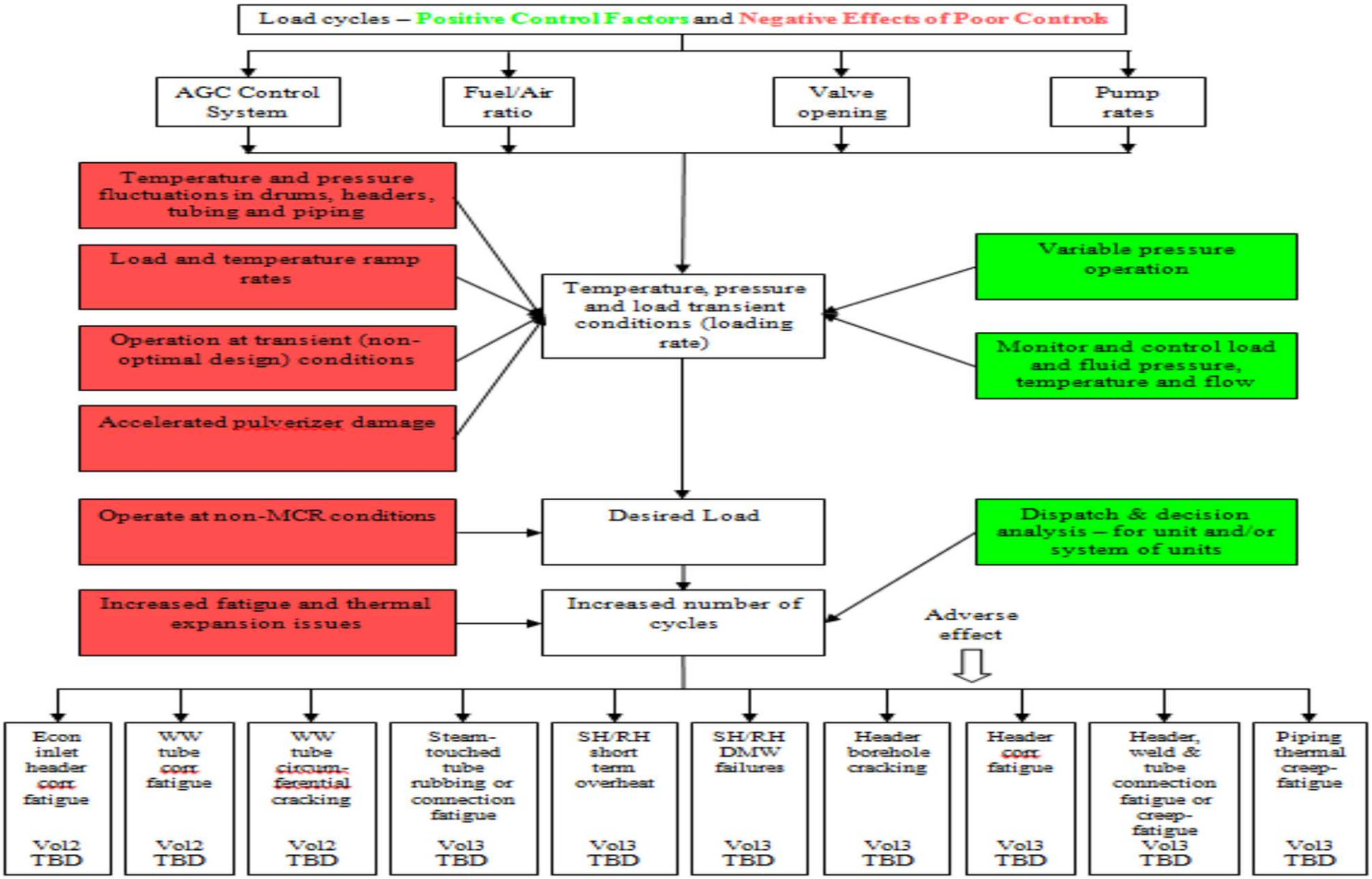
Flexible Operation

How Do Operating State Changes Influence Damage?



The effect of shutdown control

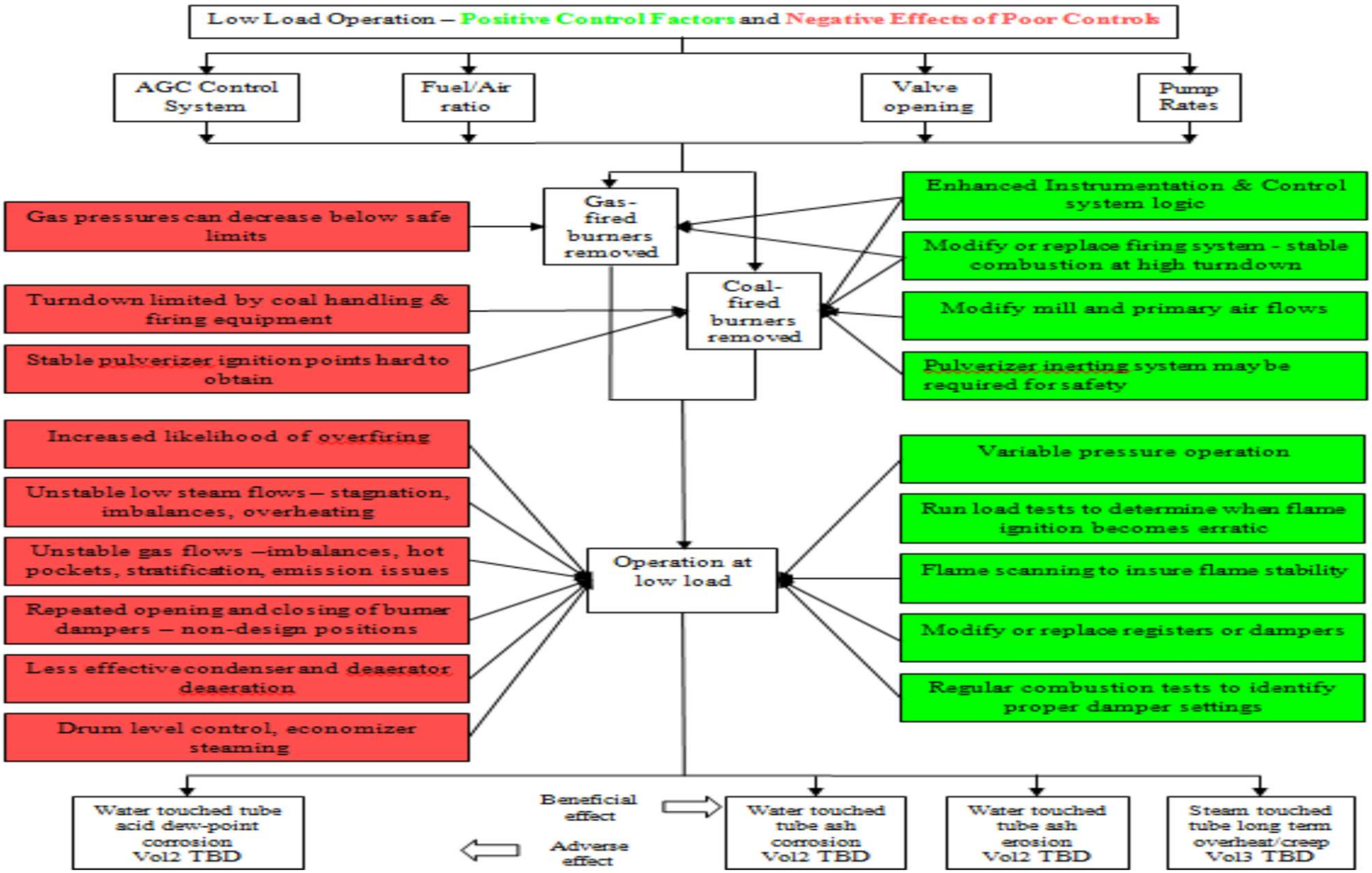
Flexible Operation

How Do Operating State Changes Influence Damage?

The effect of low-load operation control

Flexible Operation

How Do Operating State Changes Influence Damage?



The effect of low-load operation control

Flexible Operation Effects

Mitigating the Effects of Flexible Operation on Coal-Fired Power Plants (Power Magazine 2011)

Most of the Sub-critical units were designed for base load operation.

New duty cycles force baseload plants and equipment to operate closer to—or beyond—nominal design limits and through more thermal cycles than originally anticipated.

The operational impacts of flexible operation result in significantly increased occurrences of thermal transients in the material of critical high-temperature boiler and turbine components.

These transients, and other operational factors associated with flexible operation, have the following effects on coal-fired generating assets.

Additional wear on plant components requires increased spending on preventive and corrective maintenance.

Mitigating the Effects of Flexible Operation on Coal-Fired Power Plants (Power Magazine 2011)

- Increased rate of wear on high-temperature components.
- Increased wear-and-tear on balance-of-plant components.
- Decreased thermal efficiency at low load (high turndown).
- Increased fuel costs due to more frequent unit starts.
- Difficulties in maintaining optimum steam chemistry.
- Potential for catalyst fouling in NO_x control equipment.
- Increased risk of human error in plant operations.

Mitigating the Effects of Flexible Operation on Coal-Fired Power Plants (Power Magazine 2011)

Major Damage Mechanisms are:

- Thermal Fatigue
- Thermal Expansion
- Corrosion-Related Issues
- Fireside Corrosion
- Rotor Bore Cracking

Mitigating the Effects of Flexible Operation on Coal-Fired Power Plants (Power Magazine 2011)

Impacts on Environmental Control Equipment

- **Performance and reliability of flue gas desulfurization (FGD) equipment and selective catalytic reduction (SCR) systems.**
- Start-ups of FGD systems.
- Low-load operation of FGD systems
- Operation of large coal-fired plants at low load can force **units with SCR systems to operate with lower flue gas temperatures.** Low temperatures create operational problems for SCRs because of the formation of ammonium bisulfate (ABS)

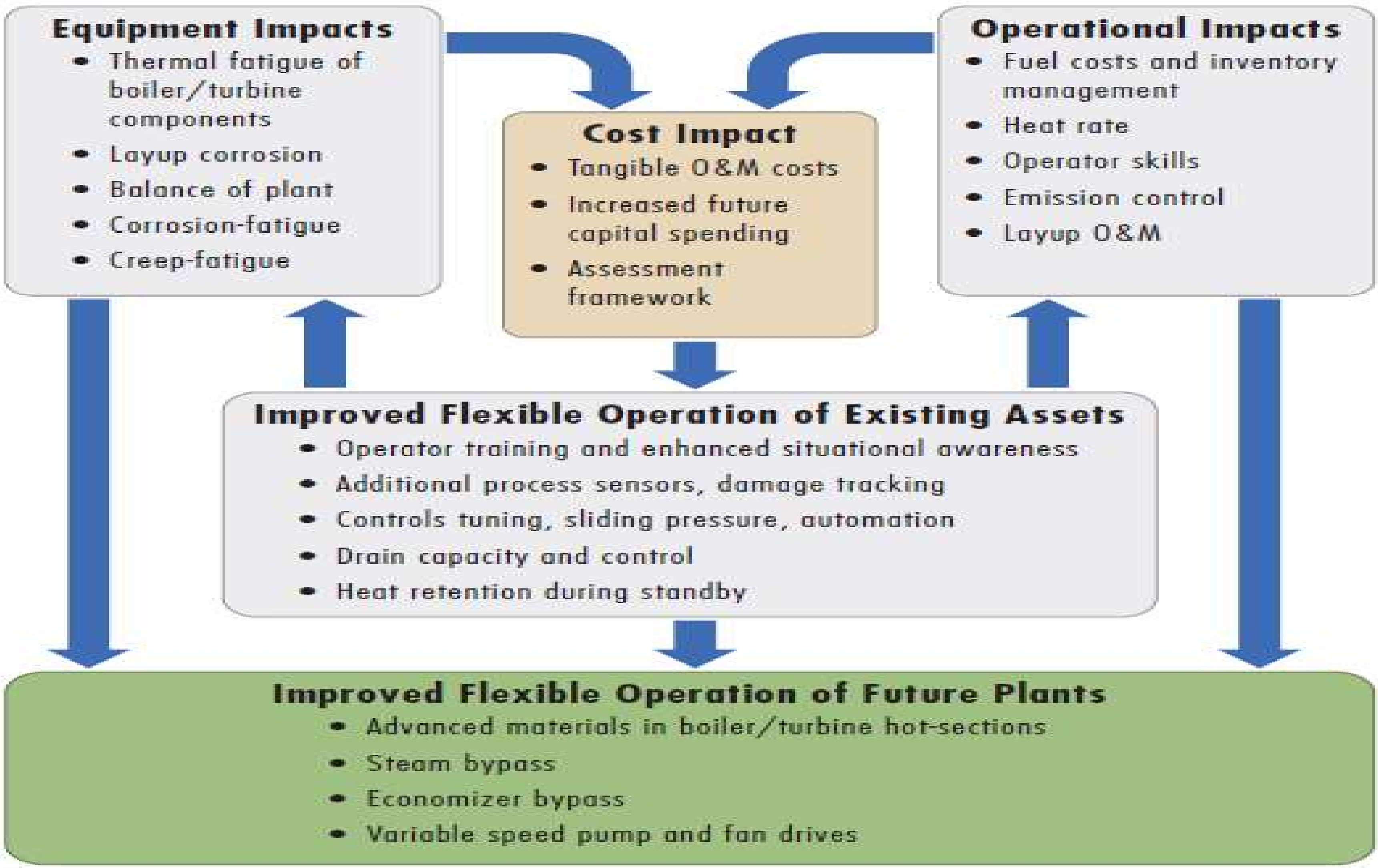
Mitigating the Effects of Flexible Operation on Coal-Fired Power Plants (Power Magazine 2011)

Strategies for Mitigating Flexible Operation Damage

- **Improved operator performance and selected plant controls upgrades**
- **Efficiency Improvements.**
- **Cycle Chemistry Guidelines for Transient Operations**.
- **Mitigating SCR Issues at Low Load.** To avoid problems with SCR units during low-load operation, conventional design practice calls for a flue gas or water-side economizer bypass to elevate the flue gas temperature at low load to a level high enough to allow reagent injection

Flexibility Challenges

Key steps to improving coal fleet flexible operation (EPRI
Electric Power System Flexibility CHALLENGES AND OPPORTUNITIES



ENHANCING FLEXIBILITY: ENVIRONMENTAL IMPACTS

- The need to operate the power grid in a flexible manner can increase generation cycling, which can impact air, water, and solid waste emissions.
- As non- or lower-emitting sources displace higher-emitting generation, overall emissions could be substantially reduced.
- **Transient increases in fossil-fueled plants' emissions rates during startup, shutdown, and other ramping periods, as well as during low load, relative to steady-state operations at full load**.
- Temporary increases in emissions rates can be due in part to incomplete combustion and incomplete warm-up of emissions control devices.
- **Biological treatment for FGD wastewater may not be able to sustain performance during cycling operation or shutdowns**.
- Fossil fuel plants on hot standby for lengths of time may increase costs and/or emissions by keeping cooling water circulators, fans, and other devices running despite the lack of power generation.
- Technical challenges in **accurately measuring emissions of chemicals during startup and shutdown, uncertainty may exist in these emissions estimates.**

Ref. **Electric Power System Flexibility** Challenges and Opportunities, EPRI

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Specific components typically affected by cycling (Power Plant Cycling Costs NREL 2012)

Unit Type	Plant Equipment with Most Significant Adverse Impacts from Cycling	Primary Damage Mechanism
Small and Large Sub-Critical Coal	Boiler Waterwalls	Fatigue Corrosion fatigue due to outages oxygen and high starts up oxygen Chemical deposits
	Boiler Superheaters	High temperature differential and hot spots from low steam flows during startup, long term overheating failures
	Boiler Reheaters	High temperature differential and hot spots from low steam flows during startup, long term overheating failures, tube exfoliation damages IP turbines

Specific components typically affected by cycling (Power Plant Cycling Costs NREL 2012)

Unit Type	Plant Equipment with Most Significant Adverse Impacts from Cycling	Primary Damage Mechanism
Small and Large Sub-Critical Coal	Boiler Economizer	Temperature transient during startups
	Boiler Headers	Fatigue due to temperature ranges and rates, thermal differentials tube to headers
	LP Turbine	Blade erosion
	Turbine shell and rotor clearances	Non uniform temperatures result in rotor bow and loss of desired clearance and possible rotor rubs with resulting steam seal damages

Specific components typically affected by cycling (Power Plant Cycling Costs NREL 2012)

Unit Type	Plant Equipment with Most Significant Adverse Impacts from Cycling	Primary Damage Mechanism
Small and Large Sub-Critical Coal	Feedwater Heaters	High ramp rates during starts, not designed for rapid thermal changes
	Air Heaters	Cold end basket corrosion when at low loads and start up, acid dew point
	Water/Chemistry Water Treatment Chemistry	Cycling results in peak demands on condensate supply and oxygen controls
	Fuel System/ Pulverizers	Cycling of the mills occurs from even load following operation as iron wear rates increase from low coal flow during turn down to minimum

Specific components typically affected by cycling (Power Plant Cycling Costs NREL 2012)

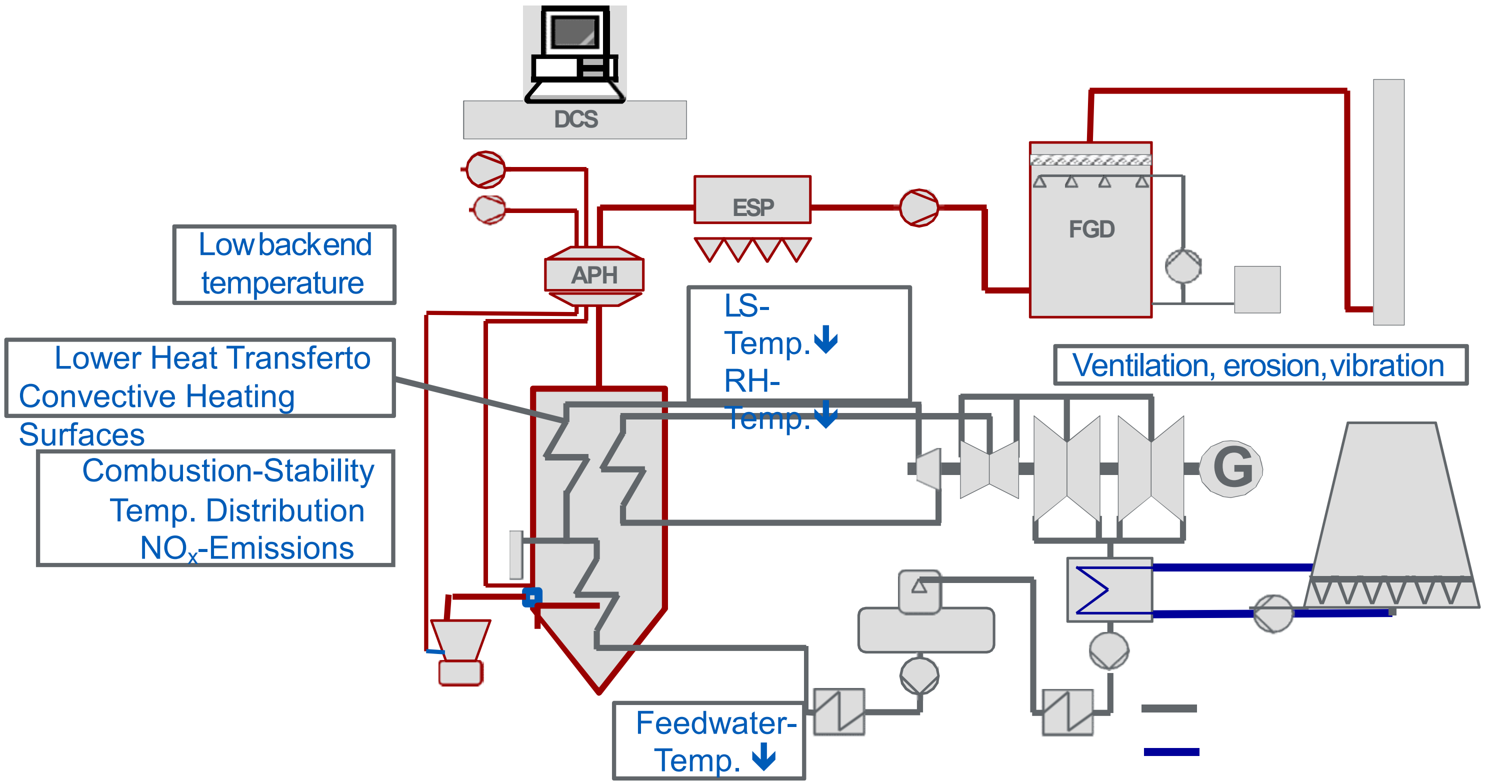
Unit Type	Plant Equipment with Most Significant Adverse Impacts from Cycling	Primary Damage Mechanism
Supercritical Coal (600-700 MW)	Same as subcritical coal except added temperatures in furnace tubing	
	Large supercritical furnace subject to uneven temperatures and distortion	Fatigue due to temperature ranges and rates, thermal differentials tube to headers

Water chemistry issues

Operating Mode	Chemistry Issues	
Load Following	• Feedwater chemistry control • Dissolved oxygen in condensate • Sampling issues	• Phosphate Hideout • Carryover (level control) • Corrosion Product Monitoring
Cycling (weekend off)	• Reheater pitting • Chemistry on startup	• General Steam Path pitting • Carryover (swell)
Cycling (two-shifting)	• Boiler chemistry control • Carryover Issues	• **Feedwater chemistry control** • Carbon dioxide ingress
Extended Layup	• **Turbine Pitting (leading to Stress Corrosion Cracking or Corrosion Fatigue)** • Chemistry System return to service	• Oxygen pitting boiler tubing • Water Treatment Layup • Instrumentation layup
Sustained Minimum Load	• **Increased steam path deposition** • FAC in economizers / IP Evaporator • FAC in BFP recirculation lines • Steaming in Economizer (two-phase FAC)	• DNB and Hydrogen Damage • High level of attemperatoring sprays • Sampling / Monitoring • Air-inleakage control

Source:EPRI

Limitations to be addressed



Ramp Rates-Limitations

- Stresses in thick walled components
- Fuel quality
- Controls and time lag between coal milling and turbine response

Minimum load limitations

- Combustion stability
- Boiler circulation
- DNB
- Minimum feed water flow & BFP
- Last stage blade flutter
- FG Exit Temp./Acid due point
- Vibration issues

Ref. Operational Strategies for Flexing in Thermal Plants, Anjan K Sinha, Indo-USAID

Water treatment

- Poor water quality causes corrosion, and the likelihood of water quality deterioration is increased as a result of frequent load changes.
- For once-through boiler systems, all-volatile treatment and oxygenated treatment are used.
- **Boilers operating in a cycling mode are best provided with all-volatile treatment together with full-flow condensate polishing. All-volatile treatment with oxygenating is preferable for ferrous-only based systems.**
- The dissolved oxygen concentration is controlled by mechanical means, while chemicals such as ammonium hydroxide and hydrazine or other substances can be used as the pH adjuster.
- Condensate polishers remove dissolved contaminants, such as sodium and silica, and filter suspended particulates that become detached from heat exchanger internal surfaces during load transitions.

Ref: Colin Henderson, September 2014, IEA Clean Coal Centre

Increasing the flexibility of coal-fired power plants

- Operation of makeup water or wastewater clarifiers can be improved by the addition of recirculation lines to allow the maintenance of adequate flow through the clarifier at low load, keeping it ready for increased load operations.

(*Many of the 200 or lower capacity units are provided with copper based tubes and no condensate polishing units are provided. Even with 500 MW units CPU is optional and generally only 33% of full flow is passed through CPU*).

Increasing flexibility – other plant areas

On/off and highly variable load operation affects other parts of the plant also.

NOx removal systems

The main potential issue with low load operation of plants with selective catalytic reduction (**SCR**) systems, which are usually placed after the economiser, is the possibility of **lower flue gas temperatures** occurring. SCR units often use ammonia as reagent, and **ammonia control may become difficult during fast load swings**, compounded by variable fuel properties. Excess ammonia can then leave with the exit gas stream. This so-called **ammonia slip can then lead to ammonium bisulphate (ABS) formation as a sticky liquid that fills catalyst pores, reducing reactivity**. ABS may also deposit in the air heater, increasing its pressure drop, and necessitating cleaning. It can even be blown from the air heater into boiler air ducts, where it can influence readings of air flow measurement devices.

Increasing flexibility – other plant areas

To avoid problems with ABS formation (**ABS is highly corrosive in nature**), the conventional solution is for a flue gas or water-side economiser bypass to be installed to enable the flue gas temperature at low load to be kept at design value.

Such an arrangement can avoid plugging without sacrificing NOx removal performance. **Where units are not, or cannot be, equipped with economiser bypass capabilities, other options are available. One is to monitor continuously the inlet NH_3 and SO_3 concentrations and temperature distribution in the SCR, and to compare these with design conditions**.

Other possibilities may be to change the fuel sulphur content or, if allowed, the NOx reduction levels at low load, or to modify the inlet temperature distribution using a static mixer (baffle). Adding a heating facility for hot gas carrying components can also be used to give shorter start-up times. **Whatever means is used, provided the correct temperature can be maintained, rapid rates of load change can generally be accommodated.**

Increasing the flexibility of coal-fired power plants

FGD Systems

The chemical processes involved in conventional wet flue gas desulphurisation (FGD) systems require precise control of the reaction conditions, which are influenced by reagent flow, water flow and flue gas temperature. Operation at varying power output can consequently affect the performance and reliability of these plants. **The number of shut-downs and start-ups of FGD systems should also be minimised because of the need to purge to avoid slurry solidification**. Reducing the number of shut-downs and start-ups is also needed to minimise the accumulation of start-up fuel oil residues on absorber linings, and to avert the lengthy warming up time that is needed by an FGD system.

It can be possible to obtain savings in energy consumption at part load by switching off some circulation pumps. However, at low-load, it will be difficult to maintain optimal performance if the reagent flow is fixed. **Keeping within required emissions limits during rapid load changes requires sophisticated control concepts, and an increased liquid/gas ratio may be needed for sufficient SO2 capture**.

Particulate removal systems

Particulate control systems can usually cope with a plant operating at partial load and rapid load changes without problems. Inlet gas temperatures need however to be watched – they must not fall so low that acidic moisture condenses on particles, causing adherence of solids to fabric filters or a resistivity that is too low for efficient ESP performance.

At partial (or full) load, enhanced dust collection may be achieved in electrostatic precipitators by increasing residence time, while energy savings of up to 80% are possible using intelligent control systems for the power supply.

Oxidation and Exfoliation in Super-Heater and Reheater Tubes

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Failure of RH/SH Tubes

Failure of RH Tubes – Tube SA 213 T22

Failure of RH/SH Tubes

Failure of RH Tubes

Failure of RH/SH Tubes

Failure of Super Heater Tubes (on Oxygenated Treatment)

Failure of RH/SH Tubes

Failure of Super Heater Tubes (on Oxygenated Treatment)

Failure of RH/SH Tubes

Failure of Super Heater Tubes (on AVT (R) Treatment)

Failure of Reheater Tubes

Failure Mechanism	Probable Root Cause
Short term overheating in RH tubing	• **Tube blockage induced (especially exfoliated oxide blockage)** • **Maintenance induced (improper chemical cleaning or repairs)** • **Operation induced (improper startup or shutdown, or overfiring with top heater out of service)**
Long term over-heating/creep	• Influences of initial design and/or material choice • Buildup of internal oxide scale • Overheating due to restricted flow caused by chemical or other • Deposits, scale, debris, etc. • Operating conditions or changes in operation • Blockage or laning of boiler gas passages • Increases in stress due to wall thinning
RH Fireside Corrosion (Sootblower or Ash)	• Influence of overheating of tubes (poor initial design, internal oxide growth during operation, high temperature laning, tube misalignment, operational problems when coal is changed, and rapid startups causing reheater to reach temperature before full steam flow)

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Failure of Reheater Tubes

Failure Mechanism	Probable Root Cause
RH Fireside Erosion	• Improper sootblower operation (control of frequency, temperatures, pressures, and travel; and mechanical malfunctions etc.) • Erosive coal ash characteristics • High gas flow velocities (gas lanes, boiler operation, etc.)
Dissimilar Metal Weld Failures (Failures occur where ferritic and austenitic steels are welded together)	• Excessive tube stresses such as caused by improper initial design or improper tube supports • Excessive local tube temperatures • Change in unit operation (increased unit cycling, change of fuel, redesign of adjacent heat duties) • Initial fabrication defects
Stress Corrosion Cracking	• Influence of environment (mainly contamination from carryover of chlorides from chemical cleaning of waterwalls, boiler water carryover, caustic from attemperator spray, condenser cooling water leaks, or ingress of fireside contaminants or flue gas during primary leaks) • Influence of excessive stresses (especially at supports) • Need to change material to a stabilized grade of stainless steel
Out of Service Corrosion	• Out of service internal corrosion damage is usually caused by dissolved oxygen pitting and is very common problem in reheaters.

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OXIDATION AND EXFOLIATION OF SUPERHEATER & REHEATER TUBES

- Scale exfoliation from the steam-side of superheater and reheater tubes can become a problem after some length of service (between 5 and 50kh).

- Most exfoliation (from superheaters, main steam line, reheaters) takes place during shut down; then, during start-up (especially at low loads), the exfoliated scale flakes are transported by the steam flow until either they settle out in tube bends, or they reach the turbine.

- High heat fluxes, flexing of the components, and creep of the substrate alloy also may be important.

- Ferritic steels, such as the 2.25Cr-1Mo alloys (T-22), are observed to undergo scale exfoliation during full cool-down and warm-up cycles, while the 300-series stainless steels typically exfoliate while cooling down.

- Recent experience suggests units that experience frequent shutdowns lead to more frequent exfoliation (probably in relatively small amounts)

OXIDATION AND EXFOLIATION OF SUPERHEATER & REHEATER TUBES

There are four principal problems associated with the steam path in superheaters and reheaters:

- Exfoliation of the steam-side oxides.
- The reaction of steam with the steel tubes to form iron oxide which acts as an insulating layer to the transfer of heat. The net effect is to raise tube-metal temperatures which both exacerbates the fire-side problems and leads to early creep failures.
- Condensate that collects in the bottom of pendents and in sagged horizontal tubes that leads to oxygen corrosion & pitting.
- Weld backing rings or excessive root bead penetration that leads to restricted steam flow.

The exfoliation of steam side scale leads to turbine blade erosion and loss of efficiency. When pieces of oxide spall, the larger pieces collect at the bottom of pendants; and the smaller pieces become entrained in the steam. At the bottom of the circuit, tumbling and abrasion lead to more very fine particlesof oxide becoming entrained within the steam. These oxide particles then lead to turbine blade erosion and loss of turbine efficiency.

OXIDATION AND EXFOLIATION OF SUPERHEATER & REHEATER TUBES

- The large flakes of oxide that are too big to be moved up the pendant with the steam flow collect at the bottom. When theunit is shut down, any fine oxide particles and condensate collect. When the unit restarts, the evaporating condensate and solid particles of scale siter to form an immovable mass. Locally, the scale acts as an insulating barrier to heat transfer. Net result is that the tube metal temperature is raised and creep damage or short term overheating may occur.

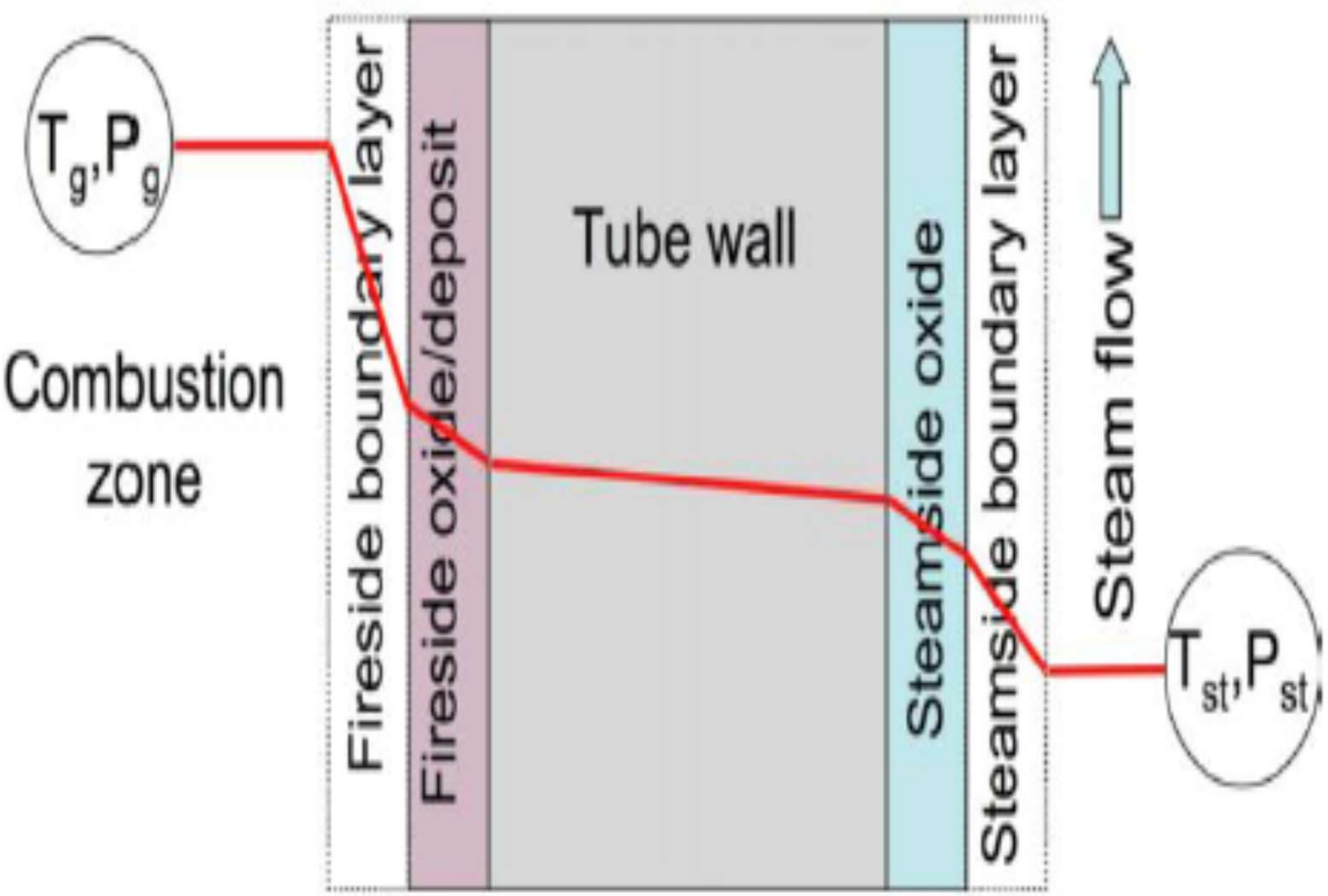
The reaction of steam with steel forms iron oxide, The rate at which the steam side scale develops is related to both the composition of the steel and the temperature of operation. The rate of oxide growth follows the parabolic law with operating temperature. **The increase in metal temperature as a result of the steam side scale formation depends on several factors such as the heat flux; the tube diameter & wall thickness; the thickness of the steam side scale.** The temperature increase is somewhere between 1 and 4 times the scale thickness. Thus **for a superheater with a fairly high heat heat flux, a thickness of 15 mils may raise the tube metal temperature between 50 oF and perhaps as much as 75 oF.**

OXIDATION AND EXFOLIATION OF SUPERHEATER & REHEATER TUBES

For a reheater where the heat flux is lower, the increase in metal temperature is somewhat less, around 25 oF to 50 oF. In any case, the increase in tube metal temperature will exacerbate the fire side corrosion.

Any moisture in the steam leads to accelerated oxidation by steam. This requires controlled operation of attempretion spray. Sudden changes in heat fluxes should be avoided as this significantly affects the internal & external oxidation.

Combustion Effects



Mid-wall metal temperature

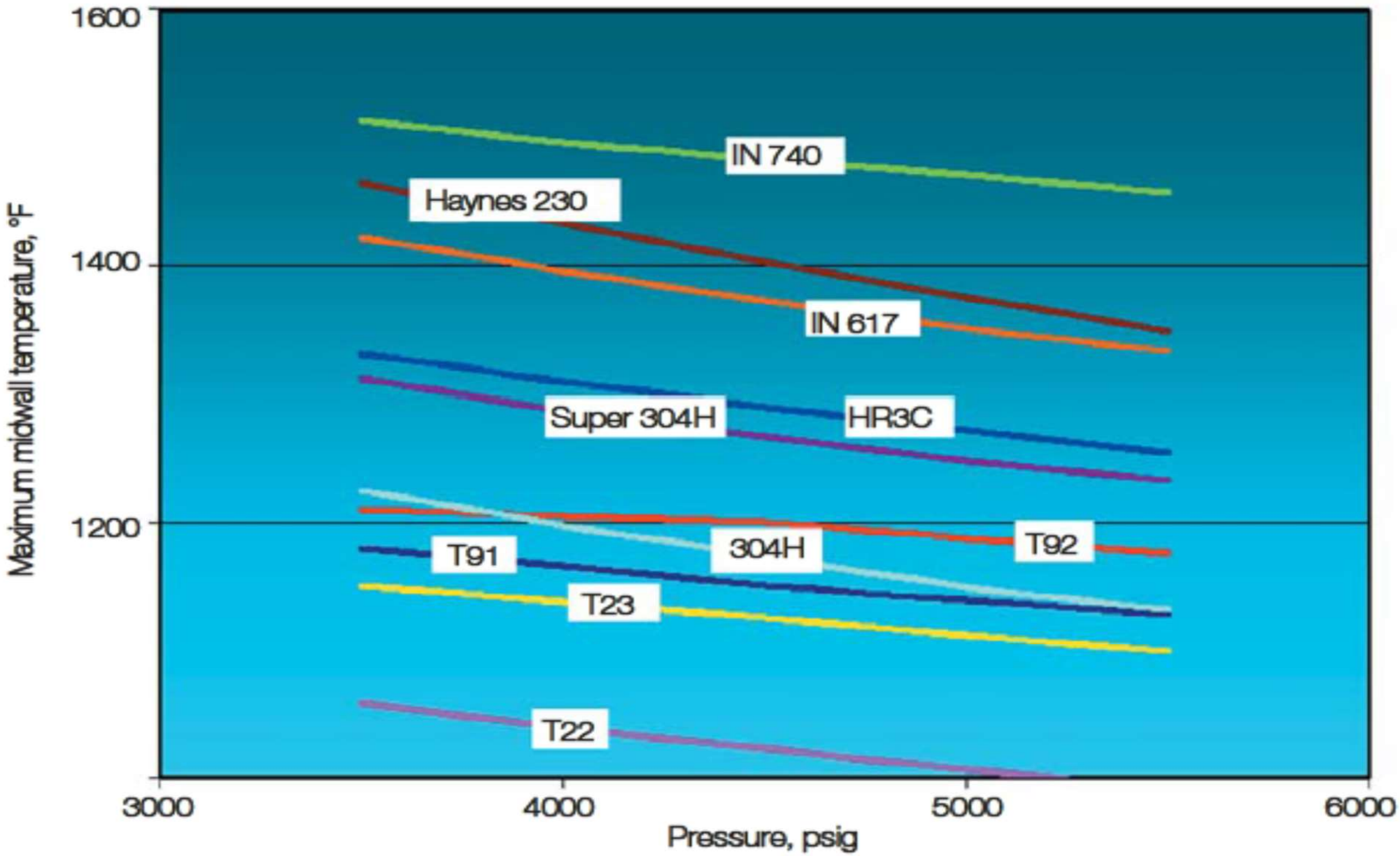


Fig. 2 — Maximum usage pressure/temperature. The best ferritic steel can go up to 620°C (1150°F). Developmental ferritics can reach 650°C (1200°F), austenitics can function up to 675°C (1250°F), and nickel alloys function above that, purely based on creep strength. Courtesy of Steve Goodstine,

Failure of RH/SH Tubes

FACTORS AFFECTING OXIDATION AND EXFOLIATION

1. Mid-wall metal temperature – (most critical factor, affected by many factors).
2. Ramp-up/Ramp Down rates (higher than designed).
3. Heat distribution within the furnace (imbalance in heat).
4. Sudden changes in coal quality (Improper blended coals and use of coals for which boiler was not designed).
5. Internal & External fouling of tubes (fireside corrosion & internal corrosion).
6. Design tube thicknesses (considering the fuel used).
7. Lay up without drying the tube (condensed water in bends).
8. High attemperator spray (higher use of spray than designed).
9. Steam temperatures higher than permissible temperatures for metals in use (non-availability of metal temperature sensors on all tubes).
10. Conversion from one to another feed water chemistry without adopting chemical cleaning (> 1 year between cleaning & conversion) (Independent of Feed Water Chemistry otherwise).
11. Choice of material of construction (long term protection)

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Water Wall Tubes Affected by Flexible Operation

Water Wall Tubes Affected by Flexible Operation

Water Wall Tubes Affected by Flexible Operation

Water Wall Tubes Affected by Flexible Operation

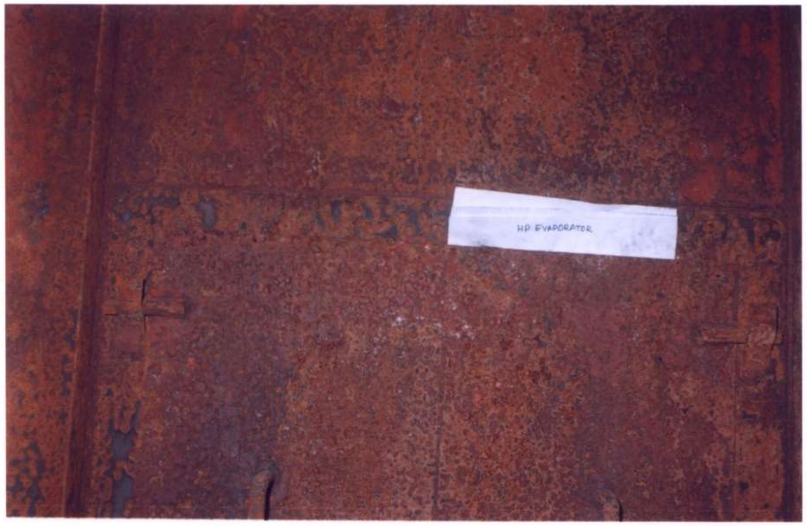
Acid Dew Point Corrosion

Acid Dew Point Corrosion

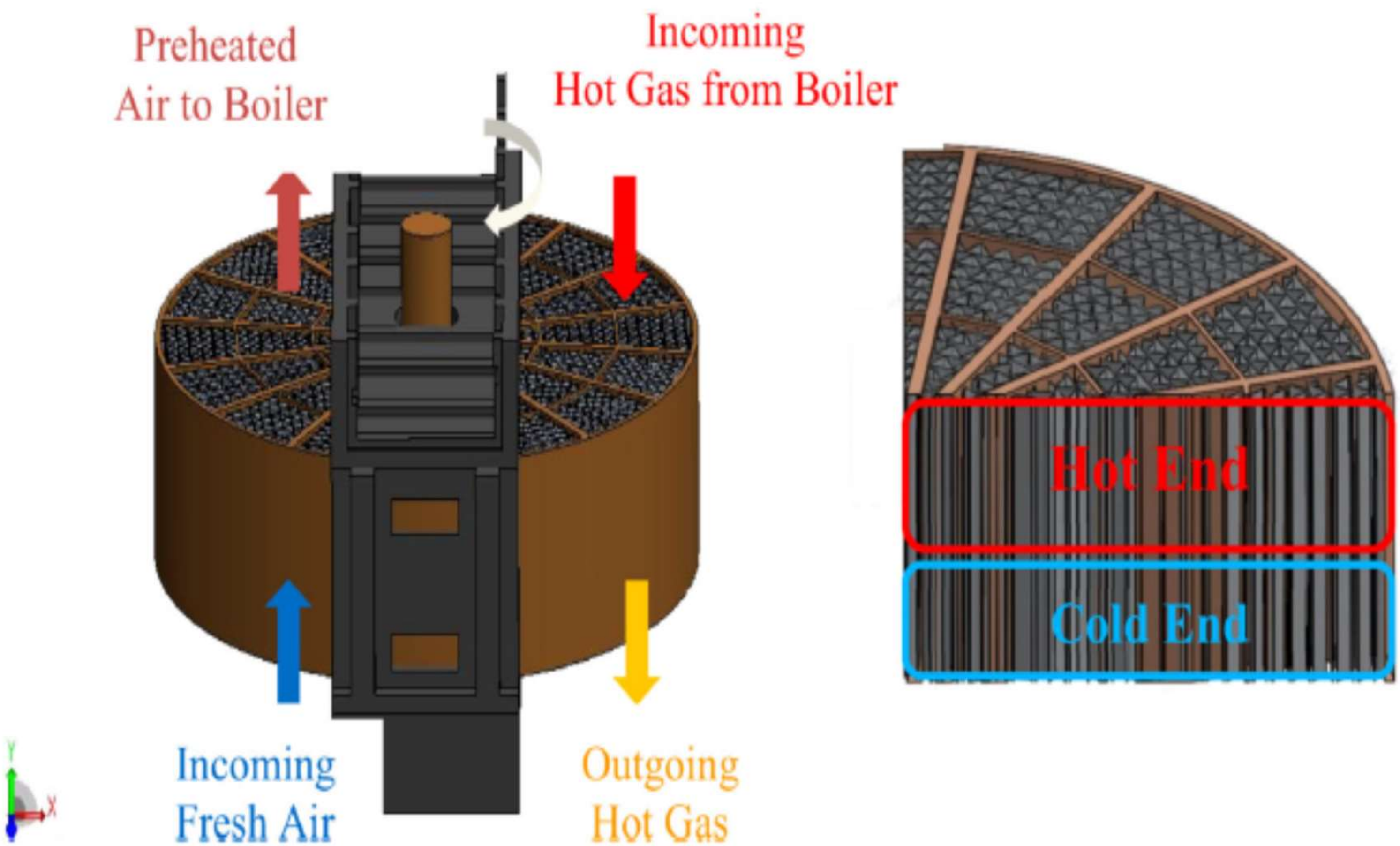
Acid Dew Point Corrosion

Acid Dew Point Corrosion of HRSG

Acid Dew Point Corrosion of HRSG



Acid Dew Point Corrosion of Air Preheater



A schematic view of the rotary preheater,

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Acid Dew Point Corrosion of Air Preheater

Fouling and plugging of air preheater.,

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Acid Dew Point Corrosion of HRSG

Loss on ignition (%)			
Temperature	105 ^{0}C	400 ^{0}C	815 ^{0}C
Loss on ignition	1.13	6.5	3.94

Chemical Analysis of deposit		
% Fe as Fe_2O_3	% Ca/Mg as CaO/MgO	% Acid Insolubles
84	4.5	11.5

Chemical Analysis of 1% water extract of Deposit						
pH	Cond	Chloride	Sulphate	Nitrate	Sodium	Potassium
	µs/cm	ppm	ppm	ppm	ppm	ppm
3.4	240	10	57.2	4	0.2	0.1

X-Ray Diffraction	
Phases Identified	FeO (OH), Fe_2O_3 (Sample amorphous in nature)

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Acid Dew Point Corrosion of HRSG

S No.	PARAMETER		UNIT	HP EVA & ECO Dust (1.0 %) extract	CPH Area Dust (1.0 %) extract
1	Temperature		Deg C	25	25
2	pH			**2.86**	**2.73**
3	Conductivity		µS	**2297**	**3137**
4	Sulphate	As SO_4^{2-}	ppm	**1040**	**2400**
5	Sodium	As Na+	ppm	2.9	4.2
6	Potassium	As K+	ppm	0.3	2.3
7	Nitrate	As NO_3^-	ppm	**17.2**	**22.5**
8	Water Soluble		%	**12.00**	**31.6**
9	Acid Insoluble		%	**14.3**	**13.2**

Sample No.	Description	Fe (%) as Fe_2O_3	Na (%) as Na_2O	Si (%) as SiO_2	Cu (%) as CuO
C- 2084	HP EVA & ECO Area Dust	54.2	0.9	7.6	0.1
C- 2085	CPH Area Dust	40.0	0.5	7.7	0.1

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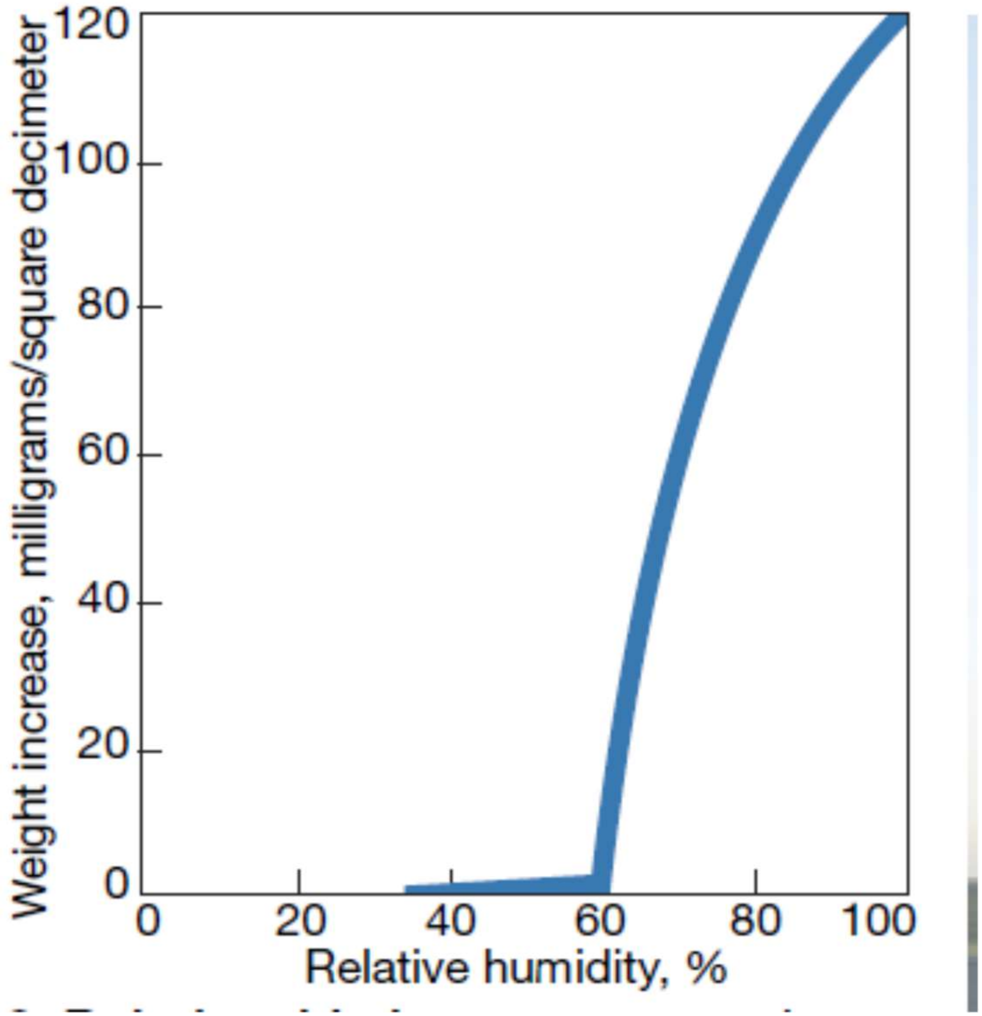
Acid Dew Point Corrosion of HRSG

S. No.	Sample No.	Description	Phase identified
1.	C- 2084	HP EVA & ECO Area Dust	Fe_2O_3, $Fe^{+3}(OH)SO_4.2H_2O$, $FeO(OH)$
2.	C- 2085	CPH Area Dust	Fe_2O_3, $Fe_2S_2O_9.5H_2O$

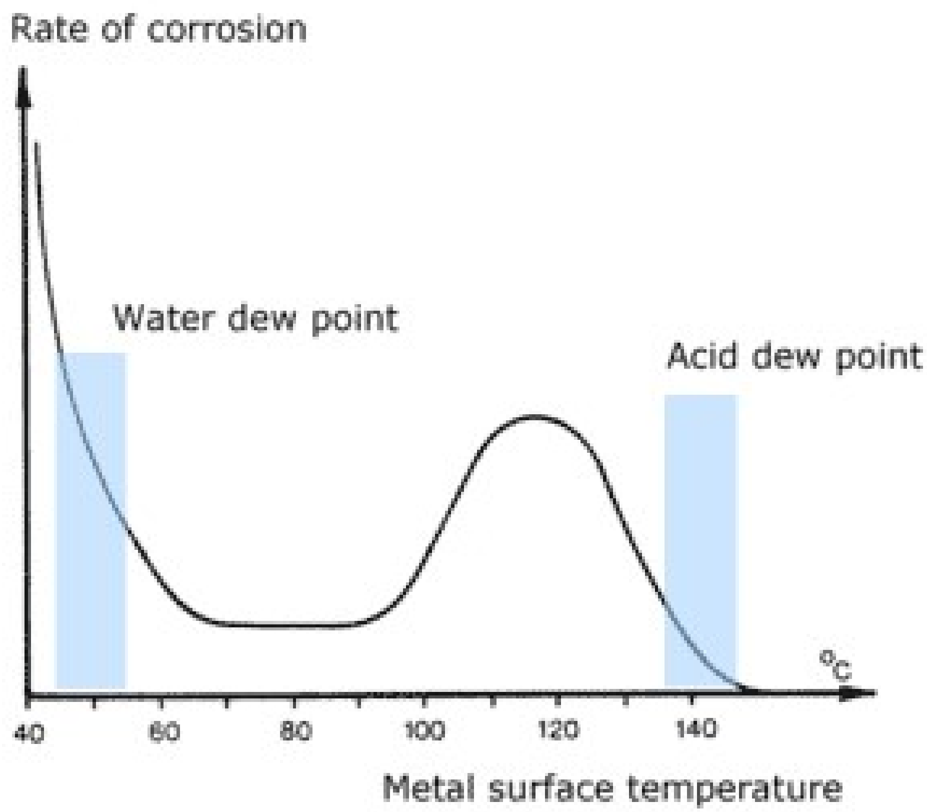
Sample	Fluoride (ppm)	Chloride (ppm)	Nitrate (ppm)	Bromide (ppm)	Phosphate (ppm)	Sulphate (ppm)
1	Nil	3.17	7.00	Nil	Nil	43.67
2	Nil	1.89	0.812	Nil	Nil	2518.6
3	1.64	1.49	14.46	7.6	Nil	60.14
4	Nil	3.08	16.57	Nil	Nil	1190.8

Acid Dew Point Corrosion



Relationship between corrosion rate and the moisture content of air shows the importance of maintaining relative humidity below about 40%.

Acid Dew Point Corrosion



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Acid Dew Point Corrosion

Coal is the fuel used in the majority of power-generation plants over the world.

However, on a global level, coal use accounts for a significant proportion of greenhouse gas emissions, particularly carbon dioxide (CO_2).

When sulfur-bearing fuel is burned, sulfur is converted to sulfur dioxide (SO_2) and sulfur trioxide (SO_3). The sulfur trioxide combines with moisture to form sulfuric acid (H_2SO_4) [See eq.(1)]. During combustion, some nitrogen is oxidized to form nitrogen dioxide (NO_2).

Nitrogen dioxide in the flue gas also reacts with water to give nitric acid [eq.(2)] and with sulfur dioxide and water to form more sulfuric acid [eq.(3)].

$$SO_3 + H_2O = H_2SO_4 \quad (1)$$
$$4NO_2 + 2H_2O + O_2 = 4HNO_3 \quad (2)$$
$$NO_2 + SO_2 + H_2O = H_2SO_4 + NO \quad (3)$$

Acid Dew Point Corrosion

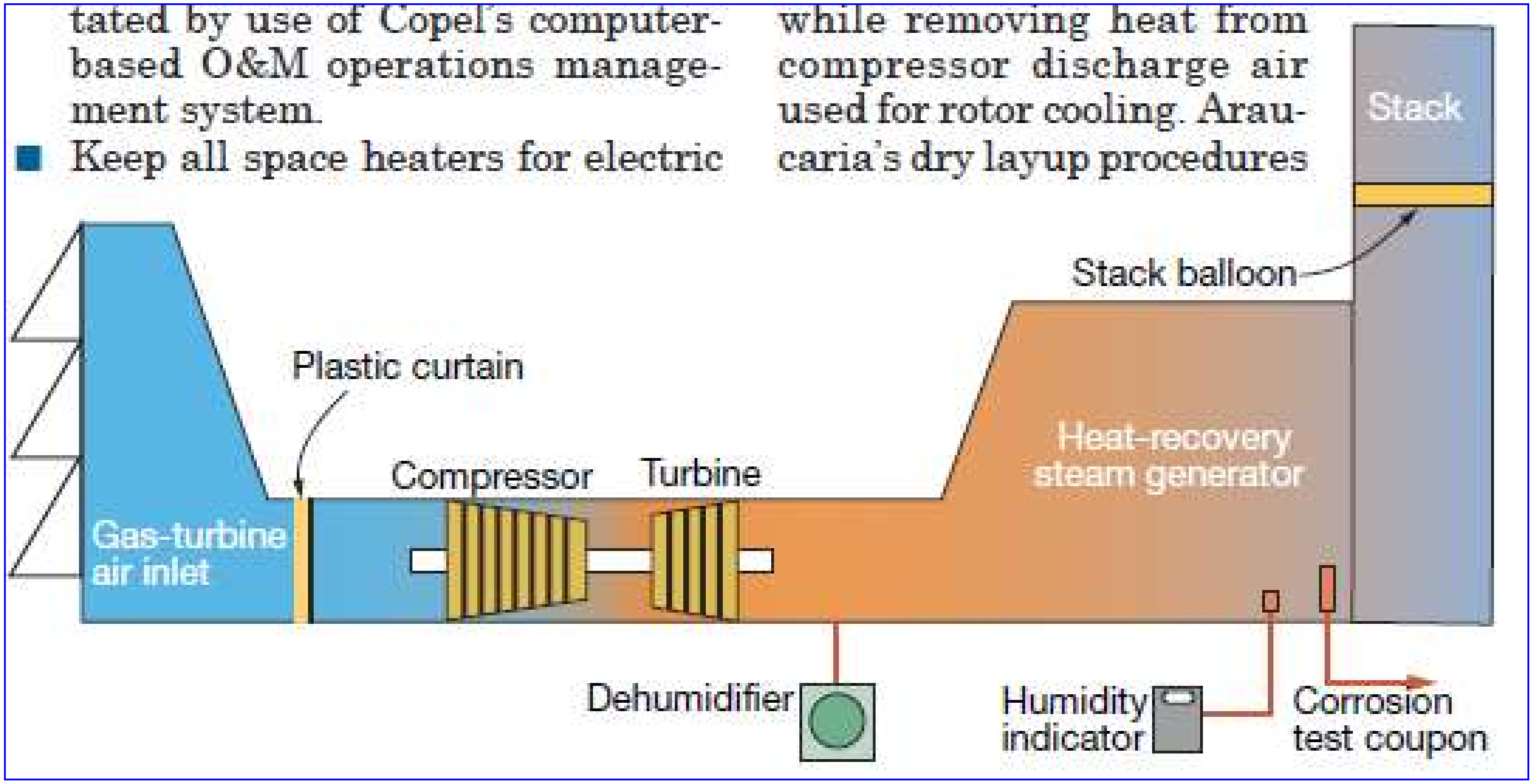
If the flue gas is cooled sufficiently, condensation will occur and liquid will appear on surfaces at temperatures below the dew point.

The liquid phase will contain highly corrosive sulfuric acid. This causes sulfuric acid corrosion, so called low-temperature corrosion.

Low-temperature corrosion needs to be taken into consideration for optimum system design of exhaust gas treatment.

Problems with regard to the prediction of low-temperature corrosion result from the fact that the dew point of flue gases depends not only on the partial pressure of water, but also on the partial pressure of H2SO4. Existing prediction methods for dew points of flue gases are not comprehensive.

Acid Dew Point Corrosion of HRSG



Installation of dehumidifier in HRSG

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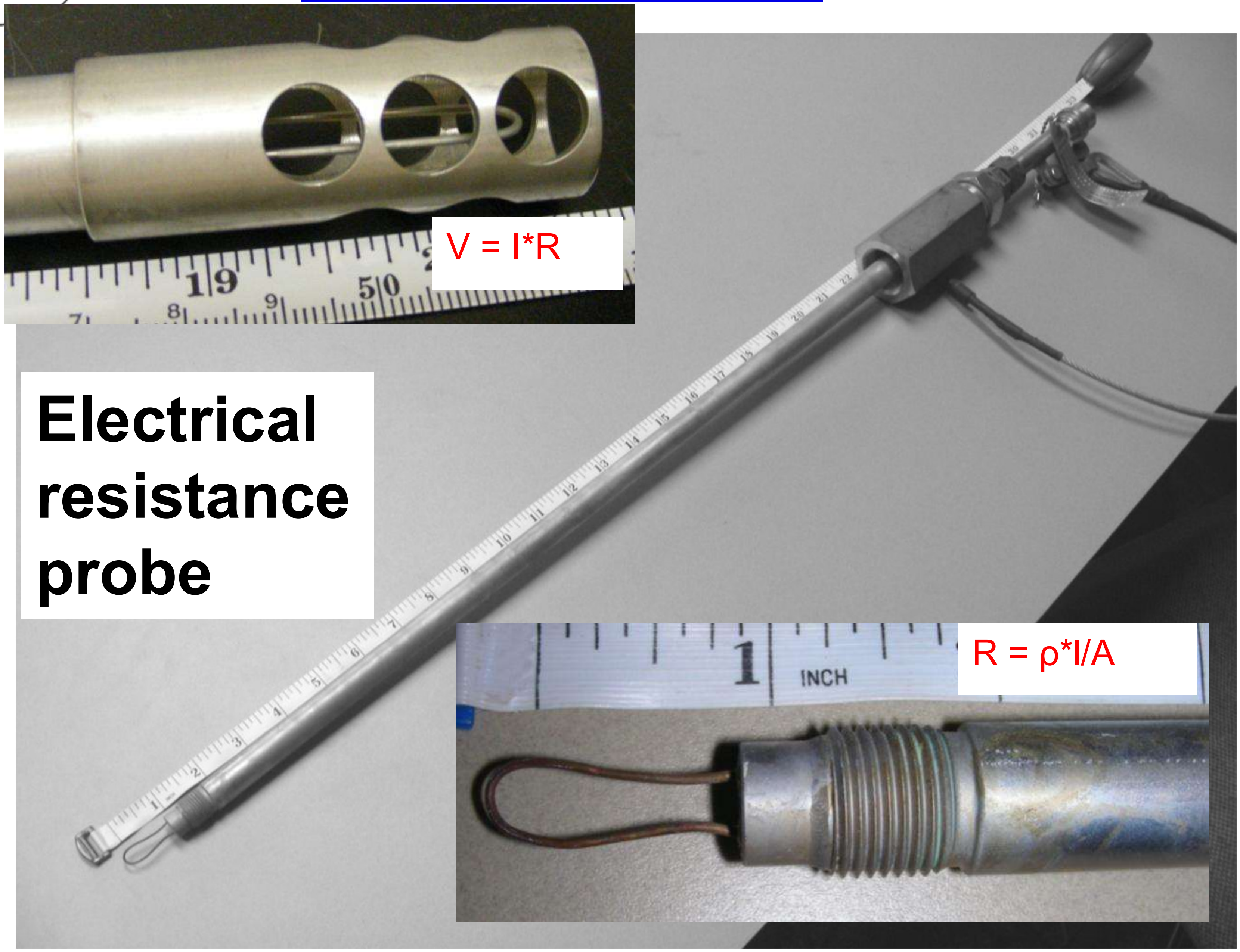
Corrosion Monitoring

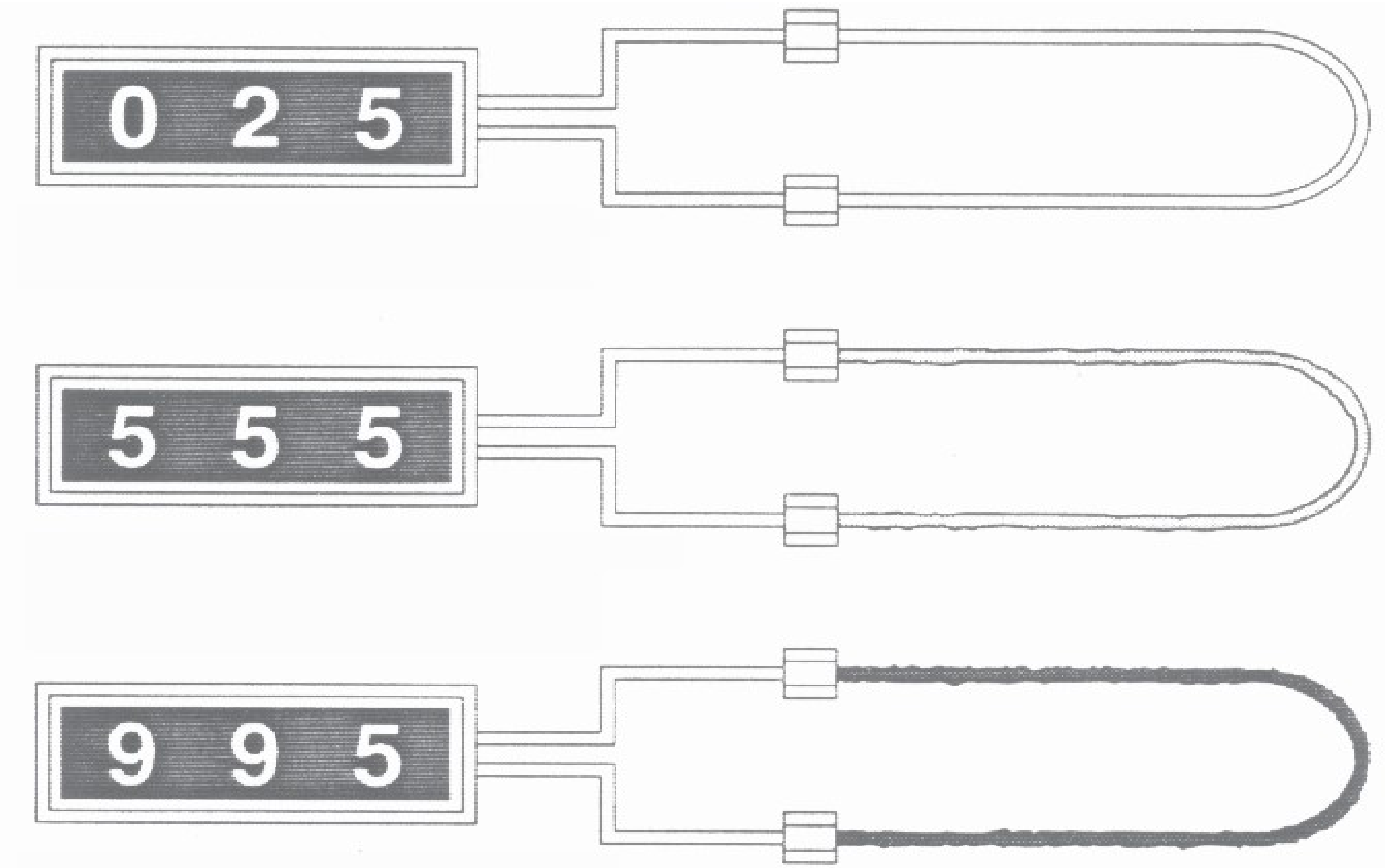


Electrical resistance probe

$V = I*R$

$R = \rho*l/A$

Corrosion Monitoring



Acid Dew Point Corrosion - Control Measures

- Application of Novolac Vinyl Ester Glass Flake coating 1000 – 1200 microns DFT on Structures of CPH and Stack Liners to improve life of the structures.
- To improve the performance of the HRSGs, there is a need to remove the deposited corrosion/flue gas condensation products from the boilers. Some methods of cleaning are indicated further.
- Proper preservation of water-side and gas-side portions of Boilers during shut down of the unit.
- Prevent ingress of humidity & rainwater into the HRSG systems. One possible method of keeping the gas side system dry is to install duct balloons at the entrance of HRSG from gas turbine and in the stack.
- It might be worthwhile to install online corrosion monitoring system to keep a check on the corrosion initiation, progress and control.
- Ceramic Enamel lining of Air-Preheater Baskets on the Cold End
- Waste Heat Recovery from Flue Gas for preheating and other applications

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CONCLUSIONS

CONCLUSIONS

- Emission control systems are yet to be installed on all units especially subcritical units, so first hand experience of effect of flexible operation on these systems is not known.

- Studies and modelling conducted by various organizations indicates negative impact of Flexible Operation on emission control systems.

- Cyclic operation and poor lay-up procedures affect the performance of components in cycle chemistry systems. Guidelines have been developed by US EPRI and VGB for proper lay-up and start-up of Cycle Chemistry for cyclic units.

- Improved monitoring and controls can help in managing transients during flexible operation, however; for some systems it may be necessary to augment the existing systems for meeting the requirements during flexible operation.

CONCLUSIONS

- Some effects of flexibility on Environmental Pollution Control Systems, acid dew point corrosion and on failures of SH, RH due to changes in flue gas temperatures and frequent start-up or shut down temperature changes in steam are discussed.

- During Cyclic operations of the units guidelines such as those from VGB S 010 and EPRI 1021767 should be used for operating boiler water treatment

- During shut down the plant systems shall be properly preserved as per EPRI 1015657 or VGB S 116

Conserve Resources

Thank You