Boilers

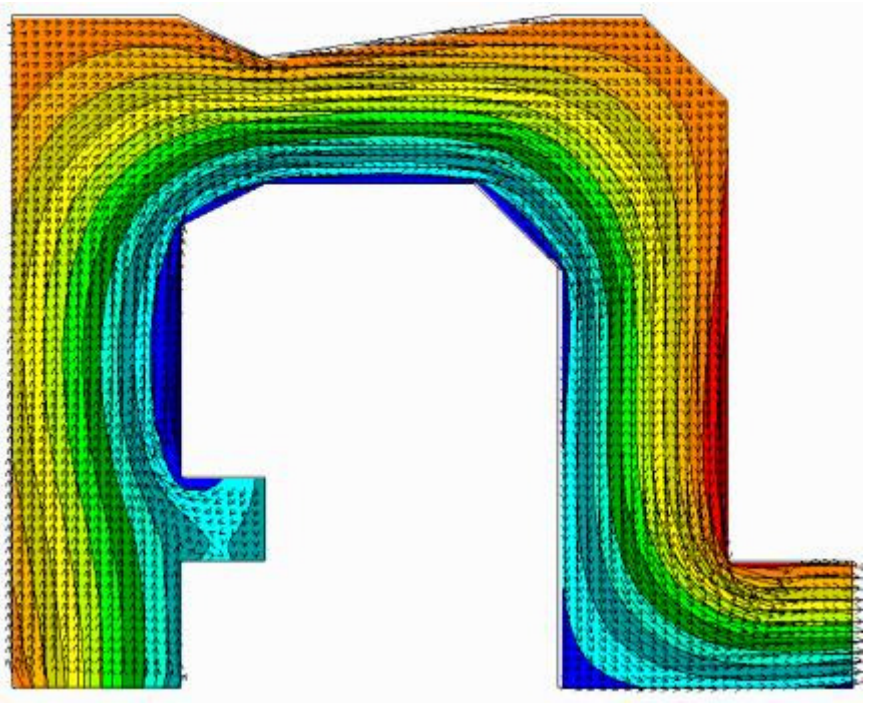
Performance & Testing

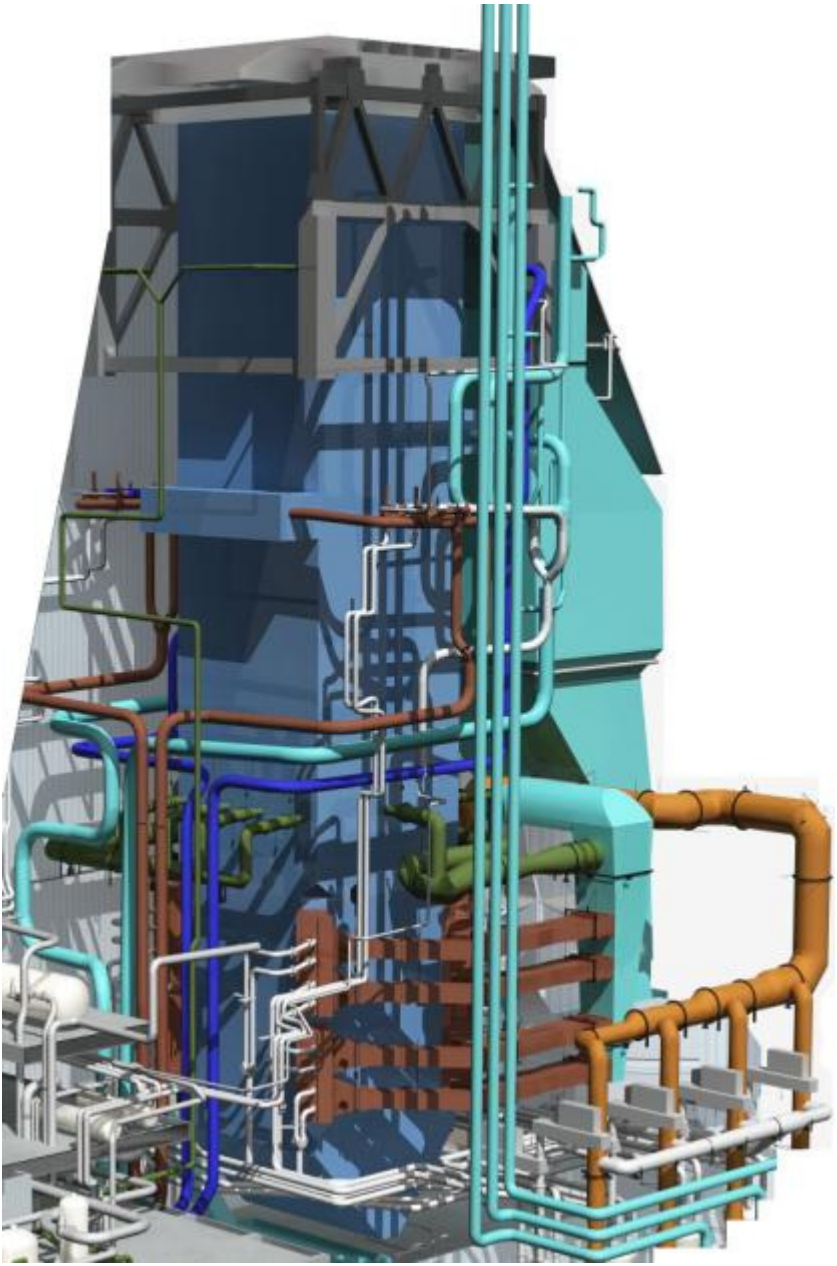
by D. James Benton

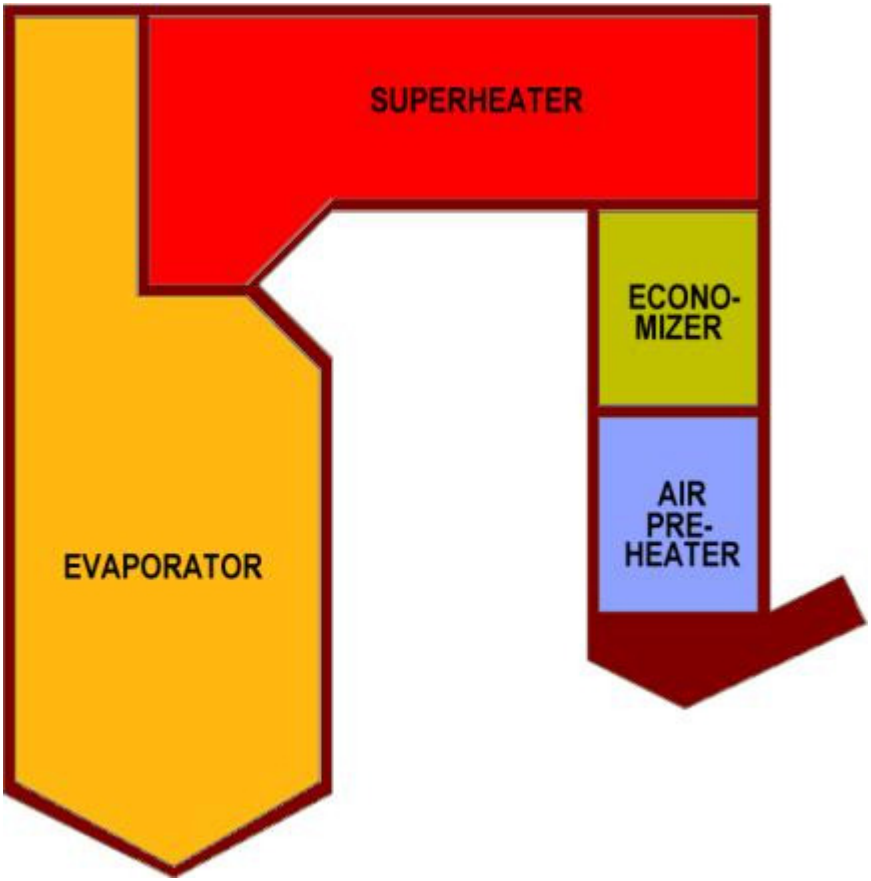
...just the color figures for those who got the B&W printed book...

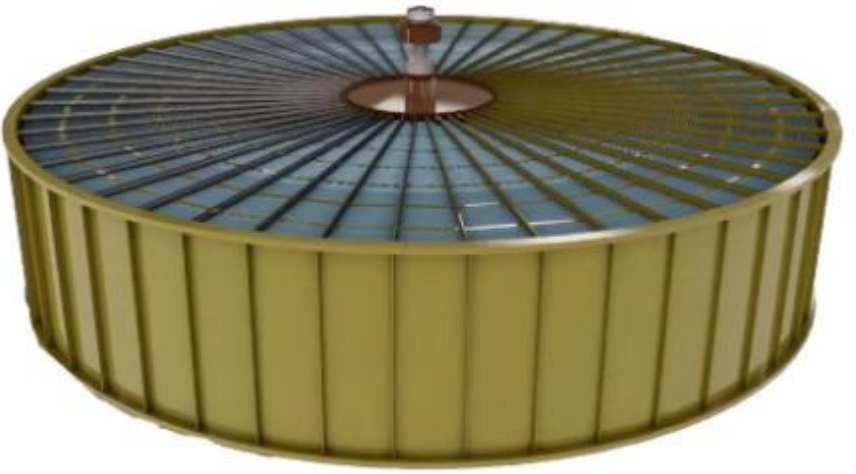
Preface

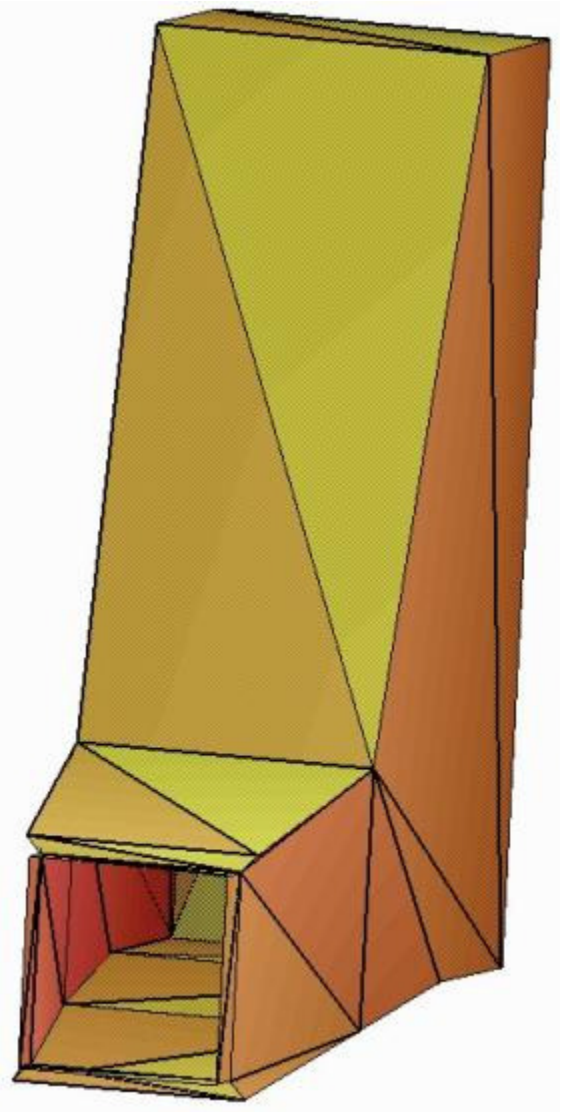
Boilers consume fossil fuels (coal, fuel oil, or natural gas) and produce steam for industrial processes or power production. Boilers have been a mainstay since the dawn of the Industrial Revolution. In the 21st century boilers are being replaced with green alternatives and renewable resources. The transition will take years. While this change is implemented, it is imperative that the remaining boilers be operated efficiently, which requires clear expectations and diligent testing. This text describes what can be achieved and how to verify. Examples are given in both English (U.S. Customary) and SI units.

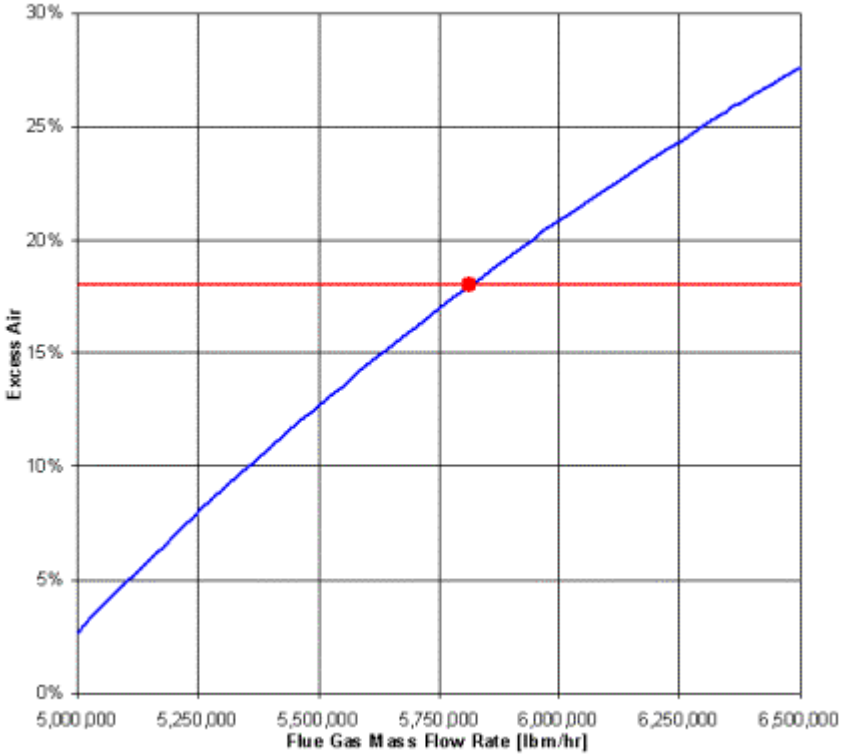


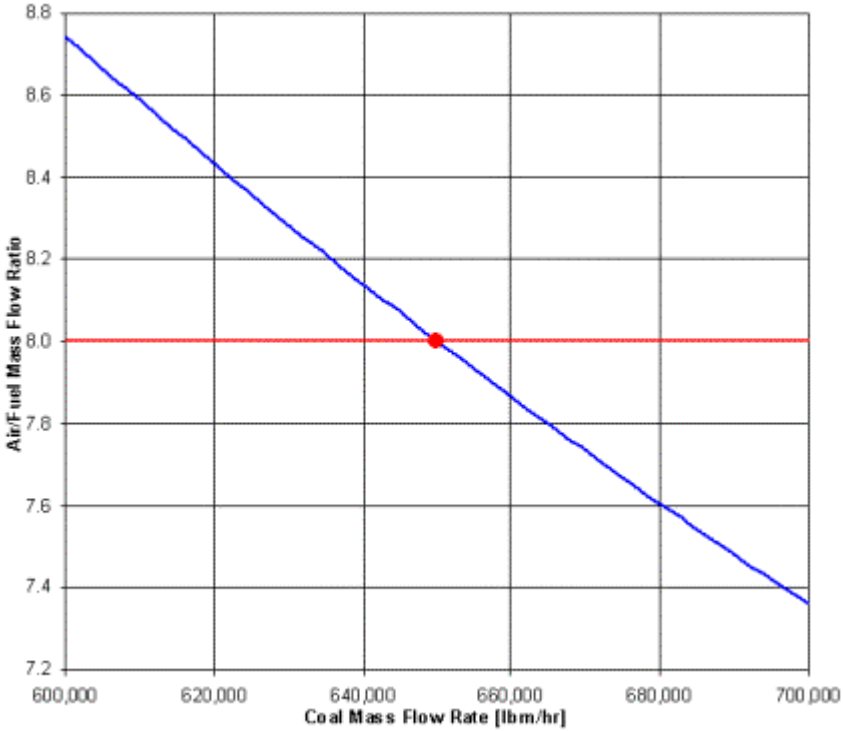


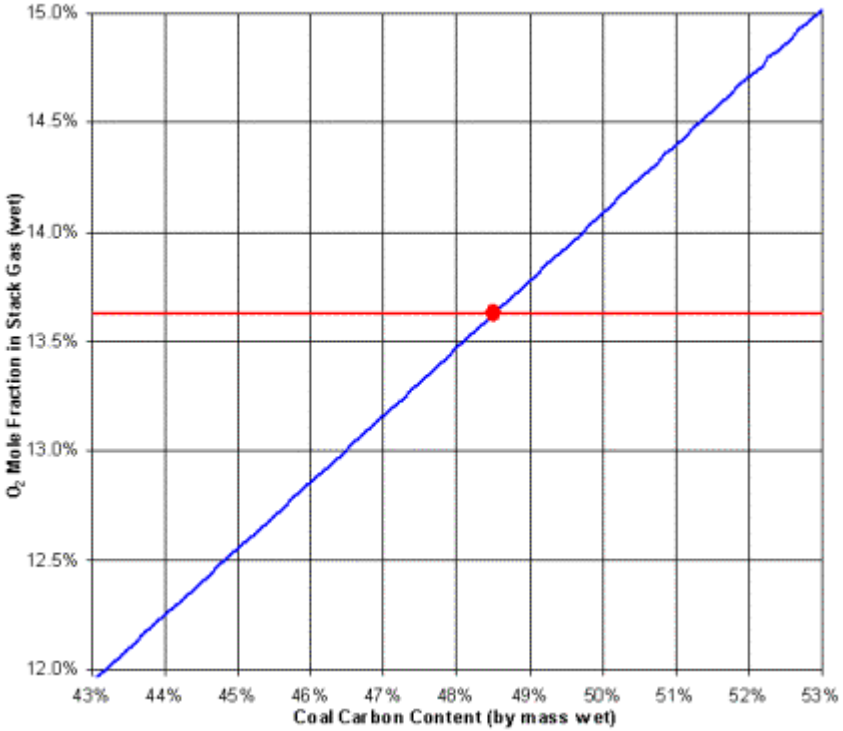

SUPERHEATER
ECONO-
MIZER
AIR
PRE-
HEATER
EVAPORATOR

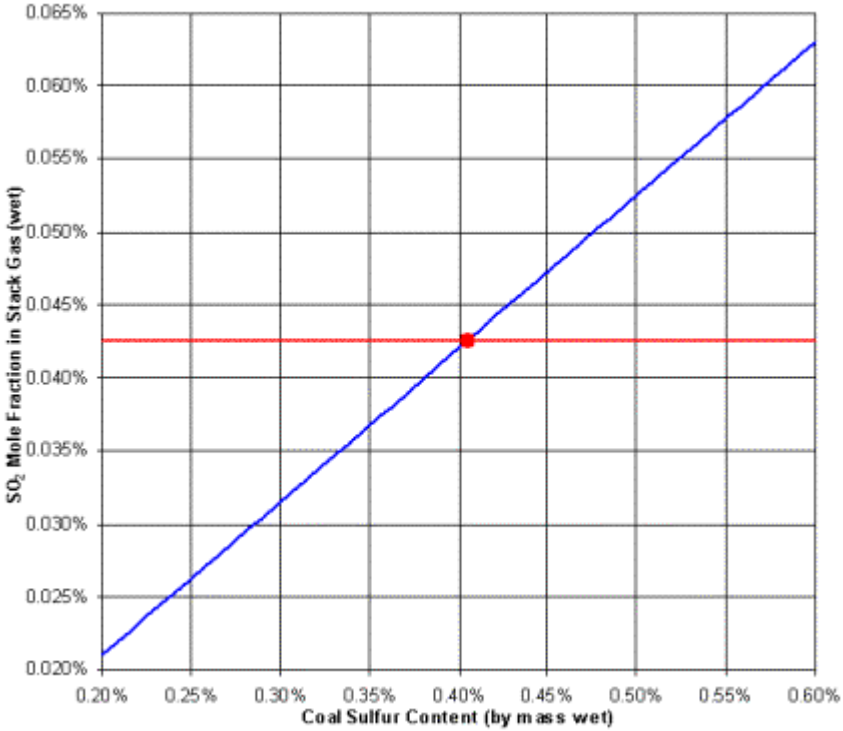


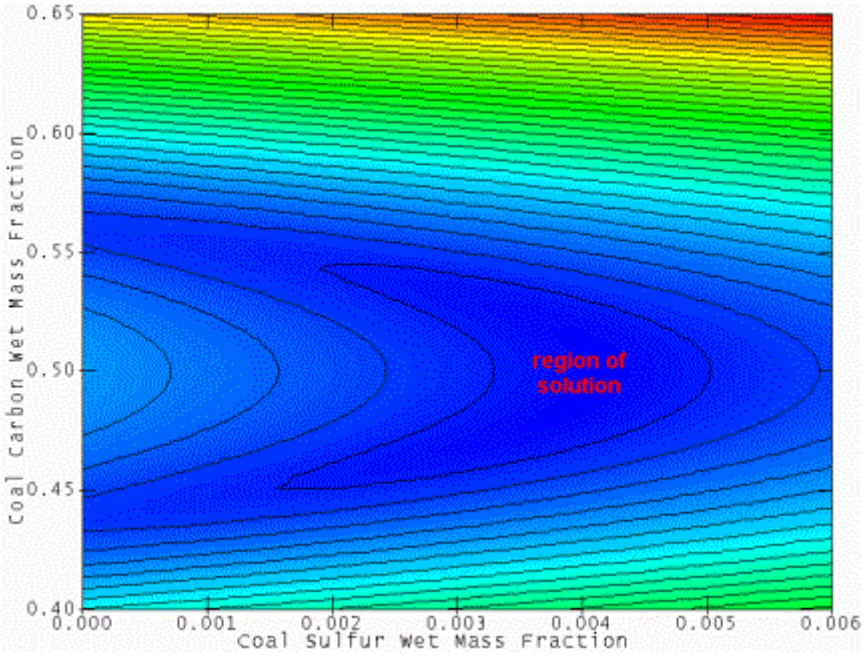


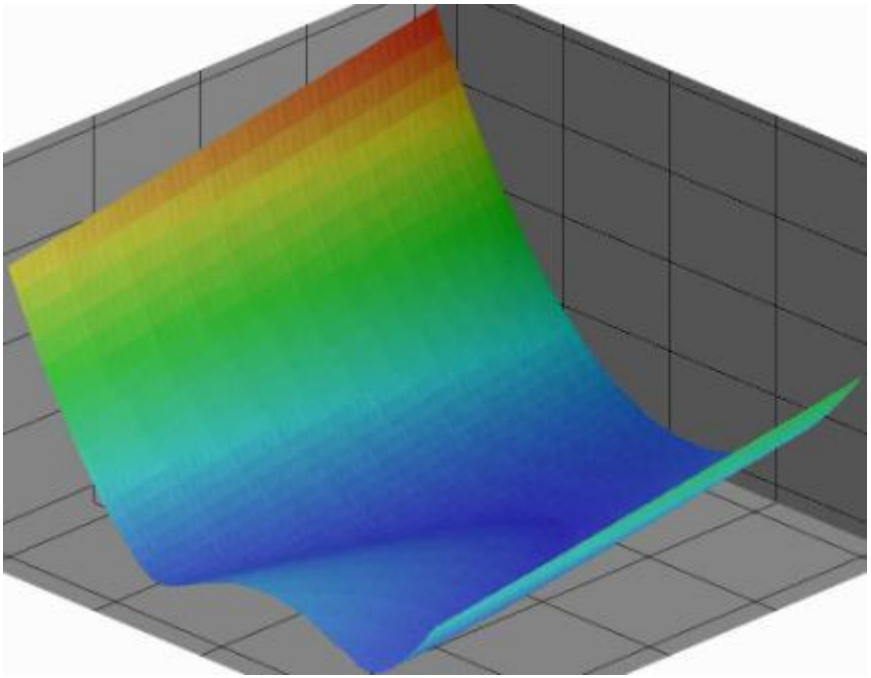

30%
25%
20%
15%
10%
5%
0%
Excess Air
5,000,000
5,250,000
5,500,000
5,750,000
6,000,000
6,250,000
6,500,000
Flue Gas Mass Flow Rate [lbm/hr]

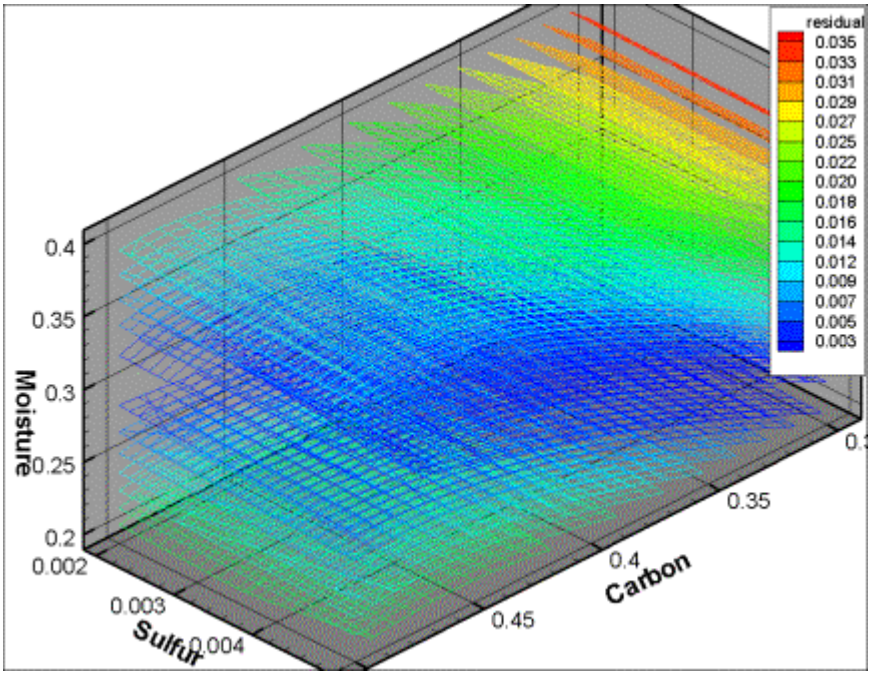

8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.4
7.2
Air/Fuel Mass Flow Ratio
600,000
620,000
640,000
660,000
680,000
700,000
Coal Mass Flow Rate [lbm/hr]


15.0%
14.5%
14.0%
13.5%
13.0%
12.5%
12.0%
O_2 Mole Fraction in Stack Gas (wet)
43%
44%
45%
46%
47%
48%
49%
50%
51%
52%
53%
Coal Carbon Content (by mass wet)

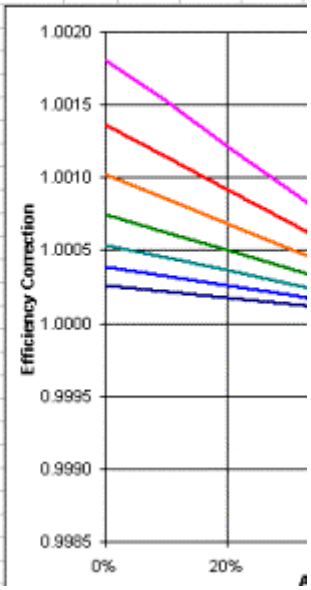

0.065%
0.060%
0.055%
0.050%
0.045%
0.040%
0.035%
0.030%
0.025%
0.020%
SO2 Mole Fraction in Stack Gas (wet)
0.20%
0.25%
0.30%
0.35%
0.40%
0.45%
0.50%
0.55%
0.60%
Coal Sulfur Content (by mass wet)

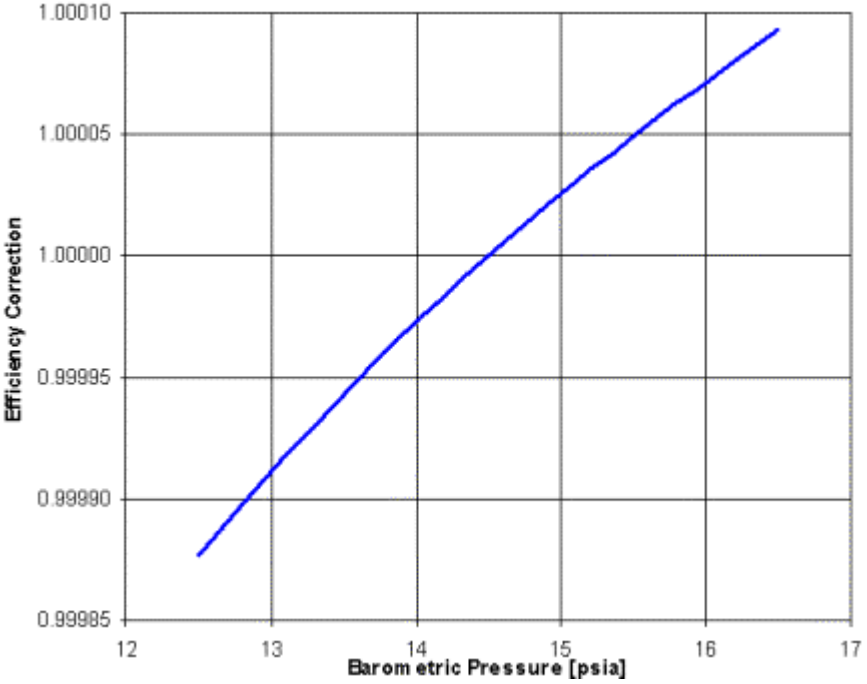

0.65
0.60
0.55
0.50
0.45
0.40
Coal Carbon Wet Mass Fraction
region of solution
0.000
0.001
0.002
0.003
0.004
0.005
0.006
Coal Sulfur Wet Mass Fraction

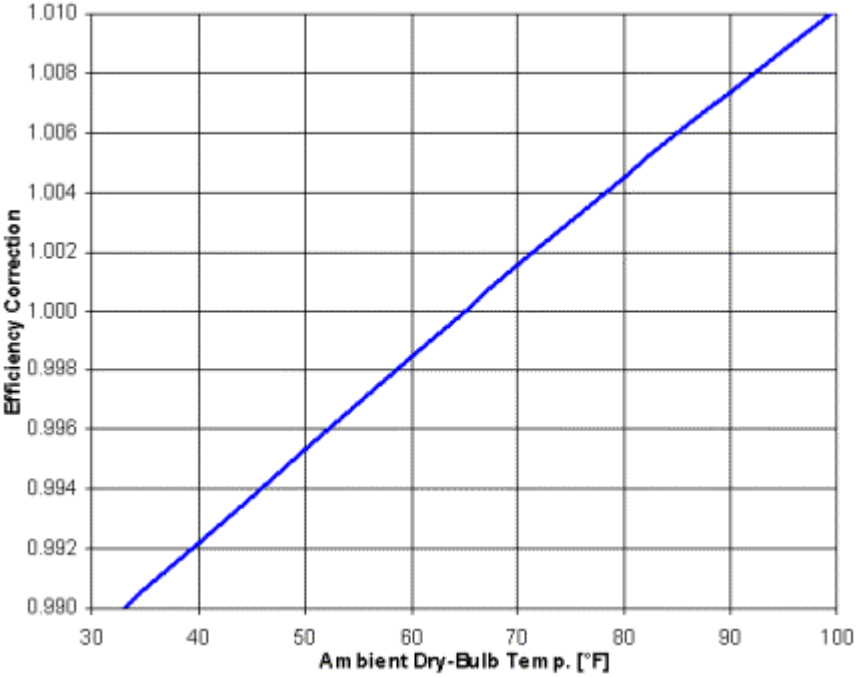


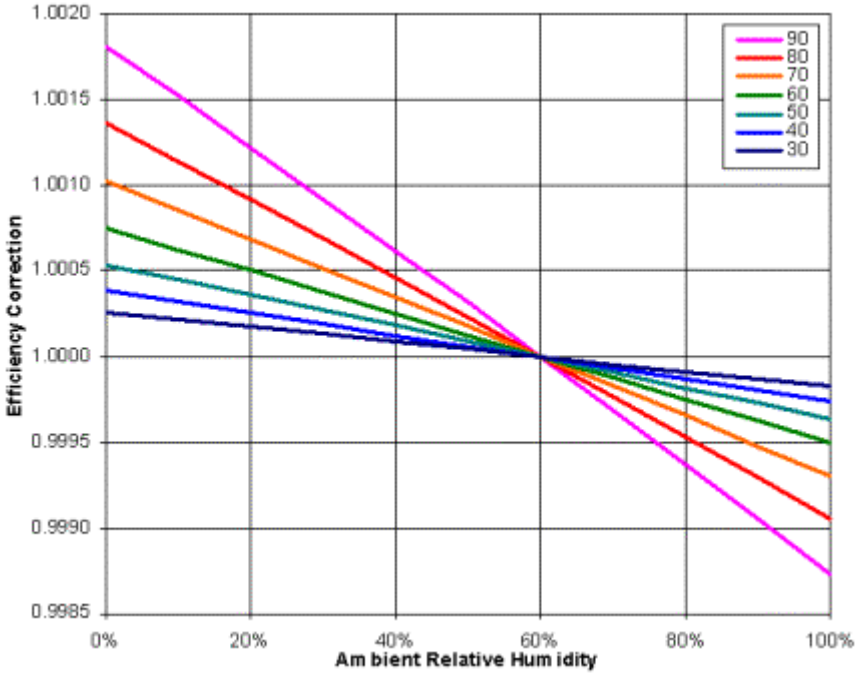

residual
0.035
0.033
0.031
0.029
0.027
0.025
0.022
0.020
0.018
0.016
0.014
0.012
0.009
0.007
0.005
0.003
Moisture
0.4
0.35
0.3
0.25
0.2
0.002
0.003
0.004
Sulfur
0.45
0.4
0.35
Carbon

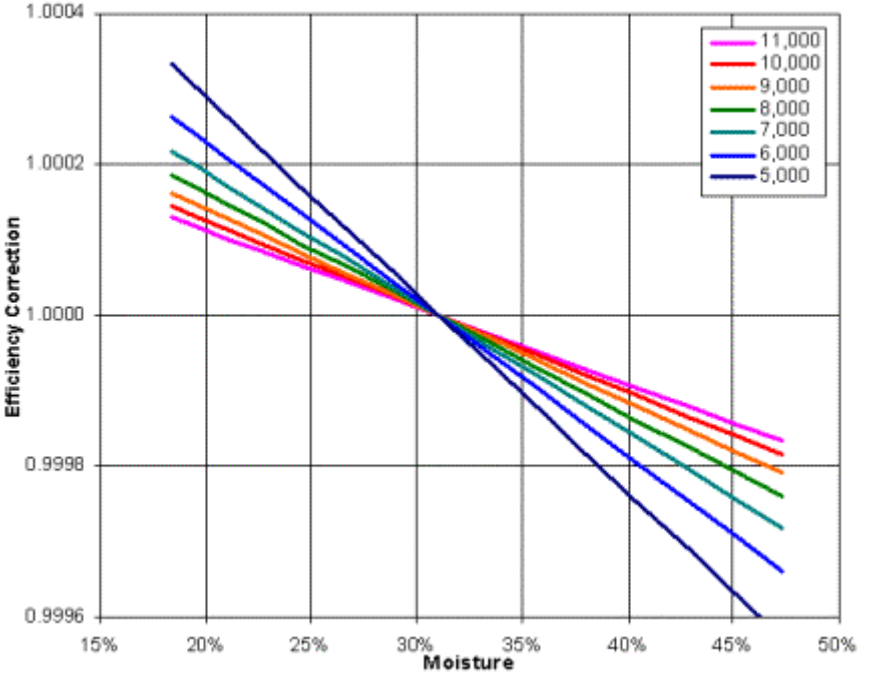
	A	B	C	D	E	F	G	H	I
1	**PTC4 SIMPLIFIED CALCULATIONS**	calculate		**Tabulated Values Calculated by Perturbing**					
2				Pamb	Corr.	RH	30	40	50
3	**Ambient Conditions**	**Value**	**Units**	12.50	0.9999	0%	1.0003	1.0004	1.0005
4	ambient pressure	14.7	psia	12.79					
5	ambient dry-bulb	60.0	Deg F	13.07					
6	ambient relative humidity	60%	%	13.36					
7	**Coal Composition**			13.64					
8	carbon mass fraction	48.50%	%	13.93					
9	hydrogen mass fraction	3.25%	%	14.21					
10	oxygen mass fraction	10.69%	%	14.50					
11	nitrogen mass fraction	0.65%	%	14.79					
12	sulfur mass fraction	0.40%	%	15.07					
13	ash coal mass fraction	5.50%	%	15.36					
14	moisture (H_2O)	31.00%	%	15.64					
15	total	99.99%	%	15.93					
16	**Normalized Coal Composition**			16.21					
17	carbon mass fraction	48.50%	%	16.50					
18	hydrogen mass fraction	3.25%	%						
19	oxygen mass fraction	10.69%	%	Tdb					
20	nitrogen mass fraction	0.65%	%	30					
21	sulfur mass fraction	0.40%	%	35					
22	ash coal mass fraction	5.50%	%	40					
23	moisture (H_2O)	31.00%	%	45					
24	total	100.00%	%	50					
25	**Ash Composition**			55					
26	fly ash	76.92%	%	60					
27	bottom ash	15.38%	%	65					
28	other	7.69%		70					

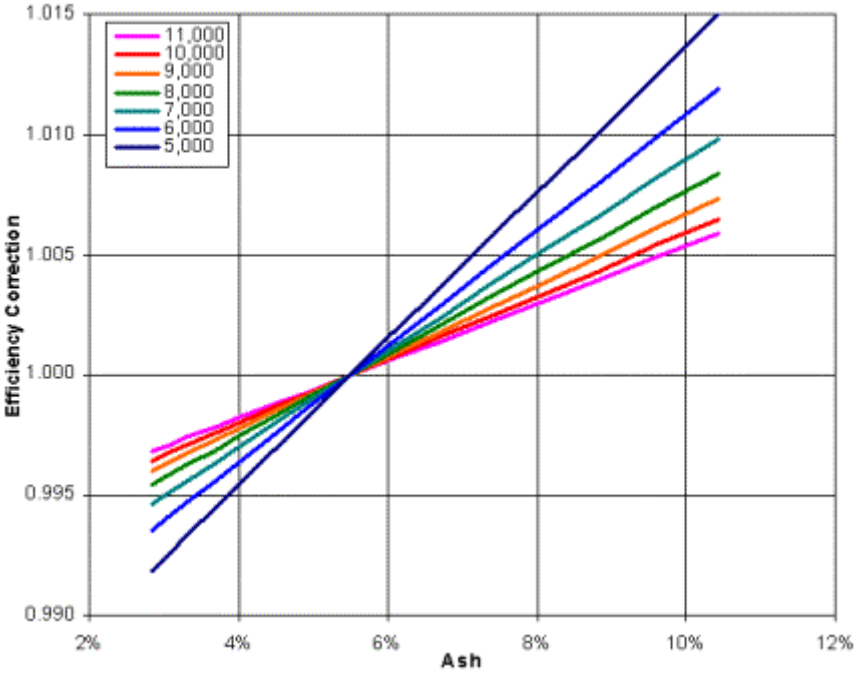


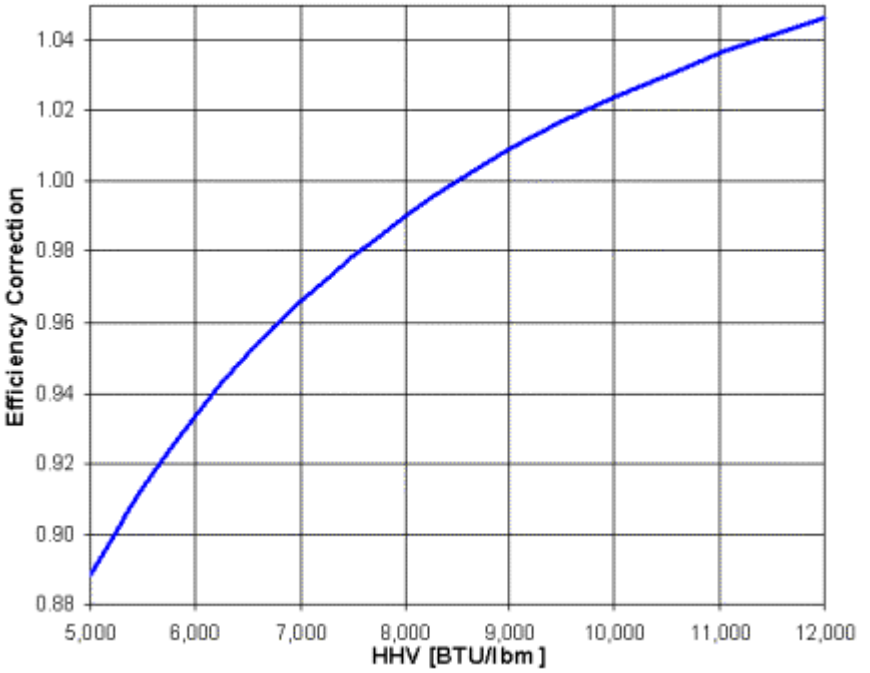

1.00010
1.00005
1.00000
0.99995
0.99990
0.99985
Efficiency Correction
12
13
14
15
16
17
Barometric Pressure [psia]

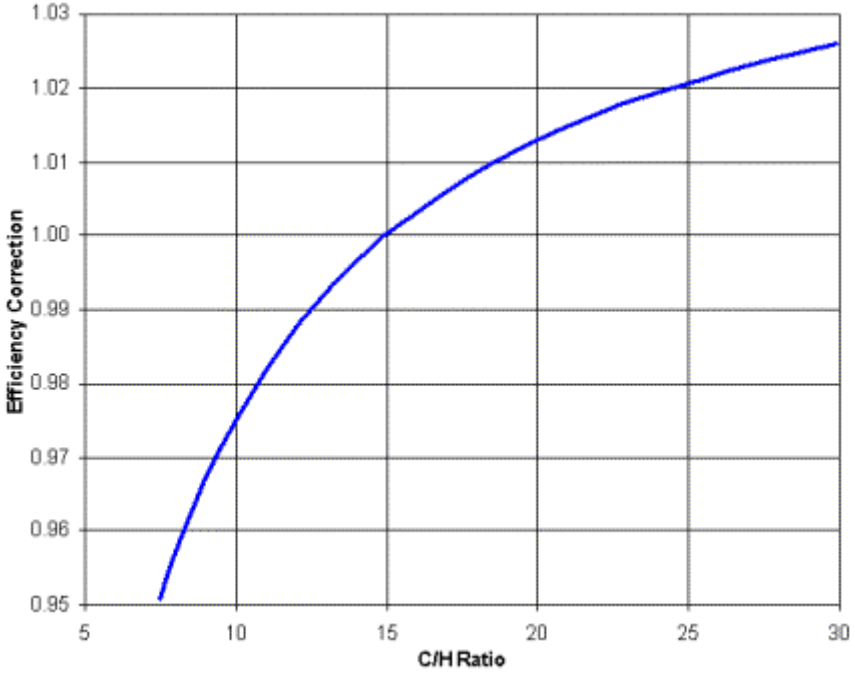

1.010
1.008
1.006
1.004
1.002
1.000
0.998
0.996
0.994
0.992
0.990
Efficiency Correction
30
40
50
60
70
80
90
100
Ambient Dry-Bulb Temp. [°F]

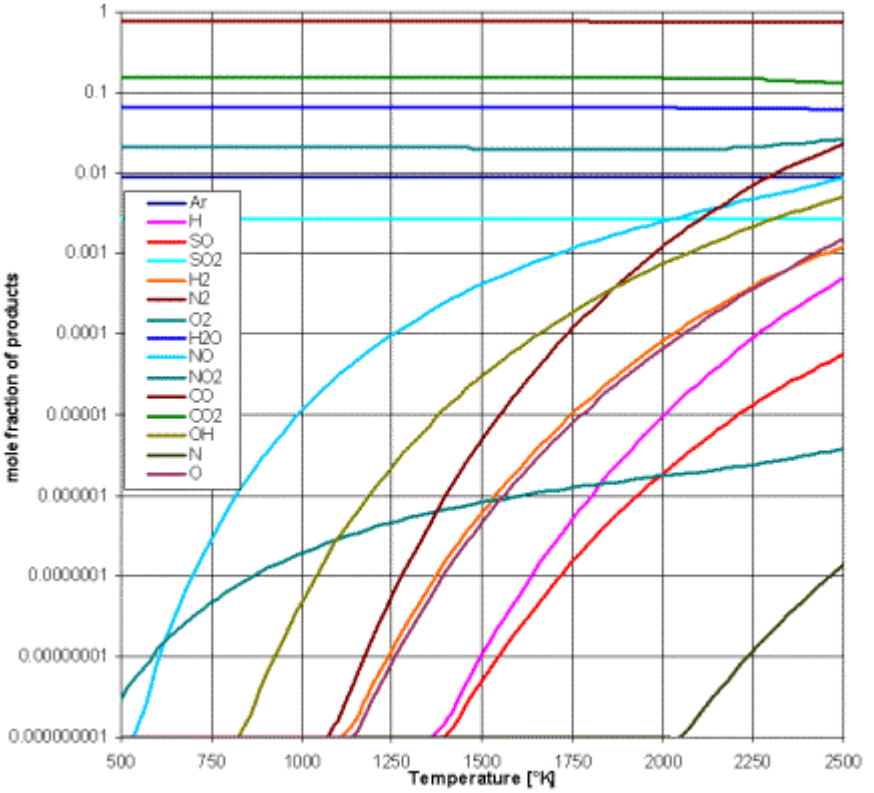

1.0020
1.0015
1.0010
1.0005
1.0000
0.9995
0.9990
0.9985
Efficiency Correction
0%
20%
40%
60%
80%
100%
Ambient Relative Humidity
90
80
70
60
50
40
30

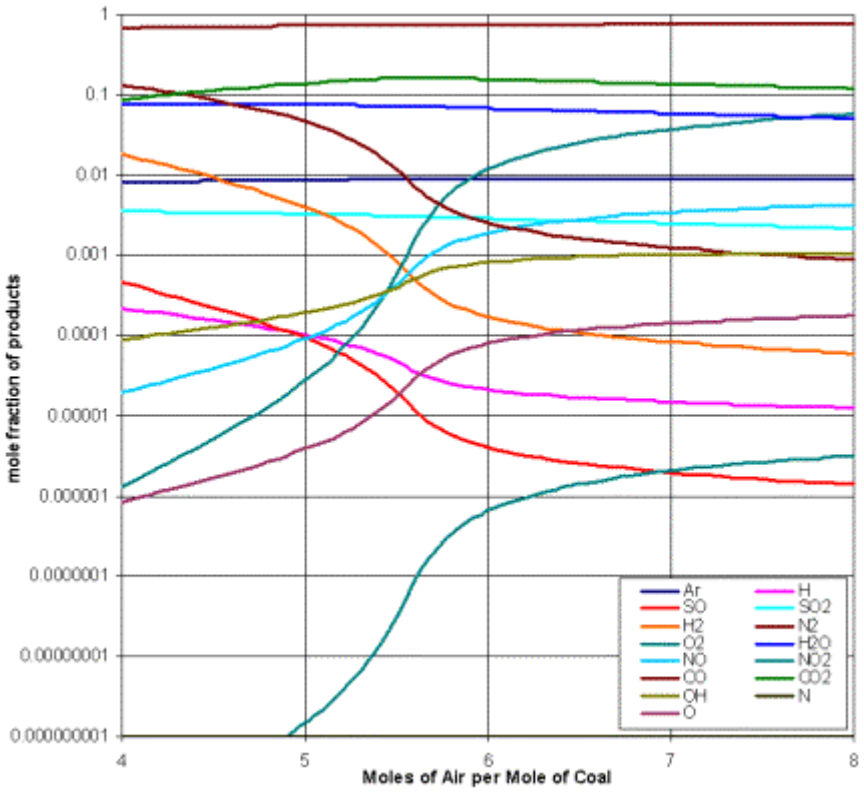

1.0004
1.0002
1.0000
0.9998
0.9996
Efficiency Correction
15%
20%
25%
30%
35%
40%
45%
50%
Moisture
11,000
10,000
9,000
8,000
7,000
6,000
5,000

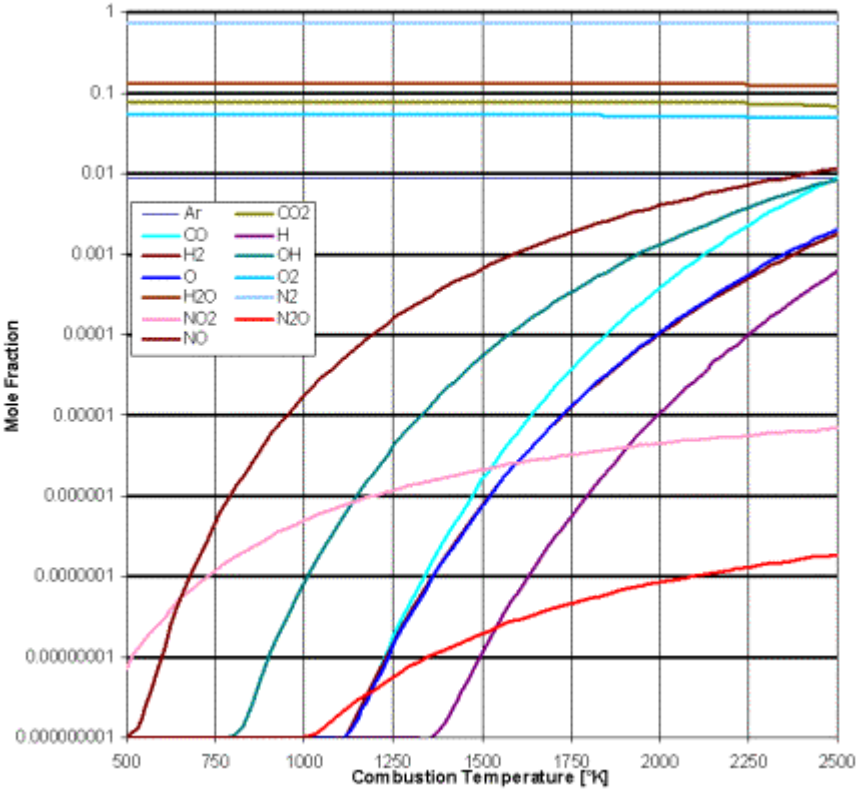

1.015
1.010
1.005
1.000
0.995
0.990
Efficiency Correction
11,000
10,000
9,000
8,000
7,000
6,000
5,000
2%
4%
6%
8%
10%
12%
Ash

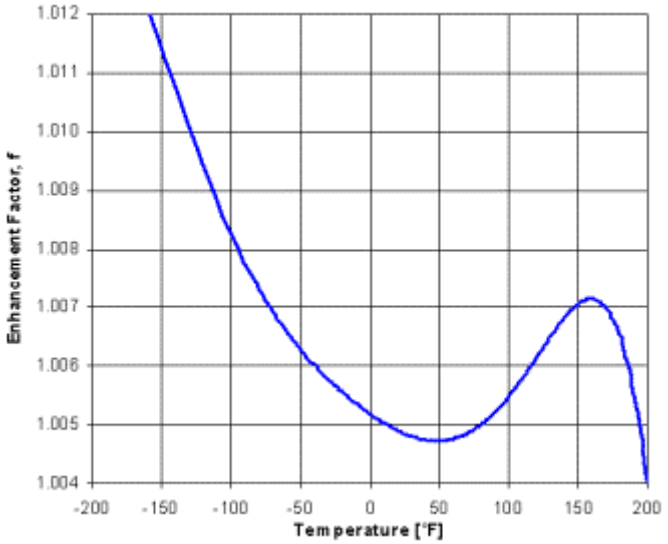

Efficiency Correction
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.88
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
HHV [BTU/lbm]

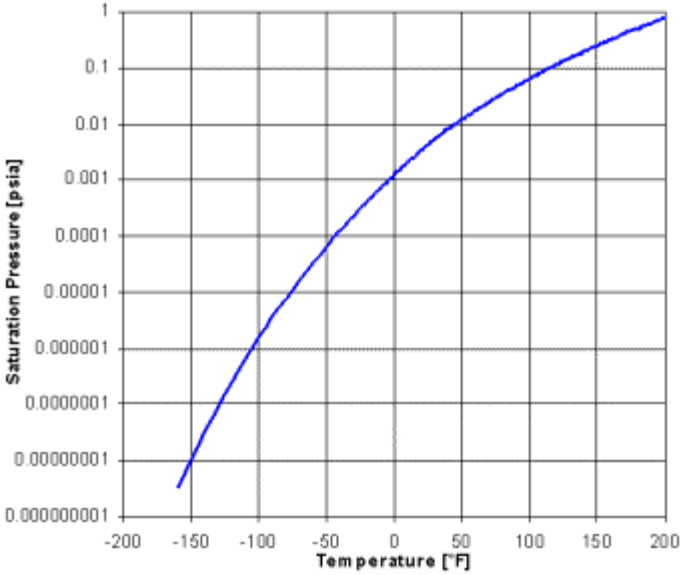

1.03
1.02
1.01
1.00
0.99
0.98
0.97
0.96
0.95
Efficiency Correction
5
10
15
20
25
30
C/H Ratio

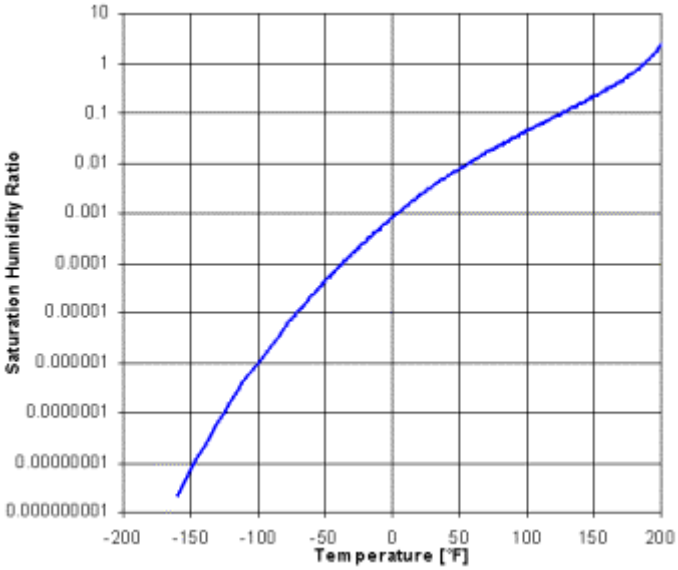

1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
mole fraction of products
Ar
H
SO
SO2
H2
N2
O2
H2O
NO
NO2
CO
CO2
OH
N
O
500
750
1000
1250
1500
1750
2000
2250
2500
Temperature [°K]


1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
mole fraction of products
4
5
6
7
8
Moles of Air per Mole of Coal
Ar
SO
H2
O2
NO
CO
OH
O
H
SO2
N2
H2O
NO2
CO2
N


Mole Fraction
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
Ar
CO
H2
O
H2O
NO2
NO
CO2
H
OH
O2
N2
N2O
500
750
1000
1250
1500
1750
2000
2250
2500
Combustion Temperature [°K]


1.012
1.011
1.010
1.009
1.008
1.007
1.006
1.005
1.004
Enhancement Factor, f
-200
-150
-100
-50
0
50
100
150
200
Temperature [°F]


1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
Saturation Pressure [psia]
-200
-150
-100
-50
0
50
100
150
200
Temperature [°F]



x	y
0.5	1.77
0.6	1.49
0.7	1.30
0.8	1.16
0.9	1.07
1.0	1.00
1.1	0.95
1.2	0.92
1.3	0.90
1.4616	0.8856
1.6	0.89
1.7	0.91
1.8	0.93
1.9	0.96
2.0	1.00
2.1	1.05
2.2	1.10
2.3	1.17
2.4	1.24
2.5	1.33
2.6	1.43
2.7	1.54
2.8	1.68