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A Methodology for Computation of Experimental Annual Station Heat Rate Benchmark

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This paper presents a methodology for assessment of annual heat rate of a coal fired thermal power unit based on a snap shot test to which various factors contributing to annual effects are added. This method is successfully used in a number of stations and represents the Unit Heat Rate (UHR) and Station Heat Rate (SHR) fairly well. This method is not a substitute for measurement of heat rate by direct measurement of coal flow and energy generated and is applicable only where direct measurement of coal flow into an individual boiler by gravimetric feeders or belt weighers is not available. This method is superior to other methods in view of its total coverage of all effects and no annual factor which affects heat rate is left out. Hence it is popularly accepted by most thermal stations. This method is superior to backward computation of UHR from SHR by apportioning.

Key words: *coal fired station, unit heat rate, station heat rate, coal quality effects, heat rate degradation, cycling losses, stacking losses, make up losses*

1.0 INTRODUCTION

The heat rate is the energy efficiency transfer function of the thermal energy in fuel consumed to the energy generated and denoted in units of kcal/kWh or kJ/kWh. It is reciprocally related to the energy efficiency and is the preferred index because it shows a higher resolution as compared to energy efficiency. Earlier studies focused on determining the sensitivity of changes in individual parameters to change in gross overall efficiency, the sum of the deviations giving the deviation in overall energy efficiency [1]. The benchmarking of heat rates was aimed at determination of deviations in Unit Heat Rate (UHR) from the Design Heat Rate (DHR) [2] to quantify the energy efficiency. Presently, the Central Energy Regulatory Commission (CERC) has set up operational norms for coal fired stations based on allowable % deviation from the design heat rate [3].

The basis of energy efficiency transfer function is the Specific Fuel Consumption (SFC) (kg/kWh) which for a given time interval is given by,

$$SFC = \frac{Coal\ consumption_{actual}}{Energy\ generated}$$

This energy efficiency index is deficient from the point of view that besides denoting the energy efficiency it is also sensitive to the gross calorific value (GCV) (kcal/kg) of the fuel fired into the unit. SFC is inversely related to the GCV. For a given level of energy efficiency, coals with inferior GCV will show a higher SFC. The sensitivity to energy efficiency and coal

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quality cannot be decoupled. To overcome this problem, it is required to have an index which is first order independent on the GCV of the fuel (kcal/kg). The heat rate serves this requirement well and is very popular in the power generating sector. The heat rate (kcal/kWh) is given by,

$$HR = SFC \times GCV$$

HR is first order independent of the GCV of the fuel as SFC and GCV are inversely related. However, HR is second order dependent on GCV and increases with deterioration in coal quality. As the quantity of coal fired into the boiler increases, the dry flue gases also increase.

The basic heat rate is the Unit Heat Rate (UHR) which is defined for an individual coal fired unit for a given time interval. The Station Heat Rate (SHR) for a given time interval is computed as the capacity weighted average of the UHRs as,

$$SHR = \frac{\sum_{j=1}^{n} C_j UHR_j}{\sum_{j=1}^{n} C_j}$$

The SHRs presently reported in many stations are based on the overall coal consumption in the station from the station entrance (typically wagon tippler or track hopper or weight bridge for trucks). The SHR so computed contains the stack yard loss component which is not unit dependent. The coal consumption is computed by periodic volumetric measurement of coal inventory stock in the coal yard. The method of calculation of SHR is based on coal receipts apportioned as per the coal factor of each unit and reconciled by the periodic inventory checks. In other words, UHR is calculated backwards from SHR. It is found that by this process, the UHR is dependent on the coal consumption and not vice versa. This major deficiency can be overcome by measurement of coal consumption at the bunkers of each unit and computing individual UHR and then using this for computing SHR.

Computation of heat rate where belt weighers/ gravimetric feeders are present:

Typically monthly UHR is computed as,

Monthly Overall UHR

= ((Coal Consumption in Unit at belt weighers (or gravimetric feeders) x GCV of bunkered coal) + (Consumption of LDO x GCV of LDO) + (Consumption of FO x GCV of FO))/Monthly energy generation

The monthly SHR is then calculated as follows:

$$SHR = \frac{\sum_{i=1}^{12} \sum_{j=1}^{n} C_{i,j} UHR_{i,j}}{\sum_{j=1}^{n} C_j}$$

Computation of station heat rate where the belt weighers or gravimetric feeders to measure the coal consumed in each individual unit are not yet installed:

In order to overcome this short term problem of the non-availability of belt weighers or gravimetric feeders, the following method of computing the heat rate is suggested in the absence of belt weighers:

Test 'Snapshot' unit heat rate: This is on the basis of computation of boiler efficiency and turbo-generator efficiency.

Component due to steam loss for non motive applications: This includes the heat rate due to steady DM make up on the basis of continuous steady online monitoring of unit DM make up over a year. The DM water make up represents the steam loss from the system.

Component due to heat consumption for cycling and abnormal operations: This includes the heat rate component due to consumption on coal, fuel oil and DM water (steam loss) for hot/warm/cold starts. This is the product of the energy per start and the number of starts.

Component due to heat consumption equivalent of mill rejects: This is the average value of the mill reject rate which is discharged from the reject gate.

Component due to heat loss in MS and RH lines in-between the boiler and turbine: This is based on the heat loss rate due to convection and radiation components for the boiler stop valve-turbine stop valve interconnecting piping.

Component due to seasonal effects: This is based on the variation in UHR over the year as per the monthly tests conducted by the station *vis-à-vis* the present month of testing.

The above components need to be computed on the basis of yearly average or with the aid of standard online software which will provide time averaged values over the year.

Unit Heat Rate: The sum of the above parameters will provide the Unit Heat Rate.

$$UHR = HR_{test} + HR_{DM\ make\ up} + HR_{cycling\ operations} + HR_{rejects} + HR_{MS,RH\ line\ losses} + HR_{seasonal}$$

Station Heat Rate: The station heat rate is on the basis of the capacity weighted average of the unit heat rates.

2.0 TEST PROCEDURE

The test procedures and methods of calculation of test unit heat rates (test UHR) are under zero make up conditions and the overall annual Unit Heat Rate (annual UHR) is computed based on considerations of DM make up, cycling losses during starts, losses due to rejects, seasonal variations and losses due to steam piping in-between the boiler and turbine. The test conditions as provided by ASME ptc 7 and are maintained for during the test.

The Unit Heat Rates are computed ex-bunker and the station rates are derived as capacity weighed averages of the individual Unit Heat Rates.

The following are considered in the annual overall heat rate assessment:

2.1 Test performance and test heat rate at 80-100% MCR load

The test performance at the normal operating conditions with zero make up is computed for each of the units.

2.2 Heat consumption due to steam lost to non-motive applications represented by DM make up

This heat loss is represented by the DM water make up which represents the steam lost from the process. Normal DM water make up is below 3% of the main steam flow.

The annual heat consumption for DM water make up (Q) in Mcal/h, is given by,

$$Q\ (Mcal/h) = \{10^{-3}[DM\ water\ make\ up\ (\%) * Main\ steam\ flow\ at\ 80\ \%\ load\ (kg/h) * (h_{steam} - h_{water})\ (kcal/kg)]\}$$

The power generated [considering 80% (or 100 %) PLF] (E) in MW is given by:

$$P\ (MW) = Unit\ capacity \times 0.8\ (or\ 1.0)$$

The heat rate component due to cycling and abnormal operations is given by:

Annual heat rate component due to DM water make up = HR_{steam} = [Q/P]

2.3 Heat consumption due to cycling/ abnormal operation- start up and shut down

This heat consumption can be computed based on the number of hot, warm and cold starts.

The heat consumption (Mcal) for any type of start as a function of the average resource (coal, fuel oil and DM water) consumption (averaged over a year) for that start is given by:

Heat Consumption/start (Mcal) = 10^{-3}{[Raw coal consumption (kg) * weighted average GCV of raw coal (kcal/kg)] + [FO Consumption (m^3) * density (kg/m^3) * GCV of FO (kcal/kg)]+ [LDO Consumption (m^3) * density (kg/m^3) * GCV of LDO (kcal/kg)] + [DM water consumption (m^3) * density (kg/m^3) *(h_{steam}-h_{water}) (kcal/kg)/(boiler efficiency=0.8)] }

The annual heat consumption for cycling operations (Q_c) in Mcal/year, is given by:

Q (Mcal/year) = {[$Q_{hot\ start}$ (Mcal) x number of hot starts/year] + [$Q_{warm\ start}$ (Mcal) x number of warm starts/year] + [$Q_{cold\ start}$ (Mcal) x number of cold starts/year]}

The annual energy generated [considering 80% (or 100%)PLF] (E) in MWh is given by:

E (MWh/year) = Energy generated = Unit capacity x 8760 x 0.8 (or 1.0)

The heat rate component due to cycling and abnormal operations is given by:

Annual heat rate component due to cycling and abnormal operations

$$HR_{cycling} = [Q_c/E]$$

This is based on the computation of average number of hot, warm and cold starts and the energy components for each type of start. The thermal energy for starts for a typical 210 MW unit is as follows:

- Hot starts: 800-2,000 Gcal/start
- Warm starts: 2,001-3,000 Gcal/start
- Cold starts: 3,001-7,000 Gcal/start

This takes into consideration the resource consumption in energy terms from boiler light up through synchronization till reaching of 80% load. In the event of constraints in loading, this is reflected in the form of slow loading rate.

Based on the number of hot/warm/cold starts and energy generated, this can be converted into a heat rate component (kcal/kWh).

2.4 Additional heat consumption due to year round variations in environmental and fuel parameters from test values

This is the algebraic sum of the difference between the test heat rate of the station in the month of CPRI test and the individual test heat rates or every month over the year. In case, in the month of test, the heat rate is the highest or higher than the standard deviation, seasonal variation is taken as zero.

$$HR_{seasonal\ variation} = \Delta UHR_{test\ month\ and\ other\ months}$$

Based on the plant efficiency test data the seasonal variations are plotted as shown in Figs. 1 and 2 for few typical units. The correction is applied to the snap shot efficiency test depending on the point at which it is conducted.

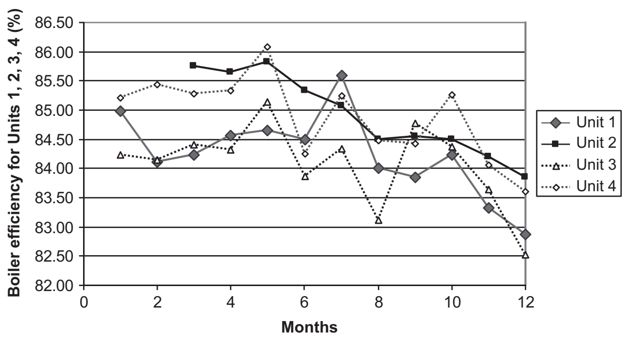

FIG. 1 BOILER EFFICIENCY FOR UNITS, 1, 2, 3, 4 Vs MONTHS

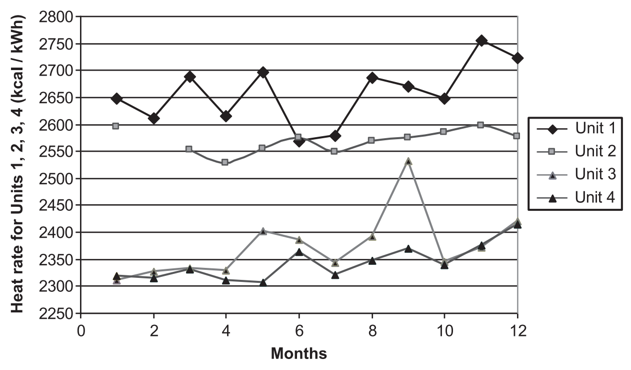

FIG. 2 HEAT RATE FOR UNITS 1, 2, 3, 4 Vs MONTHS

2.5 Accounting of mill rejects

This is taken as,

HR $_{reject}$= {(Reject production (% of coal through mill)) * weighted average GCV of Raw coal (kcal/kg)* SFC (kg/kWh))}

2.6 Accounting of heat loss in piping in-between boiler and turbine

This is taken as,

HR $_{MS, RH\ piping}$ = {px (Running length of piping (m)) x (diameter of piping coal (m)) x (convective and radiative heat transfer rate (natural convection) (kcal/hm^2°C))x (ΔT_{pipe} (°C)}/E

2.7 Overall annual Unit Heat Rate

In the present study the annual heat rate is computed as follows:

1. Test heat rate based on actual performance test under conditions of zero make up and zero auxiliary steam consumption.
2. Heat consumption translated into a heat rate component due to steam consumption for non-motive applications which is reflected in terms of DM water make up.
3. Heat consumption translated into a heat rate component due to cycling or abnormal operations like hot, warm and cold starts. This takes into consideration both the energy consumption per start and the number of such starts per year.
4. Heat consumption translated into heat rate components due to deviation in test parameters all though the year (positive and negative deviations).
5. Energy components to account for reject coal at the mill. This is because the coal entering the bunker is considered as entering coal and GCV of the bunkered coal is taken. The component due to mill rejects is to be subtracted.

The unit heat consumption is computed considering all the above which portrays the realistic heat consumption *vis-à-vis* the energy generated. The station heat rate is computed as the capacity weighted average of the unit heat rates.

2.8 Degradation

The design heat rate is used as a bench mark. This is considered on the basis of boiler and turbo generator efficiencies only and does not reflect on the steam consumption in the unit. Design heat rate is not normally given as a performance parameter by the vendor who only gives the boiler efficiency, the turbine efficiency and the generator efficiency in his performance guarantee values. The boiler and turbine efficiency tests are performed at zero make up, zero auxiliary steam consumption. The computed product of the boiler, turbine and generator efficiencies is taken as the UHR.

The annual degradation over the life time is calculated as :

$$\Delta = [UHR_{operating} - UHR_{design}]/t$$

where t is the number of operating years of service and Δ is the heat rate degradation factor (kcal/kWh/year). Only the test UHR is used and not the annual average UHR due to other factors.

The time averaged degradation factor (% degradation/year) is calculated as,

$$\delta = [UHR_{t\text{-}end} - UHR_{design}]/[\ t \times UHR_{design}]$$

Degradation between two points of time are calculated as,

$$\Delta = [UHR_{t\text{-}end} - UHR_{t\text{-}start}\ ]/[t]$$

$$\delta = [UHR_{t\text{-}end} - UHR_{t\text{-}start}\ ]/[(\ UHR_{t\text{-}start})t]$$

where δ is the degradation factor (% degradation/year) and t is the time interval in years.

Standards IEC 953 and ASME ptc 6 both prescribe these for newly installed steam turbines acceptance tests and is chosen between 0.4 to 0.7% of the turbine heat rate. OEMs assume a one time degradation of 0.2% for the first ten months of operation for accounting delayed performance certification. This approach gives grossly different results because of the following reasons:

Degradation is specific to hardware, operating culture, maintenance culture and environment of each unit including regularity of overhauls. Even in the same station different units degrade differently. Hence, the standard degradation can be used as a guideline for degradation of boiler, turbine and generator efficiencies under normal operating conditions.

Degradation is a ***broad trend indicator*** in very average conditions. The standards are guidelines for degradation of newly installed turbine efficiency only between the time of commissioning and performance guarantee test usually within 2-3 years. The degradation in the active lifespan of 30 years or more cannot be estimated from the short time degradation formula. Also the heat rate computed on the basis of degradation of parameters do not reflect on the steam consumption for non-motive applications and heat consumption (coal, oil and steam) for cycling operations. The heat rate component due to cycling components is a function of the number of such cycling operations per year. Even in the remaining life assessment the numbers of cycling operations are an important criterion for assessment of degradation. Considering all these factors, it is better to go for an experimental approach to the heat rate.

Degradation gets halted or reversed to the original design value if there is renovation and replacement of components with new components. Non-motive steam economy measures can reverse degrading trends.

For computing the SHR trajectories, the grand capacity weighted average degradation rate of TG heat rate (Test TG UHR) as per tests with reference to the life time of each unit (% degradation/year) is considered.

The degradation rates units of 30 years of age and more is around 0.3%/year.

2.9 Stacking loss

With belt weigher recording, online computation based on heat in fuel divided by the electrical energy generated is to be the basis for computation of unit and station heat rate. Stacking loss (if any) and unaccounted coal is separately identified (as coal loss only in weight percentage of receipt coal). The entrance to the bunker is the terminal point for heat rate computation. In between the bunker and receiving end, the losses are to be separately identified (as coal loss only in weight percentage of receipt coal) and will not form part of the unit heat rate.

In-between the coal yard entrance and the bunker the losses may be taken on a weight basis and not on as a heat rate component.

The terminal point for heat rate computation will be the bunker and in-between the bunker and the receiving end, the losses and unaccounted coal will be separately identified (as coal loss only in weight percentage of receipt coal) and will not form part of the unit heat rate.

$(\text{Coal consumption})_{calculated}$ = [Coal receipts – Coal stock on hand as per stacking – Stacking loss (if any)]

$(\text{Coal consumption})_{unaccounted}$ = [$(\text{Coal consumption})_{calculated}$ -$(\text{Coal consumption})_{actual}$]

Since the power station involves handling large quantities of coal there is bound to be some unaccounted losses in coal consumption which can be positive or negative. This must be brought out as coal loss only (weight % of receipt coal) and must not be accounted in the heat rate.

However, the belt weighers and coal measurement at the bunkers or feeders through gravimetric feeders must be essentially installed at the earliest for measuring the coal flow into individual units. In the absence of belt weighers/gravimetric, it is not possible to assess stacking loss.

Coal quality is normally at the receipt point or wagon tipplers or lorry weighbridges. Since the fuel bunkers consume a mixture of raw, imported and washed coals, computation of bunkered coal GCV poses some problems. One of the ways of overcoming this is to take coal quality of individual coals and deduct a value of 150 kcal/kg from the weighted average mixture coal to arrive at the coal quality at the bunkers [4]. Otherwise, differences between the GCV of receipt coal (weighted average) and bunkered coal mixture can differ by as much as 1000 kcal/kg due to various factors. Ideally, this difference must be attempted to be brought within ± 100 kcal/kg.

3.0 RESULTS AND DISCUSSIONS

The following factors affect the snap shot UHR:

1. **Test load:** The test load is normally fixed at 80% MCR to 100% MCR. For a typical 210 MW unit, the sensitivity to loading is worked out as –3.05 kcal/kWh per + 1 % change in % MCR load to account for PLF which is in excess of 80%.

2. **GCV of coal:** The choice of the coal for the test has an impact on the snap shot UHR. Coals with higher ash give lower efficiencies. The impact of coal quality on boiler efficiency for 210 MW and 500 MW units is given in Table 1 (where $\mathbf{A_0}$ and $\mathbf{A_1}$ are the intercept and the slope of the linear curve fits). Fig. 3 gives the variation of boiler efficiency with GCV for a number of units tested. The averaged curve fits are used for calibrating the GCV from the test GCV to the annual average GCV. The impact of coal quality on UHR has been worked out as –0.1247 kcal/kWh per + 1 kcal/kg of increase in coal GCV.

TABLE 1

CURVE FITS FOR THE SENSITIVITY OF BOILER EFFICIENCY DEVIATIONS WITH OPERATING GCV.

Sl. No.	**Particulars X:** GCV (kcal/kg) [Range: 3300 to 3700 kcal/kg]	A_0	A_1	Annual average GCV
	210 MW units			
01	Average variation in curve fits	70.306	0.00377	3393
	500 MW units			
02	Average variation in curve fits	70.402	0.00383	3544

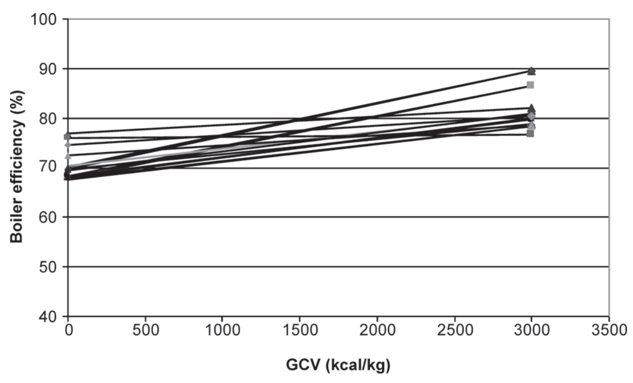

FIG. 3 BOILER EFFICIENCY (%) Vs GCV (kcal/kg)

3. **Moisture content in the coal:** Increase in moisture content in coal increases the heat rate. The sensitivity factor for boiler efficiency and UHR for moisture in coal when the moisture content exceeds 20% is –0.1293% boiler efficiency per + 1% change in moisture; and –3.8849 kcal/kWh per + 1% change in moisture content.

The factors affecting the components which make up the annual heat rate are as follows:

1. **DM make up water:** Normally DM water make up must be below 3% on an annual basis. Increase of DM make up implies that equivalent quantity of steam is lost from the system. In good plants the DM water can be reduced to as low as 0.1%.

2. **Rejects:** This must be below 1%. Increased fraction of rejects results in increased heat rate as the quantity of reject coal is not burnt but the coal is accounted in the heat rate. In good plants, the rejects can be reduced to 0.1%. In drum type ball mills rejects are nil.

3. **Starts:** Energy consumed for each start in the form of coal, fuel oil, DM water and auxiliary power. Starts are classified in hot, warm and cold starts. The average heat consumption (total of coal, fuel oil, DM water and auxiliary power) for each type of start are computed and the annual component of heat rate is computed by dividing the total heat generation by the annual energy generated. It is to be mentioned here that the criterion for heat rate component is 80% load as at low loads there may not be net generation but only consumption of resources. At loads between 20% to 80% MCR the heat rate will be abnormally higher than the heat rate at 100% MCR and hence this is to be accounted. Normal the normative heat rate effects of hot/warm/cold starts are 1/2/3 kcal/kWh. Outages involving boiler tube leaks (BTL) normally result in higher resource consumption because of the need for cooling the boiler and the internal repairs.

Table 2 gives the range of values of heat rate affecting factors for computation of annual UHR from snap shot UHR. Table 3 gives the curve

TABLE 2

RANGE OF VALUES OF HEAT RATE AFFECTING FACTORS FOR COMPUTATION OF ANNUAL UHR FROM SNAP SHOT UHR

Particulars	Units	Max	Min	Average
Test UHR	kcal/kWh	3378.30	2392.50	2583.19
HR-Seasonal deviations	kcal/kWh	60.0	0	variable
HR-Cycling deviations	kcal/kWh	199.94	18.14	51.28
HR-Deviations due to DM	kcal/kWh	161.52	15.62	94.86
HR-Deviations due to -rejects	kcal/kWh	88.8	0	33.46
HR-Deviations due to -MS and RH pipe	kcal/kWh	3.88	1.35	2.76
Annual UHR	kcal/kWh	3649.49	2499.23	2770.14

TABLE 3

CURVE FITS FOR THE SENSITIVITY OF HEAT RATE DEVIATIONS WITH OPERATING PLANT LOAD

Sl. No.	Particulars **X:** Operating plant load (MW) [Range: 200-500 MW]	A_0	A_1	R^2
01	Y: HR-cycling dev loss (kcal/kWh)	34.456	0.0836	0.462
02	Y: HR-Dev DM loss (kcal/kWh)	130.74	-0.2245	0.2825
03	Y: HR-Dev-rejects loss (kcal/kWh)	45.151	-0.0783	0.835
04	Y: HR-Dev-MS and RH pipe loss (kcal/kWh)	3.5441	-0.0049	0.5594
05	Y: Total deviations (kcal/kWh)	213.89	-0.224	0.992
06	Y: Test UHR (kcal/kWh)	2918.7	-2.1829	0.4568
07	Y: Annual UHR (kcal/kWh)	3195.8	-2.2062	0.3696

fits for the sensitivity of heat rate deviations with various heat consuming factors (where A_0 and A_1 are the intercept and the slope of the linear curve fits).

Table 4 gives the curve fits for the sensitivity of heat rate deviations with age of the unit (where A_1 is the slope of the linear curve fits).

TABLE 4

CURVE FITS FOR THE SENSITIVITY OF HEAT RATE DEVIATIONS WITH AGE OF THE UNIT

Sl. No.	Particulars **X:** Age (years)	A_1	R^2
01	Y: Test UHR (kcal/kWh)	24.826	0.5688
02	Y: Annual UHR (kcal/kWh)	28.697	0.6411

4.0 CONCLUSIONS

The annual UHR of a coal fired unit and hence the annual SHR of the station can be assessed based on a snap shot efficiency test and by adding various components responsible for annual efficiency such as DM water, rejects, cycling losses and seasonal variations. The values are corrected for annual average GCV when the test GCV is different. This method is useful when gravimetric feeders/belt weighers are not available for measuring the quantity of coal consumed in individual boilers. However, the coal measurement at the entrance to the boilers must be introduced at the earliest. This method is superior to computation of UHR from SHR by apportioning of the coal flow based on a coal factor.

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