Estimating the Rate of Coal Combustion in a Mine Fire

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Dennis A. Giardino

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Dennis A. Giardino[1]

ABSTRACT

A method is presented for estimating the mass of coal per unit time (lbs./min.) being consumed in a mine fire. The estimate is calculated using an algorithm termed the coal combustion rate (CCR). The theory supporting the CCR is given along with its derivation from basic combustion principles. Examples of its use are also given employing data from an actual mine fires.

INTRODUCTION

In some situations, during a coal mine fire, one can obtain measurements of the ventilation through the suspected fire area along with the concentrations of various gases in the airflow. These two measurements, in conjunction with coal composition data, can provide an estimate of the mass of coal per unit time being consumed in the fire. This paper will derive the necessary relationships for calculating the coal combustion rate (CCR) and give examples for its applications.

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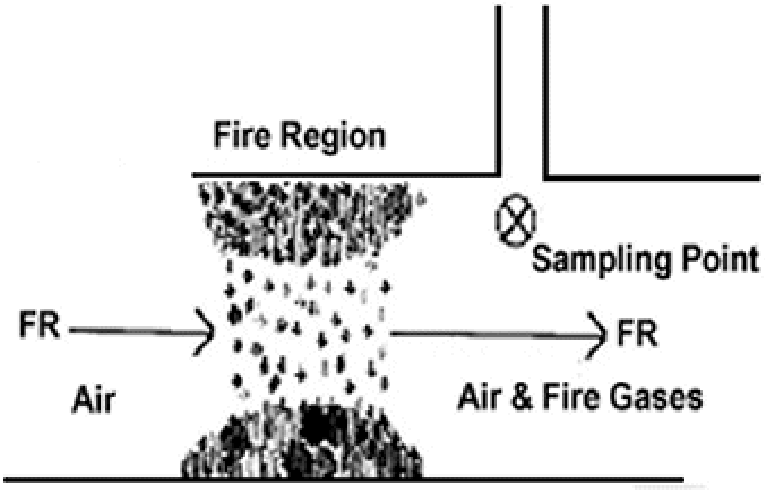
[1] Supervisory Physicist (Chief), Physical and Toxic Agents Division, Pittsburgh Safety and Health Technology Center, Pittsburgh, Pa.

THEORY

Consider the situation as illustrated in Figure 1:



Here, a quantity of air with a known flow rate, FR, is flowing through and feeding the coal combustion process in the fire region. At some distance, downstream from the fire, a sampling point is located where gases are collected for subsequent analysis by gas chromatography (GC). The species of gases reported in the usual GC analysis suite are N_2 (nitrogen), O_2 (oxygen), Ar (argon), CO_2 (carbon dioxide), CO (carbon monoxide), H_2 (hydrogen), CH_4 (methane), C_2H_2 (acetylene), C_2H_4 (ethylene), C_2H_6 (ethane), and sometimes C_3H_8 (propane).

Some understanding of the coal combustion process and the composition of coal is necessary before the data in the gas analysis suite can be usefully employed to calculate the coal combustion rate.

The composition of coal is very complex. From a strict chemical point-of-view, there is no such thing as a coal molecule. Over the years, many molecular subgroups have been identified[2]. These include benzene, naphthalene, and anthracene, along with larger ring compounds and straight chain hydrocarbons. This mix of subgroups is interlinked in an almost infinite variety of ways. Scattered throughout the structure are atoms of oxygen, nitrogen, and sulfur.

For our calculation, however, only an elemental compositional view of coal is required. This is readily obtainable from the results of the ultimate analysis[3] for the coal under consideration. The values needed are given in Appendix II.

A simplified, schematic-type reaction describing the combustion of coal can be written as:

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[2] Kasper, Stanley. "Coal Conversion Chemistry," Industrial Research and Development, January 1981, pp. 164-166.

[3] Hougen, Olaf A. and Kenneth M. Watson. "Chemical Process Principles," John Wiley & Sons, Inc., New York, 1947, pg. 324.

$$\underbrace{aCH_{(\frac{H}{C})_f}}_{\text{coal}} + \underbrace{bO_2}_{\text{oxygen used}} = \underbrace{cCO_2 + dCO + eH_2 \ldots}_{\text{fire gases}} + \underbrace{fH_2O}_{\text{water vapor}} + \underbrace{gC\,H_{(\frac{H}{C})_r}}_{\text{residual chars / tars}} \qquad \textbf{(1)}$$

Equation (1) describes a combustion process where coal reacts with the available oxygen from the air, producing fire gases, water vapor, and residual products. The subscript, $(H/C)_f$, is termed the equivalent hydrogen-to-carbon ratio of the fuel. It defines the composition of the coal taking into account compositional amounts of hydrogen, carbon, oxygen, nitrogen, and sulfur. Likewise, the subscript, $(H/C)_r$, is termed the equivalent hydrogen-to-carbon ratio of the residual products. These residual products are usually in the form of chars, tars, smoke and other nonvolatile compounds not appearing in the collected gas sample.

Besides the carbon dioxide, carbon monoxide, and hydrogen, shown as fire gases, acetylene (C_2H_2) and ethylene (C_2H_4) are also generated. Only a fraction of the methane (CH_4) and ethane (C_2H_6) should be included in the fire gas complement since, in most coal mines, their major source is the liberation of seam gas[4]. The CCR as derived in this report automatically compensates for CH_4 seam gas.

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[4] Mitchell, Donald W. "Mine Fires," McLean-Hunter Publishing Company, 1990, pg. 64.

It should be noted that only gases are collected in the sample and reported in the gas analysis suite. Neither the water vapor nor the residual products are in the collected gas sample; the former condensing before collection and the latter remaining in the mine, for the most part, as non-volatile chars and tars.

When the coal combustion is very efficient, large quantities of oxygen are consumed, and most of the products generated are fire gases and water vapor. In fact, the most efficient reaction possible generates only CO_2 and water vapor. This is known as complete combustion[5]. It rarely occurs in coal mine fires.

In less efficient reactions, which are common in coal mine fires, the combustion process is oxygen "starved." As a result, incomplete combustion occurs with the generation of significant quantities of residual products. Here, a large portion of the carbon and hydrogen of the fuel is not accounted for in the analysis suite but remains in the mine in the form of char/tar. Thus, in attempting to calculate the rate of fuel consumption from the gas analysis data, these residual products must be taken into account. Failure to do so can lead to unrealistically small numbers for the rate of fuel consumption. As previously stated, $(H/C)_r$ defines the composition of the residual products. Unfortunately, very few ultimate analyses have been done on

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[5] Harju, John B. "Coal Combustion Chemistry," Pollution Engineering, May 1980, pp. 54-60.

the remaining chars, tars, and smoke produced in mine fires so that estimates must be made for $(H/C)_r$ to calculate the fuel consumption. Fortunately, a reasonable estimate can be made for this parameter.

To estimate the rate of fuel consumption, one can define the coal combustion rate, CCR. A complete derivation of the CCR is given in Appendix I. The CCR is calculated using the following relation:

$$CCR = .021\left(\frac{M_{total}}{M_c}\right)\left(\frac{\%CO_2 + 1.3\%CO}{100 - \%CH_4}\right)\left[\frac{\left(\frac{H}{C}\right)_s - \left(\frac{H}{C}\right)_r}{\left(\frac{H}{C}\right)_f - \left(\frac{H}{C}\right)_r}\right]FR \qquad \textbf{(2)}$$

Where:

$$\left(\frac{H}{C}\right)_s = \frac{1.073\%N_2 - 4\%O_2 - 4\%CO_2 - 2\%CO + 2\%H_2 + 2\%C_2H_2 + 4\%C_2H_4}{\%CO_2 + \%CO + 2\%C_2H_2 + 2\%C_2H_4} \qquad \textbf{(3)}$$

And where:

CCR = Coal combustion rate (lbs/min)

FR = Air flow rate through the fire region (CFM)

M_{total}/M_c = Ratio of the total mass of coal to the mass of carbon in the coal as obtained from the ultimate analysis (values given in Appendix II, last column)

$(H/C)_s$ = Equivalent hydrogen-to-carbon ratio of the gas analysis suite [calculated using Equation (3)].

$(H/C)_f$ = Equivalent hydrogen-to-carbon ratio of the coal (values given in Appendix II, 2nd to last column)

$(H/C)_r$ = Equivalent hydrogen-to-carbon ratio of the char/tar products (a value of .3 is used in the calculation)

$\%CO_2$ = Percent carbon dioxide as reported from the gas analysis suite

$\%CO$ = Percent carbon monoxide as reported from the gas analysis suite

$\%N_2$ = Percent nitrogen as reported from the gas analysis suite

$\%O_2$ = Percent oxygen as reported from the gas analysis suite

$\%H_2$ = Percent hydrogen as reported from the gas analysis suite

$\%CH_4$ = Percent methane as reported from the gas analysis suite

$\%C_2H_2$ = Percent acetylene as reported from the gas analysis suite

$\%C_2H_4$ = Percent ethylene as reported from the gas analysis suite

APPLICATION

When using Equations (2) and (3) to calculate the CCR, it is important that the following conditions are met:

1. It is necessary that some portion of the measured airflow has passed through the fire region.
2. The measured airflow and gas sample need not be taken at the same location. It is only necessary that the measured airflow is representative of that flow at the gas sampling location.
3. When the fire gases are diluted with parallel airflows, the CCR will still estimate the pounds of coal consumed per minuted provided that the only gases of dilution are air and/or methane.
4. If the dilution with methane and/or air becomes too great, the resulting concentrations of carbon dioxide and carbon monoxide, generated in the combustion process, can drop near or below the limit of detectability of the gas chromatographic instrument, negating the calculation of the CCR.
5. If significant inflows of carbon dioxide and carbon monoxide from bleeder entries mix with the air flowing through the fire area, the calculated CCR will overestimate the pounds of coal consumed per minute.

6. From cursory studies of old mine fire data, it is concluded that the CCR will probably give a good estimate of coal consumption if the value of $(H/C)_s$, as calculated from Equation (3), is less than 4.
7. It should be realized that the calculated CCR is a composite estimation for the entire fire area. Some regions of the fire may have a substantially higher, while others, a substantially lower, value than the calculated CCR.

As previously stated, very little data exists for values of the hydrogen-to-carbon ratio of the residual products, $(H/C)_r$. Data on metallurgical coke shows the hydrogen-to-carbon ratio to be about .1. Results of a single ultimate analysis done on the residual product of a laboratory coal burning experiment showed the $(H/C)_r$ to be about .4. Based on this limited data, for the purpose of this report, the value of $(H/C)_r$ to be used in calculating the CCR is assumed to be .3.

Two examples will be given to illustrate the use of the CCR:

Example #1: Assume a fire is in a mine working the Pittsburgh Coal Seam. The air flow through the fire area is measured at 200,000 CFM, while at a downstream sample collection point, the following gas analysis results are obtained:

$\%N_2 = 77.84\%$ $\%O_2 = 18.91\%$ $\%Ar = .93\%$ $\%CO_2 = 1.37\%$

$\%CO = .026\%$ $\%H_2 = .015\%$ $\%C_2H_2 = 0.0\%$

$\%C_2H_4 = .0006\%$

$\%CH_4 = .91\%$ $\%C_2H_6 = .003\%$

Using Equation (3), the $(H/C)_s$ is calculated as:

$$\left(\frac{H}{C}\right)_s = \frac{1.073 \, x77.84 - 4 \, x18.91 - 4 \, x1.37 - 2 \, x \, .026 + 2 \, x \, .015 + 2 \, x0 + 4 \, x \, .0006}{1.37 + .026 + 2 \, x0 + 2 \, x \, .0006} = 1.70$$

The necessary parameters for the Pittsburgh Seam coal are given in Appendix II as:

$$(H/C)_f = .67$$

$$M_{total}/M_c = 1.23$$

Finally, a value of .3 is used for the hydrogen-to-carbon ratio of the char/tar products, $[(H/C)_r = .3]$.

Utilizing all of this data in Equation (2), including FR = $2x10^5$ CFM, we get for the coal combustion rate:

$$CCR = .021 \, (2 \, x10^5) \, (1.23) \left(\frac{1.37 + 1.3 \, x \, .026}{100 - .91}\right)\left(\frac{1.70 - .3}{.67 - .3}\right) = 277 \, \frac{lbs}{min}$$

Example #2: Table 1 presents the gas suites obtained from a mine fire in Illinois. For the sake of brevity, the higher hydrocarbons are not included in the table. The flow rate associated with the gas suites was measured as 10350 ft^3/min. The parameters for the Franklin County coal seam, as given in Appendix II, are:

$$(H/C)_f = .62$$

$$M_{total}/M_c = 1.33$$

TABLE 1. Gas Analysis Suites and the CCR for an Illinois Mine Fire

Day	(H/C)m	CCR lbs/min	CO2 %	O2 %	CH4 %	CO ppm	H2 ppm	N2 %	Ar %
1.50	0.89	11.41	1.91	18.48	0.44	1774	176	78.03	0.93
1.50	0.86	10.99	1.95	18.44	0.49	1673	334	77.95	0.88
1.56	0.78	11.39	2.35	17.97	0.59	1999	219	77.93	0.93
1.59	0.99	15.57	2.24	17.97	0.57	1738	195	77.86	0.93
1.70	1.28	44.17	4.50	14.79	1.26	3030	264	78.17	0.93
1.74	1.33	52.50	5.00	13.94	1.46	4141	13	78.09	0.93
1.76	1.34	56.18	5.28	13.57	1.57	4332	138	78.21	0.90
1.76	1.38	60.38	5.49	13.20	1.63	4532	175	78.12	0.90
1.84	1.31	55.24	5.50	13.39	1.67	3389	290	78.12	0.93
1.86	1.03	43.73	5.87	13.14	1.83	4523	252	77.75	0.93
1.88	0.99	36.56	5.21	14.04	1.62	3993	279	77.64	0.93
1.91	1.01	36.50	5.08	14.21	1.60	3805	280	77.71	0.93
1.93	1.11	37.95	4.67	14.67	1.43	3447	105	77.89	0.93
1.95	1.09	40.44	5.05	14.19	1.54	3766	122	77.93	0.93
1.97	1.16	42.71	4.91	14.27	1.58	3572	186	77.84	0.93
2.07	1.40	50.87	4.63	14.44	1.52	3224	110	78.11	0.93
2.07	1.44	58.43	5.12	13.71	1.69	3582	216	78.15	0.93
2.30	1.65	88.06	6.42	11.48	2.51	4830	751	78.07	0.93
2.38	1.36	63.21	5.97	12.58	2.24	3618	244	77.80	0.93
2.36	1.43	75.70	6.67	11.48	2.54	4343	211	77.87	0.93
2.42	1.04	43.08	6.12	13.07	1.89	1557	238	77.84	0.89
2.49	1.07	41.39	5.39	13.71	2.11	3120	148	77.45	0.92

Again, using the value of $(H/C)_r = .3$ and utilizing the data in Table 1 and Equation (2), the CCR is calculated. The resultant values in pounds per minute (lbs/min) are shown in Column 3 of Table 1.

A graphical representation of the coal combustion rates as a function of time for this mine fire is shown in Figure 2.

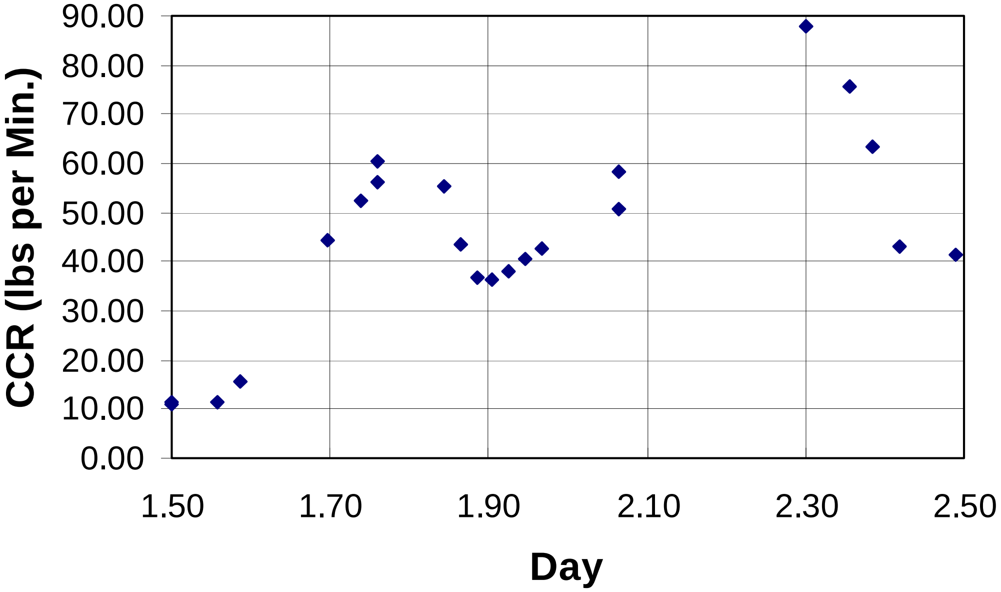

FIGURE 2. - CCR as a Function of Time for an Illinois Mine Fire

As can be seen, the pounds of coal consumed per minute varied between Day 1.50 and Day 2.50. The graph begins with a CCR of 10 lbs/min rising to 60 lbs/min in less than 6 hours. A minimum of 40 lbs/min is reached at Day 1.90 rising to a maximum of 90 lbs/min in less than 10 hours. The varying nature of the graph is probably characteristic of the beginning of most mine fires.

CONCLUSIONS

The author has presented a method for estimating the pounds of coal per minute during a mine fire termed the coal combustion rate, CCR. Its derivation from basic combustion principles was given along with two examples for its application. Conditions for its use were delineated.

Appendix I: Derivation of the Coal Combustion Rate, CCR

Consider a movement of air, of known flow rate, flowing through and feeding a coal combustion process. For this system the carbon and hydrogen gram atom balance can be represented as:

$$[C]_f = [C]_s + [C]_r \tag{4}$$

$$[H]_f = [H]_s + [H]_{H_2O} + [H]_r \tag{5}$$

where:

$[C]_f$ = gram atoms of carbon, per minute, consumed in the fuel.

$[C]_s$ = gram atoms of carbon, per minute, in the products formed as measured in the gas analysis suite.

$[C]_r$ = gram atoms of carbon, per minute, in the remaining char/tar.

$[H]_f$ = gram atoms of hydrogen, per minute, consumed in the fuel.

$[H]_s$ = gram atoms of hydrogen, per minute, in the products formed as measured in the gas analysis suite.

$[H]_{H2O}$ = gram atoms of hydrogen, per minute, in the generated water.

$[H]_r$ = gram atoms of hydrogen, per minute, in the remaining char/tar.

Hydrogen to carbon ratios describing the combustion process can be defined as follows:

$$\left(\frac{H}{C}\right)_f = \frac{[H]_f}{[C]_f} \qquad \textbf{(6)}$$

$$\left(\frac{H}{C}\right)_s = \frac{[H]_s + [H]_{H_2O}}{[C]_s} \qquad \textbf{(7)}$$

$$\left(\frac{H}{C}\right)_r = \frac{[H]_r}{[C]_r} \qquad \textbf{(8)}$$

Where:

$(H/C)_f$ = equivalent hydrogen-to-carbon ratio of the fuel (available from ultimate analysis data of the fuel).

$(H/C)_r$ = equivalent hydrogen-to-carbon ratio of the residual char/tar (available from ultimate analysis data of the residual product).

$(H/C)_s$ = hydrogen-to-carbon ratio as calculated from the gas analysis suite.

Equation (5) can be rewritten, using the defined hydrogen-to-carbon ratios, as:

$$[C]_f \left(\frac{H}{C}\right)_f = [C]_s \left(\frac{H}{C}\right)_s + [C]_r \left(\frac{H}{C}\right)_r \tag{9}$$

Solving Equation (4) for $[C]_r$ and substituting into Equation (9), we obtain an expression for the gram atoms of carbon per minute, consumed in the fire.

$$[C]_f = [C]_s \left[\frac{(H/C)_s - (H/C)_r}{(H/C)_f - (H/C)_r}\right] \tag{10}$$

Equation (10) can be rewritten as:

$$[C]_f = \left[[C]_{CO_2} + [C]_{CO} + [C]_{CH_4}\right]\left[\frac{(H/C)_s - (H/C)_r}{(H/C)_f - (H/C)_r}\right] \tag{11}$$

Where:

$[C]_{CO2}$, $[C]_{CO}$, and $[C]_{CH4}$ are the gram atoms of carbon, per minute, in the products CO_2, CO, and CH_4, respectively; or the gram moles of CO_2, CO, and CH_4 formed per minute.

They can be related to the percent of CO_2, CO, and CH_4 reported in the gas analysis suite by noting that:

$$[C]_{CO_2} = \frac{\%CO_2}{100}FR \quad ; \quad [C]_{CO} = \frac{\%CO}{100}FR \quad ; \quad [C]_{CH_4} = \frac{\%CH_4}{100}FR \qquad \textbf{(12a,b,c)}$$

Where:

$\%CO_2$ = Percent carbon dioxide as reported in the gas analysis suite.

$\%CO$ = Percent carbon monoxide as reported in the gas analysis suite.

$\%CH_4$ = Percent methane as reported in the gas analysis suite.

FR = Flow rate of effluent in gram moles per minute.

The concentration of methane reported in the gas analysis suite is composed of methane generated in the fire, $\%CH_4$(fire), and seam gas methane, $\%CH_4$(seam), i.e.

$$\%CH_4 = \%CH_4(fire) + \%CH_4(seam) \qquad \textbf{(13)}$$

In gassy mines, the methane from the seam is usually much larger than the methane generated in the fire. It acts as diluent in the complement of collected gases and, as such, must be eliminated from the gas analysis suite before meaningful calculations can be made.

An estimation of the amount of methane generated from coal combustion was obtained from the Bruceton Coal Mine Explosion data[6,7]. There, it can be seen that the methane generated in the coal combustion is about one-third of the carbon monoxide generated, or:

$$\frac{\% \, CH_{4(fire)}}{\% \, CO} = .3 \tag{14}$$

Using this ratio, the gas analysis suite can be corrected for the methane seam gas dilution. So that:

$$[C]_{CO_2} = \frac{\% \, CO_2}{100 + .3\% \, CO - \% \, CH_4} FR \approx \frac{\% \, CO_2}{100 - \% \, CH_4} FR \tag{15}$$

$$[C]_{CO} = \frac{\% \, CO}{100 + .3\% \, CO - \% \, CH_4} FR \approx \frac{\% \, CO}{100 - \% \, CH_4} FR \tag{16}$$

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[6] Rice, G. S., L. M. Jones, et. al. “Coal Dust Explosion Tests in the Experimental Mine,” Department of the Interior, United States Bureau of Mines, Bulletin 167, 1922.

[7] Rice, G. S., J. W. Paul, and H. P. Greenwald. “Coal Dust Explosions in the Experimental Mine,” Department of the Interior, United States Bureau of Mines, Bulletin 268, 1927.

$$[C]_{CH_4} = \frac{.3\,\%CO}{100 + .3\,\%CO - \%CH_4}FR \approx \frac{.3\,\%CO}{100 - \%CH_4}FR \qquad \textbf{(17)}$$

Using these values in Equation (11), we get:

$$[C]_f = \frac{\%CO_2 + 1.3\,\%CO}{100 - \%CH_4}\left[\frac{\left(\frac{H}{C}\right)_s - \left(\frac{H}{C}\right)_r}{\left(\frac{H}{C}\right)_f - \left(\frac{H}{C}\right)_r}\right]FR \qquad \textbf{(18)}$$

The mass of the coal consumed per minute is equal to the mass of carbon consumed per minute, $12[C]_f$, divided by the fraction of carbon in the coal, (M_c/M_{total}). Thus:

$$\frac{\Delta M_{fuel}}{\Delta t} = \frac{12[C]_f}{\left(\frac{M_c}{M_{total}}\right)} = 12[C]_f\frac{M_{total}}{M_c} \qquad \textbf{(19)}$$

Where:

$\Delta M_{fuel}/\Delta t$ = Grams of fuel consumed per min.

M_{total}/M_c = Ratio of the total mass of coal to the mass of carbon in the coal as obtained from the ultimate analysis

$12[C]_f$ = Mass of carbon in the fuel that was consumed (grams/minute)

Using Equation (18) in Equation (19):

$$\frac{\Delta M_{fuel}}{\Delta t} = \left(12\frac{M_{total}}{M_c}\right)\left(\frac{\%CO_2 + 1.3\%CO}{100 - \%CH_4}\right)\left[\frac{\left(\frac{H}{C}\right)_s - \left(\frac{H}{C}\right)_r}{\left(\frac{H}{C}\right)_f - \left(\frac{H}{C}\right)_r}\right]FR \qquad \textbf{(20)}$$

Noting that:

1 mole per min = .7911 CFM

1 lb = 454 grams

Equation (20) can be written as:

$$CCR = .021\left(\frac{M_{total}}{M_c}\right)\left(\frac{\%CO_2 + 1.3\%CO}{100 - \%CH_4}\right)\left[\frac{\left(\frac{H}{C}\right)_s - \left(\frac{H}{C}\right)_r}{\left(\frac{H}{C}\right)_f - \left(\frac{H}{C}\right)_r}\right]FR \qquad \textbf{(21)}$$

Where now:

CCR = Coal Combustion Rate (lbs./min.)

FR = Flow rate in CFM

The equivalent formulation for the fuel and the residual products is given in a previous publication[8] as:

$$\left(\frac{H}{C}\right)_f = \frac{[h]_f - 2[o]_f - .54\ [n]_f + 4[s]_f}{[c]_f} \tag{22}$$

$$\left(\frac{H}{C}\right)_r = \frac{[h]_r - 2[o]_r - .54\ [n]_r + 4[s]_r}{[c]_r} \tag{23}$$

where:

$[c]_f$, $[h]_f$, $[o]_f$, $[n]_f$, $[s]_f$ and $[c]_r$,$[h]_r$,$[o]_r$,$[n]_r$,$[s]_r$ are the gram atoms of the various elements, as obtained from the ultimate analysis, for the fuel and the residual char/tar products, respectively.

And, as reported in another publication[9]:

$$\left(\frac{H}{C}\right)_s = \frac{1.073\ \%N_2 - 4\%O_2 - 4\%CO_2 - 2\%CO + 2\%H_2 + 2\%C_2H_2 + 4\%C_2H_4}{\%CO_2 + \%CO + 2\%C_2H_2 + 2\%C_2H_4} \tag{24}$$

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[8] Hofer, L. J. E., D. A. Giardino, and L. F. Zeiler. "The Evaluation of Gases From Mine Explosions by Elemental Balancing," MSHA Informational Report 1231, 1996.

[9] Hofer, L. J. E. and D. A. Giardino. "A Method for the Unambiguous Determination of the Fuel Composition from Combustion Gases," <u>Fuel</u>, Vol. 69, June 1990, pp. 716-719.

APPENDIX II. - Ultimate Analyses for Various Coals

TABLE A1. - Ultimate Analysis Data for Various Coals
(Sample = 100 grams)

STATE/COUNTRY COUNTY AND/OR BED	ULTIMATE ANALYSIS BY WEIGHT (grams)							
	M_H	M_C	M_N	M_O	M_S	M_{TOTAL}	$(H/C)_f$*	$\frac{M_{total}}{M_c}$
Alabama, Bibb Co.[1]	5.31	78.33	1.40	7.58	1.21	93.83	0.68	1.20
Alabama, Blue Creek Seam[2]	4.45	81.95	1.69	4.31	0.53	92.93	0.57	1.13
Alabama, Jagger Bed[3]	5.20	69.60	1.60	12.10	0.80	89.30	0.64	1.28
Alabama, Jefferson Co.[10]	4.74	81.73	1.50	6.54	0.70	95.21	0.58	1.16
Alabama, Mary Seam[10]	4.72	82.19	1.68	3.54	0.62	92.75	0.62	1.13
Alabama, Shelby Co.[10]	5.20	75.00	1.00	10.00	0.80	92.00	0.64	1.23
Alaska, Moose Creek Co.[10]	5.30	67.60	1.90	15.90	0.30	91.00	0.58	1.35
Arkansas, Hartford Co.[10]	4.10	77.40	1.60	5.30	1.10	89.50	0.54	1.16
Arkansas, Huntington Co.[10]	4.40	78.70	1.60	4.40	1.90	91.00	0.61	1.16
Arkansas, Pope Co.[10]	3.62	80.30	1.47	3.59	1.74	90.72	0.50	1.13

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[1] Handbook of Chemistry, Tenth Edition, McGraw-Hill Book Co., Inc., 1961.

[2] Private communications, Geochemical Testing Report C12099, 10/09/83.

[3] See Footnote (7), Bureau of Mines Bulletin 268.

TABLE A1. - Ultimate Analysis Data for Various Coals
(Sample = 100 grams)

STATE/COUNTRY COUNTY AND/OR BED	ULTIMATE ANALYSIS BY WEIGHT (grams)							
	M_H	M_C	M_N	M_O	M_S	M_{TOTAL}	$(H/C)_f$*	$\frac{M_{total}}{M_c}$
British Columbia, Vancouver[4]	5.01	69.03	1.16	12.57	0.96	88.73	0.60	1.29
Colorado, Argo Bed[12]	5.80	69.40	1.50	18.70	0.40	95.80	0.59	1.38
Colorado, Gunnison Co.[10]	3.28	85.40	1.12	3.59	0.80	94.19	0.41	1.10
Colorado, Gunnison Co.[10]	5.50	70.60	1.50	12.70	0.40	90.70	0.66	1.28
Colorado, Wadge Bed[12]	5.80	65.30	1.60	21.30	0.40	94.40	0.57	1.45
Illinois, Christian Co.[10]	5.60	59.80	1.10	19.10	3.70	89.30	0.73	1.49
Illinois, Franklin Co.[10]	5.40	69.00	1.60	15.00	1.00	92.00	0.62	1.33
Illinois, No. 6 Bed[13]	5.34	66.23	1.51	17.54	0.75	91.37	0.57	1.38
Illinois, Williamson Co.[10]	5.20	67.10	1.50	16.70	0.90	91.40	0.57	1.36
Indiana, Green Co.[10]	5.80	64.50	1.50	19.80	1.10	92.70	0.63	1.44
Indiana, Knox Co.[10]	5.50	62.30	1.00	17.10	3.20	89.10	0.72	1.43
Indiana, No. 5 Bed[13]	5.77	63.77	1.10	15.64	3.36	89.64	0.78	1.41
Indiana, Sullivan Co.[10]	5.90	63.80	1.40	20.90	1.30	93.30	0.64	1.46
Iowa, Lucas Co.[10]	5.70	55.80	1.10	21.50	3.20	87.30	0.72	1.56
Iowa, Polk Co.[10]	5.50	54.70	0.80	18.80	6.20	86.00	0.85	1.57

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[4] See Footnote (6), Bureau of Mines Bulletin 167.

TABLE A1. - Ultimate Analysis Data for Various Coals
(Sample = 100 grams)

STATE/COUNTRY COUNTY AND/OR BED	ULTIMATE ANALYSIS BY WEIGHT (grams)							
	M_H	M_C	M_N	M_O	M_S	M_{TOTAL}	$(H/C)_f$*	$\frac{M_{total}}{M_c}$
Kansas, Cherokee Co.[10]	5.20	71.80	1.20	10.20	3.30	91.70	0.72	1.28
Kansas, Crawford Co.[10]	4.90	68.80	1.20	8.70	4.60	88.20	0.76	1.28
Kentucky, Keokee Bed[13]	5.56	80.94	1.52	9.11	0.52	97.65	0.65	1.21
Kentucky, Webster Co.[10]	5.10	70.40	1.60	12.60	1.10	90.80	0.61	1.29
Maryland, Allegany Co.[10]	4.30	76.90	1.90	4.90	1.10	89.10	0.59	1.16
Maryland, Allegany Co.[10]	4.50	81.00	1.90	4.00	1.00	92.40	0.60	1.14
Montana, No. 4 Bed[13]	5.25	59.25	1.28	21.37	1.00	88.15	0.53	1.49
New Mexico, No. 5 Bed[12]	5.90	62.00	1.00	22.70	0.50	92.10	0.59	1.49
New Mexico, Raton Bed[12]	5.40	70.80	1.40	8.20	0.70	86.50	0.74	1.22
Ohio, Columbiana Co.[10]	5.20	69.90	1.40	8.30	4.30	89.10	0.80	1.27
Ohio, Jefferson Co.[10]	5.20	69.70	1.40	8.00	5.10	89.40	0.82	1.28
Oklahoma, Coal Co.[10]	5.00	62.80	1.50	14.50	4.30	88.10	0.70	1.40
Oklahoma, Pittsburg Co.[10]	5.40	73.80	1.80	9.60	1.70	92.30	0.71	1.25
Pennsylvania, Allegheny Co., Upper Freeport Bed[10]	5.10	70.30	1.20	8.10	2.20	86.90	0.74	1.24
Pennsylvania, Armstrong Co.[10]	5.30	71.40	1.30	9.10	3.10	90.20	0.76	1.26
Pennsylvania, Armstrong Co.[10]	4.50	56.90	1.10	5.60	3.70	71.80	0.89	1.26

TABLE A1. - Ultimate Analysis Data for Various Coals
(Sample = 100 grams)

STATE/COUNTRY COUNTY AND/OR BED	ULTIMATE ANALYSIS BY WEIGHT (grams)							
	M_H	M_C	M_N	M_O	M_S	M_{TOTAL}	$(H/C)_f$*	$\frac{M_{total}}{M_c}$
Pennsylvania, Bedford Co.[10]	4.10	77.40	1.40	3.40	1.00	87.30	0.58	1.13
Pennsylvania, East Bed[13]	4.73	80.66	1.42	5.02	1.77	93.60	0.63	1.16
Pennsylvania, Freeport Bed[13]	4.79	76.24	1.45	4.33	2.57	89.38	0.70	1.17
Pennsylvania, Jefferson Co.[10]	5.10	76.60	1.20	7.20	2.00	92.10	0.69	1.20
Pennsylvania, Lower Kittanning Bed[13]	4.40	81.72	1.31	5.41	1.02	93.86	0.55	1.15
Pennsylvania, Miller Bed[13]	4.71	76.69	1.31	4.67	3.09	90.47	0.69	1.18
Pennsylvania, Pittsburgh Bed[13]	5.29	75.78	1.53	9.18	1.53	93.31	0.67	1.23
Pennsylvania, Somerset Co.[10]	4.30	78.50	1.20	4.50	2.50	91.00	0.61	1.16
Pennsylvania, Sullivan Co.[10]	3.64	77.90	0.95	5.07	0.81	88.37	0.47	1.13
Pennsylvania, Washington Co., Pittsburgh Bed[10]	4.80	74.40	1.50	7.90	2.20	90.80	0.65	1.22
Rhode Island, Providence Co.[10]	0.50	82.40	0.10	1.80	0.90	85.70	0.06	1.04
Texas, Webb Co.[10]	5.80	59.30	1.20	12.70	2.10	81.10	0.90	1.37
Virginia, Montgomery Co.[10]	3.60	75.30	0.90	4.80	0.50	85.10	0.48	1.13
Virginia, Tazwell Co.[10]	4.70	84.00	1.20	5.20	0.50	95.60	0.58	1.14
Virginia, Wise Co.[10]	5.10	73.70	1.60	8.80	0.90	90.10	0.66	1.22
Washington, Kittitas Co.[10]	5.50	61.30	1.50	14.40	1.40	84.10	0.75	1.37

TABLE A1. - Ultimate Analysis Data for Various Coals
(Sample = 100 grams)

STATE/COUNTRY COUNTY AND/OR BED	ULTIMATE ANALYSIS BY WEIGHT (grams)							
	M_H	M_C	M_N	M_O	M_S	M_{TOTAL}	$(H/C)_f$*	$\frac{M_{total}}{M_c}$
West Virginia, Beckley Bed[13]	4.41	82.67	1.47	4.19	0.79	93.53	0.57	1.13
West Virginia, Brook Co.[10]	5.30	72.10	1.40	10.50	2.60	91.90	0.71	1.27
West Virginia, Fayette Co., Eagle or No. 1 Gas Bed[10]	5.20	81.70	1.50	6.50	0.70	95.60	0.65	1.17
West Virginia, Fayette Co., Fire Creek Bed[10]	5.00	82.40	1.50	5.70	0.70	95.30	0.63	1.16
West Virginia, Fayette Co., No. 2 Gas Bed[10]	5.30	79.70	1.40	7.70	0.80	94.90	0.66	1.19
West Virginia, Fayette Co., Sewell Bed[10]	5.00	82.50	1.50	7.00	0.50	96.50	0.60	1.17
West Virginia, Fire Creek Bed[13]	4.84	81.25	1.58	4.64	0.86	93.17	0.63	1.15
West Virginia, Logan Co., Island Creek Bed[10]	5.10	76.70	1.30	8.90	1.30	93.30	0.64	1.22
West Virginia, McDowell Co., Pocahontas No. 3 Bed[10]	4.70	82.90	1.10	4.80	0.50	94.00	0.60	1.13
West Virginia, Sewell Bed[13]	5.09	82.59	1.63	7.26	0.52	97.09	0.60	1.18
West Virginia, War Creek Bed[12]	4.40	78.90	1.30	3.90	0.70	89.20	0.60	1.13
Wyoming, No. 1 Bed[12]	5.60	63.90	1.40	22.40	0.80	94.10	0.53	1.47
Wyoming, Owl Creek Bed[13]	5.55	58.60	1.29	26.64	0.65	92.73	0.45	1.58

*: $(H/C)_f = [M_H - 2(M_O/16) - .54(M_N/14) + 4(M_S/32)]/(M_C/12)$