POWER PLANT BOILER
EFFICIENCY MEASUREMENTS, CORRECTIVE ACTIONS, & COMBUSTION OPTIMIZATION

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27TH September, 2021
[REV-5]

SECTION - I

GENERAL

1. INTRODUCTION:

Performance of the boiler, like efficiency and evaporation capacity reduces with time, due to poor combustion, heat transfer fouling and poor operation and maintenance.

Efficiency testing helps us to find out how far the boiler efficiency drifts away from the best efficiency.

Abnormal deviations could therefore be investigated to pinpoint the problem area for necessary corrective action.

This is a pre-requisite for energy conservation action in industry.

2. REFERENCE STANDARDS.

2.1: IS 8753: Indian Standard for Boiler Efficiency Testing:
2.2: ASME Standard: PTC-4-1 Power Test Code for Steam Generating Units:

Both the above Standards define the following;
>   Direct method (also called as Input -output method)
>   Indirect method (also called as Heat loss method)

For the testing to be done, the boiler should be operated under steady load conditions (generally full load) for a period of <u>one hour </u>after which readings would be taken during the <u>next hour</u>.
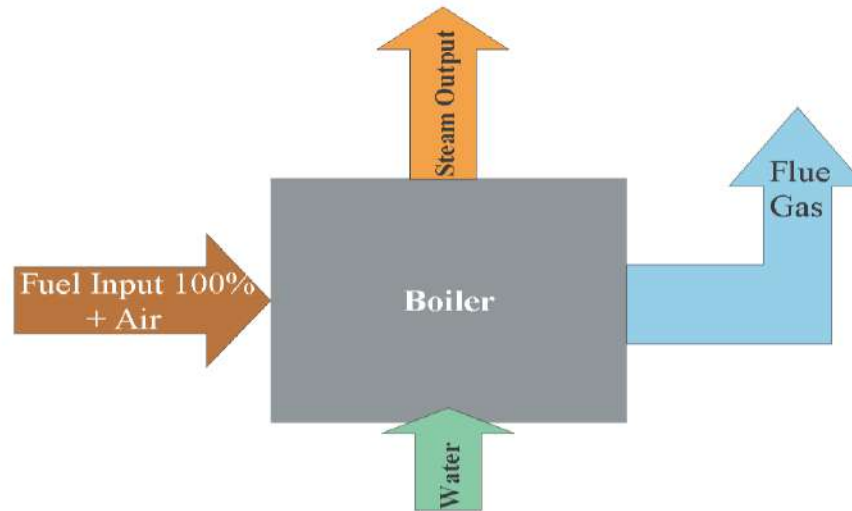
Efficiency = $\dfrac{\text{Heat addition to Steam} \times 100}{\text{Gross Heat in Fuel}}$

$$Boiler\ Efficiency = \dfrac{\text{Steam flow rate x (steam enthalpy} - \text{feed water enthalpy})}{\text{Fuel firing rate x Gross calorific value}} \times 100$$

THE DIRECT METHOD was standard for a long time, but is little used now. It is straightforward & consists of measuring the heat supplied to the boiler in a given time and the heat added to the steam in the boiler.

The trouble is that several of the quantities are difficult to measure accurately such as the coal weight. Accordingly the result may have an overall tolerance of about +/ - 1.5%.

Efficiency $= 100 - (1+2+3+4+5+6+7+8)$ (by Indirect Method)
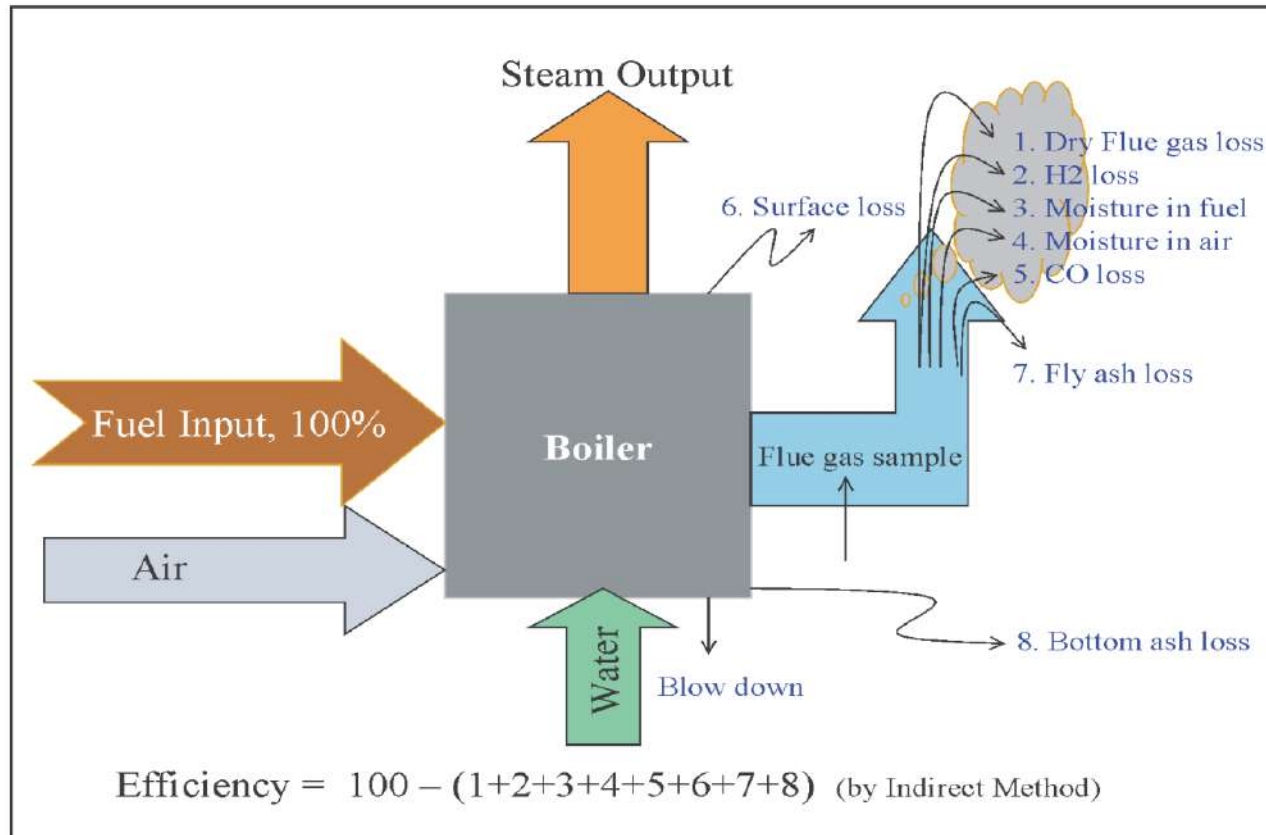
THE LOSSES METHOD has the following advantages;
1. Errors are not so significant; for example, if the losses total 10% then an error of 1.0% will affect the result by only 0.1%
2. Each Loss points to a Corrective Action for restoration of Efficiency.

3. COAL ANALYSIS:

Step I: Proximate Analysis

Proximate Pnalysis is carried out in the Station Chemistry Laboratory.
This gives:

C = % of fixed carbon

A = % of ash

VM = % of volatile matter

M = % of moisture

	As received	As tested	Dry
FC (%)	45.5	47.8	52.8
VM (%)	29.0	30.5	33.7
A (%)	11.5	12.1	13.4
M (%)	14.0	9.5	—
GCV (kJ/kg)	25353	26660	29459

Step II: Ultimate Analysis

This is a difficult and detailed series of laboratory analyses. The ultimate analysis requires the separate determination of: Carbon, hydrogen, nitrogen, oxygen, sulphur, and chlorine, in addition to the total moisture and ash already determined in the proximate analysis.

This analysis is normally carried out in National Test Labs, and generally only during PG Testing or when the Linked Coal Mines change. These Test results must be preserved always.

3.1 Determination of Ultimate Analysis from Proximate Analysis:

 In the absence of a Ultimate Analysis of a coal, the Proximate Analysis is used to approximate the Ultimate Analysis by use of the following methods:

1. Gebhardt Formula
2. Parr's Formula
3. The modified Seyler chart
4. Simplified Seyler-Dulong formula

Example: Conversion formula for proximate analysis to ultimate analysis

%C = 0.97C + 0.7 (VM + 0.1A) - M(0.6 - 0.01M)

%H2 = 0.036C + 0.086 (VM - 0.1xA) - 0.0035M2 (1 - 0.02M)

%N2 = 2.10 - 0.020 VM

Note: We need to use that particular formula which gives the closest values, when Coal is tested in a National Lab

3.2 Determination of approximate calorific value from Ultimate Analysis

Substance	Symbol	GCVv (kJ/kg)
Hydrogen	H_2	143 050
Carbon (to CO)	C	10 200
Carbon (to CO_2)	C	33 820
Carbon monoxide (to CO_2)	CO	10 165
Methane	CH_4	55 700
Sulphur (to SO_2)	S	9 304

Determination of approximate calorific value using Dulong's formula
The approximate calorific value of Coal can be determined from Ultimate Analysis of Coal by using Dulong's formula:
Thus GCV = 33 820 * C + 143 050 * (H-O/8) + 9304 * S kJ/kg fuel.
(Where O, C, H and S are the kg/kg of fuel of each. Oxygen combines with 1/8 of its mass of hydrogen, so hydrogen remaining equals (H –O/ 8).

Example

A coal has the following ultimate analysis:

Moisture	15.96%
Ash	14.73%
Carbon	54.22%
Hydrogen	3.70%
Nitrogen	1.11%
Sulphur	1.43%
Oxygen	8.85%

GCV By Bomb Calorimeter = 21 995 kJ/kg

GCV by Dulong Formula:
= (33 820 * 0.5422) + 143 050 * (0.037 -0.0885/8) +(9304 * 0.0143) kJ/kg
= 18 337 + 3711 + 133 = 22 181 kJ/kg

The discrepancy between the two results is about 0.8%.

4. Theoretical Air Required for Coal

(100/23.2) * $\big[$(32/12)*C + (16/2)*(H-O/8) + (32/32)*S $\big]$

where   C = % carbon per kg fuel

              H = % hydrogen per Kg fuel

              O = % oxygen per kg fuel

              S = % sulphur per kg fuel

The values inside the square brackets indicate the quantity of oxygen required for each combustible constituent of the fuel.

100 kg of air contains 23.2 kg oxygen, so 1 kg of oxygen is contained in 100/23.2 kg of air

Example

A certain coal has the following ultimate analysis:

	Symbol	%
Carbon	C	56.8
Hydrogen	H	3.7
Nitrogen	N	1.3
Sulphur	S	2.0
Oxygen	O	7.0
Ash	—	16.7
Moisture	—	12.5
		100.0

Theoretical air required

=(100/23.2) * [(32/12)*56.8 + (16/2)*(3.7-O/8) + (32/32)*2]

= 4.31 (151.5 + 22.6 + 2) kg/100 kg fuel

(Thus, 56.8 kg carbon requires 151.5 kg O2, H2 requires 22.6 kg O2 and Sulphur 2 kg O2.)

= 4.31 (176.1) = 759 kg/100 kg fuel

So the total O2required = 176.1 kg and the air required = 759.0 kg

. ∴ The N2= 759 - 176.1 = 582.9 kg

5. Collection of Flue Gas Sample [For CO2]:

When carrying out a traverse of a flue gas duct, we need to measure the (a)gas (b)velocity, (c)temperature and (d)percentage C0 2. To take care of stratification, we require 24 to 36 sampling points, placed equally across the length and breadth (the Grid) of the 2nd Pass of the Boiler.

Each gas temperature is multiplied by the gas velocity at the same point and the average product determined. The average product is then divided by the average gas velocity to obtain the true average temperature. Similarly each C0 2 % should be multiplied by the corresponding gas velocity, and the average of the products divided by the average gas velocity to give the true average C02 %.

For Routine Testing purposes, samples are taken from a location known to be near the mean, using a Multi-Probe. This is a tube, sealed at the remote end, about 2.5 cm diameter. It has 2.5 mm holes along its length at intervals of about 30 cm.
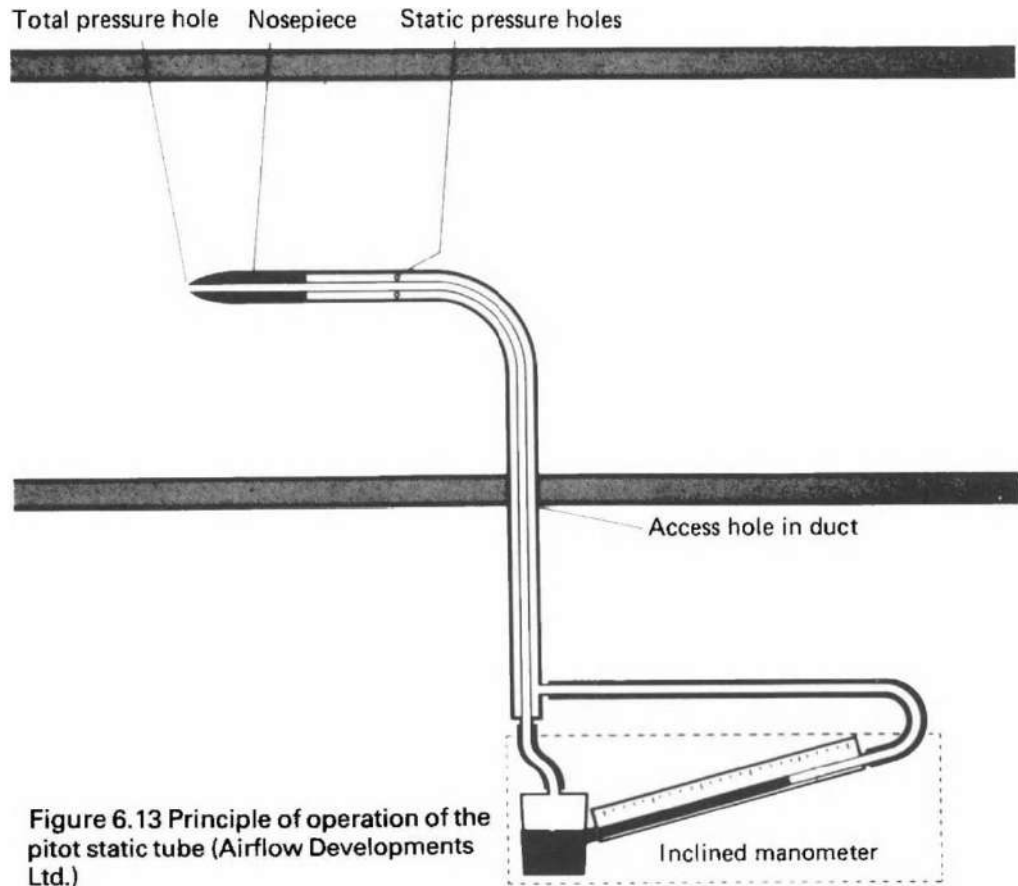
Total pressure hole   Nosepiece   Static pressure holes

Access hole in duct

Figure 6.13 Principle of operation of the
pitot static tube (Airflow Developments
Ltd.)

Inclined manometer

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Gas Samples are collected in 24-36 Rubber Bladders by use of a sucking rubber bulbs. These are then taken to the Site Chemistry Lab for analysis.

Gas Anysisis [Orsat Apparatus]

An Orsat Gas Analyser is a laboratory equipment used to analyse a fossil fuel flue gas for its Oxygen, carbon dioxide and carbon monoxide content. Although largely replaced by instrumental techniques, the Orsat remains a reliable method of measurement and is relatively simple to use.

The Average CO_2 and O_2 values are noted.

SECTION - II

CALCULATION OF LOSSES

1 Dry Flue Gas Loss:

Dry Flue Gas Loss is actually the Heat lost to the atmosphere by the Flue gasses, as they exit the Boiler (Air Heater) at a much higher temperature than the fresh Air. The components of a fuel which burn to form dry products of combustion are the carbon and sulphur.

Effect of Sulphur:

Sulfur that is an inherent constituent of coal is organic sulfur, which is considered as a non-removable impurity. When coal is burned, sulfur oxides form. Sulfur oxides, when combined with Fuels and moisture in combustion air form acids that may deposit when the combustion gas is cooled below its dew-point temperature; and causes corrosion of air heaters, economizers, and stacks.

The Flue Fas Exit Temperature is designed to keep it above the H2SO4 Due Point. The higher the Sulphur content in coal, the higher the Temperature. Resulting in higher Dry Flue Gas Loss.

Dry Flue Gas Loss -Formula:

$$\left[\frac{100}{12(CO_2 + CO)} \left(\frac{C}{100} + \frac{S}{267} - C \text{ in } A \right) \right] 30.6 \, (T-t) \text{ kJ/ kg fuel}$$

Sensible Heat Loss Per Unit Mass Of Fuel = [**Dry Flue Gas Mass**] x [**kg mol. Cp**] * [**T-t**] **kJ/kg.**

Where kg mol Cp = kilogram molecular specific heat = 30.6 kJ/kg mol.

T = Air Heater gas outlet temperature in °C.

t = Temperature at F.D. duct inlet in °C.

__Note. The derivation of the above Formula is shown at the Annexure__

The Seigert formula

The Seigert formula gives a good idea of the dry flue gas loss:

 DFG Loss =[K(T-t)]/ [%CO2]

where K = 0.68 for anthracite, 0.63 for bituminous coal, 0.70 for coke,

2 Wet flue gas loss:

The wet products of combustion are derived from the moisture and the hydrogen in the fuel.

The combustion of hydrogen is represented by: $2H_2 + O_2 = 2H_2O$ expressed as masses $4 + 32 = 36$

So the combustion of 1 kg of hydrogen produces 9 kg of moisture.

Wet flue gas loss = $[(M + 9H)/100]$ * $[1.88 (T - 25) + 2442 + 4.2 (25 - t)]$ kJ/kg fuel.

Where; M = % moisture per kg fuel

H = % hydrogen per kg fuel

T = Air heater gas outlet temperature (°C)

t = Air temperature at F.D. intake (°C)

3 Sensible heat of water vapour

This loss = [wet flue gas loss - (gross CV - net CV) kJ/kg fuel]

where the gross and net CV are in kJ/kg of fuel.

4 Moisture in combustion air loss

This is usually quite small and is not normally calculated.

Moisture in combustion air loss = Ma x h x 1.88(T-t) kJ/kg fuel

Where Ma = Dry air for combustion kg/kg fuel.

h = kg moisture per kg dry air (from psychrometric tables or chart, see next slide)
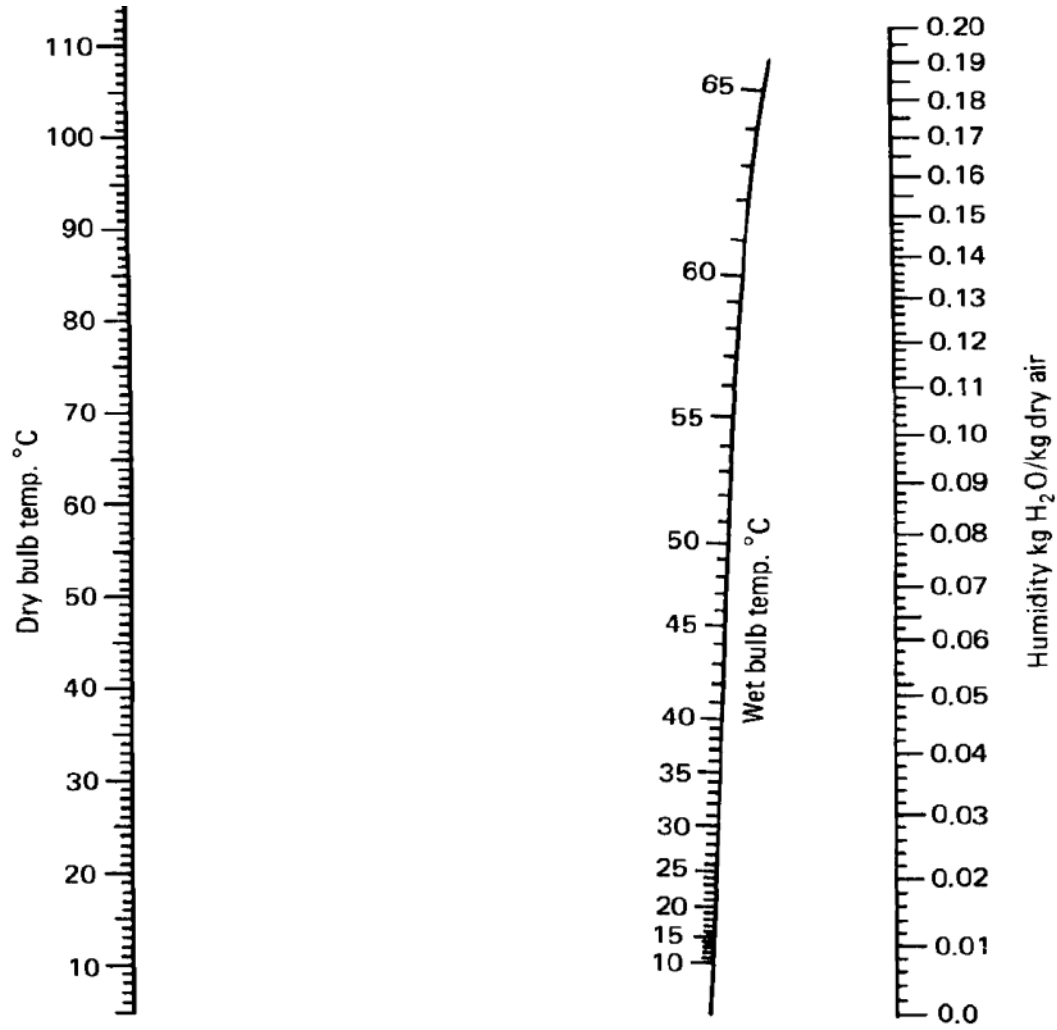
5 Combustible-in-ash loss:

Loss = (c * A/100) x 33 820 kJ/kg fuel

Where; c = % carbon in dry ash

      A = Mass of ash kg/kg fuel

      33 820 = calorific value of carbon burnt to CO_2, in kJ/kg

Note: This loss is to be calculated seperately for Fly ash and Bottom Ash

Humidity Chart

6 Radiation and unaccounted loss:

Curves below shows the value of this loss for various loads for boilers enclosed within a building. For outdoor boilers the values should be multiplied by 1.5.
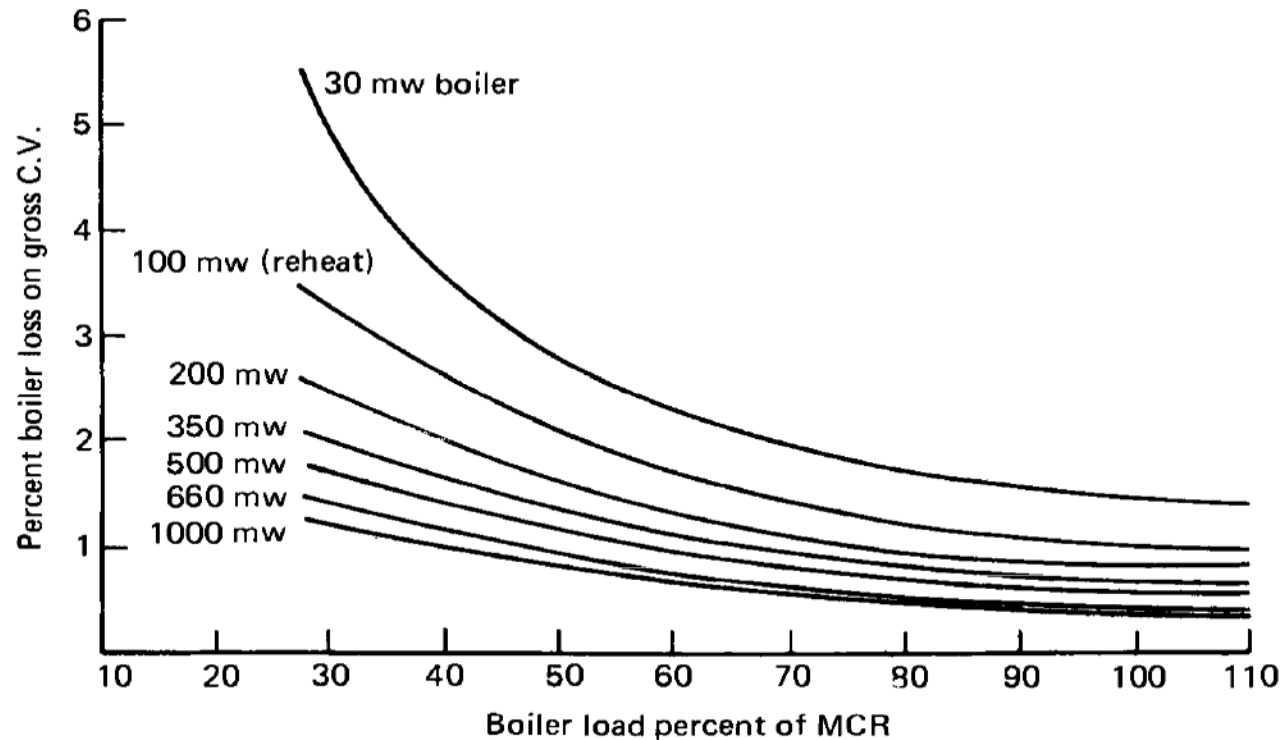

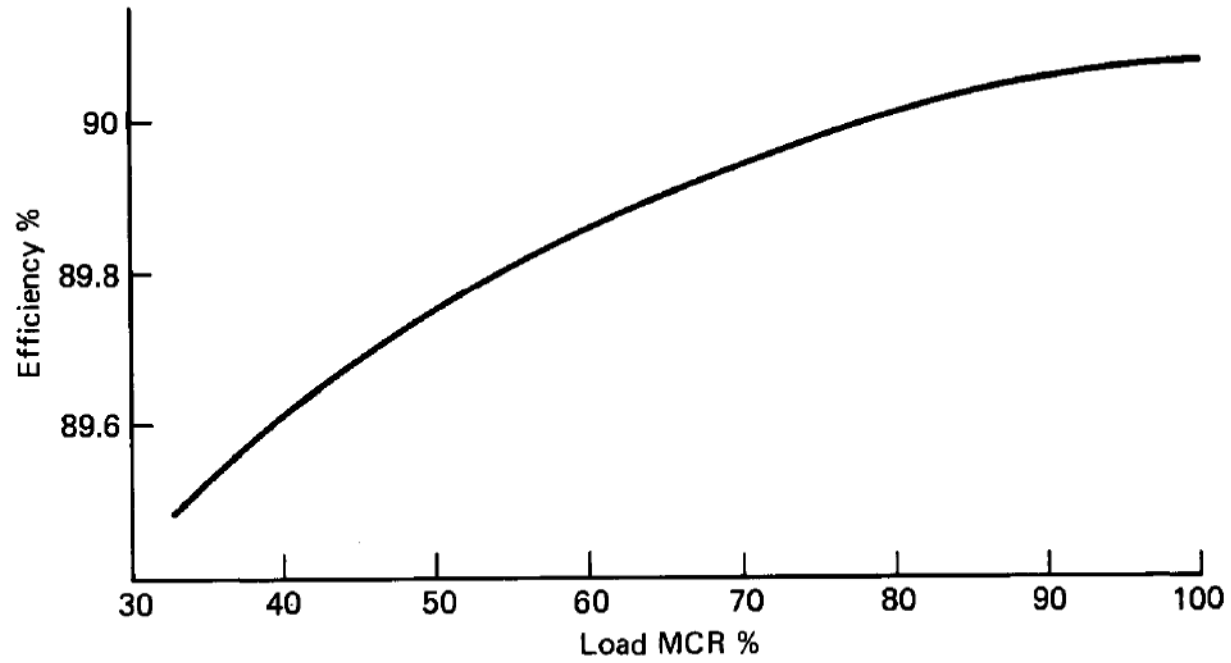Figure 8.2 Radiation and unaccounted loss (for outdoor boilers multiply value by 1.5)

Gross CV Basis

Loss due to:

Dry flue gas	3.98%
Wet flue gas	5.27%
C in A	0.24%
Radiation and unaccounted	0.44%
Total loss	9.93%
Boiler efficiency =	90.07%

SECTION – III

OPTIMIZATION OF COMBUSTION

Optimizing total air supplies:

An important information for the efficient operation of any boiler is the optimum $CO_2\%$ or $O_2\%$ for any load. Hence, the total air supplies should be optimized.

At full load, a series of four to five tests are carried out at CO_2 or $O_2\%$ which span the optimum value. Therefore, tests would be carried out at about 14.0, 15.0, 15.5, 16.0 per cent CO_2, the boiler being kept at a steady output.

Determine Boiler the following:
1. Dry flue gas loss
2. Combustible in ash loss
3. Unburned gas loss
4. Auxiliary power

Testing is carried out by Reducing Air Flow; such that the online Zirconia Probe shows 4%, 3.5%, 3%, 2.5% Oxygen.

The table lists the results of a series of tests to determine the optimum C02%.

Controllable losses calculated from test results, % boiler efficiency	Test air settings (% CO_2 at A/H inlet)				
	13.0	14.25	15.5	16.25	17.0
Dry gas	7.4	6.8	6.2	5.8	5.4
Combustible in ash and dust	0.1	0.2	0.42	0.9	2.5
Combustible gas (CO)	0	0	0	0.1	1.2
Aux power (fans)	2.2	1.9	1.76	1.65	1.6
Total loss	9.7	8.9	8.38	8.45	10.7

The optimum value is determined by plotting the total loss and so finding the C02 or 02 which corresponds to minimum loss.
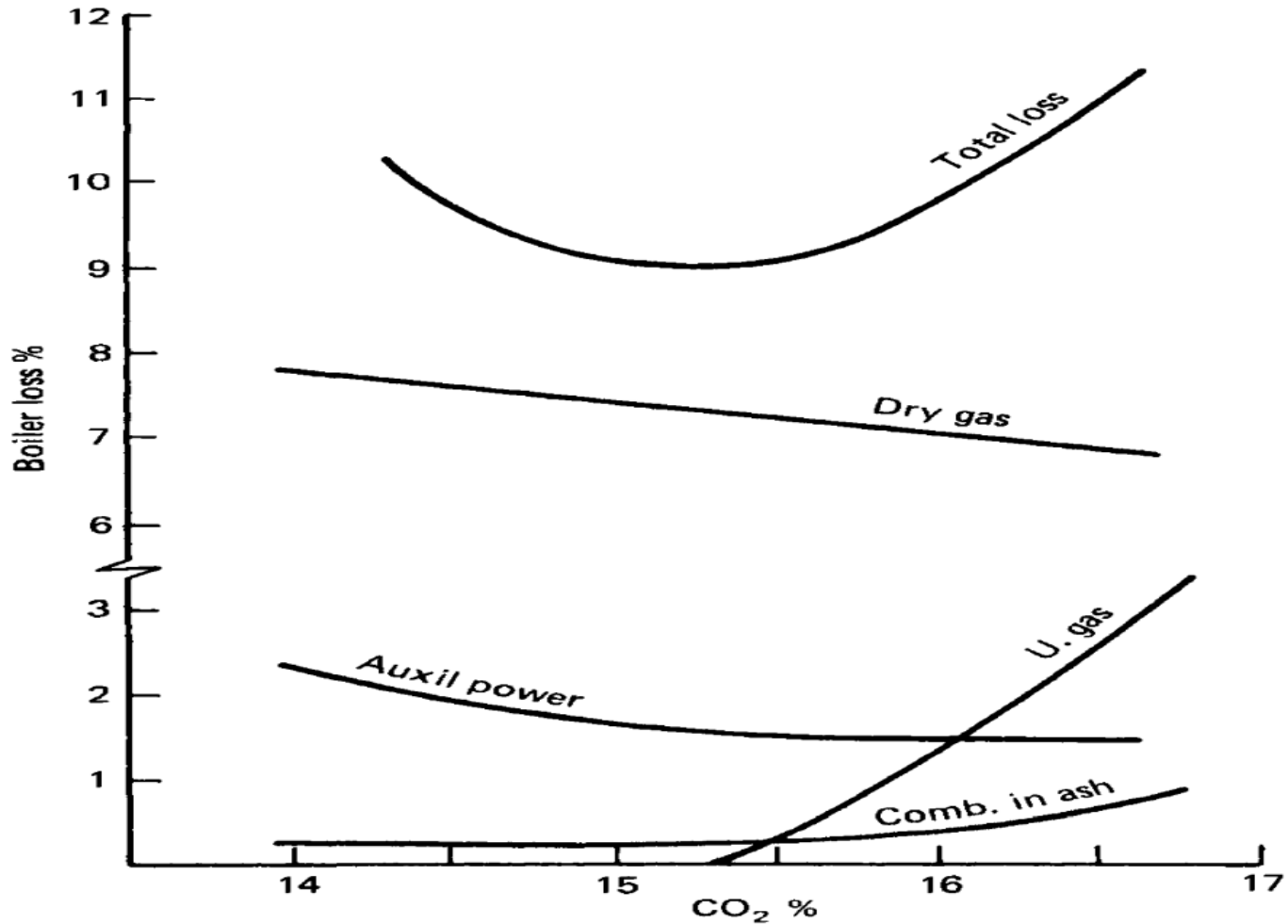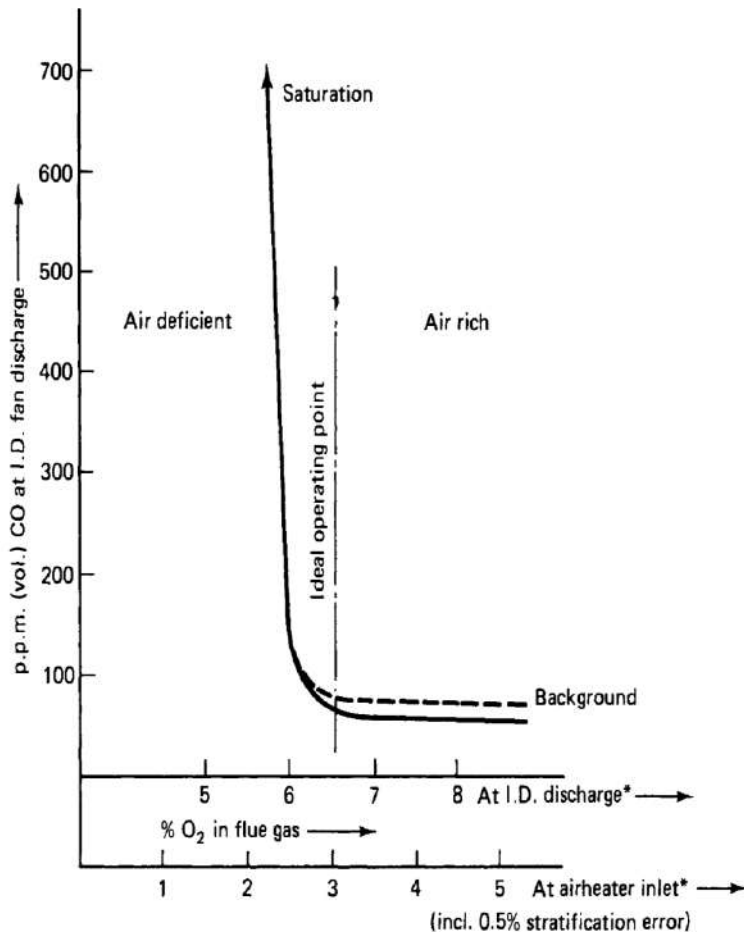
Conclusions from the Graph:

Let us note that the **Optimum C02** is just a little lower than that at which unburned gas (Carbon Mono-oxide) is produced.

Because of stratification of the flue gas, the CO Monitor is mounted after the ID fan.

Flue gas in a pulverized coal fired boiler will normally have a residual quantity of CO less than 100 ppm. As the excess air is reduced there is a slight increase in the CO content and, at a particular value of excess air, there is a dramatic increase.

It is seen that, for any 02 less than 4%, the CO increases dramatically, often exceeding 700 ppm at 2.5% 02.

The reason why the 02 is rather high is because of air ingress. Although O2% was high at the boiler outlet (where the zirconia probes were located), there was barely sufficient air at the burners.

Thus, the CO provides a valuable guide to the optimization of total air supplies. Further, added advantage that the precipitator performance is improved because of the reduced gas flow.
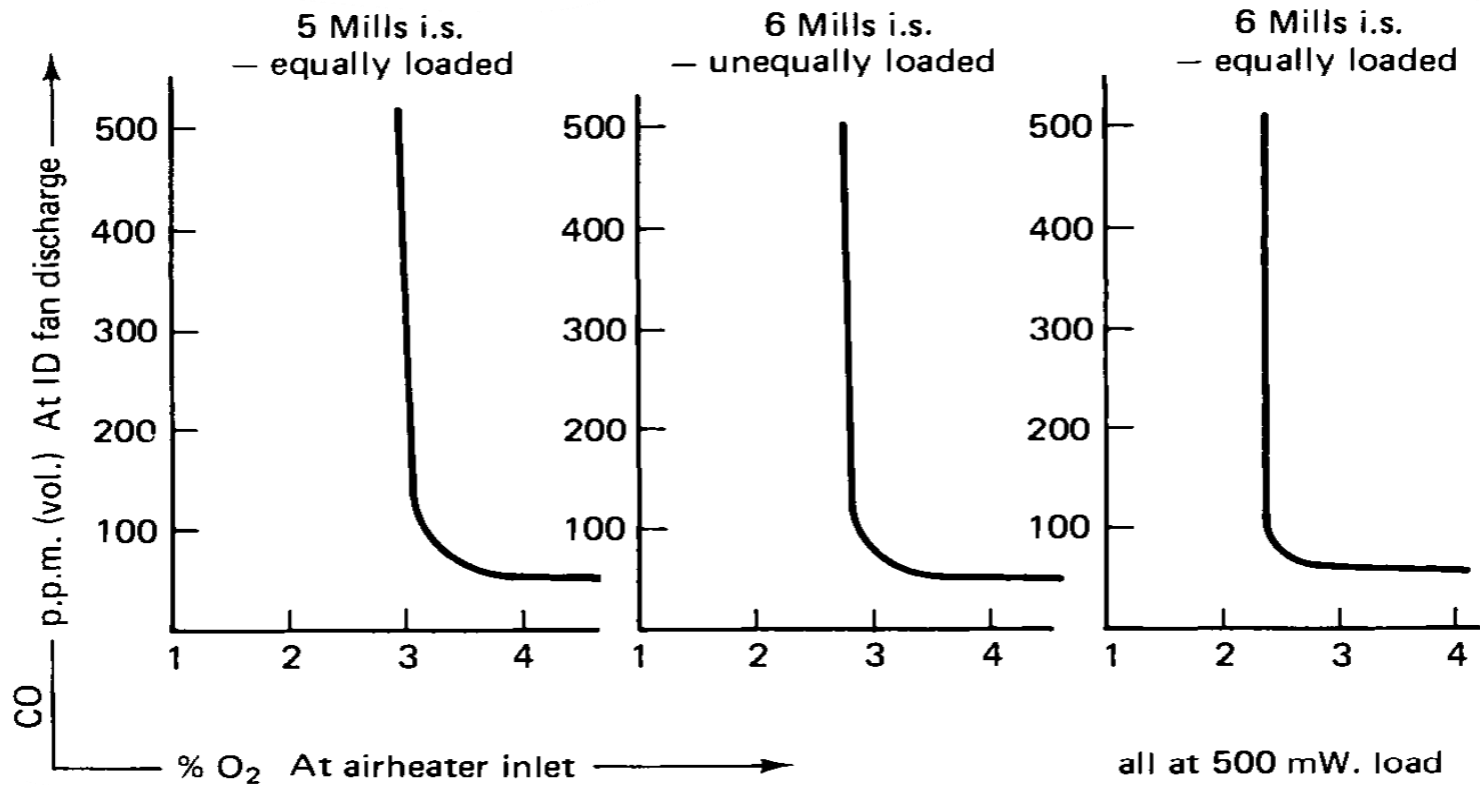
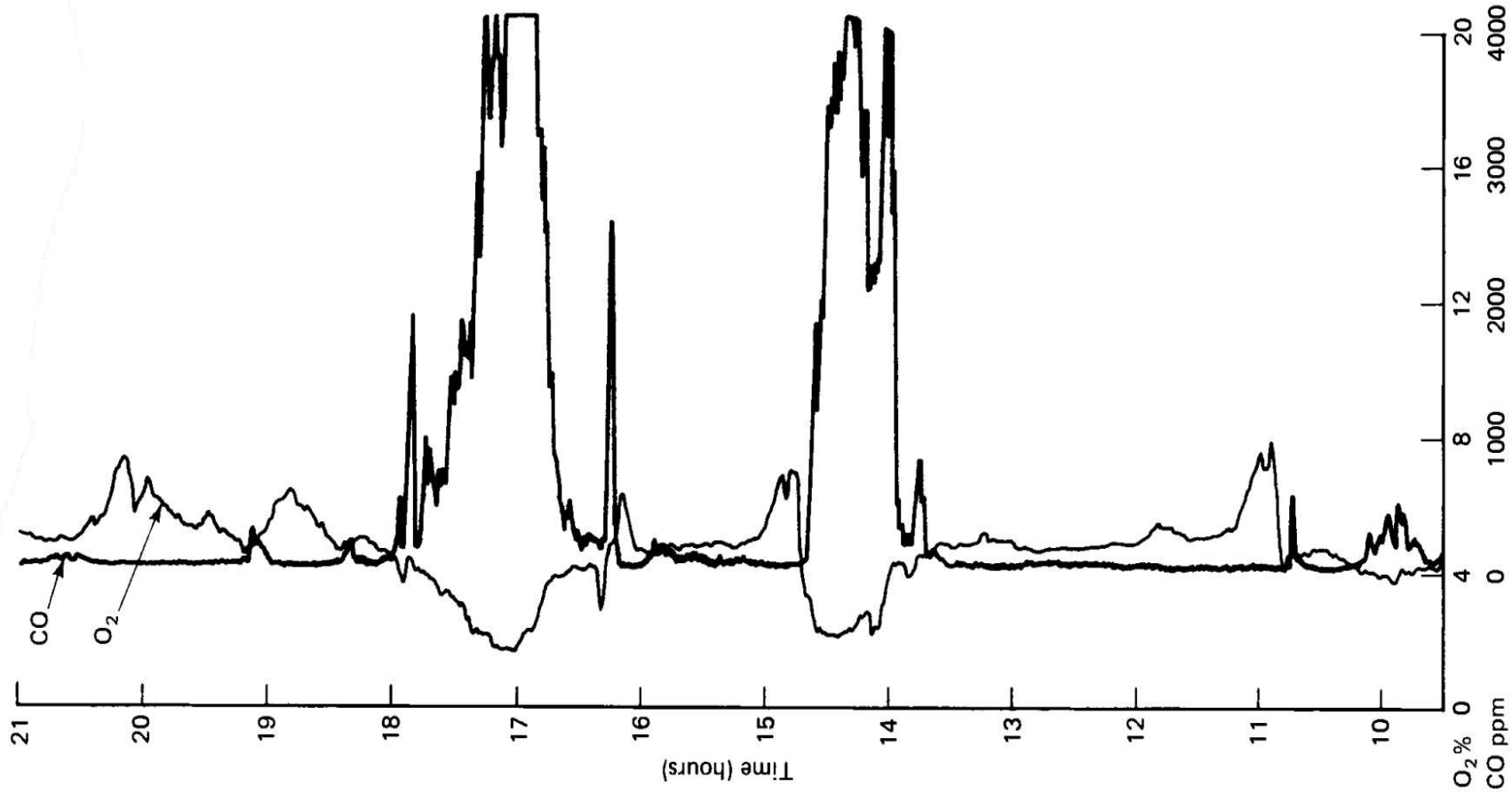Effect of operating conditions on CO breakpoint (500 MW boiler) CEGB)

Chart of CO and O_2% for various operating conditions (CEGB)

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SECTION – IV

CAUSES
OF
LOSS OF EFFICIENCY

COMBUSTIBLE MATERIAL IN ASH:

 The amount of unburned carbon is a measure of the effectiveness of the combustion process in general and the milling plant in particular. The Carbon-in-Ash Loss of upto 0.5% is accepted in good operation.

1. Causes of high carbon in ash.

If the PF is too coarse the combustion will be poor and there will be high carbon in ash. Grinding which results in 10% or more being retained on a 150 μm (100 mesh) sieve or less than 70% passing a 75 μm (200 mesh) sieve is bad. Causes of coarse grinding include:
(a) mill rolls too far off table; spring tension insufficient, etc.;
(e) excessive air inleakage to mill.

2. Causes of low carbon in ash

It is uneconomic to eliminate all the combustible matter from getting into ash - a small amount (say 1.5%) is normal. Below this, it is probable that the coal is being too finely ground. In such a case the C in A loss is reduced, but at the expense of increased milling power consumption. Reasons include:
(a) mill in need of adjustment, e.g. rolls too low, spring tension too great;
(b) rich fuel/air mixture.

Milling plant constraints [The Mill operating window]

Milling plant limitations often result in reduced load capability on plant. There are many interacting variables. One concept called the 'operational window' was developed in the CEGB.

This shows each of the constraints for a particular mill and, from this, determining the safe and practical limits of operation in terms of coal and air flow.

(a) Drying capacity

This is determined by two factors, (i) mass flow of air through the mill; (ii) temperature of the air to the mill. The higher the air temperature the lower the necessary mass flow for a given amount of drying.

(b) Grinding limit

The acceptable grading, even at full load, should not be outside the appropriate range. For example, bituminous coal should normally be within the range 70 - 80% below 75 μη (i.e. through 200 BS mesh sieve).

(c) Pulverized fuel fall-out
If the transport velocity be too low in the PF pipes and fittings, some pulverized fuel will fall out of suspension. This could result in fires inside the pipes. Normally the minimum velocity of the coal/air mixture is about 18-20 m/s.

(d) Erosion limit
Erosion varies approximately equals (air-coal velocity) to-the-power 5/2. Thus, if the velocity is doubled the rate of erosion will increase by about six times. The cost of replacement of pipes and fittings becomes uneconomic. Generally, the erosion limit is of the order of 1.5 times the fall-out limit air flow, ie 30 m/s.

(e) Flammability
Should the air/fuel ratio become too high, an explosive mixture may result. A ratio of 5:1 is regarded as the safe limit.

(f) Attemperation
As mill coal flow is reduced, it is also necessary to reduce the air flow until the fall-out limit is reached. Further reduction of coal throughput would result in excessive coal/air mixture temperature, so it is necessary to start admitting attemperating air. When the flow of attemperating air is a maximum the temperature of the hot air to mill will be at a minimum.
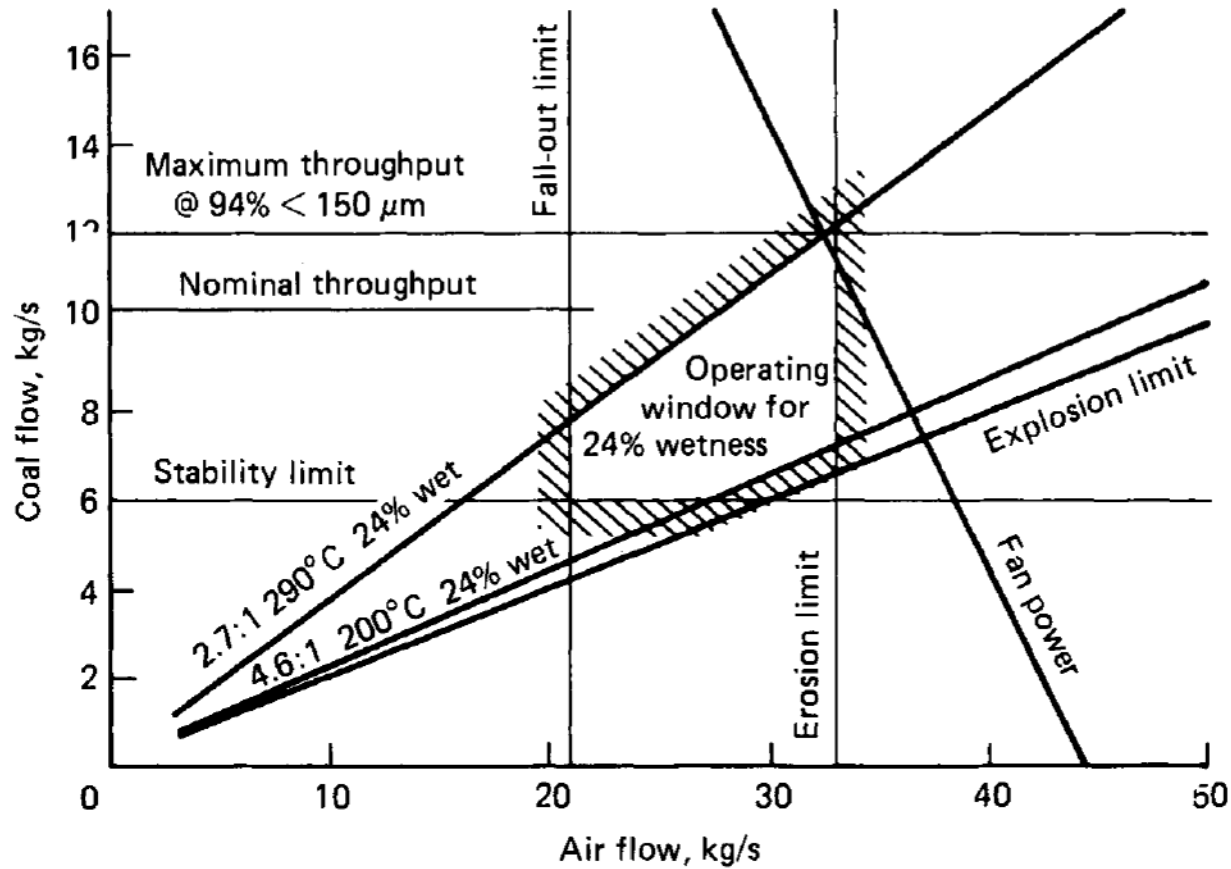
(g) Fan power
The primary air fans provide the power to transport the pulverized coal. It follows that when the fans are operated at maximum it is a milling constraint.

(h) Flame stability
Unless supported by an oil fire, it is generally accepted that a bituminous coal fire could become unstable at throughputs less than 40% of maximum.

THE MILL-WINDOW

THANK YOU

ANNEXURE

## DERIVATION OF DRY FLUE GAS LOSS FORMULA

1 Dry flue gas loss

The only components of a fuel which burn to form dry products of combustion are the carbon and sulphur. Of the two carbon has the greater significance, so for the present ignore the sulphur. The carbon can burn to either carbon dioxide or carbon monoxide thus:

(a) Carbon to carbon dioxide $\quad C + O_2 = CO_2$

So masses $\qquad\qquad\qquad = 12 + 32 = 44$
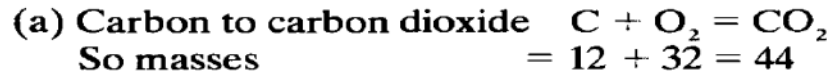
∴ 44 kg of CO_2 contains 12 kg carbon.

So 1 kg of CO_2 contains $\frac{12}{44}$ kg of carbon, i.e. $\frac{3}{11}$ kg carbon.

(b) Carbon to carbon monixide $2C + O_2 = 2CO$

So masses $\qquad\qquad\qquad = 24 + 32 = 56$
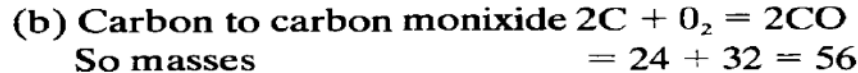
∴ 56 kg of CO contains 24 kg carbon.

So 1 kg of CO contains $\frac{24}{56}$ kg of carbon, i.e. $\frac{3}{7}$ kg carbon.

Total dry flue gas = kg carbon × (dry flue gas/kg carbon burned)

So dry flue gas/kg carbon burned = $\dfrac{\text{Total dry flue gas burned}}{\text{kg carbon in flue gas}}$

The total dry flue gas consists of the sum of all the dry constituents, i.e. $CO_2\% + O_2\% + N_2\% + CO\%$, and they will add up to 100 kg mol. For example, suppose the percentage by volume of the various constituents is:

CO_2 15.0%; $\quad O_2$ 4.4%; $\quad N_2$ 80.5%; $\quad CO$ 0.1%

Then the Relative Mass of each is:

	Vol %		Molecular mass		Relative mass
CO_2	15.0	×	44	=	660.0
O_2	4.4	×	32	=	140.8
N_2	80.5	×	28	=	2254.0
CO	0.1	×	28	=	2.8
	100.0				3057.6

Therefore 3057.6 kg of gas = 100 kg mol.

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Thus, to revert to the dry flue gas loss, the total dry flue gas equals the sum of the percentage by volume of the CO_2, O_2, N_2 and CO and is equal to 100 kg mols.

Hence dry flue gas/kg carbon burned $= \dfrac{100}{kg \text{ carbon in flue gases}}$ kg mol

It was shown earlier that the amount of carbon in the flue gas is $\dfrac{3}{11}$ kg for each kg of CO_2, and $\dfrac{3}{7}$ kg for each kg of CO.

So dry flue gas/kg carbon burned $= \dfrac{100}{\dfrac{3\,CO_2\%}{11} + \dfrac{3\,CO\%}{7}}$ kg mol.

But the $CO_2\%$ and $CO\%$ in the expression are in terms of mass of gas, whereas the flue gas analysis is usually in terms of volume of dry gas. Therefore the $CO_2\%$ by volume must be multiplied by 44 to give the corresponding relative mass. Similarly the $CO\%$ by volume must be multiplied by 28.

So dry flue gas/kg carbon burned $=$

$$\dfrac{100}{\left(44 \times CO_2\% \times\right)\dfrac{3}{11} + \left(28 \times CO\% \times\dfrac{3}{7}\right)} \text{ kg/mol}$$

where $CO_2\%$ and $CO\%$ are in terms of *volume*.

$\therefore$ Dry flue gas/kg carbon burned $= \dfrac{100}{12\,(CO_2 + CO)}$ kg mol.

The carbon burned $= \dfrac{C}{100} - C$ in A

Where $C = \%$ carbon in the fuel.

C in $A =$ carbon in rough ash and dust, in kg/kg fuel.

Hence dry flue gas $= \left[\dfrac{100}{12\,(CO_2 + CO)} \left(\dfrac{C}{100} - C \text{ in } A \right) \right]$ kg mol./kg fuel

There is a further complication. Sulphur in the fuel is almost all burned to SO_2 and this is absorbed along with the CO_2. Normally this effect can be ignored unless the sulphur content is very high, but if it is desired to allow for it the expression becomes:

Dry flue gas $= \left[\dfrac{100}{12\,(CO_2 + CO)} \left(\dfrac{C}{100} + \dfrac{S}{267} - C \text{ in } A \right) \right]$ kg mol./kg fuel

Where $S = \%$ sulphur in fuel.

Note: The ratio of the atomic weights of carbon to sulphur $= \dfrac{12}{32} = \dfrac{1}{2.67}$

The sensible heat loss per unit mass of fuel = dry flue gas × kg mol. C_p $(T - t)$ kJ/kg.

Where kg mol C_p = kilogram molecular specific heat

$$= 30.6 \text{ kJ/kg mol.}$$

T = A/H gas outlet temperature in °C.

 t = Temperature at F.D. duct inlet in °C.

So dry flue gas loss =

$$\left[\frac{100}{12(CO_2 + CO)} \left(\frac{C}{100} + \frac{S}{267} - C \text{ in } A \right) \right] \ 30.6 \ (T-t) \ \text{kJ/ kg fuel}$$