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AN INVESTIGATION OF NON-INTRUSIVE RADIOMETER FOR
ENTRAINED GASIFIER TEMPERATURE MEASUREMENT

1st Quarterly Report for the Period Oct. 30, 1983—Jan. 30, 1984

By
Paul Fairchild
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July 13, 1984
(Revised)

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For
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Morgantown Energy Technology Center
Morgantown, West Virginia

By
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An Investigation of Non-Intrusive Radiometer
for Entrained Gasifier Temperature Measurement

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for the period

Oct. 30, 1983 - Jan. 30, 1984

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Prepared for the

U.S. Department of Energy
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MASTER

SUMMARY

The emphasis during the first quarter has been directed toward evaluating radiometric approaches to find the optimum technique to measure temperature in an entrained gasifier environment. In this regard, it was concluded that while total radiation measurements were helpful in providing designers with total radiation loads to hardware, it was not acceptable as a means of measuring temperature for the gas/particle environment considered. To make the temperature measurements, one, two, and three line radiometers (pyrometers) were evaluated. It was found that a single (one) line pyrometer measurement of resonance radiation from a trace alkali metal in the gas provides a very promising technique to provide spatially resolved temperature measurements. A detailed description of governing equations controlling this technique is given. During the next quarter, laboratory prototype probes will be assembled, tested and evaluated.

1.0 INTRODUCTION

1.1 OBJECTIVES.

The objective of this project is to develop and test a nonintrusive radiometer for entrained bed gasifier temperature measurements. This first quarterly report describes the work performed under this contract during the period between 30/Sept/1983 to 30/Jan/1984. The work during the first quarter focused mainly on task 1. The project tasks are:

1. Performance Analysis.
 - 1.1 Radiometer Configuration Analysis.
 - 1.2 Establishment of Design Requirements.
2. Design, Fabrication, and Laboratory testing of Radiometers.
3. Field Testing of a Radiometer.

The performance analysis has focused on two types of instruments for performing the job. The first is a family of total-radiation-radiometers, and the second is a family of one, two, or three line radiometers, called pyrometers. The main issue to be addressed before a selection of the appropriate instrument can be made, is the measuring environment and the conditions under which the instrument is expected to operate. We will address this issue briefly below.

1.2 MEASURING ENVIRONMENT.

The project objectives call for measurements to be performed in an entrained bed gasifier, with the Mountain fuel Resources

pilot plant as a major candidate. The Texaco Coolwater plant and the BI-Gas pilot plant are two optional candidates. However, since the scheduled operation of these facilities in late 1984 is not presently known, plans are to field test a radiometer at the TRW Fossil Energy Test Site in which several pulverized coal combustors are in operation. The critical issues in selecting any field test facility are related not only to the design of the instrument for mechanical compatibility, but also to the physical principles of operation. An instrument which is optimized to operate in an environment of a gasifier may, or may not, perform as well in a combustor, and vice versa. In section 3 we have compiled the operating characteristics of several possible (gasifiers and combustors) candidates for the field test of the instrument. We have analyzed the operating characteristics of these facilities and created a data base against which the performance requirements of the measuring technique, or the instrument, are evaluated. Typical important characteristics of these coal conversion facilities are the temperature, pressure, throughput, coal particle loading, etc. The impact of these parameters and others are discussed in more detail in the following sections. We have established a goal to design an instrument to be compatible with the largest number of candidate test facilities so that the actual decision on the location of the field test can be postponed to a later date.

1.3 APPROACH.

Temperature measurement is not a simple task, and the interpretation of the measurement can be as complex as the measurement itself. Depending on the measuring technique and on the test conditions, results may give gas temperature, solid

particles temperature, wall temperature, or a weighted average of all of the above. In all cases, temperature can be obtained from the measurement of radiation in a selected band of the electromagnetic spectrum. In contrast, the measurement of total radiation provides information relevant to radiative heat loading for process control and hardware design purposes. Backing out the temperature from a measurement of the total radiation is possible but not simple. In order to do that a radiation model is needed. This model describes the spatial and spectral (direct/scattered) radiation from the gases, solids, and walls of the gasifier, and it should be coupled with the spatial and spectral collection efficiency of the radiometer/detector combination.

A key DoE interest in the past has been directed towards the measurement of temperature in stage I fo the BI-Gas pilot plant. Our assessment of the complexity of the various techniques as related to requirements, is that a **total radiation** technique is appropriate only if radiative loading is the parameter of key interest. Backing out the temperature from from a measurement of total radiation is not justifiable in light of the other available techniques. For the purpose of temperature measurements, a technique based on a selected electromagnetic band pyrometer--in which the wavelength is selected in a regime where the media is optically thick--is appropriate.

Typically, an instrument based on this technique would collect radiation from a spatially limited probe volume. This radiation may then be split into a number of photo-sensitive detectors, and filtered to pass radiation only in a narrow band of interest. This principle has been used on a number of devices developed in the past by TRW for various applications

(specifically, three color pyrometers have been used). In the present application due to the severity of the environment, e.g., the high coal particle number density, the high pressure and temperature, we find that the optimal approach would be a one-line pyrometer, operating at the Na or K emission line. As will be shown, a relatively small amount of these elements is needed to create the optically thick conditions. The technique is termed here as Sodium Line Emission Pyrometer, SLEP (or PLEP for Potassium Line Emission Pyrometer). The principle of operation and the conditions under which this technique works are described in later sections. The reason this one-line pyrometer will work well in most coal conversion facilities is that coal contains sufficient amount of sodium or potassium which are extremely effective emitters.

The measurement involves the collection of radiation from strong atomic emitters (Na or K). In order to establish the validity of the technique one needs to know the source of the collected radiation. As with other techniques this radiation could come from the gas phase Na or K atoms in the gas phase, from hot particles, and from walls. The analysis below establishes the conditions under which the medium is optically thick (i.e., the radiation is primarily from the Na or K in the gas) or optically thin (in which case radiation by particles may be collected as well). These conditions depend, of course, on the temperature, the Na or K concentration, and the coal particles number density. The analysis that follows addresses these issues and shows that at the Na or K wavelength, under typical operation of coal conversion facilities, the optically thick conditions prevail.

2.0 ALKALI LINE EMISSION PYROMETRIC (SLEP OR PLEP) TEMPERATURE MEASUREMENTS

2.1 TECHNIQUE

When a beam of light propagates along a path s through an absorbing medium in local thermodynamic equilibrium, the intensity, changes according to the radiative transfer equation,

$$\frac{dI}{ds} = \alpha(B - I) , \quad (1)$$

where I , α , and B are the intensity, absorption coefficient, and Planck's blackbody function, respectively. A general solution of equation (1) for constant conditions along the path, at some position s , is given by,

$$I(s) = \left[1 - \exp(-\alpha s) \right] B + I(0) \exp(-\alpha s) . \quad (2)$$

The sodium or potassium line emission pyrometric (SLEP or PLEP) technique is based on the assumption that the optical depth, is much greater than unity $\alpha s \gg 1$, therefore, the measured intensity, $I(s)$, is independent of the initial intensity, $I(0)$, and $I(s) = B$. The validity of this assumption is discussed below. B , which has units of $\text{watts-cm}^{-2}\text{-sr}^{-1}$ and is temperature dependent, is given by,

$$B = \frac{(c_1/\pi) d\lambda}{\lambda^5 \exp(c_2/\lambda T)} , \quad (3)$$

and thus at the particular wavelength of the alkali ($\lambda = c/\nu$) measuring $I(s)$ leads directly to a measure of the temperature of the sodium or potas-

sium atoms that are in equilibrium with the local gas temperature. It is an important requirement of this technique that the mean free path for photons emitted from Na (or K) be shorter than the average spacing between solid coal or char particles otherwise the temperature measured is biased by the temperature of the solid particles. The necessary mean free path will depend on the number density of alkali and coal present (see discussion below). The remainder of this section will be devoted to making estimates of the alkali concentration as well as expected signals based on estimates of the amount of coal present.

2.2. ANALYSIS

Of primary concern to the SLEP or PLEP technique is the question of optical depth. In order to estimate (αs) it is necessary to have some measure of the absorption coefficient, α , and its wavelength dependence. For atomic species this can be calculated from the following equation,

$$\alpha = \left(\lambda_0^2 A_{21} g_2 / 8\pi g_1 \right) \left[N_1 - (g_1 / g_2) N_2 \right] g(\nu) , \quad (4)$$

where λ_0 is the wavelength at line center for a transition from a lower level 1 with a population N_1 to an upper level 2 with a population N_2 . The probability for such a transition to occur is given by A_{21} , g_i is the appropriate level degeneracy, and $g(\nu)$ is the normalized lineshape function. For a Doppler broadened line, $g(\nu)$ is given as,

$$g(\nu) = (2/\Delta\nu_D) (\ln 2/\pi)^{1/2} \exp \left\{ - \left[2(\nu - \nu_0)/\Delta\nu_D \right]^2 \ln 2 \right\} , \quad (5)$$

and

$$\Delta\nu_D = \nu_0 \left[\frac{2}{c} (2R \ln 2)^{\frac{1}{2}} \right] \left(\frac{T}{M} \right)^{\frac{1}{2}}, \quad (6)$$

where $\Delta\nu_D$ is the Doppler half-width given in units of sec^{-1} , ν_0 is the frequency in sec^{-1} at the line center, T is the temperature in K, c is the velocity of light, R is the gas constant and M is the molecular weight. Table 1 lists some of the important spectroscopic parameters for both Na and K.

For the temperature range of interest (1200-2700K), $N_2 \ll N_1$ and $N_1 \cong N_{\text{total}}$, therefore equation (4), using equations (5) and (6), can be written as,

$$\alpha = k N, \quad (7)$$

where the absorption cross-section is given by,

$$k = \left[(\lambda_0^2 A_{21} g_2 / 4\pi g_1) (\ln 2 / \pi)^{\frac{1}{2}} / \Delta\nu_D \right] \exp \left\{ - \left[2(\nu - \nu_0) / \Delta\nu_D \right]^2 \ln 2 \right\} \quad (8)$$

Table 2 gives the values of k_0 , the absorption cross-section at line center, for Na and K, at several temperatures, relevant to coal combustors or gasifiers. These values were calculated assuming a Doppler line profile since it is difficult to estimate the collisional contributions to the line shape that result from the gasifier environment. A peak absorption cross-section for Na (5890A) at 2300K and atmospheric pressure of $1.8 \times 10^{-12} \text{ cm}^2$ has been experimentally determined (J.D. Winetordner, T.C. O'Haver, and S. Schulman, in "Luminescence Analysis in Analytical Chemistry", Wiley-Interscience, N.Y. 1972). This value is somewhat smaller than the values listed in Table 2, which probably accounts for this line broadening, thereby reducing the value at line center. This will under estimate the optical depth s at line center (listed in Table 5) by roughly 30%. Table 3 gives

values of the absorption coefficient, $\alpha_0 (= k_0 N)$ at line center for a range of number densities, N , at several temperatures. α_0 was calculated using the k_0 values in Table 2 for Na. These values are used next to calculate the optical depth.

The photon mean free path can be described by $P(s) = \exp(-\alpha_0 s)$ the probability of photon not being absorbed after passing through a path length s . The solid lines in Figure 1 gives $P(s)$ for three Na concentrations (at 1500K). The figure shows, for instance, that with a Na concentration of 10^{14} cm^{-3} the probability of a photon being transmitted over 0.01 cm is less than 0.4%. With Na at 10^{13} cm^{-3} , however, that probability is now about 57%. For our purposes we will define the optical thick photon mean free path as the distance at which the transmission probability is less than 10%. From Figure 1, therefore, at 1500K, the mean free path is about 0.004, 0.04cm and 0.4cm for Na concentrations of 10^{14} , 10^{13} , and 10^{12} cm^{-3} , respectively.

In order for the SLEP/PLEP to measure gas temperature unbiased by the coal particle temperature, the mean distance between coal particles should be greater than the photon mean free path. Figure 1 also shows two vertical lines at $s = 5.8 \times 10^{-3} \text{ cm}$ and 0.11cm. These lines represent intra-particles separation (ℓ_p) that corresponds to high and low coal loadings, respectively. As shown in Section 3, such loadings are the two extremes expected in the coal conversion facilities considered (see Table 6). When the coal particle separation is greater than the photon mean free path, the radiation collected is primarily due to the sodium since the radiation emitted by the particles is absorbed by the Na. If the particle concentration is high, however, then the measured radiation contains a contribution from the particles. The Figure shows that for $5 \times 10^6 \text{ particles/cm}^3$ and $10^{14} \text{ Na atoms/cm}^3$, the probability of a photon emitted by the particles reaching the detector is only about 4%. At Na concentration of 10^{13} cm^{-3} this probability increases to 72%. Fortunately, the particle number density is significantly below 10^6 in many gasifiers and the problem almost does not exist.

We next calculate the intensity of the radiation (B), using Equation (3), collected in a optically thick medium by an optical system represented by a lens with an arbitrary $f\#=(f/D)$. If the sample is assumed to be optically thick, emission occurs from the entire cross-sectional area at the

focal plane viewed by the collection optics. The intensity for this case is independent of the collection optics since the collection steradians times the area being viewed is λ_0^2/π . This can be seen in Figure 2 where any increase in the collection angle causes an equal reduction in the collection area. Using this result Table 4 gives the calculated values of B in watts for both Na and K at several temperatures for a 20Å bandpass and these are shown graphically in Figure 3. Here it is evident that over this temperature range emission by K is larger than that of Na by about a factor of 3 at 2700K and 15 at 1500K. This may be an important factor in determining in which atomic species to detect at the lower temperatures.

2.3 ALKALI KINETICS

The next step in evaluating the SLEP (or PLEP) technique for temperature measurements is to make some reasonable estimates of the amount of gas phase Na (or K) present in the combustor or gasifier. The upper limit on the amount of gas phase sodium (or potassium) depends on the naturally occurring content of these elements in the coal. A reasonable estimate for Na is 150 ppm. If all the Na in the gasifier is in the gas phase, then using the operating parameters and geometry of the gasifier a Na atoms concentration can be calculated. As an example, we will use the BI-Gas facility for which the operating conditions are given in Section 3 (see Table 8 and Figure 5A).

The coal feed rate and the total feed of all the various streams is 9079 and 46100 lb/hr, respectively. The Na mass fraction is therefore $\left[9097 \times 150 \times 10^{-6} / 46100\right] = 29.6 \times 10^{-6}$. If one mole of gas contains 6.02×10^{23} atoms and it occupies 22400 cm³ then there are $6.02 \times 10^{23} / 22400 = 2.69 \times 10^{19}$ atoms/cm³ at room temperature, or $2.69 \times 10^{19} \times \frac{85}{1} \times \frac{300}{1500} = 4.57 \times 10^{20}$ atoms/cm³ at 1500K and 85 atm. Since the Na concentration is roughly 29.6 ppm, there would be 1.35×10^{16} Na atoms/cm³ (assuming molecular weight of Na is roughly equal that of the gaseous mix in the reactor). Not all the Na ends in a gaseous phase however, due to the complex set of chemical reactions that are continually taking place.

A complete chemical equilibrium analysis, which takes into account all the major species present in the system has been performed (using a computer-code) in order to determine the actual equilibrium Na concentration.

Results of this analysis are listed in Table 5 along with the values of k_0 (from Table 2) and values of s such that $k_0[Na] s=1$. These results will be used to calculate the power on the detector and the effect on the measurements of the particles present in the gasifier.

3 .0 TYPICAL COAL CONVERSION FACILITIES

The following is a comparison of several entrained flow coal gasifiers, the TRW atmospheric pressure coal combustor and the 50 MW_t coal-fired MHD combustor. This comparison was undertaken to assess the feasibility of various temperature measuring techniques in these systems. Emphasis is placed on internal temperature and pressure as well as coal particle number density and the gases present since these factors will directly effect the SLEP or PLEP technique. The parameters have been summarized in Table 6.

In Figures 4 - 7 are the schematic and flow diagrams for several entrained flow gasifiers. A tabulation of the material and heat balance sheet for the particular gasifier are given in Tables 7-10. These figures and tables were taken from "Chemistry of Coal Utilization", Martain A. Elliot ed., Wiley-Interscience, N.Y., 1981. More specific information on each gasifier can be found in the above reference. Figure 8 shows a schematic of the TRW 17 in. coal combustor and figure 9 show the TRW 50 MW_t MHD combustor.

Each of the gasifiers and combustors is well suited, for the SLEP or PLEP temperature measurement technique based on the arguments that were presented above. There may be a difficulty, however, if either of these techniques are required to make temperature measurements in stage I (the lower stage) of the BI-Gas gasifier. Since coal is introduced into the upper stage (stage II) and combusted there, all of the Na (or K) in the gas phase may be removed by the cyclone separator and not available when the char is reintroduced into stage I. The exact amount of Na (or K) present in this lower stage is difficult to predict and we are uncertain if sufficient alkali concentration will be present to assure that the optical depth criteria is met. This could also be a problem with any other gasifier (or combustor) with a similar two-stage design. The other gasifiers shown in Figures 4 - 7 and the TRW combustors would be well suited for either the SLEP or PLEP technique.

4.0 Mechanical Design of Pyrometer

The collection optics of the pyrometer will be made of a fiber optic cable enclosed in a stainless-steel sheath with cooling water flow to maintain both the sheath and the fiber cool at around room temperature. This design is similar to TRW's enthalpy probe and our pinhole camera; both instruments were operated successfully inside the harsh environment in a coal combustor. The viewing port will have a gas purge (N_2) which is adjusted such that it rejects particles of slag from building over the port. This technique is presently in use on several of TRW's coal conversion facilities and it allows non-obstructing view of the inside of the combustor for many consecutive hours. The N_2 purge is typically exiting the port at sonic velocity to provide sufficient momentum to repel incoming particles; it also optimizes the flow rate of the purge gas.

TABLE 1.^aTransition Parameters

TRANSITION		(Å)	$A_{21}(10^8 \text{ sec}^{-1})$	g_1	g_2	$f_{12}^{\text{b.}}$
Na	$3^2S_{1/2} - 3^2P_{1/2}$	5889.95	0.630	2	4	0.655
Na	$3^2S_{1/2} - 3^2P_{3/2}$	5895.92	0.628	2	2	0.327
K	$4^2S_{1/2} - 4^2P_{1/2}$	7664.91	0.387	2	4	0.682
K	$4^2S_{1/2} - 4^2P_{3/2}$	7698.98	0.382	2	2	0.339

a. Data taken from W. L. Wiese, M.W. Smith and B.M. Miles "Atomic Transition Probabilities", NSRDS-NBS 22 Vol. II, U.S. Dept. of Commerce, 1969.

b. Oscillator strength for a transition between level 1 and level 2.

$$f_{12} = \frac{mc}{8\pi^2 e^2} (g_2/g_1) \lambda_0^2 A_{21}$$

TABLE 2.

Absorption Cross-Sections

	Na	K
T(K)	$k_0(10^{-12} \text{ cm}^2)$	$k_0(10^{-12} \text{ cm}^2)$
1500	5.56	9.83
1800	5.07	8.96
2100	4.70	8.31
2400	4.39	7.76
2700	4.13	7.30

TABLE 3.

Absorption Coefficients for Na

T(K)	$N = 10^8 \text{ cm}^{-3}$	$N = 10^{10} \text{ cm}^{-3}$	$N = 10^{12} \text{ cm}^{-3}$	$N = 10^{14} \text{ cm}^{-3}$
1500	$5.56 \times 10^{-4} \text{ cm}^{-1}$	$5.56 \times 10^{-2} \text{ cm}^{-1}$	5.56 cm^{-1}	$5.56 \times 10^2 \text{ cm}^{-1}$
1800	5.07×10^{-4}	5.07×10^{-2}	5.07	5.07×10^2
2100	4.70×10^{-4}	4.70×10^{-2}	4.70	4.70×10^2
2400	4.39×10^{-4}	4.39×10^{-2}	4.39	4.39×10^2
2700	4.13×10^{-4}	4.13×10^{-2}	4.13	4.13×10^2

TABLE 4.

Radiative Intensity

	Na @ 5890Å	K @ 7665 Å
T(K)	B (watts)	B (watts)
1500	5.43×10^{-8}	7.89×10^{-7}
1800	8.17×10^{-7}	6.38×10^{-6}
2100	5.67×10^{-6}	2.83×10^{-5}
2400	2.42×10^{-5}	8.68×10^{-5}
2700	7.49×10^{-5}	2.07×10^{-4}

TABLE 5.

T(K)	[Na](10^{14} cm^{-3})	<u>Na Equilibrium Concentration</u>	
		$k_0(10^{-12} \text{ cm}^2)$	$s = \frac{1}{k_0 [\text{Na}]} (10^{-3} \text{ cm})$
1500	9.2	5.6	0.19
1800	10.5	5.1	0.19
2100	10.7	4.7	0.20
2400	10.9	4.4	0.21
2700	11.0	4.1	0.22

Table 6. PERFORMANCE PARAMETERS

	Temp. (°F) T	Press. (psi) P	Coal ^b Particle Density (#/cm ³) n	Reactor Diameter (ft) D	Coal Flow Rate (gm/sec) m	Gas Velocity (cm/sec) v
Bi-Gas	2600-2900 ^a	750	2.1×10^4	2	3.7×10^3	213.4
Foster Wheeler	2800-3000 ^a	440	5.5×10^6 ^c	2(est'd)	9.7×10^2	
Koppers- Totzek	3300-3500	15	9.7×10^2	11	2.5×10^4	435.2
Texaco	2500	450	2.5×10^2 ^c	8	7.3×10^2	
Combustion Engineering	3200	15	1.3×10^3	10(est'd)	6.0×10^3	150.8
Babcox and Wilcox	3000-3400	315	5.1×10^4	4.6	4.2×10^4	180.0
TRW MHD 50 MW	5000 ^a	88	5.3×10^2	2.5	1.7×10^3	2439.0
TRW 17in. ^d Combustor	2800-3000 ^a	15	4.3×10^2	1.5	4.6×10^2	2180.0

a. Stage I

b. Density assumed to be that of carbon (1.3 gm/cm^3) and $d_p = 100 \mu\text{m}$

c. Calculated using Bi-Gas particle velocity

d. TRW is building a 34in combustor. Parameters will be scaled up appropriately.

TABLE 7. Material Balance and Heat Balance for the Koppers-Totzek Gasifier

Total input, Streams 1-4: 717.954×10^6 Btu/hr; total output, Streams, 5-8, 717.954×10^6 Btu/hr.

	Stream 1: Coal to Gasifier		Stream 2: Steam to Gasifier		Stream 3: Oxygen to Gasifier			Stream 4:	Stream 5:	Stream 6:	Stream 7:	Stream 8: Crude Product Gas			
	lb/hr	% w/w	lb/hr	mole/hr	lb/hr	mole/hr	% w/w	Quench Water lb/hr	Boiler Feed Water lb/hr	Steam lb/hr	Slag lb/hr	lb/hr	moles/hr	% v/v	
														Wet	Dry
Hydrogen	2,277	3.6													
Carbon	40,172	62.8										4,017			
Sulfur	253	0.4													
Nitrogen	887	1.4													
Oxygen	6,769	10.6													
Ash	12,905	20.2													
CO ₂											5,161	7,744			
H ₂ S												12,925	293.7	5.27	6.91
COS												240	7.0	0.13	0.17
CO												66	1.1	0.02	0.03
H ₂												76,023	2,714.1	48.96	64.29
CH ₄												2,301	1,141.6	20.52	27.08
N ₂					163	5.7	0.4					66	4.2	0.07	0.10
Ar					922	23.1	1.6					1,115	39.8	0.72	0.94
H ₂ O	638	1.0	6,327	351.1				17,805	115,225	115,225		799	20.0	0.36	0.48
HCN												24,251	1,346.0	23.85	
NH ₃														130 ppm*	
O ₂					45,282	1,415.0	98.0							100 ppm*	
Total	63,901	100.0	6,327	351.1	46,367	1,443.8	100.0	17,805	115,225	115,225	5,161	129,547	5,567.5	100.00	100.0
Temperature (°F)				261		194		86	216	459	>2,417		320		
Pressure (psig)				21.8		8.7		217.5	652.5	507.5			0.4		
Volume (scf/hr)				124,009		518,986				2,253,075			1,992,896		
Volume (scf/hr)				74,292				286	1928	104,553			3,170,096		
Average molecular weight				18.016		32.113							21.16		
HHV (Btu/scf)													333		
Heat of combustion (10 ⁶ Btu/hr)	686.215												534.074		
Enthalpy (10 ⁶ Btu/hr)	0.920		7.302			1.167		0.964	21.386	139.232	4.258		38.644		
Total heat (10 ⁶ Btu/hr)	687.135		7.302			1.167		0.964	21.386	139.232	4.258		572.718	1.746	

* Weight basis.

TABLE 8. Design Material Balance for a 5-ton/hr BI-Gas Pilot Plant

	Stream 1:		Streams 2 and 3:		Stream 4:		Stream 5:		Stream 6:	
	Coal and Nitrogen		(each) coal		High-Pressure Purge Gas to Stage II		High-Pressure Steam to Stage II		Oxygen to Stage II	
	lb/hr	mole/hr	(lb/hr)		lb/hr	mole/hr	lb/hr	mole/hr	lb/hr	mole/hr
Coal (maf)	9097		4549							
Char (maf)										
Ash	703		352							
CO ₂					1009	22.9				
CO					437	15.6				
H ₂					75	37.1				
CH ₄					112	7.0				
N ₂	223,700	7989							32	1.1
H ₂ S										
H ₂ O	17,800	988	100				9097	504.9		
Steam										
O ₂									6445	201.4
Total	251,300	8977	5001		1633	82.6	9097	504.9	6477	202.5
Total in Streams 2-8: 46,100 lb/hr										
Average molecular weight	26.9				19.8		18.0		32.0	
Temperature (°F)	550		475		200		800		60	
Pressure (psig)	1175		1175		1250		1250		1250	
Volume (scf/min)	59,705				521		3189		1280	

Stream 7:		Stream 8:		Stream 9:		Stream 10:		Streams 11, 12, 13:		Stream 14:	
High-Pressure Steam to Stage I		Boiler Feed Water Quench		Slag		Crude Gas from Gasifier		(each) Char		Gas from Cyclones	
lb/hr	mole/hr	(lb/hr)		(lb/hr)		lb/hr	(mole/hr)	lb/hr		lb/hr	mole/hr
				668		8,523		2754		260	
						1,152		372		35	
						10,762	244.5			10,762	244.5
						9,442	337.1			9,442	337.1
						937	463.9			937	463.9
						1,649	102.8			1,649	102.8
						62	2.2			62	2.2
						283	8.3			283	8.3
2947	163.7	15,945				22,001	1,220.9			22,001	1,220.9
2947	163.7	15,945	668			54,811	2379.7	3126		45,431	2,379.7
Total out, Streams 14 and 9: 46,000 lb/hr											
18.0						19.0				19.0	
800		230		170		800		800		800	
1850		1150		1150		1,150		1145		1145	
1034						15,032				15,032	

TABLE 9. Material Balance for Combustion Engineering Pilot Plant

Stream:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Solids component flows (lb/hr)																					
Coal	10,000	9858	3195	6663								3,268		3,788	520						
Char					3268							869									
Ash and carbon																		234			
Sulfur																					
Gas component flow (lb/hr)																					
CO						0	0	0	0	0	0	15,086		15,086	15,086	15,086	15,086	15,086	0	0	
CO ₂						0	0	0	0	0	0	3,973		3,973	3,973	3,973	3,973	3,973	0	27,704	
H ₂						0	0	0	0	0	0	473		473	473	473	473	473	0	0	
H ₂ O						632	470	62	63	377	129	946		3,926	3,926	5,296	2,553	2,612	767	7,603	
H ₂ S						37,310	27,763	3,636	3,719	22,370	7586	37,399		37,399	37,399	37,399	37,399	37,399	45,309	82,708	
H ₂ S						0	0	0	0	0	0	259		259	259	259	259	7	0	0	
COS						0	0	0	0	0	0	34		34	34	34	34	34	0	0	
O ₂						11,238	8,362	1095	1120	6,738	2285	0		0	0	0	0	0	13,648	1,242	
SO ₂						0	0	0	0	0	0	0		0	0	0	0	0	0	51	
Total flow (lb/hr)	10,000	9858	3195	6663	3268	49,180	36,595	4793	4902	29,485	10,000	61,438	869	64,938	61,670	62,520	59,777	234	59,584	59,724	119,308
Average molecular weight						28.62	28.62	28.62	28.62	28.62	28.62	25.75		25.22	25.22	25.00	25.45		25.42	28.62	29.50
Volumetric flow (acf/min)						11,292	17,515	1473	1506	14,232	3080	21,234		20,404	20,689	19,018	14,059		15,299	13,714	54,089
Temperature (°F)	80	180	160	160	160	80	689	300	300	689	300	300	3000	217	217	118	100	80	100	80	630
Pressure (in. w.g.)	0	.9	0	0	0	0	+8.5	+20	+20	+5	+20	-6.5	0	-9.0	-14	-30.5	+29.5	0	+19.5	0	+1

TABLE 10. Material Balance for the Babcock and Wilcox Process

	Stream 1:		Stream 2:		Stream 3:		Stream 4:	
	Coal		Flue Gas From Pulverizer		Pulverized Coal to Gasifier		Oxygen to Gasifier	
	(lb/hr)		lb/hr	mole/hr	lb/hr	mole/hr	lb/hr	mole/hr
Coal/Carbon (maf):	68,051		7.2		68,044			
Ash:	6,192		0.7		6,191			
Moisture:	8,249		0.1		1,515			
Total coal:	82,492		8.0		75,750			
CO								
CO ₂			4,417	100.4				
H ₂								
H ₂ S + COS			1.3	0.02				
O ₂			26,898	840.6			70,528	2,204.0
H ₂ O			9,246	513.7				
N ₂ + Ar			96,538	3,444	2,756	97.9	1,798	45.0
NH ₃								
Total	82,492		137,108		78,506		72,326	
Temperature (°F)	77		150		77		77	
Pressure (psig)	0		0.2		200		225	
Flow (scf/min)			30,966				14,206	
Flow (ton/day)	989.9				909.1		868	

Stream 5:		Stream 6:		Stream 7:		Stream 8:	
Steam to Gasifier		Slag from Gasifier		Steam to Superheater		Crude Gas from Gasifier After Particulate Removal	
lb/hr	mole/hr	lb/hr	mole/hr	lb/hr	mole/hr	lb/hr	mole/hr
		284				6	
		5,015				6	
						114,666	4,095.1
						22,422	509.3
						4,185	2,092.4
						2,169	60.9
15,150	840.9		27.8	215,646	11,969.7	11,937	662.5
						5,291	169.8
						0.7	0.04
15,150		5,299		215,646		160,683	
400		95		491		200	
225		0		615		145	
						47,171	
		69.6

FIGURE 1

PROBABILITY AT 1500K OF A PHOTON (AT $5890 \text{ \AA}$) BEING TRANSMITTED AFTER TRAVERSING A PATH LENGTH S

$$\text{Steradians} = \frac{D^2}{16f^2} ; \text{Area} = \pi w_0^2 = \frac{16\lambda_0^2 f^2}{\pi D^2}$$

Figure 2

COLLECTION OPTICS

Figure 3

CALCULATED RADIATION INTENSITY

Flow diagram of the Koppers-Totzek gasifier.

FIGURE 4. KOPPERS-TOTZEK GASIFIER

The Bi-Gas pilot-plant gasifier.

Flowsheet for a 5-ton/hr Bi-Gas pilot plant

FIGURE 5A. BI-GAS GASIFIER

Expanded view of
the Bi-Gas gasifier.

Figure 58. STAGE I & II OF BI-GAS GASIFIER

Conceptual diagram of a commercial Combustion Engineering gasifier.

Flowsheet for the Combustion Engineering pilot plant

FIGURE 6. COMBUSTION ENGINEERING GASIFIER

The Babcock and Wilcox gasifier.

Flowsheet for the Babcock and Wilcox process

FIGURE 7. BABCOCK AND WILCOX GASIFIER

Figure 8. TRW 17-Inch Atmospheric Slagging Combustor System

Figure 9. TRW 50 MW_t MHD Combustor

TRW ENERGY DEVELOPMENT GROUP