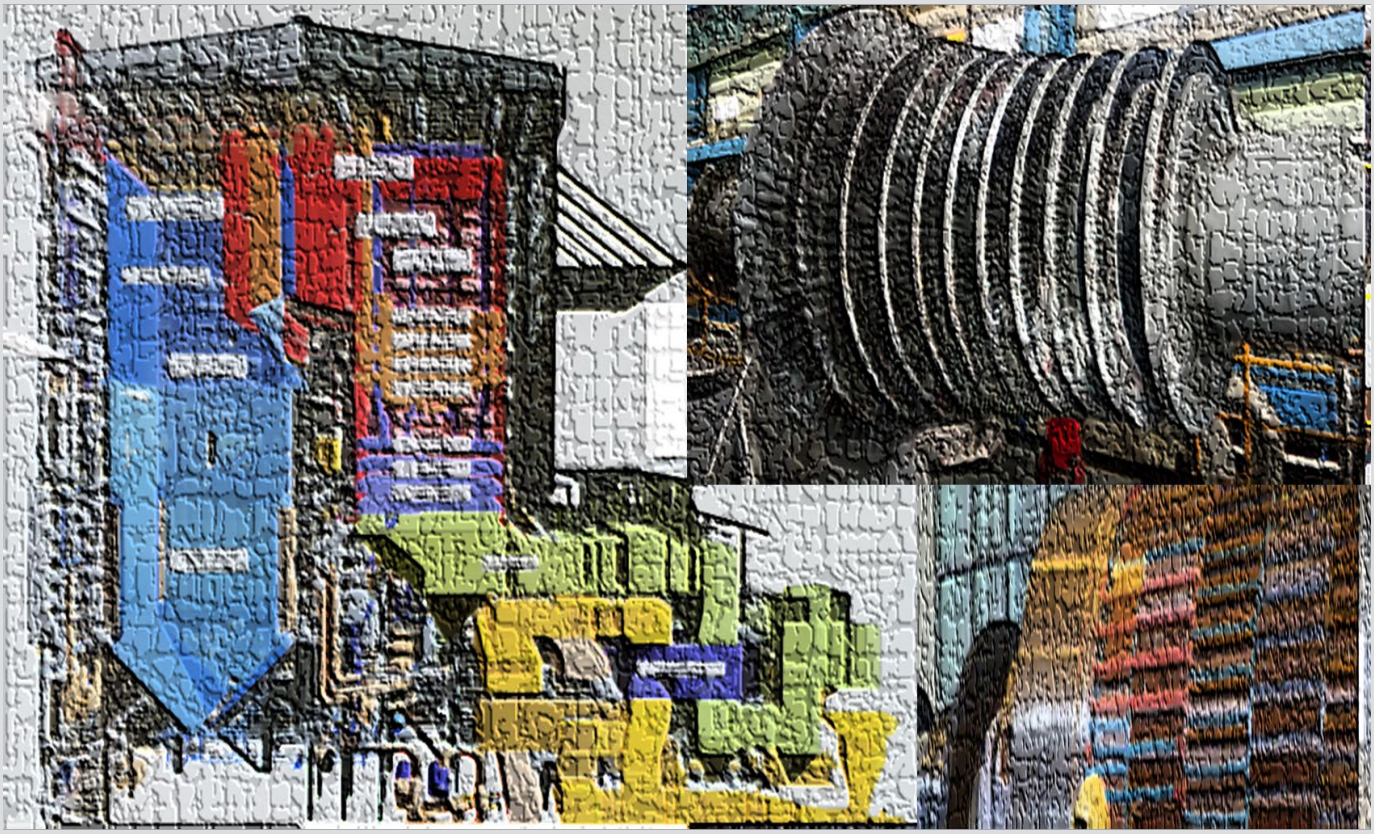
Indo-German Energy Forum

Recipe book for flexibilisation of coal based power plants

Best practices and operating procedures for flexible operation

by Anjan Kumar Sinha



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FOREWORD

India has set a target of developing 175 GW of installed Renewable Energy capacity by 2022 as a part of its commitment to reduce greenhouse gas emissions and to reduce dependence on fossil fuel. Such a large scale renewable energy generation would require balancing of grid by the conventional power generators to manage the intermittency/ fluctuation in the generation from renewable resources.

2. Flexibilisation of coal based generating units to accommodate fluctuating renewable generation is a challenge in our country, where the coal based generation is predominantly functioning as base load. The coal based units will be required to operate on much lower loads during certain time frames with high shares of power from renewables with provision of fast ramping and frequent starts. The transition of the traditional base load coal powered units to flexible mode will require adequate preparations to ensure safety, reliability and sustainability. The coal based unit will need to revisit their operational practices, technological upgrades and capacity building.

3. It is with this background, this "Recipe book for flexibilisation of coal based power plants" assumes great significance. It captures the global experiences, best practices and the findings of the various pilot studies, which I am sure, will serve as a guidance to the power plant managers in operating their units in flexible mode.

4. I would like to express my sincere appreciation to all the stakeholders, including the authors and the reviewers who have contributed to the preparation of this book. I would like to extend my heartiest congratulations to the Indo-German Energy Forum (IGEF) and United States Agency for International Development (USAID) for publishing the document.

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Ex-Director (Operations), NTPC

Date:13 Oct. 20

FOREWORD

In the Indian power systems, the thermal generating units, which were primarily designed to operate on base load, are now being increasingly operated on flexible mode due to various factors including rapid expansion of intermittent renewable energy sources. Such off-design operations result in accelerated rates of life consumption due to the initiation of fatigue-related damage mechanisms which these units were not designed to withstand. Moreover, there deterioration in part load efficiency. As a part of its commitment to reduce greenhouse gas emissions, India has targeted for deployment of 175 GW and 450 GW of installed Renewable Energy capacity by 2022 and 2030 respectively. To support such a massive addition of renewables into the grid, the Thermal Stations will be required to flexible even more in the future.

The power stations will have to address the challenges of Flexible operation proactively and make adequate preparations to ensure safety, reliability and sustainability. The power engineers will require to increase their awareness and upgrade their skills for managing the new operating regime. With better operational practices and technological upgrades, the adverse impacts of flexible operation on machine damages, safety, unit operating costs, scheduling and availability can be improved significantly.

In this context, the **"The Recipe book for flexibilisation of coal-based power stations"** provides valuable information and guidance to the operating engineers. It presents the global experiences of demonstrated techniques, best practices, findings of the various pilot studies and the Indian experience in the form of a guide book, which I am sure, will serve as a valuable reference document to the power plant engineers in operating their units on flexible mode.

I would like to express my sincere appreciation to the author, Shri Anjan Kumar Sinha for this exceptional work and the reviewers who have contributed to the preparation of this book. I would also like to express my sincere thanks to the Ministry of Power, IGEF and USAID for their efforts in bringing out this document.

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FOREWORD

Indian thermal power sector is undergoing a radical transition with the advent of highly intermittent and low-cost renewable power generation, affecting a fundamental change in the business model of fossil-based power generation. Currently, around 78% of India's energy generation is fulfilled by thermal power plants and fossil-based generation will remain the mainstay in Indian power Generation for a long time even with the Government of India's increasing RE addition target. However, in order to ensure grid security and stability, the variability of solar & wind generation has to be taken care by flexible generation from thermal plants. This will require the coal-based stations to reduce their minimum loads further down, reduce their start-up time and increase their ramping capabilities. The low merit order stations will also be required to operate on two-shift mode.

The transition of the coal-based units to flexible regime will require them to make adequate preparations in terms for ensuring safety, reliability and cost optimisation by modifying O&M procedures, upgrading controls and instrumentations and mechanical retrofits. As most of the older units in India, were designed to operate as base load plants, a fleetwide strategy for enhancing their flexibility is required in order to optimise the costs of interventions.

Although, flexible operation is a recent introduction in India, it has been practiced since a long time Internationally in many countries. The global experiences and learnings will be a valuable addition to the Indian power sector for a smooth transition into the flexible regime.

This book, **"The Recipe book for flexibilization of coal-based power stations"** has attempted successfully to capture the best International practices and experiences in flexibilization. It includes chapters on safety and part load efficiency apart from the procedures for low load and start-up operations. In my opinion, it covers most of the aspects of flexible operation and I am confident that it will serve as a guidance to the power plant engineers in operating their units on flexible mode.
My sincere appreciation to all the stakeholders, including the author who have contributed to the preparation of this book.

09/10/2020

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Foreword by USAID

As India pursues its ambitious renewable energy targets and seeks to transform its energy sector, the Governments of the U.S. and India are collaborating on the deployment and integration of Renewable Energy (RE) into the grid and undertaking many more initiatives to modernise their power systems. Recently during the Ministerial meeting of the U.S.-India Strategic Energy Partnership (SEP), key accomplishments under the partnership were highlighted by both countries and new areas for cooperation were prioritized. One of the areas highlighted as an achievement and a priority for future collaboration was flexible operation of Indian coal-based power plants.

As part of a joint initiative with Ministry of Power, called Greening the Grid (GTG), USAID is supporting pilots on the flexible operation of coal-based power plants at National and State levels. This program supports the GOI in its efforts to manage large-scale integration of RE into the Indian power grid. The central component of the program, Renewable Integration and Sustainable Energy or GTG-RISE, validates technologies and solutions to support grid integration through pilots and demonstrations, while building a foundation for policy and regulatory frameworks, building capacities and incentivising private sector engagement. GTG-RISE is a key initiative under USAID's Asia EDGE (Enhancing Development and Growth through Energy).

The learning and experiences from the GTG-RISE pilots with National Thermal Power Corporation (NTPC), the Gujarat State Electricity Corporation, Ltd. (GSECL) and the Karnataka Power Corporation, Ltd. (KPCL) to enhance flexible operations of coal power plants while at the same time minimizing operating costs and failure risks, has been instrumental in informing the book "Recipe Book for Flexibilisation of Coal-Based Power Plants - Best Practices and Operating Procedures for Flexible Operations." The book, prepared by the author Mr. Anjan Kumar Sinha, Senior Adviser to GTG-RISE, builds on his vast experience gathered through a series of pilot studies, test runs and operational experience in Indian coal stations.

I would like to express my appreciation and gratitude to Mr. Sinha for his excellent work and dedication towards coal flexibilisation. I would also like to express my profound thanks to the Ministry of Power, NTPC Ltd. and my colleagues at GiZ (Deutsche Gesellschaft für Internationale Zusammenarbeit) for their collaboration and assistance in the framing of this important analytical document. I hope the report will be a great tool for all the Indian power generation utilities looking to enhance flexible operations and support the integration of renewable energy, sustainably managing our energy resources and protecting our environment.

Best wishes for an efficient and clean energy future.

Michael Satin
Director, Clean Energy & Environment Office
United States Agency for International Development (USAID), India

Foreword by GIZ India

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Power generation from renewable energy sources is increasing worldwide. In Germany the share of electricity generation from renewables had increased faster than many conventional power supply stakeholders had foreseen. Soon coal fired power plants had to quickly ramp down whenever electricity from wind or solar was plentiful available. Else coal would have been burned at a higher cost than what was being remunerated and these plants would have generated losses. To avoid these losses, fossil fuelled power plant operators suddenly had to convert from base load plant operators to experts in flexible operation.

With increasing shares of renewables, more and more coal fired power plants of Germany's entire fleet had to decide to become flexible or to shut down their generation activity completely. With more than 50% of Germany's annual power consumption already coming from renewables and mainly from wind and solar, there is no doubt that flexibilisation of generation assets had become an important measure to keep the electricity system stable.

While the technical feasibility could be demonstrated quite easily, even with often rather minor modifications of the plant, it took Germany more than a decade to actually learn how to operate these plants in a flexible manner. Base load operators had to change their mindset and convert to flexible mode operators. It was forward thinking engineers who accepted these new challenges and introduced new practices to their colleagues. During this conversion period of more than 10 years a lot of also hard learnings were to be made. Germany would like India to benefit from these learnings. First Indian pioneers of operators are already operating their plants a lot more flexible and are willing to further improve their skills. We recognise increased interested on central, state and private sector level across the country with more and more operators gaining India specific knowledge about flexible operation of coal fired power stations. Many of these findings have found their way into this "Recipe book for flexibilisation of coal-based power stations". It captures global experiences, best practices and findings of the various pilot studies in India, which I am sure, will serve as a great guidance for a new generation of Indian power plant engineers.

I would like to express my sincere appreciation to all the parties, including the authors and the reviewers who have contributed to the preparation of this document. We wish each and every reader new insights and learnings out this book.

Dr. Winfried Damm
Head of Energy
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Preface

Compared to base load operation, flexible operation requires well planned strategies and procedures and if flexing is done with lack of awareness and inadequate preparations, it can lead to disastrous consequences. The traditionally base load plants are being forced by the power system and market requirements to operate flexibly. The recipe book of flexibilisation of coal based power plants has been prepared, keeping in mind the unique Indian conditions of power plant operation. It is intended to serve as a guidebook for Power plant engineers intending to operate their units flexibly. Overall, this guidebook highlights O&M practices for enhancing flexible operation with safety, emission reductions, improvement in part load efficiency, reduced equipment damages and cost reduction, all based on demonstrated techniques and best practices worldwide. With the guidelines provided, individual coal-based units should be able to prepare a customised operating procedure based on their unique conditions.

This recipe book has been prepared based on the experiences gathered through a series of pilot studies, test runs and operational experience in Indian coal stations. Further, a survey was carried out through questionnaires, personal interviews with power plant operators and data collection from more than two dozen coal-based power stations in India. A number of pilot studies for flexibilisation of coal-based stations were undertaken with international support, including VGB, Intertek, EPRI, Engie Laborelec, Siemens AG, GE Power, JCoal/JERA, STEAG, UNIPER which provide expert analysis of the Indian power station's capability assessment for flexibilisation and recommendations for flexibility enhancement. Besides, information available, published literature, and information collected through discussions with International experts during knowledge sharing workshop provided valuable inputs.

The assistance of experts from Intertek, EPRI, GE Power, Siemens, BHEL, VGB, RWE, Steag, UNIPER, Generation Utilities-NTPC, DVC, UPPCL, KPCL, GSECL, private IPPs, Duke Energy, EXCEL Energy and others is gratefully acknowledged. The findings, interpretations, conclusions expressed in this book are those of the author and do not necessarily reflect the views of those individuals who shared the information, nor that of any organisation.

Acronyms and Abbreviations

A/F	air fuel
APRDS	auxiliary pressure reducing and desuperheating station
ASME	American Society of Mechanical Engineers
AVT	all volatile treatment
BA	bottom ash
BFP	boiler feed pump
BTL	boiler tube leakage
CAG	cold air gate
CEP	condensate extraction pump
CERC	Central Electricity Regulatory Commission
C&I	control and instrumentation
CMC	coordinated master control
CRH	cold reheat
CS	cold start
DC EOP	DC emergency oil pump
DCS	distributed control system
DNB	deviation from nucleate boiling
DSM	deviation settlement mechanism
DM	demineralised
DO	dissolved oxygen
EFOR	equivalent forced outage rates
EHS	equivalent hot start
EOH	equivalent operating hours
ESP	electrostatic precipitator
FAC	flow accelerated corrosion (erosion-corrosion)
FE/FEM	finite elements/ modelling
FEGT	furnace exit gas temperature
FGD	flue gas desulphurisation
FSNL	fast speed no load
GCV	gross calorific value
GSC	gland steam condenser
HAZ	heat affected zone
HP	high pressure
HPBP	high pressure bypass
HR	heat rate
HRH	hot reheat
HS	hot start
HRSG	heat recovery steam generators
I&C	instrumentation and control
IEACCC	IEA Clean Coal Centre
IGCC	integrated gasification combined cycle
IGEF	Indo German Energy Forum

IoT	Internet of Things
IP	intermediate pressure
JOP	jacking oil pump
LPBP	low pressure bypass
MCR	maximum continuous rating
MI	mechanical impurities
MIC	microbial induced corrosion
MOT	main oil tank
NDT	non-destructive techniques
NDZ	notice to deviate from zero
NFPA	National Fire Protection Association
NRV	non return valve
LP	low pressure
LRSB	long retractable soot blower
OCGT	open cycle gas turbine
OEM	original equipment manufacturer
OED	original equipment manufacturer
O&M	operation and maintenance
PLF	plant load factor
PWHT	post weld heat treatment
RH/O	reheater/outlet
SB	soot blower
SCC	stress corrosion cracking
SCR	selective catalytic reduction
SH/O	superheater/outlet
SNCR	selective non-catalytic reduction
SPE	solid particle erosion
SWAS	steam and water analysis system
TCV	turbine control valve
USC	ultra super critical
USAID	United States Agency for International Development
VFD	variable frequency drive
VM	volatile matter
VRE	variable renewable energy
WS	warm start

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Introduction

We are in an era of rapid transition in the Indian power sector, driven by the imperative to limit climate change and ensuring affordable energy access. The key drivers are increased deployment of renewable energy, rapid decline in renewable energy costs, improving energy efficiency, widespread electrification, increasingly "smart" technologies, continual technological breakthroughs and increasingly well-informed policy making.

In the Indian scenario, the transition with massive deployment of renewable energy will require the coal-based units to play an important role by provide the balancing power, due to limited availability of gas and storage type hydro power plants. This will require the coal-based power plants to run on flexible operation, rather than on base load as in the past. In fact, flexibilisation of Indian power stations has already begun and is being driven by various factors like low merit order of some stations, intermittent coal shortages, fluctuating demand and addition of renewables. In the recent years, some of the stations have experiences a high level of cycling without awareness or adequate preparedness. The O&M practices have remained conservative.

It is important to understand that there would be a fundamental change in the power business of coal-based during this transition with increased RE penetration. For many of the power stations, there would be no concept of base load operation, especially for the non-pit head stations. These stations at the extreme may be required to run on two-shift mode. Further, the units which shall operate at so called "Base Load" regime, would operate at a much lower overall PLF/ load than what these are operating today.

Flexible operation is a difficult mode of operation and even the most conservative approach will increase plant O&M costs along with per MW variable costs, faster equipment degradation, damages accumulation, performance degradation, and loss of availability & reliability. At the extreme end, there can be cases of severe damage or catastrophic accidents, rendering the unit unavailable for long periods. However, those plants that can operate flexibly to meet market conditions while minimizing the financial impact of operating in this environment, will continue to be dispatched, at least for the near future. Proactive approach towards revisiting the operational procedures, Training of O&M manpower and investments in retrofits can enhance flexibilisation to a large extent as well as reduce damages, enhance safety and reliability of the units.

Methodology

The following approach has been used in this book for detailing out operational procedures and strategies:

- Review of published International literature on the subject
- Inputs from pilot studies carried out in the Indian power stations
  - VGB/Steag pilot studies at two stations for feasibility/assessment of flexibilisation studies
  - Intertek AIM at four Units for damage modelling and cost of cycling
  - Engie Laborelec damage assessment and cycling cost at two stations
  - GE power-feasibility studies at one station

    - Field test runs at six stations with support from VGB, Siemens & BHEL.
    - Tests carried out by NTPC
- Questionnaires for collection of information on current operational practices and issues with flexibilisation (24 stations across utilities like NTPC, GSECL, KPCL, Adani Power, Tata Power, DVC, UPPCL, WBPCL, PSPCL, Bajaj Power and with OEMs-BHEL, Siemens, GE & Emerson)
- Discussions with International experts, OEMs/OEDs during knowledge sharing workshops and presentations)
- Personal interviews/discussions
- Review of O&M manuals of different stations
- Collection of information through International exchange programmes/visit to power stations in US and Germany
- Information from discussions at International conferences like EPRI(Pittsburgh), Power & Electricity show, Bangkok.
- RWE Simulator in Essen, Germany

The studies were focused to address the "Indian conditions" of the stations operating in the Indian electricity markets. The following issues were considered:

- Flexible operation with Indian Coal (with high ash content, low Calorific value and varying percentage of volatile matter and moisture).
- Vintage and historical operation
- Future requirements of Flexibilisation requirements to accommodate 175 GW and above Renewable capacity addition (requirements detailed out in a report of CEA (Central Electricity Regulatory Commission, India))
- Changes required in Water Chemistry & maintenance practices
- Retrofit options based on cost benefit analysis
- Review of Operational practices
- Review of Safety
- Historical damages and the operating mode of the plant
- Potential limitations of the plant restricting flexible operation
- Review of Lay-up practices
- Best Practices implemented and benefits achieved
- O&M team's awareness and training
- Trend of the O&M costs over the years

Internationally, there has been plentiful experience and evidence of reduction of minimum loads to 25% and below but load below 55% of MCR (without oil support) was previously not attempted in the Indian conditions with the Indian coal and there were a lot of apprehensions that it may not practically be possible to achieve a stable load below 55%.

The test runs demonstrated that the minimum load of coal-based units (with Indian coal) can be reduced to 40% MCR. The stations were not comfortable of reducing the load below 55% and many of the state-run utilities are still uncomfortable reducing their loads below 60-70%, citing reasons of poor coal quality. The test run apart from boosting the confidence of the operating engineers, have dismantled many myths of operational practices, which has been discussed in detail in different sections of this book.

It is expected that the analysis, discussed in the book will help in increasing the awareness of damages and additional operating costs introduced by cyclic operations and will guide utilities to reassess their operating philosophies and adopt to flexible operation. Utilities can therefore,

choose to keep plants on-bar at minimum load during periods of reduced demand and avoid start-stop. Economically this type of operation is beneficial for the utility as well as the system. Moreover, with the modified operating procedure, issues like safety, deterioration of heat rate, unit reliability will be addressed.

It is important to mention that there is a financial merit in of controlling the damage from aggressive cycling impact. Many plants have saved a lot of money on maintenance and capital replacement costs by better controlling these variables within the plant. Too often items like APH baskets, boiler tubes, feed water heaters, economizers require replacement, that could have been deferred or eliminated completely had better temperature controls been in place from cycling damage. Most of these damages due to increased temperature transients do not show up immediately but get accumulated and affect the longevity of the component/s/. Once the first symptom appears, it may be too late to correct it and may require a complete replacement. This results in lost generation, under recovery of fixed costs from failure events.

The flexible operation of these units will lead to periods of off-bar idle op¬eration ranging from a few hours to several days or even more. Whatever is the duration of the shutdown period, a proper layup of the unit is necessary to avoid seriously jeopardizing the performance and availability of the unit. The components of unit corrode when exposed to air and moisture and the plant can have deteriorated performance, availability loss, increased startup time, and repeated failure after startups. Proper layup procedures can increase the useful life of the unit and the maintenance and other costs can be reduced. Lay-up procedures have been covered in detail in a separate chapter.

The best practices, implemented in the Indian power stations and elsewhere have been included in a separate chapter, with details of benefits achieved or achievable. This includes retrofit options, including the solutions suggested by OEMs.
Typical operating procedures, start-ups, lay-up have been included as a guide for stations to customise their procedures as per their unique conditions.

And last but not the least, this book includes a complete chapter on safety practices during flexible operation.

Basic Definitions

Operational flexibility of conventional power plants can be defined by the following flexibility parameters.

1.1 Flexibility: The term and concept of power system flexibility has evolved over time to reflect the way technology and power markets have evolved. The term was first introduced in IEA (2008) as: "*...The ability to operate reliably with significant shares of variable renewable electricity.*"[1]

A more specific definition was put forward in IEA (2011): *"the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise. In other words, it expresses the capability of a power system to maintain reliable supply in the face of rapid and large imbalances, whatever the cause."*[2]

EPRI, the Electric Power Research Institute, defined flexibility in 2016 as: *"the ability to adapt to dynamic and changing conditions, for example, balancing supply and demand by the hour or minute, or deploying new generation and transmission resources over a period of years."* [3]

1.2 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. Graphical representation of minimum load is depicted in the chart.

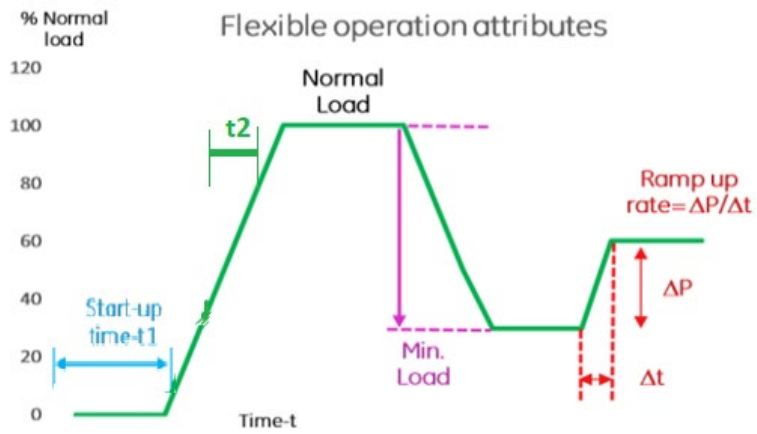


Figure-1: Flexible operation attribute

1.3 Start-up time: The start-up times are defined as the period from starting plant operation from light-up to synchronisation(t1) & further from synchronisation to 90% base load(t2). 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. The start-ups can further be defined as hot, warm and cold as per the time the units are out of operation or as per the turbine casing metal temperatures. However, defining start-up types and the criteria will depend on the OEM/OED. Traditionally, the OEMs used the criteria of turbine

[1] *IEA (2008), Empowering Variable Renewables: Options for Flexible Electricity Systems, IEA, Paris https://www.iea.org/reports/empowering-variable-renewables-options-for-flexible-electricity-systems*
[2] *IEA, "Harnessing variable renewables - a guide to the balancing challenge," 2011*
[3] *EPRI, "Electric Power System Flexibility: Challenges and Opportunities," 2016*

casing metal temperature. But it is important to understand that a hot or warm start-up on a turbine may not necessarily be the same for boiler. The boiler can cool down faster and it may be a cold start for the boiler, while the criteria for the turbine may be hot or warm start. Some OEM/OEDs have included the boiler metal temperatures also in the start-up criteria. Type of start-up for power plants is given below:

Table-1: Start-up Types & criteria

	Criteria		Time	
Start-up type	**Shut-down period (hrs)**	**Steam turbine metal temperature, °C**	**Light-up to Synch (Min)**	**Synch to 90% load (Min)**
Hot	<8	>400	50–90	60
Warm	8–48	250–400	100–300	80
Cold	>48	205	300–480	90

1.4 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.

1.5 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%.

1.6 Part Load Efficiency: Efficiency decreases (i.e. HR and APC) with decreasing load. The Heat Rates and Auxiliary power consumption measured at reducing loading rates of the unit is referred to as part load efficiency. During flexible operation, units are subjected to long hours of low load operation (part load) and optimizing the efficiency at low loads becomes important for maintaining the economic viability of utilities. In regulated tariff markets, lower efficiency would lead to higher marginal costs and direct reduction of profits of the stations. In real time markets, lower efficiency will increase the variable costs and the power may not get dispatched.

1.7 Flexibilisation Cost: The recurring costs incurred by the unit for running the unit on flexible operation modes (Variable cost) and the costs/investments incurred by the unit for enhancing the flexibilisation capability of the unit (CAPEX) together are the flexibilisation costs. The increase variable costs are incurred by the units on flexible operation due to the deterioration of efficiency, equipment life consumption, increased O&M expenses, extra oil consumption and decreased reliability (increase in outages & tube leakages (BTL)). Start-up and shutdown operations are the most expensive mode of operation because of additional life consumption of components, extra primary and secondary fuel consumption, chemical consumption and DSM charges (specific to Indian markets), besides other costs.

Table-2: Flexibility Parameters

Flexibility Parameters	Description	Present status	International Benchmark	Target
Minimum Load	Reducing the minimum stable load on coal (without secondary fuel support) to avoid frequent starts/stops. Also referred as turndown ratio.	55% to 70%	15-25% BMCR	40%
Load Ramping	Rate of change of load (% of MCR/minute).	<1%	4%/Min (Appr.)	>3%
Start-up Time	Time from light-up to synchronisation Hot<8 Hrs Warm 8-48 Hrs Cold>48 Hrs	Cold Varies widely (6-10 Hrs) Warm-180-300 minutes Hot-120 minutes	Warm start-Light-up to base load :170 min	To match the start-up curve supplied by OEM (Explore further reduction with retrofits/operational optimisation). With Installation of condition monitoring system, there is scope for further reduction.
Part Load Efficiency	Efficiency decreases with decreasing load. It is important to maximize the part load efficiency up to minimum loads to keep the operating expenditures at minimum.	Data of actual operating conditions are not available	Efficiency Range-100% -min load: reduction by 8%	-
Flexibilisation Costs	With the intent to keep part load OPEX low	Stations need to evaluate their cost of cycling.	Typically, O&M costs increase -3-5%,	

Power plant categorisation

Traditionally, power system planners have classified units on the basis of its fulfillment of demand for electricity into three categories: baseload, intermediate, and peak load.

- Baseload Plants/High merit order plants in the Indian regulated market
- Intermediate load/Mid merit order plants in the Indian regulated market
- Peak load Plants/Low merit order plants in the Indian regulated market

Categorisation of units is necessary from an economic perspective and their ability to deliver the different values of flexibilisation required by the power system. Every unit cannot optimally and cost effectively deliver/support all the values of flexibilisation viz high turndown, increased ramp rates, fast starts/stops & long periods of shutdown to cater to seasonal demand. Plants to meet the baseload are cost-optimal in terms of variable costs due to lower fuel costs and due to their location at pit heads. For peaking plants, it is just the opposite; high fuel costs are not a problem, as long as fixed costs are comparatively low. Ironically, in India, the peaking coal plants are comparatively newer plants and have higher fixed costs and as many of them are located far off from coal source, the variable costs are higher. Moreover, most of the newer plants are supercritical plants and if run at lower loads (below Benson point) lose their advantage in terms of higher efficiency.
Individual units are therefore required to make an economic and technical assessment of which value/s of flexibilisation they can best deliver/support, based on which investments they can proceed with for preparation. For large utilities, a fleet wide strategy for flexibilisation would make more economic sense.

2.1 Modes of delivery of flexible operation

Flexibilisation involves the following operations:

Low-load operation: By reducing the minimum load levels. This would enable the unit to continue operating on bar without secondary fuel(oil) support.

Weekend shutdown: The unit is shut down during the low demand period of the weekend and restarted on first weekday, e.g. on Monday. We can refer this as a warm start, about which we will discuss in the subsequent sections in this book.

Two-shift operation: This mode of operation will be mainly required for balancing the RE (solar) generation. The unit will be flexibilised and shut down/restarted every day to match the solar generation. This will, typically be a hotstart.

Extended shutdown: The system is shut down for long durations for managing seasonal demand and outages (forced and planned). This will be a cold start. The units must be prepared for adequate layup of the entire generating components.

Load-following operation: The load cycles between minimum load and full load. There may also be a requirement to maintain reserves on the unit for delivery of AGC, Ancillary services, DSM etc. within a predefined time.

Ramp rates: The rate of change of load during a low following operation or during start-up & shutdown is an important requirement of flexibilisation. Units may not be capable of delivering the ramps as required by the power system and need additional preparation/retrofits.

2.2 Limitations for flexible operation

Low load and load-following restrictions: Coal-fired units have limitations in their capability to load follow, mainly due to the delays in the responses of pulverizer systems, pulveriser turndown, problems of combustion control (which is further aggravated by accounting for changes in coal quality) and large heat capacities of the boilers makes control of temperature difficult.

Ramp rates and start-ups/shutdown: These operations involve excessive life consumption of critical components, by increasing the number of stress cycles experienced by the boiler and turbine components because of temperature transients. The rate of rise of steam temperature is limited by the allowable fatigue life consumption of the material. The control system response has to be limited to the prescribed ramp rates of SH and RH outlet temperatures to minimize the thermal stresses.

The ramp rate is associated with the issue of temperature-change rates.
Tackling environmental impacts poses another limitation in flexible operation. Managing the amount of excess air in the flue gas during load changes, can be challenging as it has an effect on NOx and SO2 emissions.

Cost of Flexibilisation

The coal-based conventional power plants in India are being subjected to increased flexible operation- frequent load following, lowering the minimum loads and frequent start-stops. Many of the Indian power utilities are facing with increased O&M costs, increased EFOR, and other operational costs. There are ample incidents of repeat failures in the flexibilising units. It is important to understand (and will discuss in details in the subsequent sections) that flexible operation introduces new type of damages not seen in base loading units and these damages get accumulated continuously and may not be visible or be difficult to estimate until damages have happened together with loss of reliability, availability and in the extreme case loss of property and life. By the time symptoms of the accumulated damage are visible it may have become very costly to correct.

Even the most conservative approach will increase plant O&M costs along with per MW variable costs. However, those plants that can operate flexibly to meet market conditions while minimizing the financial impact of operating in this environment, will continue to be dispatched, at least for the near future. Operations for Flexible Operations requires a holistic perspective of the entire plant to avoid unintended consequences.

The costs due to flexibilisation can be minimized with correct operational practices and increased awareness of the cost implications of damages. The good part is that today there are solutions available which can estimate the damages and the flexing costs online with fair accuracy.

The following factors influence the cost of Flexibilisation:

- Coal quality
- Water chemistry management
- Vintage -remaining creep & fatigue life of components
- Design of the unit (material used, thickness, design of components)
- Maintenance philosophy
- Operational practices and operational capability of operator (how trained is he)
- Level of automation/C&I systems
- Lay-up practices
- Extend of cyclic operation -depth, breadth & frequency of flexible support provided

The flexibilisation costs depend on the market context. The costs in the Indian context were estimated through pilot studies at four units by M/s Intertek AIM (under the USAID's GTG-RISE programme). The Intertek study was based on 7-10 years historical data of hourly MW, O&M costs and plant signature data.

Intertek AIM used several approaches to quantify the damage associated with cycling. The first approach uses Intertek AIM's proprietary Loads Model™ software, which has been applied to hundreds of fossil fired power plants and provides a scalable metric to determine the cycling damage over a long period of time. The second approach carefully examines the actual temperature history of selected components over specific transients, which demonstrates the physical relationship between thermal cycles and induced damage. The effect of cycling on water

chemistry was also studied. The approach accounts for creep damage, fatigue damage, erosion, corrosion, and all other types of damage that are known to occur in fossil power plants. The damage accumulation rates computed by Intertek AIM's Loads Model are related to the fatigue damage emanating from an idealized gentle load transient known as an equivalent hot start (EHS)[4].

Table-3: Flexibilisation costs

Factors	Parameters
Energy Charges	• Start-up cost increases due to increase in ▪ Heat Rate ▪ APC ▪ Oil support
O&M Cost	• Increased EFOR • Accelerated life consumption due to ▪ Start-ups ▪ Load Following
Fixed Cost	• Accelerated life consumption will have impact over unit availability in ling-term • EFOR can impact unit availability in short-term • Increased Fixed Costs per unit with lower online hours
Environmental Impact	• Although total emissions will be less, instantaneous specific emissions (Kg/MWh) NOx, SOx & CO emissions will be somewhat higher at unit level while flexing. However, looking at heat rate degradation for baseload operations, in most cases, 1% thermal efficiency improvement results with 2% - 3% less CO2 emitted (as well as improved NOX/SOX emissions). • Impact on installed emission control devices (SOx, NOx)
Other Costs	• Increased consumption of ▪ Water ▪ Chemicals-online & offline(lay-up) ▪ DSM Charges

[4] *GTG-RISE/ Kumar N, Hilleman D Intertek AIM (2018)- Pilot study on Cost of cycling study for Coal-based Flexible Power Generation*

Based on the study, the typical O&M costs (due to loss of useful life & EFOR) for one event is shown below:

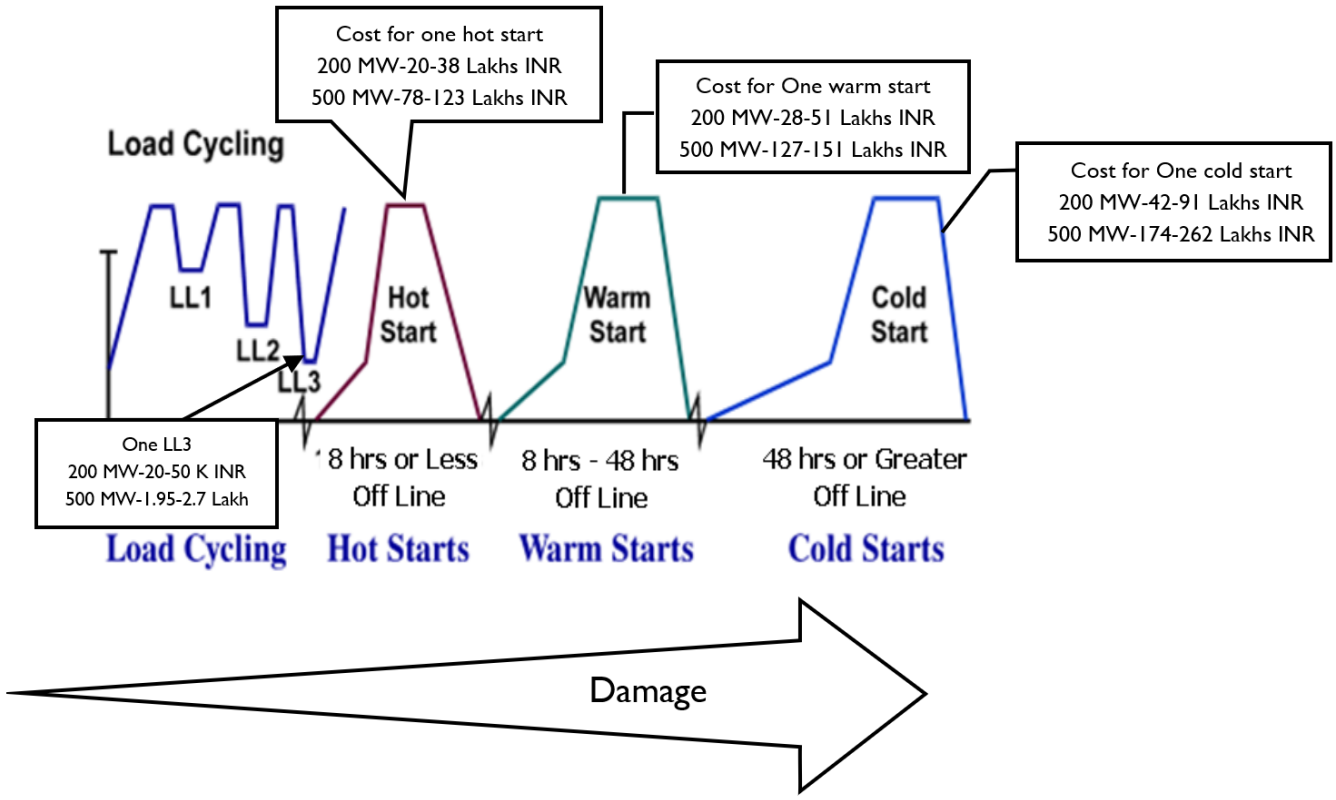


Figure-2: Damages & Cost for different modes of flexibilising from Intertek AIM modelling study[5]

Figure-2 shows that a cycle of cold start is the most damaging mode of operation, followed by cycles of warm starts and hot starts. LL3 is significant load following, which is comparatively very low. It is therefore beneficial to avoid start-ups by reducing the load to lower minimums.

It is important to understand that the costs per event as mentioned will vary, depending on the way the units are operated (present and past) and the level of automation in the plant and the preservation practices followed. As seen in one of the pilot studies, one cold start was 16 times more damaging than the best performed cold start-up. The operator therefore, must be aware of the impacts due to his actions and it would be worthwhile to install an online asset management solution (discussed later in subsequent sections). The damage mitigating operational practices, C&I systems and other precautions are discussed in detail in the subsequent sections.

[5] *GTG-RISE/ Kumar N, Hilleman D Intertek AIM (2018)- Pilot study on Cost of cycling study for Coal-based Flexible Power Generation &*
Kumar N, Hilleman D Intertek, (2018) Flexibilisation/damages/cost of cycling presented at USAID Workshop presentations

The loss on account of deterioration in efficiency of the unit at part loads is another major category of flexing cost. A typical deterioration of efficiency (net heat rate) for different categories (based on NTPC/ Study done by Laborelec)[6] is shown in Figure-3(a). It may be noted that this will vary from machine to machine and these losses will be significantly lower if the unit is run on sliding pressure (Figure-3(b).

% Deviation of Net heat rate at various load conditions

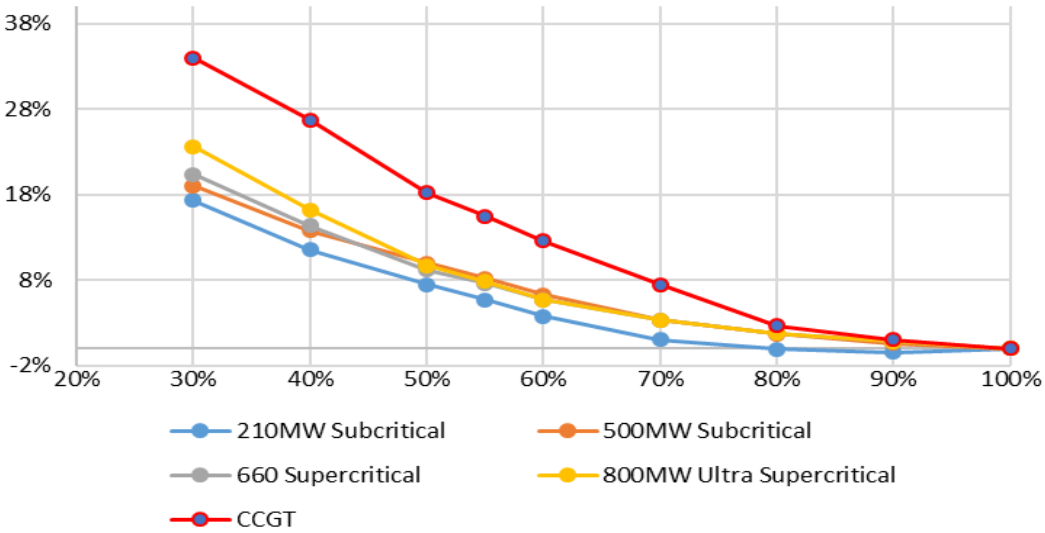
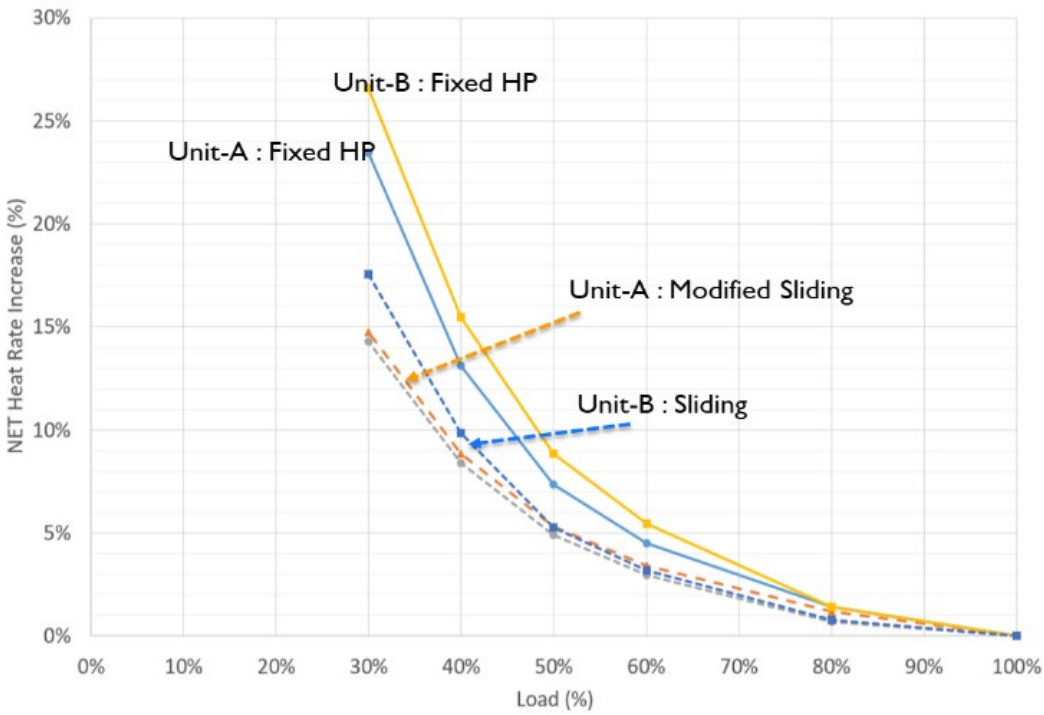


Figure-3(a): Net Heat rate Increase vs Loading Factor



3(b) NHR increase on fixed/sliding pressure

[6] *NTPC Cost of cycling study, Labrolec*

CERC has made provisions for compensation of secondary oil consumption during start-ups as shown in Table-4. Stations are being compensated for start-up (after 7th start-up in a year) if requested for reserve shutdown. However, the outages due to increased EFOR (BTL, forced outage, partial loss) is currently not getting compensated and is generator's loss.

Table-4: Compensation for Oil consumption during start-up[7]

	Oil Consumption per start-up(kl)		
Unit size (MW)	**Hot**	**Warm**	**Cold**
200/210/250	20	30	50
500	30	50	90
660 and above	40	60	110

[7] *Central Electricity Regulatory Commission (Indian Electricity Grid Code) (Fourth Amendment) Regulations, 2016*

Strategies for unlocking flexibility in existing plants

A number of different investments, system modifications/retrofits, system upgrades, operational procedural changes and policy changes can be made to increase power plant flexibility with affordability and sustainability.

However, there is **no one-size fits-all approach** to make existing power plants flexible. Based on global experience and studies carried out in Indian power plants, a diversity of strategies are available to make existing power plants more flexible. Every unit is unique in terms of age, make, historical operation, fuel type and design and will need a specific solution. The retrofit solution will have to be decided after a thorough cost-benefit analysis after conducting a test run & the expected regime of operation/ flexible operation it is expected to support in future. These strategies include:

4.1 Changes to operational practices for existing plants

Significant new capital investments are not necessarily required to operate power plants more flexibly. Changes to certain plant operational practices – often enabled by improved data collection, improved measurements, operators training and real-time monitoring –can be used to unlock latent flexibility at existing plants. For example, better monitoring and control equipment can allow plants to start faster and ramp output more dynamically without compromising reliability. As per VGB report of pilot studies carried out at NTPC Dadri and Simhadri, 50-55 % minimum load operation or even lower loads can be easily achieved with modifications in operational practices, without investment. In fact, most of the NTPC stations are operating at 55% minimum load without any equipment modification. The specific constraint to the Indian situation is poor coal quality, which will need additional preparations and system modifications. However, flexible operation at higher ramp rates and frequent startup will incur significant O&M costs due to increased life consumption of components and there will be a significant efficiency loss during part load operation. Investments in efficiency improvement technologies, condition monitoring systems and upgrades for reduced damages during cycling is worthwhile when compared on a cost-benefit scenario. The strategy for changes of operational practices will be discussed in details in the subsequent sections.

4.2 Optimisation of C&I (Control & Instrumentation)

All the pilot studies conducted on the Indian power stations, field test runs and International experience reveal that reliable control systems are important for all aspects of flexible plant operation. For close monitoring of the operation data of critical components during flexible operation and controlling the process parameters so that the temperature transients do not cross the material limits, a responsive C&I system is the key enabler. Moreover, C&I system is also important for monitoring and managing the consequences of flexible operation. Stations can decide the level of upgrades required, based on cost-benefit analysis with respect to the values of flexibility it is required to deliver and the market conditions.

There are different levels of automation in power plants[8]:

- Basic C&I system: - the basic level required to operate the plant, including all measuring and protective functions, basic monitoring and control of all processes.
- Fully automated C&I: - Automated start-up and shut-down and advanced unit control concepts and diagnostic and energy management functions. Condition monitoring systems and lifetime consumption monitoring are included.
- Fully automated C&I interconnected to the Internet of Things (IoT): The power plant, where all its processes and procedures, are integrated in a digitized environment. This will be done using of innovative technologies such as Virtual Reality (to plan outages, to simulate plant behavior) or augmented Reality (to support maintenance work) as well as big data solutions to tap the potential of predictive maintenance. Besides, the plant is linked to the company-wide network.

4.3 Operation of HP/LP bypass periodically for fast load reduction

Power plants in Europe regularly operate HP/LP bypass for fast load changes. But this cannot be done in India -not due to technical reasons but due to economic considerations. This operation mode leads to higher fuel consumption and significant loss in efficiency. Presently, there is no compensation for this loss, whereas in Europe the generators are incentivized by the market.

4.4 Flexibility retrofit investments for existing plants

Depending on the plant technology, a range of retrofit options are available to improve various flexibility parameters of power plants (e.g. ramp rates, start-up times, minimum economic or technical generation levels). Worldwide, several plants have been able to achieve between 15-35% MCR. However, with lower volatile high ash Indian coals, the scenario is much different.
As per studies carried out in NTPC Stations and State Utilities by Intertek, EPRI,JCOAL,GE, and test run conducted at some of the stations by VGB /Siemens, BHEL, the capability of 40% minimum load has been demonstrated and can be sustained with minimum retrofits like improved C&I systems, boiler condition monitoring, combustion optimizer, coal analysers etc. Earlier, for fast ramp up, a cost-effective retrofit of condenser throttling was completed at NTPC Dadri Unit6 and its effectiveness in providing fast primary response has been proven beyond doubt.

4.5 Efficiency retrofits for very old and inefficient plants

Some of the old plants can be run for a very limited duration. As per studies conducted by CEA and NREL on Indian grid requirements for 2022 and beyond, there is wide variation in power requirement during different seasons. For managing the seasonal requirements, some stations will be required to run for a very limited period during the year, probably for two months. Efficiency upgrades of these old stations along with a minimum level flexibilisation can be an effective low-cost solution.

For example, the thermal power plant fleet in Germany has upgraded its operational performance substantially in response to higher flexibility requirements. Power plants that were initially

[8] *(VGB-2018) Flexibility Toolbox-Measures for flexible operation of coal-fired power plants*

designed to run around the clock and were built over 40 years ago have been upgraded to start and stop twice a day, while also providing a range of additional services to the system.

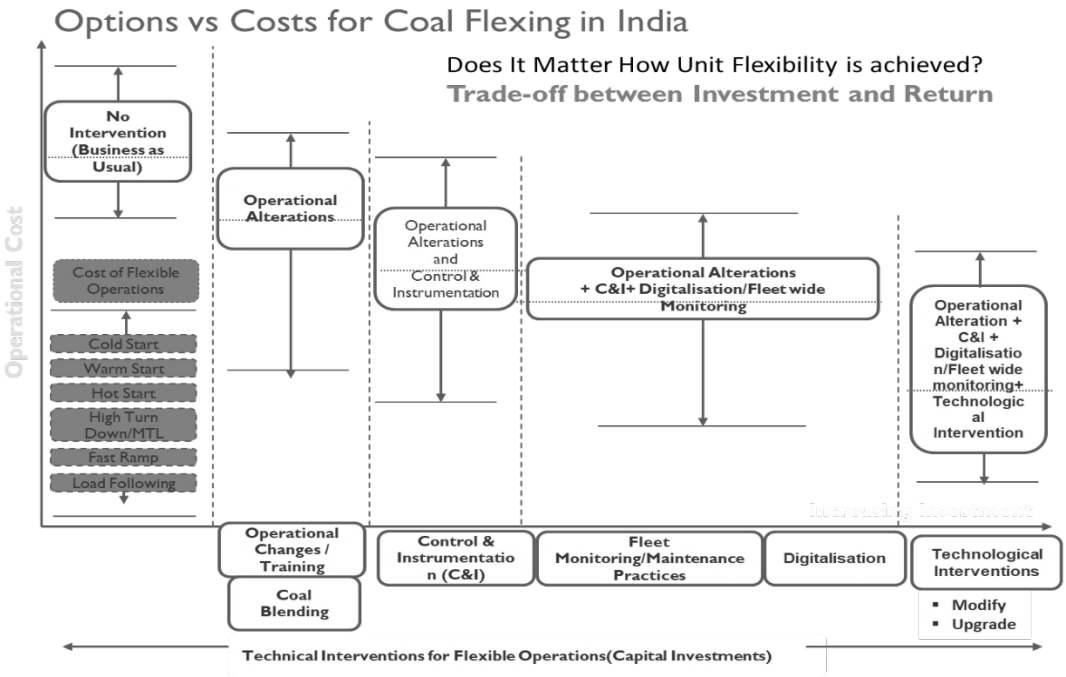


Figure-4: Flexibilisation strategies vs cost

The strategy for enhancing the flexibilisation capability of the plant must be decided after a thorough cost-benefit analysis based on the proposed value required to be delivered by the unit/station. Costly retrofits may not be necessarily required in most of the cases and even if it is required, it is to be decided after exhaustion of all the other options. In Figure-4, above, the different strategies are compared with respect to the benefits. Each strategy is represented by a box and whisker chart. It can be observed that with operational procedural changes and C&I modifications/upgrades flexibilisation can be achieved with significant reduction in operating costs, with lower costs of interventions.

A single retrofit option may only impact one flexible operation mode. The startup flexibility retrofits will reduce the startup time (can be up to 50%) and give reduced emissions, damage reduction and improvements in shut-down. For low operation (minimum load), the retrofit option must focus on improved response for load changes and part load efficiency improvement. The part-load operational flexibility for part-load regime, is related to improved response in terms of ramp rates, efficiency, and higher loading rates. The retrofit for improving ramp rates must focus on reducing the overall damage and the consequential costs.

4.6 Evaluation for Flexibilisation of units[9]

When a base load design machines are required to be placed into flexible operating regime, a certain amount of the unit's component damage is likely to happen. Assessing the capability of the unit's components prior to extensive cycling can provide valuable information from which action can be taken to prevent or minimize the component failures. Each unit is different and a custom-designed cycling evaluation plan will be necessary. The cycling evaluation can be

[9] *Nikhil Kumar, Intertek-Personal communication*

performed by the utility staff, consultants, or the OEMs. Typically, cycling evaluation of the unit involves engineering review, outage inspection, and on-line testing.

Phase-I, engineering review, includes the following:

- Review of BTL, outages, component failures, operation, maintenance, and cycle chemistry history
- Determine the critical components, identify original design weakness under the cycling operation, and perform preliminary analysis, as required.
- Establish an outage inspection plan.
- Establish a test plan and instrumentation requirement.

Phase-II, outage inspection includes the following:

- Perform an outage inspection and condition and or damage assessment.
- Analyze the inspection findings and nondestructive evaluation (NDE) results.
- Perform a root cause analysis after damage is found. Ensure that all necessary data are obtained during the outage.
- Perform the remaining life analysis. Implement the short-term solution after damage is found.
- Install the instrumentation to support on-line testing.

Phase-III, post outage testing and engineering analysis, includes the following:

- Conduct cycling and low load test and analyze the results
- Develop recommendations for implementation, for example, operation procedure changes, repair, replace, modification/upgrade, or inspection based on the analysis results.

The evaluation of the flexibilisation capability has been done at a few units of the Indian power stations and case studies of a few is included as case studies in the later section of the book.

Damage mechanism during flexible operation

The traditional, older coal-based fleet were designed to operate most of the time on creep conditions. The older design codes for power plant (ASME, DIN, BS) did not give specific requirement for consideration of fatigue as a failure mechanism. These earlier design codes were based on the assumption of base load operation which was adequate then. But, with the change of operating regime from base load to flexible regime, the damages due to the interaction of fatigue and creep is a significant concern.

Materials behave differently in a complex and synergic manner in the presence of both fatigue and creep, to cause early failure. The interaction between creep and fatigue is non-linear and very strong. For example, if the creep and fatigue damage fractions are equal, time-to-failure will be only one-eighth (versus one-half for a linear sum) the life predicted for either mechanism acting by itself.

The ASME (American Society of Mechanical Engineers) provides a guidance on this interaction of fatigue and creep and its effect on the life expectancies of the materials (see Figure 5).

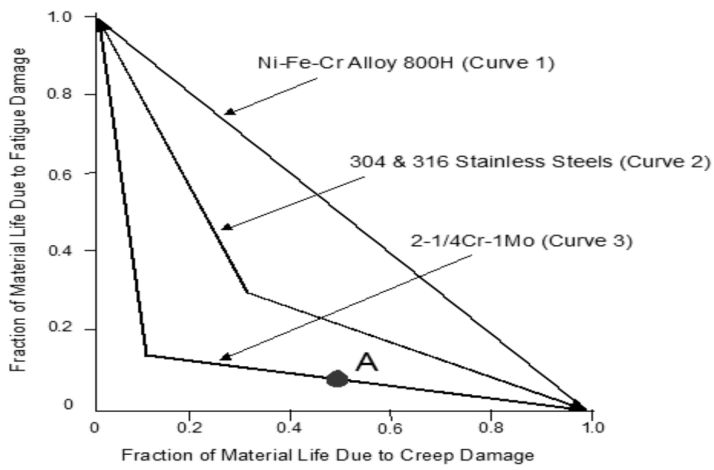


Figure-5: ASME Creep-Fatigue Interaction Curves for Several Materials[10]

5.1 Boiler Critical Components[11]

It is not feasible or necessary to evaluate in detail the life of every component in a boiler. It is, however, important to determine the critical components.
The initial step in the determination of criticality is an assessment of the consequences of a failure. If the consequences of the loss of a component are significant, then that component meets the first test of criticality. The basic parameter to be considered in evaluating the criticality of a component is its design temperature. At a minimum these should be considered:

[10] *Intertek-Cost of cycling Ramagundam*
[11] *Nikhil Kumar, Intertek, Personal communication*

- The final SH outlet header and the main-steam piping system
- The economizer inlet header
- Water wall tubes
- SH and RH outlet tubes

5.2 Equipment Failures due to Fatigue-creep Interactions

5.2.1 Cracking of thick wall components

Example: Boiler and Turbine stop valves cracking due to high wall temperature difference during start-up shutdown. Frequent failures of turbine valves have been seen in stations of NTPC (Ramagundam & Simhadri)

5.2.2 Superheater and reheater cracking

SH/RH headers have a finite life due to creep. Boiler cycling introduces the additional fatigue and creep-fatigue interaction damage mechanisms. During cold start-up of the boiler, the SH headers are subjected to humping as a result of top-to bottom temperature differences. For frequent on/off cycling, the cyclical bending stresses have caused cracking in the outlet leg tube stub-to-header welds.

Cracking of ligaments between header stubs and penetrations due to thermal fatigue is one of the main life consuming mechanisms on headers. The superheater outlet header, particularly the horizontal tube draining SH is at greater risk, including the intermediate headers operating at lower temperature during rapid start-up and shutdown.

Crack initiation and growth occurs due to the temperature transients during the following operation:

- High ramp rates: this may affect sudden changes in air flow and steam flow.
- Hot Start -when undrained condensed water formed during preceding shutdown quenches the hot headers.
- Cold start-up: when hot steam is introduced to cold headers
- Excessive water carry over and quenching of hot header surface due to excessive use of attemperator. Defective and passing attemperator nozzles can also cause the same problem.
- Boiler forced cooling -carry-over of saturated steam from drum to final SH.

Figure-6(a)/6(b): Cracking of ligaments between header stubs [Intertek-Presentation at NTPC conference]

Figure 7 (a)SH Stub (normal)

Figure 7 (a) SH Stub joint crack

Figure 8: Hanger stub joint

Figure 9: Cracked Tube

Figure 10: Cracked Tube

Figure 11: SH tube longitudinal crack

Mitigating O&M practices

- Improved boiler operation to avoid steep temperature transients.
- Improved start-up & Shut-down procedures. Monitoring and evaluating every start-up with EHS, EOH etc.
- Monitoring of temperatures at inner & outer walls, header inlets and outer stubs. Make provisions for measurements with installation of additional probes
- FE modelling to establish variations and determine allowable limits
- Installation of Condition monitoring software
- Routine inspections, inspection of the bore of headers using ultra-sonic and magnetic methods

5.2.3 Evaporator header Stub Cracking

During start-up, with incidents of non-uniform heating, the expansion of waterwall tubes is not uniform. Some tubes are more exposed to firing and expand more rapidly than the others. The waterwall tubes are connected to top and bottom headers which can be comparatively rigid. The differential expansion of the tubes leads to high stress concentrations in the stub to header connections. This leads to thermal fatigue cracking of the stub to header weld or stub to tube weld. The nonuniform temperature can also exist during shutdown & unit tripping and during forced cooling. The effect will be manifested with increased BTL.

Figure 12: Stub cracking

Mitigation:

- Replacement of long headers with shorter interconnected boxes
- Regular inspection

5.2.4 Economiser Inlet Headers cracking

During shutdown periods, the economizer retains the temperature at a relatively high level. To maintain drum level, colder water is periodically fed through the economizer to the drum, causing thermal stresses.

Mitigation:

- Economiser recirculation
- Deaerator heating
- Arrangements of hot filling of boiler. Hot filling arrangements from another running unit can be made.

5.2.5 Drain line connections

On/off cycling can lead to severe localized damage to the header as a result of thermal shock. In plants where more than one boiler or header are tied to a common blowdown tank, it has been found that condensate can sometimes back up through drain lines and enter a hot header during start-up. The resulting thermal shock can cause fatigue damage to the header immediately adjacent to the drain connection.

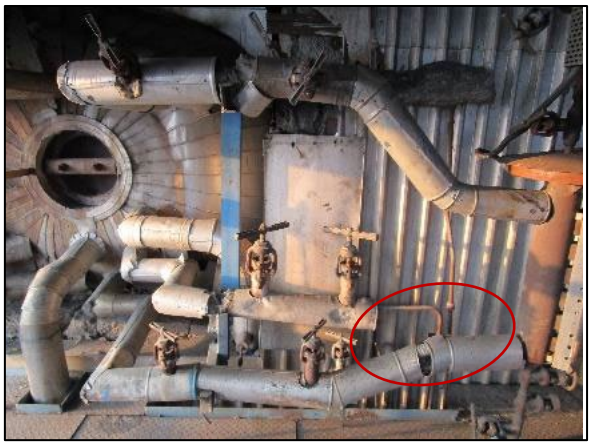


Figure 13: Drain line connections

5.2.6 Feed Water Heaters

Leakage from the thick sections of tube plates and end covers of FW heaters is a common problem in cyclic operations.

At extremely low loads the HP heaters may be bypassed. But this will increase the thermal shock on economisers inlet headers. A prewarming system to reduce the ramp rates using auxiliary steam for pegging the heaters while offline with an expected hot or warm restart will reduce the damage rates for the feed water heaters. It would require maintaining the condenser vacuum to allow and assure complete draining of the condensate accumulated to avoid the risk of turbine water induction.

In many of the stations, there have been issues with copper alloy tubing in the feed water heaters and replacing them with other materials would prevent the copper carryover to the boiler and steam turbine. This will reduce the boiler tube damage, waterwall tube failures and forced outages and the need for boiler chemical cleanings.

Figure 14: HP heater tube bundle

5.3 Improper Expansion

A boiler should expand downward from its roof this expansion has to be contained in a support framework, permitting the relative expansion. Thus, the furnace wall buck stay, gas ducts, windbox attachments, and boiler support have to accommodate the thermal movement. This is usually achieved using a slip bracket assembly. The expansion cold and hot may be checked with the OEM.

5.3.1 Boiler structures

Backstays are typically attached to the furnace walls with a link and sliding clip arrangement, which is almost static during baseload operation but during flexible operation there is a requirement for the mechanism to flex regularly and failure of the buckstay attachment is a common problem in older plants running on severe cyclic mode.

During flexible operations, there can be issues like seizure of connections that accommodate relative thermal movement between hot pressure parts and cold structural support. In the extreme case this could lead to collapse in the boiler pressure parts. Another problem can be the redistribution of load, where the support load is transferred across the boiler.

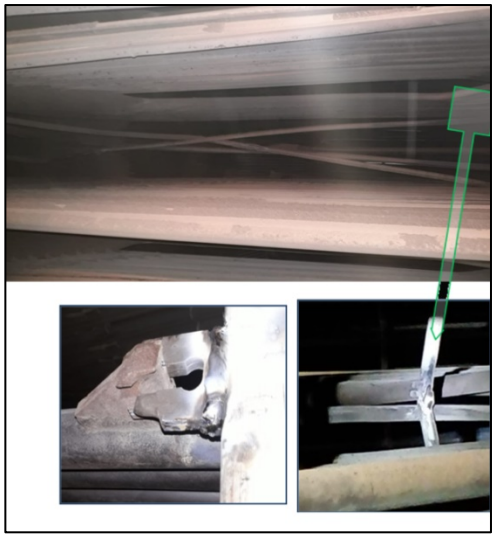


Figure 15: Platen zone spacer failure

Figure 16: Attachment weld failure

Mitigation:

- Periodic checks with reference readings
- Reference readings must be recorded and must be available with shift charge engineer
- Walkdown Checklists

5.3.2 Piping support/Hangers

The piping in the boiler, from boiler to turbine has to accommodate its own expansion as well as the movement of the boiler and turbine. These piping are flexible but can generate extreme levels of system stresses under cyclic operations if the supporting structures are inadequate.
To facilitate smooth pipe movements, mostly the piping systems are based on constant load supports and typically have a load variation of less than +- 5% over the movement range. Wear and tear of the supports, hangers and springs boxes is typical for units that are changing the operating mode. The supports are susceptible to load changes and during thermal cycling or deterioration of support mechanism there can be issues like piping drop/lift or getting locked in position and will lead to increased resultant stresses towards the terminal connections of boiler or turbine causing creep and fatigue damage. Some springs and hangers' breaks are expected in the long term due to increased frequency of thermal movement and possible water hammer incidents.

Mitigation:

- Periodic extensive walk-downs to check. A complete visual inspection of pipelines with both cold and hot position readings
- Movements of each support to be identified and compared with design.
- Detail analysis of readings with significant difference (around 25%)
- When abnormal conditions are observed, immediate action should be to avoid larger consequences.

5.3.3 Drum Humping[12]

The rate of saturation temperature change in a steam drum needs to be monitored and limited. Operated in a variable drum pressure mode necessitates considerable over firing or under firing in order to maintain the drum pressure. These firing requirements that affects steam temperature control also prevent rapid drum pressure changes.

For a drum, the top-to bottom temperature difference needs to be maintained within limits. In cases of shutdown or trips, if drum pressure collapses rapidly, the top-to-bottom drum temperature difference widens beyond limits and the drum in turn humps (as shown in Fig17). The humping is unrestrained and causes little change in the drum or support stress levels as mostly the drums have two point supports. The problem, however, is with the connections (down comers, connecting tubes and pipes, drum internals, end seals, etc., which moves with the bowed drums and if they do not have sufficient flexibility, they can be subjected to severe and unacceptable levels of stress and cracks.

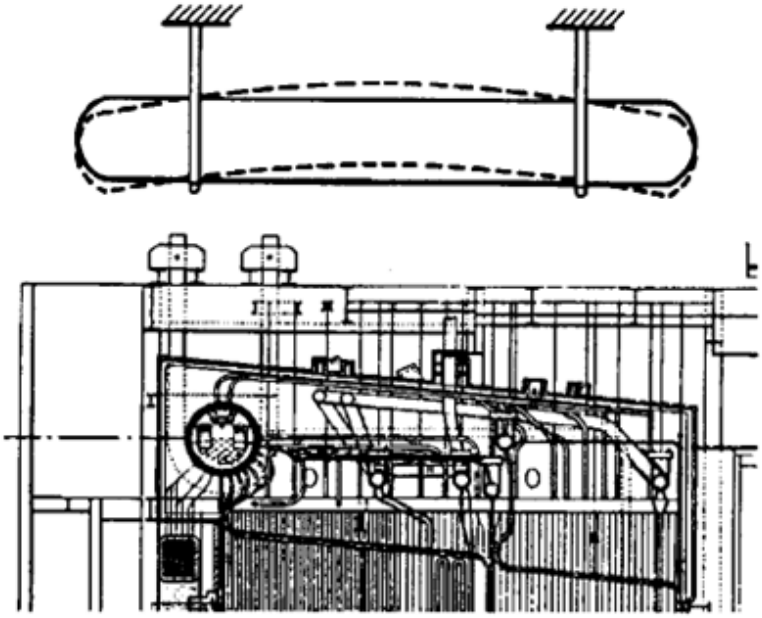


Figure: 17 Drum Humping[13]

[12] *Nikhil Kumar, Intertek, personal communication, May 2020*
[13] *Nikhil Kumar, Intertek, personal communication, May 2020*

5.4 Potential Problems in Steam Turbines

Significant design and operating problems are imposed by cyclic thermal stresses. The potential for damage to turbine rotors from cyclic stresses, for example is expressed by the cyclic life expenditure curves published by turbine companies relating the rate of temperature change to the amount of temperature change to be made (as shown in figure:18)

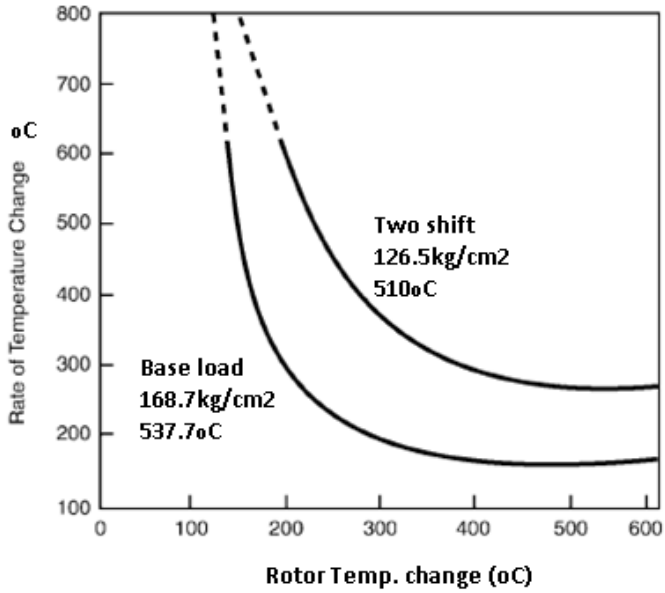


Figure:18 Turbine Rotor Temperature Limits

5.4.1 Thermal fatigue together with creep fatigue

Risk in thick walled components of turbine and stop/control valves. The following areas are vulnerable to fatigue cracking:[14]

- Governor or control valve chests
- The ligament between the stud holes on the horizontal joint flange and the inner surface of the
  casing near the inlet sections of the high-pressure turbine.
- Nozzle chambers on units without separate nozzle boxes.
- Bolted-on nozzle plate fit radius
- Circumferential fits for diaphragms, blade rings, and inner castings within the outer casing
- Rotor surface in wheel fillets and steam sealing grooves
- Rotor bore

5.4.2 Mechanical fatigue

Occurs during start-up when the turbine runs through a series of critical speeds, during which the vibrations increase significantly. With increasing number of starts, the number of such critical speed events will increase, subjecting the turbine blades to high fatigue levels. LP blades are most vulnerable to mechanical fatigue.

5.4.3 Overheating of Turbines due to windage

[14] **Rogers Dave, Hilleman D, Intertek Engineering consulting (2018),** *Cycling Damage and damage or life management of steam turbine in cyclic operation, presented at USAID (RISE) workshop on Coal Based Flexible Generation Pilot, New Delhi*

During flexible operation, there can be situations when the flow in the turbine decreases, leading to churning or the turbine blades driving the steam. This can also occur when the HP/LP bypass is opened to a level in which there is a drastic reduction in flow through the turbine. This results in high cylinder temperatures.

5.4.4 Increase in wear and tear of Turbine valves

During flexible operation, there will be additional wear and tear on the valves due to the increased operation of the valves. In some instances, there has been frequent damage of the control valves due to increased incidents of unacceptable temperature transients.

5.4.5 Erosion due to carryover oxide scale on HP/IP blades

There are instances when the oxide scales in boiler tubes get detached during thermal shocks and carried over to the turbine. It is mostly captured in the strainers before the turbine, but smaller particles can pass through the strainer and enter the turbine. In some cases, there is evidence of damages in the strainer and entry into the turbine due the high velocity impact of the oxide scales, leading to a significant level of erosion damages. Solid particle erosion (SPE) can be readily observed when the turbine is opened for inspection. The edges of the turbine blades show scouring pattern. High-pressure end of the turbine where linear velocities are highest is more vulnerable. Exfoliation occurs when the oxide thickness exceeds a critical thickness and depends on material, temperature, and time.[15] The greatest temperature change occurs when the boiler is taken off line.

Figure 19: Damaged Strainer (MS Line)

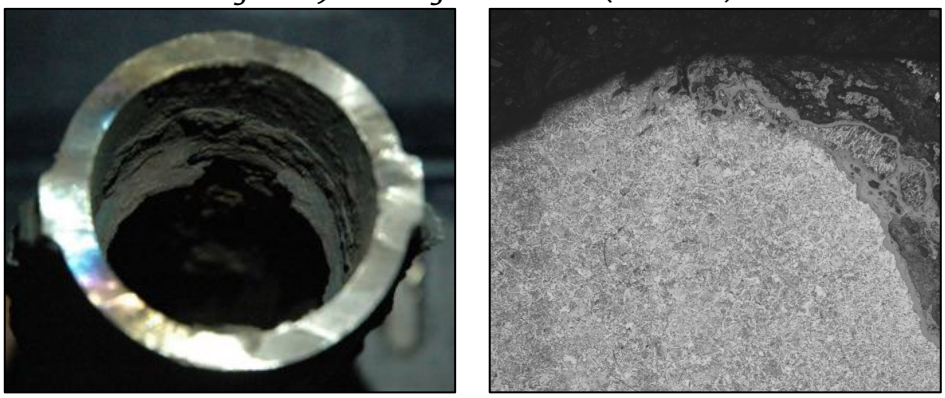


Figure 20: Severe oxide scale deposits in boiler tubes which can be carried over to turbine

[15] *Rogers Dave, Hilleman D, Intertek Engineering consulting (2018), Cycling Damage and damage or life management of steam turbine in cyclic operation, presented at USAID (RISE) workshop on Coal Based Flexible Generation Pilot, New Delhi*

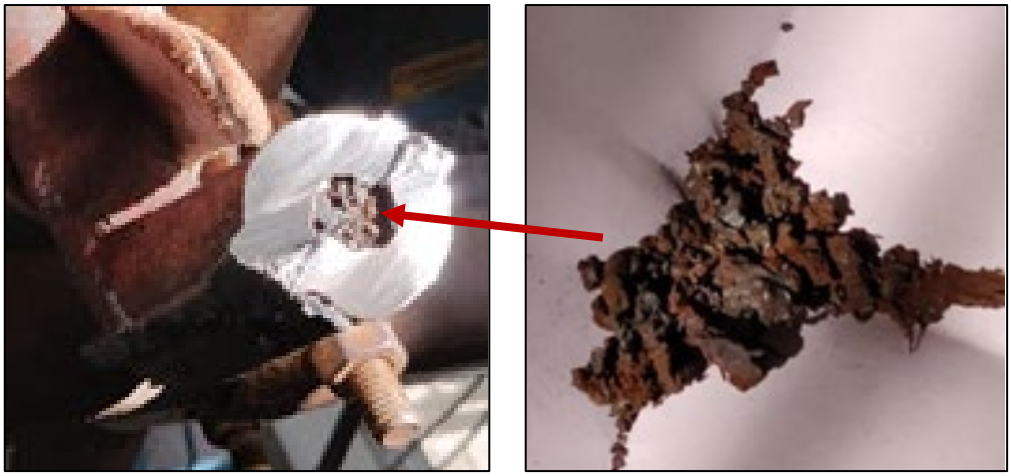


Figure 21: Blocked Tube -oxide deposits

5.4.6 LP turbine blade erosion

During low loads, the condenser back pressure can be very high, leading to high exit velocity of steam. This accelerates the erosion of the last stage of the LP turbine. Besides, LP turbines experience water impingement on the leading edges from condensed steam at low load impacts. Wet steam in the top of the condenser can be pulled back into the LP blading due to a massive flow recirculation due to turbine and condenser architecture, resulting in trailing edge damage also. Heavy or wet steam centrifugally slings to the outer diameter or rotating blade tips while low pressure voids pull the vapor back into the inner volume or area of the LP rotating blades. At low loads the cross-sectional area or volume of the LP is constant and needs to be smaller, thus resulting in recirculation and wear. Turbines are designed for full load conditions thus the volume of the LP is fixed][16].

5.4.7 Differential Expansion of Turbine Rotors and Casings

Generally, relative expansion of turbine casing and rotor does not pose a problem in flexible operation, but there have been instances in older machines which have been historically run on base load. There can be problems caused by loading or deloading rates. With rapid changes in steam temperature, the turbine rotor will cool/heat more rapidly, restricting the operating margins. There can be issues like sticking of the keyways or the pedestal, which can be resolved by proper lubrication.

[16] *Intertek, USAID Workshop presentation, 2018*

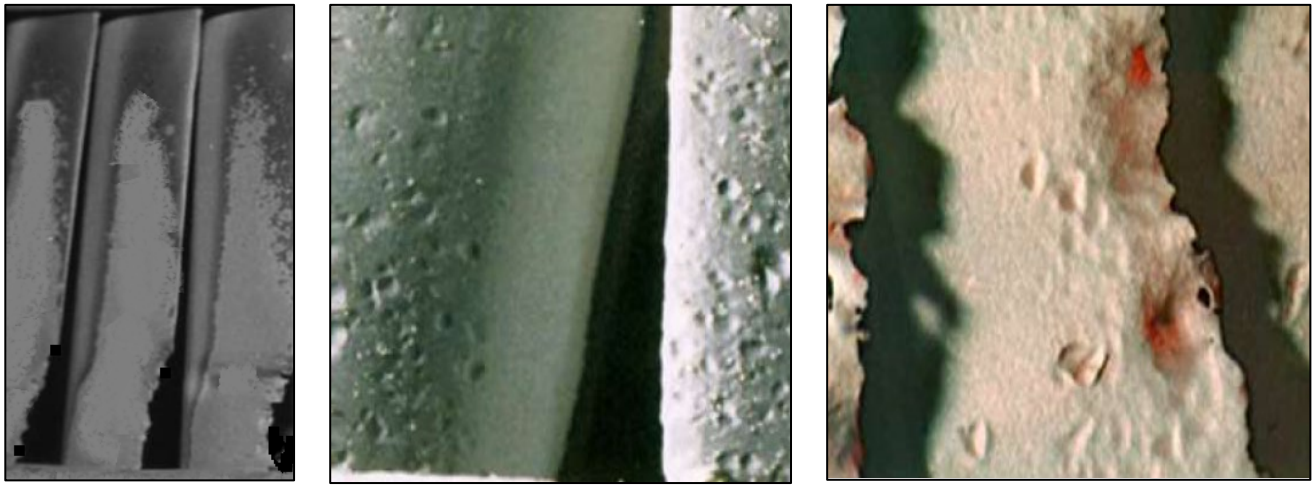


Figure-22: a. Exfoliation of turbine blades, b. Pitting, c. Damage to nozzles

5.4.8 Turbine damages and mitigating countermeasures[17]

- Manage thermal transients, including excessive ramp rates.
- Evaluate any steam turbine OEM/OED's upgrade options such as:
    - New seat contour
    - New hard facing for pressure seal head
    - Valve Stem wear detection
- Evaluate Nozzle block, initial stage of HP & IP and valve Stem Hard Facing Options
    - Limit HP steam pressure to IPC floor pressure prior to MSCVs opening
    - Once MSCVs open, then increase ST load, and place ST in IPC control at IPC floor pressure.
    - Do not ramp ST until it is in IPC control, bypass valves are closed & inlet P is steady.
- Modify start up procedures to minimize throttling
- Operate on Sliding pressure.
- Improve steam quality during startup and perform condenser dumping initial deposits to the condenser and away from ST
- Ensure operators do not exceed allowable temperatures (and ramp rates) at the SH & RH of the boiler
- Periodic inspection of high-risk areas such as LP blade root and attachments
- During maintenance outages any axial rub patterns should be noted and correlated with recent operational upsets. Cold opening clearance should be recorded. Axial clearance controls should be refurbished or replaced as necessary. Reassembled unit clearance should be established per manufactures recommendations of based on operating experience.
- Following proper transient loading procedures will reduce the likelihood of axial interference among the rotor and stationary components, control thermal fatigue damage, and sustain the thermodynamic performance of the unit.
- Adhering to proper starting, loading and unloading recommendations to minimize thermal fatigue.
- Maintaining good operating records to allow for more accurate estimates of component damage, including thermal fatigue and creep damage.

[17] *Rogers Dave, Hilleman D, Intertek Engineering consulting (2018), Cycling Damage and damage or life management of steam turbine in cyclic operation, presented at USAID (RISE) workshop on Coal Based Flexible Generation Pilot, New Delhi*

- Minimizing boiler upsets, and keeping main and reheat steam temperatures at rated conditions.
- Thorough inspection of critical rotor and casing regions during maintenance outages. While fatigue-damage (pre-crack initiation) inspection tools are not widely used, visual and magnetic particle examinations can detect early development of fatigue-creep surface cracks.
- Monitoring the lifting of blade shrouds and development of gaps in the blade root-disc attachment interface is an easy method of monitoring creep in rotors. Early detection will generally allow shallow surface cracks to be machined with little impact on component mechanical integrity.

Water Erosion related problems

- Minimize turbine operation with water sprays on.
- Ensure that direct impingement on the last stage blades does not occur.
- Ensure hood spray water chemistry is within specifications.
- Reduce the amount of water that is ingested into the turbine. Check Feed water heater non-return valves.

Solid Particle Erosion related problem

- The exfoliated iron oxide, particles originate from boiler SH, RH, Headers & main steam piping separate from the walls during boiler thermal transients. Avoid transients that are beyond allowable limits.
- Thermal transients and subsequent spalling of the oxides make their concentration significantly greater during unit startups than they do during stead-state operation.
- Heavy damage occurs to first stage nozzles, particularly to the nozzle area, associated with the first valve to open on partial arc or sequential valve units.
- The first reheat nozzles tend to erode from the suction side on the trailing edge. This is a result of particles ricocheting off the first reheat rotating blade leading edge.

Solid Particle Damage of turbine valves

- Solid particle erosion (SPE) of main stop valve components has become a larger maintenance issue as units are relegated to cycling duty.
- Steam strainers have not proven to be effective in protecting the turbine components.
- Use of harder valve materials particular satellite valve seats and discs, has reduced the rate of erosion.
- Wide spread use of harder materials has not occurred due to the need for high ductility in valve components during transient conditions and the tendency for the harder materials to exhibit brittle fracture characteristics.
- Upgrades- Example: GE digital valve package upgrade to reduce the effects of Solid particle erosion

Hood spray usage

- Units using prolonged periods of low load operation should minimize the operation with water sprays on.
- During maintenance outages, spray heads should be inspected to ensure that direct impingement on the last stage blades does not occur.

- At each inspection, the trailing edge of the last stage blades should be carefully inspected. This erosion is often the initiation site for high- or low-cycle fatigue cracking.
- Since the exhaust hood water spray source is typically taken from the condensate system, ensure that the exhaust hood spray water source chemistry is within recommended guidelines.
- Regular maintenance of non-return valves on extraction lines and feed water heaters is recommended to prevent water back up into turbine.
- All low-pressure casing drains should be inspected and cleared if plugged.

Lube oil system

- Lube oil systems should not be ignored during flexible operation as ingress of water or contaminants in the oil can be at high level to result in bearing damage. Run the oil centrifuge regularly and monitor the choking frequency of oil filters.
- Vibration is the top issue but is rather, a symptom of some other failure like blade damage or misalignment. Root cause analysis of the actual cause must be carried out.

5.5 Chemistry related damages

5.5.1 Waterside corrosion

During frequent shutdowns followed by starts, there is an increased requirement for DM (demineralized) water. With to the increased intake of DM water, there is an increased level oxygen in the boiler water and difficulty in maintaining the boiler contaminants below the normal level.

There can be various sources of oxygen ingress into feed water – starting from the DM water storage tanks, condensate storage tanks, through the vacuum system (drains, turbine parting plane) and turbine seals. Typically, Hydrazine which is dosed in feed water, cannot remove dissolved oxygen (DO) during start-up with low water temperature. High DO levels accelerate the corrosion fatigue in economisers, feed water heaters and evaporators.

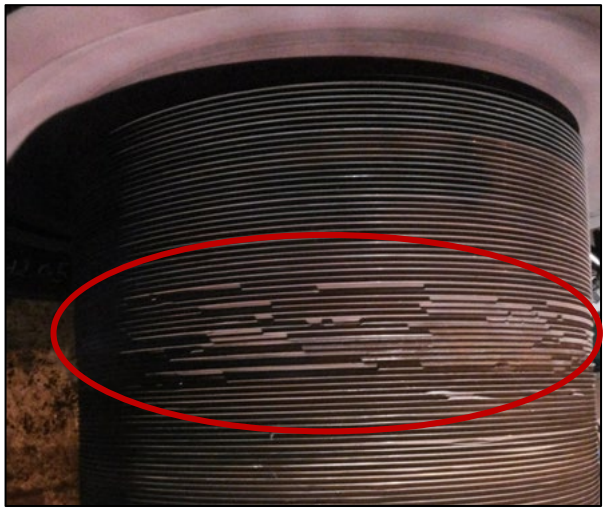


Figure 23: Damaged Turbine sealing

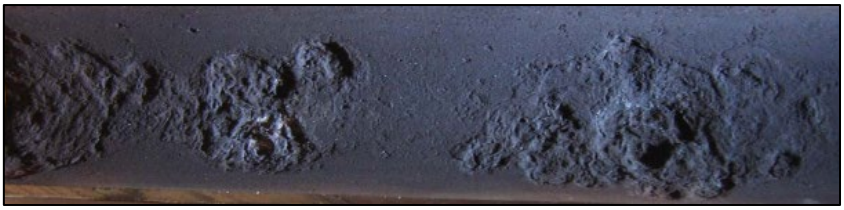


Figure 24: Water side corrosion

Another problem which increases with cycling is Flow-accelerated corrosion (FAC) - a corrosion mechanism in which protective oxide layer on a metal surface dissolves in a fast-flowing water. The underlying metal corrodes to re-create the oxide, and thus the metal loss continues. FAC is normally related to turbulence especially near fittings, e.g., elbows, orifices, valves. With the FAC conditions, the damaged surface displays a "scalloped" or "orange-peel" surface
FAC is aggravated by Water Chemistry, Temperature and oxygen levels.

The vulnerable areas include, feed water heater shells, deaerator Tank, feed rings, J-tubes, tube support plates & separator cans.

Figure 25: FAC- Economizer inlet stab joint pipes thickness is reduced

Figure 26: WW hydrogen damage

5.5.2 Fireside Corrosion-Furnace Wall, superheater and reheater

Cycling accelerates the furnace wall corrosion. During frequent starts, when the furnace wall temperature is low, proper burning of pulverized coal becomes difficult. This creates reducing conditions and triggers corrosion along with sulphidation. The furnace wall corrosion is mainly due to oxidation and sulphidation. High chlorine levels in coal lowers the ash fusion temperature and thereby increases the fireside corrosion in the superheater zone (when ash softening temperature becomes lower than the flue gas temperature entering the superheater zone).

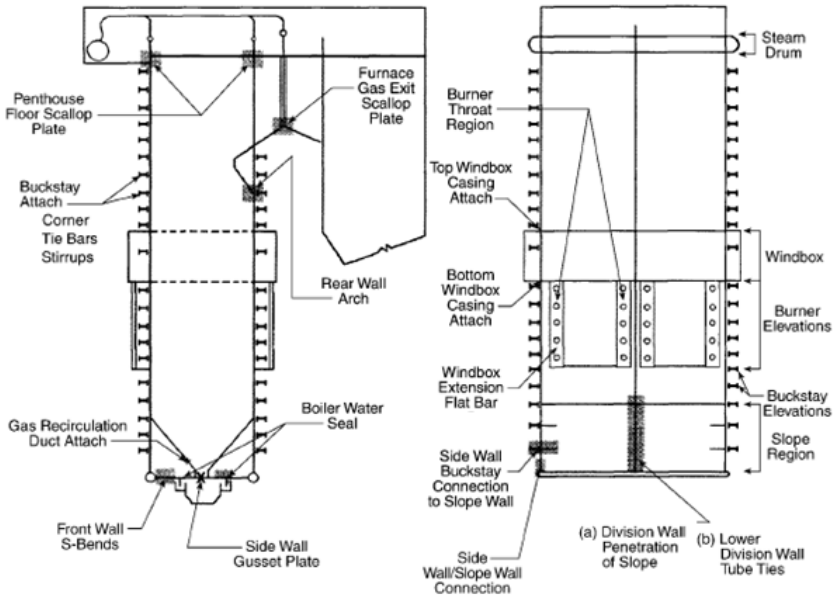


Figure 27: Typical corrosion fatigue tube failure locations (Tangentially fired Radiant Boiler) [18]

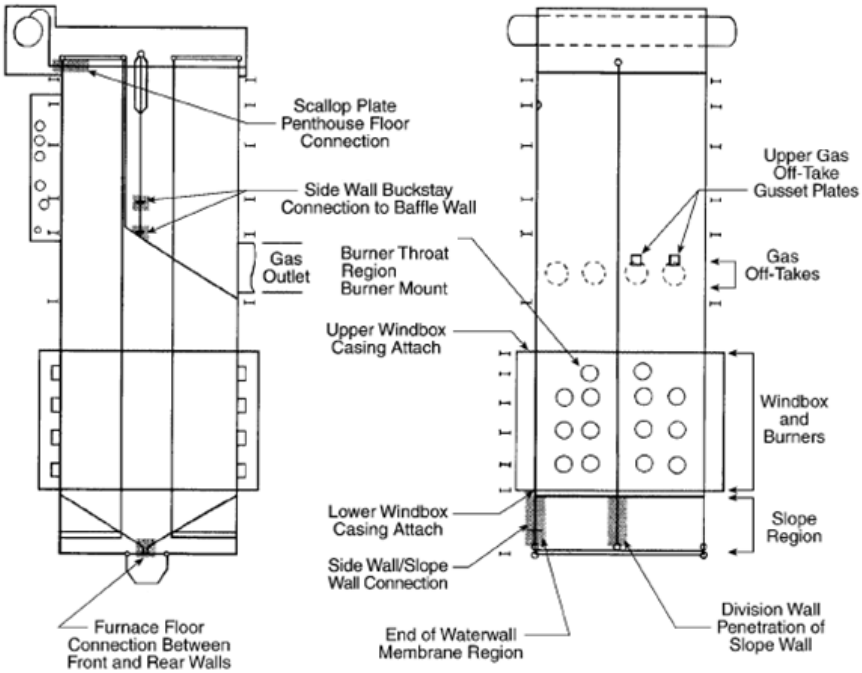


Figure 28: Typical corrosion fatigue tube failure locations (Wall-fired radiant boiler)[19]

[18] *Nikhil Kumar, Intertek-Personal communication, May 2020*
[19] *Nikhil Kumar, Intertek-Personal communication, May 2020*

5.5.3 Mitigation of Chemistry related problems

Maintain good water chemistry which assures clean steam enters the turbine, & ensure good shutdown, layup and maintenance procedures:

- Recharge condensate and makeup water demineralizers punctually and correctly to avoid sodium and chlorine contamination.
- Keep water chemistry monitoring instrumentation calibrated & functioning.
- Avoid caustic contamination of the turbine and follow OEM and other guidelines with steam purity.
- Use dehumidification or nitrogen blanketing during layup to reduce corrosion.
- Use non-contamination clean solutions on turbine components, piping, condenser and FW Heaters.
- Diligently monitor system chemistry during transients.
- During maintenance inspections pay attention to areas in the early moisture regions of the steam path where stress corrosion cracking (SCC) is most susceptible.
- Ensure that all water introduced into the boiler and turbine steam path is treated.
- Condensate water should be frequently used for attemperating sprays and exhaust hood water sprays.
- Condenser tube leaks into the hot well allow for untreated water into the condensate system. Needs diligent monitoring.

5.5.4 Air preheaters

Maintaining good performance of APH is important for enhancing the flexibility of the unit, in terms of reducing start-up time and ensuring adequate temperatures for pulverisers. Possible condensation at low temperatures during start-up could increase corrosion effects and also cause clogging because of wet deposits. During low load operation and start-up, with oil carryover, there can be issues of fire in APH.

Figure 29: Partially chocked APH baskets (removed after water washing)

Mitigation:

- APH soot blowing. Ensure adequate temperature and pressure of steam.
- Hot water washing
- Monitoring with oil carry-over probes & view glasses
- Use of SCAPH at low loads and during starts

5.5.5 Dust Removal System-ESP (Electrostatic Precipitators)/Bag filters

At low loads, there can be instances when the temperature in the ESP falls below the dew point and there is a built up of ash due the moisture, which becomes difficult to remove. Moreover, with high sulphur coal or where ammonia is dosed to control the dust emissions, there can be severe acid corrosion. There is a case where the entire ESP collapsed due to the corrosion.

Figure 30: Corroded ESP Internals

Mitigation:

- Optimise the use of ESP hopper heaters, especially during start-up and at low loads.
- Regularly inspect ESP internals & structural conditions & take corrective actions.
- Isolating one or two passes of the ESP during start-up. The ESP gas dampers must be maintained in operative condition

5.5.6 FGD (Flue gas desulphurisation)

In India, presently FGD have been installed at a very few locations. But with the stringent environment norms introduced, most of the stations will need to install FGD in the near future. During flexible operation, there can be many issues with the FGD operation, which would need precise controls and modified operation procedures. Frequent start-up can have issues of solidification of slurry and accumulation of start-up oil on the linings. Long period of shutdown will require proper lay-up and flushing of slurry in order to ensure that lime slurry does not solidify. During load variations and frequent low loads, the operation of different streams and circulating pumps need to be optimized through automated controls.

A common problem observed during low load operation is reduction of inlet flue gas temperature, which is likely to impact the reaction rates. In some of the designs regenerative heat exchangers are used but in effect there may be a substantial decrease in exit temperature which in turn will reduce the gas buoyancy and induce dew point corrosion in the duct and chimney. Some FGD units bypass FGD plants (those with flue gas by-pass system) , during start-up and low loads and charge the FGD after the temperatures stabilizes.

5.6 Other Areas: Drains, dampers, ducts, TDBFP, MDBFP, Fans, Boiler cooling water pumps

There can be issues in TDBFP pumps during load changes, when change in steam source is required (from extraction steam to CRH or Auxiliary steam). Recirculation valves of BFP can pose problems like passing. Many of the stations have a recirculation valve which is full open/close type and they pose problems during rapid load changes when the recirculation valves open with a jerk and at times causes disturbance in feed water flow.

In PA (primary Air) fans a common problem is stalling of PA fans at low load. This is common in configuration where there are two PA fans for all the mills and PA flow to mills are taken through a PA header. At low load the flow decreases, but the pressure of the PA header is required to be maintained at a particular level.

The frequency of failures in valves have seen an increase during increased cyclic operations. This is because of the wide transients in temperature.

Figure 31: PA fan blade failure due to stalling

For details of area-wise damages and mitigating operational practices refer to Annexure 2.

Review of operating procedures

Traditionally, the thermal plants have been operated on conservative base load norms, following the guidelines and safety features of the OEM (Original Equipment Manufacturer). But, due to market requirements and other factors, plants are required to operate on flexible operation with increased frequency and on regular basis.

There is a need to review the conservative operational practices and establish new set of procedures for safety, low load operation, start-ups and shutdown, chemical control and lay-up procedure.

6.1 Coal Quality and flexible operation

Many of the boilers in India are not getting coal as per original design. Stations, especially the non-pit head get supplies from multiple sources and the fuel management has to manage a complex logistic network. There is a large variation of quality amongst the different regions. At times, during scarcity, coal is procured through imports (high grade coal). Moreover, coal blending becomes very difficult with scarcity, when the stations are running with "hand to mouth" situations.

Change in coal from the design coal to a lower quality coal affects boiler operation and performance. The varying coal quality (due to multiple source) adds to the operator's woes of combustion optimisation. Further there are other problems which include:

- Boiler slagging and fouling
- Increased corrosion and erosion
- Boiler tube metal temperatures excursion
- Lower boiler efficiency
- Overloading ash handling system
- Overloading of dust removal system and increased emissions

It is important to understand, how the different constituents in coal influence the performance during flexible operation and what improvements can be made. Samples from eighteen different stations were collected and compiled below.

Table No: 5 Samples collected from Coal Stations[20]

Sample	Moist (%)	VM (%)	Ash (%)	FC (%)	HGI (No.)	GCV (Kcal/kg)
1	7.20	25.3	36.36	31.14	68.54	3795
2	6.05	25.25	29.92	38.78	59.22	4058
3	8.24	18.34	45.50	27.92	65.20	2869
4	11.45	26.06	38.92	23.57	62.50	3264
5	4.86	31.82	30.02	33.3	58.62	4623
6	6.99	27.79	35.21	30.01	76.09	3871
7	7.41	29.96	32.49	30.14	61.23	4821
8	13.28	20.54	34.46	31.72	48.69	4014
9	9.81	23.45	38.38	28.36	65.93	4268
10	12.96	22.74	46.51	17.79	57.49	2636
11	4.04	28.97	24.26	42.73	60.37	5003
12	6.08	24.01	43.85	26.06	76.65	3692
13	6.58	27.01	38.60	27.81	70.32	3962
14	2.66	22.75	53.22	21.37	57.28	3645
15	7.39	31.05	32.28	29.28	52.33	4538
16	13.60	18.71	46.97	20.72	59.22	2683
17	8.91	20.89	44.67	25.53	63.57	3066
18	4.79	22.11	41.77	31.33	62.00	3937

Table-5: Coal quality of different samples from Indian power stations

6.1.1 Moisture

Part load efficiency is an important consideration of flexible operation and moisture affects unit efficiency by impacting thermal performance. Moisture has a flame quenching tendency and absorbs latent heat. High coal moisture content will lower the coal's gross calorific value (GCV), which means that that more fuel quantity will be required to be fired for the same heat input to the unit. The increased moisture in the fuel reduces boiler efficiency. Moisture also affects the pulveriser capacity and along with increased fines in a coal adversely affects the coal handling capability. Coal moisture affects the following:

- Boiler efficiency
- Mill drying
- Tempering air requirements
- Gas velocities through the unit
- Choking in coal pipes

[20] *Data from Utilities: NTPC Plants, GSECL, KPCL, DVC, Tata Power, Bajaj Energy, WBPCL, APCL- Data obtained through Personal Communication, 2019*

- Flame stability
- Precipitator efficiency

6.1.2 Ash

In the Indian scenario, ash content in coal has caused consistent problems for the entire coal-based generation. These problems include, loss of reliability, and availability, boiler slagging, fouling, high-temperature metal wastage, cold-end corrosion, stack emissions, increased deterioration in APH performance, duct leakages, increased water consumption, maintenance costs and lower unit efficiency.
The quantity, chemical composition, and size of the ash are the variable that affect unit performance as well as the marketability of ash disposal.

- Ash quality affects the following:
- Mill wear
- Erosion
- Slagging and fouling
- Ash handling equipment
- APH performance
- SH/RH steam temperatures
- Particulate emissions
- Capacity of CHP, bunkers, mills, boiler hoppers, ESP etc.

6.1.3 Volatile Matter

The volatile matter is an index of the gaseous fuels produced upon heating of the coal as it enters the furnace, mainly hydrogen and hydrocarbons that sustain ignition. Typical range of VM is 20 to 35%, (sometimes lower). Higher VM coals generally produce less NOx and are also easier to control in the combustion system, especially in low load operation. Some of the Indian coals have VM of around 15% and stable combustion becomes extremely difficult, even at higher loads. There have been increased occasions of unit trips on flame failure (during base load operation) at stations burning low VM coal. The problem gets aggravated further when coal fineness, A/F ratio and/or distribution of A/F is non-optimal, low volatile fuel results in furnace imbalances and increased amounts of de-volatilized carbon char seeking oxygen in the upper furnace and resulting in secondary combustion.

6.1.4 Fixed Carbon

FC content is the solid combustible residue that remains after heating a coal particle and expelling the volatile matter. It is determined by subtracting the percentages of moisture, volatile matter, and ash from a coal sample.

6.1.5 Sulphur Content

Sulphur in coal determines the degree of expected corrosion in the high/low temperature regions of the boiler. The amount of SO_2 that will be produced depends on the sulphur content of the coal.

A small part (2-3%) of the sulphur in coal converts to SO_3, and the amount of SO_3 produced and retained in the flue gas determines the dew point of the flue gas and the collection efficiency of the precipitator. Besides, SO_2 emissions, Sulphur content affects APH corrosion, duct & ESP corrosion. The mineral pyritic sulphur content can mostly be removed by coal washing but the organic sulphur is difficult to remove even after washing as it is bound with other compounds.

6.1.6 Nitrogen Content

Nitrogen content (in volatile and fixed carbon) causes NOx formation. Fuel NOx ranges from 60–80% of the total NOx in pulverized coal units. The NOx formation can be reduced with staged combustion.

6.1.7 Gross calorific value (GCV)

The heat produced by combustion of unit quantity of a solid or liquid fuel when burned at constant volume in an oxygen bomb calorimeter under specified conditions, with the resulting water condensed to a liquid. There is a large variation of GCV in Indian Coal, typically varying from 2500-6000 Kcal/kg.

6.1.8 Ash fusion temperatures

Ash fusion temperatures are used to evaluate the melting and slagging behavior of coal ash .It is important to predict the tendency of different coals with high ash content to slag, and the conditions that promote the slagging conditions in a boiler While in a laboratory, the ash fusion temperatures are measured in both oxidizing and reducing atmospheres, it is more complex to determine the tendency to slag conditions in power station boilers, especially when they are dependent on many other factors.

Moreover, ash fusion temperatures can be exacerbated by reducing atmospheres that are related with penthouse or convection pass air in-leakage that is upstream of the boiler O2 probes. This can be a serious problem in Indian power stations with increased flexing and combined with high ash Indian coals.

6.1.9 Grindability

The Hard grove Grindability Index (HGI) is a measure of the relative ease with which coal can be grinded. Grindability affects pulverizer capacity. Typical HGI values lie between 30 (increased resistance to pulverisation) and 100 (more easily pulverized). OEMs rate their pulverizer capacity at 50 grindability.

6.1.10 Coal Ash Analysis

It is important to analyse the ash constituent wise to get insights. The constituents of the ash analysis, along with the total quantity, provide significant performance indications and plan the future damage mitigating measures, maintenance and inspections.

- Silica - Silica indicates the quantity of quartz in ash, it is acidic has low grindability. High silica levels increase the abrasive potential of the ash in the coal.
- Iron - Iron, mostly in pyritic form, is one of the important contributors to the slagging potential of a fuel.
- Aluminum and Titanium - Aluminum and titanium are acidic, normally in the form of clay.
- Calcium and Magnesium – As they are high in resistivity, they can adversely affect precipitator performance.
- Potassium and Sodium - Potassium and sodium, potentially cause convection pass fouling.

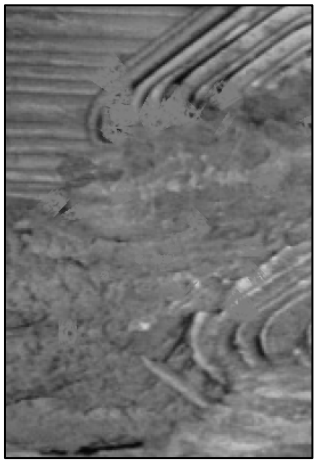
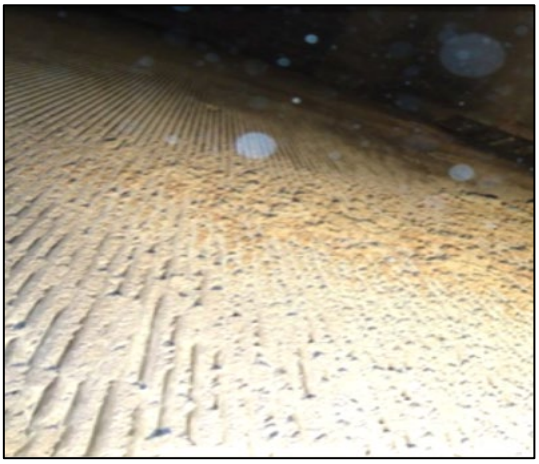


Figure-32(a): Fouling

32(b) Clinkering



32(c) Deposit on WW

6.2 Slagging and Fouling

The ash properties and ash fusion temperatures of the coal directly influences furnaces slagging and convective surfaces fouling. Controlling the slagging and fouling can be challenging for plant operators. Some parameters must be monitored, like FEGT, ash fusion temperature (based on the analysis of the coal that is fed. There are some propriety chemical additives available in the market that can be considered.

Boilers are designed to burn coal od specified quality and any changes to the specified quality will significantly impact the performance and controllability of boilers. Moreover, with flexible operation, controlling the FEGT can be challenging and steam temperatures can vary rapidly with changes in FEGT. Operating frequency of soot blowers and LRSBs must be tuned to the particular grade of coal fired with a grading of fouling indices. The Furnace Exit Gas Temperature (FEGT) must be kept bellow the Ash Softening Temperature to control slagging (Figure-34).

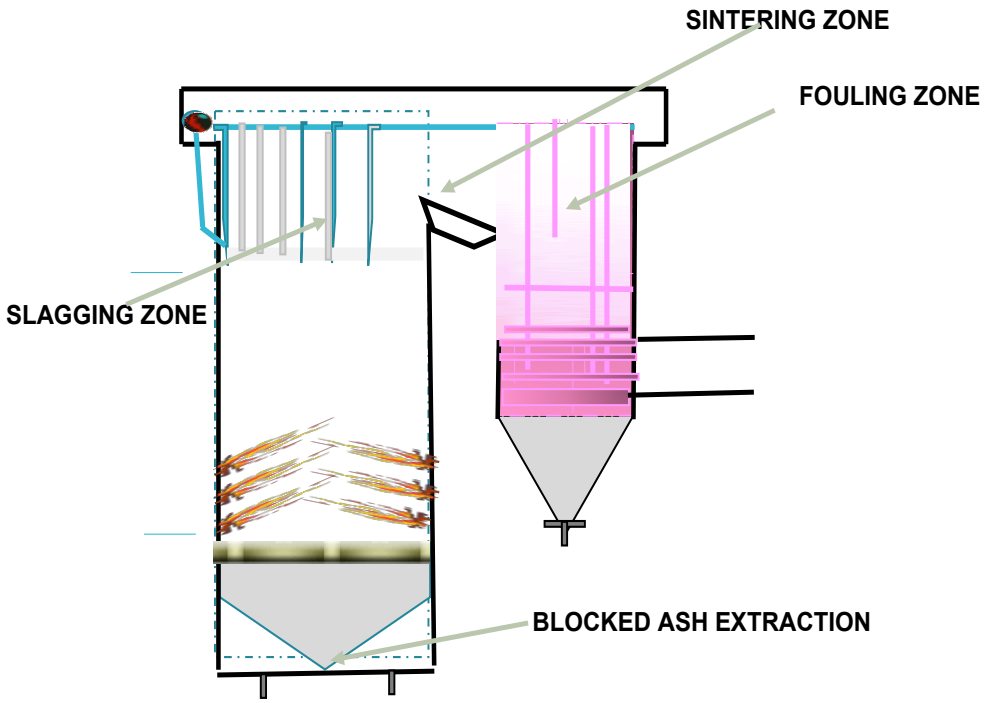


Figure: 33: Vulnerable areas of slagging and fouling

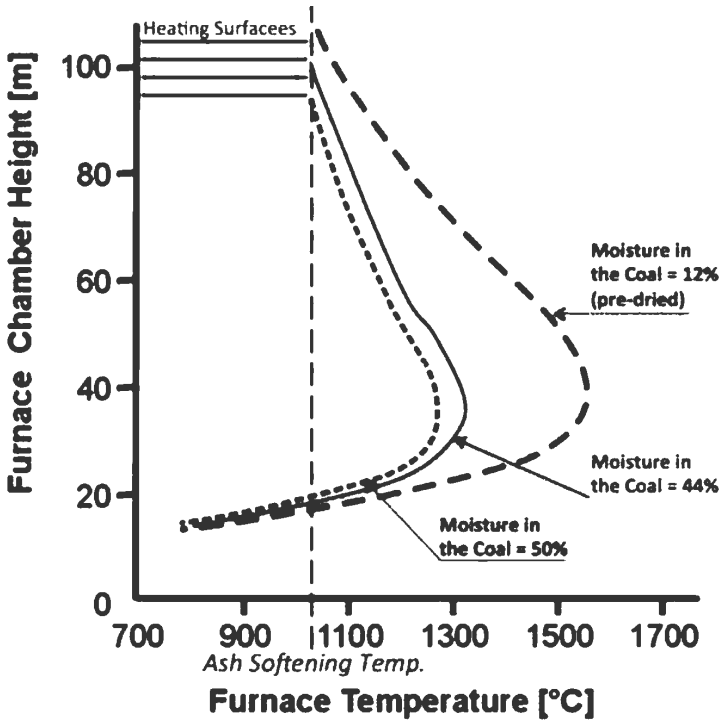


Figure-34: FEGT must be kept bellow the ash softening temp (RWE Technology International)[21]

[21] *Axel Meschgbiz, Senior Thermal Engineer, RWE Technology International GmbH, Presentation at the IGEF conference, Kolkata, 2020 on Fuel Flexibility and Fuel Change in Coal Power Plants*

6.3 Ash handing equipment

With changes to a coal sourcing (with high ash content coal) that is different from the design coal, there may be a requirement to review the operating procedure of ash handling equipment. In the extreme case, the ash handling equipment may be inadequate in capacity and may need to be upgraded.

6.4 Combustion optimisation to attain minimum load reduction potential

Reducing loads to lower minimum load depends on the ability of the operating system to sustainably reduce the heat input to the boiler, and getting back into normal operating regime by fine balancing with sufficient firing rate gradient. Combustion optimisation is necessary to maintain uniform heat distribution/ in the furnace and further ensuring proper flue gas distribution in convective path. Many factors influence combustion (as listed below), which need to be controlled for ensuring complete combustion in a purposive manner. After the combustion, the unburnt carbon in ash should be negligible and combustion must be completed at a point below the pendent superheaters zone. Optimisation of combustion is necessary for controlling NOx generation, boiler efficiency, ash quality and unit reliability.

The following parameters must be monitored for combustion optimisation:

- Balancing of Coal flow across the coal pipes
- Fuel/Air ratio, Combustion air
- Furnace exit gas temperature
- Bottom Ash & Fly Ash Unburnt
- Flue gas temperature and excess air stratification
- Excess air level/ Flue gas oxygen /CO
- Coal mill inlet/outlet temperature
- Primary Air header pressure
- Pulverized coal flow velocity /Temperature of coal pipes
- Secondary air temperature
- Windbox pressure
- Burner Tilt
- Flame scanners
- Coal fineness
- Selection of burner

For maintaining the above-mentioned parameters, it is necessary to ensure that the furnace is clean, or else soot blowers may be operated. The SADC's must be on auto operation. The airflow in the mills which are not in operation must be closed. The performance of air preheaters is also an important precursor for combustion optimisation.

The ability of the unit to change settings during frequent ramping and load change operation can be achieved with tuning/upgrade of controls. Upgrade of the existing controls is possible with minimum level of investments (details of such upgrades are given in the Annexure-1, of best practices).

However, for attempting successful optimisation, the foremost requirement is to ensure reliable, accurate and repeatable measurements in real time. This is the prerequisite for accurate control

and optimisation of air/fuel flow. As mentioned by Wiatros-Motyka M (2016)[22] all air flows in the unit must be measured and controlled in order to achieve optimum combustion at the boiler and avoid problems such as high furnace exit gas temperature, secondary combustion, overheating in the back-pass as well as slagging. However, such air streams are turbulent and stratified, hot, moist and particle laden. This makes air flow measurement a difficult task. Besides, air ducts to and from different mills have various geometries and lengths which impact air measurement devices, especially the traditional ones, as most of them require sufficient length of straight and plain pipe to be installed. In addition, many also require field calibration and most portable devices used to calibrate these systems require a laminar flow that does not exist in most combustion airflow ducts. Moreover, many devices provide air flow measurements calculated with a constant cross-sectional area of a given air duct. However, as air ducts expand and contract under hot and pressurized air streams, their cross-section changes. Hence such measurements can have a considerable error. New, more advanced technologies for combustion air flow measurement attempt to deal with all these difficulties. Such systems range from advanced pitot tubes through electrostatic based systems to virtual and optical sensors. They are also more accurate than the old ones and designed to avoid clogging, corrosion and breaking. But all technologies have limitations and care should be taken to read product specifications for restrictions (temperature, flow, particulate, moisture, straight run and more). Importantly, low NOx burners now have a choice of individual burner measurement systems.[23]

Wiatros-Motyka M (2016) further mentions that to control the excess air, the measurement of O2 must be accompanied by CO measurement for accurate information and therefore both must be done simultaneously. Accurate monitoring of both CO and O2 concentrations in the furnace is critical as it can be useful in determining excess air and hence control of air and fuel flow to the boiler. Due to the fact that the flue gas in the convective pass is relatively 'stratified' (as individual columns emitted by each burner) localized regions of high CO and O2 can be present even in the economiser exit. Hence, it is of paramount importance to choose not only the most suitable system but also to have the sensors placed at multi-point representative locations so that accurate reading and consequent flow optimisation can take place. Although, O2 measurement is a useful tool in accessing excess oxygen and it is used to trim the excess oxygen set-point and adjust the air/fuel flow, it can be affected by air ingress to the boiler. Therefore, it should always be accompanied by CO monitoring, which is considered the most sensitive and accurate indicator of incomplete combustion.[24]

6.4.1 Field Test runs

Test runs that were carried out in stations for testing of units for low load operation, concluded that minimizing the number of mills in operation is required to maintain the proper air/fuel ratio and improve the combustion. It was observed during the tests that the flame stability improved considerably when s three mills were kept in service at 40% load. As per the prevalent practice in India due to uncertainty in coal quality and frequent mills tripping, operators typically keep more mills (four or more) in service even at low loads.

[22] *Wiatros-Motyka M. Optimising fuel flow in pulverised coal and biomass-fired boilers, CCC/263, IEA Clean Coal Centre, London, UK, January,2016*
[23] *Wiatros-Motyka M. see above*
[24] *Wiatros-Motyka M. see above*

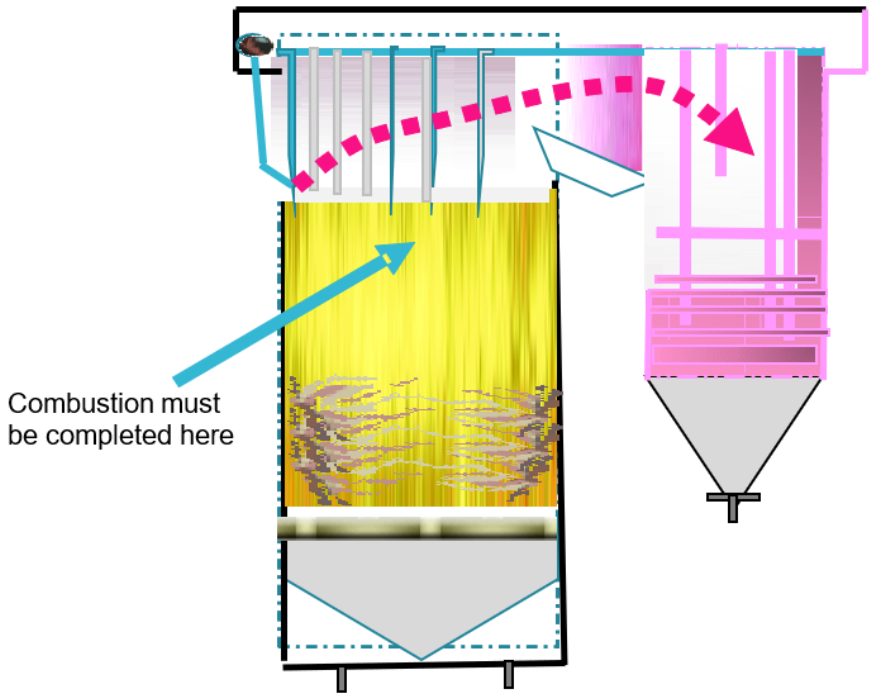


Figure-35a: Combustion zone[25]

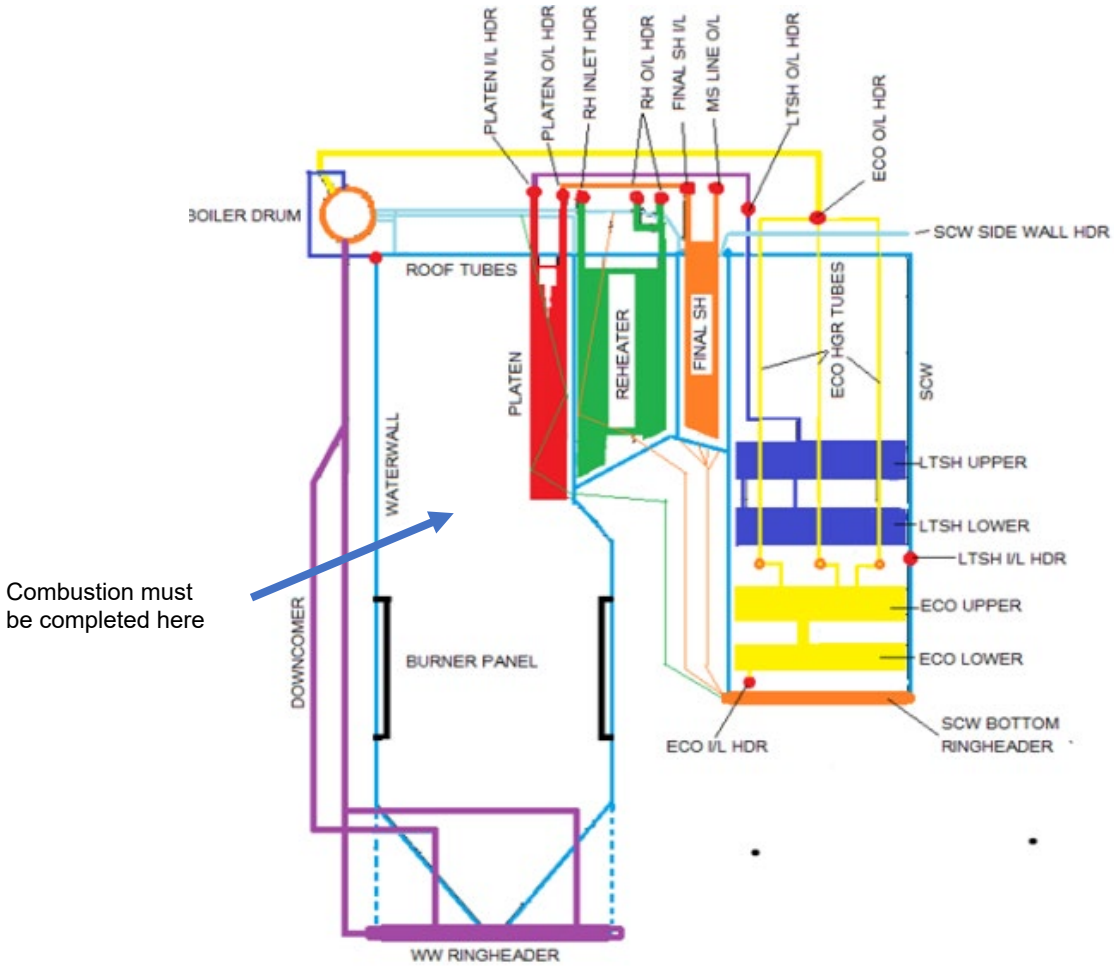


Figure-35b: Combustion zone

[25] *Stephen Storm, EPRI (2019) Low load combustion optimisation-Presentation at NTPC, Mouda*

6.3.2 Varying the number of mills in service

Coal based stations can be operated at 40 % minimum load without requirement of secondary fuel support. However, it is possible through changes to mill size and burner operating range to achieve even lower load with two mills operating.

With Indian coal, the minimum load below 40% could be challenging, unless unit combustion system is suitably upgraded/coal blending is done to achieve the necessary quality. Better instrumentation, combined with sophisticated controls can also reduce the minimum loads.

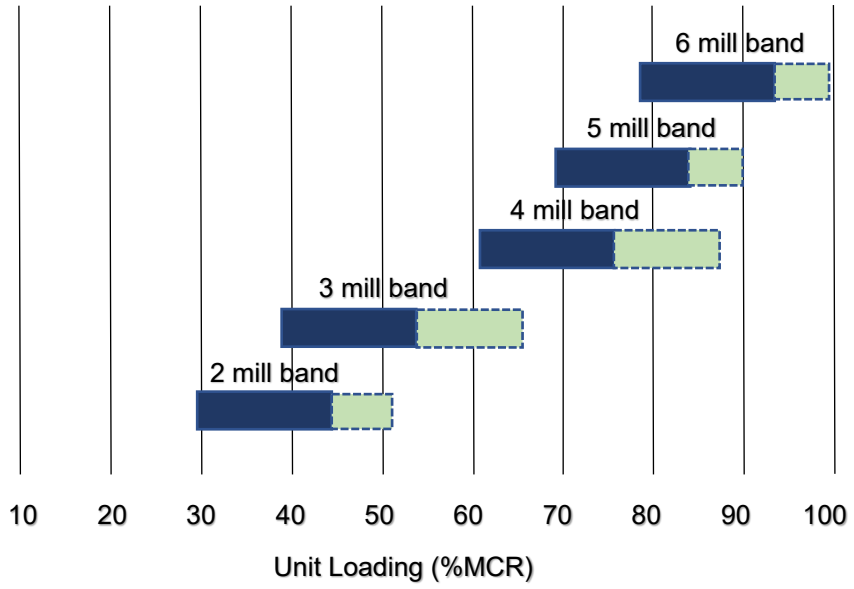


Figure-36: Mills vs load range for stable combustion

During load reduction, it is important to ensure that a minimum loading is maintained on each mill (approximately 50% mill load). There can be issues with increased wear of grinding rolls, safety and fire in mill and inability of maintaining air fuel ratio. Safe operation with down to two or three mills (depending on the coal quality) is possible. Three mills operation has been successfully proven for the Indian conditions at a number of plants (at 40% load). However, two-mill operation would set high requirements on the air damper positioning accuracy for controlling the excess air for combustion. With the XRP/MPS coal mills (widely in service in India), individual mill loading can be further reduced to 30-40%. However, the minimum mill loading (mill turndown) would be limited by the minimum grinding bed thickness required and coal/air ratio, which would depend on the coal quality (HGI, GCV, VM). For a safer side the it is better to keep mill loading at 40-50%.[26]

Operation at low coal flow can result in wear out of grind rolls due to heavy iron wear, and even more with fixed loading mechanical springs /rollers.

[26] *Intertek: Report on Pilot studies at NTPC, Ramagundam and GSECL, UKAI*

6.3.3 Approach for low load operations

Internationally, there has been plentiful experience and evidence of reduction of minimum loads down to 25% and even below but load below 55% of MCR (without oil support) was previously not attempted in the Indian conditions with the Indian coal and there were a lot of apprehensions that it may not practically be possible to achieve a stable load below 55%. The central generating stations started reducing their loads down to 55% only after a mandate from regulators in 2017, declaring the technical minimum to 55%. There is no such mandate (for 55% technical minimum) for the state utilities. Although, most of the central generating stations are operating at 55% technical minimum, many of the state utilities are still not confident of any load below 60-70%. However, there is no technical restriction in further load reduction, it is only a question of overcoming the conservative mind set.

To determine the minimum load possible in the Indian plants, feasibility studies were carried out, which were further validated with field-testing at a number of stations. These studies have presented enough evidence to convince the utilities that a minimum load of 40% of MCR is possible and can be sustained with changes in operational procedures and minimum investments in C&I systems. The approach of establishing this minimum load baseline was to decrease the load incrementally until operating problems are encountered and the limitations were identified. Modifications of procedures, control were done as the load was progressively lowered. During the field tests, some operations were done manually as per the instructions of the OEM, due to the limitations of the existing controls and protections. For regular low load operation, the utility must work towards optimizing the operation procedures to enable the unit to comfortably reach a lower load point under automatic operation where possible not compromising safety and maximizing equipment life. The details of the field tests are presented in the following chapters.

Case studies – Field tests for minimum load and ramp rate – Addressing the limitations

Three case studies of test run (Indian Power Utilities) for minimum load operation at 40 % is presented here to illustrate the issues of low load operation and ramp rate:

- Unit A: 490 MW, NTPC Dadri, Unit-6 (490 MW)
- Unit B: 500 MW, NTPC Mouda, Unit-1&2 (500 MW)
- Unit C: 500 MW: GSECL, UKAI Gujarat, Unit-6 (500 MW)

Boiler: Drum type subcritical design, Two pass boiler, Tilting tangential fired, Controlled circulation with rifled tubing, Balanced draft furnace with fusion welded water walls, Radiant reheat type.

Turbine: 3 cylinders turbine consisting of HP, IP and LP module, Single flow HP Turbine with 17 reaction stages, Double flow IP Turbine with 12 reaction stages per flow, Double flow LP Turbine, with 6 reaction stages per flow, Conventional governing system, 2-pass double flow condenser.

Generator: THDF type generator, Hydrogen cooled rotor, Water cooled stator.

Different coal samples taken during the tests:

Table-6: Coal sample analysis (field test units)

TM (%)	Ash (%)	VM (%)	FC (%)	GCV (Kcal / kg)	HGI
13.6	46.97	18.71	20.72	2683	-
8.91	44.67	20.89	25.53	3066	-
4.79	41.77	22.11	31.33	3937	62

Table-7: Coal sample analysis (field test units)

Ultimate Analysis (Air-dried Basis)			
Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulphur (%)
44.81	2.73	**1.01**	**0.65**

7.1 Common observations

- Most of the equipment and sub-group controls were in auto and the unit was running in CMC.
- Burner tilt was in manual during the field trials. [One of the key variables having significant influence on steam temperature parameter control]. In Unit A burner tilt was not operated and there was an excursion in RH temperature by 30°C. In Unit C, there was a heavy passing in the RH spray valve, but the RH temperature was maintained with the manual operation of the burner tilt.

- In Unit B, Mill firing and mill startup & shutdown was controlled manually with significant operator intervention during the field trials. [Key aspect causing sluggish/ intermediate reversals in ramp rates]. In Unit A & C fuel master was on auto, with intermediate interventions done when required, by manipulating the set points.
- In Unit B, SHO Temperature setpoint was at rated value but RHO Temperature setpoint was maintained around 555°C (rated 568°C). Both SHO & RHO temperature setpoints were being altered by operator during the tests based on MTM in SH & RH coils respectively as operators apprehended metal temperature excursions.
- The minimum load of 40% was initially achieved with three mills by gradual reduction from full load in steps of 5MW. The unit was kept at intermediate load points (75,60,50 MW) for two hours and controls were tuned. Normally, the plant operators are comfortable with an extra mill in service to take care of the exigencies of mill tripping, but in all the three units it was demonstrated that the flame stability improved by reducing the number of mills. Selection of mills (upper or lower) was based on the operator's past operating experience.
- The tests were repeated many times by increasing and decreasing the loads and finally, after tuning the controls and adjusting the set points, ramp rates of 1% and 3% were tested. The ramp rate was slower in one unit, but better controls could have improved the ramps.
- Before performing the low load tests, soot blowing was done.
- At 40% load, the flame scanners showed stable flame (comparable to full load conditions)
- Optimisation in air flow, burner tilt adjustment, mill selection/mill combination were important factors in optimisation
- Adjacent mills were kept in service
- During normal operation, Primary air flow is normally maintained higher than anticipated values as mills were operated at full mill air flow irrespective of the mill loading. Accordingly, secondary air flow is very much less than the desired level resulting in no or low windbox dP at part loads. Windbox pressure further decreased to almost zero with load reduction because of high air flow through mills and improper response of Secondary Air dampers (both Auxiliary Air Dampers & Fuel Air Dampers)
- If air in-leakage exists, at low load wind box pressure will even be more difficult to control. The WB pressure was improved by closing the secondary air dampers of the mills that were not in service and optimizing the primary air flow.
- Mill out temperatures was maintained by closing the cold air dampers
- Steam coil APH was not available in unit A & C. APH soot blowers were operated at low loads.
- Sliding pressure operation was in service. As the load was decreased, the sliding pressure had to be adjusted (increased the set point by 5kg/cm^2). The pressure in the drum was raised to avoid economiser steaming and DNB.
- In Unit C, SH spray was very high in the load range of 50-40%. This decreased substantially after adjusting the sliding pressure setting (increased by 5kg/cm^2).
- In Unit B &C, to assess the flame stability & the reliability of flame scanners at mill low load, Mills were tested for their flame condition by varying mill loading and air flow through mills up to minimum mill load, the flame scanners were able to satisfactorily sense the flame in the entire range of mill loading.
- Both PA Fans and TDBFP were kept in service for unit operation at technical minimum load. However, one set can be stopped, during continuous low load operation.
- Higher thermal transients in the SH areas were observed in Unit A & C during load ramping
- Turbine & generator vibrations were within the acceptable range during the ramp tests.
- Generator stator & rotor operating parameters were observed to be within acceptable range for the tests conducted but it may require further analysis as a few of the parameters in the primary water system were not healthy.

- The drum level was sufficiently stable during the tests. The biggest deviations occurred when switching off a boiler feed pump. These deviations, however, did not appear to cause any problems. The manual operation of the drum level control was necessary for switching off the TDBFP only. The instable TDBFP steam pressure control caused fluctuations of the feed water mass flow as well as the drum level. The implementation of the sliding pressure curve and the decrease of operational pressure to 135 bar(A) did not have any relevant negative impact on the drum level. The boiler feed pumps have recirculation valves which are full open/closed. At lower feed flow they are required to operate at intermediate positions. In all the three cases there was a jerky operation of feed water flow on opening of the recirculation valves.
- In unit C, there was a change in coal quality during the test run. Specific coal consumption (SCC) changed from 0.65 to 0.8 (SCC is arrived at by dividing the quantity of coal consumed by the number of units of electricity generated by the station, for a given period). Manual adjustments had to be done, delaying the ramping response.
- In all the cases the units were kept at 40% minimum loads for at least two hours and offline readings were taken (dirty air flow test in all the running mills), coal fineness, BA & FA unburnt, Flue gas O_2, coal analysis and temperature measurements. The analysis of results reveals that there is a good degree of imbalance in coal flow across the pipes at low load, although at higher loads, the imbalance was negligible. The imbalance is normally addressed by providing orifices in the coal pipes, which is typically done for full loading of mills. There are variable orifices available in the market, which can balance the coal flow/distribution in coal pipes during dynamic conditions of flexible operation.
- Flue gas O_2 was maintained at 5-6 % at 40% load.

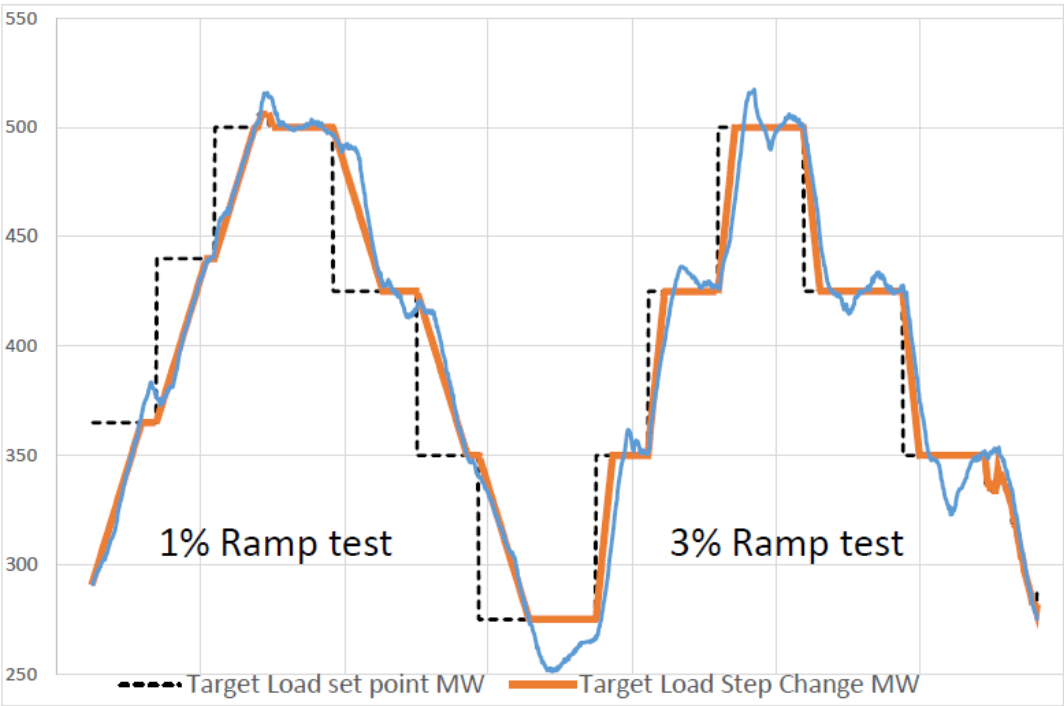


Chart-1: Ramp Test

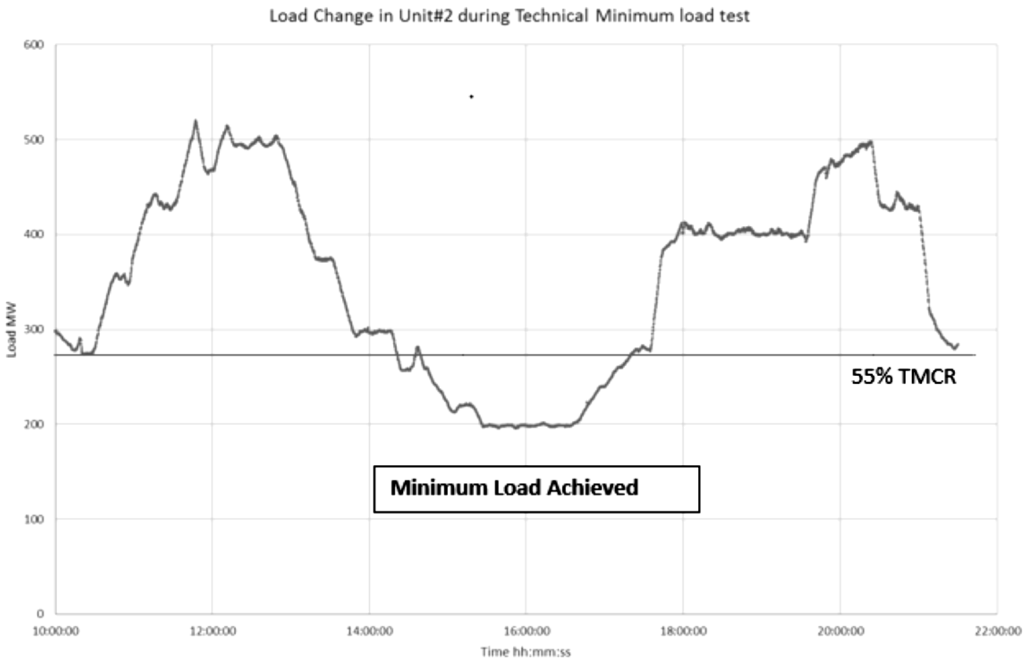


Chart-2: Low Load Test

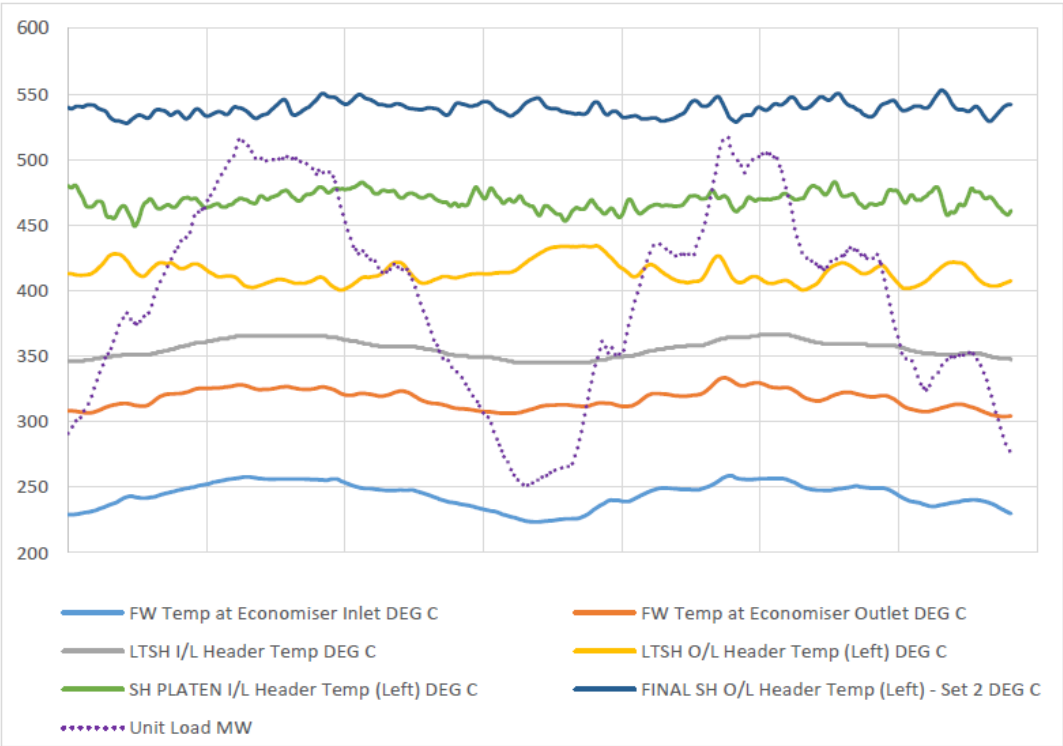


Chart-3: Parameters during test runs

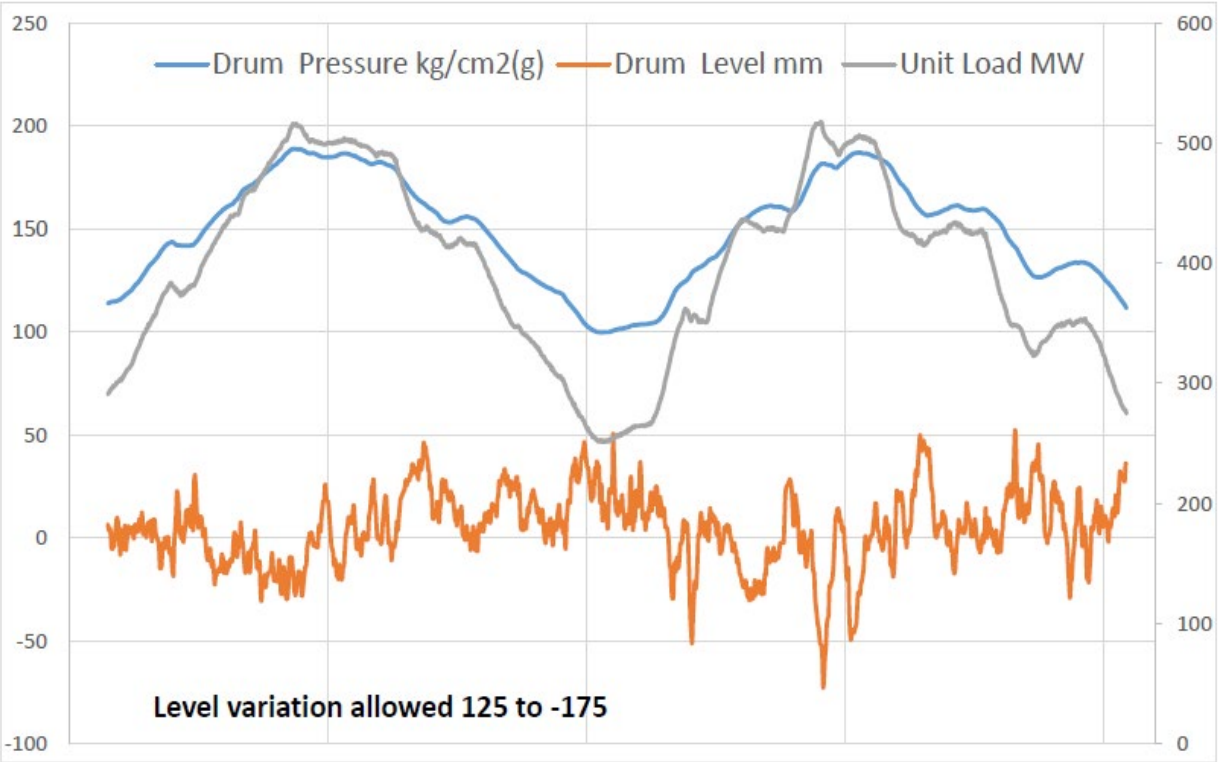


Chart-4: Parameters during test runs (Drum Level)

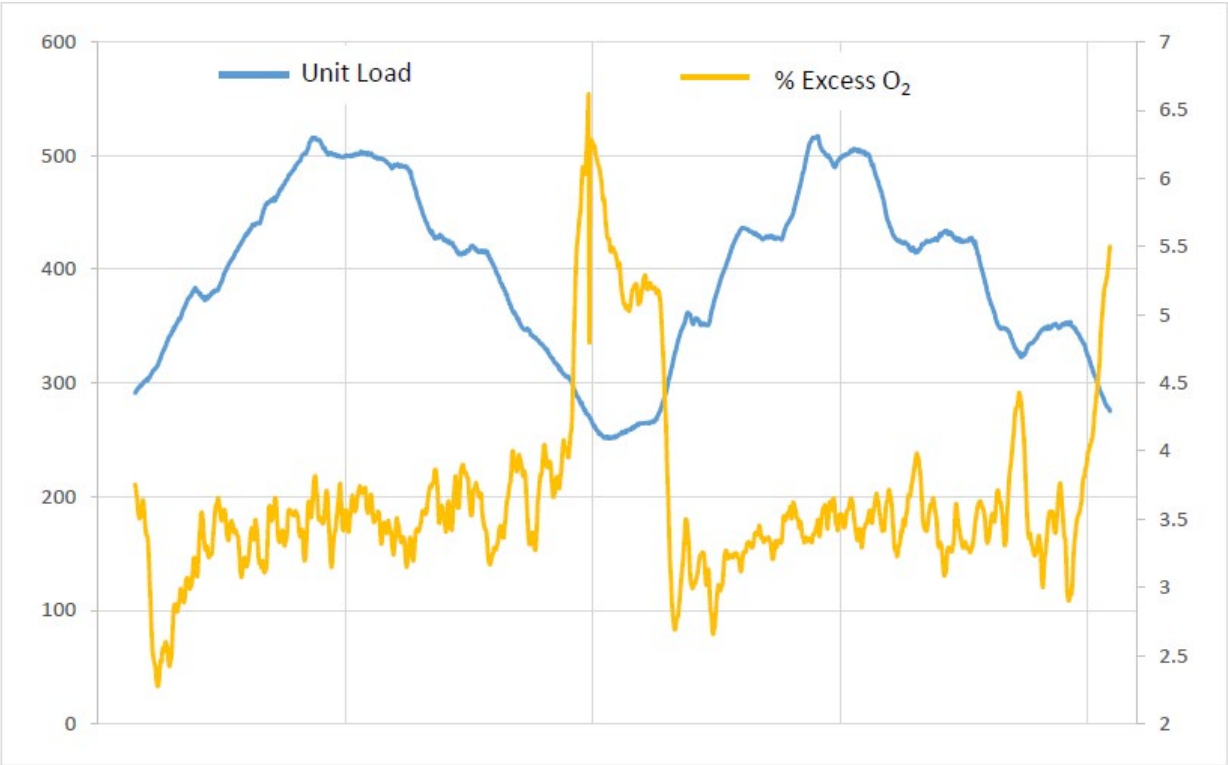


Chart-5: Parameters during test runs

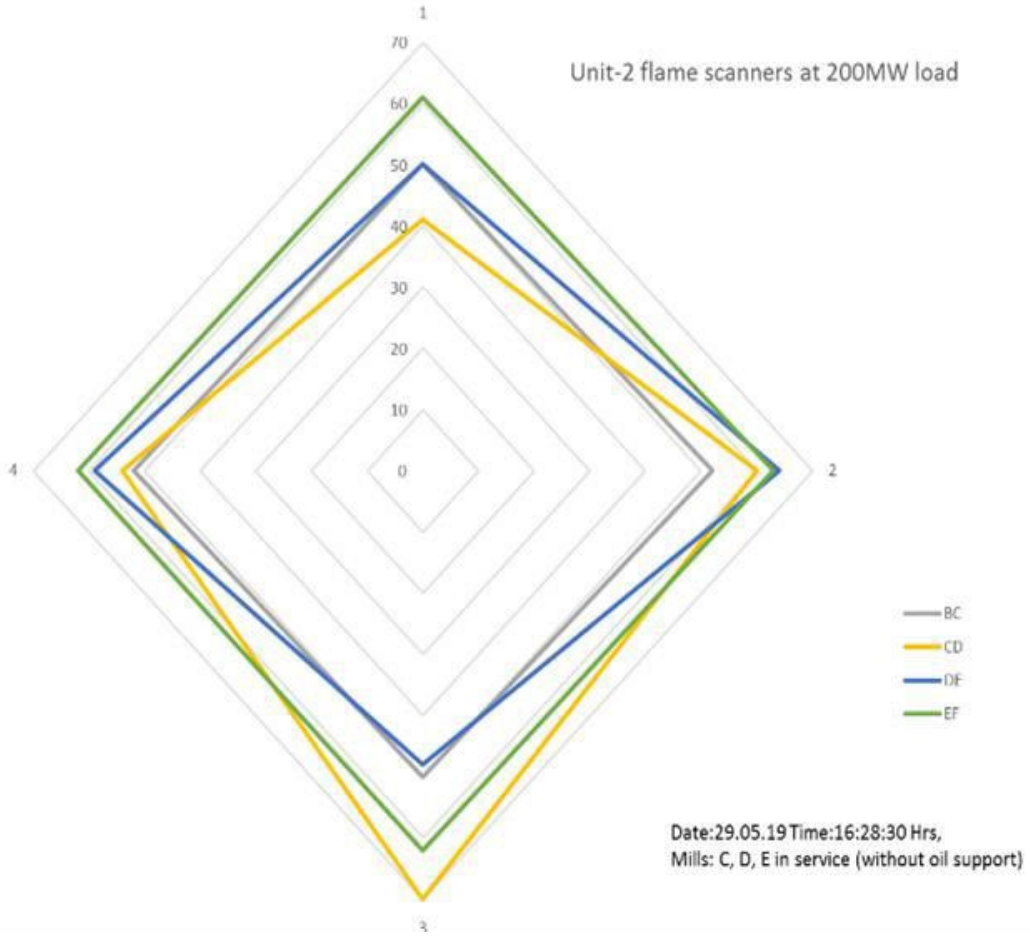


Chart-6: Flame scanner readings during test runs

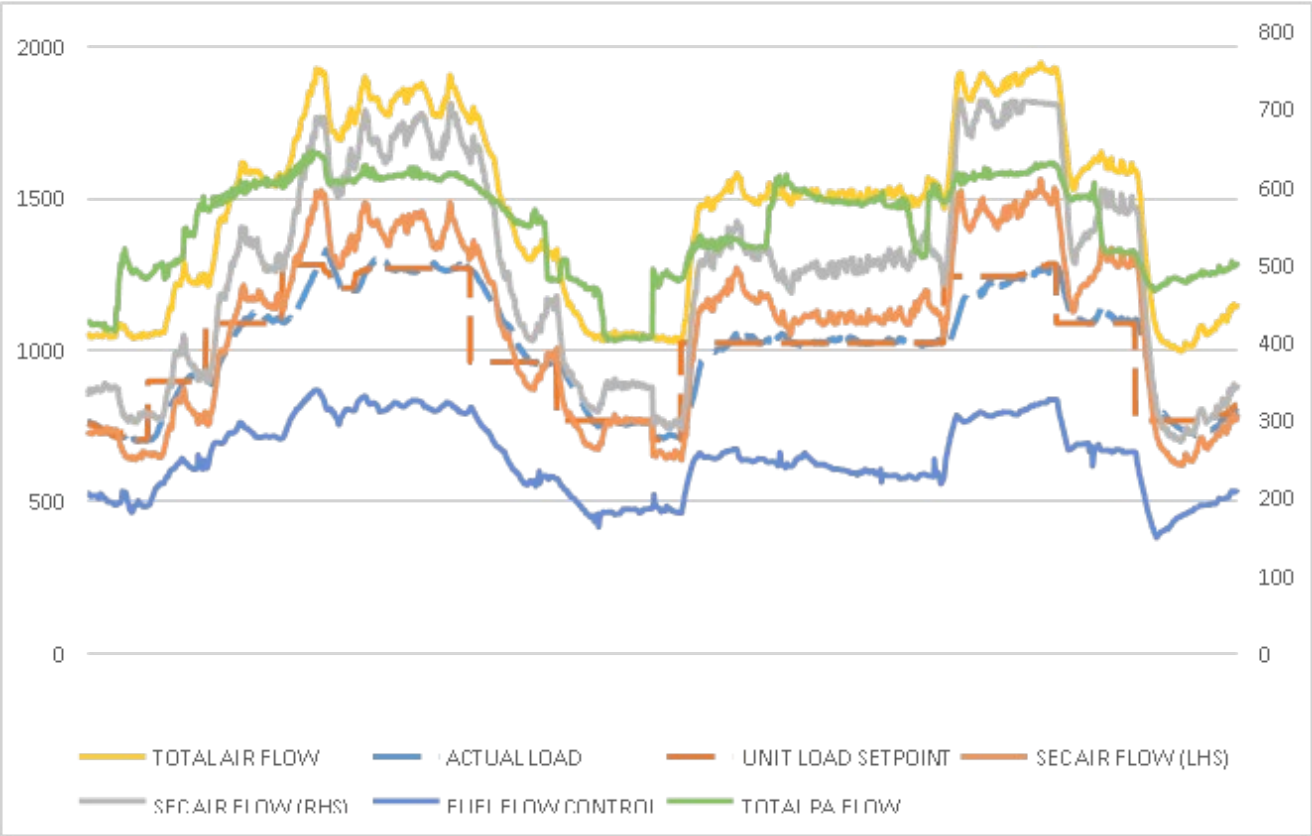


Chart-7: Parameters during test runs

7.2 Key Takeaways from the field Tests – Evolving techniques for Low Load Operations

For minimum load operation the mantra is - sustaining stable combustion by manipulating the firing rates, maintaining even temperature distribution within the different zones of the boiler, managing the coordination between the boiler and turbine. The following are the key takeaways from the field tests:

- Reducing the number of mills in service. At 40% load,3 mills were kept in service
- Optimisation of air flow. The primary air flow in mills were reduced. A review of primary air flow curve should be considered for low load.
- Optimisation of secondary air flow. Tertiary vanes of elevations that were not in service were reduced, ensuring just adequate flow for burners cooling. It was ensured that the windbox pressure did not collapse to zero. Measurement of secondary air flow was not available. This could have helped in further optimisation of the process. It is therefore recommended to make provisions for SA measurements at individual burners.
- Measurement of excess air for combustion /Flue gas O_2 measurement may be validated with CO measurement as CO is unaffected by air in-leakages. It is advisable to use both the measurements.
- Sliding pressure induces a sluggish load response for drum boilers. But the advantages are far more. Modification of sliding pressure curve (increased slightly) in small steps is to be done to ensure that there is no steaming in economizer and no DNB.
- BFP recirculation valves must be able to operate at intermediate positions (inching type). At 40 % load, one TDBFP can meet the feed water demands. The changeover of driving steam source must be ensured. Ensure readiness of MDBFP on hot standby.
- During the test runs, a number of manual interventions were made in the presence and advice of the OEM. In particular, there were issues during fast load changes and manual intervention on the firing system raising the risk of combustion instability and boiler puffs. During such operation, the safe functioning of the burner management systems must be ensured. For severe demands during regular low load and ramping operation, enhancement of controls, monitoring and diagnostic systems is worthwhile and has been recommended in all the studied carried out, including the OEM's. As per the limitations encountered during the field tests, upgrades for automatic loading control and combustion management will be required.
- The unit control system consists a number of loops and sub loops, with master controllers and coordinated by CMC. In older base load units, the C&I systems were designed to provide responsive control in the higher load range and often the C&I specs aimed at automatic operation in the range of 60% to 100% MCR. The automatic control at lower loads becomes poor and sluggish mainly due to changing unit response characteristics.
- Another limitation with low load operation is the improper sizing of many control valves for low load or low flows operation, causing poor control response and sometimes hunting of valves. All these control valves must be checked for correct operation at low load and necessary modifications be done. Replacement or placing additional valves may be necessary.
- Additionally, for cyclic operation, review and modifications will be required for the alarms and protection logic. A review and evaluation of the alarms and protections setting is required as the unit would operate at a different level from those for which these were designed to operate. Before finalizing any changes, the opinion of the OEM must be taken.

Examples include-minimum air flow, minimum mills loading, temperature setting, modification of sliding pressure curve, primary air flow curve, temperature settings etc.

- When a base load unit is converted to operate on flexible mode, the operator's view of the process (displayed on LVS or other screen) needs to be modified to include the actions that may be needed during the particular operating regime. These screens can include the important or problematic processes along with trends to facilitate the operator to react fast in case of any process deviation during the cycling operations, for example, a screen for low load operation and for start-up (cold, warm & hot) and for shutdown.

7.3 Addressing the limitations based on field test experience (as per suggestions of OEMs BHEL, GE, Siemens and other international experience)

7.3.1 Review of primary air flow curve (with the following considerations)

- The velocity in the coal pipes must be high enough to prevent settlement of coal particles in the coal pipes (not less than 20m/sec)
- The velocity at the burner nozzle must be more than the speed of flame propagation to avoid backfire within the coal pipes (not less than 15m/sec)
- The velocity at the burner nozzle should not exceed the blow-out velocity of the flame. Too high velocity will increase the flame distance from the burner, risking a flame failure.

A typical primary air flow curve is illustrated in Figure-37. In all the units it was seen that the primary air flow curve was linear from low load to full load (orange line). In order to operate the units at lower loads ,the primary air flow is to be maintained constant for coal flow range rate in the range 0-50% to remain above the settlement velocity(as shown by the blue line).This will help in stabilisation in coal transportation and flame stability during low load operation.

Units which intend to perform low load operation must test this curve on individual mills. While performing the tests, the shape of the flame needs to be monitored for verifying the flame stability. Based on the test of a mill, the curve can be replicated for other mills but if time permits, it is recommended to test on for all mills.

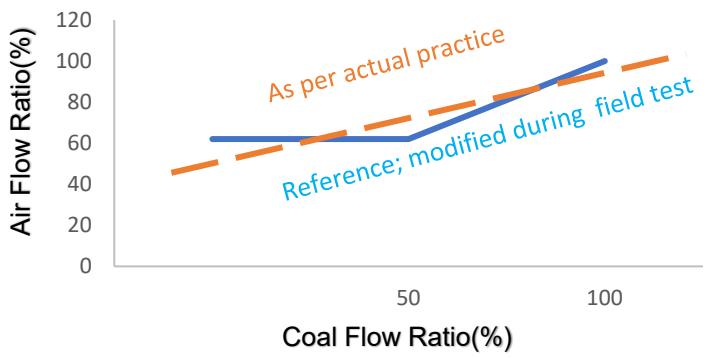


Figure-37: Primary Air Flow Curve

7.3.2 Temperature of primary Air

Mill outlet temperature is required to be optimized in order to ensure that moisture in fuel is evaporated and for proper ignition of coal at the burners. Maintaining low mill outlet temperature also poses a penalty on heat rate, besides it may lead to poor fineness and blocking of coal pipes. Very high mill temperature may cause fire in mills. The milling capacity gets deteriorated with increased moisture in coal. The limit of the mill outlet temperature will depend on where it is measured. Typically for a Raymond bowl mill, the temperatures at the exhauster outlet are usually 10° to 15°C higher than at the classifier outlet. In coal with VM below 30%, the mill outlet temperature of 75-80°C is recommended by BHEL. With higher VM, the mill outlet temperature of 55-65°C is recommended (BHEL). However, International literature suggests a temperature in the range of 70-93°C with low VM coal (15-30%) and a range of 60-80°C for higher VM coals.

Maintaining a slightly higher mill outlet temperature at low loads will help faster stabilisation of the flame. Another consideration for mill inlet temperature is the moisture in coal. A general thumb rule can be used as shown below (based on in-house experiences at NTPC):

Table 7: Mill inlet temperature at different moisture levels/GCV

Moisture in Coal (%)	Up to 6%	6-8 %	8-10%	10-15%	15-20%
Mill Inlet Temperature (Lower GCV Coal)	230°C	250°C	270°C	280°C	290°C
Mill Inlet Temperature (Higher GCV Coal)	210°C	230°C	250°C	270°C	280°C

The mill outlet temperature should be the final check point. A good best practice is to periodically evaluate mill performance, air heater "air" outlet temperatures and do heat balance evaluations to assess degradation of mill outlet temperature control and/or air heater heat transfer due to erosion and/or air in-leakage.

7.3.3 Primary air flow

Controlling the air flow is important for combustion optimisation, as too low air flow can keep coal particles suspended above the pyrite zone unless the air is supplied with a sufficient velocity to prevent coal particles from settling. However too high an air flow to a pulveriser provides an abundant source of air for combustion of ignition sources such as smouldering coal in the classifier, pulveriser or raw coal under the bowl. High primary airflow can cause poor coal fineness as well as poor fuel balance. Optimum primary airflow depends on the type of pulverizer. Primary air should typically be between 15% and 20% of the total airflow to achieve optimum combustion while maintaining a low NOx level. Optimum primary air flow depends on the type of pulveriser and as per Innovative Combustion Technologies (2007), the optimum pulveriser air/fuel flow ratios are shown in Table 8. [27]

[27] *Wiatros-Motyka M. Optimising fuel flow in pulverised coal and biomass-fired boilers, CCC/263, IEA Clean Coal Centre, London, UK, January,2016*

Table-8 Typical air/fuel ratios for different mill types [28]

Mill type	Air/coal ratio
MPS and EL	1.5 to 1.8
Raymond Bowl	1.8 to 2.0
Ball tube	1.1 to 1.3
Attrita	1.2 to 1.6

7.3.4 Coal fineness

In most of the cases, significant potential exists for improving the combustion performance of pulverized coal-based stations by improving the coal fineness. Wiatros-Motyka M (2016) mentions that the finer the coal particles, the more the coal/air mixture resembles fluid flow rather than solids in suspension. This means better homogenisation of the mixture and consequently better distribution between burner lines. But, increasing the fineness beyond a certain level decreases the mill capacity. It is therefore important to tune the pulveriser correctly so it is delivering fuel of the required fineness.[29]

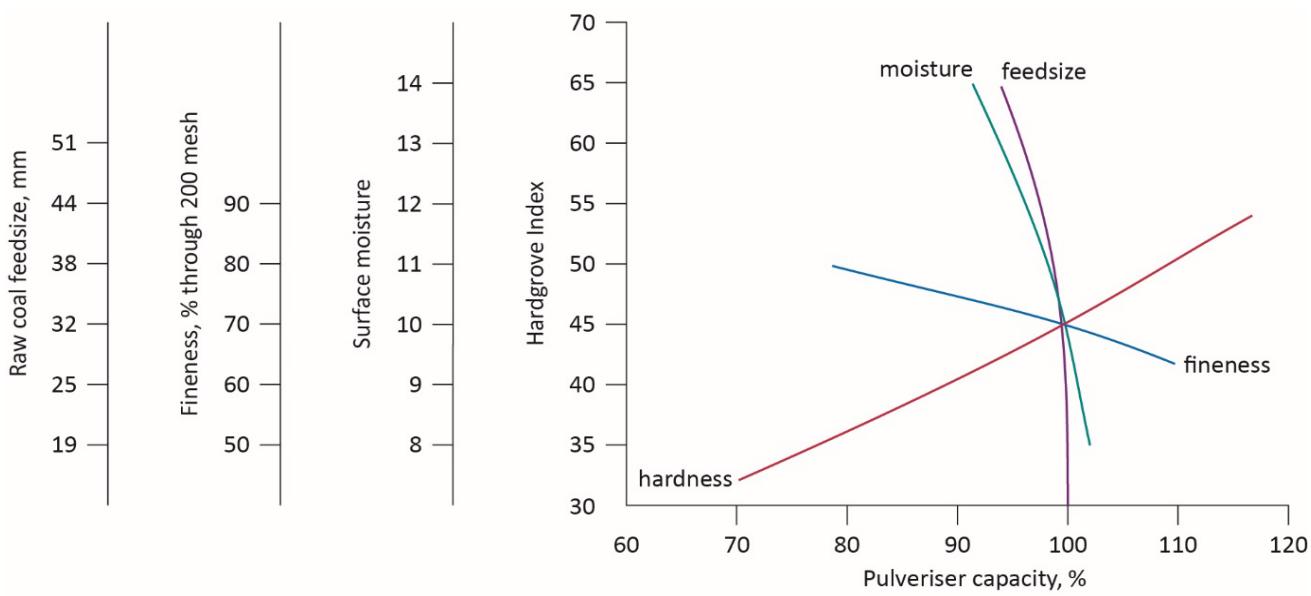


Figure 38: Pulveriser capacity changes with varying fuel properties and required fineness[30,29]

The problem with controlling the coal fineness in the Indian power stations arises with the varying coal quality, sometimes a station gets coal supplies from 10-12 different sources with wide variations in moisture and grindability and the traditional isokinetic method(offline) does not give a representative sample for the different coal used. With cycling operations, optimisation of coal fineness becomes even more difficult. In these cases, online particle size measurement solutions that allow simultaneous measurement of particle size as well as particle/air velocity and coal concentration in all coal pipes would be helpful. Some commercially available

[28] *Innovative Combustion Technologies (2007) A summary of experiences related to achieving optimum pulverizer performance and fuel line balance.*

[29] *Wiatros-Motyka M. Optimising fuel flow in pulverised coal and biomass-fired boilers, CCC/263, IEA Clean Coal Centre, London, UK, (Jan 2016)*

[30] *Storm R F (2008) Finessing fuel fineness. Power (NY); 152(10); 72-76 (Oct 2008)*

systems/equipment for online particle size measurement are show in Table 9.

The coal feed size is also important parameter which determines the mill capacity. Additionally, it has been observed in some Indian power stations, a lot of the nuisance mill trips are related to large rocks getting into the feeder and/or damaging the feeder/mills. While the unit trips on flame stability, it can be exacerbated by issues with poor temperature sensors, too large raw coal (or Rock) sizing, etc.

Table 9: Commercially available systems/equipment for online particle size measurement[31]

Examples of particle fineness measurement technologies			
Technology	**Example**	**Other measurements**	**Company**
Acoustic emission	CFM System Coal Flow monitoring system	Coal flow, differences between roping and other changes	MISTRAS
Electrostatic	Electric Charge Transfer (ECT)	Mass flow, velocity, fineness	Foster Wheeler Energy Corporation
Laser	EUcoalsizer	Coal and air flow, coal mass flow, velocity and air/fuel ratio	EUtech Scientific Engineering
	Mecontrol PSA	Coal and air velocity and mass flow	PROMECON
Manual/isokinetic	Rotoprobe	Air/coal flow	Various
White light	MillMaster®	Coal velocity	Greenbank

7.3.5 Individual Secondary air flow measurement

All the units on which field tests were performed are equipped with a common wind box. The total secondary air flow is controlled with FD fans. The air flow to each individual burner is adjusted with internal individual air dampers but the individual air flow is not known as it is not measured. The operable air registers do not have position feedback. The only parameter that the operator can control is the set point to the air register, which is inadequate to control the combustion in a cycling unit. The air flow through individual burner is also a crucial factor to control the NOx in the furnace. It is therefore recommended to

- Install an online system to monitor the air flow based on hydraulic modelling of air system, ducts, windbox, fans etc.
- Install position feedback devices on all burners.

[31] *Wiatros-Motyka M. Optimising fuel flow in pulverised coal and biomass-fired boilers, CCC/263, IEA Clean Coal Centre, London, UK, January,2016*

7.4 Retrofit Options (as suggested by OEMs after field tests and international practices)

7.4.1 Thermo-Mechanical Assessment

As observed during the field tests, the units are capable for 3%/minute load ramping for sliding pressure operation with steam temperature fluctuations restricted within ±10°C at SHO and within ±15°C at RHO. Though, the units were not tested for higher ramp rates, higher load ramping is possible at constant pressure operation. Deviation from above limitations will have an added impact on boiler life consumption.

Thus, it is strongly recommended to carry out a detailed thermo-mechanical assessment of the entire unit for capturing the current state of the equipment, their response and capability for flexible operation with a set of proposed fuel. Thermo-mechanical assessment will define the boundary conditions for a particular unit with a proposed set of fuels to define operating life of the unit under flexible operation.

7.4.2 Fine tuning of existing CMC logic

The existing CMC logic (in the field test target units) would be performing well for steady state operation in load range of 55%–100% TMCR and almost meeting the load ramping requirement at 1%/minute which is evident from the respective ramp test results. But responses of the existing CMC logic were giving higher deviation for tests conducted at 3%/minute ramp rate. These deviations in actual ramp rate achieved can be mitigated by fine tuning of existing control loops.
Further, control is required to be made capable for unit operation in CMC at low load condition of 40% TMCR which were currently not available in the tested units. The load ramping for entire new operating range from 40% TMCR to 100% TMCR also needs to be established.

7.4.3 Optimisation of existing controls

The following upgrades are required for enhancing the C&I system:

Unit Control and Automatic Mill Operation (Mill Scheduler)

The main task of the unit control is to provide set points for the steam generator and the turbine, which meet specific requirements defined by the operator or load dispatcher. The two main variables - steam pressure and unit load - have to be controlled by the slow acting boiler and the fast-acting turbine. The dynamic behavior of the plant is replicated using a simplified model of the unit dynamics, which only includes the components for boiler dynamics and steam storage.
An additional task of the unit control is to take fans, boiler feed pumps and mills automatically into operation during load ramps in order to allow smooth and uninterrupted load changes. A mill scheduler is subordinate to the unit control and switches coal mills ON / OFF automatically depending on the firing demand and the actual number of firing devices in service. The center line for the firing devices in service can be specified. This enables the boiler's firing balance point to be ascertained, e.g. depending on the start-up conditions of the boiler (cold, warm or hot start). The system also has an automatic replacement strategy should one mill not go into service or fail during service.

Main Steam Temperature Control

During the tests, the main steam temperature deviations were too large and the high values will potentially result in higher lifetime consumption of boiler parts. Therefore, the implementation of a temperature controller is necessary.

The major task of the temperature controller is to achieve stable steam temperatures so that main steam temperatures can be controlled based on a load dependent set point in all load situations. In normal load operation, set point changes occur very rarely. Disturbances have to be compensated for quickly - so as to allow the unit to be operated close to the material limit in the most critical situation.

The temperature control concept should be suitable for all boiler types, regardless of the load, fuel, type of evaporation (drum or Benson-type boiler), or pressure characteristics such as fixed or modified sliding-pressure mode. These influences are reflected in the temperature control parameters, but the basic structure is always the same.

The control structure should comprise two main parts:

- The dynamic set point calculation
- The subordinated control loop that controls the temperature based on the dynamic set point calculation

Reheat Steam Temperature Control

From a control point of view, the reheat steam temperature is very difficult to handle due to:

- its sluggish and extremely non-linear dynamic behavior
- the nonlinearities of the water/steam table
- the non-linear behavior of the attemperator injection valves
- non-measurable disturbances from the flue gas

The reheat steam temperature should be controlled using burner tilts as part of the automated control. Currently, in most of the cases, the burner tilts are operated manually and consequently reheat steam temperatures drops during low load operation. The implementation comprises further test runs to investigate the influence of the burner tilts as well as the design and integration of the logic for the automated reheat steam temperature control.

Flue Gas Temperature Control

The steam air preheater (SCAPH) should be taken into operation automatically, when needed. This control combined with the upgraded temperature control would prevent corrosion in the rotary air preheater. For plants which do not have a SCAPH it is worthwhile to install it.

On-Line Boiler Condition Monitoring

Without the installation of sophisticated instrumentation and on-line diagnostic systems, the plant personnel rely heavily on the human senses and individual experiences to identify equipment and process malfunctions. The inability to detect the faulty conditions on a timely

basis can lead to chronic performance degradation and, ultimately, equipment failure. Condition monitoring systems should monitor highly loaded boiler and piping components against creep and fatigue. Such a system monitors the temperature differences, pressure, and signals when the allowable limits during load changes have been exceeded. It will be integrated into the existing C&I system. It comprises different sub-systems that are explained below.

Possible On-Line Monitoring Techniques for monitoring Steam-Touched Tubes Under Cycling Operation[32]

Table 10: Examples of On-Line Monitoring Techniques

Failure Mechanisms	Possible On-Line Monitoring Techniques	Remarks
Long-term overheating	Tube temperature monitoring	It is the most used technique to monitor tube temperature imbalance
Short-term overheating	FEGT monitoring	FEGT can be used as a bulk flue gas temperature control indicator
Dissimilar Metal Welds	Infrared thermography(IRT) monitoring	
Stress corrosion cracking	Startup/ shutdown monitoring Outage layup monitoring	
Fireside corrosion	FEGT monitoring	This is indirect monitoring approach. However, if controls are properly localized, fly ash erosion can be reduced.
Pitting(RH loops)	Startup/shutdown monitoring Outage layup monitoring	This is an approach for which further study is required.

Boiler Fatigue Monitoring System

The Boiler Fatigue Monitoring System can determine the residual lifetime of highly stressed components by calculating the creep and low-cycle fatigue of specific components during realtime operation. These components are water and steam piping systems with limited service life, which are implemented in power plant boilers such as headers, drums, separator, attemperators, and piping. The system enables deviations to be detected online and early on, based on real time signals and active management of an operating database. The benefits are:

- Transparency in operating mode on residual life
- Detection of high-wear operating modes
- In-time notification for overhaul and inspection requisite
- Enhanced power plant safety and reliability
- Utilisation of component material reserves
- Cost-effective in-service monitoring and analysis

[32] *Nikhil Kumar, Intertek- Personal communication*

EOH (Equivalent Operating Hours)

The EOH (Equivalent Operating Hours) concept provides an overview of the life consumption of standard operating hours as well as of equivalent start up hours (ESH) that reflect load changes and actual stress on the turbine components subjected to ramp up and ramp down. The so-called equivalent start-up hours ESH are calculated from temperature differences in thick-walled turbine components arising during turbine start-ups, shut-downs and load changes with distinct steam temperature changes. Hence the ESH represent the turbine service life expenditure caused by temperature induced stresses.

Performance Monitoring System

The Performance Monitoring System helps to identify the losses and thereby to control the performance loss in lower load conditions. If it is employed with thermodynamic based calculations rather than characteristics-based systems, it eliminates the need for correction curves to be used and provides information about the actual and expected performance for the real operating conditions.

For example, at lower load the reheat temperature reduces, now for power plant there is no direct measure to compare the actual performance at 50% load and lower reheat temperature. Therefore, the use of thermodynamic modeling is useful. The flow diagram for such thermodynamic monitoring system is shown in Figure 39.

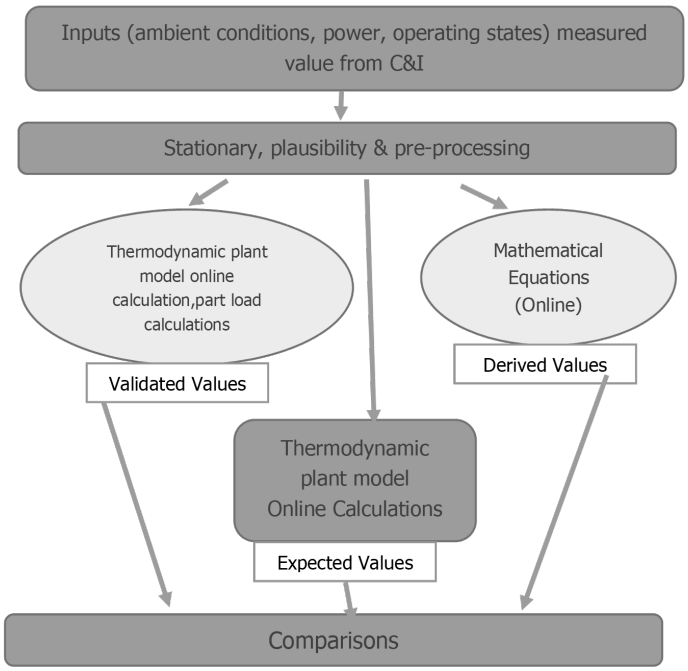


Figure 39: Flow diagram for thermodynamic monitoring system

7.4.4 Feed water recirculation valve

Based on stable operation of TDBFP (especially for TDBFP switch-on/off procedure) the feasibility of replacing the feed water recirculation valve – from ON/OFF valve – by a control valve should be investigated. This new feed water control valve should be open for base load operation. The negative impact to plant efficiency has to be investigated. This hardware change would improve the controllability of the feed water flow.

Optional measures

The following measures are not strictly required for a safe and reliable minimum load operation, but are recommended to improve the operability of the power plant in the long term.

7.4.5 Advanced unit control

Condensate throttling is a proven measure for Primary Frequency Control, enabling a quick increase in turbine power in case of a steep reduction of grid frequency. The throttled condensate reduces the condensate flow through LP heaters compared to the flow from turbine to condenser. With a certain response time, the extraction flow of the LP heaters and feed water tank are reduced. The residual surplus steam in the turbine generates additional power that is utilized to respond to the change in the frequency.
This concept already has been successfully implemented in NTPC, Dadri power plant. The response time of 20 seconds for 7% power increase at 100% load has been achieved through condensate throttling at NTPC Dadri. Further references, such as the coal-fired power plant Iskenderun in Turkey and the lignite-fired power plant Neurath in Germany demonstrate the effectiveness of the method.
The approximate cost of implementing the advanced unit control concept is INR 4 crores. Implementation would take about six to eight months.

7.4.11 Automatic plant start-up

Automatic Plant Start-up sequence is suggested for flexible operation as it will help in executing startup and shutdown cycles smoothly and will guide operator wherever an issue is faced.

7.4.12 Combustion optimisation using an online coal flow measurement

An online coal flow measurement system provides detailed information about the coal distribution between mills and the coal dust pipes, and enables combustion to be optimized by trimming the air/fuel ratio. The main benefits of such a system are:

- Imbalances occurring during minimum load operation can be detected and balanced.
- Optimized air/fuel ratio in all load conditions can be ensured at all load conditions.

Practical experience shows that a uniform coal flow distribution inside one coal dust pipe seldom arises. Thus, the system must be able to identify and compensate rope formation.

A precondition for ensuring a long-term measurement lifetime is designing the coal flow measurement in such a way that no mechanical parts extend into the inner pipe. The following figure shows a project example[33] from the Farge steam power plant (351 MW), operated by ENGIE Deutschland AG (Germany).

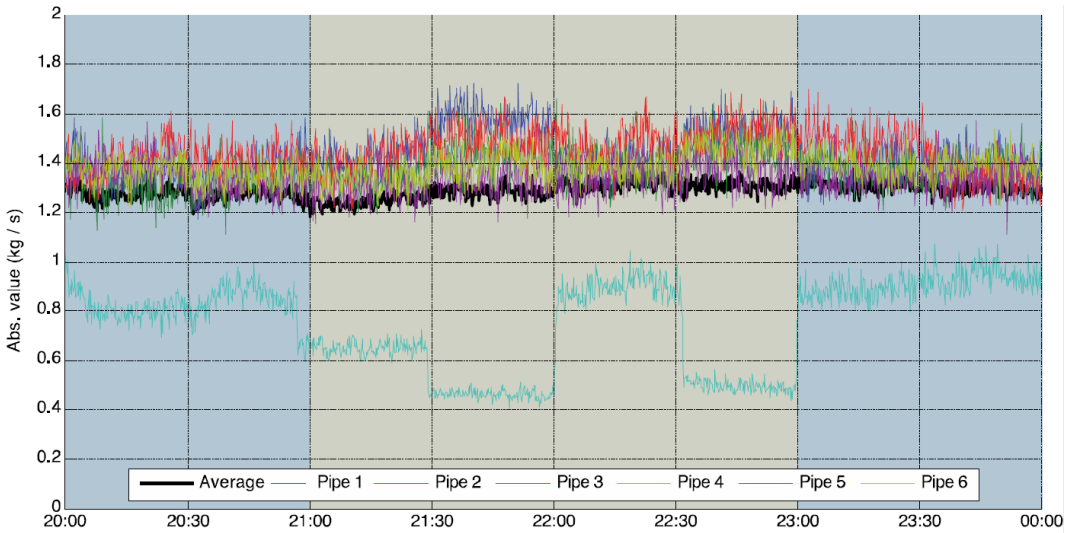


Figure-40: Coal flows (in kg/s) in different pipes at the Farge power plant

With the throttling of coal mass flow (75% valve position during 21:00 to 21:30; 50% valve position during 21:30 to 22:00; 100% valve position during 22:00 to 22:30) in pipe number four, the total coal mass flow is distributed to the remaining dust pipes with different portions.
The cost to optimize combustion by implementing an online coal flow measurement system is estimated at INT 3.6 Crores. Implementation will take four to six months.

Some stations have installed variable orifices supplied by BMW Steel, for coal balancing across different pipes while also maintaining/creating a more homogenous coal distribution in the coal/air stream of the coal pipe.[34] However, a common issue with these in the USA has been related to erosion of the variable orifice plates and/or sensors. O&M upkeep is challenging and likely to be much more challenging with Indian (high ash) coals.

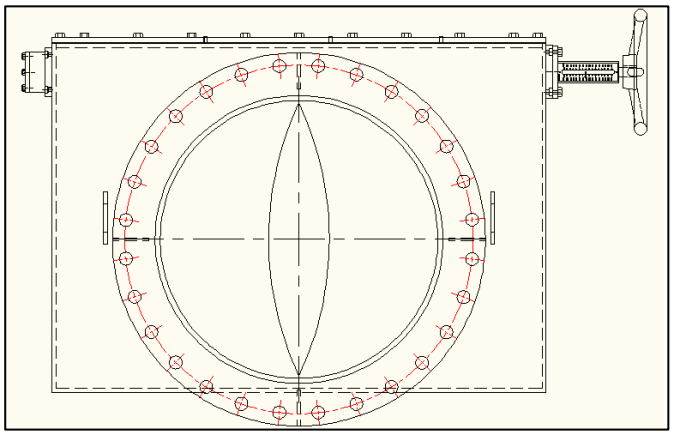


Figure-41a: Sketch of BMW Variable Orifices[35]

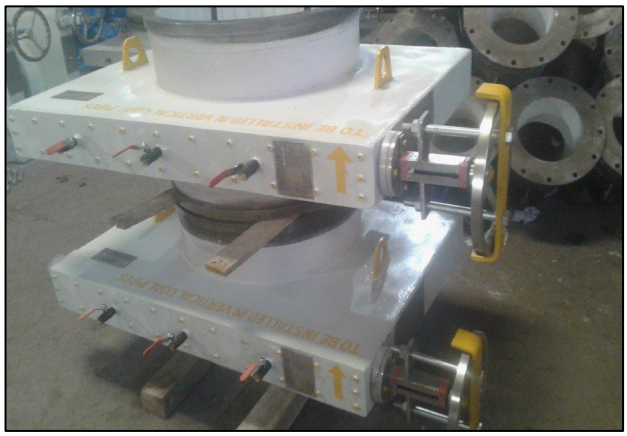


Figure-41b: Installed BMW Variable orifice

Safety during low load operation

[33] *IGEF/VGB/Siemens: Report - Case Study, Flexibility Assessment, Dadri Power Plant*
[34] *Duger Sneh, BMW Steel Ltd (2020), Personal communication*
[35] *Duger Sneh, BMW Steel Ltd (2020), Personal communication*

Personnel safety is of first and foremost priority in operation and maintenance of coal based generating unit whether it is on flexible operation or on base load. Flexibilisation of units adds to the safety risks and calls for added precautions. Sometimes serious and fatal injuries are caused by catastrophic equipment failure due to negligence and poor operation and maintenance practices.

In most of the cases, the boiler is often the most dangerous equipment, if not operated and maintained properly and in that case, it can act like a potential explosive.
Analysis of international literature and case studies/data base from utilities in India on major incidents of safety lapses was done and the main caused and preventive measures have been tabulated in Table 11.

The measures tabulated below are in compliance to the NFPA (National Fire Protection Association) guidelines. The NFPA in the Standard for the Prevention of Furnace Explosions/Implosions in Multiple Burner Boilers (NFPA 8502) establishes the minimum standards for the design, installation, operation, and maintenance of boilers and their fuel-burning, air supply, and combustion products removal systems. The requirements as per the standards for coordination of operating procedures, control systems, interlocks, and structural design must be strictly adhered to. In all the combustion control and mills, the airflow is to be maintained = or > the purge rate during all operations, as per NFPA.

Table 11: Safety during Flexible operations

Safety incidents	Causes	Preventive measures
Furnace explosion	**Fuel-rich mixtures** due to insufficient air especially during load transients.	The standards of NFPA 8502 which requires that the airflow is maintained at or above the purge rate (not less than 25% of the full load mass airflow) during all operations must never be violated. Never add air to a dark smoky furnace. It is advisable to trip the unit & remove all ignition sources, then purge thoroughly before restarting.
	Improper purge after a unit tripping can leave residual combustible mixture in a boiler, which may be sufficient to cause explosion during attempts to relight a burner.	Investigate the cause of trip and purge the furnace thoroughly before any attempt to relight.

	Passing/dripping oil guns & Poor atomisation of oil can lead to accumulation in the furnace and create a localized volatile mixture of unburned fuel and may result in an explosion.	Prevention- Maintain proper pressure of oil and steam/ air. Steam temperature & temperature in case HFO is also important. Regular inspection of oil gun tip and passing of valves.
	Coal pipes choking & accumulation of PF due to low air velocities, high moisture in coal and improper balancing of coal pipes. During furnace pressure fluctuations there can be sudden rush of large quantity of PF into the furnace when the coal pipes clear out. This fuel quantity may be sufficient for creating an explosive Fuel/Air mix.	Regular monitoring of coal pipes temperature. Thermocouples may be installed with alarms for deviation monitoring.
	Slagging /Puffing: seen during wall blowers operation especially if done after a long interval after accumulation of large quantity of clinkers. The falling big sized clinkers disturb the Bottom Ash seal trough, causing sudden air ingress through the hopper and disturbing the flame and sudden rise of furnace pressure. This can be dangerous. Sometimes there can be high levels of ash build-up due to blockage of BA hoppers with clinkers.  *Figure 42: Explosion in BA hopper*	Optimisation of soot blowing. Monitoring of furnace exit gas temperatures and analysis of coal samples for ash fusion temperature. BA hoppers deashing and monitoring for ash build-up. Detailed instructions must be prepared and made available for the O&M staff.
	Sudden Disturbance in secondary air flow. Attempts to control secondary air flow on manual mode may lead to situation of rich Fuel air mixture.	During sudden reduction in air flow, PF fuel must be reduced, preferably by cutting out mills. Never attempt to take oil guns into service during a disturbed condition. It is better to trip the unit and carry out a hot start-up after proper furnace purging.

Mill explosions	Mill Explosions: The temperature and the fuel air ratio inside the mills may be conducive for sudden combustion. This is especially common with high GCV coal. The residual coal left over inside a mill after mill a trip may lead to combustion in the mill. Besides, there are ample examples of explosions inside the coal feeders.	Ensure minimum loading of mills. All pulverizers have a limit on the minimum primary air flow to ensure that pulverized fuel does not stagnate in the pipes carrying the fuel to the boiler. This minimum air flow value coupled with the limits on the air /fuel mixture (air/fuel ratio of around 4 to 1 is not exceeded) effectively defines the minimum load of the mill Appropriate fire detection system to be maintained in running and standby mills. Proper start-up and shut-down procedures to be maintained. Mill inerting system to be always kept in service. Auto closing of hot air gate from mill outlet temp. high protection is worthwhile. Routine cleaning of feeder from inside to reduce extent of residual coal left compacted in dead spaces within the feeder. Bunker gates and mill dampers to be maintained to prevent the passage into the feeder of combustion products from fires elsewhere in the system. Feeders protection on "No Coal on Belt" to be ensured.
Furnace implosion	During sudden flame out conditions and malfunction of draft system causing a negative pressure excursion of sufficient magnitude to cause structural damage. The ID Fan is capable of producing more suction head than the boiler structure is capable of withstanding. This condition can be caused by malfunction of control system and or operational error.	Periodic checking of controls.

Fires	Bunker Fires: In cycling units there can be periods of long layups.	If the unit is taken off bar without emptying the bunkers, adequate care must be taken to prevent fire in the bunkers. Residual, compacted coal should be avoided in bunkers and bunkers should be emptied and cleaned thoroughly during overhaul of unit. Bunker gates to be maintained to ensure that they close properly when bunker is not in use.
	Fire in Air Preheaters: During startup, when the furnace is cold, there is a tendency of oil carryover and stick on the APH baskets surface. Sometimes the accumulation can be large enough to catch fire.	Water washing of air heater. Regular Soot blowing of air heaters. Oil to be burnt with maximum attainable efficiency in the furnace by appropriate cleaning & adjustment of burners, to minimize the quantity of unburnt particles, elimination of tramp air and consequent chilling of the flame and by ensuring that combustion chambers are gas tight. Air heaters can be put under observation during light up with the help of digital camera. Fire detection system which has been found to be more reliable to be kept in service for monitoring air heater temperatures. Burner flushing to be done and testing for their sprayer leakage and atomisation to be done.
Interruption of Feed water/ Water starvation	Possible causes: Control valve failure Feedwater pump failure Drum level controller failure Drum level controller inadvertently left in “manual” position, Feed regulating station maloperation Malfunction of deaerator or makeup water system.	Routine checking and maintaining protocols of checklist. In case of any malfunction it is better to trip the unit instead of allowing the limits to exceed the dangerous levels.

Trip /Protective devices circuits	Disabled trip circuits - Sometimes the operators have a tendency to bypassing the switches to eliminate nuisance trips due to improperly tuned controls, safety device failure, etc. • Inoperative trip switches • Flame scanners setting • O2 probes • Alarms	This approach of temporary "jugaad" to hide the real problem should never be allowed. If it is required, it is to be done only after the approval of the head of the plant with a well-defined guidelines, precautions and duration. Trip switches should be blown regularly to test the trip devices and remove potential ash/debris buildup. Regular checking of protection devices with signed protocols must be maintained Furnace pressure switches are to be cleaned regularly Regular checking of FSSS/BMS logics with protocols. The checked records must be readily available with the operating staff. Important do's and don'ts' s must be displayed on notice boards/walls.
Others	Water hammer, High pressure steam lines burst, high energy piping, hangers and support, Water carry over into turbine	It is important to match the temperatures of steam with the piping and to ensure the healthiness of drains. Equalizing valves if available must be used for initial charging of lines. Passing of spray lines & accumulation of water in steam pipes must be given extra care.
Incidents due to untrained staff	The safety measures during flexible operation calls for additional awareness and skills compared to base load operation. Flexible operation poses a lot of risks and challenges in decision making during emergencies.	Training programme to be developed to enhance the skill set of O&M staff with increased awareness of the entire plant viz damage mechanism, risks, short term/long term implications of actions taken.

Part load efficiency

Most of the Indian subcritical coal fired units were base loaded units, and were not designed for low loads. It is understandable they were designed for maximum efficiency at full load. The operational strategies were devised for maximizing the gains in marginal contribution (gains in revenue from efficiency) at full load.

Due to various factors, including increased penetration of renewables, coal-based units are faced with regular periods of reduced demand for power and likely to be increased in the near future. It is therefore worthwhile to run units on flexible operation and to focus on the advantages of minimum load operation in terms of additional earnings and avoidance of frequent shutdown. The additional earnings will depend on how the utility maximizes it part load efficiency under a dynamic load cycling condition. The CERC (Central Electricity Regulatory Commission, India) provided a compensation for deterioration of heat rate and Auxiliary power consumption at part load (up to 55%), besides other products like Ancillary services, AGC and DSM.

The decision on which unit is to be run on minimum load and at what level is be based on a number of factors which can vary widely. These factors include unit design, age, daily loading profile and fuel costs.

The figure below gives an estimate of the deterioration of net heat rate of different designs of fossil based units.

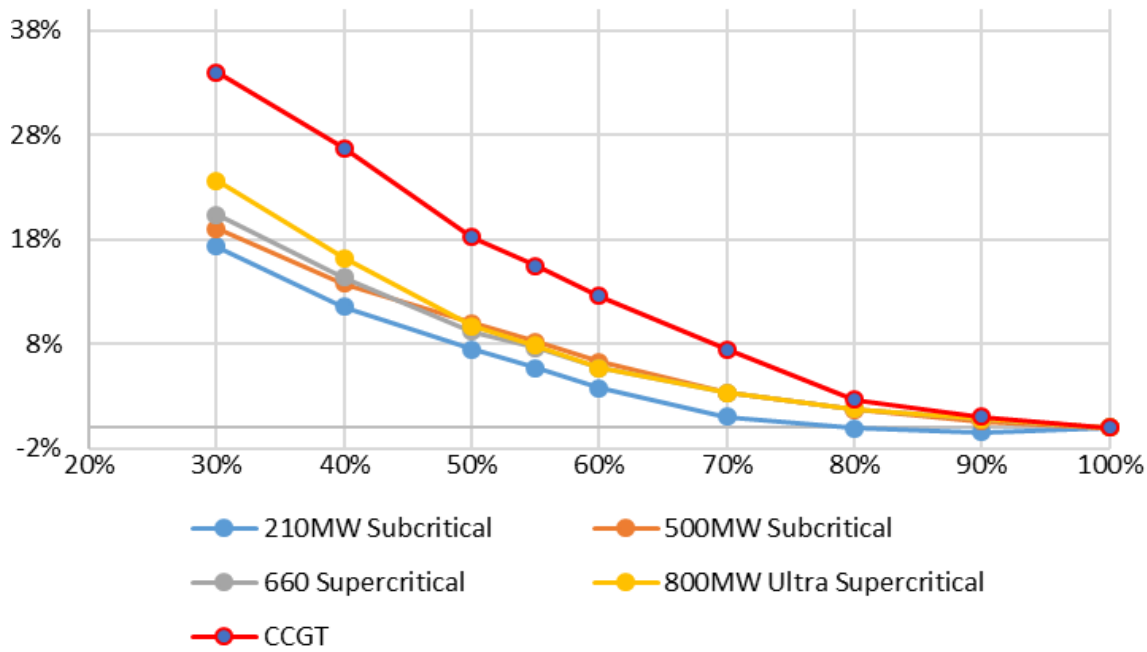


Figure-43a: NET heat rate (%) vs unit loading, Source: GE Power

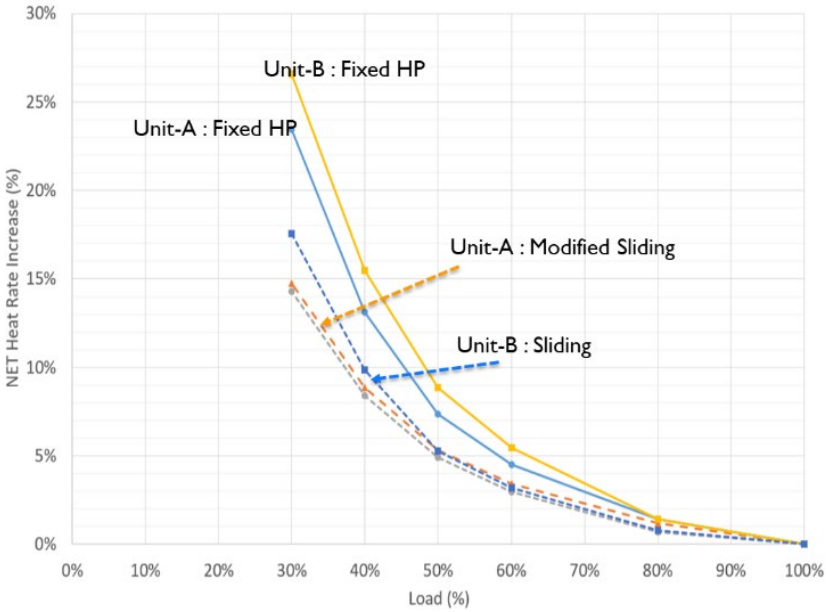


Figure-43b: NET heat rate vs Unit loading with fixed, sliding and modified sliding
Source: NTPC/ Study done by Laborelec[36]

There is a good reason to put in extra efforts in modifying the operational practices for improvement in part load efficiency. Any plant modification/retrofits for improving the efficiency at part load will have a very short payback as degradation in efficiency is the biggest cost for low operation.

In a pulverized coal unit, there would be a less significant loss in efficiency if the unit operates on variable pressure mode. It is therefore worthwhile to make provision for sliding pressure operation for improved part load efficiency. Combustion optimisation and reduced excess air, further improve the heat rate.

Similarly, during a test runs conducted at different units (500 MW coal fired of State Utilities, India), the heat rates were measured at different loads (90%,55% and 40 %) under various conditions. One of the areas, where optimisation became difficult was the air flow requirements at 40% load which contributed to the increased stack losses. Otherwise at upper load conditions, significant improvement in heat rates were observed after optimisation of air flow and operating the unit on sliding pressure. However, during varying load conditions, optimisation is difficult and can interfere with the unit's ramping capability. Upgrading the C&I systems would be necessary for achieving the desired benefits.

Various auxiliaries in water and steam cycle of the unit have been designed with 2 X 50% configuration required at 100% TMCR for ensuring reliability. For low load operations at 40% TMCR, running both set of auxiliaries may not be required and thus single stream operation may be adopted which will allow for reduction in auxiliary power consumption. VFD installation may also be explored in units which operate on low loads for long duration.

A cautions decision would be required based on cost benefit analysis between APC reduction and controls and hardware modification cost for unit reliability.

[36] *NTPC/Laborelec -Cost of cycling study done at NTPC stations*

Optimisation of start-up

When a unit is shutdown, the various components of the boiler and turbine cool at varying rates, based on their mass, insulation, and location in the boiler or turbine. In order to minimise the start-up time it is important to contain the heat and maintain uniform temperatures to avoid temperature difference during start-up. Air in leakage will cool the furnace and drum filling with cold feed water will cause temperature differentials. The headers in the boiler top will retain heat while the headers near the bottom ash hoppers will cool.

The thermal transients can be avoided by following modified operating procedures for unit shutdown, offload operation and start up. Forced cooling of unit which is done during BTL is to be totally avoided.

The modification of the operating procedures will depend on the type and, design of the unit based on the following:

- Coal quality
- Natural circulation drum/forced circulation
- Sub-critical or supercritical
- Other facilities available/local conditions
- Control System available/level of automation
- Value of flexibilisation required to be delivered by the unit/market conditions

Sliding pressure is advantageous for flexible operation as it enables steam admission into the turbine earlier during start-up, thereby ensuring uniformity of turbine temperatures. However, issues like economiser steaming, DNB and local overheating in case of disruption of flow needs to be taken care.

Drum type boilers can be controlled to maintain uniform temperature compared to once through boilers. Maintaining the drum level can be challenging due to the inherent thermal inertia.

Where HFO is used as secondary fuel, availability of steam (tracing and tank heating, and atomising) will need extra efforts compared to stations which use LDO.
Coal quality: Coal with high moisture will require drying and will in turn require adjustments in temperature, set points (or manual adjustment depending on the level of automotation) mill inlet temperatures. High grade coal (with high GCV) will require changes in the mill operating sequence like mill purging between operating intervals.

Local conditions like availability of DM water, readiness of regenerated CPU (Condensate Polishing Unit),

10.1 Review of start-up & Shutdown procedure

10.1.1 Planned shutdown

During rapid shut down of unit with high load drop within minutes due to a unit trip or forced outage, SH and RH temperatures make a steep drop that can exceed the allowable ramp rate. This activity can be prevented easily in planned shutdowns, if the load drops were less aggressive. Closer coordination with the system dispatcher for a normal shutdown may be beneficial when shutting down the unit. If a problem existed and a fast shut down was required, then the operator must do what is required for safety of equipment issues. Most well controlled shutdowns should not result in much damage to the equipment if all components are in automatic mode and these components and systems are in good working condition and tuned as designed.

10.1.2 Improved Shutdown procedure (for short duration, when hot or warm start follows the shutdown):

- Shutdown the steam turbine starting from maximum load as quick as possible avoiding to cool down to prolonged holding points at low load
- Unload the unit to roughly 50 % of MCR, preferably on sliding pressure mode and maintaining temperatures close to rated SH and RH temperatures. Then a faster unloading can be done on fixed pressure mode instead of sliding pressure while trying to keep the drum as hot as possible.
- The drum level must be maintained and if required fill the drum before the burners are turned off.
- Try to maintain the installation as hot as possible especially in a context of warm & hot starts.
- Box up the boiler. Stop all fans and try to retain maximum heat.
- Continue with pegging steam injection to keep the boiler hot, especially in a context of warm starts
- The turbine casings can be covered with heating blankets. Some power plants have electrical heating matrasses installed on steam turbine admission valves & on the steam turbine body. In addition, some pipelines are also equipped with electrical tracing arrangements.
- At low load ensure that adequate aux steam is available for sealing. Auxiliary seal steam temperature must be maintained above 290°C (for typical KWU series). Auto operation of drain valve must be ensured at lower temperatures.
- Keeping the vacuum in the condenser will benefit with start-up time reduction.

Additionally, in any unit where an extended outage follows load rejection (because of high cost of replacement power or the risk of initiating an area blackout), one of the following options should be practiced/implemented.
Use of turbine bypass system (ideally this should be 100% capacity, but in most of the Indian coal based units, 60% bypass system is installed). In drum boilers, the bypass capacity must be set to avoid boiler trips.

The capacity to trip to house load following load rejections should be developed. This requires careful system design, control tuning. And thorough training and rehearsal of operating personnel to accomplish purging and refiring while the turbine operates on stored energy from boiler.

In units where frequent system disturbances are experienced or expected, momentary or sustained fast valving should be considered as a means of maintaining system stability without the need to reject load. In conjunction with sustained fast valving, either a turbine bypass or a power-assisted pressure relief valves are needed, at least with drum boilers, if lifting of safety valves is to be avoided.[37]

10.1.3 Boiler Start-up tips

- Ensure the availability of Auxiliary steam. If other units are interconnected, ensure that proper aux. steam parameters are maintained. If required, operate the drains valves. Ensure the healthiness of oil firing system.
- Most of the starting delays during cold start-up happens due to HFO system malfunction. Either the guns are not clean or the steam /oil temperatures not adequate. Improving the oil burner reliability and stability can reduce the start-up time to a large extent and ensure a better control on temperatures. Proper atomizing steam parameters must also be ensured.
- The reliability of the flame scanners installed on the oil burners is important. The pressure fluctuations in the furnace during start-up and shut-down can cause dust/ash/soot deposits on the scanners. Regular cleaning or a purge air system is needed.
- Charge the SCAPH (Steam coil air pre heaters). Low boiler exit gas temperature when cycling or operating at low loads will increase the corrosion from operation below the wet acid dew point. It will result in reduced life in the air preheater (APH), exit duct work, and gas cleanup components.
- Ensure availability of DM water, and condensate polishing unit. Start-ups uses a great deal of demineralized water. Cleanup of condensate also facilitates reaching operating pressure without experiencing undue delays to control silica. If the equipment cannot consistently produce high purity water with a conductivity of < 0.1µS/cm and < 10 ppb silica, or if these parameters are not being continuously monitored, the condition of the boiler, and especially the turbine, could be at risk of damage.
- Startup problems with oxygen-saturated feed water in the storage tanks is a common problem. Boiler tube failures and the need for routine boiler chemical cleanings identify the need for improvements in the startup water chemistry. The issue is the off-specification chemistry events during transients. Suggested countermeasures are- to modify the tanks to a nitrogen-blanketed system. This will support a plan to minimize long-term corrosion damages for the planned cycling
- Commence the boiler light up sequentially, pull condenser vacuum-fire in a balanced pattern
- Ensure that the deaerator pegging steam is charged and maintain the chemical dosing as suggested by the shift chemist. Ensure the availability of SWAS. Open drains progressively starting with primary SH up to final SH.
- Operate Economizer recirculation if available.
- To avoid cooling of main steam pipes, delay opening of turbine drains.
- Ensure adequate flow through the reheater. Monitor the metal temperatures. During the hot start the steam turbine temperature spread between the HP steam and the RH steam temperature is high at times, which must be better controlled.

[37] *Nikhil Kumar, Intertek-Personal communication, May 2020*

- Residual oil from oil burners can be deposited on the APH elements, which can be a potential cause of fires. Operate APH soot blowers. Ensure that the steam temperature and pressure before entry into APH is adequate.
- Avoid charging ESP fields. ESP hopper heaters must be on auto or switch on manually. It is a good idea to isolate some passes of the ESP during oil firing. The gas dampers of ESP must be operable.
- After synchronisation, start taking mills into service. Ensure that the minimum air flow of 25% is not breached.
- Tip: boiler hot Filling can be done from another operating unit. It is a small modification which should be considered. This has great advantage as it will reduce the start-up time (especially during hot start-up) as well as reduce the thermal shock in the economizer inlet headers and reduce the tendency to ligament cracking in this vulnerable area. The economizer inlet temperatures and their swinging in the HS, WS, CS, and SD can cause severe thermal shocks resulting in premature failure to the economizer
- Perform a walk down check of the unit. Check boiler expansions, hangers support or other deviations.
- Boiler temperature raising - damage prevention limit:
    - Secondary superheater temperatures increase no more than 78°C/h.
    - Reheaters limit of 90 to 100 °C/hr for steam tubes or surfaces
    - Boiler tube metal temperature increase: no more than 83.3°C/h. & no more than 9.4°C/5-min period
    - Maximum differential temperature between individual furnace riser and the risers average of 44°C.
- Turbine temperature raising Limits:
    - Steam turbine metal temperature increase of no more than 28°C/h.
    - Steam turbine throttle steam temperature increase of no more than 1.6°C/min.
    - Feed Water heaters- 40°C/hr
- In units where daily or weekly shutdowns are anticipated:
    - The boiler should operate with variable pressure during turbine start-up, loading, and unloading to avoid a large temperature drop due to steam expansion through the valves and HP control stage.
    - Use HP bypass to allow raising the throttle steam temperature to 427-482°C prior to turbine acceleration.
    - A stress monitoring should be used to guide the boiler and turbine startup, loading, and unloading, thus minimizing the duration and cost of startup without exceeding the recommended stress levels for the long rotor life.

Unit lay-up

With increasing requirements for flexibility, units will operate on different modes, depending on their variable costs, and the ability to utilize market opportunities of providing different values for flexibilisation. The different modes would be:

- load following when the unit provides flexible power by stating on bar
- weekly starts/stops
- daily starts & two-shifting
- Seasonal operation-there would be some units which will be required to operate only during a few months in the year, in order to meet high seasonal demand or low generation from RE available during that particular season. There can be other reasons, like disruption of fuel supplies.

The flexible operation of these units will lead to duration of off-bar idle operation and may range from a few hours to several days or even more. Whatever is the duration of the shutdown period, a proper layup of the unit is necessary or else could seriously jeopardize the performance and availability of the unit. The components of unit corrode when exposed to air and moisture and the plant can have deteriorated performance, availability loss, increased startup time, and repeated failure after startups. Proper layup procedures can increase the useful life of the unit and the maintenance and other costs can be reduced.

As per information collected through questionnaires and site surveys for Indian power stations, it was observed that proper layup practices are very often ignored or in many cases, not deployed. Most of the stations ignore the short-term preservation, although they have a well-documented comprehensive procedure for long term preservation. Misguided neglect of short-term preservation activities ends up in damaging the machine much more as the corrosion starts rapidly at beginning of the exposure to the corrosive environment aided by a higher metal temperature. These stations need to implement proper layup practices for reducing the risk and improve their availability. Many of the failures in the boiler and boiler tubes can be attributed to poor layup practices.

11.1 Layup Techniques

The layup strategies should be based on a variety of factors. The common practice is based on the shutdown durations and the requirements of the unit to be brought back on-bar within a specified timeline. Various techniques employ wet or dry preservation or a combination of these. The specific technique may be customized for the unit based on local conditions. The following techniques or a combination of these can be customized for the station:

- Wet Layup – With chemicals maintained in feed water and condensate systems to prevent corrosion. There may a requirement for additional piping connections and when unit is required to be lighted up, draining of the water & chemicals before refilling is required.
- Wet Layup with Nitrogen Blanketing – With addition of a nitrogen gas blanket above the liquid level. provides a better method for protecting equipment than the wet only mode.
- Dry Layup with Dehumidified Air or Nitrogen Blanket – N_2 blanketing is more effective in protecting an air-tight vessel for short periods. Dry air offers the same advantages as

compared to nitrogen gas and is better where the equipment/vessel is required to be opened for frequent inspection, thus preventing the loss of costly gas.

- Shutdown with selected equipment and systems kept in operation with the existing water and chemicals if required for extremely short durations. However, for longer durations there is risk of air ingress.
- Continued Circulation with modified arrangements to allow for system circulation
- With Surface Barriers application– Paints, primers or other coatings can be used to protect most external surfaces, structures and other equipments.
- Long term Storage – Some components, spares, motors, breakers etc may require long term storage. Need to be wrapped with a protective cover and placed in dehumidified environment.

11.2 Determining the Correct Layup Technique

The practices during shut down and lay up period should be equally focused in continuation along with regular operational practices. This would be required even more during Flexibilisation of the units. The key objective of cycle chemistry is to provide protective oxide surfaces on all components throughout the steam and water circuits whereas the primary purpose of lay-up practice is to maintain those protective surfaces during offload condition. The lay-up procedure is generally categorized into two modes- the wet and dry procedures. Wet lay-up requires filling of most of the system with an alkaline reducing solution (ammonia and hydrazine) and preventing air ingress by nitrogen capping. Dry lay-up requires drainage while hot, and removal of all water followed by pressurizing with a moisture free inert gas or by use of dehumidified air to maintain a low moisture environment. The following factors are important for selecting a proper lay-up procedure:

- maintenance of protective oxides formed during operation
- compatibility between the chemistry required for lay-up and the chemical regime maintained during operation
- facilities for disposal of lay-up solution
- time, within which the unit is recalled for generation
- practicality (as per the unit configuration) of maintaining all the required conditions of a given procedure
- local atmospheric conditions
- availability of various inputs as envisaged in the lay-up procedure.

For details of lay-up procedures, a typical procedure is attached in Annexure 4. Units may customize the lay-up procedure as per their requirements and plant conditions.

ANNEXURE 1 - Best practices in flexibilisation

1. Increased ramp rate with Rapid response for frequency control

In many of the coal-fired units, meeting the primary frequency response or rapidly changing supply/demand gaps has been challenging and often due to plant design. Renewable energy generators do not provide frequency control so the fossil-fired units will be necessary for primary and secondary response in the future, as many. In India, although primary frequency response is mandatory (5% of load) many of the stations fail to comply with the requirement.

Globally, there is evidence of many coal-fired units having retrofitted one or the other means of delivering a very rapid power output changes (primary frequency response) of > 5% to 10% within a short time as well as secondary response within minutes.

Methods deployed for primary frequency control include -opening & throttling the main steam valves, condensate throttling, feed water heater bypass and HP stage bypass. Installing a thermal storage system can also increase the load range.

1.1 Condensate Throttling

The three Torrevaldaliga North 660 MW USC units (OEM: turbine- MHI Ltd, boiler- Ansaldo Caldaie S.p.A. and Babcock Hitachi Kure) commissioned in Italy (2009 - 2010) have been designed to provide primary frequency control through turbine throttling. Each unit can deliver 4% change in power within 30 seconds.

Condensate throttling is an alternative or supplementary method of providing a fast load range capability and comes down to utilizing the thermal energy stored in the feed water tank. The principle of condensate throttling is that the turbine control system opens the governor valves to utilize the reserve steam storage capacity of the boiler. When additional power is needed, the condensate flow is reduced, usually by throttling of the condensate control valve. In the current regime of renewable energy integration into the power grid, this technology provides flexibility to the thermal power plant unit. The processes of steam generation and storage are dynamically decoupled in such a way that this method allows the unit to effectively contribute to fast load changes while stabilizing steam generator and fuel control. It was retrofitted (with a low cost) in one unit at NTPC Dadri Unit 6 (490 MW), India and at Waigaoqiao No 3 plant in Shanghai, China by Siemens. Since no mechanical retrofit was carried out, this is a low cost solution. However, for new units, with enlarge storage volume, fast condensate control valve and fast control valves in LP extractions can further improve the load ramp rate and size.
Siemens has installed similar solutions at Altbach, Germany 420 MW, hard coal with proven 5% load changes in 30 s up to 100% load (with turbine & condensate throttling + partial deactivation of HP preheaters).

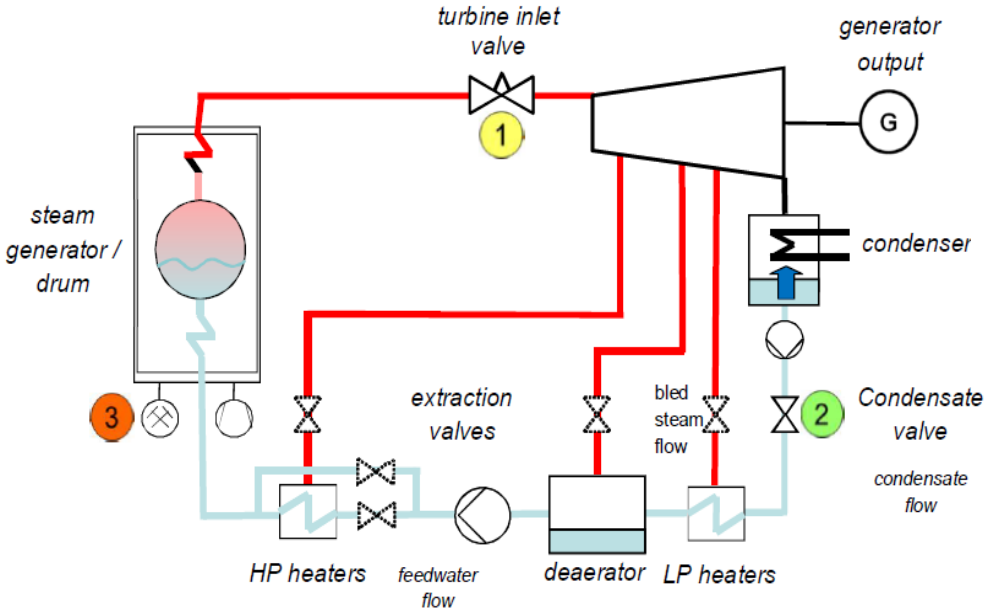


Figure-44: Overview of the water-steam cycle and the particular actuators used for condensate throttling (NTPC Dadri)

The CTS is an integral of two modules- The condensate throttling module and the Unit control module.

The Condensate Throttling Module

Condensate throttling is used for immediate (within 1 minute) generation of additional power. This additional power is normally used for frequency control.
When additional power is needed, the condensate flow is reduced, usually by throttling of the condensate control valve. With less condensate flow through the LP heaters, there is less cooling of the extraction steam within the LP heaters. There will be less condensation of extraction steam, and therefore the extraction steam flow will be reduced. The steam which was extracted from the turbine before will flow through the turbine now and will create additional power.
At the same time, the hotwell level will increase, and the deaerator level will go down. The condensate throttling has to be stopped (back to normal) before the limits of the hotwell or the deaerator have been exceeded. After some time, either the hotwell level will be high or the deaerator level will be low.

All these described functions are coordinated closely using the SPPA-P3000 condensate throttling module and the SPPA-P3000 unit control module. While the condensate throttling module takes care of the condensate flow, the affected tank levels and the fuel which is needed to carry out the recovery of these levels, the unit control module coordinates the fuel demand according to the produced pressure drop during primary frequency response as well as the increase firing rate to keep up the desired load.

With a given drop of the turbine controller, condensate throttling can be used either to reduce main steam pressure reserve by means of the turbine inlet valve and thus increase the base load range of the power plant where primary frequency control can be offered or to increase the load capability for primary frequency response while keeping the main steam pressure reserve at its original value.

The Unit Control Module

The unit control coordinates the main controllers for thermal steam generator output, electrical generator power and main steam pressure as a function of the current condition of the plant and the selected operating mode in order to ensure

- stable operation on constant load demand and
- the required dynamic behavior for normal load changes and primary and secondary control requirements.

The main control variables, electrical generator power and main steam pressure, must be controlled using the fast-acting steam turbine control valve and the slow-acting power plant boiler. Steam production in the steam generator can only follow the fast adaptation of electrical output and consequently of steam flow that is required during fast load changes with a delay due to the slow action of the steam generator. This results in an imbalance between steam extraction by the turbine and steam production by the boiler. The steam pressure drops as a consequence. The steam pressure must be stabilized by a temporary increase in the amount of fuel for this reason.

Benefits

Improved flexibility in the plant with respect to the dynamic changes in the load

- Better Steady state unit load response (+/- 1.08 MW@ 490 MW Unit load and +/- 0.59 Ksc @168 Ksc Throttle pressure).
- Unit Average load ramp rate improvement up to 3.6%/min (17.8 MW/min.) realised with retrofitting solution. This will help unit to ramp up/down quickly to meet grid requirement with better throttle pressure stability.
- Unit primary frequency response improvement by 2% realised with condensate throttling. Now unit can have 7% Primary frequency response and the same can be maintained (due to improved unit control module).

Efficiency improvement with respect to the heat rate of plant by 2.5 kcal/kWh (due to operational restriction) in Unit-6 but the potential is of 5kcal/kWh from the solution. Besides, there are other indirect benefits like reduction in Maintenance costs and improved plant reliability as the new control concepts also are helpful in unusual plant operation situations.

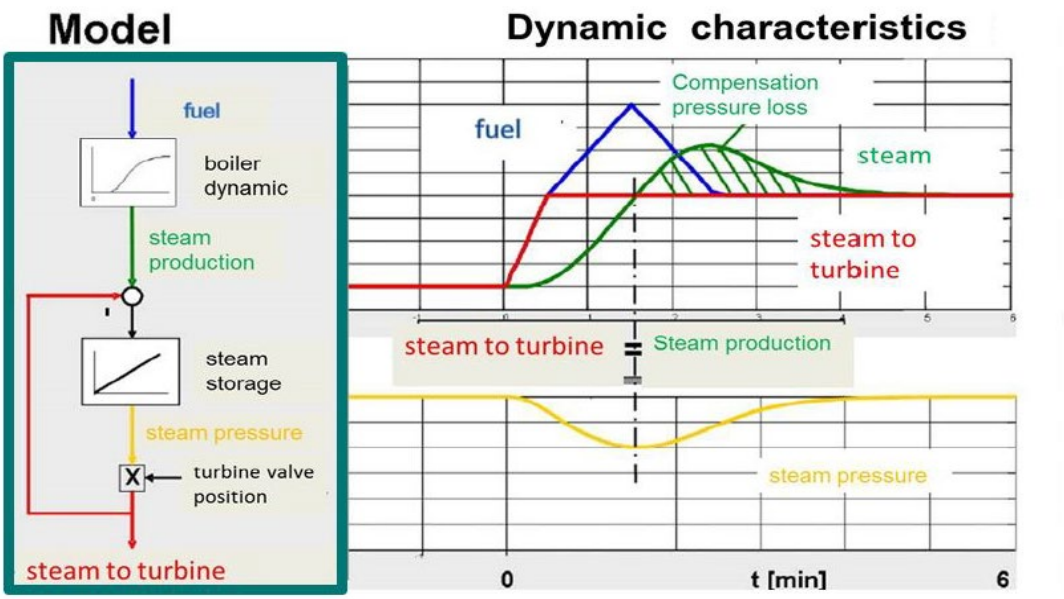


Figure-45: Dynamic characteristics of fuel demand, steam flow and steam pressure during load changes[38]

1.2 Turbine HP stage bypass for frequency control and power increase

Generally, there are many different proven and well-established methods for controlling frequency and increasing ramp rates. The condensate throttling or preheater bypass address reserve requirements within minutes while the turbine valve throttling provides increase in power within seconds. In the HP stage bypass a design modification is done in the main steam piping by routing a second main steam line onto the HP turbine allowing the stage bypass steam to enters the turbine through at least two inlet belts in the HP blade path section.

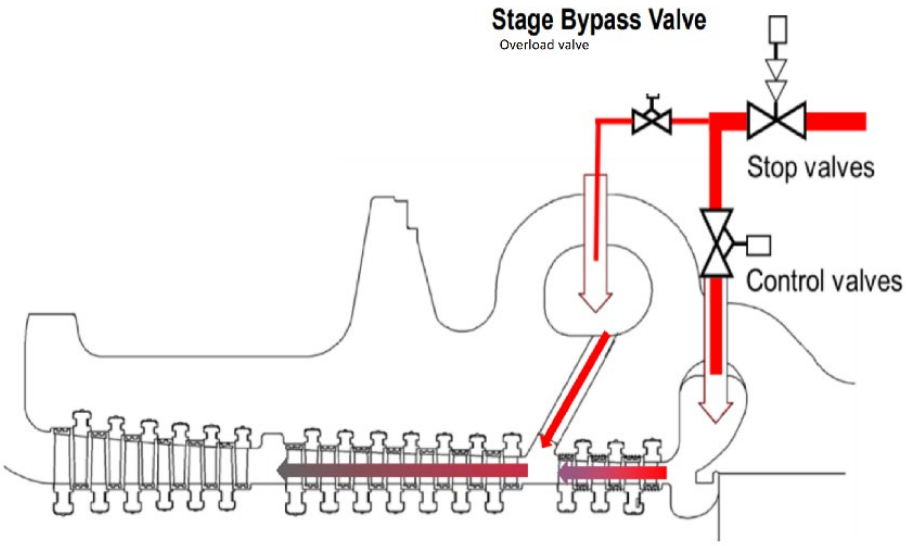


Figure-46: HP Stage bypass valve
Efficiency improvement on steam power plants at flexible load Conditions[39]

[38] *Chittora S & Rajdeva R, Siemens Limited, Presentation on Flexibilisation of thermal power plants - need of hour at CERC, (29th July 2019) & NTPC Dadri, Implementation Report on Condensate Throttling*
[39] *Efficiency Improvement on Steam Power Plants at Flexible Load Conditions, EEC Conf., New Delhi, 30. November 2018- Thorsten Strunk*

As it creates two load conditions at which there are minimal throttling losses, the HP stage bypass is the most efficient solution for rapid increase/decrease of load. The first condition-when the MS inlet valves are wide open and the stage bypass is closed & the second condition occurs with all valves wide open representing the maximum load point. Thus, the bypass governing achieves a better part load performance than throttling of all the valves at the 100% load point.[40] GE has a similar solution with primary frequency control capability of 10% in 10 seconds.

1.3 Advanced process control

Conventional controls are designed to provide responsive control under the unit's normal operating range. However, at low loads the response profiles are significantly affected due to the unit's design, valve sizing and age related degradation. There is a degradation in performance of the controls when the dynamic response of the boiler changes with time and eventually the unit's stability during flexible operation suffers. To overcome such issues, manufactures have developed solutions - For example, Siemens Energy has developed a solution (advanced process controller – APC) for controlling the main steam pressure by adjusting the fuel flow (Figure 47). APC methods allow the reduction of variances of control variables by stablising the non-stable control loops by feed-forward model-based approaches. Thus, the load will follow its set point with a very high degree of accuracy and the APC can act as a full pressure controller, and dynamic tracking of the pressure set point.

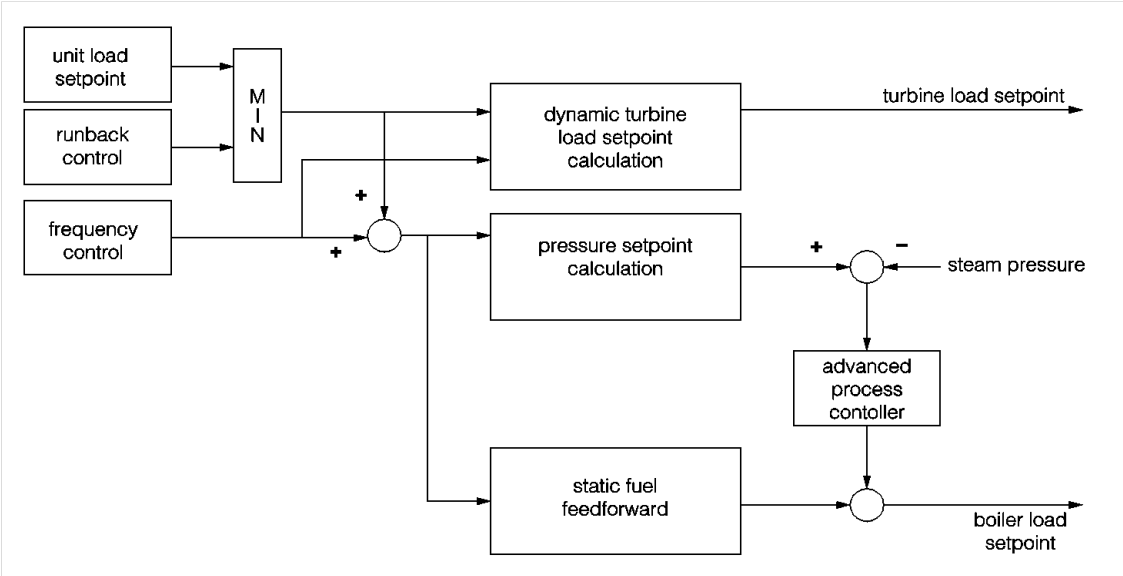


Figure-47: Unit control concept with APC, Source Siemens AG

Siemens and Emerson have installed APC at multiple units of NTPC, Simhadri, India. It is expected to improve the ramp rates, efficiency and reliability with insignificant deviations in process parameters.

[40] *USC Steam Turbine technology for maximum efficiency and operational flexibility - Dr Rainer Quinkertz , Siemens and others,2008]*

2. Combustion optimisation solutions - Burners

2.1 Plasma ignition system[41]

GE offers a state of art AC (Alternating Current) based Plasma Ignitor technology. The system produces a high energy plasma, ~50000C (Ionized gas, air, which is highly electrically conductive) which supports the volatile release and the subsequent volatile ignition of coal. The released volatiles ignite and produces further heat to further fuel de-volatilisation. Full flame formation results at the burner mouth in the furnace.

Coal Plant generators will benefit from Cold start and Low load solutions that minimize or eliminate start up fuel oil consumption. GE's Plasma Ignitor technology is aimed at providing a reliable solution to this need.

Furthermore, GE's AC technology-based offering is suitable for Indian coal application compared to DC (Direct Current) technology. The DC (Direct Current) technology were not suitable for the Indian coal.

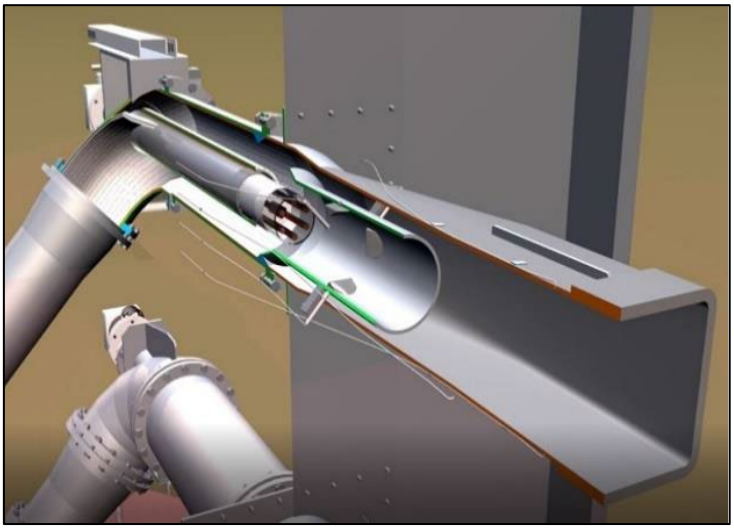


Figure-48: AC Plasma Burners, Source- GE Power

Table 12: Comparison of DC /AC based technology

DC based Plasma Ignitors	GE's AC based Plasma Ignitors
High temperature plasma (~8000 deg C). Requires lance cooling water due to very high temperature.	Medium temperature plasma (~5000 deg C) with no requirement of infrastructure like cooling water system. Simple retrofit of coal compartment at the elevation where Plasma Ignitor is to be installed.
Lower efficiency ~ 60-65%	Higher efficiency > 90%

[41] *Khende M (2019), GE Power- Plasma Ignitor Development. Personal communication, 2019*

Higher aux power consumption ~ 300 kW per ignitor	Lower aux power consumption ~ 120-150 kW per ignitor for Indian conditions
Lower electrode life ~ 400 hrs	Better electrode up to 1000 hrs and easy cost of replacement of electrodes
Limited coal and plasma arc intermixing	Improved coal and plasma arc intermixing due to multiple electrodes
Requires lance cooling air fan due to very high temperature	No additional lance cooling fans needed
Need to take unit on outage to change electrodes	Electrode replacement possible online by just taking the mill on outage.

2.2 Electric ignition

Another solution is available where, coal is ignited using a hot burner nozzle solely heated by electric energy. Significant cost saving potential by reducing / replacing the use of start-up / auxiliary fuel (depending on whether all burner levels or only specific burner levels will be equipped with electric ignition)[42].

2.3 High turndown burner tips[43]

The design of many of the early large steam generators installed in India (and other locations burning similar fuels), often used design practices based on earlier experience which were properly adjusted for the higher ash and lower CV and apparent reactivity of Indian fuels.

However, the maceral structure of these Indian coals further reduced the reactivity actually experienced leading to furnace instability at higher loads than would have been anticipated. This may not be a problem while units are operated at high loads, however unit turndown is now increasingly a requirement and flame stability with such coals poses a real challenge to achieve the same. GE has observed and developed a solution that corrected this problem on several units with challenges caused by coals similar to and from the same family found in India (similar Maceral analysis). The correction for the mechanical part is replacement of present nozzle tips with high turn down nozzle tips. These Tips can produce locally stabilized flame front when air and fuel are maintained in proportion. The same is established with individual trimming of various secondary aux. air dampers to compensate for fuel imbalances.

Overall, the re-design focuses on stabilizing the near field conditions of the burner by manipulating the entry velocity, turbulence and therefore flame stability at low load, while minimizing changes to the balance of the burner system and still maintaining the full load capability.

[42] *VGB PowerTech (2014), Leisse, A.; Rehfeldt, S. and Meyer, D.: Das Zündverhalten fester, staubförmiger Brennstoffpartikel an heißen Oberflächen.*
[43] *Khende M (2019), GE Power- Plasma Ignitor Development. Personal communication*

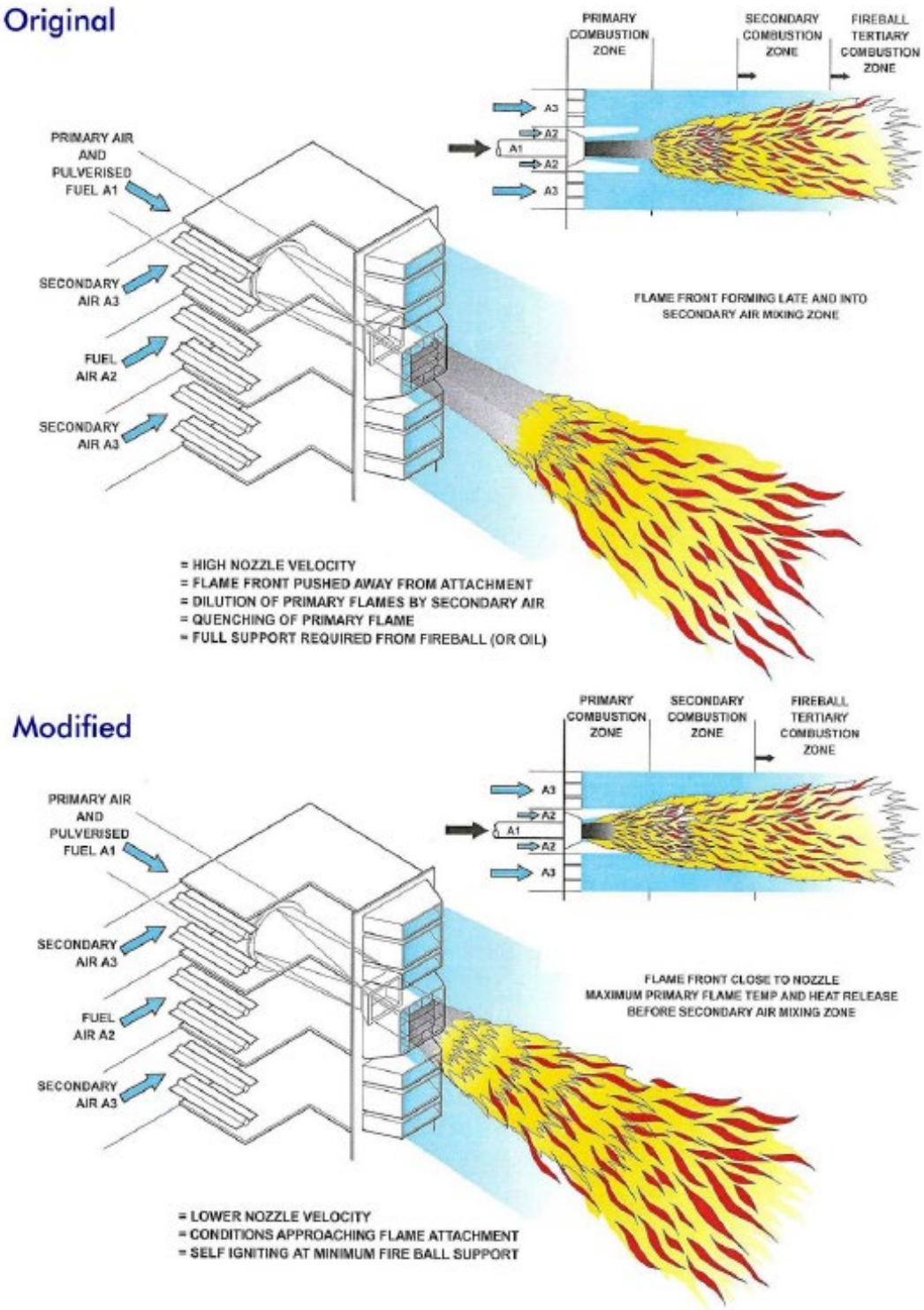


Figure-49: Modification to High turndown burner tips (GE Power)[44]

[44] *Kendhe M, GE Power-Personal communication/workshop presentations*

3. Online Combustion Optimisation (Pulveriser, air/fuel measurements and control)

Presenting real-time information to operators on process optimisation will identify best practice operating for the future cycling with appropriate procedural revisions to standardize on best practice operation.

3.1 Automatic Mill Scheduler[45]

Burner maintenance will be more critical for stable combustion on two or three mills at low loads and the thermal mapping will be a tool to identify trends and problematic combustion with the ability to identify specific problem burners that are contributing to poor combustion or flame stability.

One solution (automatic mill scheduler) is being implemented at one unit of NTPC Ltd for enhancing and sustaining its minimum load operation and combustion stabilisation during frequent load changes. The SPPA-P3000 Mill Scheduler being supplied by Siemens is subordinate to the unit control system and automatically selects coal mills. This solution switches coal mills ON and OFF automatically depending on the firing demand and the actual number of mills in service. The system also has an automatic replacement strategy, should one mill not go into service or fail during service. The center line for the firing devices in service can be specified. This enables the firing balance point for the boiler to be ascertained, e.g. depending on the start-up conditions of the boiler (cold, warm or hot start).

For fully automatic load operation, burners or coal mills have to be switched on and off automatically as a function of the load and the actual number of burners and mills in service. If a burner or mill that is supposed to be started or switched off does not perform accordingly, a backup strategy automatically determines which component to start or stop instead. Finally, if there is more than one mill or burner that could be started or stopped, additional criteria can be evaluated to determine the appropriate component. Classical burner and mill schedulers based on binary logics have proven to be very difficult to understand and maintain. They are also unable to consider process criteria like bunker filling, distribution of fire in the furnace, etc. To solve the problems of burner and mill scheduling, the problem is divided into two smaller sub-problems:

- Determining when to start or stop a burner/mill and
- Determining which burner/mill has to started/stopped where necessary

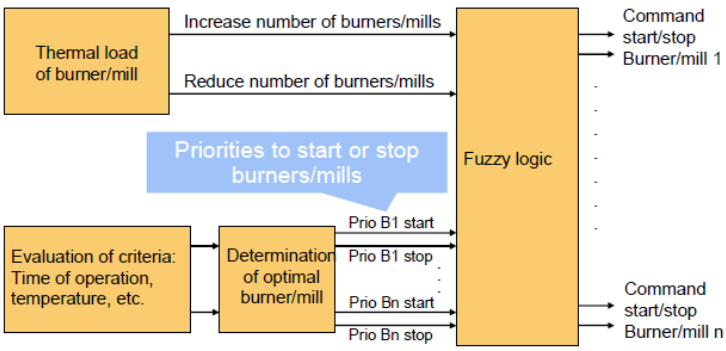


Figure-50: Mill scheduler

The first problem is solved relatively easily by monitoring the thermal load of the burners. If the thermal load falls below a limit, a burner/mill has to be stopped to restore the normal operating

[45] *Chittora S, Siemens (2018) - Report on Minimum Load Test run, NTPC Dadri Unit 6*

range. On the other hand, if the thermal load exceeds a limit, a burner/mill has to be started to restore the normal operating range.

The second problem, however, is more difficult. For each burner and mill, several criteria such as bunker filling, distribution of fire in the furnace, etc. are defined and prioritized. Based on these criteria, a priority for each mill/burner to be switched on/off is calculated continuously. Of course, this priority also reflects that a burner that is already in service cannot be started any more. As a consequence, there is continuous calculation of the priority for each burner and mill to started or stopped. These numbers can be viewed as trends and put into the archive. It is thus easy to understand why a burner/mill was started/ stopped and how different process conditions influence these numbers.

Advantages

- Utilisation of the module offers the following advantages:
- Fully automatic operation of all burners/mills without manual intervention between a
- load of 0 and 100 %
- Automatic switching of burners/mills on/off
- On burner failure automatic selection of the best alternative burner
- Automatic adaptation to changed load requirements
- Plant operators can remove individual burners from the regime of the burner and mill
- scheduler while the remaining burners continue to be controlled optimally
- The furnace fireball can be shifted vertically where required by boiler temperature
- Conditions
- Fast troubleshooting thanks to easy-to-understand concept

3.2 Online Coal Flow measurement & optimisation solutions

An online pulverized coal and air distribution management system is capable of measuring the air-fuel ratio to coal burners in each PC pipe to coal burners in real time which can be optimized automatically based on the received coal quality. Unequal distribution of carbon dust to burners is mitigated. Optimal fuel/air flow is important, especially in low NOx burners which require precise fuel control in order to maintain uniform and efficient combustion.
There are several systems for online optimisation of fuel/air flow. Some of the systems are listed in Table 13.

Table 13: Examples of coal flow measurement and control technologies[46]

Technology	Example	Measurements	Company
Acoustic emission	CFM System Coal Flow monitoring system	Coal flow, differences between roping and other changes	MISTRAS
Electrostatic	Electric Charge Transfer (ECT)	mass flow, velocity, fineness	Foster Wheeler Energy Corporation
	PFMaster	PF distribution, velocity and mass-flow rate	Greenbank
Laser	MECONTROL PSA	Coal velocity, particle size	PROMECON
	EUcoalsizer	Coal and air flow, particle size	EUtech Scientific Engineering
Microwave	EUCoalflow	Coal mass flow control	EUtech Scientific Engineering
	MECONTROL Coal/Pf-FLO III (in the USA)	Coal velocity, mass flow, coal concentration	PROMECON/ AMC
	MIC one	Relative coal flow in each pipe	MIC-USA
White light	Mill Master®	Coal velocity, particle size	Greenbank

An Online Coal Flow Solution is under implementation at one unit of NTPC (being integrated in the Unit's existing Siemens SPPA-T3000 architecture). It measures the pulverized coal flow online in all coal dust pipes and provides detailed information about the coal distribution from the mills to the burner. Based on this information,

- the optimisation of fuel/air ratio in all load phases would now be possible.
- the stability and availability during minimum unit load conditions can be improved.
- the conditions in the mill(s) like choking or low loads can be detected and thus enable for single mill or two mill operation.

[46] *Wiatros-Motyka M. Optimising fuel flow in pulverised coal and biomass-fired boilers,CCC/263, IEA Clean Coal Centre, London, UK, January,2016*

This includes the measurement & monitoring of the coal flow in all the 36 coal dust pipes (9 Mills X 4 Pipes per mill). This is a new advanced version of CFMS, a common SWR/Siemens development, based on SWR`s microwave sensor technology, as this is a real microwave technology, opening the whole potential of radar-based technologies for the use of coal flow measurement.

Based on the existing robust design of the sensors, SWR and Siemens engineers together have introduced an improved way of microwave application, signal processing and evaluation, which makes the measurement absolutely process-safe, supplying trustable information of the coal flow as a reliable basis for an automatic online control.

Coal flow control avoids imbalances in coal flow, enables homogeneous combustion and improves emission profile. The customer benefits are:

- Imbalances can be identified and equalized in a short time
- Individual burner adjustment is possible
- Less NOx, higher efficiency
- Mill and burner operation at Low Unit Loads

Technical Concept

The Siemens/SWR coal flow measurement is a real time system using high frequency microwave. The sensors can be used in metallic ducts. The coal flow sensors are working with a Transceiver-unit (transmitter and receiver) which is measuring into the pipe by means of a special hollow antenna with a frequency of 24 GHz and with an output of approx. 3mW.The transmitter sends in CW (Continuous Wave) and thus a homogeneous high frequency field is developed in the coal dust pipe. This field is developed just before the measurement sensor. The microwave energy is being reflected by the coal particles and received by the sensors. These signals are evaluated in frequency and amplitude. The sensor works like a particle counter, which counts the quantity of moving particles per time unit. This relates to a mass flow-proportional signal. If a particle is moving into the field, an additional reflection is produced and recognized as an impulse with a shifted frequency due to the Doppler's effect. Each particle generates an impulse output, the larger the particles the larger the amplitudes. The signals are being evaluated in frequency and amplitude. The measuring signal is independent of pressure and temperature in the duct.

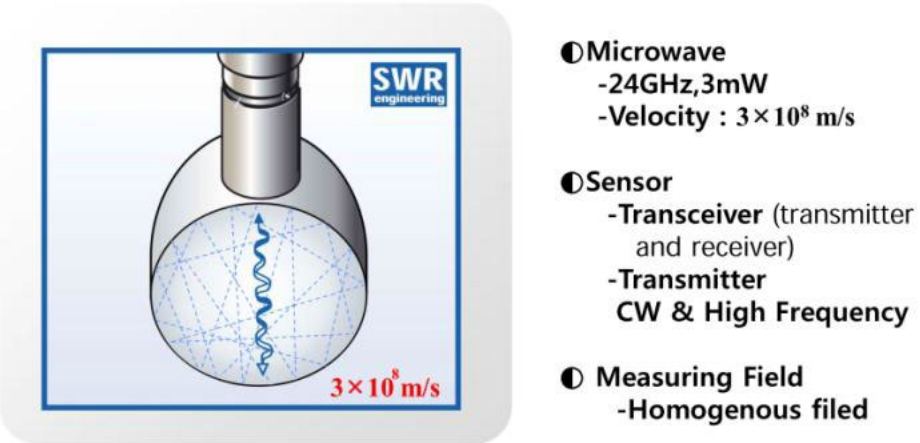


Figure-51: Coal flow sensor using microwave technology 24GHz[47]

[47] *Chittora S, Siemens (2018) - Report on Minimum Load Test run, NTPC Dadri Unit 6*

The online coal flow measurements have been installed at Farge steam power plant(351MW), Engie Deutschland AG, Opile Power Plant-Unit 5&6 (2X900 MW), PGE Group, Poland and Yeongheung, Incheon Coal power Plant, Unit 6(870MW), KOSEP Co.

Online Coal Analysers

Based on questionnaires and personal interviews with operators, concerning actual situation of operation in the Indian power stations, one important factor that emerged out which makes combustion worse is fluctuation of coal calorific value.
For example, in one case during the operation of 500MW, when calorific value was high, amount of coal consumption was 250 ton/hour, but when calorific value was low, amount of coal consumption was 400 ton/hour. With frequent changes in coal quality, combustion optimisation becomes very difficult. A general requirement for flexible operation is the provision of coal of a sufficient quality. With an online coal analysis, flame stability and reliable operation can be continuously maintained, leading to fewer trips and faster response times.

4. Solutions for improving the milling capacity and safety

4.1 Hot gas generator for coal drying[48]

At times the moisture in coal is too high and at low loads and during start-up, PA temperature at mill inlet is not sufficient to dry the air, leading to poor combustion, delay and can lead to coal accumulation in coal pipes. To guarantee the sufficient drying of coal, hot air is required and if the hot air comes from the air pre-heater, the entire system (boiler and flue gas path) has to be warmed-up using start-up fuel, and at times, at the cost of secondary air.

A hot gas generator is capable of providing sufficient primary air temperature almost instantaneously. Consequently, the coal mills can be started earlier, leading to cost savings by allowing expensive start-up fuel to be substituted earlier. It is particularly effective for drying extremely wet coal, caused by heavy rainfall, as well as drying coal that is out of the range from worse coal as specified for the grinding process.

Moreover, the hot gas generator can be used to keep the required flue gas temperatures in order not to adversely affect flue gas cleaning equipment as well as avoiding flue gas temperatures falling below dew point of SO3 in particular at the cold end of the air pre-heater.

4.2 Exploiting the storage capabilities of mills[49]

To get faster heat output, the storage capabilities of mills can be exploited by adapting the grinding pressure, purposely releasing or storing coal from/in the mill. Response time improvement and storage capacity severely depends on mill type. This is particularly helpful for improving the ramp rates. Reference: German power plants Voerde and Bexbach.

[48] *European Patent 12 162 930, German power plants Bexbach / Weiher and Herne unit 4.*
[49] *VGB/EEC(IGEF) - Flexibility Tool Box-Measures for flexible Operation of Coal-Fired Power Plants*

4.3 Dynamic classifier

To get faster heat output the storage capabilities of mills can be exploited by purposely adapting the classifier's rotational speed. A lower classifier rotational speed releases more coal dust to the burner whereas a higher speed separates more coal. Some of the Indian power stations have installed dynamic classifiers. International reference-Walsum unit 10[50].

4.4 Mills steam inerting

Stations with increased cycling should consider installing steam inerting on the mills to prevent mill puffs when cycling a mill out of service. Some Indian power stations have the system (originally supplied by the manufacturer), but are not using it.

4.5 Mills with increased drying capacity

For burning coals with higher moisture contents and lower GCV than the original design coal range for a plant, there are retrofit solutions available for the mills to increase the drying capacity. These retrofits can be - larger mills with dynamic classifiers, new primary air fans of greater capacity and arrangements for additional heating of primary air.

5. Solutions for start-up optimisation/ two shifting

5.1 Steam coil air pre-heater

Although SCAPH is included in the standard design of most of the newer stations, in many cases it is not used. As informed by many of the stations, the potential benefits of SCAPH were underestimated and it did not get the priority it deserved in maintenance and up keeping. For example, in more than one case, it was observed that the SCAPH was out of service after a steam leakage and it was never attended.

5.2 Reliable flame detection

Usually zonal flame detection becomes inappropriate at reduced minimum load. Thus, direct flame detection is recommended and, consequently, new sensors are to be installed at least for the burner levels active at reduced minimum load. In addition, more reliable flame detection might allow for more reproducible start-ups.

5.3 Automatic plant startup and guide

Automatic Plant Startup sequence has been proposed by BHEL (after analysis of field tests in a couple of units), to help in executing startup and shutdown cycles smoothly and will guide operator wherever an issue is faced. The automatic start-up sequence is available for the turbine, but the start-up activities in boiler are mostly carried out manually.

An automatic start-up sequence lights off burners automatically, rolls the turbine as soon as the necessary conditions are reached and realizes a smooth transition between the particular start-up phases in order to avoid unnecessary waiting times. Automated start-up is only possible once all relevant drains and vents are automated. Several power plants in Germany, e.g. power plant

50 VGB/EEC(IGEF)-Flexibility Tool Box-Measures for flexible Operation of Coal-Fired Power Plants

Voerde unit A/B, power plant Herne unit 4 have "one-button" automatic plant start-up. Others like West 1/2, GKM unit 9 have Start-up optimisation solutions installed51.

Experiences of automated start-up show that even the best manual start-up do not match the near perfection of an automated start-up. The Figure 52 shows the comparison betweed a good manual start-up vs an automated start-up.

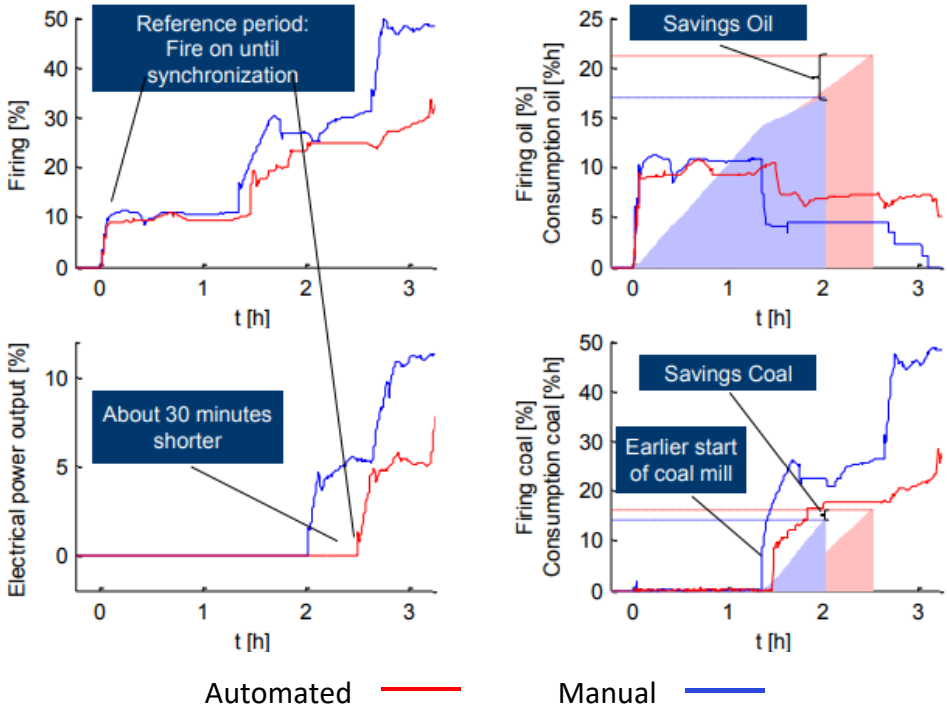


Figure 52: Automated start-up vs a good manual start-up[52]

5.4 Digital Boiler Plus (DB+) Low Load Advisor

In low load operation, GE's Digital Boiler Plus provides improved control over fireball stability. Depending on the constraints of the unit and in combination with the firing system upgrade, Digital Boiler Plus can allow the unit to assist with lowering minimal load without support oil.

In low load operation Digital Boiler Plus provides better monitoring and control over fireball stability. The DB+ fireball diagnostic stability monitoring function will allow boilers to operate safely at reduced load without spurious flame stability safety trips. As load demand decreases, pulverizers are taken out of service until a minimum of two-three pulverizers are in operation). However, at lower loads, the pressure drop in the coal piping can negatively affect fuel-air distribution between burners and thereby reduce flame stability. With only two-three mills in service it is more important that stable combustion be maintained locally as well as in the fireball and that the flame scanners handle the turndown reliably, that is when a stable flame is present this is detected properly.

The Low Load advisor of Digital Boiler Plus uses new high turndown "Perfecta" flame scanners that provide fuel-air balancing information, and control logic that compensates for fuel-air local

[51] *VGB/EEC(IGEF)-Flexibility Tool Box-Measures for flexible Operation of Coal-Fired Power Plants*

[52] *Dr. Kaminski (Jan 2020), Steag Energy Services, "Improving the flexibility of hard-coal fired power plants by means of APC", presented at IGEF/EEC conference at Kolkata*

Mal-distributions. In addition, furnace pressure sensors and a furnace camera and multi-feature 2D image processing monitors Fire Ball Stability.

Burner Flame Stability and Fire Ball Stability are used to provide immediate alerts if support fuel is needed due to an unexpected event. The low load optimizer can prove boiler flame at different loads using flame scanners, which is a mandatory safety feature of boiler operation. At full load operation, flame scanners see a bright flame; whereas at low load operation the devices see a dim flame. Many flame scanner models lack the dynamic range to prove flame at both full load and low load without being recalibrated. This means that a flame scanner that is calibrated to prove a flame during full load operation, might show that there is no flame at lower load, when in fact there is one that is simply dimmer. The combustion and low load advisor flame scanners sensors have a wide dynamic range with the proprietary logarithmic filter that can prove flame at full load as well as at the lowest loads without recalibration. These features help avoid "nuisance" trips where a scanner may not "see" a still stable flame.

5.5 GE's Flexisuite Steam[53]

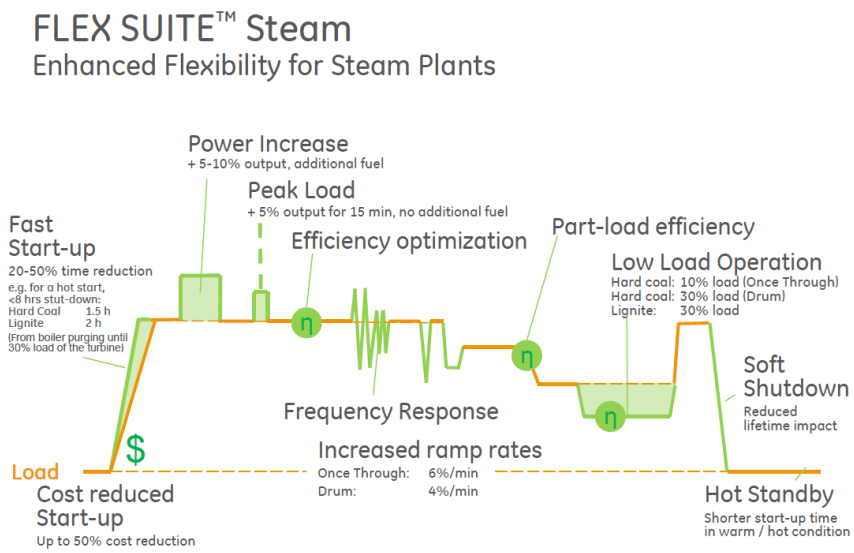


Figure 53: Flexsuite (GE)

This is a consolidated solution from GE Power for flexible operation. It covers all aspects from start-up, minimal load, frequency response, part load optimisation to shutdown optimisation.

5.6 Heating blankets

Heating blankets used to keep turbine warm during stand-stills by balancing the upper and lower casing and thus avoiding the bending of the shell

5.7 Modifications for hot filling of boiler

Some stations, particularly the large captive power plants have a configuring where more than one boiler supplies the steam to a single turbine, allowing a greater degree of flexibility. Further, there are units in which the deaerators' feed water lines are also connected so that hot water can

[53] *Kendhe M (2018), GE Power, Presentation at the USAID Workshop at NTPC, New Delhi*

be taken from the deaerator of one unit to the unit that is to be started up. The boiler of one unit can be used to run the turbine of the other unit. This offers a great advantage in terms of reduced start-up time and greatly reducing the thermal stresses on the components. (Example: NSPCL, Durgapur, India has two units).

For the existing stations it is worthwhile to consider a design modification to use hot treated feed water from a running unit to fill a hot stand by boiler to establish a drum level prior to firing during the hot restart. This feed water cross tie system has been proven effective and cost beneficial on similar units in cycling duty to reduce the thermal stresses and damages in the economizer and the feed water piping. It is beneficial when only one unit at a site is cycling and doing a hot restart.

6. Optimisation of existing control loops

6.1 Fine tuning of existing controls loops for low load operation

Flue gas temperature

Flue gas temperature is controlled by means of a steam air preheater. An average temperature between steam and air is controlled. If this temperature is too low, corrosion to the air preheater will increase. If the temperature is too high, more heat will escape through the chimney, and the efficiency will drop.

Automatic start of fans

Fans can be taken in and out of service automatically depending on the required load. An automatic master group controller can create start and stop orders to the fans (ID, FD, PA). The fans will be taken in and out of service not only by actual load, but also by predicted future load, mainly based on the target load set-point.

Automatic start of BFP

BFPs can be taken in and out of service automatically depending on the required load. An automatic start-up and shut-down sequence will be implemented on each BFP. An automatic master group controller will create start and stop orders to the BFPs. The BFPs will be taken in and out of service not only by actual load, but also by predicted future load, mainly based on the target load set-point.

With the automation of the mills, fans and BFPs the start and stop the components can be done without having to stop the load demand. Ramps should be executed without interruption and without waiting times for subordinated open loop controls.

Burner tilts on auto

Use of tilting burners to avoid need for reheat attemperation at partial load is common in Indian power stations. But mostly, the burner tilts are operated on manual (-30% to +30%) and the tilting operations are not optimized. With automatic burner tilting operation with command from Steam Temperature Control loop, there is a high potential of optimisation.

6.2 Modification of BFP recirculation valve

For ensuring smooth operation of both BFP at low load, modifications of BFP recirculation valve from on/off type to regulating type along with changes in operating logic is required.

6.3 Measurement of excess air

Flue gas O_2 measured at economiser inlet is normally used as an indicator of excess air. But this measurement may not indicate the actual excess air due air-in leakages. O_2 measurement along with CO measurement gives a better picture.

6.4 Reliable temperature measurements

The measured temperatures directly affect the firing rate and all operating actions will be based on the measured temperature. The availability of adequate measurements and accuracy of measurements of the thick-walled components are important for evaluating the thermal stresses, during the start-up/shut-down and fast ramping. Moreover, the temperatures for process controls must be accurate.

Further, the measurement range might not be sufficient for reduced minimum load, in particular with respect to pressure, temperature and flow.

The quality of flow measurements usually deteriorates at the lower limit of the measurement range, potentially adversely affecting the corresponding control.

Thus, investing in reliable temperature measurements has a high potential of benefit.

6.5 Replacement of actuators: to improve fast load ramping and to meet the requirements of low load operation

Reliable actuators (fans, pumps, valves) are a basic requirement for optimized start-ups. Many of the actuators & valves have operating range which is not suitable for low loads and poses problems for control system at low load operations.

Actuators might not be fast enough to fulfill the more involved requirements of flexible operation. The use of power converter-driven fans and actuators enables speed control and thereby a fast reaction time and enhanced dynamics in a broad operation range.

6.6 Operational dampers in air and flue gas ducts

Traditionally, many of the dampers were operated only during start-ups and shut-down as the units were running on base loads. Least attention was paid to some of the dampers to keep them operative (e.g. APH, ESP dampers).But during flexible operation, these dampers are required to be kept operational or if needed , a new damper may be required to be installed.

6.7 Long life high temperature fabric joints

The metal expansion joints may be replaced with long life high temperature fabric joints that are easier to install and repair.

6.8 Load following with sliding pressure operation

A critical constraint on ramping operation is matching steam and turbine metal temperatures, and more rapid output changes can be achieved using sliding pressure. Sliding pressure also offers advantages over throttle control during start-up, by establishing a flow to the turbine earlier in the sequence, with lower overall heat input and by retaining high temperatures on shutdown. Sliding pressure operation has become common practice in the new units. However, it can have issues with:

- Economiser steaming & DNB
- Increased O_2 attack through condenser air ingress

Stations at NTPC are using a modified sliding pressure curve as a trade-off for various issues. The best practice for low load operation is to slide the drum pressure down to 100kg/cm^2 or less to maintain the steam temperatures and the resulting minimal change in the high-pressure turbine metal temperatures.

6.9 Advanced sealing in the turbine (smart seals)[54]

During low load operation and start-ups/shutdown, the turbine seals are prone to thermal deformations. Several smart seals such as retractable, anti-swirl and brush seals are available on the market. They are less prone to damage during flexible operation and allow the necessary clearances to remain almost the same during variations in load (Wiatros-Motyka , 2019). The smart seals also increase the turbine efficiency.

7. Chemistry

7.1 Nitrogen Blanketing of Demineralized water storage tanks

Demineralized water storage tanks are open and vented to atmosphere and will require a nitrogen blanket to prevent oxygen-saturated feedwater addition to the boiler for any startup, especially cold startups. This will reduce the oxygen-pitting damage and the need for any oxygen scavenger. NTPC is installing the system at most of its stations.

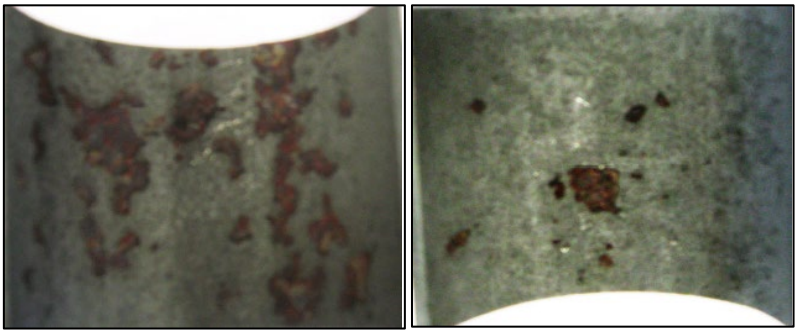


Figure 54: Pitting on internal surface

[54] *Wiatros-Motyka M. Power plant design and management for unit cycling, CCC/295, IEA Clean Coal Centre, London, UK, September 2019*

7.2 Use of Film Forming Amines (FFA)

Used as a way to mitigate potential for oxygen-caused corrosion. Advanced products are available, which are more stable and have solved several previous problems (like difficult to inject, formation of gumballs in the circuit etc.).

7.3 Increasing the drainage capacity

The superheater and the LTSH should have an automation draining using a thermal drain pot that assures complete removal of accumulated condensate. This is a typical and most frequent cause of tube-to-header failures in these down-flow superheater sections. The condensate acts as a quenching spray and creates very high stress levels from rapid thermal differentials. The failures and existing tube distortion noted in the inspection reports are a clear indication that the condition exists. Temporary thermocouples may be installed to confirm the condition and size of drain lines, and to measure the effectiveness of the final countermeasure. Some plants have carried out modifications, for increasing the drainage capacity.

7.4 Coatings in APH baskets

Air preheater baskets will need to be corrosion-resistant (enameled or corten) for future cycling and the replacement of the cold end baskets will be more frequent than for baseload operation and will increase the cost of the system, as well as reduce the efficiency due to metal loss and corrosion fouling.

8. Fleet optimized operation method for group/s of power units for securing economic rationality[55]

A power generating utility, while optimizing at the unit level should also focus on fleet optimisation in order to derive the maximum economic gains and reductions in emissions. JERA, Japan, co-developed a simulation system with a manufacturer in order to create an economically rational power generation plan that supports the forecasted demand corresponding to the system reform in the Japanese electricity market. It is based on the analysis of about 100 basic conditions, including unit thermal efficiency, output, ramp rate, generation cost, etc. and about 60 operational restrictions, including limitations on the start/stop, output suppression, and fuel constraints, which have a great impact when determining operating status and generation output. These were entered as variable data so that an optimal generation output for each unit reflecting the demand from the system could be obtained.

An optimized operation method for one group of units can be developed by optimized operation analysis on a group of units with assigned weights to highly economic units, taking into account operational limitations. The generation costs largely vary, based on fuel costs, age, operating procedures & O&M costs. It is important for thermal power producers to minimize the total

[55] *JCoal / New Energy and Industrial Technology Development Organisation / JERA Co., Inc /Mitsubishi Research Institute,Inc.(July 2019), "Final Report- Flexibilisation Study at Vindhyachal Super, Thermal Power Station (VSTPS)"*

operation cost by operating a group of units with optimal output distribution considering the cost of each generation unit in operating the power unit.
The Indian power utilities can replicate this simulation based on different scenarios:

(a) Optimized operation method based on the track record of previous year demanded of the target plant.
(b) Demand forecast based on the 2022 renewable energy introduction plan.

Based on the recommendation of Ministry of Power and Central Electricity Authority, JCOAl (Executed by JERA) has undertaken a pilot study at NTPC's Vindhyachal Super Thermal Power Station (VSTPS), where these aspects are being demonstrated, apart from unit level optimisation.

9. Fatigue Monitoring/Life assessment/Condition Monitoring Tools

9.1 Cycling Advisor / COSTCOM

This low-cost-high-impact solution by Intertek offers real time communication of costs and components damages rates (wear and tear), for all types and characteristics of cycling and MW operation levels for helping to develop an optimal system dispatch schedule. The damage types considered cover the following operating procedures:

- On-off cycling
- Load following cycling
- Load changes with varying MW ramp rates
- Load following at varying load depths
- Higher than rated capacity operation, and
- Minimum load operation.

The objective of Intertek's Cycling Advisor is to reduce plant damage and total combined fuel and damage costs while meeting system loads, including flexible operations. Intertek's proprietary LOADS model is used to provide wear and tear rates. COSTCOM computes damage accumulation rates and costs for specific types of cycling operation based on a cost of cycling analysis.

9.2 Creep Fatigue Pro

Creep-Fatigue Pro is an automated on-line life consumption monitoring system for fossil plant equipment developed by EPRI and Structural Integrity Associates (SI) for tracking creep fatigue life consumption in high-temperature fossil plant components. By tracking creep-fatigue damage accumulation and crack growth on a continuous basis using actual plant operating data, the accuracy of remaining life predictions is improved, and the impact of plant operating parameters on component life consumption can be estimated. The system is useful to detect and calculate the extent to which variations in cyclic operating procedures might impact component useful life based on actual plant operating conditions.

9.3 TULIP

Tube Life Probability (TULIP) is a Windows software based on continuum creep damage mechanics that considers the radial gradient of conditions in the material, including temperature.

This software uses Monte Carlo simulation to derive the probability of failure of superheater/reheater tubing.

9.4 B-LMS

Boiler Life Monitoring System developed by Serco Assurance is designed to assist plant operators to meet the needs for generation at minimal operating costs, high plant availability and operational flexibility, while ensuring mechanical integrity and consistency with health, safety and environmental damage to boiler components. B-LMS is a hardware and software system which continuously monitors damage to boiler components based on actual usage.

9.5 PHILAS

The Plant Health Indicators and Life Assessment System (PHILAS) by Technology Services International, a division of ESKOM is similar to Creep- FatiguePro and B-LMS. Although the development of the creep-fatigue module in PHILAS was primarily based on heavy sectioned turbine components, i.e. spindles and valve chests, the program is very flexible and can be used successfully on boiler components such as headers.

The setup of PHILAS requires some pre-calculated characteristic curves that are specific to the component to be investigated. The characteristic curves allow rapid evaluation of thermally induced stress from the actual plant data to enable strain-based creep-fatigue assessment. The characteristic curves are functions, calculated by finite element analysis.

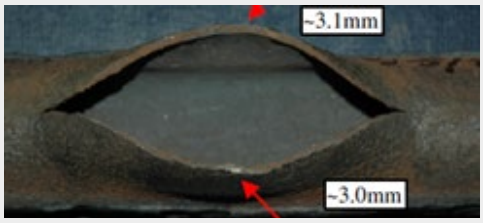
9.6 Boiler Start-up Advisor

Power Technology's software product assists online in unit start-up while minimizing plant damage due to high temperature plant components (e.g. headers). The start-up procedure is optimized based on current plant conditions as well as historical data. Targets for boiler pressure, temperature and load are set by the operator and based on creep-fatigue and the analyses of damage risk, the optimal procedure for the boiler start up is provided. Alternatively, the start up procedure can be optimized to minimize secondary fuel consumption. Advice output from the software can be tailored based on user preferences.

ANNEXURE 2 - Areawise operational practices to mitigate cycling related damages

Table-Annex 1/1 Areawise operational practices to mitigate cycling related damages

Component Damage due to cycling operations	Possible causes	Practices for Mitigation
Waterwall, Drum and associated components		
WW headers & tubes	Stub to header cracking due to steep thermal transients at low loads & start-up/shutdown at low flow conditions	-Water quality management -Reduce DNB -Even out temperature distribution/circulation -Control temp. gradient during starts/stops. *Refer to shutdown procedure(section:10.1.2) for details*
Water tube -acid phosphate corrosion	Frequent cycling, at high pressures can result in phosphate hide out under the existing or new deposits in a high heat flux area of water walls, in units dosing phosphate.	-Water chemistry management with adequate O2 removal system. -Use CPU
Damage to water tubes due to falling slag	Slag accumulated at the upper levels around the pendant platen SH periodically fall off and strike the sloping water walls above the hoppers. This causes external erosion, crushing & cracking of tubes and leading to WW BTL. This problem is further aggravated during flexible operations with improper combustion. During load fluctuations there can be sudden temperature transients in the steam-cooled tubes and can cause big sized, dense slags to fall.	-Ensure effectiveness and proper frequency of soot blowing. -Optimise combustion with automated solutions -Welding steel hex bars at the vicinity of the slop tubes can minimize the rate of tube war.
Long term overheating/creep of steam-touched tubes	Increased cycles of low load operation of base load units in the damaging regime without adequate preparation, causing scale build-up, exfoliation.	-Ensure proper steam flow during start-up. -Automate operations of drains.

Short term overheating	Continued operation in this mode causes an increase in the mid-wall temperature and long-term creep. Localized, long term overheating happens when the deposits fall off.  *Figure 55: WW failure, 3 hours of start-up-Short term overheating*	-Monitor FET (Flue gas exit temp) during start-up and low load.
Drum shell, Header cracking and bowing	Headers and drum bowing because of large top-bottom DT during cycling due to rapid feeding with cold water during hot starts and quenching of headers during high ramp rates. There can also be localized cracking at stress concentration/welds. Internally, there can be thermal fatigue cracking of attachments and seal welds.	-Fill the drum completely before shutdown. -Using the low load or motor driven start up boiler feed pump/boiler fill pump is recommended for routine cycling to offset the potential and current damage for cycling from using the main boiler feed pumps at low pressure for each start up cycle. The option of a feed water cross tie is even better than using the motor driven pump when the cross tie is available from a running unit. -If filling is required, do it slowly by controlling the firing rates and careful operation of HP/LP bypass (if required). -Review of inspection schedules of stubs, attachments and welds.
Circulating pumps	The submerged motor windings are prone to leakages on repeated starts stops due to thermal cycling and due to the high current drawn by the motors during starts.	-Review operation practices - keep the pumps in circulation during short downs and start the pumps early, to avoid temperature differences.
Condensate System		
LP heaters	Increased corrosion and fatigue with poor water quality	-Monitor water chemistry -Check for tube erosion and fatigue during inspections

CEP(condensate extraction pumps)	During low flow conditions it is kept on recirculation, so normally there are no issues.	-Maintain adequate hotwell level and keep recirculation healthy
Deaerator	Thermal fatigue cracking of internal fixtures, extreme temperature transients or water hammer can cause cracking of shell welds and line connections, vents. Poor chemical regime can cause corrosion fatigue	-Charge deaerator heating early during start-up, use bypass lines during initial filling, ensure that vents are healthy. -Review lay-up procedures, consider using anti-corrosion coatings.
Feed Water System		
Boiler Feed Pumps/MDBFP & TDBFP	During low load operation, ensuring minimum flow can be challenging. Frequent operation of recirculation valves often leads to passing. Typically, many of the R/C valves are full open and close type and the operation of these valves are jerky and causes a disruption of feed water flow. There can be severe problems during R/C valves mal operation or failure of feed regulating stations; like failure of thrust bearings. At low load there can be overheating and leak-off issues. There are common issues of change of source of steam for TDBFP, when there is a wide variation is temperatures of different sources, affecting the reliability of the TDBFP. Maintaining the reliability of MDBFP at varying load conditions sometimes becomes difficult (maintaining top-bottom dt). At extremely low loads, sometimes the supply to attemperators can become challenging.	-Using the low load or motor driven start up boiler feed pump/boiler fill pump is recommended for routine cycling to offset the potential and current damage for cycling from using the main boiler feed pumps at low pressure for each start up cycle. The option of a feed water cross tie is even better than using the motor driven pump when the cross tie is available from a running unit. -Replace the R/C valves of BFP to control valve type -Monitor the standby MDBFP for availability of permissive to start; if required keep the drain cracked open to maintain the DT
HP Heaters	Excessive thermal transients during start-up and low load operation can cause failures due to thermal fatigue cracking in thick	-HP heaters should be maintained in a pre-warmed condition to reduce the thermal shock damage for routine cycling.

	walled end plates and tube plates, distortion and cracking of tubes.	-Pegging steam and recirculation of the boiler feed pump would be beneficial to maintain the HP heaters at or near the economizer inlet metal temperatures. -These ramp rates to be maintained below the prevention limit (typically 40°C/hr)
Feed Regulating station(valves)	Thermal fatigue cracking due to cold feeds during cycling	- In addition to above mentioned practices, optimize dp across the FRS
Economisers		
Thermal fatigue in Eco inlet headers	Due to wide thermal gradients during start-ups, particularly by feeding cold water during hot/warm start-up and shutdowns, causing a rapid cooling of the eco inlet headers. There can be ligament cracking, stub to header cracking & quench cracking due to the cold feeds and fatigue cracking due to water hammer on steaming economizers during starts. Moreover, there can be thermally induced bending during low load operation due to stratified water flow.	-Eco recirculation, Deaerator pegging steam. -The process to fill the boiler for hot or warm cycles should be modified to reduce the thermal shock damage. The feed water should be near the temperature of the components in the boiler and the economizer inlet header to reduce the thermal shock
Water tube caustic gouging	Due to lower circulation, higher deposition and steam blanketing. Common in a steaming economizer, water-cooled support as a result of boiling, steam blanketing of the top portion of the tube.	-Ensure uninterrupted flow in economizer or recirculation during start-up. -Continuous makeup and blowdown to prevent steaming in feed water and economizer, besides protecting the HP heaters
Superheaters/Reheaters		
Header borehole cracking	Condensate accumulation in pendent tubes which flashes during start-ups	-Ensure proper drainage

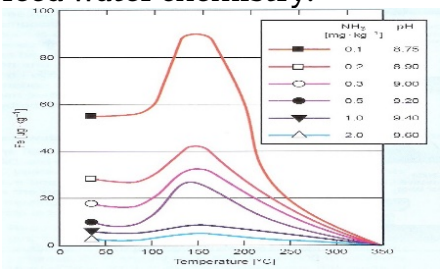
Piping fatigue	Thermal fatigue due to MS & RH cold quenching, Mechanical fatigue due improper supports/hangers & vibrations in the piping	
Short term/long term overheating in SH/RH tubes	Can be caused by imbalanced steam flow during start-up, water blockage, blocked tubes due to oxide exfoliation, insufficient flow through RH  *Figure 56: Platen SH-LT overheating/heavy deposits*  *Figure 57: Platen SH LT Heating*	-Optimisation of HP/LP bypass, Judicious load ramping, monitoring of furnace exit temp during starts/shutdown. -During inspection- decide on acid cleaning or rather replace the sagged tubes to prevent secondary damages up to turbine due to scales carryover.
Piping Thermal shocks & header water hammer	Water condensation in steam pipes which are not drained, direct water ingress in steam pipes. More common in hot start. Another common reason is passing valves like spray valves (SH & HPBP)	-Automated drains, proper drain sizing to ensure complete drain out. While charging a pipeline always use a bypass valve and charge the lines very slowly. -Monitor the piping & drain temperatures. If required, install additional temp measurements.
Pitting of water tubes/ tubes stress corrosion cracking	High level of O2 in feed water, poor lay-up practices, & poor water quality Water spray from attemperator is another source of pitting. Stress corrosion cracking in steam cooled enclosure tubes at corners and penetrations is caused by high local stresses during start-ups/shutdown through initiation of surface cracks, progressively	-Deaerator pegging, review lay-up procedures, nitrogen blanketing of condensate storage tanks 

	propagated by corrosion and cycling.	*Figure 58: Pitting in RH Outlet Tube*
Boiler valves		
Stop Valves	Thermal fatigue cracking of valve body due to rapid temperature transients, cracking of valve seat and disc hard facing, cracking of drain connections	-Use bypass valve for initial charging
Safety valves	Frequent operation likely during cycling operations with poor pressure and temperature control, Passing pf valves	-Prevent sudden pressure shoot up, check valve settings (operating and reset pressures)
Vents & Drains	Increased wear and tear with frequent operation	-Review inspections and maintenance schedule
Desuperheaters		
Piping corrosion fatigue	In desuperheaters there are increased quenching events in cycling operations. Passing attemperators increases the damage. Excessive attemperation can also lead to water carry over to turbine during extremely low loads.	-Enhance monitoring and maintenance of desuperheaters. -Arrest the leakages from passing attemperators. If frequent passing occurs, replace the attemperator with a high-quality valve.
Supports, Structures, housing & Insulation		
Boiler structures	Increased air ingress due to failure of housing and insulations Windbox and ducts attachment, expansion joint failures Thermo-mechanical fatigue of structure, buck stay bowing Cracking of welded roof and wall seals	-Combustion optimisation, Increased inspection frequency of supports, hangers, ducts, expansion joints. -Perform air tightness test for ducts followed by repairs
Fatigue of steam-touched tubes		-Proper supports and inspection schedule for supports
Rubbing/fretting of steam touched tubes	Rubbing of tubes may be due to failed alignment lugs/support bars and uneven thermal expansion.	-Scheduled inspection and resupport. -Consider upgrading attachments with superior alloy.

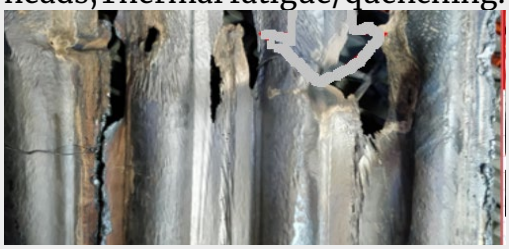
Piping support misalignment	Water hammer, creep damage and uneven thermal expansion	-Scheduled inspection of piping system (checks w.r.t. settings) -Prepare a walkdown checklist (hot and cold)
Insulation	Deterioration of thermal insulation and shielding has an increased impact on the overall performance of the unit running on flexible mode. Cold spots can cause internal corrosion, water ingress and stagnation will induce corrosion under the insulation layer plus faster cooling of the unit with increased depressurisation rate, ununiform cooling will increase thermo-mechanical stresses. All these will further cause thermal stress related issues in several areas & deteriorate the overall performance of the unit.	-Systematic repair/restoration of damaged insulation. -Regular temperature checks of insulation performance -Insulation checks through walkdown checks.
Combustion System		
Oil Burners, Ignitors	Adequate Oil (HFO) temperature, Steam temperature, reliability of valves, drain lines	-Reliability of oil burners: Regular cleaning of oil guns, ensure that there is no stagnant condensed steam in steam/oil pipes, operate the drains. Ensure proper scavenging of oil guns. It is a good practice to keep the steam valves crack open.
Scanners, Scanner air fans	Fouling of scanners Misalignment of scanners	-Clean the scanners regularly Angle of scanners need be adjusted initially to match the position of the flame's line of sight.
Coal Burners	Erosion of burner plates, Improper fuel/air flow flows across different burners ,overheating due to insufficient cooling air flow, damage of tertiary vanes, damage of tilting mechanism	-Optimise combustion, install combustion control system, -Maintain adequate windbox pressure
Mills & coal pipes	Increased grinding roll metal wear out due to low load operation, Explosion hazard due to mill shutdown without emptying mill/maintaining low air flow (in	-Ensure a minimum loading of mills at around 50%, Monitor mill inlet PA temperature. -Purge mills after shutdown

	the zone of explosive fuel-air mixture) Fuel-air imbalance across coal pipes, mill outlet temperature can cause choking of coal pipes, which is a potential explosion hazard	-Monitor temperatures of individual coal pipes – install thermocouples
Feeders	Damage to belts in case there is interruption of coal flow from bunker after long shutdown	-Ensure coal on belt, Install "No coal on belt" monitor.
PA Fans	In CE design boilers with two PA fans there can be issues of PA fan stalling at low loads causing damage to fan blades and casing	-Review operating procedures. Run as per the PA fan flow-pressure curve supplied by the OEM. Before starting PA fans ensure that air and gas dampers of PAPH are open
Fans		
ID & FD Fans	Low cycle fatigue of fan runners can cause cracking of blades.	-Ensure uniform cooling during shutdown -Review Inspection schedule
Flue Gas path		
Air Preheaters	Dew point corrosion, choking of baskets due to condensation at low loads, damage of seals due to temperature differences during start-up, Potential fire hazard due to oil carry over on initial oil firing during light-up.	-Maintain adequate steam parameters for APH soot blowers and operate periodically, more frequently during oil firing. -Install & monitor oil carry over probes, view glass, carry out hot water washing, but ensure proper water draining and dry out
Ducts	Dew point corrosion at low loads	-Repair patches or replace leaking sections, Use of corrosion resistant coatings
Expansion joints/seals	Increased cycling operation causes additional wear and tear	-Review inspection schedule and maintenance. -Upgrade with superior quality fabric expansion joints
ESP	Low load operation can cause ash buildup due to condensation. Clogging of plates during oil firing.	-During initial start-up with oil firing, one or two passes can be isolated. Switch on

		hopper heaters early during start-up, improve thermal insulation to retain heat, -Avoid charging ESP fields during oil firing.
Chemistry Related Issues		
Acid dew-point corrosion	Particularly at low loads, start-ups & lay-ups. Can corrode the tubing, APH & ducting	-Take SCAPH (steam cooled air heaters) in service during start-ups and at extremely low loads. Plants not having SCAPH must install it, if it operated on cycling mode.
Water tubes hydrogen damage	Condensor leakage, increase iron and copper release rates, poor water quality(low pH)	- Air ingress monitoring and control. -Nitrogen blanketing of condensate storage tanks. Use of CPU. Replacement of copper tubes in condensers.
Boiler chemical cleaning damage	Proper chemical cleaning depends on the skill of the chemistry staff and proper procedures. Improper selection of cleaning chemicals	-Adequate control & monitoring of cleaning process. Preference of EDTA over HCl -If frequent cleaning is required, there can be other reasons like condenser tub leakages, improper O2 removal system, which needs to be controlled.
Flow accelerated corrosion in piping/headers	Flow-accelerated corrosion (FAC) is a corrosion mechanism in which protective oxide layer on a metal surface dissolves in a fast-flowing water. The underlying metal corrodes to re-create the oxide, and thus the metal loss continues FAC is normally related to turbulence especially near fittings, e.g., elbows, orifices, valves FAC is aggravated by Water Chemistry, Temperature and oxygen levels Common issue in feed water and desuperheater circuits in cycling units which occur due to improper cycle chemistry control during start-ups and especially in low	-Control chemistry parameters during start-up, modify chemical regimes if required. Use on line COPU (condensate polishing units) during start-up to improve water quality. Some stations have benefitted with Oxygenated treatment (OT) which uses addition of oxygen in feed water can further reduce the FAC because in AVT(O) the lower levels of oxygen maintained by air in-leakage control are not high enough to passivate 100% of the feed water surfaces. OT can be considered

	alloy carbon steel piping, during temp ranges of 120-150°C at locations where flow regulations causes a flashing/two-phase steam water mixture, during rapidly changing load. Another common area is eco. inlet headers.	as the next step for implementation on the units presently operating on AVT(O) feed water chemistry.  *Figure 59: Effect of Temperature on FAC*
Fly ash erosion of water tubes	In cycling units, with frequent load changes, the fly ash particle size increases with corresponding increase in metal erosion. Another issue is slag accumulation and periodic spalling. Moreover, there is variation in excess air, gas velocity and tube metal temperatures and sometimes these make ideal combinations for increased metal erosion.  *Figure 60: WW External erosion*	-Programmed operation of wall blowers and LRSBs. -Defensive strategies (with analysis of gas flow and velocities, erosion pattern etc.)-welding steel hex bars near slope tubes scallop bars, divertors & shields.

Main Steam Lines, Valves

MS Pipelines & Valves	Failures: Thermal stress due to temperature transients during start-up and thermal quenching during shutdown. Thermal fatigue and creep fatigue in welds. Cracking of valve seats and heads,Thermal fatigue/quenching.  *Figure 61: Second pass hanger tube erosion*	-Review operating procedures to match steam temperatures with the pipe temperatures. -Operate on variable pressure operation to reduce saturation temperature. -Monitor pipe temperatures and drain temperatures. -Operation of the steam line low point drains prior to startup or turbine before seat drains. -Ensure warm of stop valve before opening.

Main Turbine (HP & IP)		
Casing	Thermal fatigue & creep fatigue of thick wall. Turbine casing deformation	-Use of heating blankets will ensure the balancing of steam & metal temperatures. -Turbine casing deformation inspection.
Rotor/blades	Increased erosion of HP blades under wet conditions during starts. Solid particle erosion due to spilling oxide layers Turbine differential expansion has been an issue during startups often due to swinging of superheat and reheat temperatures after the turbine roll and is loaded and on line. The potential cause of the swinging is the control loop and size of the desuperheaters. turbine water induction can be another issue	-Improved steam turbine temperature matching on the main steam to allow for the turbine valve temperature drop on startup would benefit the sudden drop in turbine metal temperature during initial loading of the turbine. Uncontrolled swings in the steam temperature t may be an indication of desuperheater temperature control problems and or accumulated condensate in the steam lines. Operation of the steam line low point drains prior to startup or turbine before seat drains will reduce the problem by assuring that any accumulated condensate is removed prior to opening the turbine valves. During the ramp up and increased steam flow the differential expansion problem needs to be alalysed and temperature swings corrected. -Water chemistry management with AVT-R on Unit and (PT) phosphate for Unit. This is critical to avoid damage to the turbine and boiler for base load and even more important for a cycling unit design and operation. -For hot or warm startup cycles the turbine should be started at reduced pressure with full arc emission to maintain metal temperatures

		and reduce first stage thermal shock. Optimise HP/LP bypass operation
Seals	Increased air ingress from seals at extremely low load, starts & stops. DE related seal damage	-Maintain gland seal steam parameters.
Main Turbine (LP)		
Rotor	Blade erosion at low load when exhaust hood spray is used, especially at the last stage of blades. At extremely low loads the vacuum can be very low and further accelerates the blade erosion with high exit velocity. Low load cycling can cause stress corrosion cracking of the blade attachments from operating in the wet region of the Wilson line on the last stages of the low-pressure section.	-Maintain optimum condenser vacuum. -Optimise exhaust spray
Barring Gear	Although there is no influence of barring gear performance due to cyclic operation, but TG's availability on barring has a direct effect on start-up time of the unit. Issues with barring gear stalling which have delayed bringing back the unit on bar is fairly common in India, especially with KWU turbines. The reasons can be struck seals, expansion related, problems of JOP, seal steam issues.	-Ensure a condensate free auxiliary seal steam (temperature above 290^0) -Check Steam traps on drains -Ensure continuous draining through warm up orifice provided -Healthiness of Jacking oil System, lub oil system -Lifts at individual bearings are adequate -Ensure that the oil pumps and JOP comes into service during turbine coasting down
Condenser		
Condensor tubes	Thermal cycling and CW pressure variations can cause tube leakages. Increased Air ingress with cycling, which creates O2 related problems.	-Perform Helium leak tests/flooding tests to identify air ingress -Review inspection schedules
Electrical Systems		
Generator-Stator Winding	Reported cycling related problems: Due to expansion differences at a start and stop, the stator slot wedges can become loose faster,	Monitoring -Early detection of a loose end winding structure with an online end winding vibration

	even with ripple springs below the wedges The forces during the start can also have an impact on the circular phase connections and the connections to the bushings. Ageing of insulation material depends of the temperature and electrical stress during operation, which increases with cycling operation. The O-rings of the stator cooling water hoses can deteriorate faster due to expansions. O-rings made of standard NBR material are of the highest risk and / O-rings made of EPDM also at risk. Leakage in Stator Water/primary water cooling due to thermal cycling and vibrations.	system. -Visual inspection of the leads up to the bushings during a minor overhaul. Testing of the wedges with a robotic inspection. Performing a bump test during the major overhauls. Insulation degradation can be detected by several kind of measurements, such as trending of tangens-delta and partial discharges with AC voltage and leakage current with DC voltage. Preferably use O-rings made of HNBR material. -Perform a vacuum test, or an overpressure test, of the stator cooling water during every major overhaul.
Generator-Stator Core	Reported problems of the stator core as result of cycling operation are: For paper insulation there is additional aging of insulation. In case of over flux during synchronisation, overheated core ends and keybars with risk of core hotspots	-A good way to evaluate the starting of ageing problems is by performing a ring flux measurement during a major overhaul. Also deeper hotspots can be detected with this measurement. Criteria of detected hotspots are: (need to check with OEM) • <5K Acceptable • 5 – 10K Try to repair • >10K Repair Some excitation systems create a short over flux during the synchronisation resulting in a short term overheated core end and key bars. This can be damaging to the core insulation and multiple starts/stops can create a hotspot in the core. This can be detected by measuring the excitation current during the synchronisation and calculating the associated flux. The excitation system must be adjusted (as per the OEM's recommendation) if there is over fluxing.
Generator-Brush gear enclosure	Reported problem at the brush gear due to cycling operation is	-Measure and maintain the following conditions:

	loss of patina layer resulting in wear or smooth surface of the slip rings and sparking between the brushes and slip rings. During low loads and barring gear operations the current density can become too low and as a result, the slip ring temperature drops and the patina layer can reduce or may completely disappear.	-Current density of the brushes (as per OEM) Temperature of the slip rings (50°C -70°C)-check with OEM. -Roughness of the slip rings of (0,75 -1,25mu with at least 100peaks/cm) check with OEM. Adequate pressure between the brush and slip ring (140 -180gr/cm2) check with OEM. Moisture content in the air (8 -15gr/m3) check with OEM.
Switch gears, transformers, motors	Increased wear & tear due to frequent switching operations. Improper layup may lead to moisture and dust ingress	-Keep space heaters On Megger all motors under stopped condition since long period. -Consider installing VFD Review inspection schedule
Offsites		
DM Plant	With cycling operation/frequent starts, there is an increased requirement for DM water. This can sometimes become a limiting factor for unit start-up. There is a requirement of chemicals and monitoring of different chemical regimes.	-Ensure availability of COPU (condensate polishing units) Availability of online monitoring system at DM plant and at unit level (SWAS). -In the extreme case, units transitioning from base load to flexible regime may need to upgrade the capacity of their DM plants.
Coal handling plant(CHP)	Coal feeding as per requirement of flexible operation. There may be periods, when coal feeding will not be required. The variation of the feeding quantity and quality will be challenging. The practices will vary as per the flexibility requirement from the unit. There can be potentials for fire.	-The bunker levels need to be monitored and filled with required quality of coal. -For units required to operate at very low loads, coal blending will be required and the CHP must be equipped with the capability to perform large quantity of coal blending. -When units are under lay-up for long durations, the bunkers may get compacted with long standing coal. It may be required to be emptied and

		additional safety precautions will be needed for fire.

ANNEXURE 3 - Typical start-up procedures

3.1 A typical start-up procedure

Table Annex 3/1 :Start-up Preparation and checks

Area	Checks	Additional precautions
Offsite areas	CW pumps and cooling towers readiness	
	Compressed air system ready, Instrument air pressure adequate	
	LDO/HFO system: LDO pressurizing pump for the respective unit is in service and on long recirculation. HFO temperature adequate (heaters on). Pressure& temperature before trip valve is adequate. Maintain HFO temperature at 100-120^{0}C	
Alarms/Protections & Interlocks	Ensure availability of protocols for alarms and protection/interlocks checking. Record deviations	
Fire Fighting System	Fire hydrants and sprinklers healthy (check pressure)	
Availability of auto control loops	All auto control loops must be available	
Auxiliary steam PRDS	If available from other units, ensure proper pressure and temperature of Aux steam, Check line up from MS line & CRH, Check the lineup of spray water from the Condensate & Feed water system, Keep all drains open while charging	Operate the drain lines in the unit to flush out water accumulation.
Boiler	All clearance received-No pending permits, manholes and doors closes and man/material removed	
Boiler	Boiler drum vents open, drains closed, RH vents and drains open, SH header drains open, SH and start-up vents open, drains before MS safety valves open	

	CBD/EBD tanks lined up	
	All impulse lines and sampling lines root valves open	
	Ensure one CC pump in service, discharge valves are open, warm up system is lined up	
	One ECW pump is in service, Tank level adequate and makeup water available	
	Ensure availability of DM water, Adequacy of condensate storage tank levels, Coordinate with Chemistry department. Check availability of regenerated CPU	
	Eco. SV is open, Eco drain closed, Eco recirculation line to Bottom Ring header is open	
	SH /RH spray is lined up from respective BFP 's, air supply to the block valves available, drains closed, all manual isolating valves open	
	ID Fans-VFD Ac source available, Lub Oil systems are in service & LOP auto change over checked, Cooling water system charged for Lub oil coolers, all damper operation checked	
	PA/FD Fans-Power supply, lub oil, discharge dampers, blade pitch and permissive checked	
	SCAPHs lined up for all FD/PA fans. Return lines are lined up to IBD tank	
	All seal air fans & valves operation checked	
	APH- power, air motors, receiver tank pressure, dampers, soot blowers, Thermocouples for hotspot detection, lub oil system, cooling water, Oil carry over probe, firefighting system	
	HFO/LDO & Atomising air & steam system, isolating valves open, short recirculation valve open, return line open,	Check steam traps and ensure that the steam lines are

	Atomising air/steam are charged, drains closed, tracing steam charged, no leakage. Pressure control valve is lined up and pressure of 8-10 kg is maintained.	hot/no water accumulation in the lines (can cause potential delays in proving of oil guns)
Burner system	Physically inspect the burners for any visible damage or fouling.	Damaged burners can result in fireside corrosion and damaged/ fouled burners can interfere with stable combustion
	Scanner cooling air fans (Ac & DC) available	
	Burner tilt in operable condition. Set it at horizontal position during lightup.	
	All igniters are in position and fixed to guide pipe.	
	SADC operable	
Milling system	CHP informed about light-up programme, bunker level normal, bunker level indicators available, bunker outlet gates opened. Fire hydrant pressure and sprinkler pressure at bunker floor normal.	
	Check mills availability-power supply on for available mills, seal air fans lined up, Cooling water system for gear box cooler is lined up, Check MDV , Burner isolation valves are open for the available mills, CAG/CAD, HAG/HAD are lined up, Pulveriser interlock criteria satisfied, mill reject system available	
Feeders	Feeder inlet manual gates are open, Seal air valve operable, no coal on belt' switch healthy, drag chain ready	
ESP	All four passes available, all auxiliaries are in service and all field power supplies are normalised and EC panel isolators are ON, dampers operable, rapping motors power on, hopper heaters on, Shaft & Support insulator heater are ON	Note: During start-up or oil firing, ESP fields are not to be charged. Initially, during oil firing & during low temperatures two

	Purge air blower in service, Hopper level probe power supply extended, and no high alarm inform EMD accordingly	passes can be kept isolated.
BA hoppers	All Manhole doors are closed for both hopper and Clinker Grinders, BALP pumps are in service for refractory cooling and seal trough make up, BA Hopper and seal troughs are filled and seal trough is overflowing. No ash settlement is there in seal trough. (Adjust pressure to around 1.2 Ksc), All CG power supply is normalized	
FA system	Check Instrument air is charged from main plant or its compressors are in service, Check all auxiliaries are available and power supplies are normalized, Keep the system lined up to take start before Boiler Light up, run the system and clear the hoppers, Ensure ESP fluidising blower readiness with its heater. Keep them in service	
Turbine side	Condenser box charged pr. dp Ok, OLTC available system lined up, hotwell level normal, makeup lined up(normal/emergency), ECW cooler/PHE lined up	
	Turbine drain system checked (CRH, MAL, HRH, turb), flash tanks-all manual valves open, spray to flash tank lined up	
	D/A level controller, GSC, min RCV, LPBP spray, APRDS spray, LPT exhaust hood spray, valve gland sealing lines lined up, CEPs power supply normal, CPU available	
	Deaerator-All drains closed, pegging/D/a heating, spray lined up, level controllers instrumentation, strand pipes ok	
Feed Water System	Feed water heaters charged from water side, ensure proper venting up to economiser, drain lines closed, MDBFP lined up and can be started on recirculation	
	Feed Water Heaters-HP/LP- All isolating valves of drip lines (normal & emergency)	

	open, Power supply of all block valves & drain valves, FCNRVs are available, Manual drains closed, strand pipes charged	
Feed regulating station	Power supply on and selected on remote, All lines are available (low/high streams)	
LP & HP dosing pumps	Check availability, solution tank level normal, chemical in metering tank ok, Shift chemist informed to take hydrazine pump after light-up	PO4 pump is to be started after attaining boiler pressure > 30 ksc based on chemist instructions .
Vacuum System	SLC vacuum system is ON	Seal Steam temp. temp > 265 ^{o} C
Lub oil System	MOT level is normal, Availability of AOPs & DCEOP, Cooler is charged from water side. TCV is on auto, other Cooler is filled from both oil & water side, Status of Lub filter to Bearings in service and stand by filter, if choking tendency is there then changes over and clean it and make available before turbine Rolling, Check Return oil flow in all the bearings, JOP & barring gear lined up. Turbine to be taken on barring if not, centrifuge available, MOT sprinkler system available, dirty oil tank empty and MOT area clean/no leakage	
Hydraulic oil system	Hydraulic oil system-On auto, regeneration pump in service, coolers charged, CFT level normal, oil canal sprinkler system charged	
Governing System-	Governing System-Power supply normalized, EHC oil line valves are open, Stop valves test valves open, plunger coil power supply on, check records of oil injection tests / actual overspeed tests	Actual overspeed test of turbine must be done periodically as decided by OEM & local management
HPBP system	HPBP system-Manual drains closed, warm up lines drains open, Warm-up lines open, Check the temp.& pr. Set point of HPBP system, HPBP spray lined up	Ensure that there is no passing in the HPBP spray lines, else drain the line before charging the HPBP system
LPBP System	LPBP system governing rack is charged & all isolating valves in impulse lines open,	

	LPBP warm up valves are open, Drains closed, LPBP spray line main isolation valve from condensate system & individual spray isolating valves open	
Seal Oil System	Seal Oil System- SOT I SOST levels are adequate, Any one AC SOP is in service and SLC is ON, H2 side oil pump is in service Seal Oil coolers charged, DPR line up is OK	
Main Turbine	TG is on barring gear and SLC is on, barring speed normal, Turbine is reset. (starting Device is 0 %), Hand barring gear lever is available	Ensure availability of rod/lever in control room /turbine floor for manual barring gear (in case of emergency)
Stator Water	OH Tank level adequate, One pump in service and standby pump available, flow through winding and bushing normal, conductivity in main ckt within limit, N2 capping pressure normal	Typically-Flow through winding > 60 M3/hr & bushing >1.89 m3 /hr, Conductivity in main ckt = 2.0, Regen Ckt < 1.2 ms/cm start > 2.5 stop, N2 capping pressure = 0.2 ksc
Generator Gas System	All H2 coolers are charged & vented properly,H2 Pr. Ok, Check availability of adequate No of H 2 I CO 2 Cylinder connected to rack,H2 charging stream available,CO2 charging racks with flexible pipes and keys, available, H2 purity>98%(instruct shift chemist to check),H2 drier & regeneration system available	H2 pressure is > 3.3 kg/cm^2, (For Better DP control , after synchronisation pressure should be made 3.5 ksc)
TDBFPs	FW side charged for both BFP, Oil system is normal , DC EOP available .JOP Running, Governing system charged, All turbovisory parameters are OK, Gland steam charged and exhaust valve is open, All manual & Motorized drain valves are open, Extraction manual block valve is open, Steam side both vent valves are open	
	Generator and Electrical Systems	

Main Generator-	All GRP relays are reset, H 2 Coolers are charged, Gen casing is under pressurised condition with H 2 pressure, H 2 purify ok	
	GCB- GCB DC power supply is normalized; GCB earth switch is open	
GTs & UATs	Check status of electrical checking done, Check on manual mode all fans /oil pumps are available for GT and UT, Marshalling box both feeders are charged.(From SSSWGR - GT I SACDB - UT), Oil level & fans are in service, OLTC is made off, Sprinkler system kept charged & deluge VN is on auto	
Isolators & Earth Switches	Check earth switch is opened from switchyard Engineer, Status of MCC /SWGRS as per check list attached, All charged breakers No fault should flicker	
DG Sets	DG Available, oil ok, Radiator, cooling water level ok, DG set breakers at EMCC end are racked in DC ON (both Main & stand by,) No Fault in Breakers, check records for regular checking of DG sets	
DC system	checked, Cable galleries checked	

3.2 Typical Cold Start-up Procedure

Table Annex 3/2: Typical Cold Start-up Procedure

Step	Unit Condition	Operation	Remarks/Additional precautions for damage mitigation
01	Boiler ready for light up & turbine on barring	Purge and Light up boiler with 4 oil burners in AB elevation. Keep 6 guns preferably at the beginning till the swelling in the drum is over.	Air flow >25%<40%, Ensure that Drum, SH & RH vents are open, SH &RH drains closed, MSVs closed & drains before MSVs open.
		Take additional burners and limit drum metal temperature rise to <2°C/min. Monitor the Boiler Drum Top /Bottom DT. It should not be > 50° C. Check CC	Regulate oil pressure to 8-10 kg/cm² Atomizing steam pressure must be 6-8 kg/cm².

		pump cavity temp as boiler temp. rises.	
02		Take SCAPH into service	APH soot blowers to be operated. Ensure that steam pressure (10-12kg/cm^2) Charge oil carry over probe. Check through view glass. Ensure availability of IRDS Eco recirculation valve to be kept open till 30% BLI or till flow in economizer is established.
			Keep one stream CBD lined up to maintain the chemical parameters. Keep LP dozing system in service. HP dosing system will be taken in to service after attaining 40 ksc drum pressure. Sampling will start at 40 KSC.
03		Charge heating steam to deaerator form Aux PRDS	Keep economizer-recirculation valve open till there is no feed flow through economizer.
04		Open HPBP warm up valves, Put LP bypass interface ON & LP bypass on auto. Check Fixed Set point is set at 12.0 ksc	
05	Boiler Drum pressure 2 kg/cm^2 (saturation temp-120^{0}C)	Close Blr, SH, RH vents, Open MSV Bypass lines	MS, HRH & CRH lines will get warmed up
06	Boiler Drum pressure 5-6 kg/cm^2 (saturation temp~160^{0}C)	Slow charging of Main Steam Open HP bypass (around 5-8%) Take additional 4 oil guns	Monitor the rate of rise of metal temperatures Check the chemical parameters.
		Close SH & RH drain at 14 kg/cm^2. Close SH start-up vents.	
		Close HPBP warm up valves Start 3rd CC pump if required.	
			Put ESP rapping system in to service on auto mode. Hopper heaters on auto.

07	MS pressure 25kg/cm²	Take 4 more oil guns in service/maintain the oil pressure at the gun tip (between 9-10 kg/cm²). At this stage total guns in service will be 12-14 guns. Gradually increase HPBP set point	Ensure positive pressure in RH ckt. Ensure that RH protection is in service. Drains control on auto (SLC drains ON). Check all MAL drains are open & TEMP in all drain line is raising
			Temp curves as per standard curves are all satisfied. Ensure temperature limits are as mentioned in section:10.1.3.
08		ATRS programme ON. Open stop valves	HP control valve body metal temp. HP Casing temp. Monitor Turbovisory readings
09	MS/HRH pressure 50kg/cm² / 12kg/cm², MS/HRH temp-350°C/330°C.	TG rolling on ATRS	Ensure before rolling-Cond. Vacuum normal (0.88 kg/cm2) All SLCs ON Lub Oil /seal oil system normal, H2 Pr ok. LPBP/LPBP on auto Standard temp. Temperature curves satisfied
		Raise turbine speed to 360 rpm (Or as per soaking speed specified by OEM)	Soaking (check with the particular machine), check TSE margins Check lub oil return flow, turn vibrations.
10		Close all drains & strainer drains in MS, CRH, HRH & other areas	
11	MS pressure 60kg/cm², MS/HRH temp-350°C/330°C.	Start second sets of ID/FD fans Start PA fans. Keep PA Header pressure control on auto. (typical set point of 860 mmWC). Start one mill when Hot PA Hdr temperature > 150 o C and warm it. Subsequently take the mill in service	Before starting PA fans ensure that air and gas dampers of PAPH are open. Check all other mills & feeders are lined up & all necessary permissives/interlock are available. Mill warming will save time. Early charging of SCAPH and performance of PAPH will ensure sufficient temperature at mill inlet. Regulate the SAPH dampers & keep PAPH dampers full open.

			Ensure that minimum air flow in each mill >25%
12		TDBFP rolling from Aux steam and kept at 1000 rpm	Note: rolling can be done with TDBFP for APC reduction. However a trade-off had to be made between start-up time reduction and APC.
13		TG rolling to 3000 rpm Monitor vibrations, Ensure TSE margins, turbine expansions	Check the respective standard criteria is satisfied. (HP casing -MS Temp before HPBP) Check JOP cut out at around 600 rpm, AOP cut out at 2850 rpm. Check lub oil pressure-MOP oil pressure
		Synchronize the unit. Observe the block load of 50-70 MW. Ensure, load controller has come in to auto.	If load does not raise on auto ,then raise the speed reference immediately and increase the load to around 70-80 MW.
14	Load 60Mw, 65 kg/cm² pressure	Observe that HP bypass closes automatically as MS pressure drops after load pickup. Raise the HPBP pr set point gradually so that it should not open. If HP BP valves are kept on manual then close /open is to be done very slowly, otherwise the drum level will change very fast & may lead to Unit Tripping. If kept open for prolonged period, then the HP Exhaust temp will rise. Keep it under watch. LP bypass closes on auto immediately after synchronisation. Otherwise close it & put it on auto after making the deviation - ve {By reducing the fixed set point if required). Afterwards when the sliding set point > 14 ksc change the fixed set point to 12 ksc.	
15		Charge the LPH 2 & 3 , put their drip control valve on auto.	

		Pegging of deaerator to 3.5 kg/cm² gradually from CRH steam	
		Take the second mill in service	Increase the windbox pressure to 100 mmWcl
16	Load 100MW, 75 kg / cm² pressure, HRH 18 kg / cm²	Charge HPH. Put the normal/emergency control valves on Auto. Check the level set Point.	
17		Take the 3rd mill into service. Adjust firing such that the pressure rises with load.	Observe the temperature limits Rate of increase in firing to be limited to 1.5T/min
18		Start 2nd PA Fan (after 3 mill in operation). Balance both blade pitch. Now adjust the FG dampers of Both PAPH to 100 % open. Observe the APH FG outet temp.	PAPH performance is important for reduction in start-up time
19	Load 150 MW, MS Pr 100 kglcm² (HPBP pr set point - 120 kg/cm²)	Raise the speed set point of both TDBFP to 3000-3500 RPM Charge the DIA from Ext steam. CRH control valve put on auto.	
20	Load 180 - 200 MW MS Pr 120 kg/cm²(HPBP pr set point - 140 kg/cm²)	As Load increases slowly regulate the PAPH FG outlet dampers & open up the SAPH FG outlet dampers to equalise the FG temp at APH outlet Depending upon the temp, isolate the SCAPH once ESP inlet temp >120°c	
		Take Feed Water High Range line into service. (Check the drum level should not change much)	
		Start withdrawing oil support. Keep one elevation oil support	
21	Load 250MW: (MS pressure - 130 kg/cm²) (HPBP pr set	Cut in the 4th Mill in service. Take out one elevation oil support	

	point - 150 kg/cm²)		
		Reduce fuel oil pressure to around 7 kg/cm²	
22	Load 320 MW (MS pressure - 150 kg/cm²) (HPBP pr set point - 170 kg/cm²)	Charge the APRDS from CRH source	
23		Cut in 5th mill and withdraw all oil support	Adjust burner tilts
		Charge ESP fields Ensure that all the passes are charged, if passes were isolated during oil firing	Ensure that FG inlet temp to ESP 110-120°C.
24		Load 2nd TD BFP. Unload MD BFP (if rolling if taken in service) & keep it on recirculation for 1 hrs. After TDBFP stabilisation Stop MDBFP & permissive available & it is on Rapid loading Mode	Ensure that the permissive of stopped MDBFP is available
25	Load 400 MW (MS pressure - 160 kg/cm²) (HPBP pr set point - 175 ksc)	Cut in additional mill if required	Ensure that all the running mills are near fully loaded, before starting an additional mill. Additional mill may be kept into service if fast reserves on the unit is required (secondary reserves)
		Slowly increase the parameters to full load	
26	Unit at 500 MW	Check all boiler, turbine parameters at full load. Take local round to monitor any abnormal sound, water/steam leakage etc. Check boiler, turbine expansions, leakages.	

3.3 Typical Hot Start-up

Table Annex 3/3: Typical Hot Start-up Procedure

Step	Unit Condition	Operation	Remarks/Additional precautions for damage mitigation
01	Boiler drum pr.0 kg/cm², SH/RH temp 150-300°C	Start with 4 oil burners in lowest elevation	Ensure atomizing steam pr of >6kg/cm²
		Take additional burners, limit drum metal temp. raise of <2°C/min	Regulate oil fuel pressure soot blowing Pr 10-12 kg/cm²
02	Boiler drum pr.2 kg/cm²	Close SH& RH vents	
		Open HPBP warmup valves Open MSV bypass	Ensure that there is no water accumulation in HPBP lines-passing of spray valves
03	Boiler drum pr.5 kg/cm²	Open MS stop valve	Ensure MS, CRH & HRH lines get warmed up
		Open HPBP 8-10 % and close bypass valves, Put HPBP spray in auto	For temp. transients guideline, refer section 10.1.3.
04	Boiler drum pr.14 kg/cm²	Close SH & RH header drains	
05	MS 80-100 kg/cm² Temp-365°C HRH 12 kg/cm²/325°C Check OEM's rolling curve	Take additional 4 oil guns (EF el.) and float mills at MS Flow>200T/Hr	Ensure availability of mills/feeders/bunker level
06	MS/HRH to be maintained as per TSE	Take first mill into service, maintain minimum air/coal flow	No SH/RH spray is to be given. Just keep it lined up and available. If there is a requirement of spray, it indicates that combustion optimisation is required or a requirement of soot blowing. Adjust burner tilt for maintaining RH temp Secondary air temp >175°C, Reduce firing if required to control temp rise. **Regulate PAPH/SAPH dampers** .

07	Turbine speed 3000 rpm	Synchronise machine and pick up block load	
		Increase HPBP set point Float second mill and increase the loading on the first mill	Ensure closure of HPBP steam & spray valves. Regulate firing to limit coal flow raise to 1.5T/min. There should be no abrupt requirement for spray
08	Load:60 MW MS pr-60 kg/cm² Temp. Matching with TSE requirement	Take LP heaters 2 & 3 into service	Ensure switching of load controllers at 60 MW
09		Changeover pegging from Aux. steam to CRH. Cut out heating steam from Aux PRDS to D/a.	
		Ensure that all auto controllers are in service	
		Take second mill into service	
10	Load: 110 MW MS 80 kg/cm² MS temp to be matched as per TSE requirement	Charge aux. PRDS from CRH with spray and maintain temp of PRDS (typically at 250°C. Take HP heaters into service and put level controllers on auto	Charge HP heaters slowly, preferably with bypass valves if available in order to avoid rapid temp. transients
11	Load: 150 MW MS 100 kg/cm² MS temp 435°C	Take third mill into service and gradually load it	
		Control MS & RH temp	
12	Load: 250 MW MS 125 kg/cm² MS temp 450°C	Start second PA fan and cut in fourth mill. Start withdrawing oil support	
13	Load 300	All oil guns withdrawn	Ensure that all ESP fields are charged
14	Load: 350 MW MS 145 kg/cm² MS temp 480°C	Cut in fifth mill Increase the set point of SH/RH spray	Auto controllers on auto
15		Sixth mill may be taken depending on the coal quality	
16	Load 500 MW Rated parameters		

ANNEXURE 4 – Typical lay-up procedures

Step-1: Short term shut down

This very term itself implies that the unit will be required to be on operation mode within a relatively short time frame. Thus, no major changes are required from normal operating conditions except the fact that it must be protected from air ingress. The condenser vacuum and turbine seals are maintained, the de-aerator, the heater shells and boiler are inerted with nitrogen or steam, and, the feed water chemistry is maintained as follows:

Units with phosphate and all volatile treatment: Parameter Limit

pH (For all Ferrous) 9.2 – 9.6
(For mixed metallurgy) 8.8 - 9.1
ACC < 0.2 µs/cm
Oxygen, ppb (For all ferrous) 1-10 ppb
(For mixed metallurgy) < 5 ppb

Units with oxygenated treatment: Parameter Limit

pH 8.0 – 8.5
ACC < 0.15 µs/cm
Oxygen, ppb 30 – 150

Step-2: Intermediate and long term shut down

Intermediate and long term shut down require additional steps to be taken to prevent corrosion during intermediate periods of lay-up, such as for maintenance and indeterminate cycling requirements; and during long shut down up for indefinite period of time. It may be noted that certain procedures are common regardless of whether the units are laid up dry or wet. During shutdown, the turbine, condenser (steam side) and re-heater are generally considered together because, unless special facilities are incorporated, there is no practical way to isolate them. These equipments are normally stored dry.

During shut down, the re-heater should be evacuated by utilizing the vacuum in the condenser. The vacuum is then broken using nitrogen pressure. The condenser should be drained under nitrogen. If the turbine steam is supplied from a header system, all valves must be tight to prevent moisture entrance into the turbine.

Step-3: Dry air lay up

The dry air lay-up procedure requires that all components of the system be drained
by maintaining dry air flow through the equipment

Step – 4: Dry lay-up with Nitrogen

Nitrogen can be used for blanketing equipment, which is drained but not completely dry, or for blanketing equipment either filled with water or not, to prevent air ingress. Step-4 is similar to

step-3 except nitrogen is used for a positive small pressure on all component rather than dry air purge. A small continuous purge of nitrogen is required to protect the turbine, de-aerator and deaerator storage tank.

Step-5: Wet lay up

The traditional method of wet lay-up involves filling the boiler, feed water cycle and super heater with de-mineralized water containing 10 ppm of ammonia and up to 200 ppm of hydrazine. But for oxygenated treatment, hydrazine should be eliminated.
For units with copper alloy condenser tubes and/ or feed water heaters, feed water pH should be restricted to 9.0 – to 9.2 by ammonia. Hydrazine is held at 40-50 ppm. For these units, it is most important to maintain reducing conditions to prevent attack of copper alloys associated with a change of surface oxide layers from cuprous to cupric oxide. A nitrogen cap of 5 psi is maintained on the boiler.

Step-6: Wet lay up: Low oxygen scavenger method (Boiler and Feed Water Heaters)

One of the procedures uses 5-10 ppm of hydrazine equivalent is injected through normal chemical feed system into the boiler when the boiler pressure decays to 200 psi (usually it takes about 3 days) thereby facilitating homogenisation of these chemicals in the boiler. When the boiler pressure decays to 5 psi (typically 7 days) a nitrogen cap is applied to the boiler. Up to return to service, the boiler may be fired without draining the boiler.

Step-7: Wet lay up (Balance of cycle)

As turbine slows down, nitrogen is added to the condenser, which also purges the re-heater system. A continuous purge of nitrogen is necessary to account for leakage through the turbine steam seals. Nitrogen is added to the de-aerator and storage tank while this system is still hot. A small flow of nitrogen is provided to purge this system. A nitrogen cap is maintained on the shell side of the feed water heaters. The super heater is back filled with a solution up to 200 ppm of hydrazine and 10 ppm ammonia and a nitrogen cap maintained. (In case of O.T. hydrazine solution is not required).

Step-8: Very long outage

For very long storage periods, the re-heater is isolated from the turbine, and back filled with a solution of 200 ppm hydrazine and 10 ppm of ammonia capped with nitrogen. The super heater is treated similarly.

Step-9: Maintenance

Only equipments requiring maintenance needs to be drained (in case of wet storage), and nitrogen (If used) purged with air to provide an environment suitable for entry of personnel. Since nitrogen does not support human life, it is extremely important to ensure that nitrogen is completely displaced by air. The atmosphere within the equipment should be tested with suitable devices to ensure that the equipment is safe for personnel entry. However, if the unit is planned to be taken under overhauling after shutdown, it advisable to hot drain the unit at 3-5 kg/cm^2 pressure before shut down.

A comparison of various advantages and disadvantages of dry and wet lay-up:

Table Annex4/1: Wet vs Dry storage

	Wet storage with ammonia/Hydrazine with N2 capping	Dry
Advantages	-Independent of relative humidity -Ease of testing and maintenance -SH & RH covered	-Basic constituents readily available -Ease of monitoring & maintenance -Safety
Disadvantages	-Need to be recirculated & monitored -Pollution hazard -Proper sealing -Risk of asphyxiation to operating personnel if not vented before access	-Drying equipments/blowers -So2/dust free air is required -Depend on climatic conditions -Hermetical seal required -System must be completely dry -Sediments may cause corrosion if hygroscopic.

Wet lay up

This generally involves filling the unit with D.M. water containing an excess of N2H4. Circulation may be used coupled with positive nitrogen pressure. A nitrogen cap allows (a) boiler and feed water equipment to remain full, (b) requires no excessive addition of chemicals (c) permits nitrogen to rush in where steam collapses, preventing oxygen from entering the system.
The following procedure for nitrogen addition will be handy:

Main condenser and turbine

- Nitrogen addition starts while turbine is spinning down
- Nitrogen is added quickly at first, then slowly as the vacuum approaches zero.

Deaerator and storage Tank

- Nitrogen is added when the de-aerator is still hot.
- Nitrogen is purged for about 20 minutes followed by maintenance of a small nitrogen positive flow.

Feed water Heaters

- Nitrogen is supplied through shell-side vent line.

Steam Drum

- Nitrogen supplied to drum through vent lines.
- Nitrogen feeding is started while the drum is still hot.

The boiler and economizer water should be circulated routinely to prevent stagnant condition developing.

Nitrogen does not support human life; hence the relevant safety precautions are extremely important. Before any equipment that has been laid–up with nitrogen can be entered by personnel, all nitrogen supply lines must be disconnected, the equipment purged with air, and oxygen levels verified as safe by proper oxygen test procedures like using ORSAT / portable oxygen analyser. Minimum oxygen percentage should be 18% before entry of working personnel.

Table Annex4/2: Wet lay-up procedure (for drum type units)

Type of shut down	Procedure	Remarks
Pre-operational period (post hydro)	With boiler filled to overflowing pressurize the unit with nitrogen to 0.35 atm pressure. Blanketing and filling in case of drum type boilers	- All non-drainable section to be hydraulically tested and should be filled with DM water containing 10 ppm of NH3 and 200 ppm of N2H4. It should produce a solution of pH 10. The super heater should be first filled to over flow into the boiler drum. Then the boiler can be filled through normal fill connection.
Preoperational period (post chemical cleaning)	-Introduce DM water containing 10 ppm of NH3 and 200 ppm of N2H4 into super heater, feed water heaters (tube side) and associated piping, economizer and boiler. -Nitrogen cap the super heater, feed water heater (shell side) and drum. Maintain 0.5 atm of N2 pressure.	-Hydrazine and ammonia are to be added to the system by pumping concentrated solution through the chemical dosing pumps. It is important to have fluid temperature in the cycle below 200°C before addition of hydrazine. If this temp. is exceeded N2H4 will decompose.
Short outage 4 days or less unit not drained	-Maintain the same hydrazine and ammonia concentration as those present during normal operation and normal water leveling boiler. -Establish and maintain 0.35 atm nitrogen cap on the super heater and the steam drum -Nitrogen cap the shell side of the feed water heaters.	-The tube side of copper alloy feed water heaters should be filled with D.M. water containing 0.5 ppm of NH3 and 50 ppm of N2H4. - Nitrogen cap should be applied through the drum vent and super heater outlet header drain/vent as the unit is cooled. When pressure drop to 0.35 atm. Admission of air through atmospheric vents should be avoided.
Short outage 4 days or less unit drained	-Maintain the same hydrazine and ammonia concentration as those present during normal operation and normal water leveling boiler.	During every cold start, visually check the feed water. Only clear water should be admitted to into the boiler and used for desuper heater spray from the beginning.

	- Drain and open only those sections requiring repair. - Isolate the remainder of the unit under 0.35 atm N2 pressure. - Nitrogen cap the shell side of the feed water heaters	
Long outage 4 days or more unit not drained	-Establish and maintain a 0.35 atm. Nitrogen cap on the super heater and steam drum. -After that Fill the super heater through the outlet of non- drainable section with DM water containing 10ppm of NH3 and 200 ppm of Hydrazine. -Increase the hydrazine and ammonia concentration to 200ppm and 10 ppm respectively in boiler, economizer and feed water heaters (tube side) - Nitrogen cap the shell side of the feed water heaters	
Long outage 4 days or more unit drained	- Drain and repair only those section requiring repair. - Fill the super heater through the outlet of non-drainable section of NH3 and 200 ppm of Hydrazine. - Increase the hydrazine and ammonia concentration to 200 ppm and 10 ppm respectively in undrained circuit of the boiler, economizer and feed water heaters (tube side). - Establish and maintain a 0.35 atm. Nitrogen cap on the undrained section of the unit where possible. - Nitrogen cap the shell side of the feed water heaters. - After repair fill the drain section with hydrazine and ammonia concentration to 200 ppm and 10 ppm respectively and cap with nitrogen.	

Dry lay up

Storage of plant under complete dry-out conditions has more benefits for longer periods of storage, however, it needs great care to obtain complete dry-out, as the retention of localized

small pools of water can lead to serious off-load corrosion. In using dry storage, the residual heat in the unit is to be used to the full extent possible to assist in drying out process. When boiler is off loaded, it is normally blown empty along with associated circuit at around 3-5 bar. However, it would be considerable advantageous if the boiler starts emptying from a higher pressure (e.g. 20 bars)/or within the operational limitations. When the drying is being with natural air, during the cooling down, header caps and drum doors should be removed without delay to establish proper ventilation.
Complete dry-out of super heaters, re-heaters and economizer tubing might not be achieved in spite of these conditions, and circulation of dehumidified air through the plant to remove residual moisture is essential. Clean, dehumidified air (Relative humidity < 30%) must be ensured to purge the boiler and auxiliary equipment during lay-up periods.

Feed water heaters, condenser, re-heater and turbine

These components constitute one group, which cannot be isolated without special arrangements. Protection of these equipments during shutdown needs additional efforts. Generally dry storage procedure is used for these components.

Metallurgy of feed water side condensers and feed water heaters is the most important factor while deciding feed water chemistry for intermediate and long-term storage. For system with copper alloys, regulated quantity of hydrazine and ammonia solution to give a pH of around 9.0 may be used. O2 ingress must to be avoided to minimize copper corrosion. Contact of copper alloys with high concentration of ammonia should be prevented.

Systems with ferrous metallurgy can go for a wet lay-up with a pH of around 10, with ammonia, & or hydrazine and completed with nitrogen blanketing. Units on oxygenated treatment should not use hydrazine.

Shell side feed water heaters feed water heaters should be protected by a nitrogen blanket or a steam blanket (short term lay-up) when the unit is out of service.

Condenser

If the unit is required to be brought within a short time, it is advisable to maintain vacuum. Some units cycle frequently during peak generating seasons, and may be required to be on frequent ON/OFF conditions. Under these conditions, the chemistry control is significantly better when a vacuum can be maintained on the condenser and steam turbine. This prevents oxygen and carbon dioxide from saturating the water in the hot well (resulting in high cation conductivity on startup) and potentially initiating pitting on the low-pressure turbine.
Hotwell should be filled with water and wet layup chemistry is established, CW remains in service. If shut down period extends to longer periods, condenser vacuum may be withdrawn, hotwell drained and condenser taken on dry lay-up

Turbine

Turbine dry lay-up using dehumidifier air can be combined with dry lay-up of the unit steam side circuits.

Deaerator and storage tank

The deaerator and deaerator storage tank should be protected by a small but steady nitrogen purge.

Mills

For long shutdown of the unit, ensure the coal bunkers, pulverizers and coal feeders are emptied to reduce the risk of fires in bunker, mills and feeders. Ensure sufficient air purge for the burners. For short shutdown, the bunkers must be covered and the temperature inside the bunkers must be monitored. The healthiness of the bunker floor fire hydrants and sprinkler system must be ensured. Check the fire hydrant pressure at the bunker floor.

Figure 62: Coal bunkers must be emptied when unit is under long shutdown

APH

Hot water washing of air preheater baskets before shutdown. Utilise the shutdown time for inspection and repairs (depending on the shutdown time available). Inspection should include baskets, seals, rotors,washing nozzles and lub oil system.
Ensure complete drying during after water washing and check the hoppers for cleanliness. If required, run the ID/FD fans for drying and rotate the APH, preferably with air motors.

Coal Pipes

For long shutdown, perform visual inspection for any coal accumulation/compacting inside the coal pipes with a flexible pipe camera.

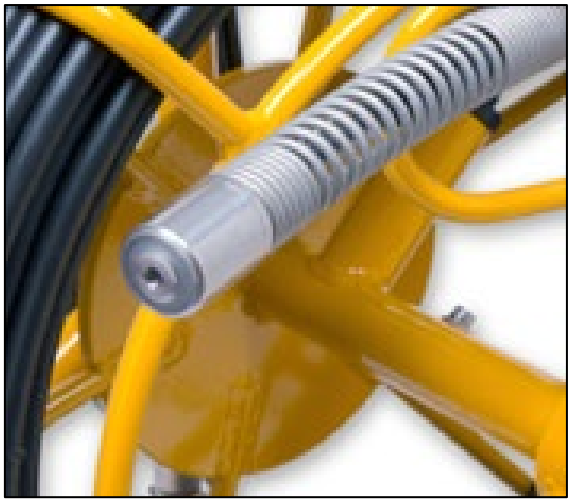


Figure 63: Flexible Pipe Camera

Generators

- Hydrogen Pressure to be maintained for the generator, H_2 dryers in service, Check the purity of H_2.
- Stator water system to be kept in service with proper chemical parameters.
- Keep seal oil coolers in service (with coolers for one week, after which coolers can be isolated)
- Hydrogen may be purged out with CO_2, if the outage is for long.
- Force-cooled bus systems to be kept in service with proper dehumidification
- Check LLD (liquid level in generator)
- Exciter- For long shutdown, lift the exciter commutator brushes and the collector ring brushes. commutator and collector rings may be cleaned.

Turbine lub oil

The lube oil and lube oil cooling system to be kept in service. Oil centrifuge may be operated at regular intervals (or as per parameters-moisture and MI). Coolers are required to be in service for about a week.

Water teatment plant

If station is in shutdown, water treatment equipment needs to be properly laid up to prevent damage. This includes proper layup of the reverse osmosis system and the demineralizer, as well as any pretreatment equipment, such as filters. This also includes chemical pumps and chemical storage tanks. In particular, all membrane- based equipment (reverse osmosis) is very susceptible to biofouling during idle periods. EPRI has recently published a volume of recommendations for the layup of water treatment equipment. Additional cycle chemistry limits have been included in this IAPWS Technical Guidance Document.

Film forming amines

It is recommended to add nitrogen to the steam side of all of this equipment as the unit is coming offline and maintain a slight positive pressure with nitrogen during the layup to eliminate the ingress of oxygen in critical areas. Some utilities have seen excellent results by using film forming products, such as film forming amines, instead of a conventional AVT chemistry. These products

have been shown to coat metal surfaces in the deaerator, shell, and waterside of the feed water heaters, condenser, and even the turbine blades and rotor, preventing oxygen attack of the metal surface. In these cases, the equipment can be left wet or dry.

Prior to moving to cycling operation, the plant could choose to install a nitrogen blanketing system or move to one of the film-forming chemistries as a way to mitigate potential for oxygen-caused corrosion. If a film forming amines/product is the desired option, the plant should be aware that there are many different film forming products currently being marketed. Some contain amines; some do not. Some vendors are happy to share the constituents in their product with their clients; others do not. In addition to ensuring that the plant can properly apply and test for the product, criteria should be established to show that the product is actually preventing corrosion during periods when the unit is offline. This may include additional corrosion product monitoring at least until the product is well-established. In addition, the plant needs to ensure that the particular product selected does not interfere with (coat) online instrumentation.

Figure 64: Film Forming Amines[56]

Lay-up monitoring

All lay-up conditions, dry or wet must be monitored at regularly to ascertain that the lay-up water / air quality (RH-30%) is maintained. In the event of deterioration of the lay-up and water chemistry to corrosive conditions in a particular component, either that component needs to be drained or if proper mixing can be provided requisite additional chemicals can be added. Records of all readings and monitoring activities must be maintained.

Environmental consideration

The disposal of lay-up solution containing high concentration of ammonia and hydrazine needs to be carried out after treatment so that the final effluent is in compliance to the pollution monitoring agencies (Pollution control boards). This explains the reasons why the most popular choice of lay-up procedure is the one which does not necessitate draining of boiler prior to start up.

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