Flexibilization Field Report

Practice Guide to Get Ready for Flexible Power Plant Operation

Based on results of activities carried out under the auspices of the Indo-German Energy Forum

ENERGY IS US

December 2022

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[1] Pictures and graphs shown in this report were developed in the course of the IGEF project either from vgbe, Siemens Energy or Steag Energy Services

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List of Abbreviations

ACV	Auxiliary Control Valve
APH	Air Preheater
BFP	Boiler Feed Pump
CFMS	Coal Flow Measurement System
EOH	Equivalent Operating Hours
ESH	Equivalent Starting Hours
FD fan	Forced Draft Fan
GCV	Gross Calorific Value
HP	High Pressure
HR	Hot Reheat
ID-fan	Induced Draft Fan
MCR	Maximum Continuous Rating
MDBFP	Motor Driven Boiler Feed Pump
MS	Main Steam
RH	Reheat
SA	Secondary Air
SCAPH	Steam Coil Air Preheater
SH	Superheater
TDBFP	Turbo Driven Boiler Feed Pump

Abbreviations referring to companies, institutions and common measurement units (e.g. MW, min) are not included in this list.

1 Background

To ensure the power supply in the country, India is aiming to double its electricity generation capacity by 2030. The Indian government has also set ambitious goals for the expansion of renewables – aiming to install at least 300 GW of solar PV and 140 GW of wind power by 2030. The Indian Prime Minister Modi has announced that India will reach a non-fossil capacity of 500 GW by 2030. 50% of India's energy requirements will come from renewable energy by then. Currently, the renewable capacity excluding hydro power accounts for more than 115 GW. These developments will mark a huge change in the Indian power system, as currently around 58% of the installed capacity (407.8 GW in total) comes from conventional thermal power plants[2]. While India, on a national level, can rely on solar energy generation every single day of the year, wind is not always available at peak demand times in the morning and evening.

As such, flexibilization – which aims at managing the fluctuations in renewable supply by converting baseload power plants into flexible generating facilities – has become the new paradigm in thermal power generation. Therefore, it has become a topic of the Indo-German Energy Forum (IGEF) – a high level platform created to enhance and deepen cooperation within the energy sector. The IGEF was founded by the German Chancellor and the Indian Prime Minister at the Hannover Fair in April 2006. It focuses on both promoting private sector activities and putting in place an enabling environment to further develop the market for power plant technologies, energy efficiency and renewable energies in India.

A special task force on flexibilization has been created. On the Indian side, National Thermal Power Corporation Limited (NTPC), the Central Electricity Authority (CEA), the network operator POSOCO (Power System Operation Corporation Limited) and BHEL (Bharat Heavy Electricals Limited) are involved in the task force. On the German side, both the Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) and vgbe have been supporting the task force on behalf of the Federal Ministry of Economic Affairs and Climate Action (BMWK). The task force is headed by the Director Operations at NTPC, and the Excellence Enhancement Center (EEC) holds the secretariat and coordinates the work.

One of the key purposes of the task force was to showcase the technical feasibility of flexible power plant operation. Therefore, investigations at four Indian power plants were conducted in the period from January 2017 to July 2022. They included test runs at the Dadri power plant operated by NTPC, at the Maithon power plant operated by Tata Power and at the Andal power plant operated by DVC. Another study was conducted at NTPC's Simhadri power plant. The investigations focused on 500 MW subcritical units.

This handbook summarizes the main results and learnings of the studies. It provides an insight into power plant flexibilization which can serve as a blueprint for other Indian plants.

[2] Central Electricity Authority (CEA), Installed Capacity in India as of 30 September, 2022: https://cea.nic.in/installed-capacity-report/?lang=en, retrieved on 31 October, 2022

2 Introduction

The flexible operation of coal-fired power plants forms an important pillar of India's energy transition. Therefore, it is worth reflecting on some important aspects of flexible power plants that are not only valid for India but also for many countries worldwide.

+ Flexible thermal power plants are key to ensuring sufficient system integration of variable renewable energies such as wind and PV.
+ Flexibility of coal-fired plants contributes to the reduction of CO_2 emissions – the decrease of full-load operating hours outweighs the effect of lower efficiency at part or minimum load.
+ The successful deployment of flexibility measures depends on the market design – the economic viability of the plants has to be ensured, preferably through incentives for flexible operation.
+ Special focus should also be placed on the further training and skill development of the power plant personnel.

Flexible operation comprises aspects of low minimum load, fast start-ups and shut-downs and high ramp rates. The IGEF investigations focused on subcritical coal-fired power plants. The original design and set up of these plants include some favourable configurations for flexible operation – e.g. they are equipped with a high number of mills, tilting burners and frequency-driven fans and actuators. The following units were investigated:

- 210 MW and 500 MW (test runs 2018) at Dadri
- 500 MW at Simhadri (no test run)
- 500 MW at Maithon
- 500 MW at Andal

The following results were achieved during the test runs. The ramp rate refers to a% load change per minute.

Unit capacity	500 MW	500 MW	500 MW
Operator	NTPC	Tata	DVC
Date	June 2018	July 2021	April 2022
Minimum Load	40%	36%	32%
Ramp Rate	2.0–3.0%/min	1.5–2.0%/min	2.0%/min

Table 1: Achievements of the IGEF test runs.

Moreover, the results of the investigations at the 210 MW unit at Dadri and at the 500 MW unit at Simhadri power plants also indicated that a minimum load of 40% should be possible without major interventions and investments.

The following table shows examples for the composition of coals which were burned during the test runs.

Fixed Carbon%	32.8	38.4	36.4
Volatile Matter%	20.4	16.6	22.3
Total Moisture%	8.1	7.4	4.0
Ash%	42.3	37.6	37.3
Gross Calorific Value kcal/kg	3,932.8	4,268.7	4,017.0

Table 2: Coal composition during the test runs.

The following table shows examples for the composition of coals which were burned during the test runs.

The flexibility studies were conducted by vgbe in co-operation with Steag Energy Services GmbH and Siemens Energy Global GmbH & Co. KG, both member companies of the vgbe association. The following reports were developed and published – they served as the basis for this Flexibility Handbook:

No	Title	Issued	Partner
1	Flexibility Assessment for the NTPC Plants Dadri and Simhadri	Sept 2017	Steag
2	Flexibility Assessment – Implementation Plan for the 500 MW Unit at Dadri Power Plant	Sept 2018	Siemens
-	Pre-Test Data Assessment Report Andal Power Plant	Sept 2020	Siemens
-	Pre-Test Data Assessment Report Maithon Power Plant	Sept 2020	Siemens
3	Flexibility Assessment and Implementation Plan for the 525 MW Unit 2 at Maithon Power Plant	Dec 2021	Siemens
4	Flexibility Assessment and Implementation Plan for the 500 MW Unit 2 at Andal Power Plant	June 2022	Siemens

Table 3: Study reports issued during the IGEF project.

The following pictures were taken after the successful completion of the test runs.

Figure 1: Test runs at NTPC's Dadri power plant in June 2018.

Figure 2: Test runs at Tata Maithon power plant in July 2021.

Figure 3: Test runs at DVC Andal power plant in March 2022.

Note of Thanks

On behalf of the Indo-German Task Force Flexibility which was established on request of Ministry of Power, Govt. of India and the German Ministry in charge of Energy, Govt. of Germany, vgbe expresses its deep gratitude to the power plant teams of Simhadri, Dadri, Maithon and Andal for the professional and well-organized preparation and execution of the flexibility investigations and test runs undertaken. We thank the management of NTPC, DVC and TATA Power for their valuable inputs and highly appreciated support given to the activities carried out.

All test runs were only possible thanks to the guidance and full support by the Ministry of Power (MoP), Central Electricity Authority (CEA), Grid Controller of India (Grid India), Bharat Heavy Electricals Limited (BHEL) and NTPC. We would like to specifically thank Shri Alok Kumar, Hon'ble Secretary (Power), MoP; Shri V.K. Dewangan, former Additional Secretary, MoP; Shri Piyush Singh, Joint Secretary (Thermal), MoP and its predecessors Smt. Archana Agarwal and Shri Aniruddha Kumar; S.K. Kassi, Chief Engineer (Thermal), MoP; Mr. B.C. Mallick, Chief Engineer (Thermal Renovation & Modernization), CEA and the chair of the Indo-German Task Force Flexibility, Mr. Ramesh Babu (Director Operations), NTPC and its predecessors Mr. Prakash Tiwari and Mr. K.K. Sharma. Without their personal involvement, dedicated support and trust, those test runs would have not been possible.

We would also like to thank Mr. A.K. Sinha (rtd.), NTPC and Mr. Tobias Winter, Director, Indo-German Energy Forum (IGEF) Support Office for their active support, which was essential to the smooth execution of the flexibility test runs. We are very grateful to the Excellence Enhancement Centre (EEC) for the Indian Power Sector and the team led by Director Mr. Rakesh Chopra for the continuous support to the task force throughout the entire project. Vgbe and EEC thank their partners and members, Steag and Siemens, for the excellent and fruitful technical cooperation.

Last but not least, we would like to thank the very many people not mentioned here, who have contributed their time, knowledge and contacts to make the test runs possible. It was all of you, who formed part of this exciting journey of demonstrating the technical viability of flexible power plant operation in India.

3 Flexibilization Approach

Based on the investigations at the four power plants, a generic procedure for the technical flexibilization can be deducted. Test runs form a core activity, as they provide insights into the real performance of the plant with respect to minimum load, start-up time and ramp rates. The procedure is shown in the following figure.

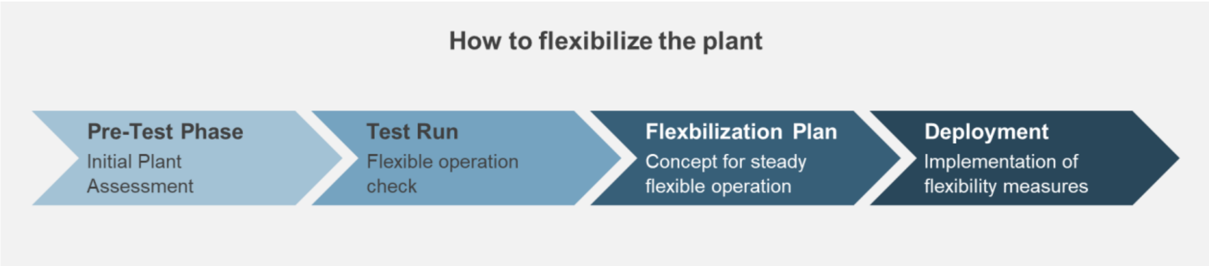


Figure 4: Technical flexibilization procedure.

The technical flexibilization procedure comprises four steps which are explained in detail in the following chapters. In brief, these four steps focus on:

(1) **Pre-Test Phase:** Before the test runs are conducted, the status quo of the plant is analyzed with respect to flexible operation. The assessment of operating data at different load conditions is the key activity. Based on this assessment, potential obstacles and limitations for low load operation, as well as for load ramps, can be identified.

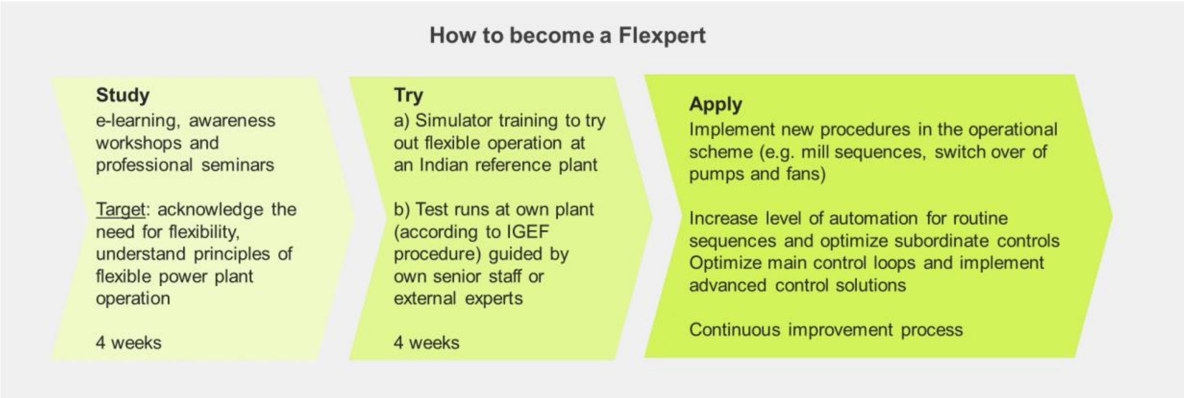
(2) **Test runs:** The program comprises part-load and minimum-load operation, as well as ramp-up and ramp-down tests for a set period. The tests follow a defined test schedule that needs to be released by the system operator prior to the test. An experienced team of operators follows a test procedure that also needs to be prepared in advance. Health and Safety (HSE) requirements have the highest priority. A defined set of operating data, including the coal composition, is collected during the tests.

(3) **Flexibilization plan:** The operating test data are analyzed in order to ensure steady, flexible plant operation. This analysis covers all areas of plant operation: from combustion to water-steam cycle through to flue gas and turbine operation. Based on the results, measures to enhance and/or to sustain flexible operation are derived. These measures need to be assessed according to techno-economical evaluation.

(4) **Deployment:** Finally, the flexibilization plan needs to be implemented. As the measures will most likely involve a higher level of automated operation of equipment, sufficient time should be foreseen. This step is not just about technology, it is also about trust in automated procedures and sequences – and, moreover, in optimized control logics.

It might be beneficial to engage an experienced third party at the starting point of the flexibilization activities. This engagement might help to overcome some uncertainties in flexible operation. However, the skill level of Indian power plant personnel is regarded as sufficient to manage the flexibilization, with only limited requirements for external support.

In this context, it should be noted that the technical flexibilization procedure should be accompanied by a skill development program. A principle description of such a program is presented in another report. The following figures provide an overview of the training program for so-called ***Flexperts*** – trainees acquire an understanding of the flexibility principles and learn how to operate a plant accordingly. The program is divided into three steps – study, try and apply.



FLEXPERT

Figure 5: Flexibility skill development program "study, try and apply" and Flexpert logo.

4 Pre-Test Phase

This phase provides transparency about the plant status with respect to flexible plant operation. At the end of the pre-test phase, a Pre-Test Data Assessment report provides an insight into the status quo and the potential obstacles and limitations for flexible operation. A quantitative assessment of operating data, as well as qualitative assessments of operating personnel's feedback, form the basis of the report.

4.1 Information and Data Input

Besides the operating data, some general plant information is required to investigate the plant design. Such information comprises P&IDs and operational manuals for main power plant areas – boiler, including water-steam-cycle, and turbine. The following design information is especially important for the flexibility assessment:

- boiler type, evaporator and combustion design
- the number and arrangement of mills and fans – Induced (ID), Force Draft (FD), Primary Air (PA), Secondary Air (SA)
- type and number of boiler feed pumps (BFP) – motor-driven (MDBFP), turbo-driven (TDBFP)
- Air Preheater (APH) design – availability of Steam Coil APH (SCAPH)
- philosophy for unit control – sliding (boiler follow) mode or fixed pressure (turbine follow) mode – and main control loops (e.g. steam temperature and drum level)

The following picture shows the principle design of the subcritical 500 MW units with two-pass boilers that were investigated in the course of the studies. It is mainly based on a two-pass boiler manufactured by BHEL and a turbine with KWU/Siemens design.

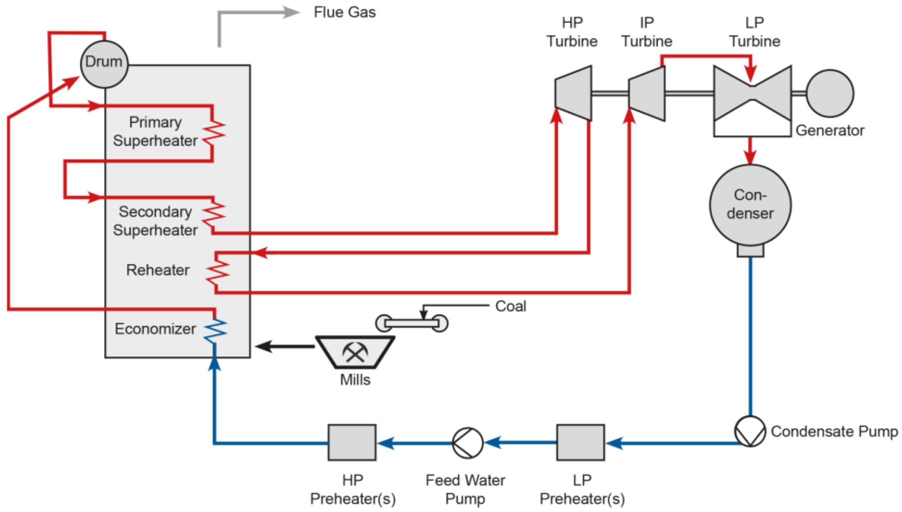


Figure 6: Principle design of the subcritical 500 MW units.

In order to prepare a pre-test data assessment, **operating data** at different load points and during transient operation are required. In steady-state operation, data should be provided for performance at full load (100% maximum continuous rating (MCR)) and at the lowest operated load in the last couple of months. Transient operation data comprise the following operational situations:

1. Cold start-up to full load (if not available, then warm start-up)
2. Ramp down from full load to low load (lowest operated load in the last couple of months)
3. Ramp up from low load to full load (lowest operated load in the last months)

The operating data should have a time resolution of less than 1 minute and comprise at least the following parameters:

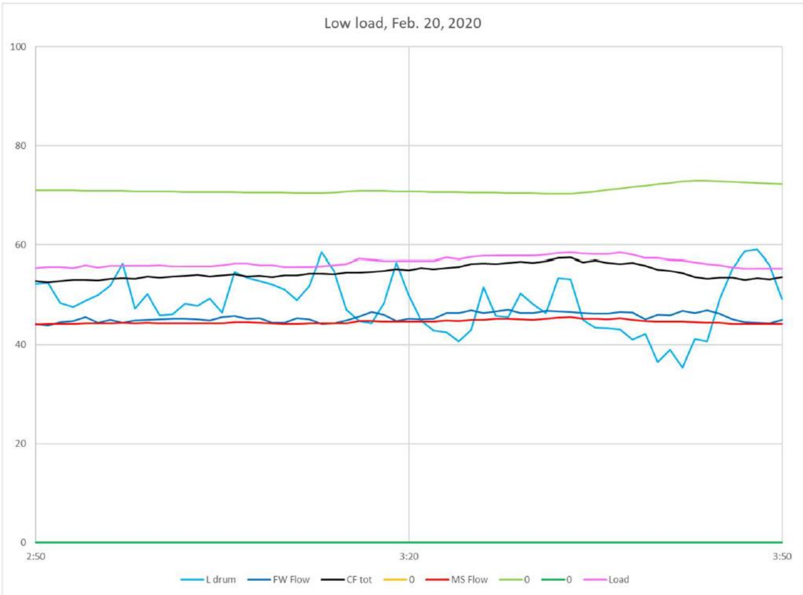
- Load
- O_2 values and O_2 average in excess air
- NO_x
- CO
- Main steam pressure
- High pressure (HP) steam temperature
- Reheat (RH) steam temperature
- Superheated (SH) steam temperature
- Flue gas exhaust temperature
- Mill load
- Flame scanner intensity
- Status signal of burner (on/off)
- Drum level
- Metal temperatures

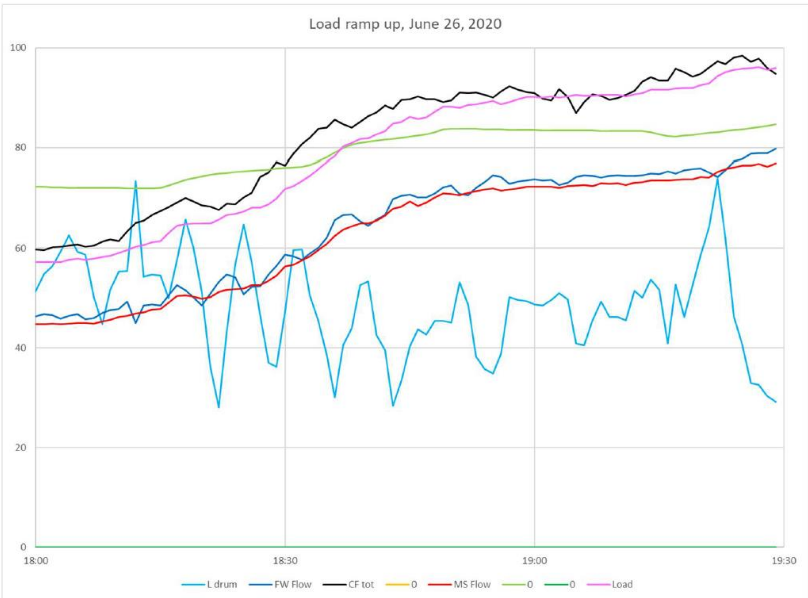
In addition to the operating data, the operating power plant personnel should provide answers to the following questions:

- What prevents you from operating at lower load?
- What do you consider as the main problem during minimum load operation?
- Do you use burner tilt to reduce main steam temperature during ramp up?
- Can flame scanners influence the ability to operate at lower loads?
- How do flame scanners influence the ability to operate at lower loads?
- Do you consider combustion stability / flame stability at minimum load as a challenge?
- During start-up: At what threshold of coal flow / number of mills in operation, do you switch off the auxiliary fuel (oil)?

- How do you assess the level of automation at your plant? As this aspect is very important, a detailed questionnaire will be provided in order to assess the current automation status in depth.

A **Pre-Test Data Assessment Report** presents the results of the data analysis and the assessment of the other information. The following figures show results of the data analysis – here with respect to main plant parameters during steady low load operation and during ramp up.





- drum level (light blue): -100 to 10 mm
- el. generation (pink): 0 to 525 MW
- coal flow (black): sum of feeder speed 0 to 320%
- main steam pressure (green): 0 to 200 bar
- main steam flow (red): 0 to 2000 t/h
- feed water flow (dark blue): 0 to 2000 t/h

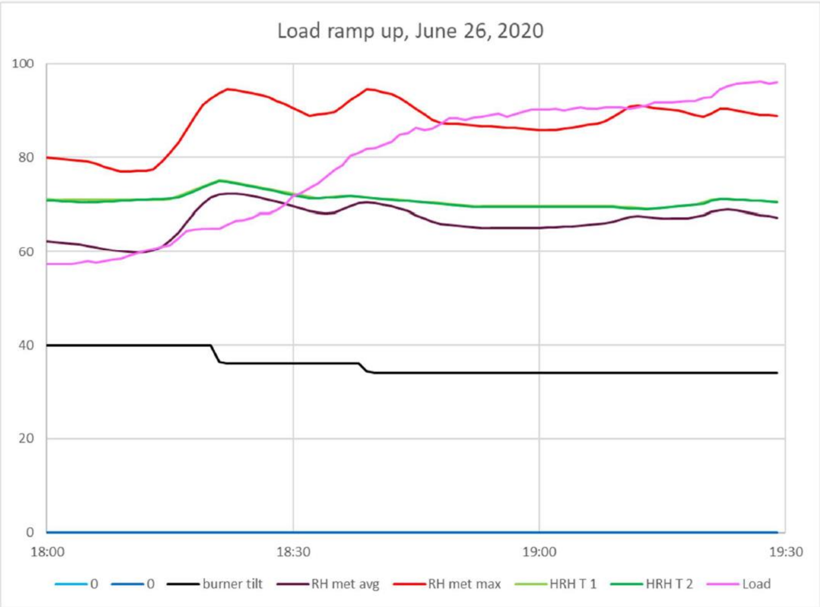
Figure 7: Main plant parameters during low load operation (above) and ramp up (below).

These descriptive diagrams use a uniform scaling from 0 to 100% of the associated measurement range of the operating variable. In this case, the following statement regarding the drum level was submitted:

Drum level was within approximately +/- 40 mm and in the first 50 minutes showed signs of periodical oscillation. The oscillation implies that control structures are not optimized and/or not tuned properly. The speed of the load ramp is not that big (less than 1% per minute), and it is possible to minimize deviations in drum level. Deviations of +/- 40 mm are not considered a problem, but when increasing the speed of load ramps, it is also assumed that drum level deviations will increase, which could become a problem.

According conclusions were also provided: *For increased speed of load ramps, the drum level control should be optimized. It looks sufficient for low load operation, but it is yet unknown how this will change when lowering load further. With faster speed of load ramps, it is assumed that deviations in drum level will increase. Tuning (and/or structural changes) are recommended. The correct setting for drum level control is a fast slave controller for flow difference (between steam and feed water) (integral time approx. 20 seconds), with a slower master controller for level (about 3 to 5 minutes integral time, gain as much as possible as long as still stable, derivative action recommended).*[3]

The next figure shows the metal temperature development during load ramps.



- red: max. RH metal temp. 400 to 600°C
- green: hot RH steam temp. 400 to 600°C
- brown: average RH metal temp. (of 44 measurements) 400 to 600°C
- pink: el. generation, 0 to 525 MW
- black: burner tilt position, 0 to 100%

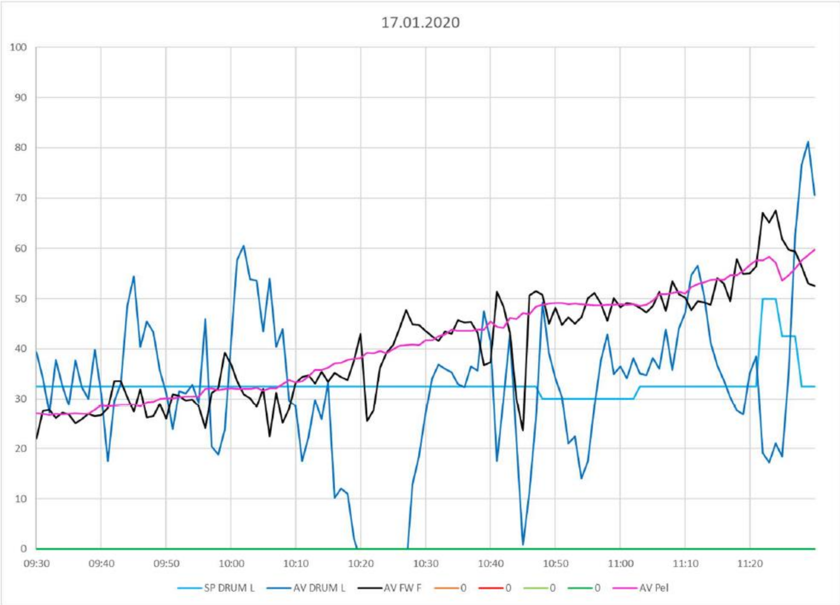
Figure 8: Steam and metal temperatures during ramp up.

The analysis of the findings was as follows: *There is a big increase in RH metal temperatures (both max. and average) at the beginning of the load ramp. At the same time, the hot RH steam temperature is increasing slightly. The burner tilts are hardly reacting. (They may be in manual, as they seem to change position in steps.)*

[3] Pre-Test Data Assessment Report for the Maithon Power Plant, issued by the IGEF team in September 2020

This indicates that the burner tilts are not working properly. Either they are in manual, which shows a lack of confidence in the controls, or they are in automatic and do not react sufficiently.[4]

The next figure shows a very typical issue that came up during the pre-test phase and which was verified in the test runs at all three plants.



- black: feed water flow 0 to 1,500 t/h
- blue: drum level setpoint and value -200 to 200 mm
- pink el. generation (0 – 500 MW

Figure 9: Feed water flow and drum level during ramp up.

This figure was generated during the pre-test phase for the Andal power plant (IGEF report issued in September 2020). It clearly indicates a problem with the control of the drum level and feed water flow during ramp up. The high fluctuations are caused by a closing or opening of the recirculation line, which is equipped with on/off valves. This is discussed in the next chapters in more detail.

At all investigated plants, the following common issues could be identified:

- steam temperature control at low load
- drum level control at low load and during load ramps
- flame stability and furnace pressure and windbox delta pressure during load ramps
- low flue gas at low load

These issues will most likely cause problems during flexible operation in any plant. The main reason is that the control logics are not optimized for lower load and higher ramp rate ranges. The exact behaviour needs to be investigated during the test runs.

[4] Pre-Test Data Assessment Report for the Maithon Power Plant, issued by the IGEF team in September 2020

5 Flexibility Test Runs

The test runs mark an important step in the technical flexibilization procedure. In the Indian context, the test runs aim at finding the lowest minimum-load operation, as well as highest ramp-up and ramp-down rates. Prior to the tests, it is necessary to check whether any existing control setting might become an obstacle during load reduction. However, no modifications are permitted that may potentially affect the safety of the boiler during, in-between or after the tests. The complete boiler and plant protection should be activated. If necessary, the control systems should be switched to manual mode (e.g. attemperator / steam temperature control).

As safety has highest priority, the test should be interrupted if there is any concern. Preferred operation procedures should include all expected operating modes of the boiler and the usage of average coal. Average coal means that the coal should not be of better quality than in usual daily operation. The tests should reflect the real situation of the plant. Hence, they are conducted by the plant team – in the IGEF project, with support from Indian and German experts.

The tests follow a defined test schedule which needs to be released by the system operator prior to the test. As this is an important pre-requisite of the test runs, the involvement of relevant stakeholders such as the system operator or beneficiaries is essential.

Furthermore, a detailed test procedure gives instructions on how the test should be carried out in detail.

5.1 Test Run Schedule

The duration of a test run, including minimum load and ramping tests, is usually about a week. The following table shows an example for the program.

Date	Weekday	Test	Target Load
28 March	Monday	Minimum load test	200 MW (or less)
29 March	Tuesday	Minimum load test	200 MW (or less)
30 March	Wednesday	Load ramp test	between 200 and 500 MW
31 March	Thursday	Load ramp test	between 200 and 500 MW
1 April	Friday	Reserve	

Table 4: Example of a test schedule.

For each day, a dedicated load profile should be provided by the system operator. The next two figures show examples of such a profile – for a minimum load test and for a ramping test.

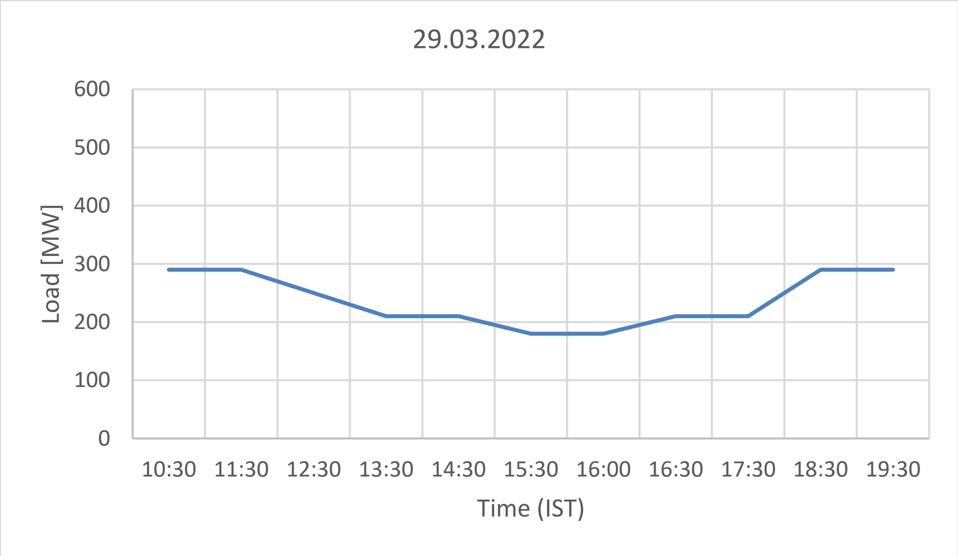


Figure 10: Example of a load profile for minimum load tests.

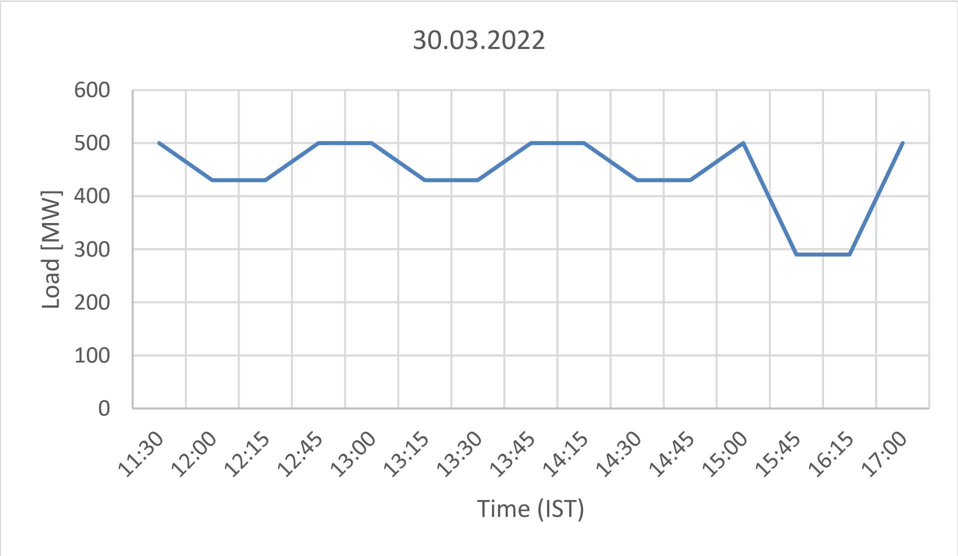


Figure 11: Example of a load profile for ramping tests.

5.2 Test Runs Procedure

In both tests – the minimum load and the ramping test – the load will be reduced and respectively increased until an obstacle occurs. The load is changed in pre-defined steps. If an obstacle occurs, there needs to be a discussion about how to overcome it. Possible solutions range from manual intervention to a changed operation regime (e.g. changing combination of mills, changing main steam pressure, ...). This principle approach is shown in the next figure.

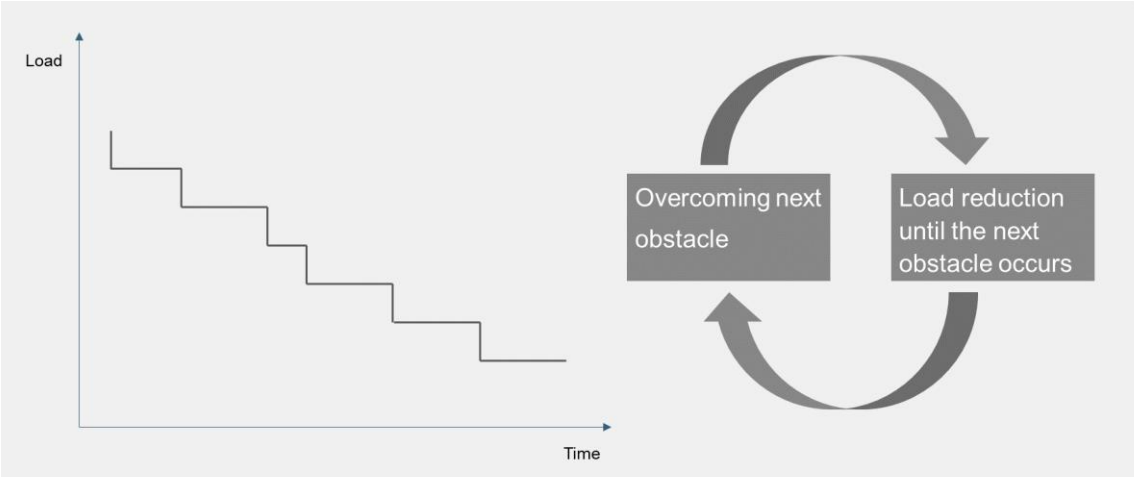


Figure 12: Test run approach.

Before starting the test, it is recommended to reflect on any potential limitations identified in the Pre-Test Data Assessment. Mitigation measures should be available to overcome obstacles during the tests. As many issues are related to control logics, which are not optimized for a wide load range, the most common approach to mitigate this situation is to operate the plant in manual mode. This was the case in all test runs conducted. Hence, a very experienced operating team is required to manage this complex situation.
During the test process, data needs to be recorded. At least the following parameters should be included:

- burner tilt positions
- oxygen in flue gas before air preheater
- total air flow
- speed of all boiler feed pumps
- feedwater flow
- position of steam valves (e.g. from extraction and cold reheat) feeding the TDBFP
- unit load
- throttle pressure setpoint
- throttle pressure actual value
- main steam temperatures
- main steam temperature setpoint
- main steam flow
- hot reheat steam temperatures
- hot reheat steam temperature setpoint
- feeder speeds

- total coal flow
- turbine HP control valve position
- reheat pressure
- drum level
- drum level setpoint
- superheater spray flows
- superheater injection control valve positions
- reheat spray flows
- reheat injection control valve positions
- APH flue gas outlet temperatures
- NO_x and CO emissions
- metal temperatures
- raw water flow
- heat rate
- coal composition

The sequence in which mills will be taken into or out of operation should also be clear. The same is true for fans and pumps. However, alternative sequences can also be tried out during the tests.

5.2.1 Minimum Load Test Procedure

The following text refers to a real test procedure that was applied in the IGEF project.

Preparation

- *Select coal quality. It is recommended to conduct test with a medium coal quality. (A good coal quality would increase the probability of successful test completion but would also raise expectations for all-day operation.)*
- *Discuss function of existing unit control. Turbine follow mode available? Turbine follow mode stable? Transfer to and from turbine follow mode bumpless?*
- *Clarify if load setpoint for unit coordinated control can be adjusted below 55% or if it is limited by the control system. If limited, remove limitation (parameter change in logic, location to be determined); only necessary for test in unit coordinated control.*
- *Inform system operator that there is an increased risk of tripping during the tests.*

Execution

- *Put the unit in actual minimum load (55%), using mills B–E.*
- *Reduce O_2 setpoint by 0.5% for 30 minutes. Check influence on APH temperatures.*

- *Put O_2 setpoint back to normal.*
- *Slowly decrease main steam pressure setpoint by 10 bar. It is expected that hot reheat steam temperatures will increase. This may also lead to higher APH outlet temperatures. Remain at lower pressure for 30 minutes. Observe APH temperatures.*
- *Slowly put pressure setpoint back to normal.*
- *Slowly increase burner tilt position until main steam temperatures or hot reheat steam temperatures approach alarm limits. (If there are reheat spray injections, they may come into operation.) Wait for 30 minutes. Observe APH temperatures.*
- *Slowly put burner tilt position back to normal.*
- *If positive effects on APH temperatures have occurred, adjust one or several of above parameters in a way that improves APH temperatures.*
- *Put SCAPH in operation for increased APH flue gas temperatures.*
- *Reduce main steam temperature setpoint by 5 K in order to get a higher margin before reaching material limits.*
- *Take feed water pump out of operation as early as possible and operate with one pump. If possible, before reducing load below actual min load.*
- *Take mill E out of operation. Operate with the minimum number of mills (three) that are required for this load. Use mills B, C and D.*
- *Switch to turbine follow mode.*
- *Put feeders in manual.*
- *Lower load slowly and in steps by manually reducing feeder speeds. Switch over to one boiler feed pump as early as possible. Load changes should be around 25 MW (equaling 5%). This can be achieved by reducing each of the three feeder speeds by 5%, e.g. in the first step from 56% to 51%, in the second step from 51% to 46%. The third step could be smaller, e.g. from 46% to 43%. After each load reduction, wait about 30 minutes for stabilization and identify process instabilities. If no instabilities, reduce load further. The third step should get us to about 210 MW. If not, reduce feeder speed further.*
- *If there are instabilities, try to solve them by manual intervention. It might be necessary to temporarily increase load if instabilities are becoming too dangerous for operation.*
- *When instabilities cannot be eliminated, go back to last safe load.*
- *Depending on which instabilities occur, determine whether to maybe change mills, main steam pressure, burner tilts, etc., and repeat to lower load.*
- *After reaching 40% (210 MW) or when obstacles cannot be overcome, get back to 288 MW by reversing the last steps in the procedure. Increase feeder speed slowly. (May not be necessary to wait 30 minutes after each increase. This depends on the stability. Increase load when it is safe to do so.)*

- *At 288 MW, put unit control back to normal, feeder speeds to auto, start feedwater pump, and start 4th mill. Exact sequence to be determined during operation.*
- *Put coal dampers to fully open position, if not yet fully opened.*
- *If successful, repeat test in coordinated mode of the unit control.*
- *Put the unit in actual minimum load (55%), using mills B–E.*
- *Select burner tilt, O^2 and main steam pressure as found most suitable in last test.*
- *Put SCAPH in operation for increased APH flue gas temperatures.*
- *Reduce main steam temperature setpoint by 5 K to get a higher margin before reaching material limits.*
- *Take feedwater pump out of operation as early as possible and operate with 1 pump. If possible, before reducing load below actual min load.*
- *Take mill E out of operation. Operate with the minimum number of mills (three) that are required for this load. Use mills B, C and D. (Remain in unit coordinated control).*
- *Lower load slowly and in steps by adjusting the unit control setpoint. Load changes should be around 25 MW (equaling 5%). This can be achieved by reducing the load setpoint from 288 MW to 263 MW to 243 MW to 220 MW to 210 MW, using a slow slope (e.g. 0.5%/min). After each load reduction, wait about 30 minutes for stabilization and identify process instabilities. If no instabilities, reduce load further.*
- *If there are instabilities, try to solve them by manual intervention. It might be necessary to temporarily increase load if instabilities become too dangerous for operation.*
- *When instabilities cannot be eliminated, go back to last safe load.*
- *Depending on which instabilities occur, determine whether to maybe change mills, main steam pressure, burner tilts, etc., and repeat to lower load.*
- *After reaching 40% (210 MW) or when obstacles cannot be overcome, get back to 288 MW by reversing the last steps in the procedure. Increase load setpoint slowly. (May not be necessary to wait half an hour after each increase. This depends on the stability. Increase load when it is safe to do so.)*
- *At 288 MW, start feedwater pump and start 4th mill. Exact sequence to be determined during operation.*
- *Put coal dampers to fully open position, if not yet fully opened.*
- *This test may have to be conducted on several days, if obstacles occur.* [5]

These steps can be further detailed as shown in the following table.

[5] Test Procedure for the Maithon Power Plant, issued by the IGEF team in June 2021

Time (IST)	Load	Procedure
11:30	290 MW	Reduce O_2 setpoint by 0.5% for half an hour
12:00		Put O_2 setpoint back to normal
12:00		Slowly decrease main steam pressure setpoint by 10 bar
12:30		Slowly put pressure setpoint back to normal
12:30		Slowly increase burner tilt position until main steam temperatures or hot reheat steam temperatures approach alarm limits
13:00		Burner tilt back to normal
		If positive effects on APH temperatures have occurred, adjust one or several of above parameters in a way that improves APH temperatures.
13:00		Put SCAPH in operation for increased APH flue gas temperatures.
13:15		Reduce main steam temperature setpoint by 5 K in order to get a higher margin before reaching material limits
13:30		Take feedwater pump out of operation as early as possible and operate with 1 pump. If possible, before reducing load below actual min load.
14:00		Take mill E out of operation. Operate with the minimum number of mills (three) that are required for this load. Use mills B, C and D.
14:30		Switch to turbine follow mode
14:30	290 MW	Put feeders in manual
15:30		Lower load slowly and in steps by manually reducing feeder speeds
		After each load reduction, wait about 30 minutes for stabilization
		If no instabilities, reduce load further
		When instabilities cannot be eliminated, go back to last safe load
17:30	210 MW	Reach 40% load
18:00		Slowly reduce damper position of burner with highest load, until it reaches average load, or until 30% damper position are reached
		Wait for stabilization
		If another burner is also high on coal, repeat. Wait for stabilization.
		Repeat with other burners until equal coal flow
		Slowly open all coal dampers or keep them in actual position, depending on outcome of the test
18:30	210 MW	Slowly increase load to 290 MW
20:30	290 MW	290 MW reached
20:30		If not opened before, put coal dampers to open position
		Normalization (not part of the test):
20:30		Put feeders in auto
20:30		Switch to unit coordinated control mode
20:30		Start feedwater pump
21:00		Start 4th mill
21:00		Put SCAPH out of service

Table 5: Detailed test procedure for a minimum load test.

This table refers to the load profile given in Figure 10.

5.2.2 Ramping Test Procedure

The following text refers to a real test procedure that was applied in the IGEF project.

Preparation

- *Discuss possibilities to improve burner tilt and drum level control. If this is done prior to the load ramp test, it requires some hot commissioning (drum level approx. ½ day at full load, and ½ day at low load. Same for burner tilts. Corrections will only be active during the hot commissioning and during the load ramp tests.)*
- *Discuss lowest load that can be achieved with 6 mills (while still maintaining some margin for the mills to control).*
- *Discuss target speed of load ramp.*
- *Discuss, how fast load ramps can be when mills have to be stopped/started.*

Execution

Tests without starting/stopping mills:

- *Put the unit at full load, operation as usual.*
- *Put speed of load ramp to 0.5%/min.*
- *Change load setpoint in one step from 525 MW to 450 MW (operation of (up to) 6 mills is possible at this load setpoint). Will take about 30 minutes to get to 450 MW.*
- *Wait for stabilization (30 minutes).*
- *Change load setpoint in one step from 450 MW to 525 MW. (Will take about 30 minutes).*
- *Wait for stabilization (30 minutes).*
- *If successful, and all control loops have been stable enough during the ramps: repeat test with a faster load gradient. The speed of the load ramp should be decided based on the outcome of the previous test. Preferably 1%/min, if outcome was positive.*
- *If successful, and all control loops have been stable enough during the ramps: repeat test with a faster load gradient. The speed of the load ramp should be decided based on the outcome of the previous test. Preferably 1.5%/min, if outcome was positive.*
- *Repeat with ever-increasing speeds until alarm limits are approached during one of the ramps.*

Tests with starting/stopping mills:

- *Put the unit at full load, operation as usual.*
- *Put speed of load ramp to 1%/min. (Depends also on previous tests. To be discussed prior to the test.)*
- *Change load setpoint in one step from 525 MW to 288 MW. Time to reach new load depends on speed of the load ramp:*

Speed of ramp	***Time to reach load***
0.5%/min	*90 min*
1%/min	*45 min*
1.5%/min	*30 min*
2%/min	*23 min*

- *Optionally, instead of lowering load to 288 MW, lower load to below 288 MW, depending on the outcome of the min load tests.*
- *During ramp, manually take mills out of operation.*
- *If problems occur, stop ramp and stabilize.*
- *After completion of ramp: Wait for stabilization (30 minutes).*
- *Change load setpoint in 1 step from 288 MW (or lower, whatever actual load is) to 525 MW.*
- *During ramp, manually start mills.*
- *If problems occur, stop ramp and stabilize.*
- *After completion of ramp: Wait for stabilization (30 minutes).*
- *If successful and all control loops have been stable enough during the ramps, repeat test with a faster load gradient. To be discussed based on the outcome of the previous test, how fast the load ramp should be. Consider time for starting and stopping mills.*
- *Repeat with ever-increasing speeds until alarm limits are approached during one of the ramps, or target speed has been reached, or time for starting/stopping mills is not sufficient any more.*
- *This test may have to be conducted on several days, if obstacles occur.* [6]

[6] Test Procedure for the Maithon Power Plant, issued by the IGEF team in June 2021

Time (IST)	Load	Procedure
12:30	500 MW	
12:30		Put speed of load ramp to 0.5%/min (or faster, depending on previous tests)
12:30		Change load setpoint in one step from 525 MW to 450 MW (operation of (up to) 6 mills is possible at this load setpoint). Will take about ½ hour to get to 450 MW
13:00	430 MW	Wait for stabilization (15 minutes)
13:15		Change load setpoint in 1 step from 450 MW to 525 MW. (Will take about ½ hour.)
13:45	500 MW	Wait for stabilization (15 minutes)
14:00		If successful, and all control loops have been stable enough during the ramps: repeat test with a faster load gradient. The speed of the load ramp should be decided based on the outcome of the previous test. Preferably 1%/min, if outcome was positive.
14:15	430 MW	Wait for stabilization (15 minutes)
14:30		Setpoint to 525 MW
14:45	500 MW	Wait for stabilization (15 minutes)
15:15		If successful, and all control loops have been stable enough during the ramps: repeat test with a faster load gradient. The speed of the load ramp should be decided based on the outcome of the previous test. Preferably 1.5%/min, if outcome was positive.
15:30	430 MW	Wait for stabilization (15 minutes)
15:45		Setpoint to 525 MW
16:00	500 MW	Wait for stabilization (15 minutes)
16:00	500 MW	Put speed of load ramp to 1%/min. (Depends also on previous tests. To be discussed prior to the test.)
16:00		Change load setpoint in one step from 525 MW to 288 MW
		During ramp, manually take mills out of operation
		If problems occur, stop ramp and stabilize
16:45	290 MW	After completion of ramp: Wait for stabilization (30 minutes)
17:15		Change load setpoint in one step from 288 MW to 525 MW
		During ramp, manually start mills
		If problems occur, stop ramp and stabilize
18:00	500 MW	After completion of ramp: Wait for stabilization (30 minutes)

Table 6: Detailed test procedure for a ramping test.

This tables refers to the load profile which is given in Figure 11.

6 Test Run Assessment: Flexibilization Plan

The test run assessment is based on the observations and findings during the test runs in combination with an analysis of the recorded operating data. In general, the assessment is structured according to the following areas:

- combustion
- steam conditions
- feed water (e.g., drum level)
- mill load
- flue gas conditions
- metal temperatures
- heat rate
- NO_x emission

The data are visualized in the same way as in the Pre-Test Data Assessment. The following figure is taken from a test run assessment providing an overview of the main plant parameters during the minimum load test.

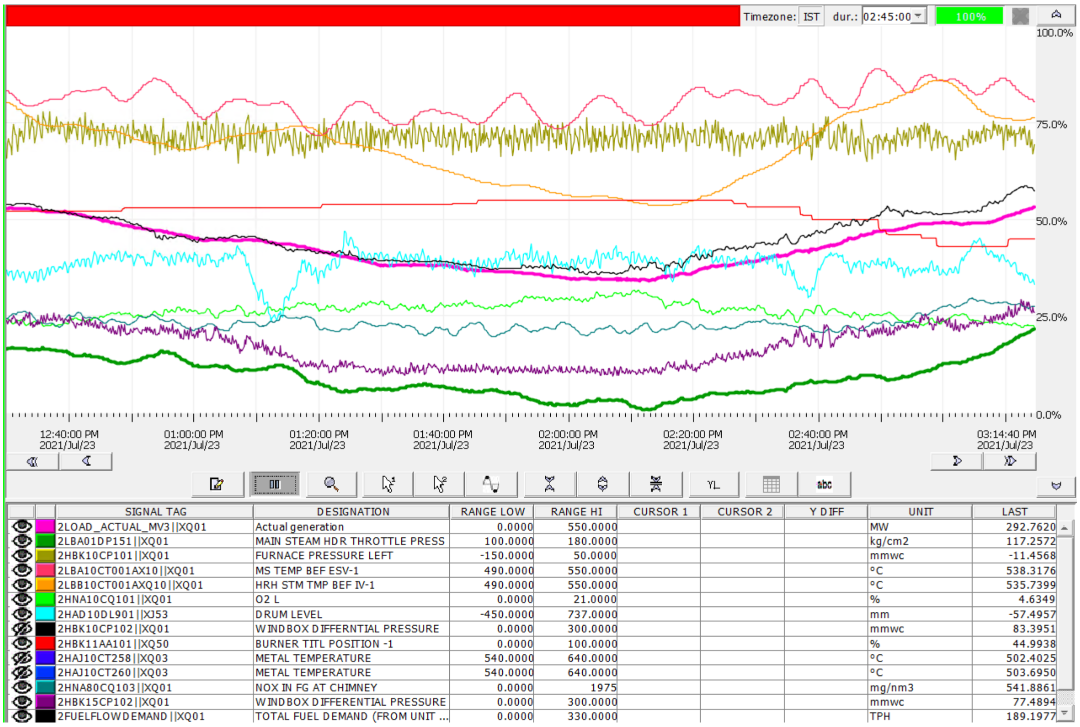


Figure 13: Main plant parameters during a minimum load test.

In this example, the following observations were made at 190 MW:

- *RH steam temperature low (523°C and decreasing → efficiency loss). However, the values were not as low as those at other comparable plants.*
- *FD fan positions 8%, which is not a good range for control.*
- *Manual drum level control. During minimum load operation, TDBFP A auxiliary control valve was controlled manually throughout. Drum level setpoint to vary accordingly.*
- *Flue gas exit temperature at APH outlet decreased to 109.4°C and 112.4°C (below actual acid dew point).*
- *Flame intensity at AB2, AB3 and BC2 showing low. Fireball at AB was flickering intermittently.*
- *Hotwell level remained high >2000 mm Water Column (steam consumption from U1).*
- *U1 steam flow was increased to 40 t/h at U1 load >500 MW. U1 cold RH bypass motorized valve was opened. Dependency on other unit for steam.*
- *MDBFP was kept in manual throughout.*
- *Logic modification required; single fan operation was not possible due to ID fan current remaining on higher side and due to flame instability.*
- *Turbine vibration for HP front bearing (bearing 1) shaft X rose to 116 microns. At 290 MW it is maintained at 100 microns.* [7]

Such observations were collected for all test situations – also for the ramp test. The next figure shows an example depicting main parameters for a ramp test.

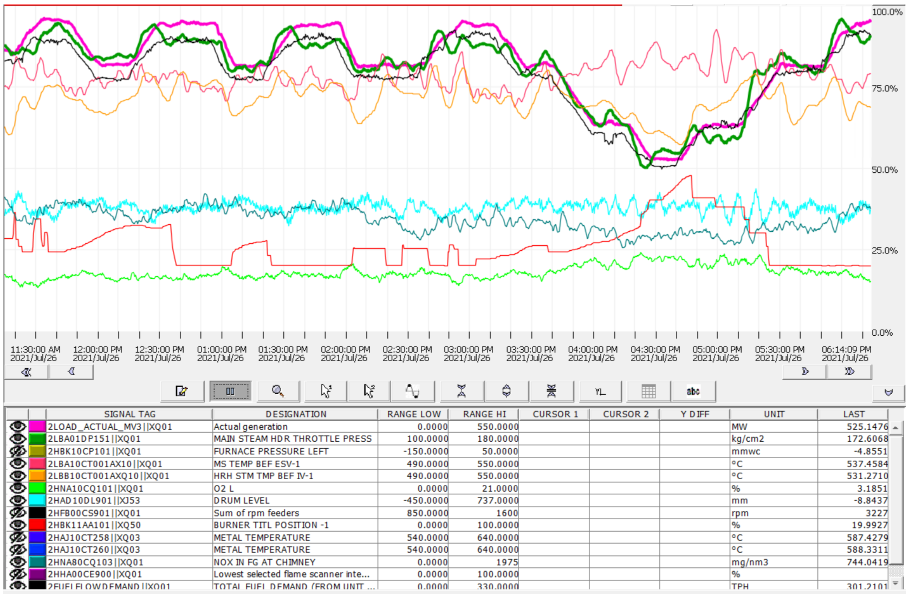


Figure 14: Main plant parameters during a ramp rate test.

[7] Maithon Test Report issued by the IGEF team in June 2021

The classification of theses curves was as follows: *When ramping up, the unit control gives priority to building up the pressure. First of all, the increase of fuel leads to a build-up of pressure and only later to more generation (Megawatt). This can be seen in the graph above whenever the green curve (pressure) increases ahead of the pink curve (MW). This is only the case in the upward direction.* [8]

6.1 Common Findings

Based on the results of the test runs in India, it was possible to identify the main areas that pose problems for flexible operation. They are shown in the following figure.

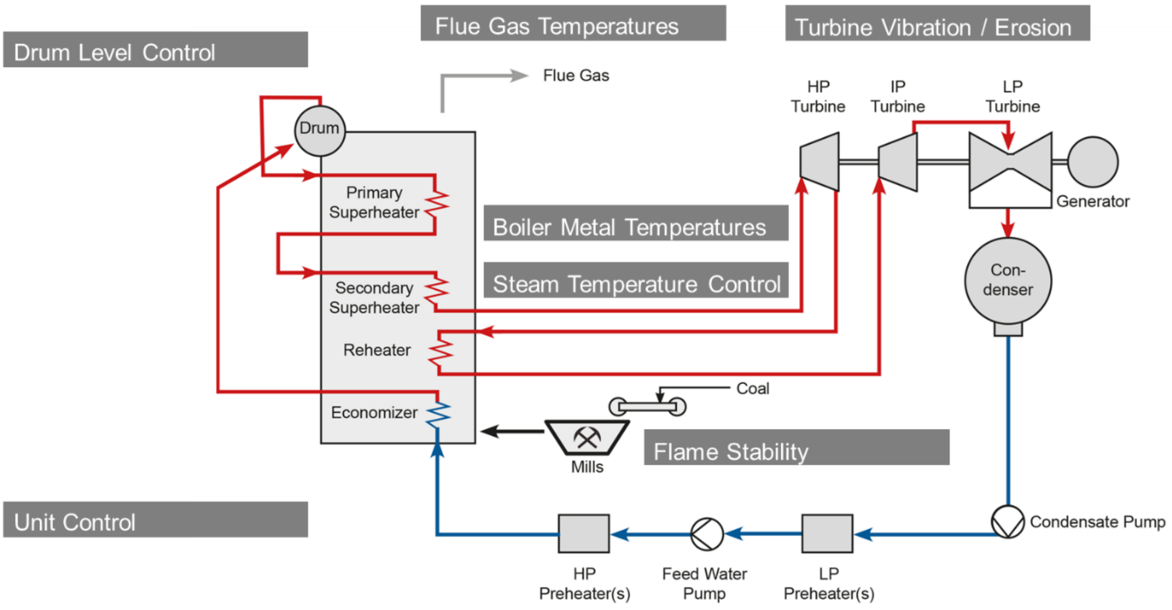


Figure 15: Potential issues during flexible operation.

Combustion and Boiler

One of the biggest challenges is to ensure **flame stability** in low load ranges. Besides the monitoring of important combustion parameters, such as oxygen and CO content, it is essential that flame scanners operate properly. Ideally, there should be individual flame scanners for each burner – this is not usually the case in Indian power plants.

The high number of **coal mills** is an advantage in Indian power plants. This provides flexibility for load adjustments. A key challenge here is the smooth transition of mills when reducing or increasing the load. As a general rule, it is better to keep lesser mills running in a higher operational range than the other way round. This operation mode is more stable – during the test, at a minimum load of about 35% to 40%, usually three mills were in operation.

[8] Maithon Test Report issued by the IGEF team in June 2021

During fast load changes, high temperature gradients in thick-walled components can cause thermal stress. Therefore, **metal temperatures** should be closely monitored to ensure that critical operating situations can be avoided, e.g., by using burner tilts.

Water-steam cycle

An unstable **drum level control** was one of the key obstacles during the test runs. Switching between feed water pumps in low load operation, in particular, caused stability issues. One reason is that the recirculation valve of the turbo-driven boiler feed pump (TDBFP) is usually an on-/off-type of valve. The opening and closing of this valve causes significant turbulence in low load ranges. Therefore, these valves should be substituted by control valves to improve the controllability of the process. Moreover, low **steam temperatures** also become an issue at low load – especially in view of the heat rate. This problem can be mitigated by improving the spray controls. Burner tilts can also serve as a measure to increase steam temperatures.

The turbine can also become a problem – although, usually this is not the case. However, turbine vibration should be closely monitored in order to avoid critical situations.

Flue gas

In low load conditions, low flue gas temperatures can become a major concern if they fall below the flue gas dew point. This can cause significant damage to the air preheater. Therefore, the flue gas temperatures at the air preheater (APH) outlet need to be monitored and controlled properly. It is recommended to use the steam coil air preheater (SCAPH) to ensure that necessary temperature levels in low load conditions are maintained. Such SCAPH are usually available in Indian power plants – but are often not in service.

NO_x

It can be excepted that NO_x decreased with load. This could also be detected during the test runs (see the following figure).

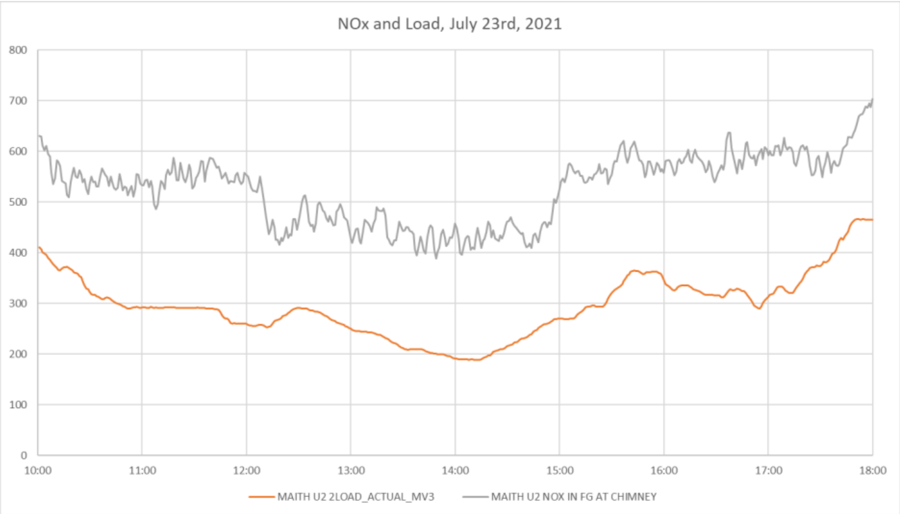


Figure 16: NO_x emissions and load during the minimum load tests.

However, the generation of NO_x strongly depends on the amount of O_2. The major source of NO_x production from nitrogen-bearing fuels is the conversion of fuel bound nitrogen to NO_x during combustion. During combustion, the nitrogen bound in the fuel is released as a free radical and ultimately forms free N_2, or NO. During the release and before the oxidation of the volatiles, nitrogen reacts to form several intermediaries which are then oxidized into NO. If the volatiles evolve into a reducing atmosphere, the nitrogen evolved can readily be made to form nitrogen gas, rather than NO_x. It can be seen from the test data that NO_x increased with the amount of O_2 in the flue gas.

This means that the amount of air available at the burners in service is too important and causes a combustion in an oxidizing environment which releases NO_x instead of N_2. The NO_x level also depends on the burner constellation.

Heat Rate

The heat rate at various load points during one test run is provided in the next figure. The data represent stabilized conditions during the test runs. However, the coal quality variation was very high as a result of blending. Therefore, as an example, the Gross Calorific Value was in a range of 3,545 kcal/kWh to 5,640 kcal/kWh.

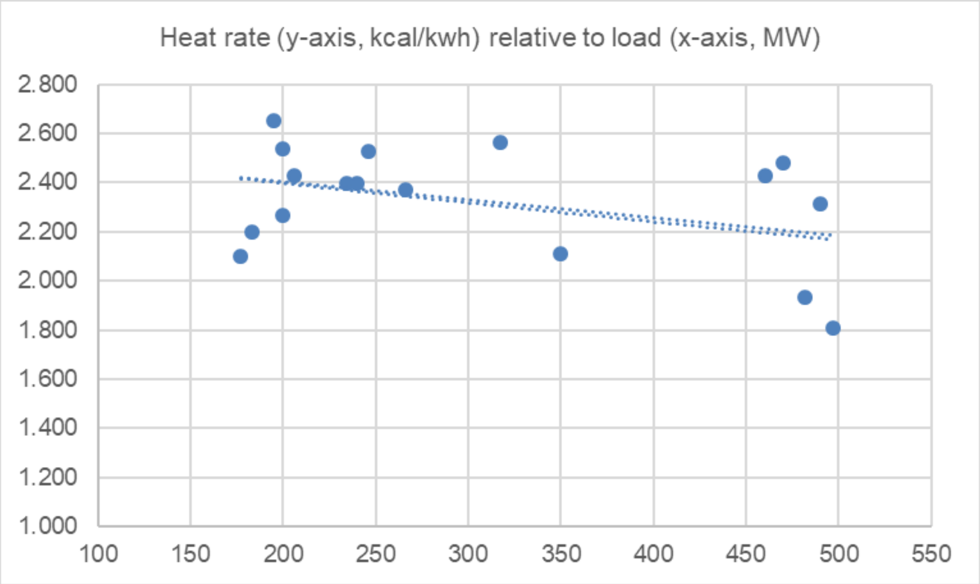


Figure 17: Heat rate relative to load during the test runs.

For these test runs – in addition to the conversion of the heat rate values – the unit efficiency was calculated based on the heat generated in the superheater and the re-heater. These values were in the range of 37% at low load and increased to 41% or 42% at high load. These efficiency values seem to be more conclusive as the data derived from the coal analysis.

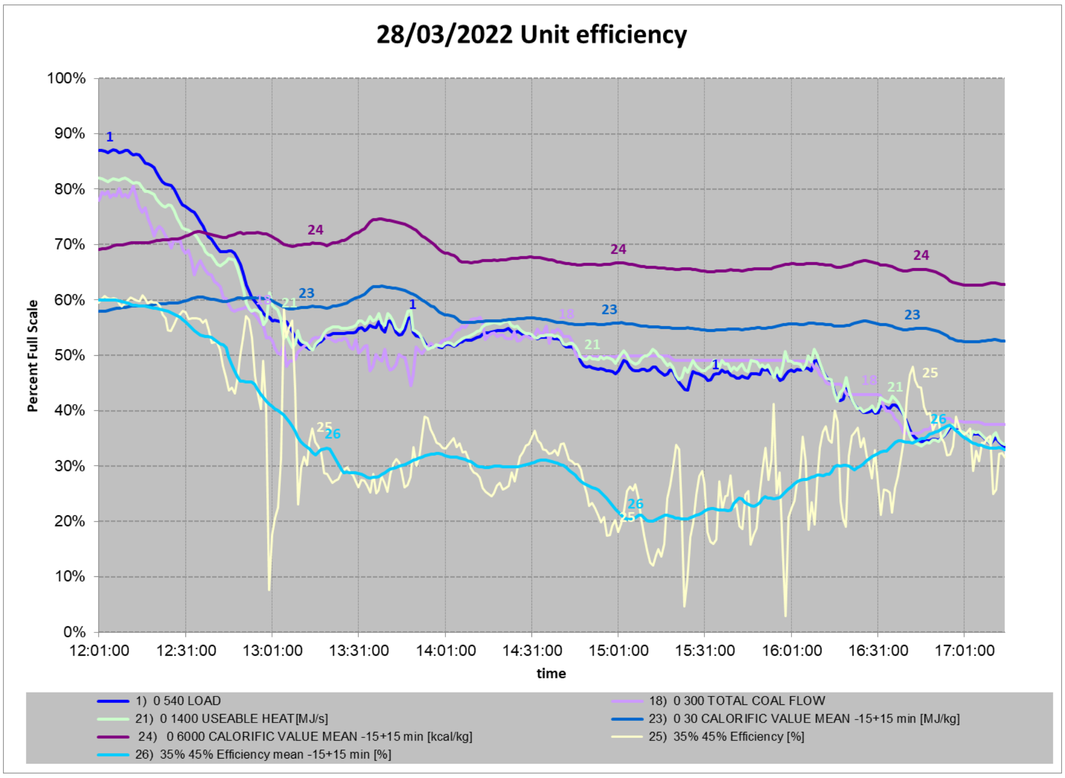


Figure 18: Efficiency during the test runs.

6.2 Flexibility Measures

Based on the findings, measures to ensure a safe, reliable and steady minimum load operation, as well as reasonable ramp rates to enhance the dynamic behavior of the plant, were proposed. Most of the proposed measures were similar in all three test plants. Therefore, it can be assumed that they also apply to other plants with a similar design. As a result of the test runs, it is anticipated that the minimum load of such plants is about 40%. This is a level that can be reached without too much effort. With respect to ramp rates the achievable level is estimated at about 2% load per minute.

The measures are divided into mandatory and optional categories. The following section discusses common measures for both categories.

6.2.1 Mandatory Measures for Minimum Load Operation

Thermal Feasibility Study

In order to get transparency about the temperature conditions in the boiler and, thus, about the stress on important components, a thermal feasibility study of the boiler is recommended. Such a study would involve the evaluation of process limitations and an assessment of the impact of low load operation and temperature, as well as the impact of pressure gradients on the boiler components and equipment. As such, the study would also be essential for enhancing the ramp rates of the plant.

The thermal feasibility study of the boiler for part load operation should be based on a thermal boiler model that is calibrated with the test data. The calibrated thermal boiler model should include a thermal evaluation of minimal achievable stable boiler part load for coal range, a boiler heating surface degradation evaluation, a hardware/software check and a risk evaluation of boiler components and mitigations. All relevant systems of the boiler (pressure/non-pressure parts, combustion/burner system, flue gas part, I&C etc.) should be examined with regards to the long-term operation of all relevant new part load cases (incl. power degradation potential).

Using the test data, a thermal feasibility study of the boiler should be carried out in order to find and avoid mid and long-term damage/limitations of the boiler systems (design and operation). Evaluation of process limitations should be carried out. The most commonly used coal should be analyzed, as well as the potential full range of coal – including coal with maximum problematic contents such as ash, moisture, sulphur, etc..

Based on the study’s findings, further relevant measures can be defined. These measures range from advanced (automated) control strategies, including combustion optimization, ramping and start-up, to the concept of an economizer bypass to increase the APH flue gas outlet temperatures at low load.

Control Optimization and Feedwater Recirculation Valves
Further mandatory measures focus on control optimization.

A) Drum Level Control

The tests showed that drum level controls were not tuned for low load operating ranges that require auxiliary steam from another unit for TDBFP operation. That is why it is recommended to upgrade or implement new controls for turbine-driven boiler feedwater pumps when fed by auxiliary steam from another unit. The current operating regime is associated with an increased trip risk and requires a lot of operator attention. In this context, the replacement of the feedwater recirculation valves with modulating type valves will also improve the drum level control. Currently, the opening of the valves causes big disturbances.

Furthermore, an upgrade or implementation of new controls is necessary for the turbine-driven boiler feedwater pumps when fed by auxiliary steam from another unit. Currently, these controls are not working properly – there is increased trip risk and a lot of operator attention is required. An automated start and stop sequence of the BFPs is also required.

B) Flue Gas Temperature Control

The SCAPH should be taken into operation automatically whenever needed. This would enable the flue gas temperature to be controlled through the use of the steam APH. This control combined with the upgraded temperature control would prevent corrosion in the APH.

C) Automated Start and Stop of Mills

Automated start-up and shut-down sequences for the mills are necessary to enhance the flexible operation.

D) RH Steam Temperature Control

Although the re-heat steam temperature was sufficiently high for the turbine during the tests, improvement of the heat rate at part load operation is recommended. The re-heat steam temperature should be controlled by using burner tilts as part of the automated control. Currently, burner tilts are operated manually and consequently re-heat steam temperatures are dropping during low load operation. This causes an avoidable loss of efficiency. 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 RH steam temperature control.

6.2.2 Mandatory Measures for Ramp Rate Improvement

As already mentioned in the previous chapter, a thermal feasibility study of the boiler will also be essential for enhancing the ramp rates of the plant. With the help of the model which will be developed in the course of this study, it will be possible to derive measures to decrease

SH and RH metal temperatures in cycling operation regimes, e.g. by effectively applying the burning tilts. The findings of the thermal feasibility study will also provide the basis for the optimization of various controls.

Control Optimization
Further mandatory measures focus on control optimization.

A) **Upgrade furnace/windbox delta pressure (dp) control**
The setpoint should be given automatically depending on load.

B) **Upgrade furnace pressure control**
The secondary air control and furnace/windbox dp control should be decoupled. This will stabilize the furnace pressure and remove oscillations.

C) **Change unit control (Coordinated Master Control CMC)**
These changes should enable the load to change sooner in the upward direction, and the pressure later. This would have the following effects:

- better cooling of RH tubes when steam flow increases, less MTM increase
- better drum level stability
- better fuel / air coordination
- better fuel / load coordination
- faster and smoother ramps

It should be noted that ramp rate improvements, as well as stable minimum operation, strongly depend on a stable and optimized combustion – some control optimization measures have already been mentioned. Coal flow balancing, which is based on an online coal flow measurement system and variable orifices, is another promising measure, not only to enhance flexibility parameters but also to increase efficiency and to reduce NO_x emissions. Although the functioning of such systems could already be demonstrated (see next chapter), a full-scale test – equipping at least the mills in operation at minimum load with such a system – has yet to be carried out. Such a test would provide valuable insights into the effectiveness of coal flow balancing for the benefit of flexibilization, efficiency and emissions.

6.2.3 Further Measures for Flexibility Enhancement

Control Solutions
If mandatory measures are implemented, some further control upgrades can be implemented to ensure smooth and efficient plant operation at different load levels as well as with minimum load:

A) Unit Control and Automatic Mill Operation (Mill Scheduler)

The main task of the unit control is to provide setpoints for the steam generator and the turbine that 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 automatically take fans, BFPs and mills 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.

B) Main Steam Temperature Control

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

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

The same structure should be applied to different steam temperature control concepts.

Coal Flow Balancing

An online coal flow measurement system (CFMS) provides detailed information about the coal distribution between mills and coal dust pipes. It also enables combustion optimization by trimming the air/fuel ratio. Ideally, in addition to the coal flow measurement, controllable variable orifices should be installed so that coal flow balancing is possible. The main benefits of such a combined system of online coal flow measurement and variable orifices are:

- imbalances occurring during minimum load operation can be detected and balanced
- air/fuel ratio can be optimized in all load conditions
- inherent storage of mills can be used by increasing primary air flow
- individual burner adjustment is possible
- less CO at boiler walls prevents boiler corrosion
- less NO_x emissions and higher efficiency through combustion optimization

Practice shows that a uniform coal flow distribution inside coal dust pipes seldom arises. Thus, the system must be able to identify and compensate such rope formation – ideally, by actively manipulating the coal flow via variable orifices.

The effectiveness of CFMS has been demonstrated in various applications, e.g. by Siemens Energy in power plants in Poland and South Korea, as well as by BMW Steels. The latter executed CFMS tests at one mill at MPL in September 2021. According to BMW Steels' report, coal flow balancing was achieved by adjusting temporarily-installed variable orifices. It was thereby possible to equalize the coal flow in the four pipes to the mill up to a maximum percentage deviation of 5.85%. The maximum percentage deviation prior to the balancing was up to 47.80%.

Condition Monitoring

Condition monitoring systems monitor highly loaded boiler and piping components against creep and fatigue. Such a system monitors the temperature differences and pressure, and signals when the allowable limits during load changes have been exceeded. It would be integrated into the existing I&C system and calibrated based on the FEM analysis. It would comprise different sub-systems that are explained in the following paragraphs.

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 (in line with EN12952) during real-time operation. Water and steam piping components such as headers, manifolds, drums, attemperators and piping all have a limited life span. 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
- utilization of component material reserves
- cost-effective in-service monitoring and analysis

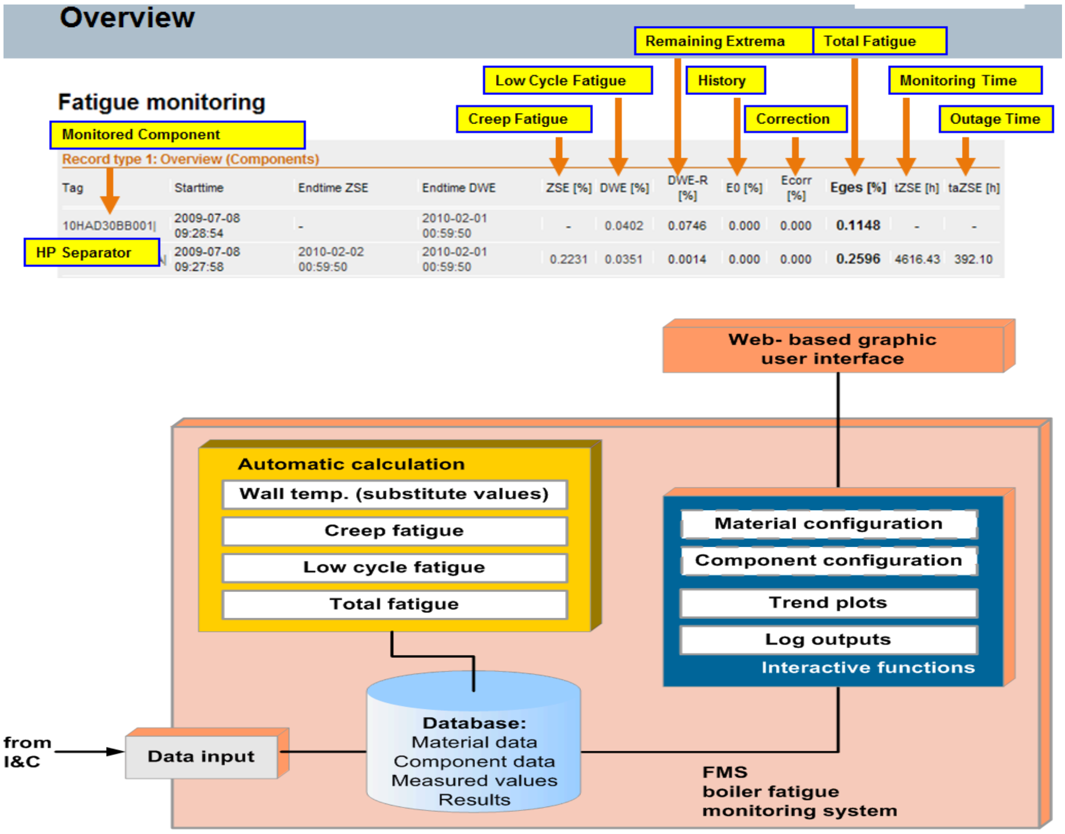


Figure 19: Overview of a boiler fatigue monitoring system.

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

7 Implementation Recommendation: Deployment

As a result of the IGEF test runs, NTPC decided to implement a set of flexibility measures in their Dadri power plant (unit 6). This set comprised the optimization of existing control loops as well as the introduction of a mill scheduler – a control logic that takes the mill in or out of operation automatically based on the plant requirements. Furthermore, a controllable recirculation valve was installed in order to ensure smooth control of TDBFP operation at low load. The according logics were also implemented. In the course of this control optimization process, sequences to take in or take out operation main components - such as ID, FD, PA fans and BFPs - were also automated. These logics did already exist in the MAX DNA system of BHEL – in many cases these logics had to be modified and/or commissioned.

Building confidence in automated solutions

Gradually, the plant team is learning to trust in the automated solutions key to enhancing the flexibility of plant. Therefore, it is strongly recommended to foresee enough time in the planning for the introduction of automated solutions. A good starting point would be an inventory of the current status of main equipment and control loops with regards to the level of automation (e.g. from 0 – manual operation to 5 – fully automated operation). Experience shows that the higher the automation level, the better the flexibility of the plant. Manual interventions should be reduced to a minimum, especially with respect to fast and efficient start-up.

However, the level of confidence in automated solution needs to be built up. Therefore, a good compromise should be found according to the plant situation. A no-regret activity is that every Indian plant check the start and stop sequences of its fans, pumps and mills. These logics are most likely already existing in the control system and just need to be aligned to the actual operating procedure.

Due to the high ash content of the Indian coal, it is unlikely that coal-fired power plants can reduce the minimum load to below 40% without any additional coal treatment. If lower loads need to be achieved, a concept for homogenization and enhancing coal quality should be developed. Such a concept could include washing, blending, coal cleaning at site as well as online coal analysis.

In order to ensure proper combustion control and thereby guarantee a reliable minimum load operation, proper flame detection – ideally, individual for each burner but not feasible in many Indian plants – and reliable measurement of O_2 and CO are essential.

In any case, a review of all operating procedures is required in order to adapt and modify them for flexible operation. The following listing provides some practical tips that could be considered in this context.

Plant area	**combustion / mills**
Issues	− minimum number of mills / burners / burner level ensuring a sufficient ignition and, respectively, combustion − minimum coal flow − air distribution control − inertia and smooth switch over
Mitigation	− Many Indian plants have six or more mills. For minimum load operation, the boiler will be most likely operated with three mills. − Optimized combustion control based on the test run experiences in part load operation; special focus on reaction time and mill switch-over. Note: It is better running fewer mills at higher load than more mills at low load – the combustion stability increases. − Optimized grinding: enables better usage of the fuel – improving the combustion process, precondition is the use of washed coal, respectively coal without stones, rocks and other hard impurities. − The control criterion for taking the first mill into operation should be the temperature inside the respective coal mill (classifier). This temperature should be higher than 70°C in order to avoid water dew point in the mill and, consequently, to avoid corrosions and blockings inside the coal mill caused by wet coal dust.

Plant area	**combustion / burners**
Issues	− Flame stability (flame pulsation and blow-off) − Air distribution
Mitigation	− Ensure reliable flame detection − Improve air-fuel ratio − Increase mixture and swirl − Ensure equal coal dust distribution to burners − Reduce cooling air flows − Improve positioning accuracy of air control flaps − Use upper burner levels to keep required steam temperatures at low load, in order to shift heat transfer from the evaporator to the super-heater / reheater sections

Plant area	Water-steam cycle / chemistry
Issues	− Proper water and steam quality at all load conditions in order to avoid corrosion − Cycling results during peak demand on condensate supply and oxygen controls
Mitigation	− Strict adherence to proven quality standards such as VGB-S-010-T-00; 2011-12.EN “Feed Water, Boiler Water and Steam Quality for Power Plants/Industrial Plants”

Plant area	Water-steam cycle / evaporator and superheater
Issues	− Differences of wall temperatures and material stress − Avoidance of overheating
Mitigation	− Ensure sufficient water / steam flow − Optimize operation procedures for ramping − Check for design buffer in minimum feedwater flow, especially in once-through boilers − Use circulation mode − Monitor conditions

Plant area	Turbine
Issues	− Ventilation (reverse steam flow in the exhaust steam zone) − Vibration excitation at the last-stage blades − Water droplet erosion − Vibration and expansion due to thermal stress (casing, bearings and shaft)
Mitigation	− Implement protective functions in the HP and LP turbine − Extend vibration monitoring − Cool blades and casing – for LP a, controlled flow and fast evacuation via direct link to condenser − Improve condenser vacuum − Optimize drainage − Optimize start-up procedures − EOH (Equivalent Operating Hours) counter to quantify the lifetime consumption due to thermal stress − Improve condition and temperature monitoring

Plant area	Generator
Issues	− Thermo-mechanical stress on generator components, especially at stator windings
Mitigation	− Integrate online monitoring and diagnosis: control of the cooling temperature, partial discharge measurement and stator end winding vibration measurements

Plant area	DeNOx
Issues	− NH_3 slip − Fouling and corrosion − Ammonium sulfate formation
Mitigation	− Ensure minimum flue gas temperature at all load conditions (use higher burner level and higher air ratio) − Improve dosing control − Enamel coating required at the cold end

Table 7: Issue lists for different plant areas.

Condition monitoring to manage life-time consumption

In order to mitigate negative consequences of flexible operation, condition monitoring systems are a very useful tool. With their help, it is possible to operate the plant in cycling mode without compromising the material limits of the plant components. Changing pressure and temperature-related stresses on the components pose the greatest challenge. This can lead to increased wear, which is due, in particular, to fatigue damage caused by the cyclical loads. In the past, the damage mechanism caused by the creep was the main cause of service-life wear and tear. With flexible operation, the wear and tear caused by fatigue comes into focus.

Moreover, there is also wear and tear due to higher utilization and corrosion caused by changes in plant chemistry and water excess from increased condensation. The following table lists the typical plant equipment most affected by cycling operation.

Plant equipment with most significant impacts	Primary damage mechanism
Boiler water-walls	Fatigue corrosion; corrosion due to oxygen and chemical deposits (depending on water quality)
Boiler superheaters	High temperature differential and hot spots from low steam flows during start-up, long-term overheating failures
Boiler reheaters	High temperature differential and hot spots from low steam flows during start-up, long-term overheating failures, tube exfoliation damages IP turbines
Boiler economizer	Temperature transient during start-ups
Boiler headers	Fatigue due to temperature ranges and rates, thermal differentials tube to headers; cracking in dissimilar metal welds, headers and valves
Drum	Thermo-mechanical stress at drum walls
LP turbine	Blade erosion
Turbine shell and rotor clearances	Non-uniform temperatures result in rotor bow and loss of desired clearance and possible rotor rubs with resulting steam seal damages
Feed water heaters	High ramp rates during starts; not designed for rapid thermal changes
Air heaters	Cold end basket corrosion when at low loads and start up, acid and water dew point
Fuel system / pulverizers	Cycling of the mills occurs from even load following operation as iron wear rates increase from low coal flow during turn down to minimum

Table 8: List of critical components.

A thermal feasibility study of the boiler would set the baseline for the assessment of proper temperature conditions in the boiler and the stress on the listed components (except the turbine parts). This study provides transparency about the limitations and set points (e.g., for metal temperatures) for efficient, dynamic but gentle operation. In order to ensure strict compliance with these values, the instrumentation for relevant combustion-related measurements needs to work properly. Furthermore, we recommended implementing condition monitoring systems to monitor the lifetime consumption. Hence, the Dadri team decided to integrate a Boiler Fatigue Monitoring System and EOH counter for the turbine.

The following table provides an overview of helpful (European) regulations and vgbe standards with regards to inspections, testing and calculating the operational lifespan of equipment.

	Pipeline	Header / drum	Injection cooler
Calculation/ design	− VGB-S-109 − VGB-R 507 section 4.3.2 with references to: FDBR Guideline “Design of power piping” and VDI manual Energy Technologies − VGB-S-013 (boiler interior) − VGB-S-503 − VGB-R 510 − EN 13480-3 − TRD series 300*, 508* − AD 2000 series B/S − AD 2000 series HP 100R (replacement for TRR 100) − Finite elements method	− VGB-S-109 − VGB-S-013 − EN 12952-3 − EN 13445-3 (A1 item 19) − TRD series 300*, 508* − AD 2000 series B/S − Finite elements method	− VGB-S-109 − VGB-S-013 − VGB-S-540 − EN 13480-3 − EN 13445-3 − TRD series 300*, 508* − AD 2000 series B/S − Finite elements method
Extended inspection	− VGB-R 508 − VGB-R 510 − EN 13480-5	− VGB-S-013 − DIN EN 13445-5 − DIN EN 12952-6	− VGB-R 540 − DIN EN 12952-6
Diagnostic test	− VGB-S-509 (periodic inspection) in conjunction with VGB-R 510 − VGB-S-517 − (microstructure rating charts)	− TRD series 500* − VGB-S-509 (periodic inspection) in conjunction with VGB-R 510 − VGB-TW507 − (microstructure rating charts)	− TRD series 500* − VGB-R 540 in conjunction with VGB-R 509 − VGB-S-517 − (microstructure rating charts)
Diagnostic lifetime calculation	− TRD 508*/EN 12952-4 − TRD series 300* / EN 12952-3 − Force/displacement transducer with diagnostic system by the manufacture − Finite elements method	− TRD 508*/EN 12952-4 − TRD series 300* / EN 12952-3 − DIN EN 13445-3 A1 (Appendix M) − Finite elements method	− TRD 508*/EN12952-4 − TRD series 300* − EN 12952-3 − Finite elements method

Table 9: Existing regulations and vgbe standards with respect to condition monitoring.

Need for preservation or lay-up procedures
Preservation or lay-up procedures are another important aspect. Boiler tube failures and other corrosion fatigue effects can be reduced by defining lay-up procedures, depending on the duration of the plant being off-line. For implementing suitable preservation procedures to protect equipment, the vgbe standards "Preservation of Power Plants" and "Preservation of Steam Turbo-Generator Set" could serve as a guideline.

Flexible operation with cycling, part load and minimum load operation should be considered in the **design of the flue gas equipment**. The flue gas treatment needs to comply with environmental norms at all potential load conditions. Cycling load operation has an impact on $DeNO_x$ and $DeSO_x$ systems – e.g. pumping operation scheme and dosing control.

7.1 Flexibility Checklist

The following table includes a summary of the most important elements in the flexibilization process of a typical sub-critical Indian power plant. For each equipment and control loop, operational procedures should be reviewed and extended for a wider load range. In a continuous improvement process the effect of these measures should be monitored and further actions might be taken to further optimize.

Designation	Optimized load range	Autom. Level: 0 none – 5 fully	Remark
Equipment			
Mills			− Define optimized mill sequence for ramp-up and ramp down − Define optimized mill configuration for minimum load − Ensure automated start-up and shut-down of mills − Consider a mill scheduler for automated ramp-up and ram-down of mills
ID fan(s)			− Optimize load range of fans − Ensure automated start-up and shut-down of fans − Ensure optimized switch-over from or to one-fan operation (in case there are > 1 fan) − Consider automated fan control and switch over
FD fan(s)			see ID fan
PA fan(s)			see ID fan

Designation	Optimized load range	Autom. Level: 0 none – 5 fully	Remark
SA fan(s)			see ID fan
MDBFP(s)			− Optimize load range of pumps − Ensure automated start-up and shut-down of fans − Ensure optimized switch-over from or to one-pump operation − Consider automated pump control and switch over
TDBFP(s)			see MDBFP − Ensure that the recirculation valve is a controllable one – optimize the control in low load range, e.g. even consider automated control
APH			Critical equipment in low load operation – ensure flue gas temperatures above acid dew point
SCAPH			− Keep this equipment in “ready-to-operate” state – beneficial to ensure flue gas temperature level above acid dew point − Automated start-up and stop are desirable
Burners			Burner tilts are a key lever for steam temperature control (esp. in low load)
Control loops			
Drum level			− MDBFP and TDBFP need to be optimized for the full load range (see above) − Optimized control parameter for the full load range – consider automated control − Include feed-forward control to ensure higher dynamics

Designation	Optimized load range	Autom. Level: 0 none – 5 fully	Remark
Main steam temp.			− Optimized control parameter for the full load range – consider automated control − Use burner tilts for control − Include feed-forward control to ensure higher dynamics
RH steam temp.			See main steam temp.
Flue gas temp.			Consider SCAPH operation to maintain temperatures above acid dewpoint
SH RH metal temp.			− Use burner tilts for control − Adjust set points according to the results of the thermal feasibility study for the boiler
Windbox dp and furnace pressure			− Use automated set points − Decouple (secondary) air control and furnace/windbox dp control
Unit Control			− Significant influence on the dynamic behavior of the plant – can be enhanced by integrating a simplified model of the unit dynamics that only includes the components for boiler dynamics and steam storage − Integration of advanced solution such as condensate throttling improves the flexibility of the plant
Others			
Start-up sequence	Full range		− Decrease of start-up time requires optimized procedures for all steps (start of fans, pumps, mills etc.) − The higher the automation level, the faster the start-up

Designation	Optimized load range	Autom. Level: 0 none – 5 fully	Remark
Instrumentation (e.g. for RH metal temp., O_2, NO_x and CO, windbox dp, furnace pressure, flame scanners, steam temp. and pressures, flue gas temp.)	Full range	n.a.	− Reliable measurements in the full range are essential – quality and quantity of existing instrumentation should be checked − If necessary, a substitution/modernization of instrumentation should be considered
Condition Monitoring Systems such as Boiler Fatigue Monitoring System, EOH counter for the turbine, vibration monitoring			− Provide important information about the equipment status with respect to the operational lifespan − Not directly required for flexible operation but very beneficial to mitigate

Table 10: Flexibility check list for sub-critical Indian power plants.

8 Useful Publications and Standards

8.1 International Reports and Publications on Best Practices

1) Nepper-Rasmussen B. C. et al., Development and Role of Flexibility in the Danish Power System, 2021

The study presents the development of flexibility options in the Danish Power System from 2000 to 2020. It reflects the lessons learnt gathered over the past two decades and puts a special focus on the Combined Heat and Power (CHP) concept which is very common in Denmark.

2) Sinha, Anjan: The Recipe Book for the Flexibilization of Coal Based Power Plants, Indo-German Energy Forum, 2020

This book presents best practices and operating procedures for the flexible operation of coal fired power plants in India. It is based on the review of published international literature, inputs from pilot studies carried out in Indian power stations (including the test run activities under the auspices of the Indo-German Energy Forum with VGB involvement) and experts' interviews. It was compiled by Mr. Anjan Sinha, a highly acknowledged Indian expert on this subject who worked for NTPC for many years.

3) Storm, Stephen: High-Level Flexibility Assessment and Benchmarking Tool, Electric Power Research Institute, Report 3002019900, 2020

This publication introduces flexibility templates to support power plant operators in complex flexibility assessments. By using theses templates, it is possible to identify design limitations and operating gaps, as well as areas for improvement. The templates are applicable to both subcritical and supercritical steam generators with a capacity of more than 100 MW. The publication also provides recommendations on mitigation measures to prevent costly equipment damage due to flexible operation.

4) Wiatros-Motyka, Malgorzata: Power Plant Design and Management for Unit Cycling, Report from IEA Clean Coal Centre CCC/295, 2019

In this study, different modes of cyclic operation of coal-fired plants and strategies for managing the negative impacts are identified. Options include new operating practices, use of advanced materials, suitable design features, power plant preservation during standby and installation of improved control systems. Such measures can improve unit heat rates and reduce the number of forced outages in existing fossil fuel-fired plants, as well as in new builds. This study also identifies potential trade-offs associated with technology selection for enhanced flexibility. Examples from Germany, India, Poland and USA are given.

5) Central Electricity Authority: Flexible Operation of Thermal Power Plants for Integration of Renewable Generation, CEA-Report, 2019

   This is an official Government of India report which reflects on the implications of large-scale renewable generation integration and the need for flexible operation of other types of generating units, especially coal-fired power plants. Flexibilization measures, implementation strategies and pilot projects are described. It presents a preliminary estimate of the capital investment & increase in operational expenditure for flexible operation. Furthermore, it sets out a road map for the cost-effective and flexible operation of various sizes of thermal units.

6) vgbe's Flexibility Toolbox: Compilation of Measures for the Flexible Operation of Coal-Fired Power Plants, VGB-B-033, March 2018

   The Flexibility Toolbox supports operators of coal-fired power plants in switching from base-load to flexible operation. It contains information on technologies, further training courses and management topics. The Toolbox offers 40 different measures to increase flexibility through retrofits or technical interventions. The measures concentrate on combustion, water-steam cycle, turbine, control technology and auxiliary systems.

7) IEA: Status of Power System Transformation: Advanced Power Plant Flexibility 2018, IEA Report, 2018

   The Status of Power System Transformation 2018 report was jointly prepared by the International Energy Agency (IEA) and the US National Renewable Energy Laboratory (NREL). The report presents the findings of the Advanced Power Plant Flexibility (APPF) Campaign, which was supported by two Clean Energy Ministerial initiatives: the 21st Century Power Partnership (21CPP) and the Multilateral Wind and Solar Working Group.

   This report provides a comprehensive overview of how power plants can contribute to making power systems more flexible, as well as offering a range of guidance on strategies to promote cost-effective and system-appropriate power plant flexibility measures. Based on a wealth of real-life case studies and data, it provides a reference source for the technical capabilities of power plants in a diverse set of country contexts.

8) Clean Energy Ministerial: Thermal Power Plant Flexibility, Publication of the Clean Energy Ministerial, 2018

   This report examines the situation in China both today and in the future, with detailed analyses of the power system using a power system model developed by the China National Renewable Energy Centre (CNREC), combined with expertise on thermal power plants from the Electric Power Planning Engineering Institute (EPPEI). In the analyses, experiences from Denmark and the Nordic power market are used in a Chinese context to provide insight into how to incentivize flexibility in the Chinese power system.

9) Agora Energiewende: Flexibility in thermal power plants, Study by Prognos AG and Fichtner GmbH & Co. KG, 2017

This study provides a broad analysis of possible flexibility measures for thermal power generation, focusing on coal power plants. The first part of the study analyzes major challenges with regards to the integration of large shares of renewables. The second part describes in detail current technical characteristics related to the flexibility of thermal power plants. The third part analyzes some retrofit measures to increase the flexibility of coal power plants, including their technical and economic parameters. Fourth, findings regarding challenges and opportunities are discussed and put into perspective by spotlighting the situation in South Africa and Poland, two countries with large coal power generation shares.

8.2 vgbe Standards

The most relevant documents are the vgbe standards which provide detailed information on important aspects of flexible operation.

1) Feed Water, Boiler Water and Steam Quality for Power Plants / Industrial Plants, VGB-S-010-T-00;2011-12.EN
2) Preservation of Steam Turbo-Generator Sets, VGB-S-036-00-2017-04-EN
3) Preservation of Power Plants, VGB-S-116-00-2016-04-EN
4) Condition Monitoring and Inspection of Components of Steam Boiler Plants, Pressure Vessel Installations and High-Pressure Water and Steam Pipes, VGB-S-506-R-00;2012-03.EN
5) Cooling Water Guideline, VGB-R 455e
6) Recommendations for the operation and monitoring of boiler circulating pumps – Based on extensive follow-up examinations relating to the damage event in 2014; VGB-TW-530, 2019
7) Material specification for components under pressure in fossil-fired power plants, VGB-S-109-00-2012-08-EN, 2012
8) Construction and installation supervision in the manufacture and assembly of water-tube boilers and associated systems in thermal power plants, VGB-S-013-00-2017-04-EN, 2017
9) VGB-Standard for the Internal Pipework of Turbine Systems, VGB-S-503-00-2017-06-EN, 2017
10) Herstellung und Bauüberwachung von Rohrleitungsanlagen in Wärmekraftwerken (German only), VGB-R 508
11) Guidelines for rating the microstructural composition and creep rupture damage of creep-resistant steel for high pressure pipelines and boiler components and their weld connections, VGB-S-517-00-2014-11-EN, 2014

8.3 Relevant Publications in the vgbe Energy Journal (formerly VGB POWERTECH Journal)

1) Heim, S., Komogowski, L.; Methods for the flexibilization of thermal power plants: A literature review, VGB POWERTECH Journal, 6/2021

2) Aydt, M. Bader, J. Bareiß, R. Mohrmann, I. Pfaff, S. Prost, R. Uttich and H. Wels, Flexibilisation – Analysis of the effects by evaluation of the VGB database KISSY, VGB POWERTECH Journal, 1-2/2021

3) Trzeszczyynski, J., Trzeszczyynska, E.; Diagnostics as a source of knowledge and strategy of coal-fired power units operated in a flexible mode; VGB POWERTECH Journal, 9/2020

4) Scharfetter, C. and Abel-Günther, K.; Steam turbines: Old iron or innovative component for the energy turnaround? VGB POWERTECH Journal, 6/2020

5) Richter, M., Oeljeklaus, G. and Görner, K.; Dynamic simulation of flexibility measures for coal-fired power plants, VGB POWERTECH Journal, 4/2020

6) Garmatter, H., Marks, E., Kostenko, Y., Veltmann, D. and Scharf, R.; Simulation of hot standby mode for flexible steam turbine operation in combined cycle power plants, VGB POWERTECH Journal, 10/2019

7) Hoppe, T., Braune, J. and Nielsen, L.; Dynamic System Simulation for New Energy Markets – Optimization of a Coal Fired Power Plant Start-up Procedure, VGB POWERTECH Journal, 9/2019

8) Pieper, C. and Beckmann, M.; Transformation of the German energy system, VGB POWERTECH Journal, 8/2019

9) Dinkel, K. and Peterseim, J.; Battery augmented biomass and waste power plants – A new approach to provide grid services, VGB POWERTECH Journal, 1-2/2019

10) Moxham, B.; Converting coal to biomass: Making the energy transition feasible, VGB POWERTECH Journal, 6/2018

11) Bolhar-Nordenkampf, M., Kokko, A. and Kinni, J.; Multifuel CFB solutions – Producing power in a flexible environment, VGB POWERTECH Journal, 4/2018

12) Ke, Z., Lin, L., Schröder, H.-C. und Guoqing, F.; Plasma ignition system for oil free power plant Zetes in Turkey and its advantages for the changed circumstance of energy market, VGB POWERTECH Journal, 7/2017

13) Heddoun, H.and Richard, J.-M.; Last stage blade trailing edge erosion feedback in EDF LP turbines with flexible operation, VGB POWERTECH Journal, 3/2017

14) Biesinger, F. et.al; Steam turbines subject to flexible operation, VGB POWERTECH Journal, 11/2016

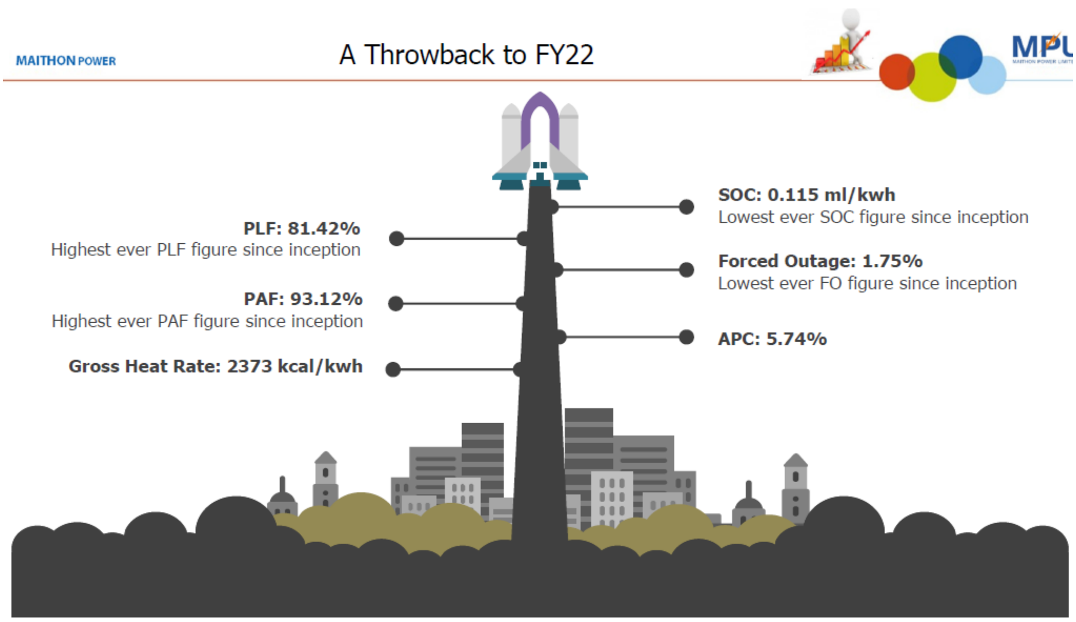
15) Baca, M., Joswig, A.; Extended requirements on turbo-generators due to changed operational regimes, VGB POWERTECH Journal, 6/2016

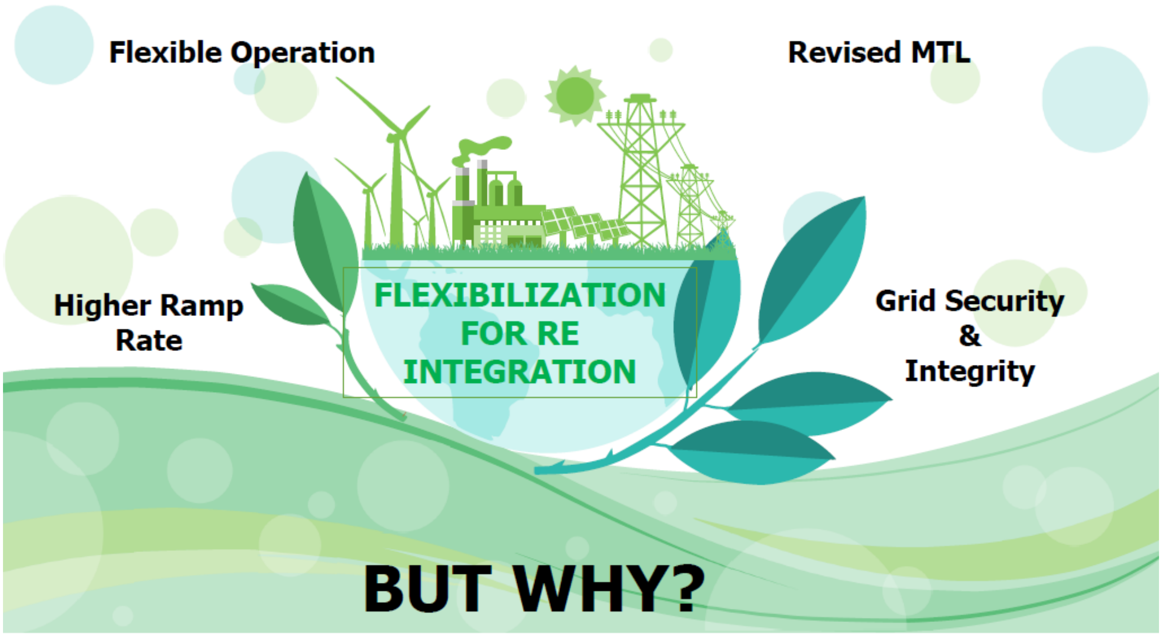
16) Michels, B. and Kotzan, H.: Retrofit of an ECO bypass to reduce minimum load of a 750 MW hard coal-fired power plant, VGB POWERTECH Journal, 4/2015

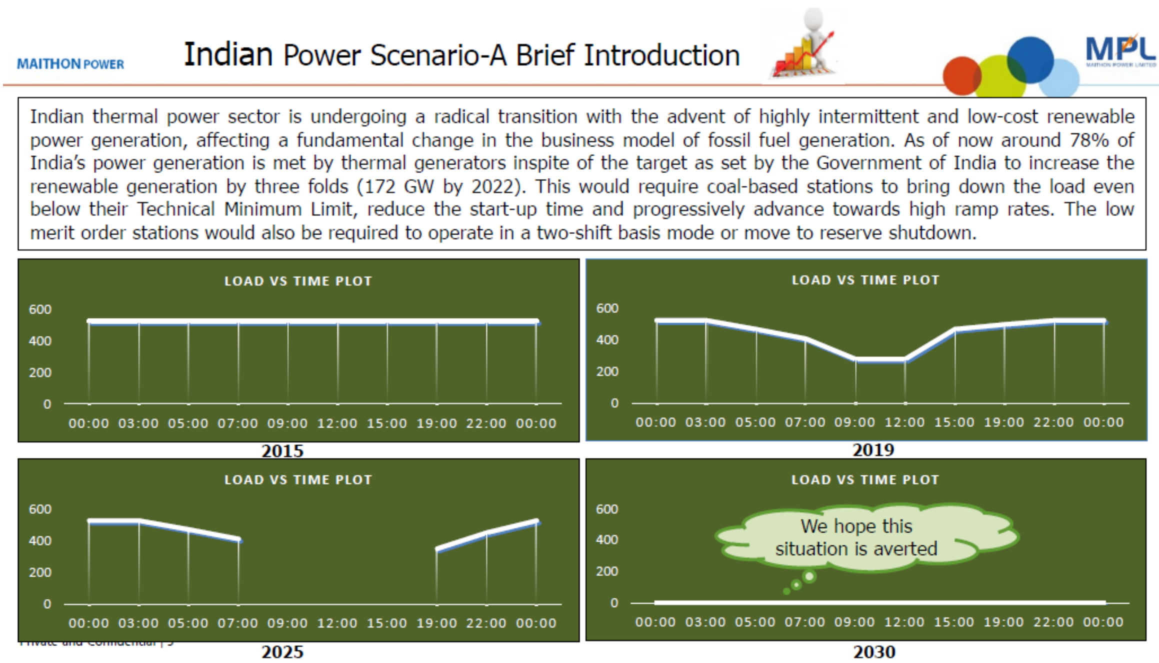
17) Heinzel, T.; Meiser, A.; Stamatelopoulos, G.-N. and Buck, P.: Implementation of Single Coal Mill Operation in the Power Plant Bexbach and Heilbronn Unit 7, VGB POWERTECH Journal, 11/2012

9 Maithon Power Limited “Journey towards Flexibilization – Minimum Power Limit REDEFINED”

A team of Maithon Power Limited (MPL) contributed to the IGEF workshop in Kolkata on 22 November 2022 with the following presentation. It reflects MPL’s perspective on the the IGEF flexibility project.




Flexible Operation
Revised MTL
Higher Ramp Rate
FLEXIBILIZATION FOR RE INTEGRATION
Grid Security & Integrity
BUT WHY?


MAITHON POWER
Indian Power Scenario-A Brief Introduction
MPL
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 fuel generation. As of now around 78% of India's power generation is met by thermal generators inspite of the target as set by the Government of India to increase the renewable generation by three folds (172 GW by 2022). This would require coal-based stations to bring down the load even below their Technical Minimum Limit, reduce the start-up time and progressively advance towards high ramp rates. The low merit order stations would also be required to operate in a two-shift basis mode or move to reserve shutdown.
LOAD VS TIME PLOT
600
400
200
0
00:00 03:00 05:00 07:00 09:00 12:00 15:00 19:00 22:00 00:00
2015
LOAD VS TIME PLOT
600
400
200
0
00:00 03:00 05:00 07:00 09:00 12:00 15:00 19:00 22:00 00:00
2019
LOAD VS TIME PLOT
600
400
200
0
00:00 03:00 05:00 07:00 09:00 12:00 15:00 19:00 22:00 00:00
2025
LOAD VS TIME PLOT
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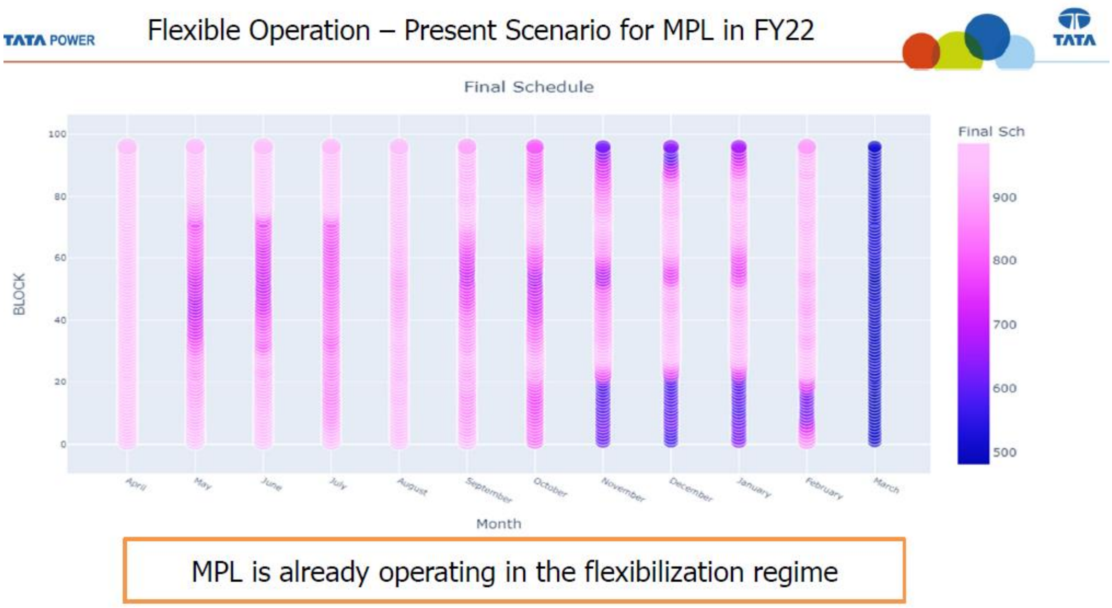
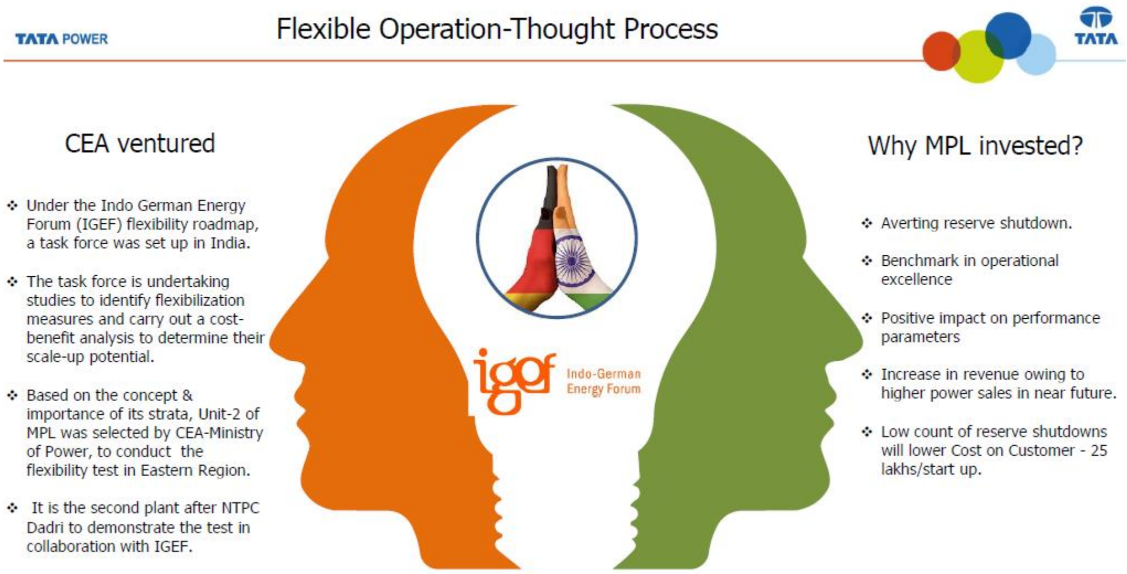
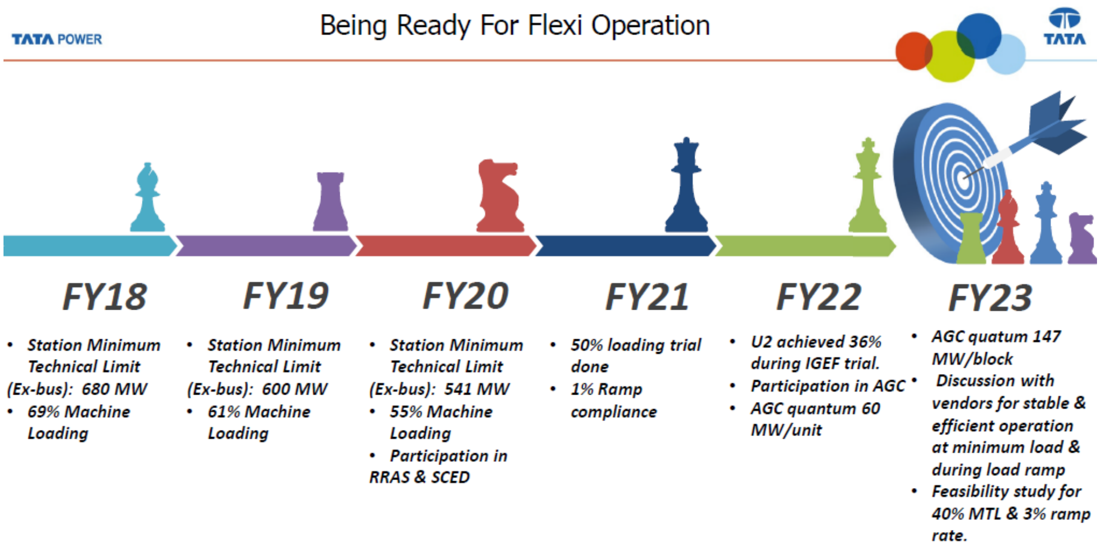
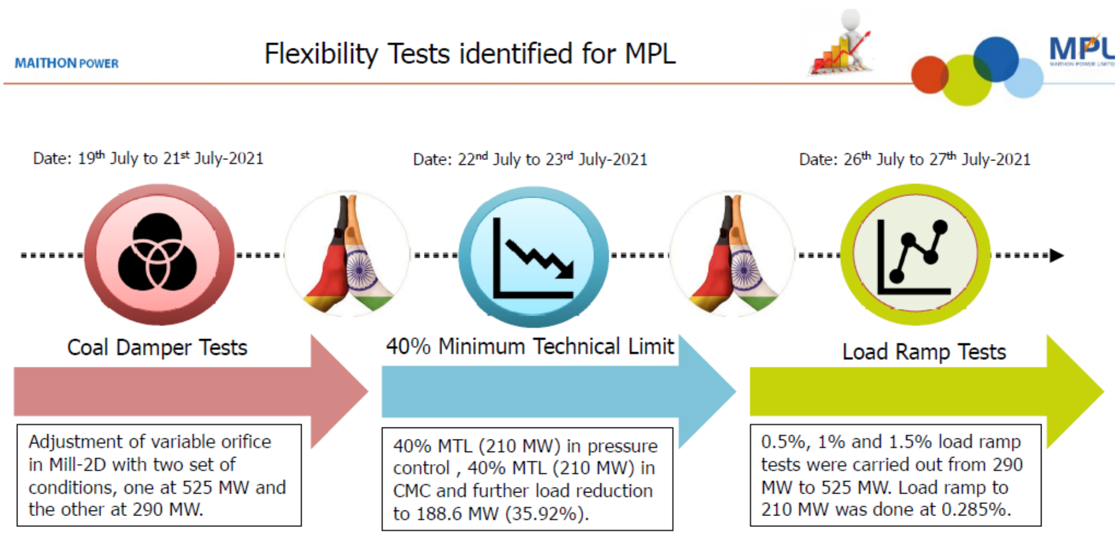
400
200
0
We hope this situation is averted
00:00 03:00 05:00 07:00 09:00 12:00 15:00 19:00 22:00 00:00
2030


TATA POWER
Flexible Operation – Present Scenario for MPL in FY22
TATA
Final Schedule
Final Sch
900
800
700
600
500
BLOCK
100
80
60
40
20
0
April
May
June
July
August
September
October
November
December
January
February
March
Month
MPL is already operating in the flexibilization regime


TATA POWER
Flexible Operation-Thought Process
TATA
CEA ventured
❖ Under the Indo German Energy Forum (IGEF) flexibility roadmap, a task force was set up in India.
❖ The task force is undertaking studies to identify flexibilization measures and carry out a cost-benefit analysis to determine their scale-up potential.
❖ Based on the concept & importance of its strata, Unit-2 of MPL was selected by CEA-Ministry of Power, to conduct the flexibility test in Eastern Region.
❖ It is the second plant after NTPC Dadri to demonstrate the test in collaboration with IGEF.
igef
Indo-German Energy Forum
Why MPL invested?
❖ Averting reserve shutdown.
❖ Benchmark in operational excellence
❖ Positive impact on performance parameters
❖ Increase in revenue owing to higher power sales in near future.
❖ Low count of reserve shutdowns will lower Cost on Customer - 25 lakhs/start up.


TATA POWER
Being Ready For Flexi Operation
TATA
FY18
• Station Minimum Technical Limit (Ex-bus): 680 MW
• 69% Machine Loading
FY19
• Station Minimum Technical Limit (Ex-bus): 600 MW
• 61% Machine Loading
FY20
• Station Minimum Technical Limit (Ex-bus): 541 MW
• 55% Machine Loading
• Participation in RRAS & SCED
FY21
• 50% loading trial done
• 1% Ramp compliance
FY22
• U2 achieved 36% during IGEF trial.
• Participation in AGC
• AGC quantum 60 MW/unit
FY23
• AGC quatum 147 MW/block
• Discussion with vendors for stable & efficient operation at minimum load & during load ramp
• Feasibility study for 40% MTL & 3% ramp rate.


MAITHON POWER
Flexibility Tests identified for MPL
MPL
Date: 19th July to 21st July-2021
Date: 22nd July to 23rd July-2021
Date: 26th July to 27th July-2021
Coal Damper Tests
40% Minimum Technical Limit
Load Ramp Tests
Adjustment of variable orifice in Mill-2D with two set of conditions, one at 525 MW and the other at 290 MW.
40% MTL (210 MW) in pressure control , 40% MTL (210 MW) in CMC and further load reduction to 188.6 MW (35.92%).
0.5%, 1% and 1.5% load ramp tests were carried out from 290 MW to 525 MW. Load ramp to 210 MW was done at 0.285%.

MAITHON POWER

Unfavourable Pre-Test Conditions and Mitigation Plan

MPL

Minimum Load Test was conducted in a relatively controlled conditions as has been mentioned.

Following were the apprehensions that were possible in all the tests that were conducted:

1. SCC could not be predicted. It varied from 0.58 to 0.65 kg/kwh. Coal flow variations were obvious.
2. Availability of adjacent mills can be an issue (breakdown).
3. Low ambient temp would increase the duty of SCAPH, if FGET could not be maintained above dew point temp, it would lead to cold end corrosion of APH baskets.
4. LTSH, Divisional, Reheater metal temp excursions.

1 Good quality coal has been fired (SCC was maintained at 0.60-0.62 kg/kWh) during the Minimum load test as well as Ramp test.

2 3 adjacent mills were in operation (B-C-D). Prior to the test, maintenance job of all 3 mills were completed and was ensured to run without any issue.

3 AGC and RGMO was kept intentionally OFF to prevent any load variations. RRAS and SCED were also stopped during the test periods

4 Steam coil air preheater (SCAPH) was charged at low load. Additional auxiliary steam supplied from adjacent unit

5 Coal flow distribution and velocity profile for all the 4 coal pipes of Mill-2D were tried to equalize for better combustion and flame stability.

Private and Confidential | 11

MAITHON POWER

Test Schedules

MPL

The tests commenced from 19th of July and was completed on 27th of July-2021. Experts from IGEF, Siemens, VGB, BMW Steel were all connected via MS Teams for proper co-ordination and execution.

Date	Activity
19.07.2021	Adjustment of Measurement Equipment
20.07.2021	Coal Damper test at 525 MW
21.07.2021	Coal Damper test at 290 MW
22.07.2021	40% MTL in Turbine Follow Mode
23.07.2021	40% MTL in CMC and further load reduction to 188.6 MW
26.07.2021	Load ramp test from 525 MW to 290 MW
27.07.2021	Load ramp test from 290 MW to 210 MW

MAITHON POWER

Coal Damper Test-525 MW and 290 MW

MPL

On 20th July, Coal Damper Test was carried out in Mill-2D at 525 MW with a specific coal consumption (SCC) of 0.696 kg/kWh. Feeder loading of Mill-2D was kept in manual at a demand of 84% and its average coal flow was 58 TPH.

On 21st July, Coal Damper Test was carried out in Mill-2D at 290 MW with a specific coal consumption (SCC) of 0.631 kg/kWh. Feeder loading of Mill-2D was kept in manual and its average coal flow was 45 TPH.

- Variable orifice adjustment to equalize fuel in each corner.
- Low coal flow through D-3 (shortest pipe).
- Coal pipe temp were uniform in nature.
- Isokinetic sampling was done to rule out pipe choking.
- Longest pipe D-1 was kept at 100%.
- Coal flow of Mill-2D was reduced to 25 TPH, flame conditions at corner-1 and 3 deteriorated (at 290 MW).

Coal Pipe Corner	Damper Position (%)	Coal Flow (TPH)	Coal Pipe Velocity (m/sec)	Coal Flow Distribution (%)
D-1	100	18.8	28.3	30.8
D-2	60	20.6	17	35.7
D-3	100	5.5	27	11.6
D-4	73	8.5	29.6	21.4

Observations:

- Coal pipe-1,2 and 4 were OK as per Siemens and IGEF. Pipe-3 is suspected of being choked.
- Changes in PA Flow by 5 TPH did not influence Corner-3. Changes with respect to NO_x, O_2 were not appreciable.
- Low mill outlet temp (70ºC) due to wet coal.
- Issue may persist with the coal flow sensors.
- GCV of coal improved and mill outlet temp improved to 90ºC.
- Damper position of D-3 was kept at 65% and preparations for 40% MTL started.

Final Condition of Mill-2D:

Coal Pipe Corner	Damper Position (%)
D-1	100
D-2	60
D-3	65
D-4	73

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Minimum Load Test- 40% in Turbine Follow Mode (TFM)

MPL

On 22nd July, Minimum Load Test (40%) to 210 MW was carried out in Turbine Follow Mode with a specific coal consumption (SCC) of 0.63 kg/kWh.

Pre-test conditions:

- Load : 290 MW (55% load)
- Coal Flow : 182 TPH (SCC=0.63)
- MS Pressure : Manual at 140 kg/cm2
- Mill Combination preferred : B, C, D, E (44 TPH,46 TPH,44 TPH and 42 TPH of coal feeding)
- Burner Tilt : Manual control
- SADC : Auto control at 75-90 mmWC.
- MS/HRH temp : Auto control
- O_2 SP : Auto control SP 4.9%.

0.5% O_2 reduction by providing a bias of -0.5% at 10:40 hrs.

- There was no change in APH outlet flue gas temp after O_2 was reduced from 4.91% to 4.41%. Same was reverted to 4.91%.

→

10 kg/sq.cm MS Press reduction (140 kg/sq.cm to 130 kg/sq.cm)

- There was no noticeable change in APH outlet flue gas temp.

→

SH Spray in Auto and BT increased to 68% from 55% at 11:29 hrs.

- There was no change in APH outlet flue gas temp. BT was again reduced to 55%.

MAITHON POWER

Minimum Load Test- 40% (TFM)

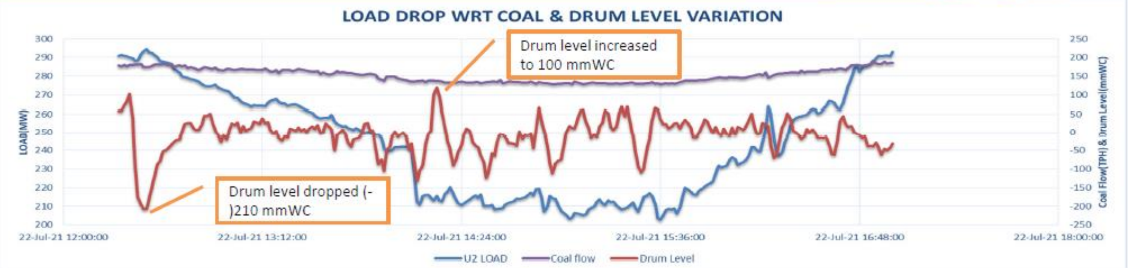
MPL

1. SCAPH was taken in service at 12:20 hrs 2. RCV of TDBFP-2A was opened at 290 MW and further load drop to 275 MW.	• Increase in SA temp from 35⁰C/35⁰C to 66⁰C/86⁰C. • FGET at APH outlet increased to 129.6⁰C/127.7⁰C • Fluctuation in drum level was in the range of +120 to -218 mmWC which was manually controlled.
1. BT was reduced to 50% from 55%. 2. Load was reduced to 275 MW in CMC at 12:50 hrs and further reduction to 255 MW. MS press was 123 kg/sq.cm.	• LTSH metal temp crossed the alarm limits (460⁰C). • At 255 MW, TDBFP-2A was taken out of service. MCV and ACV of TDBFP-2B opened to 100% to cater the feedwater flow due to low extraction steam press.
1. Feeder-2E speed was reduced to minimum. 2. Switch over to Turbine Follow mode at 240 MW. MS press SP was 110 kg/sq.cm where actual press was 109 kg/sq.cm.	• At 13:55 hrs, Mill-2E was taken out of service. • Load drop from 240 MW to 210 MW at 14:08 hrs. Feeder speed of B, C and D were reduced by 5% manually to reach 210 MW.
1. Load=210 MW, MS press=107 kg/sq.cm was kept for 1 hour for stabilization	• Post stabilization load was increased to 230 MW in press control. Mill-2E was taken in service at 250 MW and TDBFP-2A at 270 MW. Unit load was further increased to 290 MW. CMC was taken in service and SCAPH was isolated.

MAITHON POWER

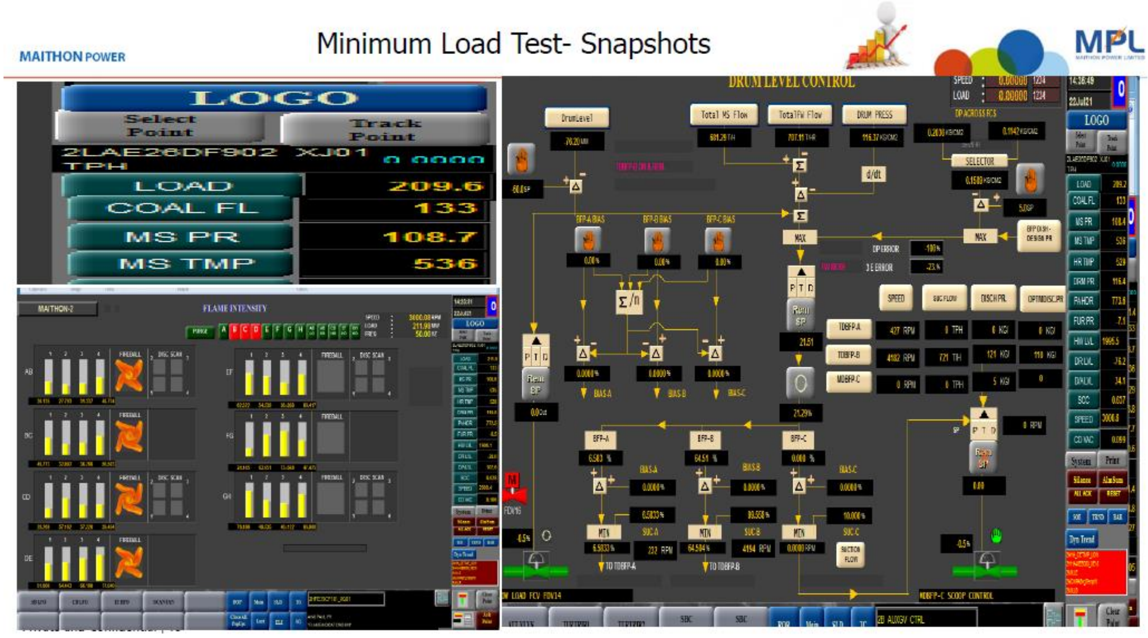
Minimum Load Test- 40% (TFM)

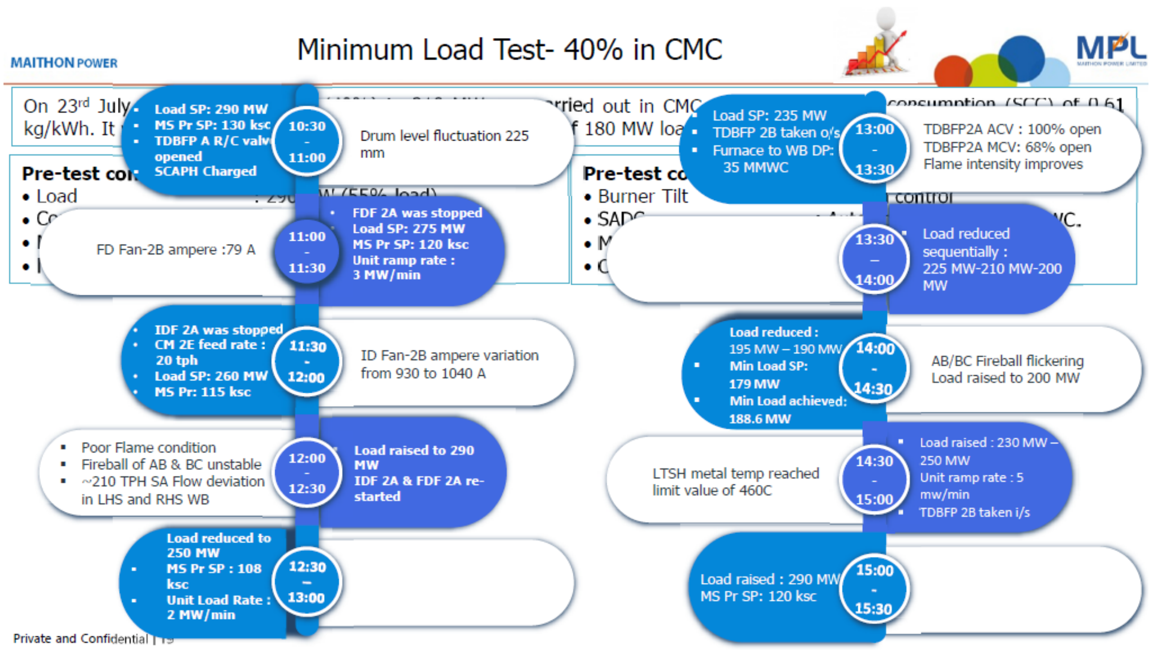
MPL

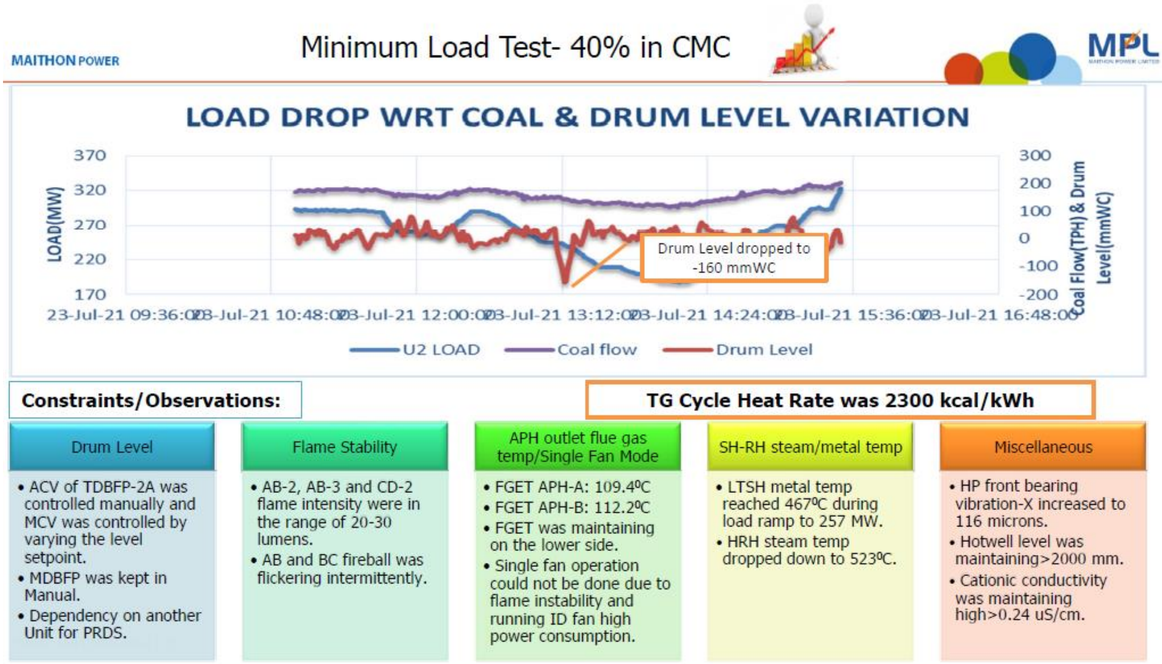


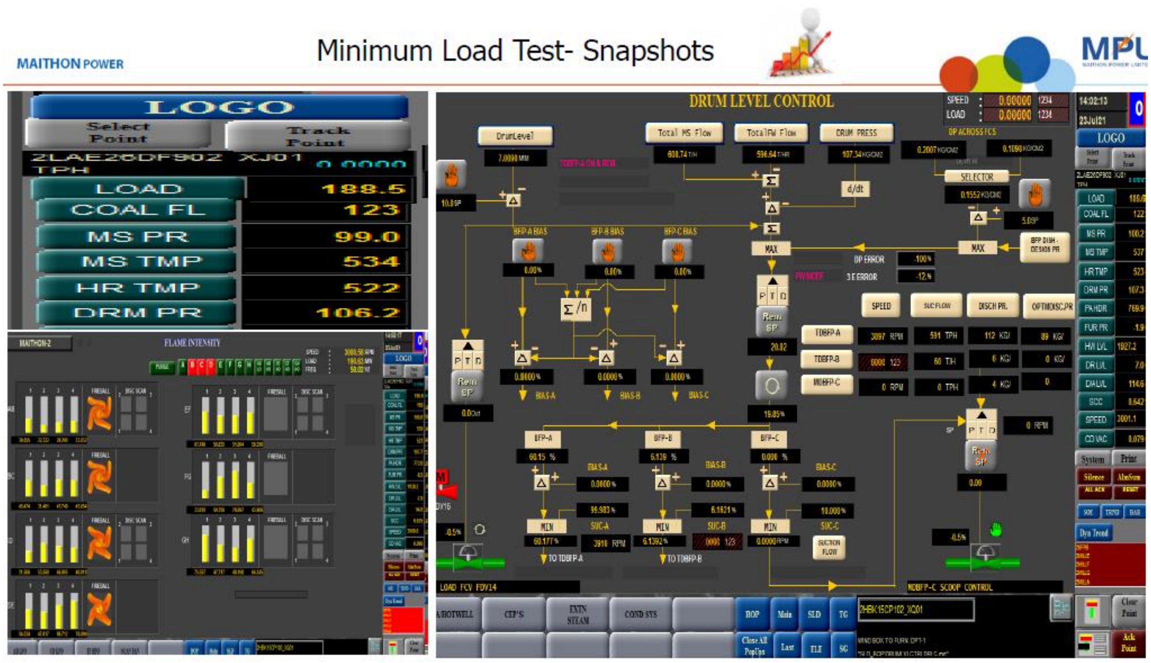
Constraints/Observations:

Drum Level	Flame Stability	APH outlet flue gas temp/Single Fan Mode	SH-RH steam/metal temp	Miscellaneous
• ACV of TDBFP-2B was controlled manually and MCV was controlled by varying the level setpoint. • MDBFP was kept in Manual. • Dependency on another Unit for PRDS.	• AB-2, AB-3 and CD-2 flame intensity were in the range of 20-30 lumens. • AB and BC fireball was flickering intermittently. • Furnace to Windbox DP dropped to 33 mmWC from 55 mmWC.	• FGET APH-A: 115.8⁰C • FGET APH-B: 115.1⁰C • FGET was maintaining on the lower side..	• LTSH metal temp reached 467⁰C during load ramp to 257 MW (Tag no-141). • HRH steam temp dropped down to 529⁰C.	• HP front bearing vibration-X increased to 116 microns. • Hotwell level was maintaining>2000 mm. • Cationic conductivity at CEP discharge was maintaining high>0.303 uS/cm.


MAITHON POWER
Minimum Load Test- Snapshots
MPL
LOGO
Select Point
Track Point
LOAD 209.6
COAL FL 133
MS PR 108.7
MS TMP 536
FLAME INTENSITY
DRUM LEVEL CONTROL


MAITHON POWER
Minimum Load Test- 40% in CMC
MPL
Load SP: 290 MW
MS Pr SP: 130 ksc
TDBFP A R/C valve opened
SCAPH Charged
10:30 - 11:00
Drum level fluctuation 225 mm
FD Fan-2B ampere :79 A
11:00 - 11:30
FDF 2A was stopped
Load SP: 275 MW
MS Pr SP: 120 ksc
Unit ramp rate : 3 MW/min
IDF 2A was stopped
CM 2E feed rate : 20 tph
Load SP: 260 MW
MS Pr: 115 ksc
11:30 - 12:00
ID Fan-2B ampere variation from 930 to 1040 A
Poor Flame condition
Fireball of AB & BC unstable
~210 TPH SA Flow deviation in LHS and RHS WB
12:00 - 12:30
Load raised to 290 MW
IDF 2A & FDF 2A re-started
Load reduced to 250 MW
MS Pr SP : 108 ksc
Unit Load Rate : 2 MW/min
12:30 - 13:00
Load SP: 235 MW
TDBFP 2B taken o/s
Furnace to WB DP: 35 MMWC
13:00 - 13:30
TDBFP2A ACV : 100% open
TDBFP2A MCV: 68% open
Flame intensity improves
13:30 - 14:00
Load reduced sequentially : 225 MW-210 MW-200 MW
Load reduced : 195 MW – 190 MW
Min Load SP: 179 MW
Min Load achieved: 188.6 MW
14:00 - 14:30
AB/BC Fireball flickering
Load raised to 200 MW
LTSH metal temp reached limit value of 460C
14:30 - 15:00
Load raised : 230 MW – 250 MW
Unit ramp rate : 5 mw/min
TDBFP 2B taken i/s
Load raised : 290 MW
MS Pr SP: 120 ksc
15:00 - 15:30
Private and Confidential


MAITHON POWER
Minimum Load Test- 40% in CMC
MPL
LOAD DROP WRT COAL & DRUM LEVEL VARIATION
LOAD(MW)
370
320
270
220
170
300
200
100
0
-100
-200
Coal Flow(TPH) & Drum Level(mmWC)
23-Jul-21 09:36:00
23-Jul-21 10:48:00
23-Jul-21 12:00:00
23-Jul-21 13:12:00
23-Jul-21 14:24:00
23-Jul-21 15:36:00
23-Jul-21 16:48:00
Drum Level dropped to -160 mmWC
U2 LOAD
Coal flow
Drum Level
Constraints/Observations:
TG Cycle Heat Rate was 2300 kcal/kWh
Drum Level
• ACV of TDBFP-2A was controlled manually and MCV was controlled by varying the level setpoint.
• MDBFP was kept in Manual.
• Dependency on another Unit for PRDS.
Flame Stability
• AB-2, AB-3 and CD-2 flame intensity were in the range of 20-30 lumens.
• AB and BC fireball was flickering intermittently.
APH outlet flue gas temp/Single Fan Mode
• FGET APH-A: 109.4ºC
• FGET APH-B: 112.2ºC
• FGET was maintaining on the lower side.
• Single fan operation could not be done due to flame instability and running ID fan high power consumption.
SH-RH steam/metal temp
• LTSH metal temp reached 467ºC during load ramp to 257 MW.
• HRH steam temp dropped down to 523ºC.
Miscellaneous
• HP front bearing vibration-X increased to 116 microns.
• Hotwell level was maintaining>2000 mm.
• Cationic conductivity was maintaining high>0.24 uS/cm.


MAITHON POWER
Minimum Load Test- Snapshots
MPL
LOGO
LOAD 188.5
COAL FL 123
MS PR 99.0
MS TMP 534
HR TMP 522
DRM PR 106.2
DRUM LEVEL CONTROL

MAITHON POWER

Load Ramp Tests

MPL

On 26th and 27th July, Load Ramp test (0.5%, 1% and 1.5%) was carried out in CMC with a specific coal consumption (SCC) of 0.61 kg/kWh. It was also in the schedule to check for the feasibility of 180 MW load.

Pre-test conditions:

- Load : 525 MW
- Coal Flow : 296 TPH (considering SCC=0.56)
- MS Pressure : Auto control at 172.9 kg/cm²
- Mill Combination preferred : B, C, D, E, F, G All feeders in Auto.
- Burner Tilt : Auto control
- SADC : Auto control at 75-90 mmWC.
- MS/HRH temp : Auto control
- O_2 SP : Auto control SP 3.56%.
- RGMO & AGC was kept OFF at 11:23 hrs after communicating to the concerned authority.
- Superheater spray : 30 TPH (LHS/RHS=0/30 TPH)
- Reheater spray : 11 TPH (LHS/RHS=5/6 TPH)
- Superheater temp : 539⁰C at 11:33 hrs
- Reheater temp : 535⁰C at 11:33 hrs
- Reheater MTM temp : 592⁰C max at 11:38 hrs (tag no- 260,258)
- UOFA and LOFA : Auto control

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Load Ramp Tests (525 MW to 290 MW) : Challenges

MPL

Reheater MTM Excursion

- Max. RH Metal Temperature during trial: 606°C
- RH MTM excursion beyond alarm limit of 590°C
- No improvement even after lowering steam temperature < 537°C (rated)
- Manual intervention to control RH MTM excursion

Ramp Rate

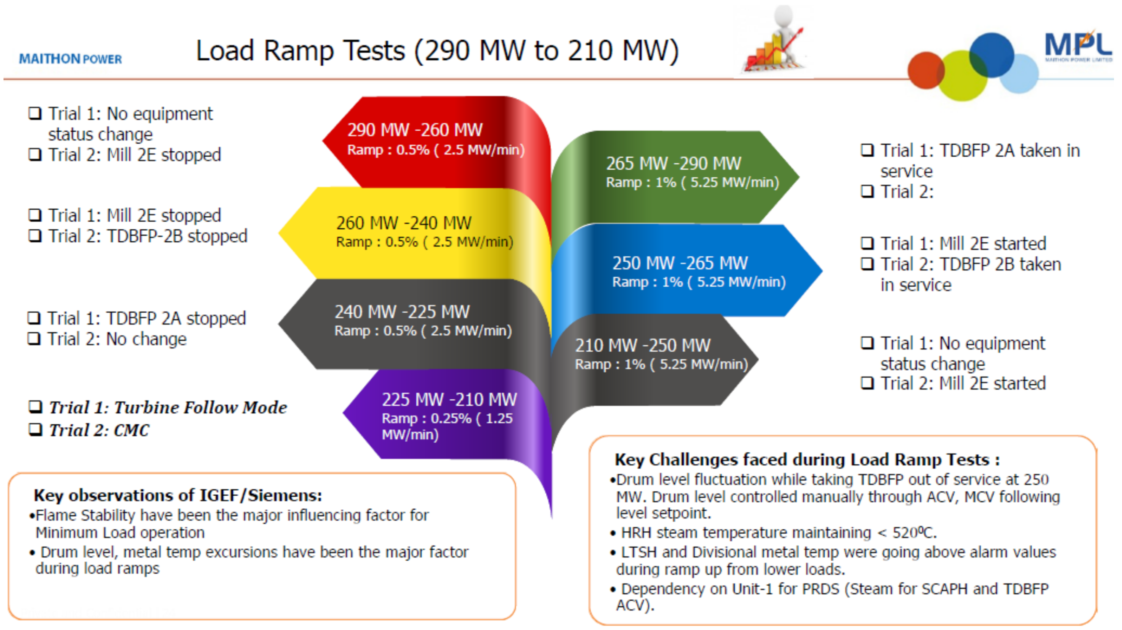
- **1.5% ramp up** rate not attempted due to limiting factors of RH MTM excursion
- **1.5% ramp down** rate successful for 525 MW to 450 MW load range

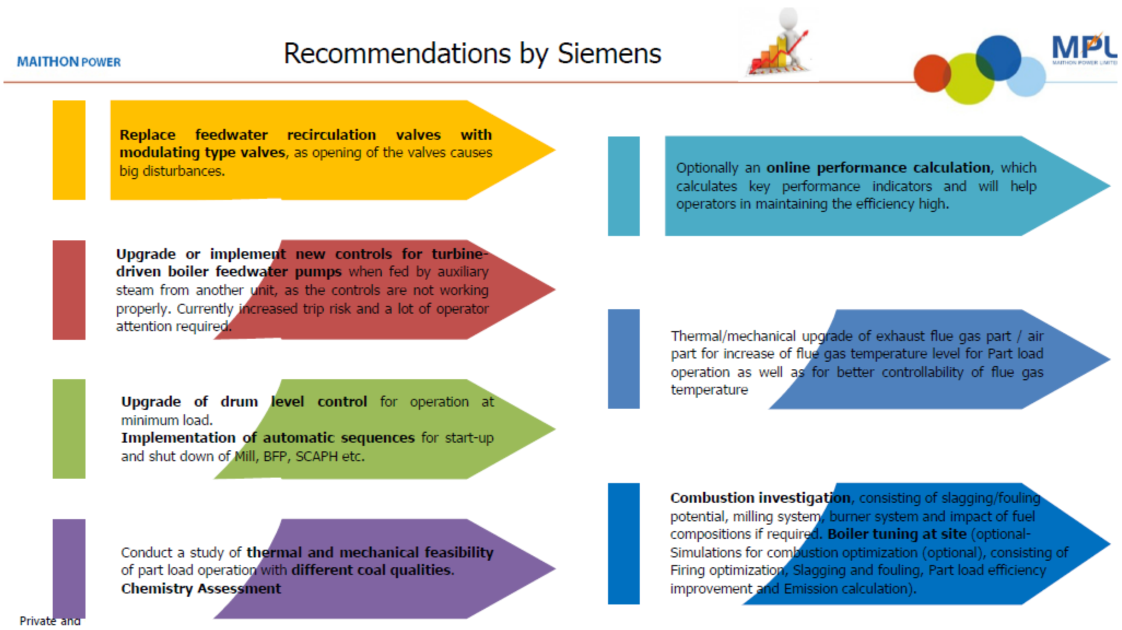
Control Loop Response

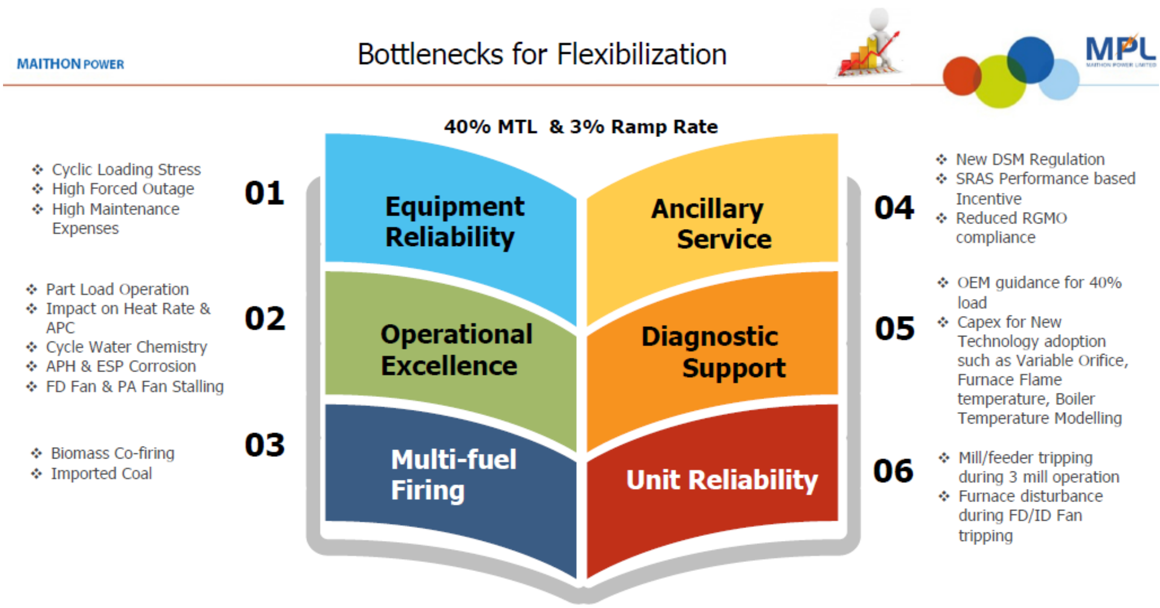
- Sluggish response by CMC
- Further control tuning is required to achieve aggressive rame rate

IGEF Team response

- Drum level, RH metal temp excursions have been the major factor during load ramps


MAITHON POWER
Load Ramp Tests (290 MW to 210 MW)
MPL
Trial 1: No equipment status change
Trial 2: Mill 2E stopped
Trial 1: Mill 2E stopped
Trial 2: TDBFP-2B stopped
Trial 1: TDBFP 2A stopped
Trial 2: No change
Trial 1: Turbine Follow Mode
Trial 2: CMC
290 MW -260 MW
Ramp : 0.5% (2.5 MW/min)
260 MW -240 MW
Ramp : 0.5% (2.5 MW/min)
240 MW -225 MW
Ramp : 0.5% (2.5 MW/min)
225 MW -210 MW
Ramp : 0.25% (1.25 MW/min)
265 MW -290 MW
Ramp : 1% (5.25 MW/min)
250 MW -265 MW
Ramp : 1% (5.25 MW/min)
210 MW -250 MW
Ramp : 1% (5.25 MW/min)
Trial 1: TDBFP 2A taken in service
Trial 2:
Trial 1: Mill 2E started
Trial 2: TDBFP 2B taken in service
Trial 1: No equipment status change
Trial 2: Mill 2E started
Key observations of IGEF/Siemens:
•Flame Stability have been the major influencing factor for Minimum Load operation
• Drum level, metal temp excursions have been the major factor during load ramps
Key Challenges faced during Load Ramp Tests :
•Drum level fluctuation while taking TDBFP out of service at 250 MW. Drum level controlled manually through ACV, MCV following level setpoint.
• HRH steam temperature maintaining < 520ºC.
• LTSH and Divisional metal temp were going above alarm values during ramp up from lower loads.
• Dependency on Unit-1 for PRDS (Steam for SCAPH and TDBFP ACV).


MAITHON POWER
Recommendations by Siemens
MPL
Replace feedwater recirculation valves with modulating type valves, as opening of the valves causes big disturbances.
Upgrade or implement new controls for turbine-driven boiler feedwater pumps when fed by auxiliary steam from another unit, as the controls are not working properly. Currently increased trip risk and a lot of operator attention required.
Upgrade of drum level control for operation at minimum load.
Implementation of automatic sequences for start-up and shut down of Mill, BFP, SCAPH etc.
Conduct a study of thermal and mechanical feasibility of part load operation with different coal qualities.
Chemistry Assessment
Optionally an online performance calculation, which calculates key performance indicators and will help operators in maintaining the efficiency high.
Thermal/mechanical upgrade of exhaust flue gas part / air part for increase of flue gas temperature level for Part load operation as well as for better controllability of flue gas temperature
Combustion investigation, consisting of slagging/fouling potential, milling system, burner system and impact of fuel compositions if required. Boiler tuning at site (optional-Simulations for combustion optimization (optional), consisting of Firing optimization, Slagging and fouling, Part load efficiency improvement and Emission calculation).
Private and



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Conclusion:

- Any unit can be flexed; however, all units need not. The flexing needs is to be decided based on the grid support required from the unit.
- Moderate amount of flexibilization can be achieved with modification in operational practices.
- Higher level of flexibilization can be achieved with retrofits and the decision should be taken on case-to-case basis as in some cases the retrofit cost may be prohibitive.
- The providers of flexibility must be motivated by incentivization.

Questions, If Any ?

vgbe ENERGY IS US

vgbe energy is the new name of
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