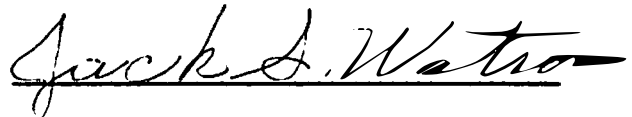


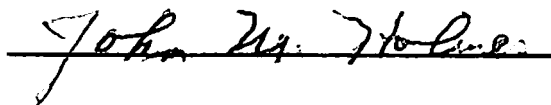
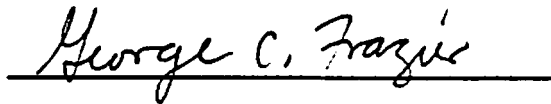
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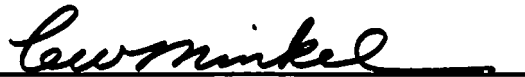


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Date May, 1989

**Heat Transfer Model and Computer Program
for a
Direct-Fired Rotary Kiln**

**A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville**

Steven J. Kirsliis

August 1989

ACKNOWLEDGMENTS

It is essential to recognize the outstanding assistance from my major professor, Dr. Jack S. Watson, and my father for their patience and tireless review of this thesis. Their ardent support and encouragement merits my lasting gratitude. I also wish to thank Jeff Fleming and Dave Pitts of IT Corporation for their contributions in the model development.

ABSTRACT

An improved heat transfer model has been developed for a direct-fired rotary kiln. The model can be used to verify kiln design, to optimize operating conditions, to predict the temperature history of the solids, and to evaluate if local areas of the kiln will be overheated. The treatment of radiant heat transfer was based on the Reflection Method developed by Succes and applied by Gorog, and was extended to account for radiation from a flame. Some elements of the Resistive Network Method and Zone Method were incorporated in the model. This method results in a more straightforward and flexible treatment of radiant heat transfer than other methods of analysis. The model also accounts for conductive and convective heat transfer within the kiln and heat conducted through the kiln wall and lost from the outer kiln shell to the ambient surroundings.

The model divides the kiln into a flame region where the flame is present, plus a downstream gas region. The flame and gas regions are each subdivided longitudinally into kiln sections of equal length. A new method was devised to model the grey body emissivity of an axially centered flame of given area. It was treated as equivalent to a black body of reduced area. This treatment greatly simplified the calculation of radiant heat transfer to and from the flame. A method was devised for calculating the gas transmissivity for its own radiation in the Reflection Method. The model also includes an approximate treatment of the recirculation and entrainment of combustion gas in the flame region, and assumes plug flow

downstream of the flame region. A regression method was developed for calculating the emissivity of combustion gases of varying CO_2 and H_2O concentrations based on Hottel's real gas data. The temperature and heat transferred to or from the flame, gas, wall, and solid bed in each axial section of the kiln is calculated using the Reflection Method by simultaneously solving a set of algebraic expressions involving the emissivity, area, and radiative (geometrical) view factors for the various surfaces in the kiln. The model was verified with a computer program written in LOTUS 1-2-3 using a set of operating data from a direct-fired kiln used for the incineration of lightly contaminated soil. The model yielded good agreement between the calculated and reported values of the solid and gas exit temperatures as shown in Fig. 8.1-1 and Table 8.1-1. The percent error for the estimated solids exit temperature was 6.8 and for the gas was -3.2.

The new heat transfer model was also extended to provide an approximate treatment of heat transfer in IDF kilns. The model used two separate heat balances to (1) estimate the heat transferred from burning fuel in the outer gas to the outer surface of the inner shell, and (2) the heat transferred through the inner shell and radiated to the solid bed and inner gas. As with the direct-fired kiln, the kiln was divided into uniform longitudinal sections, each with constant temperatures and surface properties. The use of a constant outer gas temperature is only approximate because of the steep temperature gradient

that exists between the bottom temperature where the fuel combustion occurs and the top temperature where the combustion gases exit. Model calculations for a hypothetical data set (no actual data were available) indicated approximate agreement with vendor reported kiln characteristics and temperature profiles.

This model is the first treatment of heat transfer in an IDF kiln reported in the literature.

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1.0 INTRODUCTION

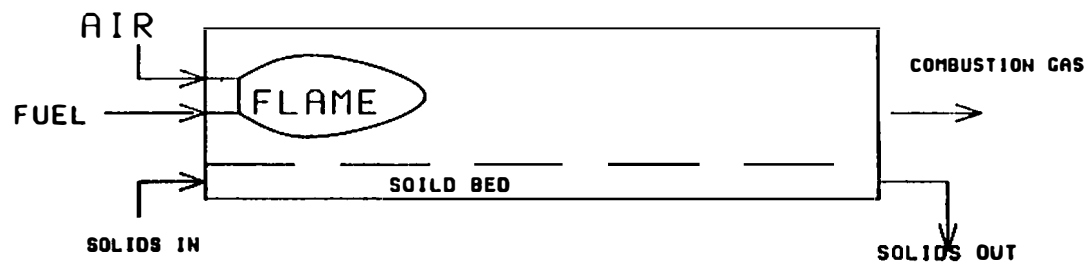
Furnaces are widely used pieces of industrial equipment, and the mathematical modeling of heat transfer to predict the temperature and heat flux distribution in furnaces is of interest to industry for the improvement of furnace design and the selection of operating conditions for better efficiency. Models for heat transfer in direct-fired and indirect-fired rotary kilns, the type commonly used to incinerate hazardous waste, are developed in this thesis. The results calculated using the direct-fired kiln model are compared with experimental data from a small scale actual kiln used to incinerate hazardous waste.

The primary objectives of the thesis are (1) to apply the Reflection Method radiant heat transfer analysis to characterize the various heat flows and mechanisms of heat transfer within a direct-fired kiln and an indirect-fired kiln, and (2) to provide a more complete and realistic model for the direct-fired kilns than published treatments by including in the model a number of additional important effects. These include the effect of a radiating flame within the kiln, the effect of gas recirculation and entrainment, the effect of heat transfer to and through the wall by convection and conduction, heating of the solid bed by convection and conduction, and the effect of using a real gas data base to characterize the radiative heat transfer in the gas phase. The effect of gas circulation and entrainment, and the use of a real gas data base have not been considered in

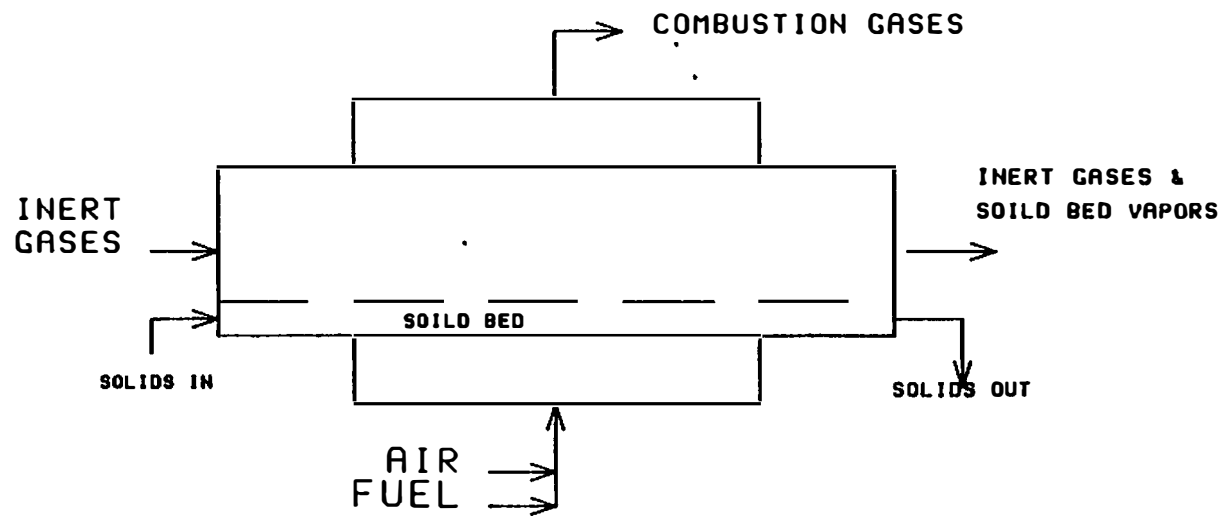
previously published treatments of heat transfer in a direct-fired kiln.

The prediction of the temperature profile within a kiln is needed to ensure proper heat treatment of solids in the kiln and to ensure that local areas of the kiln are not over-heated. Direct-fired kilns are essentially heat exchangers in which solids are heated by hot gases flowing in the freeboard above the bed. Material is fed co-current or counter-current to the gas flow as the kiln rotates. The material moves down the kiln due to a slight angle of inclination of the kiln axis. Indirect-fired kilns have two concentric cylinders between which hot combustion gases are passed to transfer heat to the inner steel cylinder which contains the solid bed. (See Fig. 1.0-1).

At the high temperatures of normal operation in furnaces, radiation is the dominant mode of heat transfer, and a considerable amount of effort has been applied to developing methods of calculating radiant heat transfer. The heat transfer is complex because it involves radiative exchange between the flame, gas, solid bed, and kiln walls as well as convection (solid and gas) and conduction between the solid bed and the wall. The complexity of the heat transfer phenomena encountered in rotary kilns has necessitated the use of a number of simplifying assumptions such as gray gas behavior, simplified geometries, and the neglect of end effects and axial heat transmission.¹⁻¹⁵



A) DIRECT FIRED KILN



B) INDIRECT FIRED KILN

Figure 1.0-1. Direct and Indirect Fired Kilns

2.0 SELECTION OF THE BASIC RADIANT HEAT TRANSFER MODEL

A number of models for analyzing radiant heat transfer in enclosures such as a rotary kiln are described in the literature. The methods of analysis commonly used include the Zone Method⁴, the Flux Method⁵, the Resistive Network Method^{3,8}, and the Reflection Method¹. Each of these approaches are valid for particular types of kilns and are based on the same basic heat transfer equations. However, each method has its drawbacks. The models which use the Zone Method⁴ and the Flux Method⁵ have not included a solid bed in the models. The Resistive Network Method is limited to treating the gas as a 'gray gas'^{3,8}. It is difficult to account for axial heat transmission or kiln end effects in the Reflection Method and the Resistive Network Method. Each of the four methods of analysis will be described in the following portions of this section to indicate the reasons why the Reflection Method was chosen in this thesis as the basic model for radiant heat transfer.

No models for indirect-fired (IDF) kilns have been found in the literature. Modeling IDF kilns is a future area of work to be developed.

2.1 Zone Method of Analysis

The zone method of analysis, developed by Hottel and Cohen¹⁷, is the most complete and theoretically sound mathematical model of radiant heat transfer. The zone method

approximates the non-isothermal enclosure and gas by subdividing the enclosure and gas into surface and volume zones so that each zone is small enough that its temperature and radiative characteristics can be considered to be uniform. A gas volume and its adjacent wall surface may be at different temperatures. An energy balance at steady state is written for each surface and gas zone by equating the 'heat in' to the 'heat out' for each zone. The 'heat in' includes all energy generated in or absorbed by the zone from all the other zones in the kiln. The 'heat out' includes heat transferred to all of the other zones in the kiln. Each radiative interchange is obtained by determining radiative exchange factors for each zone pair combination in the enclosure, taking account of attenuation by intervening gas, and including the effects of reflection within the enclosure. The exchange factors for each zone pair determine the fraction of radiation leaving one surface that is transmitted to the other surface of the pair. For each surface the energy emitted is proportional to the fourth power of the surface temperature.

Total energy balance equations for each zone can then be drawn up, taking account of all forms of energy transfer in the enclosure such as convection of heat due to gas flow, chemical heat release, and net radiative transfer (interchange) with other zones. This leads to a set of simultaneous nonlinear algebraic equations in terms of the temperature of each zone, which on solution yield the temperature profile within the furnace, and this then enables the heat fluxes to be evaluated.

The evaluation of the exchange factors forms an essential part of the zone method of analysis. They are constructed according to the laws of radiation, taking account of the emissivity, absorptivity, and geometry of the radiating media.

To minimize the computational difficulty, the number of zone subdivisions is kept as low as possible. Unavoidably, this results in an approximate representation of a non-isothermal region by the finite number of isothermal subregions. With the availability of still larger computers, the subdivision could be made as fine as necessary to yield the desired accuracy, but the improvements would become progressively less. For some simple geometries, exchange areas have been calculated previously and are available in published tables^{4,5}. Where tabulated data are not available, the exchange areas must be evaluated by numerical integration for each value of adsorption coefficient considered in the gray/clear gas model. To date none of the published zone method models have included a solid bed, presumably because it would involve added computational difficulties. Predictions by the zone method of analysis have been limited to the gas and wall temperature profile for a rotary kiln.

2.2 Flux Method

The basis of most flux methods of analysis is a balance for the flux of radiant energy in a specified direction through an elementary volume, derived on the assumption that the material within the element is optically gray (improved accuracy can be obtained by relaxing this restriction). The method considers a

small elemental volume, or surface element in the furnace enclosure, and, by calculation of the net heat flux to and from that element in one or more directions, generates a total energy balance for that element. This procedure can be repeated for as many elements as required to obtain the desired degree of accuracy.

Differential equations are used to describe the unknown flux densities which are similar in form to those which describe mass, momentum, and energy transfer at a point, and these equations can therefore be combined and solved numerically.

The flux method has been limited in practice to consideration of only two flux directions (radial and axial) and a gray gas. Also, when the Flux Method has been applied to a rotary kiln, a solid bed has not been included in any published application of the method to date. The gases can be modeled as real gases using a gray/clear gas model, but this increases the number of flux components, and greatly increases the calculational difficulty, requiring faster computers. With the advances of computer capabilities, interest in this method may increase.

2.3 Resistive Network Method

The use of network representations to solve enclosure radiation problems was first suggested by Oppenheim.¹⁹ To include radiation in a thermal network involving mainly convection and conduction, it is convenient to define a unit thermal radiative conductance, or radiant-heat-transfer

coefficient, h_r , as follows:

$$\begin{aligned} h_r &= q_r / A_1 (T_1 - T_2) \\ &= \sigma F_{12} (s_1 T_1^4 - s_2 T_2^4) / (T_1 - T_2) \end{aligned} \quad \text{Eqn. 2-3.1}$$

where:

σ = Boltzmann radiation constant

s_1 = emissivity of surface 1

s_2 = emissivity of surface 2

F_{12} = view factor between surface 1 and surface 2

A_1 = radiating surface area upon which F_{12} is based,
sq. ft.

$T_1 - T_2$ = temperature difference between surface 1 and
surface 2, R

h_r = radiant heat transfer coefficient, in Btu/hr sq ft R

q_r = radiant heat flow, Btu/hr

Once a radiant-heat-transfer coefficient has been calculated, it can be used similarly to the conductive and convective heat transfer coefficients because the rate of heat flow is treated as if it is proportional to the first power of the temperature difference, and radiation can be incorporated directly in a thermal network where the temperature difference is the driving potential, as in convection and conduction. From Eqn. 2.3-1, it is clear that the value of h_r varies with the values of T_1 and T_2 , as well as their difference.

If radiation heat transfer is the dominant mode of heat transfer²³, as is common in a rotary kiln, the convective heat

transfer coefficient can be approximated in the following form:

$$h'_{cv} = q_{cv} / A(T_1^4 - T_2^4) ,$$

where the convective heat transferred now is treated as if it depends on the difference of the fourth power of the absolute temperatures. This form is related to the non-radiative coefficient defined by

$$h_{cv} = q_{cv} / A(T_1 - T_2)$$

by the expression,

$$h'_{cv} = h_{cv} / ((T_1^2 + T_2^2)(T_1 + T_2))$$

A conductive heat transfer coefficient for the radiation-dominant case can be defined similarly. The resistive network defined in this manner can incorporate conductance and convection directly in the radiative resistive network.

The resistive elements in the radiative network are functions of the view factor (or angle factor), surface emissivities, and the emissivity and transmissivity of the intervening medium. The resistive network method, unlike the other methods discussed, is only applicable for a gray gas¹⁰ i.e. the emissivity, transmissivity, and absorptivity of the medium are constant fractions of those for black body radiation. Because a real gas containing CO₂ and H₂O emits

and absorbs radiation only at discrete wavelengths, the transmissivity of a real gas for its own radiation frequency (wave length) is much lower than the transmissivity of a real gas for thermal radiation (black body spectrum) from solid surfaces. Therefore when radiation emitted by a real gas is reflected from a surface, the gas reabsorbs more of the reflected radiation, so that only a smaller amount remains after the next reflection from a solid surface. This, of course, assumes that the reflected light has principally the spectrum of the incident light. (The total light leaving the surface will contain both reflected light and emitted light.) However for a gray gas, the transmissivity is much higher (equal to 1 minus the emissivity of the gas) and allows more reflected energy to be transmitted to the solids. For this reason, use of the gray gas assumption in predicting the radiative exchange in rotary kilns may lead to significant errors, even greater than 20 percent¹ if the surface reflectivity exceeds 0.2.

The great advantage of a resistive network model is that it can be easily set up for any number of surfaces in the presence of an isothermal gray absorbing-emitting medium and solved by straightforward matrix algebra. The method solves a system of algebraic equations simultaneously, usually by a matrix inversion technique using a digital computer. The simultaneous system of equations is generally solved for the radiosities of the respective surfaces. Once all the radiosities are obtained, the net radiative heat transfers and temperatures from the n surfaces and the gas are determined. Details of the derivation,

and an explanation of how the network diagram is constructed and the algebraic method used to solve the network is discussed in the literature^{21,22,23}. Brimacombe et al.^{1,2,3,4} have used the resistive network method extensively to model a rotary kiln with a solid bed with fair success, even though axial radiation and end effects from the kiln end surface were neglected. They stated that the predicted maximum flame temperatures, flame lengths and maximum heat fluxes were in broad agreement with the limited industrial data available.

2.4 Reflection Method

In the Reflection Method (Succes¹⁶), the radiation leaving each emitting surface or gas volume element is traced through one or more (diffusive) reflections from the surrounding surfaces which intercept the radiation before final absorption. Account is taken of the energy absorbed from the emitted rays and the reflected rays by the freeboard gas and by the solid surfaces encountered. The net radiant loss for each surface (or gas) is the difference between the total amount of radiant energy emitted from a surface (or gas) and the total amount absorbed by the surface (or gas) from the energy emitted by the gas and other surfaces in the enclosure.

The emitted energy from the kiln wall or solid bed is traced through two reflections and the energy remaining after the second reflection is considered to be distributed between the solids and wall as if they were black bodies. 'Reflection' as used here refers to diffuse reflection (cosine law), rather than

specular reflections (angle dependent). The amount of radiant energy attenuated by the gas for each ray is equal to the difference between the energy initially emitted (or reflected) and that which is transmitted through the gas to either the solid bed or kiln wall.

A real gas adsorbs radiation only within certain discrete wavelengths. Therefore, the gas is clear to other wavelengths, but the radiant energy lying within the wavelength regions where adsorption occurs is rapidly attenuated. For this reason the gas absorbs almost no radiation emitted from the solid surfaces after the second reflection, since all the radiant energy within the adsorption bands has been absorbed previously, i.e. the gas becomes transparent after only two reflections. Also, after two reflections a large percentage of the radiant energy initially emitted by the solid surfaces has been absorbed by the kiln wall, or solid bed, or gas. (The spectral distribution of reflected radiation from a gray or black body is the same as the initial ray from a gray or black body). For these reasons the approximation is permissible that the energy remaining after two reflections is distributed between the kiln wall and solid bed as if they were black bodies. That is, all of the energy of the third reflection from the solid bed is assumed to be absorbed by the wall, whereas the energy of the third reflection from the wall is assumed to be absorbed by the wall and solid bed according to the view factors from the wall to itself and to the bed.

The path of energy emitted by the freeboard gas is traced

through only one additional reflection after the gas-emitted radiation originally hits and is reflected from a solid surface because of the high absorptivity of a real gas for its own radiation. The energy remaining after the second reflection is considered to be completely absorbed by the freeboard gas. An important item in the Gorog and Brimacombe model was the development of a method to calculate the transmissivity of a gas for its own radiation. This method is discussed in detail in Section 4.5.

A radiation balance using the Reflection Method has been developed by Gorog¹ for a rotary kiln modeled as a single well-mixed tank. This simplified treatment does not provide a method for representing temperature profiles nor the variation of other parameters from one end of the kiln to the other. (See Fig. 2.4-1). Based on these assumptions this modified Reflection Method was used to describe the net radiant loss for the freeboard gas, kiln wall and solids. In Gorog's¹ work there was no verification or demonstration of the applicability of the radiative balance by comparison with experimental observation.

2.5 General Description of the Modifications of the Reflection Method Used in the Present Model

The fundamental radiation balance used to model radiative heat transfer in the present work is based on the Reflection Method proposed by Succes^{3,4}. The present work develops a more complete heat transfer model than that developed by Gorog¹. The model includes (1) a flame added to the the radiative balance,

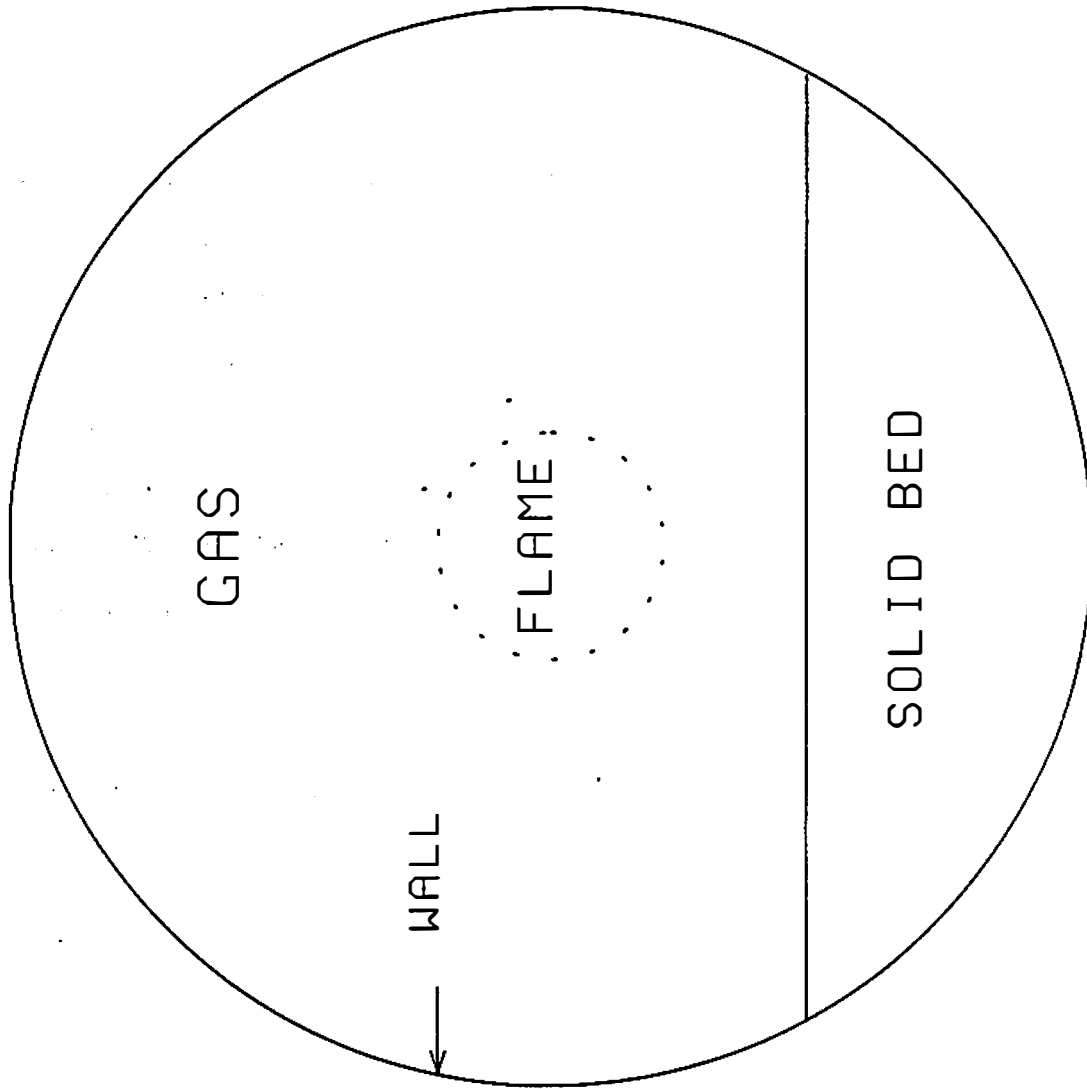


Figure 2.4-1. Kiln Cross Section

(2) a gas flow model which divides the kiln into a flame and gas region, each of which is 'zoned' in sections, (3) recirculation of gases in the flame region, (4) a flame heat release model for a turbulent flame, (5) a method to estimate the emissivity and absorptivity of the kiln gas based on real gas data, (6) a method to estimate the emissivity of the flame, and (7) calculation of the heat transferred by conduction and convection within the kiln and through the kiln wall.

The present work is the first model published in the open literature to (1) include a flame in the radiative balance, (2) use the Reflective Method and divide the kiln into sections, (3) include recirculation of gases in the flame region, and (4) calculate the gas emissivity and absorptivity based on a real gas database. The validity of the model developed is demonstrated using a computer program and verified with a set of experimental data obtained from operation of a direct-fired rotary kiln which included a flame and solid bed.²³

The model developed is for a radiation balance for an enclosure with two gray surfaces (i.e., wall and solid bed) and one black body or axially centered gray body surface (e.g., the flame) with any selected CO_2 and H_2O concentration for the gas in the enclosure. In the present work, the model has been applied to a rotary kiln with the flame as an interior modified black body surface and the solid bed and wall as gray surfaces. The temperature profiles of the three surfaces and the gas determine the flow of heat within the enclosure. All parameters required to calculate the radiation balance are variable inputs

to the program, and can be modified as needed for different geometries, surface properties, and kiln gas compositions.

CO_2 and H_2O are the only gas constituents which are considered to absorb or emit radiation. The flame itself is treated in Section 4.7 as a gray body to account approximately for the presence of 'soot', or ash particles in the flame. (The gray body flame is treated as a black body of reduced area.

Consideration of 'soot' and ash or solid particles in the gas surrounding the flame has been excluded from the model.)

Convective heat transfer from the gas to the two gray surfaces (wall and bed) and conductive heat transfer between the gray surfaces (wall to bed) are considered in the model. Heat loss through the enclosure shell is also estimated for a shell of 3 separate materials. Conduction through these shell layers is considered, as well as convection and radiation from the outer surface of the shell to the ambient surroundings.

Numerous simplifications and assumptions are required in developing a heat transfer model for direct-fired kilns. The combined effect of these simplifying assumptions on the model accuracy is difficult to ascertain. Gorog^{1,2} has quantified the individual error in percent of total radiative exchange (flux) in a rotary kiln resulting from three such assumptions: (1) the neglect of axial radiation resulted in less than a 15% error¹, (2) the assumption of a constant circumferential wall temperature resulted in less than 3% error for the net radiant energy transfer to the solid burden², and (3) the effect of the gray gas approximation led to an error of less than a 20% for

wall and solid emissivities greater than 0.8^1 . The first two assumptions were incorporated in the present work while the gray gas approximation error was avoided in the present model by using a real gas data base to estimate gas emissivities and gas absorptivities.

The errors have not been estimated in the literature for other assumptions such as (1) neglecting recirculation of combustion gases, (2) neglecting kiln end effects, (3) the extent of solid bed mixing (i.e., temperature varying with bed depth), (4) coarseness of kiln zoning, and (5) the effect of postulating that the temperature of each element in each zone (gas, flame, wall, and bed) remain constant in each zone. In actuality the temperatures may vary by 100°K or more from one end of a zone to the other. The cross relations and co-variances of these effects with each other make them difficult to estimate separately. For instance, axial radiation impacts several of these assumptions: kiln end effects, kiln zoning, and recirculation of combustion gases. In a number of cases, some of these effects will partly compensate for each other. Further studies will be required to quantify the effects of all of the assumptions used in this or any similar model.

Experimental data to quantitatively evaluate the heat transfer uncertainty resulting from these assumptions are not available at this time. For the ERRU (Environmental Rapid Response Unit) kiln, the author's crude estimates, based on limited sensitivity calculations, of the effects of these assumptions on model predictions of total heat transfer to the

solid bed are as follows: (1) recirculation of combustion gases, 5 to 10%, (2) kiln end surface effects, less than 5%, (3) extent of solid bed mixing, 10 to 20%, (4) coarseness of section zoning, 5 to 10%, and (5) determination of average temperature within a section, 5 to 20 %. The background and basis for each of these estimates is discussed in the particular section concerned with each of these phenomena.

The influence of recirculation of combustion gases, coarseness of zoning, and definition of the average temperature within a zone for the gas and solid bed are discussed in Section 3.2 and 8.0. An increase in the number of zones would be expected to reduce these effects. The results of the heat transfer analysis with and without recirculation are discussed in detail in Section 8.0.

Axial radiation and end effects also affect the temperature distribution in the flame, the gas surrounding the flame, and the downstream gas. These effects are discussed in Section 4.3. These effects cool the flame and heat the gas and are similar to the effects of recirculation. A study that used the zone method⁴ and included axial radiation and end effects indicated fair agreement with gas and flame temperatures in the flame region compared with experimental data. This study did not include recirculation effects because the author⁴ considered there was little gas recirculation.

The temperature gradient of the gas and solid bed in the flame region is very steep, with a temperature change of several

hundred degrees in each zone. The model selects 'average' effective radiative temperatures of the gas and solids in each zone that are characteristic of heat transfer in that zone. If the heat transfer were based on the exit temperatures of the bed and gas of the previous section, more heat would be transferred to them from the wall and flame than if the calculations were based on the average temperatures of the bed and gas in a section, particularly for the initial sections where the temperature gradient is steep. The steady-state radiative temperatures of the gas and solids in each zone were determined from a trial and error solution. Gas and solids temperatures were estimated such that the heat transferred to the gas (or solids) plus the enthalpy of the entering gas (or solids) corresponded to the temperature estimated. In this calculation, all of the processes affecting heat flow within the zone are considered: combustion, mass flow, radiation, convection, and conduction. No discussion was found in the literature of the basis by which the average temperature within each section is selected.

3.0 MODEL DEVELOPMENT OF THE KILN FLOW PATTERN AND FLAME MODEL

The determination of temperature distribution in a rotary kiln involves the simultaneous solution of three basic problems:

- a) The flow pattern of gases and solids.
- b) Heat release rate by fuel combustion.
- c) Heat transfer to and from the flame, gas, solid bed, and wall.

Rotary kilns of widely varying characteristics are used in industrial operations, and approximate models have been developed to estimate the operating characteristics of particular kiln designs. However, published data on the operating characteristics of rotary kilns which are detailed enough to verify the models are scarce. The particular type of kiln selected to verify the model (a kiln²⁵ with two skewed high intensity oil burners) was chosen because (1) sufficient data were available to verify the model, and (2) this type of kiln is used in several important applications such as incineration of hazardous waste (for example, soils contaminated with dioxin). The kiln modeled had an internal diameter of 4 feet and was 16 feet long. The burner configuration for this kiln produced a short, bushy, turbulent flame, which was observed to have a flame length of about three feet. The general features of the model developed could be applied to kilns of other dimensions, but appropriate modifications would be required to describe other flame types and burner configurations. The model needs information on the particular flame length, flame heat release

rate, flame diameter, solid bed characteristics, and other operating characteristics of the specific kiln studied.

The three major problem areas mentioned above are discussed separately in the following sections for the kiln selected to demonstrate the model. The simpler sub-models developed for treating each of these basic problems are combined in the final complete model.

3.1 Mathematical Model of the Gas Flow Patterns in a Kiln

Previous Work -

Heat flow and temperature distribution in a rotary kiln will be affected by the gas flow patterns in the flame, in the gas region surrounding the flame, and in the gas region downstream of the flame. The complex mass flow equations describing these turbulent flows are difficult to solve analytically in ways which can be incorporated in a heat transfer model. Therefore, most modeling efforts resort to simplifying assumptions for the flow patterns, such as breaking up the kiln volume into a number of well-stirred tanks or assuming that the gases would move in plug flow in some reactor regions. The term 'well-stirred tank' is used to indicate a section of the kiln in which the temperatures of the gas and solid surfaces are constant but not necessarily equal. In the Zone Method (Hottel)¹⁶ and the Resistive Network Method (Brimacombe)^{3, 8}, the volume and surfaces are subdivided into a large number of zones with uniform temperature and concentration within each zone. (See Figs. 3.1-1 and 3.1-2).

A flow model used by Field et al.³⁶ considers the burner region of the kiln as a partially stirred reactor, and the remainder of the kiln is assumed to be operating with plug flow (Fig. 3.1-3). Figures 3.1-1, 3.1-2, and 3.1-3 illustrate the nature of the flow patterns in these models. Other mathematical treatments of flow patterns are discussed in the literature (Hottel¹⁷, Spalding⁴⁹).

Current Work -

The Reflection Method of radiant heat transfer as applied by Gorog¹ makes use of a single well-stirred reactor gas flow model, and average values of the kiln operating variables to predict radiant heat transfer within the kiln. This approach has been modified in the present work to consider the gas flow in the kiln as taking place in a combination of well-stirred reactors with differing temperatures, gas compositions, and gas flows in each. The kiln volume is divided transversely into a flame region, containing the flame surrounded by gas, and a gas region containing no flame (See Fig. 3.1-4).

3.1.1 Selection of Flame Length in the Modeled Kiln

The selected burner configuration and kiln dimensions used in the calculation were taken to be those of the EERU³⁶ kiln.

A model or calculational procedure to predict the flame length for this type of burner configuration is not available in the

	P	Q	R	S	T	
F1	A	B	C	D	E	V
E1	FLAME J	I)	H	GAS G	F	W
D1	K	L	M	N	O	X
	C1	B1	A1	Z	Y	

Figure 3.1-1. Division Zoning for Zone Method

A	B	C	D	E
FLAME	I)		GAS	
		SOLID	BED	

Figure 3.1-2. Division Zoning for Resistive Method

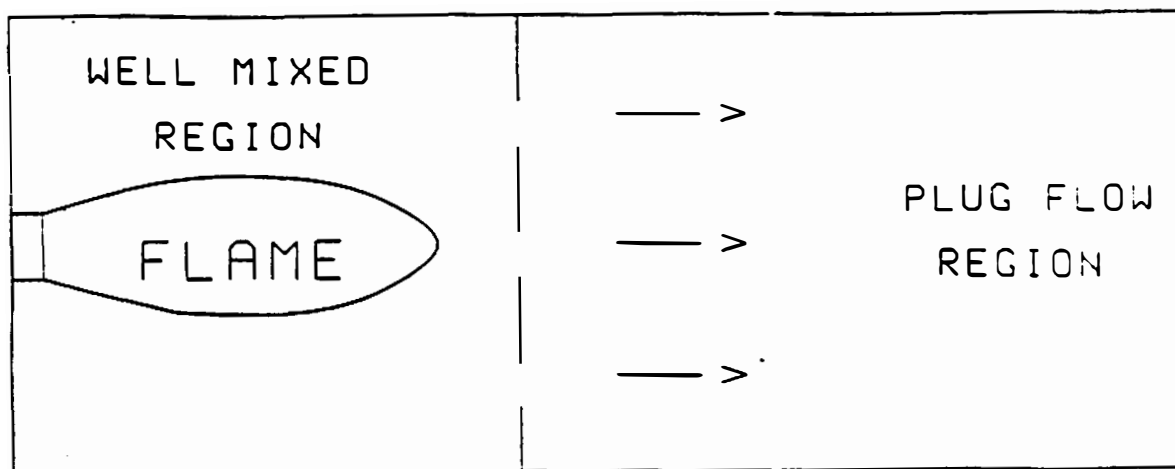


Figure 3.1-3. Partially Stirred Reactor with Plug Flow

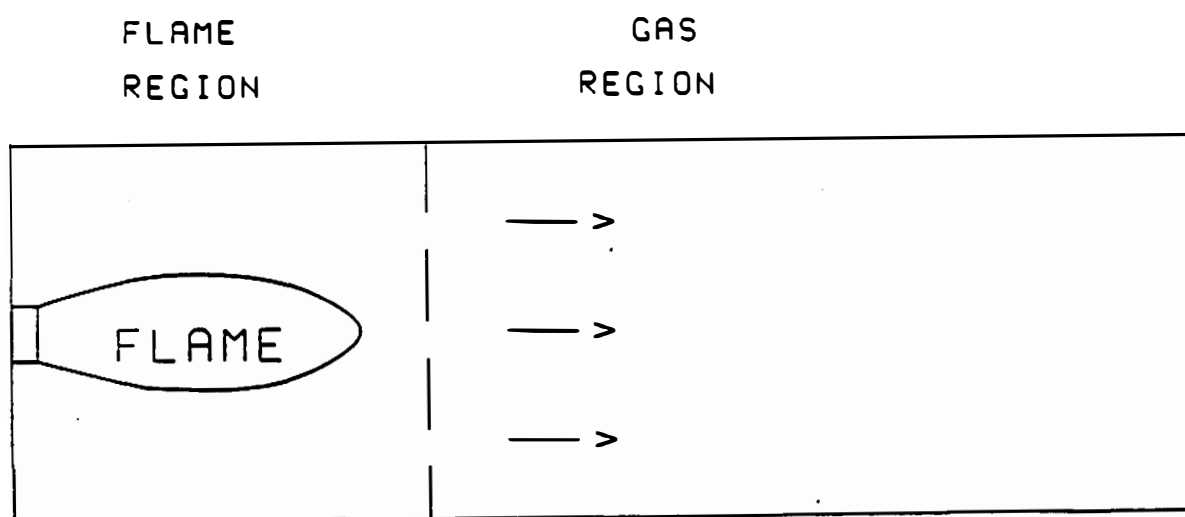


Figure 3.1-4. Flame/Gas region of Direct Fired Kiln

literature. Only procedures for the diffusion type flames observed in large kilns are available¹. The flame in the present model is not a diffusion type flame because of the turbulent mixing induced by the skewed burners and the excess stoichiometric air introduced through the burners. The diffusion flame length models in the literature (for example the work of Thring and Newby^{2,3}) are not applicable for this particular type of burner configuration and kiln operating mode, but they could be used in this model when the appropriate type of burner is used. Their models are based on single axial jet behavior where the length of the flame is controlled by the rate at which air is entrained into the jet stream, resulting in a long slightly divergent flame. It was not possible, therefore, to justify the flame length on the basis of correlations for diffusion flames. The flame length used in the calculation, three feet, was that experimentally observed during the collection of the data set for the EERU kiln (listed in Appendix D).

3.1.2 Selection of Zone Length in Modeled Kiln

The number of well-stirred tank sections used determines the coarseness of the resulting representation of the temperature profile. A larger number of sections is particularly important in regions of steep temperature gradient such as the flame region. However, increasing the number of well-stirred regions beyond two for the flame region significantly increases the calculational difficulties required to determine the temperature

profile in the kiln. These difficulties are compounded for the flame region when the effect of recirculated gases is considered. (See below Section 3.2 - Recirculation and Entrainment of Combustion Gases). The flame region is modeled in this study as a combination of four 'well-stirred reactors'. The flame itself is modeled as an axially symmetrical cylindrical flame which is divided into two well-stirred tanks in series (Fig. 3.1.2-1). The gas in the flame region surrounding the flame is divided into two annular well-stirred tanks. This diagram is explained further in Section 3.2. For the kiln region downstream of the flame, the temperature gradients are less steep and heat transfer results are less sensitive to zone length.

The lengths of stirred tank sections mentioned in the literature (Brimacombe³) are between one and three feet. Brimacombe reported that shortening the section lengths further does not affect the resulting temperature profile significantly. For the present model two 1.5-foot long flame sections were considered sufficient to model the flame, for the reasons given in the following. A single 3-foot long flame section model would not provide a way to describe any temperature gradient in the flame region. Further, the use of two sections to model the flame (1) provides a more realistic temperature of the flame and surrounding gas in the flame region than using one section, and (2) allows the calculation of the effect of recirculated gases to be performed without unreasonable difficulty. Dividing the flame region into more

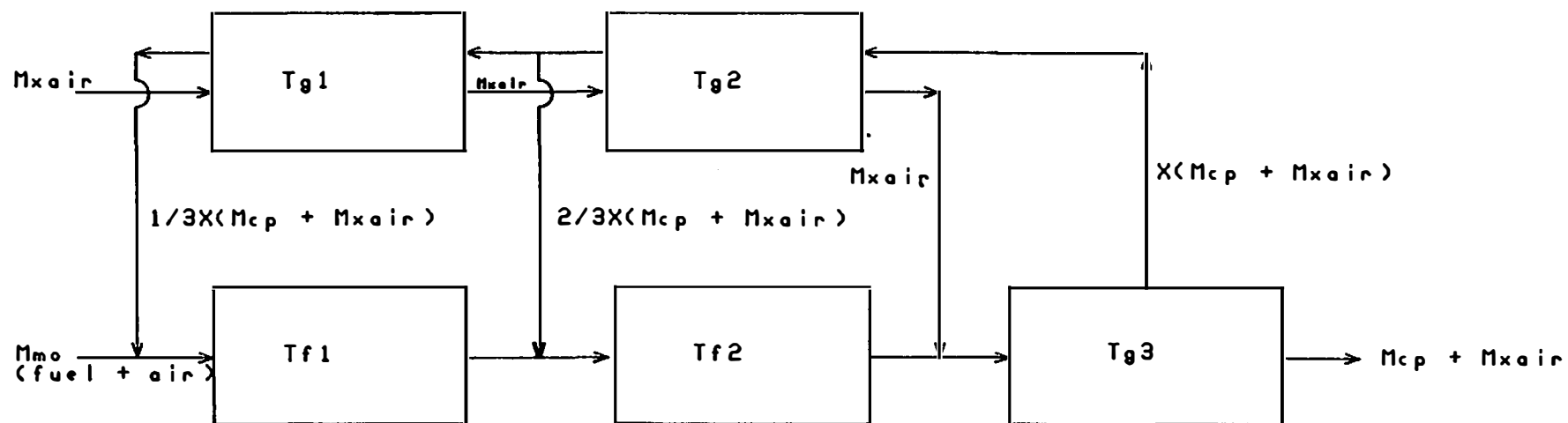


Figure 3.1.2-1. Block Diagram of the Flame Region

than two sections was felt to be unjustified for this short flame of the present kiln model in light of the reported small increase in accuracy, and the associated increased computational difficulties. The present model could be extended to incorporate a larger number of sections in the flame region for kiln designs with longer flames. The Discussion of Results (Section 8.0) compares the temperature distribution resulting when the flame consists of one three foot section with that when it contains two 1.5 foot long sections.

The gas surrounding the flame is also modeled as two well-stirred annular tanks in series. The remainder of the kiln downstream of the flame is considered as the gas region (without a flame present) and is modeled as a series of 'well-stirred tank' sections each 1.5-foot long. In the gas region, the gradient of the temperature profile within the kiln does not change abruptly, and 1.5 foot long sections are considered to be reasonable.

3.2 Recirculation and Entrainment of Combustion Gases

Previous Work -

Recirculation is the reverse flow of fluid from a point in the downstream section of a jet, with re-entrainment of this fluid into the jet nearer the injection source. If additional air is added outside the jet, this gas may also be entrained in the jet. Recirculation and entrainment are important effects to include in the model because they significantly increase the temperature of the gas surrounding the flame (by adding hot

combustion gases from the down stream gas region) and decrease the flame temperature (by the entrainment of the lower temperature gases surrounding the flame) and hence affect heat transfer. The amount of gases entrained is a function of the burner configuration and operating characteristics. The amount of gases recirculated depends on how the air (that required for combustion and any excess air used) enters the kiln. If an adequate supply of secondary air is available to fill the vacuum created by the jet, less recirculation from the jet itself will occur, and recirculation will not be as significant to heat transfer in the kiln.

The effect of gas recirculation has not been treated in heat transfer models for rotary kilns found in the literature survey. Jenkins³⁸ discussed the amount and significance of this phenomenon for some kiln types. For a particular kiln, Jenkins predicted (using the Curtet correlation) a recirculation ratio of 1.87^{38} . However, Jenkins did not incorporate the recirculation results into an overall heat transfer model. For a particular kiln (Johnson³⁴), the amount of recirculation predicted by the Thring and Newby correlation³⁷ and the Curtet, et al., correlation³⁹ was found to be in fair agreement with the experimentally measured value of m_r/m_o (the ratio of mass recirculated to mass fired). The measured value was 1.05, while the Thring and Newby correlation predicted a value of 1.6, and the Curtet, et al. correlation predicted a value of 1.1. A more closely applicable entrainment model for the type burner configuration modeled in these calculations has not been found in the literature.

The basic entrainment correlation has been verified reasonably well in a number of experimental investigations (for example Beer³⁰ or Barchillon and Curtet³¹). More detailed discussion of the equations used to describe entrainment is included in Appendix A. More refined theories of confined jets have been proposed, such as the work of Curtet et al.³², and Becker³³. The literature indicates that a swirl burner increases mixing in the flame region (Neissen)³⁴ even further, and it is expected that the skewed burner configuration would also increase mixing.

Current Model-

The effect of recirculation and entrainment of gases by the flame is addressed in the present work with a simple model, drawing on the work of Thring and Newby. The recirculation/entrainment phenomenon is illustrated above in Fig. 3.1.2-1. This pattern shows that downstream gas is recirculated to the second gas section of the flame region and that part of the second section gas is recirculated to the first gas section. The correlation of Thring and Newby, as modified by Field et al.³⁵ was used to estimate the mass of gas recirculated to and entrained from the surrounding gas. See Fig. 3.2-1. The Thring and Newby correlation states that the jet entrains as a free jet and the entrainment, m_r , (in addition to the initial jet flow, m_0) up to any distance x from the burner nozzle to this point is given by the equation (Eq. 3.2-1):

$$m_r = [0.32(\rho_g/\rho_o)^{1/3}(x-6d_o)/d_o m_0] - m_o \quad \text{Eq. 3.2-1}$$

where ρ_a = density of gas entrained in the jet, lb/ft³

ρ_o = density of jet stream, lb/ft³

m_o = mass fired through the burner lb/hr

m_r = additional flow at distance x due to recirculation
and entrainment

x = distance from the burner nozzle, ft

d_o = burner nozzle diameter, ft

This correlation, based on empirical studies of entrainment for a free jet, indicates that the degree of entrainment by the flame per unit jet length is proportional to the axial distance from a point $6d_o$ downstream of the burner. The $6d_o$ distance is required for the jet to become fully developed. At x/d_o less than 6, the entrainment rate per unit jet length is lower, increasing progressively with distance until it stabilizes at the constant value corresponding to Eq. 3.2-1. Consequently, to account for the lower entrainment rate in the jet region (first flame section) where the distance x from the burner is less than 6 nozzle diameters (24 inches for the EERU flame)^{2f}, the mass of gas entrained by the second section of the flame in the modeled kiln was arbitrarily taken to be twice the mass entrained in the first section of the flame (in place of equal entrainment rates per jet length). This is seen above in the block diagram (Fig. 3.1.2-1) where 1/3 of the recirculated gas is entrained in the first flame section while 2/3 of the recirculated gas is entrained in the second flame section. The resulting flow pattern is shown in the block diagram of Fig. 3.1.2-1. Increasing the recirculated fraction of combustion gases would

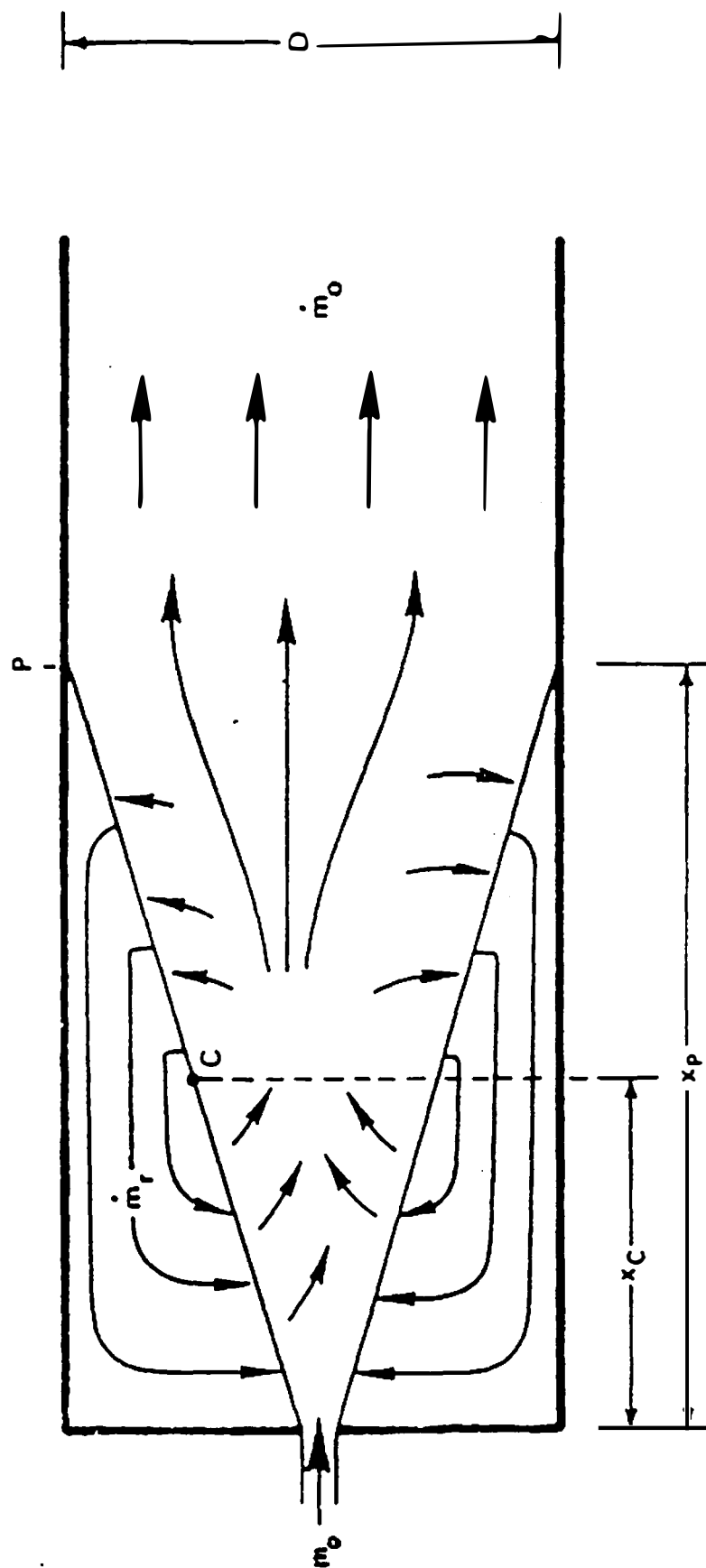


Figure 3.2-1. Gas Recirculation of a Free Axial Jet

effectively increase the mixing in the flame region.

The overall mass balance of the flame region requires that the total mass entering the region (the sum of the excess air and the mass fired through the burner) be equal to the mass leaving the flame region (the mass of the combustion gas products plus the mass of excess air). Expressed mathematically,

$$M_o + M_{\text{xair}} = M_{\text{cp}} + M_{\text{xair}} \quad (\text{Eq.3-2.2})$$

Note also that this equation requires that $M_o = M_{\text{cp}}$, where M_o includes the stoichiometric mass of air required to burn the fuel and M_{cp} includes the mass of nitrogen in the stoichiometric amount of air. If extra air is introduced with M_o , the extra mass is included in M_{cp} . Also, the mass of gas recirculated must be less than or equal to the total mass entrained in the flame, or less this mass for the case with added secondary air.

The effects of recirculation and entrainment can be qualitatively thought of as a partial mixing of the gas surrounding the flame with the flame. The surrounding gas is cooler than the flame. The principal results of considering recirculated gases in the flame region are the increased temperature in the gas surrounding the flame, the decreased temperature in the flame sections of the flame region, and the resultant lowering of the heat transfer in the flame region of the kiln. These effects are discussed further in Section 8.0

(Results and Discussion). Downstream of the flame region, the jet is considered to be completely dissipated and the gas is completely mixed. In this region it is assumed that the gas temperature within each section is uniform.

The application of this model to the present work is approximate in light of the differences between a free jet for which correlations are available and the short turbulent 'bushy' conical-shaped flame used in the kiln modeled. Data from the operation of the ERRU kiln provide no information regarding recirculation nor results which could be compared with the Thring Newby correlation. However it will be shown later (see Section 8.0) that the temperature profile, as indicated by the shell temperatures, is more closely predicted by a model including recirculation. Also, the exit temperature in the solid bed was lower than could be accounted for with a hot flame not cooled by recirculation. The flame region is modeled in the approximate way (shown in Fig. 3.1.2-1) as a combination of four 'well-stirred tank' sections. This model provides an approximation of the entrainment phenomenon. The mass of gas recirculated, $X(M_{op} + M_{cp})$ is allowed to be a variable input in the program, and, as discussed above, 2/3 of this amount is recirculated in the second section and 1/3 in the first section of the flame region.

The correlation of Thring and Newby was modified slightly as discussed in Appendix A in calculating the amount of gas recirculated to make allowance for the broader conical angle of the observed short 'bushy'-shaped flame in the ERRU kiln as

compared to the longer, narrow-angled shape of a diffusion type flame. The use of a wider flame angle results in the flame envelope striking the enclosure wall (where developed flow is assumed to begin) closer to the burner. This results in a shorter distance over which entrainment can occur.

Consequently, less gas is entrained by the shorter flame modeled than would be entrained by a longer diffusion type flame. This modification of the Thring Newby theory is detailed in Appendix A. The modification results in 1/3 as much gas being recirculated as for a longer flame. Using the modified correlation, the mass of gas recirculated was calculated to be 3/4 of the mass of air and fuel fired through the burner. (See Appendix A for details).

3.2.1 Temperature and Composition of Recirculated/Entrained Gases

The gas downstream of the flame region is composed of combustion gases (including the nitrogen content of the combustion air) and excess air. Following the method of Thring Newby³⁷, and Thring³⁴, the downstream (third section) gas of this temperature and composition is recirculated to the second gas section of the flame region. See Fig. 3.1.2-1. The temperature of the gas recirculated to the first gas section is that of the second gas section. These recirculated gases in the first and second gas sections are entrained in the flame.

The initial gas temperature for each gas section was calculated by an enthalpy balance of the secondary excess air

mass flow and recirculated gas mass flow entering and leaving each gas section. The details of this calculation are given in Appendix B. (See Eq. B11 in Appendix B). For each section, this initial temperature was then used in the radiation balance to determine the heat gained by the gas from the flame and wall as the gas reaches its final section temperature. This procedure will be discussed in further detail in the discussion of the program development.

The composition and heat capacity of the gas entrained by the flame were assumed to be those of the recirculated gas. The effect of mixing the secondary air and recirculated gas on the heat capacity of the gas entrained by the flame is considered to be small since the compositions were very similar (primarily nitrogen) and the heat capacities were approximately the same.

Thring and Newby made the assumption that the secondary air is entrained before any recirculated gases are entrained. Their assumption was based on a burner configuration where the secondary excess air was introduced immediately around the burner nozzle. In the present model secondary air was assumed not to be entrained directly into the flame. In the ERRU kiln for which calculations were made³⁶, the secondary air enters in other ways, mainly through leaks around the kiln end seals and feed chute. (The kiln was operated at a negative gauge pressure of about 0.3 to 0.5 inches water to prevent leakage out of the kiln of potentially hazardous gases). The amount of leak air (approximately 65% of the stoichiometric air) was determined by an overall heat and mass balance based on the data obtained from

the ERRU kiln. If cool leak air were entrained directly into the flame, it would cool the flame, and reduce heat transferred to the solid bed.

Further details of the fluid flow model for the flame region are discussed in Appendix A. The enthalpy balance is discussed in more detail in Appendix B.

3.2.2 The Effect of Using a Single Zone for the Flame Section

Recirculation and entrainment in the flame was modeled both for a single (3 foot length) section and for two (1.5 foot length) sections. The recirculation of combustion gases modeled as a single section is a much simpler subset of the block flow diagram (Fig.3.1.2-1 above), and a description is given below in Fig. 3.2.2-1. Except for the number of sections in the flame region, the heat and mass balance calculations were carried out in the same way. The results of the comparison are given in Section 8.0 (Results and Discussion).

3.3 Chemical Reaction and Heat Release

Previous Work -

The combustion process is a chemical reaction. The rate of reaction depends on the concentrations of the the fuel and oxygen, and on flame temperature. The rate of reaction can be controlled either (1) by the rate at which reacting molecules are brought together, 'diffusion controlled combustion' or (2) by 'kinetically controlled combustion', where the reaction rate

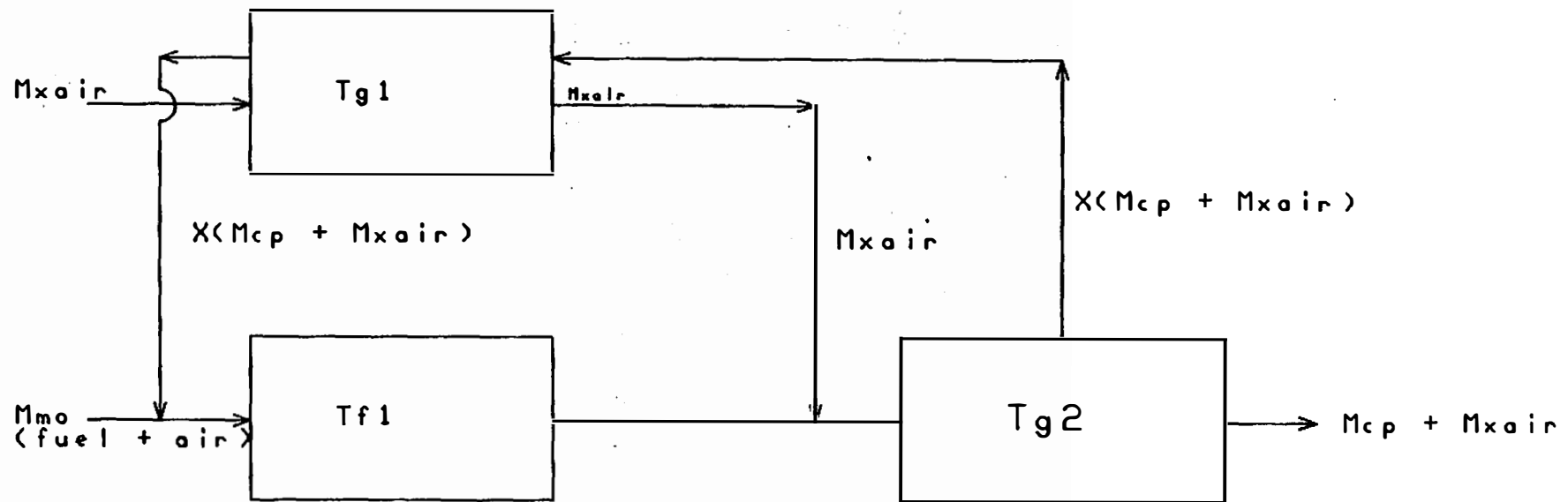


Figure 3.2.2-1. Block Diagram of Single Section Flame Region

is limited by chemical reaction rate constants. Under some circumstances both mechanisms can contribute significantly to the overall rate of reaction.

Diffusion controlled combustion is generally the limiting case for combustion of flames in those kilns where the reaction rate constants are high and the fuel and air react as soon as they are mixed together by turbulent diffusion. Generally, the fuel used in kilns (atomized fuel oil or pulverized coal suspended in 10% to 20% of the stoichiometric amount of air), enters the kiln at a high velocity. For diffusion control, the remaining air required for combustion enters as 'secondary air' at a lower velocity around the burner nozzle. The rate of combustion is then determined by the rate at which the secondary air is entrained into the high velocity fuel jet stream (or flame shell). In this process, the fuel stream is depleted of oxygen, and combustion occurs on the outer edge of the fuel stream. Flames of this type in large kilns can range in length from 10 feet to 60 feet depending on the burner configuration, operating conditions, and firing rate. (See for example Thring³⁴, Brimacombe³, Johnson³⁶, Jenkins³⁶, or Sarofim³⁶).

Kinetically controlled combustion occurs when the rates of mixing are extremely high (or when the fuel has been vaporized and premixed with the air prior to combustion) and the rate of reaction is not limited by the supply of oxygen or the removal of combustion gases, but principally by the rate constant of the chemical reaction. The kiln modeled falls into this category because the fuel stream is well-mixed (due to the burner

configuration) with slightly more than the stoichiometric requirement of air (110%), and hence the rate of burning is not likely to be limited by the supply of oxygen in the fuel stream. Additional secondary air (about 65% of the stoichiometric amount) enters into the kiln (though not through the burner) and contributes to the surplus of air for combustion.

An argument has been made by Williams¹⁷ that a combustion process of the type modeled is not entirely controlled by the kinetic reaction rate because the atomized fuel oil droplets must be evaporated before combustion occurs. Either diffusion of oxygen to the oil droplet or evaporation of the oil droplet could be the rate limiting step in the combustion process.

Similar rate limitations have been studied by Lee, Thring, and Beer¹⁸ for the burnout rate of soot in the later stages of combustion, where the flame has entrained a sufficient amount of air so that combustion is not limited entirely by diffusion of oxygen only. At this later stage of combustion, the relative magnitudes of the reaction rate due to the diffusion rate of oxygen to the soot particle and the kinetic rate of the soot burnout are considered similar¹⁸. However, the short, intense flame observed in the kiln modeled is strong evidence that the combustion was not controlled by diffusion of oxygen into the flame envelope (as in diffusion flames).

Current Model -

Unfortunately, very little information is available in the open literature to model heat release rates in flames of the type used in the particular kiln for which the model was

applied. Most kilns operate with long narrow flames which are under diffusion control, and hence the models used in the literature were developed for these type flames. However, some useful information can be extracted from the following observations on diffusion controlled flames:

1. Several experimental studies have been made or reported which indicate that 80% of the heat is released in the first half of the flame length. (See for example Cross and Young²⁹, Johnson³⁰, Jenkins³¹, and Brimacombe³) This result suggests that the slower reaction in the second half of the flame is primarily the burnout of soot and/or CO formed in the flame, and only in part is the result of combustion of vaporized fuel.

2. There is some short distance (typically up to 6 burner diameters) for diffusion controlled flames before jet stabilization and entrainment of gas occurs (Thring and Newby)³⁷. Combustion is slow or absent until sufficient air is entrained into the fuel jet. In the kiln modeled, the distance before combustion occurred was visually estimated to be a few inches (about one burner diameter), suggesting sufficient mixing of air for almost immediate combustion.

3. Model and experimentally measured temperatures in diffusion flames increased throughout the length of the flame. (See for example Johnson³⁰, Jenkins³¹, Brimacombe³).

As discussed above in the flow model (Section 3.2), the division of the short flame region into two sections instead of one section provides a better description of fluid flow with recirculation for the kiln modeled in this study. To provide a

positive increasing temperature gradient in the flame region, at least a two section flame region is required. From measured temperature profiles in diffusion flames¹, it may be inferred (as discussed below) that (1) with kinetically controlled flames more than half of the combustion reaction also takes place in the first flame region and that (2) the temperature increases throughout the length of the flame.

The first inference is consistent with simple bimolecular reaction rate theory where reaction rates generally vary directly with the product of the concentrations of the reactants. The concentration of fuel in the first section is higher than in the second section, while the oxygen concentration decreases from the first to the second section to a lesser degree due to entrainment. Consequently one would expect more fuel to be burned in the first section. In the second section, the fuel and air have been preheated nearly to the maximum combustion temperature in the first section, and the burning of the remaining fuel served to heat the combustion products to the maximum flame temperature in the second section. It has been observed in the ERRU kiln that the maximum shell temperature is in the vicinity of the second section of the flame (see Fig. 8-1.1 and Appendix D). It is clear that the gas temperature must decrease beyond the flame region since no internal heat is generated but heat continues to be lost from the gas region beyond the flame. But, as discussed below, if too large a fraction of the combustion heat were generated in the second flame section, the relative temperature rise in the

second section predicted by the model would be too large.

The three observations quoted above in this section and the subsequent discussion led to a choice of 70% combusted in the first section. This choice is slightly less than that of diffusion flames discussed in the above observations (observation 1). Sensitivity calculations using the computer model (developed in this thesis) were made which indicated that a value of at least 60% and not more than 80% is required for the model to predict reasonable temperatures, i.e., where the second section is slightly hotter than the first section (observation 3 above).

4.0 DEVELOPMENT OF RADIANT HEAT TRANSFER MODEL

The primary intent of the thesis is to develop and demonstrate the validity of a heat transfer model for a rotary kiln including a number of modifications and improvements over previous models. The initial model is based on the Reflection Method^{3,4} as developed by Gorog and Brimacombe¹. The modifications include the additions of a flame region, and division of both the flame region and the downstream gas region into a number of well-stirred zones to account for axial variation in temperature. The modified model considers convective and conductive modes of heat transfer, as well as radiative heat transfer. Further modifications involve an improved method for treating the emissivity of a flame and the use of a real gas data base to estimate the emissivity and absorptivity of the gas as a function of the solid and gas temperatures.

The overall model is then a set of algebraical equations representing for each kiln zone all of the ways (radiation, convection, and conduction) in which heat is transferred between zone components (gas, solid bed, wall, and flame). In the flame region zone, the heat added by fuel combustion and the effect of gas recirculation on heat transfer are also represented in the algebraical equations. This set of complex equations for the temperature of each component in each zone is solved simultaneously by trial and error. For a particular set of operating conditions (fuel, air, and solid bed feed rate), the solution involves selecting a trial set of component

temperatures for a particular zone, calculating the heat transfer and temperature changes of each component in the zone which determine the entering temperatures in the successive zone. The original set of trial temperatures for a zone are modified until they are consistent with the heat balance and other constraints represented by the set of simultaneous equations.

For example, the wall temperature is selected such that the heat transferred to (absorbed by) the wall is equal to the heat conducted through the wall refractory and lost to the ambient surroundings from the shell. If a different wall temperature were selected, there would not be a balance between the heat transferred from the flame and other kiln components to the wall and the heat transferred through the wall. (See Section 5.1 and 6.1 for further discussion). The gas temperature is selected such that the heat absorbed (or lost) by the gas (composition and mass) is sufficient to raise (or lower) the enthalpy of the gas corresponding to the temperature selected. Similarly, the solid bed temperature is determined in the same fashion as the gas temperature. The flame temperature is specified such that the sum of the flame combustion products and heat transferred from the flame to the gas, wall, and solid bed is equal to the heat released in that zone of the flame. In this way, the temperature of each component in each zone can be simultaneously determined with independent component constraints. For a particular zone for a selected set of trial component temperatures, different sections of the LOTUS 1-2-3 worksheet

simultaneously calculate the heat transferred, the gas emissivity, shell heat loss, and the enthalpy of the gas, flame combustion products, and solid bed.

The radiation, convection, and conduction balances determine the net heat gained or lost from the gas and each surface for a given set of temperatures. The set of gas and surface temperatures selected (by the user) must satisfy the overall balance (Eq. 4.0-1) and any further constraints, such as steady state operation, (including heat transferred by convection and conduction).

The overall balance for the total kiln or any particular zone in the kiln is represented by the following overall heat and mass balance equation:

$$H_{\text{air}} + Q_{\text{comb}} = \Delta H_{\text{gas}} + \Delta H_{\text{solids}} + Q_{\text{shell loss}} \quad (\text{Eq. 4.0-1})$$

where,

H_{air} = enthalpy of the entering combustion gas and excess air

Q_{comb} = heat of combustion of the fuel

ΔH_{gas} = change in enthalpy of the combustion gas and excess air

ΔH_{solids} = enthalpy of the solids

$Q_{\text{shell loss}}$ = heat conducted through the wall and lost from the outer shell

At the steady state kiln conditions, the temperature of all kiln components from the beginning to the end of each zone remain

constant with time. The temperature of each component will make a discontinuous change (step) to the temperature in the next zone which will be determined by the constraints described by the set of simultaneous equations for that zone. Further discussion of steady state constraints for the solid bed, gas, wall and flame are included in Sections 6.1-1, 6.1-2 and 6.1-3.

4.1 Reflection Method of Analysis

The heat transfer model developed uses the Reflection Method (Succes)^{2,4} to predict the heat transferred by radiation within each section of the kiln. The Reflection Method radiation balance, as presented by Gorog¹, treated the entire kiln as one large section with two surfaces (wall and solid bed) and a participating gas, without a flame present.

Radiation is emitted by the solids and gas in accordance with the Stefan-Boltzmann law of radiation which requires that the rate, Q_1 , at which the total radiation is emitted from a surface i at temperature T_1 , is proportional to its surface area, A_1 , surface emissivity, ϵ_1 , and surface temperature T_1 to the fourth power. This relationship is expressed mathematically as follows:

$$Q_1 \text{ emitted} = \sigma A_1 \epsilon_1 T_1^4 \quad (\text{Eq. 4.1-1})$$

where the σ is the Stefan-Boltzmann constant.

In the Reflection Method, the radiation initially emitted by a surface is followed through several (diffuse) reflections from the enclosure surfaces, taking account of the amount of radiation absorbed and reflected by the solid surfaces at each

interception, and of the amount of radiation absorbed by the gas in the enclosure between surface interactions until all the initially emitted radiation has been absorbed. As the method was applied by Gorog¹, the radiation initially emitted by a solid surface was followed through two reflections, after which so little radiation remained that it was considered completely absorbed on its next interaction with a solid surface. The number of reflections which need to be followed, of course, depends upon the absorptivity of the surfaces.

The radiation emitted by the gas, on its initial collision with a solid surface, was partially absorbed and partially reflected. A large part of the reflected radiation was absorbed during passage through the gas, since the absorptivity of the gas for its own (reflected) radiation is high. On the next (second) collision of what remains of this reflected radiation with a solid surface, again it was partially absorbed and partially reflected. So little of the initial gas radiation remained after this reflection that it was considered to be completely absorbed by the gas during its next (second) passage through the gas.

The fraction of radiation which is absorbed by a surface i is determined by its absorptivity, α_i , which for a gray body is equal to its emissivity, ϵ_i . The reflectivity, ρ_i , defines the fraction reflected by an opaque solid, which is equal to $1 - \alpha_i$.

Air containing combustion products emits and absorbs radiation only in particular wavelength bands. Otherwise it is

transparent to radiation. Its absorptivity, α_g (a function of gas composition, radiation wavelength distribution, and temperature), is the fraction of incident radiation absorbed in traversing the gas. The transmissivity, τ_g , the fraction transmitted, is equal to $1-\alpha_g$. The radiation characteristics of the gas are discussed in detail in section 4.5.

When the kiln geometry, governing view factors, and the radiation characteristics of the solid surfaces and of the gas (emissivity, reflectivity, and transmissivity) are specified, equations can be written for each emission and absorption step in the radiation balance. The radiation paths, including reflections with a flame, and the associated equations are discussed in Section 4.2.

This process will be demonstrated in the following sections for a simplified example where the enclosure contained one gas, no flame, and two surfaces (solid bed and wall). The individual emission, absorption, and reflection terms will be developed for the radiation from each of these emission sources. Reflection diagrams for the solid bed surface and gas are shown in Fig. 4.1.4-1 and Fig. 4.1.6-1.

4.1.1 Construction of a Radiation Balance Using the Reflection Method

To construct a radiation balance in a kiln section using the Reflection Method, the first step is to calculate the radiation emitted from each surface in the section. As discussed in Section 4.3, several simplifying assumptions were made in this

model including the neglect of axial radiation to adjacent zones and kiln end surface effects. The surface emits radiation to the surrounding surfaces as governed by the view factors, which in turn are determined by the geometry used to model the enclosure. The view factor from one surface area to another is the fraction of radiation leaving the first surface which is intercepted by the second surface. The sum of the view factors for one surface in an enclosure to all the surfaces in the enclosure (including itself) is unity i.e.

$$\sum_{j=1}^N F_{1j} = 1$$

The view factors used for each section of the kiln are based on the areas of the wall, solid, and flame in each section, as well as the kiln configuration. The view factors in each region are taken to be the same for each section. Determination of these factors are discussed in Appendix C.

As radiation passes through the gas in the enclosure, the gas absorbs a fraction of the radiation. The remainder is transmitted to the receiving surface as determined by the view factor. All the radiation leaving a surface is either absorbed by the gas or intercepted by the surfaces in the enclosure. The intercepted radiation will be partly absorbed and partly reflected (diffusely). By tracing the emissions of radiation from a surface and its subsequent (diffuse) reflections and absorptions, the fraction of the emitted energy absorbed by the gas and by all the surfaces in the kiln section can be estimated. Sections 4.1.4 through 4.1.6 discuss the equations required to trace radiation emitted, reflected, and absorbed by the gas and surfaces.

The amount of radiation emitted and absorbed by the surfaces and by the gas in a section of the kiln is a function of their temperatures and their emissivities, absorptivities, and reflectivities. To construct the radiation balance, the emissivity, absorptivity, and transmissivity of the gas must be known as a function of temperature. Likewise the absorptivity, emissivity, and reflectivity of the solid surfaces must be known. Finally, the geometry for each section of the kiln must be known to determine the view factors.

At steady state the temperatures within a section of the kiln must reach constant values such that the net energy gained or lost by the section is zero. This is the basic overall energy balance for a section. (See Section 4.2 for the detailed drawings of the radiation paths used in the radiation balance and the resulting set of equations from which kiln heat flows and kiln temperatures are calculated).

4.1.2 The Absorption of Radiation Originating from a Solid Surface

Previous Work -

In the Reflection Method^{23, 1}, the radiant energy emitted from a solid surface is traced through two reflections, and the energy remaining after the second reflection is distributed to the solid surfaces in proportion to their view factors, as if they were black bodies. The amount of energy attenuated by the gas for each ray is the difference between the energy initially emitted or reflected and that which is transmitted through the

gas to a solid surface.

$$I_{\text{absorbed}} = I_{\text{initial}} - I_{\text{transmitted}}$$

For a real gas, absorption only occurs within discrete wavelengths. Therefore the fraction of energy from a solid surface attenuated by successive reflections is decreased for each reflection since there is less radiant energy lying within the wavelength region where absorption occurs. For this reason the gas absorbs almost no radiation after the second reflection since all the radiant energy within the absorption band has been absorbed previously, i.e. the gas becomes essentially transparent after only two reflections. Also after two reflections, a large percentage of the radiant energy initially emitted has been absorbed by the gas or solid surfaces. For these reasons, the energy remaining after two reflections is distributed between the solid surfaces as if they were black bodies. This is of course, an approximation, but the remaining energy is so small that small errors in its distribution can be neglected.

Current Work -

There is no difference between the Reflection Method model discussed above for radiation from solids and that used in the present model. It may be noted that if some of the radiation were specularly reflected from a curved surface, there would be a different distribution of radiation due to the focusing effect

of the curved surface. This would require a different set of view factors for reflected radiation for the balance to be exact. However, in the present work only diffusive radiation is considered.

4.1.3 The Absorption of Radiation Originating from the Gas Previous Work -

For radiation emitted by the gas, the path of emitted energy is traced through only two reflection because of the high absorptivity of a real gas for its own 'banded' radiation (as discussed in Section 2.4). After the second reflection, the energy initially emitted has been largely absorbed by the gas and solid surfaces, and the remaining energy is assumed to be completely absorbed by the gas during its next passage.

Current Work-

The same method for the absorption of radiation originating from the gas was used in the present work. Description of the gas emissivity, absorptivity, and transmissivity of the gas for its own radiation are discussed in Sections 4.4 and 4.5.

4.1.4 Derivation of Equations for Distribution of Radiation Originating from the Solid Bed

In this section, the equations are derived for describing the distribution of radiation originating from the solid bed for an enclosure containing two solid surfaces (wall and solid bed) and gas. The radiation is traced through two complete

reflections. The number of radiation paths leaving (and view factors for) a surface is determined by the number of surfaces the surface can 'see'. The view factors for reflected radiation assume that the radiation has been diffusely reflected.

The radiation from the solid bed can only 'see' (be intercepted by) the wall, and its view factor, F_{sw} , the fraction of radiation emitted by the bed which is 'seen' by the wall, is equal to 1. The radiation reflected from any area of the wall can see other areas of the wall as well as the solid bed, so that two view factors are required to describe the reflected radiation from the wall. The fraction of radiation from the wall intercepted by itself is defined as F_{ww} , and the fraction of radiation from the wall intercepted by the solid bed is defined as F_{ws} . In the equations listed in Section 4.2 and the actual computer program (see Appendix E), the terms involving F_{ww} are included. However in the following description, the F_{ww} terms are omitted in order to simplify the description. These F_{ww} terms are similar in form to the terms involving F_{ws} and are shown in Fig. 4.1.4-1.

The basic law of radiation states that the rate at which radiation is emitted from the solid bed surface in the kiln is given by the following equation:

$$Q_{so} = \sigma A_s \epsilon_s T_s^4,$$

where the sigma is the Stefan-Boltzmann constant, A_s is the area of the solid bed, ϵ is the emissivity of the solid bed surface, and T_s is its temperature. When this radiation, Q_{so} , passes through the kiln gas with absorptivity

$$a_{g1} = 1 - \tau_{g1},$$

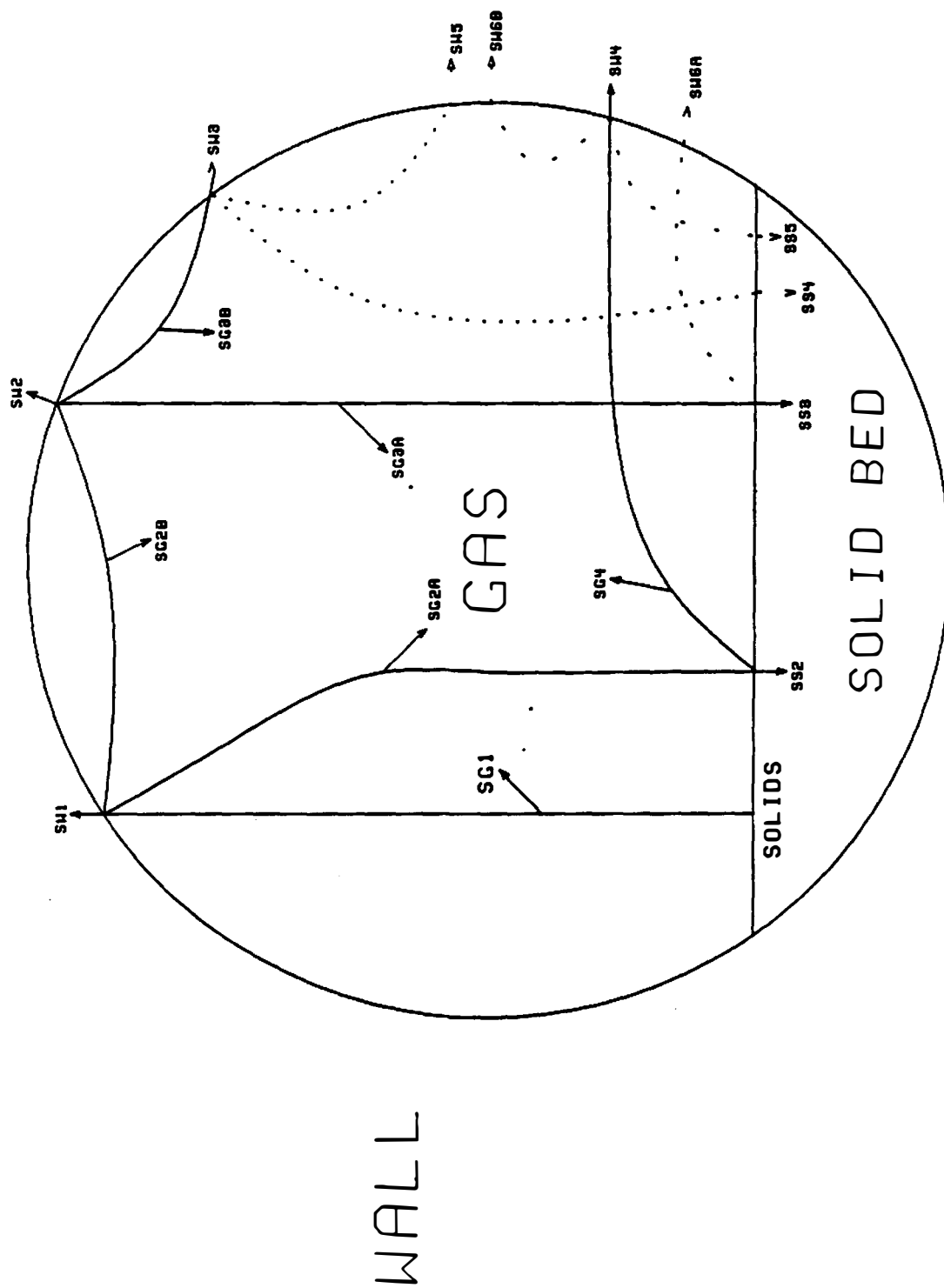


Figure 4.1.4-1. Solid Bed Radiation Drawing w/o Flame

where τ_{g1} is the gas transmissivity for the solid radiation, the rate of absorption is $\alpha_{g1} F_{sw} Q_{so}$ (where α_{g1} is equal to the absorptivity by the gas from the first passage of solid radiation through the gas). When the transmitted radiation hits the wall, the fraction absorbed is α_w and the fraction reflected is ρ_w , or $1-\alpha_w$. Thus the rate of absorption by the wall is

$$GW1 = \alpha_w \tau_{g1} F_{sw} Q_{so}$$

and the rate of reflection is

$$\rho_w \tau_{g1} F_{sw} Q_{so}.$$

When the reflected radiation again traverses the kiln gas space, the fraction transmitted to the solid bed is

$$\tau_{g2} \rho_w F_{ws} F_{sw} Q_{so}.$$

Therefore the fraction absorbed in this gas path is

$$SG2a = \rho_w F_{ws} F_{sw} Q_{so} (\tau_{g2} - \tau_{g1}).$$

τ_{g2} is greater than τ_{g1} because some of the radiation frequencies which are absorbed by H_2O and CO_2 have been partially absorbed in the first gas path. After traversing the gas, the radiation again hits the solid bed surface, and is absorbed at the rate

$$SS2 = \alpha_s \rho_w \tau_{g2} F_{ws} F_{sw} Q_{so}$$

and is reflected (to the wall) at the rate

$$\rho_s \rho_w \tau_{g2} F_{sw} F_{ws} F_{sw} Q_{so}.$$

Very little of this twice reflected radiation is absorbed by the next gas path.

$$SG4 = (\tau_{g3} - \tau_{g2}) \rho_s \rho_w F_{sw} F_{ws} F_{sw} Q_{so},$$

because the gas has absorbed nearly all of the solid radiation

which overlaps the real gas spectrum. The rate at which the twice reflected radiation is transmitted through the gas is,

$$\rho_s \rho_w \tau_{g,} F_{sw} F_{ws} F_{sw} Q_{so}$$

and the fraction absorbed when it collides again with the wall is

$$SW4 = \alpha_w \rho_s \rho_w \tau_{g,} F_{sw} F_{ws} F_{sw} Q_{so}.$$

For the small remaining fraction (reflected from the wall to the solid bed) the gas is considered to be clear ($\tau_{g,} = 1$) and the remainder, that is all of the remaining thrice reflected radiation rate is considered to be completely absorbed ($\alpha_s = 1$) by the next solid surface (solid bed) collision,

$$SS5 = \rho_w \rho_s \rho_w \tau_{g,} F_{ws} F_{sw} F_{ws} F_{sw} Q_{so}.$$

The overall radiation balance for the solid bed may be stated as

$$Q_{so} \text{ emitted} = Q_{\text{absorbed}}.$$

That is, the rate of energy radiated from the solid bed, Q_{so} , is equal to the sum of the absorption terms including those considered above involving F_{ww} . Stated as an equation:

$$Q_{so} = Q_{sw} + Q_{sg} + Q_{ss}$$

where Q_{sw} includes the energy absorbed by the wall from the initial ray and from its subsequent two reflections from either the bed or from the wall, including the terms involving F_{ww} . Q_{sg} includes three terms corresponding to the three gas passes of the original ray before it is completely absorbed. Q_{ss} includes two absorption terms, one from the first reflection from the wall to the solid, and the other from a second reflection ray which at first had a wall-to-wall reflection.

4.1.5 Equations for the Distribution of Radiation Originating from the Wall and from the Flame

The radiation originating from the wall of the kiln is treated very similar to the way that the solid bed was treated, with similar absorption terms and radiation balance. The listing of these equations are shown in Section 4.2. The luminous character of the flame is due to its content of solid particles (soot and ash) which radiate and absorb radiation like any other solid surface. Therefore the flame, also, is treated in this model as a solid surface, with radiative characteristics similar to those of the solid bed or kiln wall. As will be discussed later in Section 4.3, special provision is made for the partially transparent nature of the flame. Otherwise, the treatment of absorption terms and of the radiation balance is similar to that discussed for radiation originating from the solid bed.

4.1.6 Derivation of Equations for Distribution of Radiation Originating from the Gas

A similar description of the terms required to describe the radiation balance for radiation originating from the gas is given below and listed in Fig. 4.1.6-1. Fewer terms are required to determine the distribution of radiation from the gas to the enclosure due to the high absorptivity of the gas for its own radiation, α'_g . The energy remaining after two reflections of the radiation emitted by the gas is absorbed essentially entirely by the gas. The gas radiates to both the solid bed and

wall. For simplification, only the terms describing the energy radiated to the solid bed will be discussed below. The terms involving the wall are similar in form to those involving the solid bed and are shown in Section 4.2.

The rate at which radiation is emitted from the gas in the kiln, Q_{go} , is given by the equation:

$$Q_{go} = \sigma_s A_g T_g^4,$$

where the sigma is the Stefan-Boltzmann constant, A_g is the total perimeter area of the enclosure, ϵ_g is the emissivity of the gas, and T_g is its temperature. When this radiation, Q_{go} , strikes the solid bed, the rate of absorption is

$$GS1 = \alpha_s F_{gs} Q_{go}.$$

The fraction reflected is ρ_s , or $1-\alpha_s$. Thus the rate of reflection from the solid bed and starting towards the wall is

$$\rho_s F_{sw} F_{gs} Q_{go}.$$

When the reflected radiation traverses the kiln gas space, a large fraction of the gas radiation is absorbed by the gas, due to the high absorptivity of a real gas for its own radiation. The transmissivity of the gas for its own radiation is given by:

$$\tau'_g = 1-\alpha'_g.$$

The fraction transmitted to the wall is

$$\tau'_g \rho_s F_{sw} F_{gs} Q_{go},$$

therefore the fraction absorbed in this path by the gas is

$$GG1 = (1-\tau'_g) \rho_s F_{sw} F_{gs} Q_{go}.$$

After traversing the gas, the radiation intercepts the wall surface, and is absorbed at the rate

$$GW3 = \alpha_w \rho_s \tau'_g F_{sw} F_{gs} Q_{go}$$

and is reflected (from the wall) at the rate

$$GG4b = \rho_w \rho_s \tau'_g F_{sw} Q_{so}.$$

All of this twice reflected radiation is assumed to be absorbed by the path through the gas due the high absorptivity of the gas for its own radiation. The remaining radiation after two reflections is smaller, and an approximate accounting for this remaining radiation will not affect the results significantly. Similar adsorption terms can be written for the gas radiation which strikes the kiln wall first. The radiation balance equations of the gas for an enclosure with two surfaces is described by Gorog¹ and is similar to the radiation balance for the gas shown in Section 4.2.

4.2 Derivation of Equations for Net Heat Transfer

Previous Work -

As illustrated in Sections 4.1.1 through 4.1.6 for the simplified (no flame) case, the method estimates how the radiated energy, Q_1 in Eqn. 4.1-1, is distributed to the gas and the surfaces (including itself) in the enclosure as a function of the surface and gas temperatures, areas, emissivities and absorptivities, and geometrical relationships (view factors) in the enclosure.

The heat absorbed by a surface i may be summarized by

$$\begin{array}{llll}
 Q_1 \text{ absorbed} & = & Q_{gi} & + \sum_{j=1,n} Q_{ji} \quad (\text{Eq. 4.2-1}) \\
 \text{[Total heat} & & \text{[heat absorbed} & \text{[heat absorbed by} \\
 \text{absorbed by} & = & \text{by surface } i & + \text{ surface } i \text{ from} \\
 \text{surface } i] & & \text{from the gas]} & \text{other surfaces } j]
 \end{array}$$

The net radiant heat change for a surface (or the gas), ΔQ_i , is the difference between heat emitted and heat absorbed:

$$\Delta Q_{\text{gained or lost}} = Q_{\text{emitted}} - Q_{\text{absorbed}} \quad (\text{Eq. 4.2-2})$$

Therefore,

$$\Delta Q_i = Q_i - (Q_{gi} + \sum_{j=1,n} Q_{ji}) \quad (\text{Eq. 4.2-3})$$

These relationships are shown in Fig. 4.2-1 for the radiation from the solid bed, wall, gas, and flame.

Applying Eq. 4.2-4 to Gorog's model, which contained only two surfaces (wall and solid bed), the gas, and no flame, results in the following equations:

$$\Delta Q_s = Q_s - (Q_{ss} + Q_{ws} + Q_{gs})$$

$$\Delta Q_w = Q_w - (Q_{sw} + Q_{ww} + Q_{gw})$$

$$\Delta Q_g = Q_g - (Q_{sg} + Q_{wg} + Q_{gg}),$$

where the subscripts s, w, and g represent solid, wall, and gas respectively. An absorption term such as Q_{ws} represents the radiation absorbed by the solid bed (s) from radiation originating from the wall (w). As illustrated in Section 4.1.1 and Section 4.1.3 each absorption term in these equations is determined by tracing the emission from each surface through two reflections. Each term Q_{ij} is the energy originally emitted by surface i which is absorbed by surface j and is defined by the sum of

- (1) the fraction of radiation initially emitted from surface i which is absorbed by surface j during two reflections, and
- (2) the fractions of the remaining reflection after two reflections which is assumed by the model to be absorbed by surface j.

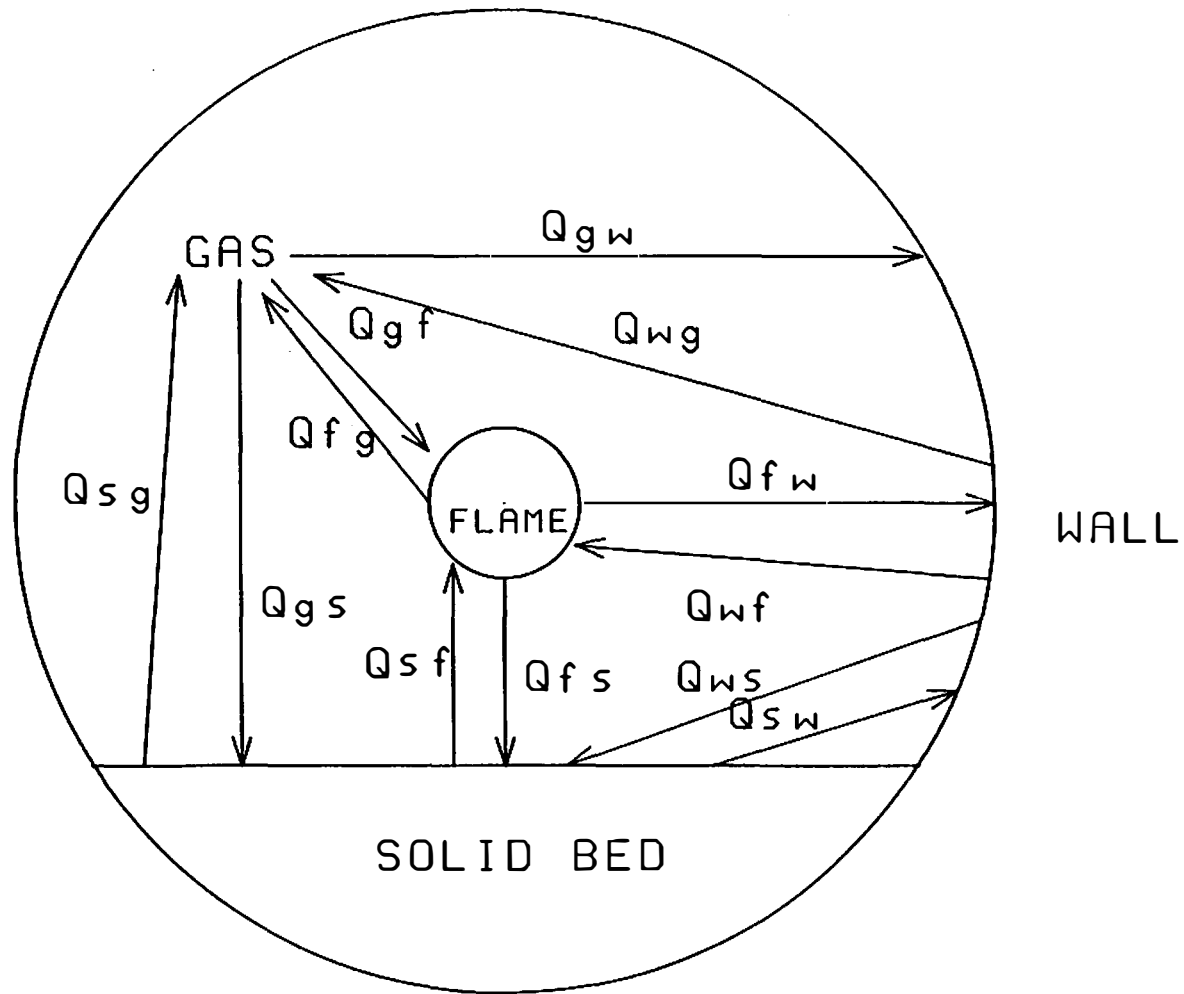


Figure 4.2-1. Crossection of kiln with Overall Heat Transfer Equations

The term Q_{1g} is the energy originally emitted by surface 1 which is absorbed by the gas and is defined by the sum of (1) the fraction initially emitted from surface 1 which is absorbed by the gas, and (2) the fraction of the originating ray's reflections which are absorbed by the gas. The resulting set of equations defines the radiation balance for the kiln. The determination of these terms is discussed further in Section 4.1.

Current Work -

The kiln model as presented by Gorog is modified in the present work by dividing Gorog's single section kiln into a number of 1.5 foot long sections and by the addition of the flame as a third surface in the flame region. For each 1.5 foot long section in the gas region downstream of the flame, the radiation balance developed by Gorog for 2 surfaces and a gas is used. The neglect of axial radiation and end effects is shown later in Section 4.3 to result in a tolerable error. A further modification of Gorog's model was to treat the kiln gases as a real gas (see Section 4.4). Each 1.5 foot long section of the kiln is treated as a separate radiation enclosure with uniform (but not equal) temperatures T_1 in the wall, gas, and solids.

The addition of the flame surface as a third surface in the flame region complicates the radiation balance. For each 1.5 foot long section of the flame region, the net radiation absorbed or emitted is determined by the following equations:

$$\Delta Q_s = Q_s - (Q_{ss} + Q_{ws} + Q_{gs} + Q_{fs})$$

$$\Delta Q_w = Q_w - (Q_{sw} + Q_{ww} + Q_{gw} + Q_{fw})$$

$$\Delta Q_g = Q_g - (Q_{sg} + Q_{wg} + Q_{gg} + Q_{fg})$$

$$\Delta Q_f = Q_f - (Q_{sf} + Q_{wf} + Q_{gf} + Q_{ff})$$

It is seen that the addition of the flame surface added a fourth equation, as well as an additional term in each of the equations.

The radiation balance could be extended, if necessary, to consider more surfaces, such as the end surfaces of the kiln. The treatment would be similar to that indicated for the added flame surface. For each added solid surface, there would be the added complication that its presence would affect each of the other absorption terms such as Q_{ws} . Radiation originating from surface w may be reflected from the added surface before being absorbed by surface s. Therefore, the presence of the added surface would affect the values of Q_{ws} .

The complete radiation reflection diagrams and the associated equations are shown in Figs. 4.2-2, 4.2-3, 4.2-4, 4.2-5, and 4.2-6 for the radiation emitted by the solid bed, wall, flame, and gas. Figure 4.2-6 presents a print of functions from the portion of the spreadsheet program which calculates the heat transfer in a zone of the kiln. As indicated in the figures, the presence of the additional flame surface complicates the radiation balance considerably.

WALL

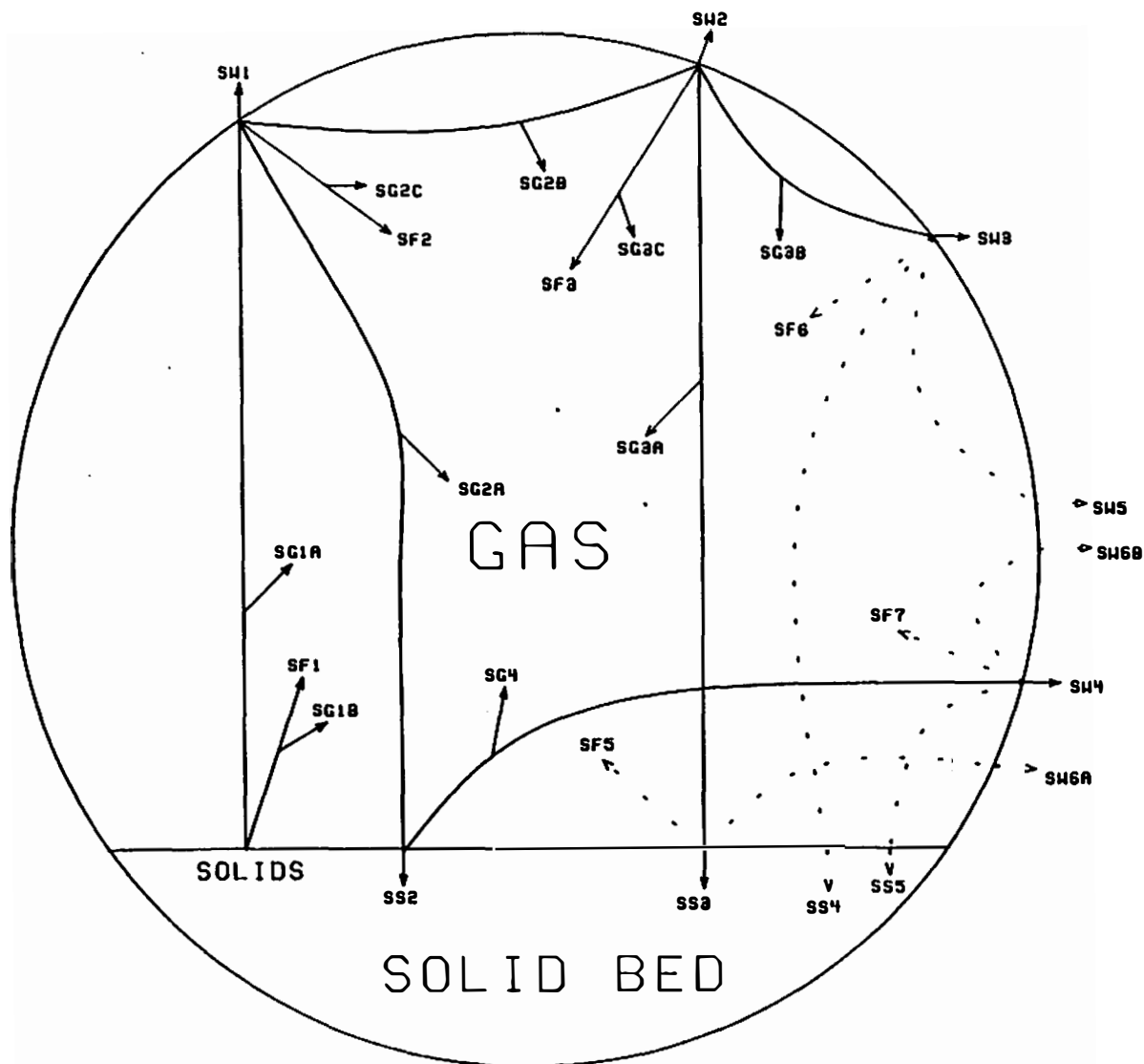


Figure 4.2-2. Solid Bed Radiation Drawing

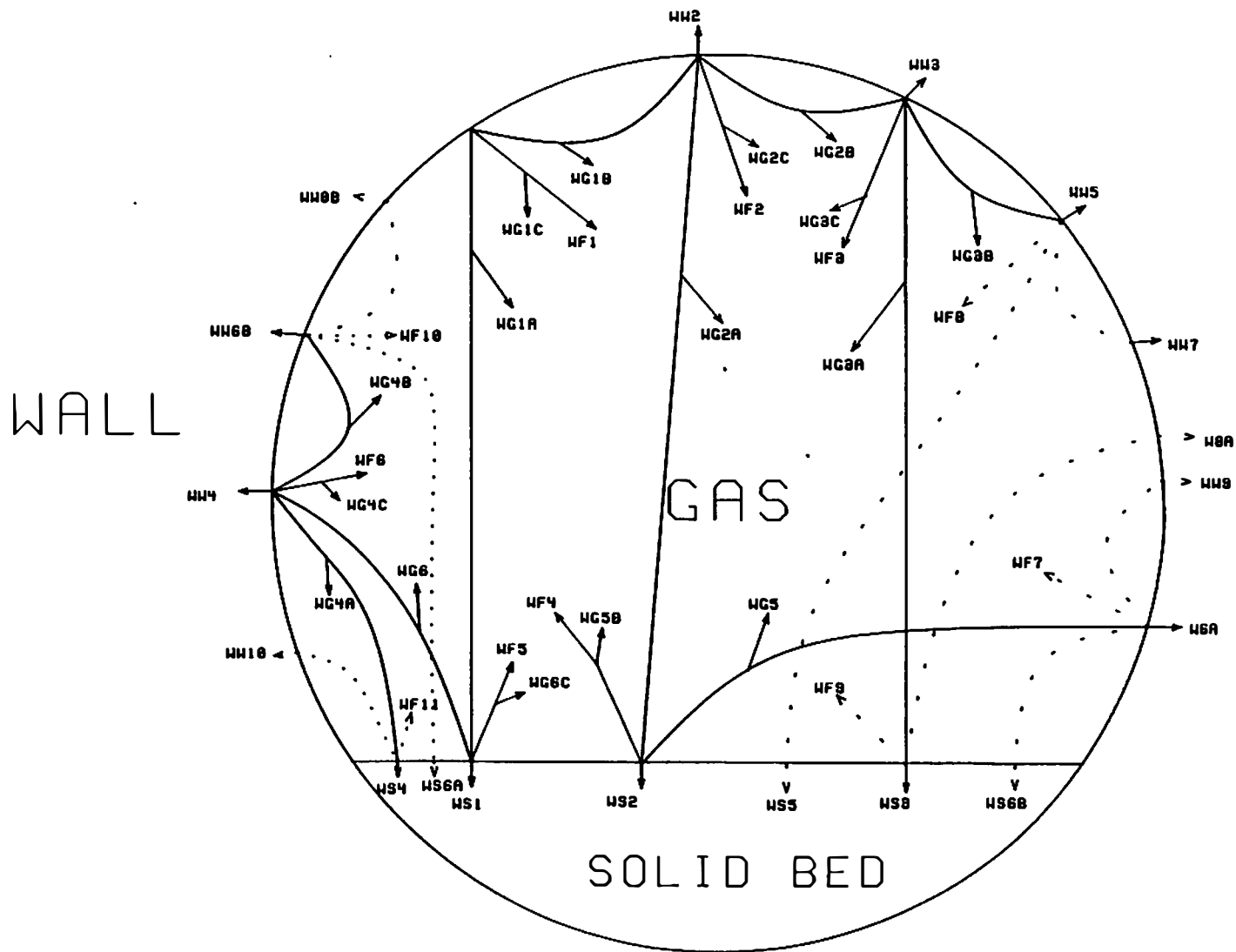


Figure 4.2-3. Wall Radiation Drawing

WALL

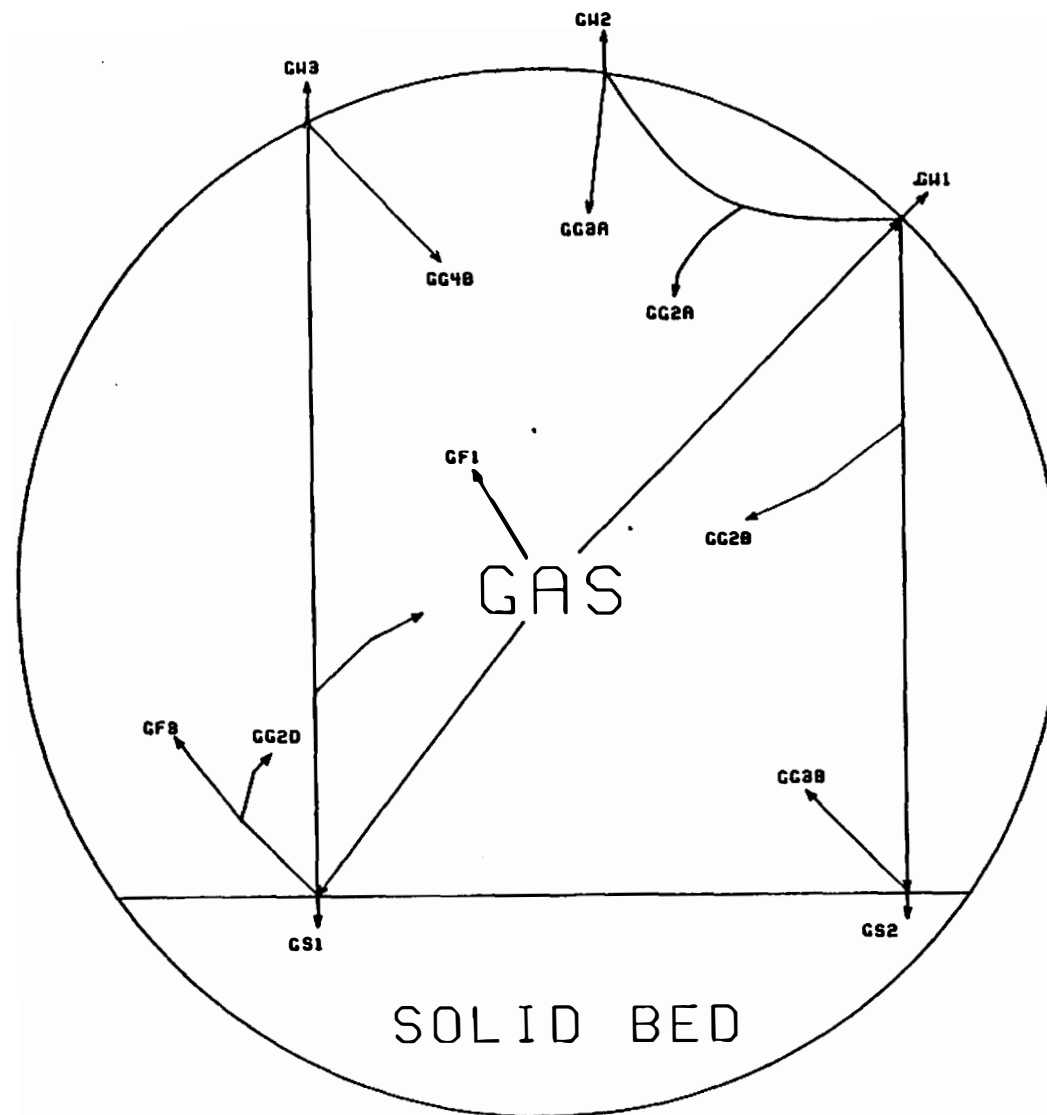


Figure 4.2-4. Gas Radiation Drawing

WALL

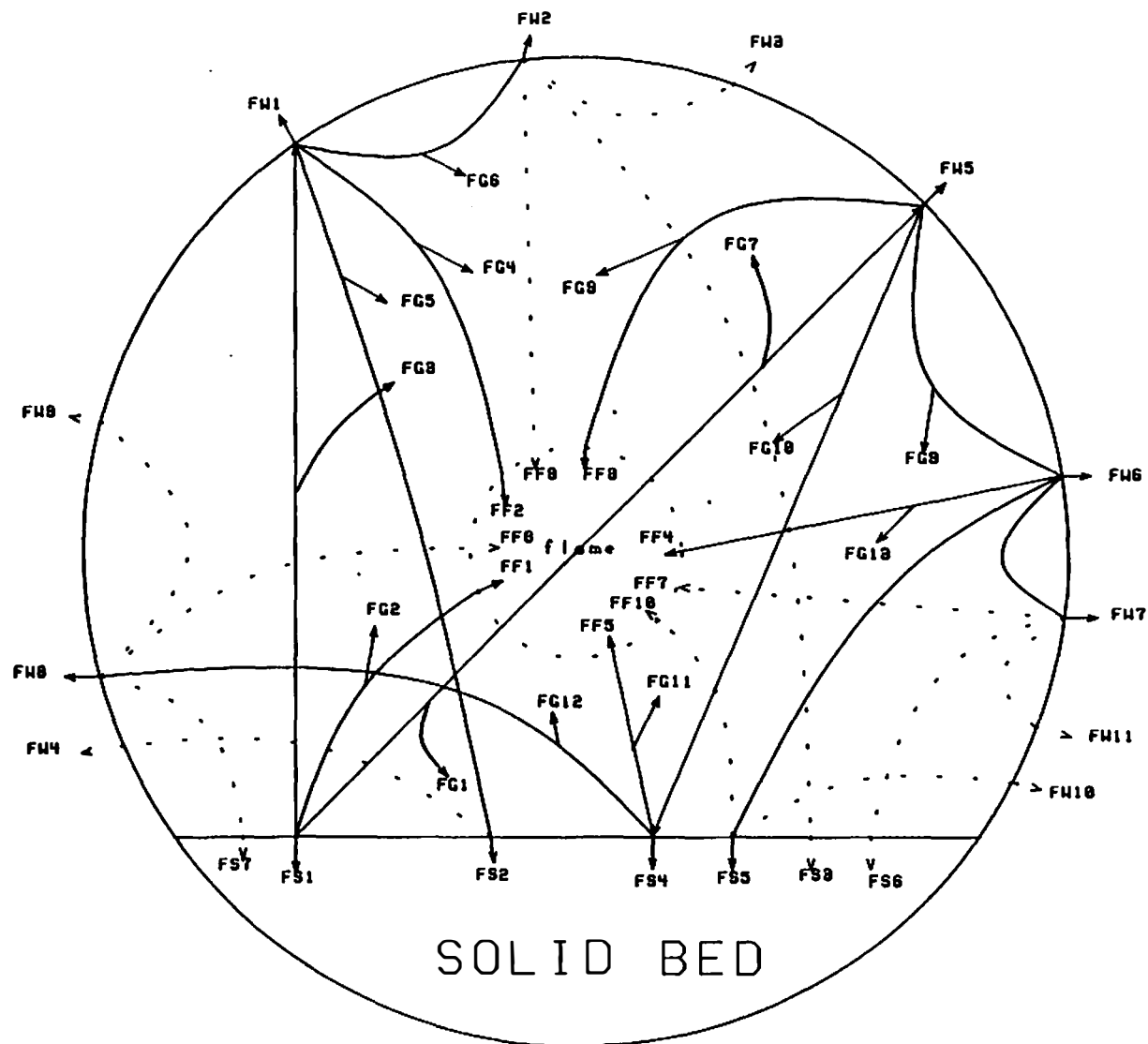


Figure 4.2-5. Flame Radiation Drawing

$Q_s = ssEs + wsEw + gsEg + fsEf + hcvws(Tw - Ts) + hcvgs(Tg - Ts)$									
$Q_w = swEs + wwEw + gwEg + fwEf + hcvgw(Tg - Tw) - hcdwsh(Tw - Tsh)$									
$Q_g = sgEs + wgEw + ggEg + fgEf - hcvgs(Tg - Ts) + hcvgw(Tg - Tw)$									
$Q_f = sfEs + wfEw + gfEg + ffEf$									

							Watts	BTU/HR	
Es	ss	1	EMs*As			0.3308			
		2	-ABs*TRgs2*Fws*Fsw*pv*EMs*As			-0.0043			
		3	-ABs*TRgs3*Fws*Fww*Fsw*pv*pv*EMs*As			-0.0004			
		4	-Fws*TRgs3*Fww*Fww*Fsw*pv*pv*pv*EMs*As			-0.0001			
		5	-Fws*TRgs3*Fws*Fsw*Fsw*ps*pv*pv*EMs*As			0.0000			
Qs	<=	Qs				0.3259	15,924	54,364	
Ew	ws	1	-ABs*TRgw1*Fws*EMw*Aw			-0.1463			
		2	-ABs*TRgw2*Fws*Fww*pv*EMw*Aw			-0.0140			
		3	-ABs*TRgw3*Fws*Fww*Fww*pv*pv*EMw*Aw			-0.0014			
		4	-ABs*TRgw3*Fws*Fws*Fsw*ps*pv*EMw*Aw			-0.0006			
		5	-Fws*TRgw3*Fww*Fww*Fww*pv*pv*pv*EMw*Aw			-0.000178			
		6	-2*Fws*TRgw3*Fws*Fww*Fsw*ps*pv*pv*EMw*Aw			-0.0002			
Qs	<=	Qw				-0.1626	(37,509)	(128,056)	
Eg	gs	1	-ABs*EMg*As			-0.0835			
		2	-ABs*Fws*pv*TRgs11*EMg*Aw			-0.0029			
Qs	<=	Qg				-0.0864	(4,000)	(13,656)	
Ef	fs		-ABs*TRgf1*Ffs*EMf*Af			-0.0972			
		2	-ABs*TRgf3*ps*pv*Ffs*Fsw*Fws*EMf*Af			-0.0004			
		3	-TRgf3*ps*pv*pv*Ffs*Fsw*Fww*Fws*EMf*Af			-0.0001			
		4	-ABs*TRgf2*pv*Ffw*Fws*EMf*Af			-0.0116			
		5	-ABs*TRgf3*pv*pv*Ffw*Fww*Fws*EMf*Af			-0.0012			
		6	-TRgf3*pv*pv*pv*Ffw*Fww*Fww*Fws*EMf*Af			-0.0002			
		7	-TRgf3*pv*pv*ps*Ffw*Fws*Fws*Fsw*EMf*Af			-0.0001			
						-0.1106	(50,425)	(172,150)	
hcvws			+hcvws*(THIrad*D/2)*(Tw-Ts)			12627	(12,627)	(43,108)	
hcvgs			+hcvgs*As*(Tg-Ts)			-107	107	366	

Qs	->						(88,529)	(302,238)	

Figure 4.2-6. Radiation Balance Equations

Qw			

sw	1	-ABv*TRgs1*Fsv*EMs*As	-0.1330
	2	-ABv*TRgs2*Fvw*Fsv*pv*EMs*As	-0.0128
Es	3	-ABv*TRgs3*Fvw*Fvw*Fsv*pv*pv*EMs*As	-0.0012
	4	-ABv*TRgs3*Fvs*Fsv*Fsv*ps*pv*EMs*As	-0.0005
	5	-Fvw*TRgs3*Fvw*Fvw*Fsv*pv*pv*pv*EMs*As	-0.000160
	6	-2*Fvw*TRgs3*Fvs*Fsv*Fsv*ps*pv*pv*EMs*As	-0.0001
Qv <- Qs			-0.1479 (7,224) (24,664)
ww	1	+Etv*Av	1.2574
Ew	2	-ABv*TRgv1*Fvw*Etv*Av	-0.4314
?*Fvw	3	-ABv*TRgv2*Fvw*Fvw*pv*Etv*Av	-0.0414
	4	-ABv*TRgv2*Fvs*Fsv*ps*Etv*Av	-0.0181
	5	-ABv*TRgv3*Fvw*Fvw*Fvw*pv*pv*Etv*Av	-0.0040
	6	-2*ABv*TRgv3*Fvs*Fvw*Fsv*ps*pv*Etv*Av	-0.0035
	7	-Fvw*TRgv3*Fvw*Fvw*Fvw*pv*pv*pv*Etv*Av	-0.0005
	8	-2*Fvw*TRgv3*Fvs*Fvw*Fsv*ps*pv*pv*Etv*Av	-0.0005
	9	-Fsv*TRgv3*Fvw*Fvw*Fvs*ps*pv*pv*Etv*Av	-0.0002
	10	-Fsv*TRgv3*Fvs*Fvs*Fsv*ps*ps*pv*Etv*Av	-0.0001
Qv <- Qv			0.7576 174,743 596,574
Eg	gw	1 -ABv*EMg*Av	-0.3175
		2 -ABv*Fvw*pv*TRgv11*EMg*Av	-0.0086
		3 -ABv*Fsv*ps*TRgv11*EMg*As	-0.0029
Qv <- Qg			-0.3290 (15,225) (51,977)
Ef	fw	1 -ABv*TRgf2*ps*Ffs*Fsv*EMf*Af	-0.0126
		2 -ABv*TRgf3*ps*pv*Ffs*Fsv*Fvw*EMf*Af	-0.0013
		3 -TRgf3*ps*pv*pv*Ffs*Fsv*Fvw*Fvw*EMf*Af	-0.0002
		4 -TRgf3*ps*ps*pv*Ffs*Fsv*Fsv*Fvs*EMf*Af	-0.0001
		5 -ABv*TRgf1*Ffv*EMf*Af	-0.3402
		6 -ABv*TRgf2*pv*Ffv*Fvw*EMf*Af	-0.0342
		7 -ABv*TRgf3*pv*pv*Ffv*Fvw*Fvw*EMf*Af	-0.00344
		8 -ABv*TRgf3*pv*ps*Ffv*Fvs*Fsv*EMf*Af	-0.0015
		9 -TRgf3*pv*pv*ps*Ffv*Fvs*Fsv*Fvw*EMf*Af	-0.0002
		10 -TRgf3*pv*pv*ps*Ffv*Fvw*Fvs*Fsv*EMf*Af	-0.0002
		11 -TRgf3*pv*pv*pv*Ffv*Fvw*Fvw*Fvw*EMf*Af	-0.0004
			-0.3942 (179,652) (613,333)
hcvws		+hcvws*(THIrad*D/2)*(Tv-Ts)	12627 12,627 43,108
hcvgw		+hcvgw*Aw*(Tg-Tv)	-7382 7,382 25,204
hcdwsh		+hcdwsh*area3*(Tv-Tsh)	7346 7,346 25,080

Qv ->			(2) (8)

Figure 4.2-6. (continued)

```

Qg
*****

Es  sg  1 -(1-TRgs1)*EMs*As                -0.0829
        2 -(TRgs1-TRgs2)*Fsw*ps*EMs*As        -0.0026
        3 -(TRgs2-TRgs3)*Fsw*ps*ps*EMs*As      -0.0002
        4 -(TRgs2-TRgs3)*Fws*ps*ps*EMs*As      -0.0001
Qg <= Qs                -0.0858      (4,192) (14,311)

Ev  wg  1 -(1-TRgw1)*EMv*Av                -0.2213
        2 -(TRgw1-TRgw2)*Fsw*ps*EMv*Av        -0.0085
        3 -(TRgw2-TRgw3)*Fsw*ps*ps*EMv*Av      -0.0007
        4 -(TRgw2-TRgw3)*Fws*ps*ps*EMv*Av      -0.0003
        5 -(TRgw2-TRgw3)*Fws*ps*ps*EMv*Av      -0.0002
        6 -(TRgw1-TRgw2)*Fws*ps*EMv*Av        -0.0029
Qg <= Qv                -0.2338      (53,917) (184,072)

Eg  gs  1 +EMg*Ag                        0.6559
        2 -ABg11*ps*EMg*Av                -0.0587
        3 -(+ps*Fsw+ps*Fws)*ps*TRg11*EMg*Av    -0.0029
        4 -(+ABg11+ps*TRg11)*Fsw*ps*EMg*As     -0.0111
Qg <= 2a -ABg11*ps*Fsf*As*EMg            -0.0051
                                0.5781      26,752      91,332

Ef  fg  1 -(1-TRgf1)*EMf*Af                -0.0657
        2 -(TRgf1-TRgf2)*ps*Ffs*EMf*Af        -0.0008
        3 -(TRgf2-TRgf3)*ps*ps*Ffs*Fsw*EMf*Af  -0.0001
        4 -(TRgf1-TRgf2)*ps*Ffs*EMf*Af        -0.0029
        5 -(TRgf2-TRgf3)*ps*ps*Ffs*Fws*EMf*Af  -0.0001
        6 -(TRgf2-TRgf3)*ps*ps*Ffs*Fws*EMf*Af  -0.0003
                                -0.0699      (31,869) (108,800)

hcvgs +hcvgs*As*(Tg-Ts)                -107      (107)      (366)
hcvgw +hcvgw*Av*(Tg-Tv)                -7382      (7,382) (25,204)
*****
Qg ->                                (70,715) (241,421)

```

Figure 4.2-6. (continued)

Qf				*****			
Es	sf	1	-TRgs1*Fsf*EMs*As	-0.0816			
		2	-TRgs2*pv*Fsv*Fvf*EMs*As	-0.0093			
		3	-TRgs3*pv*pv*Fsv*Fsv*Fvf*EMs*As	-0.0009			
		4	-TRgs3*pv*ps*Fsv*Fvs*Fsf*EMs*As	-0.0003			
		5	-Fvv*TRgs3*Fvs*Fsf*Fsv*ps*pv*pv*EMs*As	0.0000			
		6	-Fvf*TRgs3*Fsv*Fsv*Fsv*pv*pv*pv*EMs*As	-0.0001			
		7	-Fvf*TRgs3*Fvs*Fsv*Fsv*ps*pv*pv*EMs*As	0.0000			
				-0.0923	(4,508)	(15,389)	
Ew	wf	1	-TRgv1*Fvf*EMv*Av	-0.3140			
		2	-TRgv2*pv*Fvv*Fvf*EMv*Av	-0.0301			
		3	-TRgv3*pv*pv*Fvv*Fvv*Fvf*EMv*Av	-0.0029			
		4	-TRgv3*pv*ps*Fvv*Fvs*Fsf*EMv*Av	-0.0011			
		5	-ps*TRgv2*Fvs*Fsf*EMv*Av	-0.0111			
		6	-TRgv3*ps*pv*Fvs*Fsv*Fvf*EMv*Av	-0.0013			
		7	-Fsv*TRgv3*Fvf*Fvv*Fvs*ps*pv*pv*EMv*Av	-0.0001			
		8	-Fvf*TRgv3*Fsv*Fsv*Fsv*pv*pv*pv*EMv*Av	-0.0003			
		9	-Fvv*TRgv3*Fvs*Fvv*Fsf*ps*pv*pv*EMv*Av	-0.0001			
		10	-Fvf*TRgv3*Fvs*Fvv*Fsv*ps*pv*pv*EMv*Av	-0.0001			
		11	-Fsf*TRgv3*Fvs*Fvs*Fsv*ps*ps*pv*EMv*Av	0.0000			
				-0.3612	(83,318)	(284,447)	
Eg	gf	1	-Af*EMg	-0.1546			
		2	-TRgf11*pv*Fvf*Av*EMg	-0.0063			
		3	-TRgf11*ps*Fsf*As*EMg	-0.0018			
				-0.1627	(7,527)	(25,698)	
Ef	ff	1	+EMf*Af	0.6124			
		2	-TRgf2*ps*Fsf*Ffs*EMf*Af	-0.0077			
		3	-TRgf3*ps*pv*Ffs*Fsv*Fvf*EMf*Af	-0.0009			
		4	-TRgf2*pv*Ffv*Fvf*EMf*Af	-0.0249			
		5	-TRgf3*pv*pv*Ffv*Fvv*Fvf*EMf*Af	-0.0025			
		6	-TRgf3*pv*ps*Ffv*Fvs*Fsf*EMf*Af	-0.0009			
		7	-TRgf3*pv*ps*pv*Ffv*Fvf*Fvv*Fvv*EMf*Af	-0.0003			
		8	-TRgf3*pv*ps*ps*Ffv*Fvs*Fsv*Fvf*EMf*Af	-0.0001			
		9	-TRgf3*ps*pv*pv*Ffs*Fsv*Fvv*Fvf*EMf*Af	-0.0001			
		10	-TRgf3*pv*pv*ps*Ffv*Fvv*Fvs*Fsf*EMf*Af	-0.0001			
		11	-TRgf3*ps*ps*pv*Ffs*Fsv*Fsf*Fvs*EMf*Af	0.0000			
				0.5748	261,946	894,283	
Qf ->				*****			
					166,593	568,749	

		Qs -		(88,529)	(302,238)		
		Qv -		(2)	(8)		
		Qg -		(70,715)	(241,421)		
			Qf -	166,593	568,749		

Figure 4.2-6. (continued)

4.3 The Effect of Neglecting Axial Radiation and End Effects Previous Work -

Two simplifying assumptions used in the Resistive Network radiation model as presented by Gorog and Brimacombe which have been included in the present model are important to note: (1) The effects of axial radiation are neglected, and (2) the effects of radiation from the end surfaces of the kiln have been neglected. These simplifications are made to avoid calculational difficulties associated with including these effects when the kiln is divided into sections as is done in Resistive Network Method, and in the present work. The Zone method also divides the kiln into sections, but generally considers both of these effects.

The second simplification is considered to be reasonable because the surface areas of the ends of most kilns are small compared to the areas of the wall and solid bed, and are reported to not contribute significantly to the overall heat transfer in the kiln^{2,3}. Including the kiln ends in the model would principally affect heat transfer in the first and last zones of the kiln. The effect can be crudely thought of as increasing the wall surface area in those zones.

Axial radiation refers to the effect of radiation from the gas and surfaces in one section radiating to the gas and surfaces in other sections of the kiln. Consideration of this effect is omitted in the present work. The effect of this omission has been studied by Gorog for a 300°K/W flame temperature gradient and is reported to result in at most a 20%

error' for the cases they considered. This neglect of axial radiation effect is reasonable if the temperature gradient between sections is not large, because the radiation gained from adjacent sections largely compensates for the axial radiation lost from a given section to adjacent sections in the kiln. The effects of axial radiation have been shown to be negligible for distances beyond $3/4$ of a kiln diameter¹. The radiation from the gas has a high absorptivity for its own radiation, and axial radiation from the gas is quickly reabsorbed by the gas in the same section. The beam length for gas radiation used in the present calculations is approximately $1/2$ the kiln diameter (see Section 4.4) which also limits the effect of axial radiation from the gas.

Both of these effects would tend to increase the gas temperature and lower the flame temperature in the flame region of the kiln. These effects are less important in the downstream gas region of the kiln due to the relatively smaller temperature gradient between sections in the gas region and the larger distance from the front end of the kiln.

Current Work -

The effect of radiation from an end of the kiln to its adjacent section could be treated in the model by including the end of the kiln as a fourth surface in the balance. However, considering axial radiation would significantly increase the calculational difficulty involved in determining the temperature profile of the kiln, requiring an additional trial and error

process using assumed temperatures for the adjacent sections of the kiln. An additional set of view factors would have to be calculated for each of the adjacent sections considered. (If axial radiation from only the immediately adjacent sections were considered, one additional set of view factors would be required). In view of the considerable added computational difficulties from including the effects of end surface and axial radiation, and cited information that neglecting these effects would provide only marginal improvement in the results, it was decided to neglect these effects in the present study.

4.4 Radiation Model of the Flame

Previous Work -

As discussed earlier (Section 3.2 and 3.3), an accurate prediction of the flame behavior must be based on the experimental measurement of the effects of factors such as flame temperature, flame length, flame emissivity, flame shape, etc. Such modeling based on detailed experimental data has been done by Jenkins⁴ and Johnson⁵. Where data are not available, the flame emissivity is treated as a gray or black body of constant emissivity and the shape of the flame is treated as an axial symmetric cylinder of a constant diameter⁵ or as a cone with diameter increasing with axial distance from the burner^{4,5}.

Current Work -

The Reflection Method can in theory be applied to as many surfaces as needed to model an enclosure, however, the number of

equations required increases greatly with each increase in the number of surfaces. The addition of the flame to the radiation balance as a third solid surface doubles the number of equations to represent the emissions, reflections, and absorption of radiant energy required to predict the radiant heat transfer in the flame region. The flame was modeled as a solid surface which approximated a semi-transparent medium such as the gas. Gorog¹ presented the radiative balance with only two surfaces (the kiln wall and solid bed) and the gas. The presence of a flame is an important factor in a heat transfer model due to its high temperature and high emissivity as compared to the gas, and significantly increases the heat transferred to the solid bed and wall of the kiln. Without a flame much less heat is transferred. This treatment results in an entirely different temperature profile of the flame region. The effect of this treatment is described further in the discussion of the results.

In the present calculations, the flame is modeled as an axial cylinder of constant diameter. The flame surface is different from the gray solid surfaces of the solid bed and wall because some of the radiation is transmitted through the flame, and essentially no radiation is reflected. The flame is treated as a black body of reduced crosssectional area. The reduced area core of the flame is treated as a solid black body (which does not reflect radiation) and radiation transmission can take place through the additional gas volume made available by the reduction of flame diameter. This reduction of flame area is made in such a way that the product of the black body emissivity

($\epsilon=1$) times the reduced area is equal to the original emissivity times the unreduced area. This treatment of the flame is an innovation of this study and has not been discussed previously in the literature. This relationship causes the original area and emissivity of the flame to be changed to a new 'effective' area (A'_f) and emissivity ($\epsilon'_f=1$) in the equation for radiant heat from the flame to another surface (s) in the kiln becomes

$$q_{f \rightarrow s} = \sigma A_f \epsilon_f F_{fs} T_f^4$$

$$q_{f \rightarrow s} = \sigma A'_f \epsilon'_f F_{fs} T_f^4$$

The relative view factors from the flame to the other surfaces do not change because of the axial symmetry of the flame.

The reduced area of the flame causes a reduction of the operative view factors (F'_{sf}) for the surface to the flame which determines the fraction of radiation emitted by the surface which is seen by the flame. This reduction compensates for the energy that would have been transmitted through the flame if it were a gray (translucent) body. The radiation for a kiln surface (s) radiating to the flame (f) is given by the equation:

$$q_{s \rightarrow f} = \sigma A_s \epsilon_s F'_{sf} T_s^4$$

Treating the emitting flame as a black body of reduced area is equivalent to considering it as a gray body with its actual area. The result is less absorption and emission by the flame, as if it were a gray body. This treatment greatly simplifies the calculation of the radiation balance. Treating the flame as a gray body would double the number of equations required to

calculate the flame radiation absorbed by the gas and surfaces in the kiln. The additional equations would account for radiation which passed through the flame. The mathematical details of this treatment of the flame are described in Appendix C.

4.5 Emissivity Characteristics of the Gas

Previous Work -

The freeboard gases common to a direct-fired rotary kiln operation are composed mainly of CO_2 - H_2O mixtures in nitrogen resulting from the combustion of hydrocarbons fuels and moisture from the solid bed and air. These gases emit and absorb radiation in discrete frequency bands. The absorptivity and emissivity of the gas need not be equal or constant (as they are considered in the Resistive Method) and are functions of the gas temperature, composition, and beam length (the gas is not a gray body). Absorptivity is also a function of the wavelength distribution of the incident radiation and thus of the emitting surface temperature.

The mean beam length, L_m , is an approximate representation of the geometry of an isothermal gas volume. Physically, the mean beam length is the radius of an equivalent gas hemisphere which radiates a flux to the center of its base equal to the average flux radiated to the area of interest by the actual volume of gas. The emissivity of a gas is generally modeled as a gray gas or gray/clear gas. For a gray gas model, the emissivity is equal to the absorptivity of the gas, and it is

not considered to be a function of the temperature of the solids, the gas composition, or the gas temperature. The resistive network method is limited to this type of treatment of the gas emissivity¹⁰. The error introduced by this approximation may be greater than 20%, depending on the reflectivity of the surrounding solids (Gorog)¹.

The 'gray/clear' gas model, initially proposed by Hottel and Cohen¹⁷, attempts to model a real gas more closely. Hottel and Sarofim¹⁶ suggest that gas radiation can be represented as the weighted sum of a sufficient number of gray and clear gas components to approximate the banded characteristics of a real gas. The accuracy of this model increases with the number of gray or clear components used. The model is generally developed for a combustion gas of a fixed composition which is equimolar in CO₂ and H₂O. However, additional water is introduced during the kiln operation due to the presence of moisture from the solid bed and water in the air (humidity). This variation of moisture concentration during kiln operation reduces the accuracy of the gray/clear gas model.

In Hottel's method¹⁶, the absorptivities of water vapor and CO₂ are estimated by the following formula respectively:

$$\alpha_{H_2O} = \epsilon_{H_2O} \tau_{s, (pL_m T_s / T_g)} (T_g / T_s)^{.45}$$

$$\alpha_{CO_2} = \epsilon_{CO_2} \tau_{s, (pL_m T_s / T_g)} (T_g / T_s)^{.65}$$

and,

$$\epsilon_g = (\epsilon_{g_{CO_2}} + \epsilon_{g_{H_2O}})(1 - C_{so})$$

$$\alpha_g = (\alpha_{g_{CO_2}} + \alpha_{g_{H_2O}})(1 - C_{so})$$

The formula for α_g has been used by Johnson¹⁵ with the exponent of 0.5 to provide an approximate value for absorptivity of combustion product gases.

Current Work - Emissivity of CO₂ and H₂O

In the present work the gas emissivity of CO₂ and water was calculated using Hottel's data¹⁶ for emissivity. Hottel's data were regressed using a least squares method which enabled emissivity of any partial pressure of CO₂ and H₂O to be calculated for a wide range of temperatures and beam lengths. The data regression was carried out using the computer program listed in Appendix G. The average beam length, L_m , of the gas used in the present work was calculated using the following formula:

$$L_m = [\pi / (4(2)^{1/2})] D(1 - F/D)$$

$$L_m = 0.55D(1 - F/D)$$

where F is equal to the depth of fill, and D is the kiln diameter, ft. The beam length used, L_m , is corrected for the fill ratio¹, F/D . The factor $0.55D$ is based on the geometrical average chord length from a point to any other point on a circle of diameter D . This factor considers the beam length for an infinitely thin kiln section volume. The beam length for a kiln volume of kiln length equal to the kiln diameter has a value of

0.6 and is defined by the equation

$$L_m = 0.9(4V/A)$$

where V is the volume, A is the bounding surface area, and 0.9 is a correction factor to correct for finite optical thickness.

The relative partial pressures of CO_2 and H_2O , throughout the kiln were assumed to be the same as the gas exiting the kiln. This assumption is thought to be reasonable because the water in the solid bed of the kiln is likely to be evaporated in the first few feet. For a co-current kiln, the gas composition does not change appreciably further down the kiln, only the temperature changes significantly.

The objective of the gas database is to predict the gas emissivity at a specific gas partial pressure, P , for CO_2 and H_2O and specific gas beamlength, L_m , within a range of gas temperatures (500°R to 4000°R) and PL_m (0.2 to 5 ftAtm). The emissivity of H_2O and CO_2 are calculated separately and then, using Hottel's equations (discussed above), the emissivity and absorptivity of the gas mixture are calculated.

The first step is to regress Hottel's gas emissivity data for H_2O to determine gas emissivity as function of PL_m at 500°R increments of temperatures between 500°R and 4000°R . This results in 8 sets of constants, one set for each temperature, which can be used to estimate the gas emissivity at a specific PL_m . These 8 values (at a specific PL_m) are then regressed to determine gas emissivity as a function of gas temperature.

A similar procedure is used to determine the gas emissivity

of CO_2 as a function of temperature at a specific PL_m . At this point, Hottel's equations are then used to calculate first the gas mixture emissivity and secondly the gas mixture absorptivity as a function of the surface radiating temperature. This procedure is outlined in further detail below:

- (1) In a separate program listed in Appendix G, the emissivity data from Hottel were tabulated for each temperature in the temperature range of interest (500°R to 4000°R) for partial pressure times beam lengths (pL_m) of 0.2 to 5 (ft-atm.).
- (2) These data were then regressed by a least squares method to give emissivity as a function of pL_m for the different temperatures tabulated (i.e. 500, 1000, ..., 4000°R). For each temperature, the regression method calculates the emissivity with a three term quadratic equation fit of the form:

$$\epsilon_g = A + B(\text{pL}_m) + C(\text{pL}_m)^2$$

An example of this regression procedure is shown in Table 4.5-1 for 500°R . This regression procedure resulted in a matrix of constants (Table 4.5-2) which were then used in the heat transfer program to generate a set of emissivity values (Table 4.5-3) for the tabulated temperatures ($500, 1000, \dots, 4000^\circ\text{R}$) at a specific pL_m value calculated for the geometry of the kiln modeled.

- (3) The set of emissivity values for a specific pL_m at the tabulated temperatures was then regressed a second time by the least squares method to yield a three term quadratic equation

Table 4.5-1. Least-Squared Regression Table for H2O and CO2 for
Emissivity at Constant Temperature Versus P*L

T, R	b Y=EMg	X=P*L FT*ATH	X^2	X^3	X^4	XY	X^2Y	N	Comparison of Estimated Values vs Actual Values T = 500 R			
									X=P*Lm	Eng calc ^a	Eng act ^b	Regression Constants
H2O												
500	0.19	0.2	0.04	0.008	0.0016	0.038	0.0076	1	0.2	0.221	0.19	a = 0.193360
	0.23	0.3	0.09	0.027	0.0081	0.069	0.0207	1	0.3	0.234	0.23	b = 0.140591
	0.25	0.4	0.16	0.064	0.0256	0.1	0.04	1	0.4	0.247	0.25	c = -0.01491
	0.29	0.6	0.36	0.216	0.1296	0.174	0.1044	1	0.6	0.272	0.29	
	0.31	0.8	0.64	0.512	0.4096	0.248	0.1984	1	0.8	0.296	0.31	A = -0.01491
	0.33	1	1	1	1	0.33	0.33	1	1	0.319	0.33	B = 0.066708
	0.38	1.5	2.25	3.375	5.0625	0.57	0.855	1	1.5	0.371	0.38	C = 4.954584
	0.41	2	4	8	16	0.82	1.64	1	2	0.415	0.41	D = 0.239271
	0.46	3	9	27	81	1.38	4.14	1	3	0.481	0.46	E = -3.07878
	0.53	5	25	125	625	2.65	13.25	1	5	0.524	0.53	
	3.38	14.8	42.54	165.202	728.637	6.379	20.5861	10				
	Y	X	X#2	X#3	X#4	XY	X#2Y	N				
CO2												
500	0.108	0.2	0.04	0.008	0.0016	0.0216	0.00432	1	0.2	0.121	0.108	a = 0.113014
	0.12	0.3	0.09	0.027	0.0081	0.036	0.0108	1	0.3	0.124	0.12	b = 0.038437
	0.13	0.4	0.16	0.064	0.0256	0.052	0.0208	1	0.4	0.128	0.13	c = -0.00432
	0.14	0.6	0.36	0.216	0.1296	0.084	0.0504	1	0.6	0.135	0.14	
	0.15	0.8	0.64	0.512	0.4096	0.12	0.096	1	0.8	0.141	0.15	A = -0.00432
	0.152	1	1	1	1	0.152	0.152	1	1	0.147	0.152	B = 0.017004
	0.165	1.5	2.25	3.375	5.0625	0.2475	0.37125	1	1.5	0.161	0.165	C = 4.954584
	0.17	2	4	8	16	0.34	0.68	1	2	0.173	0.17	D = 0.126333
	0.18	3	9	27	81	0.54	1.62	1	3	0.189	0.18	E = -3.07878
	0.2	5	25	125	625	1	5	1	5	0.197	0.2	
	1.515	14.8	42.54	165.202	728.637	2.5931	8.00557	10				
	Y	X	X#2	X#3	X#4	XY	X#2Y	N				

a EMg = a + b*(P*L) + c*(P*L)*(P*L)

b Emissivity Data from Hottel and Sarofim

**Table 4.5-2. Least-Squared Reduction Constants for H2O and CO2
Emissivity at Constant Temperature vs P*L**

Degrees Rankine	Emissivity Regression Constants ^a		
	a	b	c
H2O Constants			
500	0.193360	0.140591	-0.01491
750	0.150427	0.146890	-0.01723
1000	0.136173	0.144277	-0.01638
1500	0.109983	0.139809	-0.01478
2000	0.082221	0.129614	-0.01381
2500	0.057915	0.116838	-0.01258
3000	0.044245	0.099847	-0.01027
3500	0.034452	0.083375	-0.00838
4000	0.024206	0.074278	-0.00771
CO2 Constants			
500	0.113014	0.038437	-0.00432
1000	0.085994	0.045063	-0.00570
1500	0.097287	0.047224	-0.00544
2000	0.094390	0.059833	-0.00743
2500	0.077821	0.060663	-0.00717
3000	0.061488	0.056025	-0.00637
3500	0.049351	0.045795	-0.00480
4000	0.039099	0.036061	-0.00344
4500	0.072831	0.140905	-0.04336

$$a \quad EM_g = a + b*(P*L) + c*(P*L)*(P*L)$$

shown in Table 4.5-3 which now calculated the emissivity for a specific pL_m as a function of temperature:

$$\epsilon_g = a + b(T) + c(T)^2$$

Table 4.5-4 shows a comparison of emissivity values calculated by this method with Hottel's data.

(4) The correction factor required to compensate for the overlap of the CO_2 and H_2O radiation spectra was calculated as a function of pL_m for an average temperature of $1000^\circ K$ and mole fraction ratio of CO_2 to $H_2O = 0.35$. Typically the CO_2 partial pressure is about 0.12 atmospheres as determined from the overall kiln heat and mass balance gas composition. The temperature and gas composition were chosen as values characteristic of typical operation for this kiln. The use of a single average temperature and mole fraction ratio for calculating the correction factor C_{so} is considered reasonable in light of the small emissivity correction (1% to 7%) that is involved. Again, a least squares regression method was used to calculate a function for the correction factor, C_{so} , of the form:

$$C_{so} = A + B(pL_m) + C(pL_m)^2$$

The table used to generate the equation for the correction factor is shown in Table 4.5-5 and listed in Appendix G. The program could be used to generate new values for the constants, A, B, and C for different average temperatures and CO_2/H_2O ratios. The CO_2/H_2O ratios are calculated based on the

**Table 4.5-3. Least-Squared Reduction Table for Emissivity at
Constant P*L vs Temperature**

										Comparison of Estimated Values vs Actual Values:			
^a Y=EMg (Lm = 5)	X=T, R	Y=EMg	X=T	X^2	X^3	X^4	XY	X^2Y	N	X=T	^b Emg calc	^a Emg act	Regression Constants
H2O													
0.524	500	0.524	500	250000	1.3E+08	6.2E+10	261.7507	130879.3	1	500	0.502	0.524	a = 0.5414497507
0.454	750	0.454	750	562500	4.2E+08	3.2E+11	340.4708	255353.1	1	750	0.481	0.454	b = -0.000078845
0.448	1000	0.448	1000	1000000	1.0E+09	1.0E+12	447.9210	447921.0	1	1000	0.461	0.448	c = -0.000000001
0.439	1500	0.439	1500	2250000	3.4E+09	5.1E+12	659.0545	988581.8	1	1500	0.419	0.439	
0.385	2000	0.385	2000	4000000	8.0E+09	1.6E+13	770.0440	1540088.	1	2000	0.377	0.385	A = -0.000000001
0.327	2500	0.327	2500	6250000	1.6E+10	3.9E+13	818.7107	2046776.	1	2500	0.334	0.327	B = -0.000086220
0.287	3000	0.287	3000	9000000	2.7E+10	8.1E+13	859.6425	2578927.	1	3000	0.290	0.287	C = 4400
0.242	3500	0.242	3500	12250000	4.3E+10	1.5E+14	846.4041	2962414.	1	3500	0.245	0.242	D = 0.5472118973
0.203	4000	0.203	4000	16000000	6.4E+10	2.6E+14	810.4573	3241829.	1	4000	0.199	0.203	E = -3437500
		3.308	18750	51562500	1.6E+11	5.5E+14	5814.464	14192772	9				
CO2													
0.197	500	0.197	500	250000	1.3E+08	6.2E+10	98.52694	49263.47	1	500	0.193	0.197	0 < T < 2500 R 2500 < T < 4000 R
0.169	1000	0.169	1000	1000000	1.0E+09	1.0E+12	168.5753	168575.3	1	1000	0.180	0.169	
0.197	1500	0.197	1500	2250000	3.4E+09	5.1E+12	295.7766	443664.9	1	1500	0.186	0.197	A = 0.000000038 A = -0.000000005
0.208	2000	0.208	2000	4000000	8.0E+09	1.6E+13	415.1764	830352.9	1	2000	0.211	0.208	B = 0.000012042 B = -0.000046021
		0.770	5000	7500000	1.3E+10	2.2E+13	978.0554	1491856.	4	2500	0.202	0.202	C = 2500 C = 6500
										3000	0.182	0.182	D = 0.177547454 D = 0.318483269
										3500	0.159	0.158	E = -1250000 E = -10250000
										4000	0.133	0.133	
0.202	2500	0.202	2500	6250000	1.6E+10	3.9E+13	504.6909	1261727.	1				a = 0.226150349 a = 0.2618517862
0.182	3000	0.182	3000	9000000	2.7E+10	8.1E+13	546.9544	1640863.	1				b = -0.00008516 b = -0.000010108
0.158	3500	0.158	3500	12250000	4.3E+10	1.5E+14	553.9544	1938840.	1				c = 0.000000038 c = -0.000000005
0.133	4000	0.133	4000	16000000	6.4E+10	2.6E+14	532.7577	2131031.	1				
		0.676	13000	43500000	1.5E+11	5.3E+14	2138.357	6972462.	4				

^a Values from first regression; EMg = a + b*(PL) + c*(PL)*(PL)

^b EMg = a + b*(T) + c*(T)*(T)

Table 4.5-4. Actual vs Estimated Emissivity

P*L FT*ATM	ACTUAL ESTIMATE DELTA			ACTUAL ESTIMATE DELTA			ACTUAL ESTIMATE DELTA			ACTUAL ESTIMATE DELTA			ACTUAL ESTIMATE DELTA			ACTUAL ESTIMATE DELTA			ACTUAL ESTIMATE DELTA			ACTUAL ESTIMATE DELTA		
	TEMPERATURE = 500			TEMPERATURE = 750			TEMPERATURE = 1000			TEMPERATURE = 1500			TEMPERATURE = 2500			TEMPERATURE = 3000			TEMPERATURE = 3500			TEMPERATURE = 4000		
H2O																								
0.2	0.19	0.210	-10.5%	0.15	0.189	-26.2%	0.13	0.170	-30.6%	0.115	0.135	-17.4%	0.065	0.081	-25.1%	0.05	0.063	-25.0%	0.039	0.049	-25.8%	0.03	0.041	-36.4%
0.3	0.23	0.224	2.7%	0.185	0.203	-9.7%	0.175	0.183	-4.7%	0.14	0.148	-5.6%	0.088	0.092	-5.0%	0.07	0.072	-3.4%	0.053	0.057	-8.3%	0.042	0.048	-13.2%
0.4	0.25	0.237	5.1%	0.205	0.216	-5.5%	0.19	0.196	-3.4%	0.165	0.161	2.7%	0.105	0.103	1.6%	0.083	0.082	1.2%	0.067	0.066	2.2%	0.053	0.054	-1.9%
0.6	0.29	0.263	9.3%	0.25	0.242	3.2%	0.235	0.222	5.6%	0.2	0.185	7.6%	0.13	0.124	4.4%	0.108	0.101	6.9%	0.088	0.081	7.6%	0.07	0.066	5.0%
0.8	0.31	0.288	7.2%	0.275	0.266	3.2%	0.26	0.246	5.4%	0.23	0.208	9.6%	0.155	0.144	7.0%	0.125	0.118	5.4%	0.105	0.096	8.2%	0.085	0.078	7.8%
1	0.33	0.311	5.8%	0.3	0.289	3.5%	0.28	0.269	4.0%	0.25	0.230	8.0%	0.17	0.163	4.0%	0.14	0.135	3.5%	0.115	0.111	3.8%	0.098	0.090	8.4%
1.5	0.38	0.363	4.4%	0.34	0.342	-0.4%	0.325	0.320	1.5%	0.295	0.280	5.2%	0.21	0.206	1.8%	0.177	0.173	2.0%	0.15	0.143	4.5%	0.12	0.116	3.6%
2	0.41	0.408	0.6%	0.36	0.386	-7.1%	0.35	0.364	-4.0%	0.32	0.322	-0.6%	0.23	0.243	-5.7%	0.2	0.206	-3.2%	0.16	0.171	-7.1%	0.14	0.138	1.3%
3	0.46	0.472	-2.5%	0.42	0.450	-7.1%	0.4	0.428	-6.9%	0.38	0.384	-1.1%	0.29	0.298	-2.8%	0.24	0.256	-6.6%	0.2	0.214	-7.0%	0.17	0.173	-1.5%
5	0.53	0.502	5.4%	0.46	0.481	-4.6%	0.455	0.461	-1.3%	0.445	0.419	5.8%	0.33	0.334	-1.2%	0.29	0.290	0.1%	0.245	0.245	0.0%	0.205	0.199	2.8%
AVERAGE % ERROR			5.3%	7.1%			6.8%			6.4%			5.9%			5.7%			7.4%			8.2%		
CO2																								
0.2	0.108	0.118	-9.3%	0.085	0.102	-20.3%	0.095	0.099	-4.3%	0.095	0.109	-14.3%	0.08	0.090	-12.0%	0.064	0.073	-13.5%	0.052	0.058	-11.8%	0.04	0.046	-15.6%
0.3	0.12	0.122	-1.4%	0.095	0.106	-11.8%	0.108	0.104	4.0%	0.108	0.114	-5.6%	0.09	0.095	-5.9%	0.074	0.078	-5.1%	0.06	0.063	-4.3%	0.048	0.050	-3.4%
0.4	0.13	0.125	3.6%	0.105	0.110	-4.9%	0.12	0.108	9.8%	0.12	0.119	0.4%	0.1	0.101	-0.9%	0.083	0.083	0.1%	0.067	0.067	0.2%	0.053	0.053	0.0%
0.6	0.14	0.132	5.5%	0.115	0.118	-2.4%	0.127	0.117	7.9%	0.13	0.130	0.1%	0.119	0.112	6.1%	0.096	0.093	3.5%	0.079	0.075	4.7%	0.062	0.059	4.1%
0.8	0.15	0.139	7.4%	0.125	0.125	0.1%	0.135	0.125	7.3%	0.145	0.140	3.7%	0.128	0.122	4.8%	0.108	0.102	5.6%	0.087	0.083	4.4%	0.069	0.066	4.9%
1	0.152	0.145	4.6%	0.132	0.132	0.3%	0.145	0.133	8.4%	0.155	0.149	4.0%	0.138	0.131	4.7%	0.119	0.111	7.0%	0.094	0.091	3.4%	0.076	0.072	5.8%
1.5	0.165	0.159	3.6%	0.142	0.147	-3.2%	0.16	0.150	6.2%	0.17	0.169	0.4%	0.158	0.153	3.2%	0.133	0.130	1.9%	0.11	0.108	1.9%	0.088	0.085	3.2%
2	0.17	0.171	-0.4%	0.152	0.159	-4.6%	0.17	0.164	3.4%	0.18	0.186	-3.5%	0.168	0.171	-1.6%	0.148	0.147	0.6%	0.12	0.123	-2.2%	0.097	0.097	-0.1%
3	0.18	0.187	-4.0%	0.162	0.176	-8.8%	0.18	0.183	-1.9%	0.2	0.209	-4.5%	0.185	0.196	-5.7%	0.163	0.171	-5.0%	0.138	0.145	-4.8%	0.11	0.116	-5.4%
5	0.2	0.193	3.4%	0.171	0.180	-5.2%	0.2	0.186	7.1%	0.21	0.211	-0.6%	0.205	0.202	1.4%	0.185	0.182	1.7%	0.16	0.159	0.8%	0.135	0.133	1.5%
AVERAGE % ERROR			4.3%	6.2%			6.0%			3.7%			5.8%			5.7%			7.5%			8.2%		
(ACTUAL EMISSIVITY DATA FROM HOTTEL AND SAROFIM)																								

Table 4.5-5. CO₂ and H₂O Emissivity Overlap Correction Factor

Regression Table

Comparison of Estimated Values vs Actual Values:										
Y=C _{so} ^a	X=PL	X ²	X ³	X ⁴	XY	X ² Y	N	X=PL C _{so} calc ^b	C _{so} act ^a	Regression Constants
0.016	0.10	0.01	0.00	0.00	0.00	0.00	1.00	0.10	0.02	a = 0.0122
0.030	0.25	0.06	0.02	0.00	0.01	0.00	1.00	0.75	0.05	b = 0.0660
0.052	0.75	0.56	0.42	0.32	0.04	0.03	1.00	1.00	0.06	c = -0.0193
0.059	1.00	1.00	1.00	1.00	0.06	0.06	1.00	1.50	0.07	A = -0.02
0.065	1.50	2.25	3.38	5.06	0.10	0.15	1.00	2.00	0.07	B = 0.03
0.068	2.00	4.00	8.00	16.00	0.14	0.27	1.00			C = 2.05
0.290	5.60	7.89	12.81	22.38	0.34	0.51	6.00			D = 0.02
Y	X	X ²	X ³	X ⁴	XY	X ² Y	N			E = -0.60

^a GAS PARTIAL PRESSURE RATIO OF $P_{CO_2}/(P_{H_2O}+P_{CO_2}) = .35$

GAS TEMPERATURE = 1000 R

Data from Hottel and Sarofrim

^b $C_{so} = a + b(P^*L_m) + c(P^*L_m)^2(P^*L_m)$

results from the overall heat and mass balance gas composition for the kiln. A procedure similar to that used to calculate the emissivity (i.e., by regressing data) could have been used. However it was felt that the small gain in accuracy did not justify the additional computational effort.

(5) The emissivity of the gas mixture was determined as specified by Hottel's equations by adding the separately calculated emissivity values for CO_2 and H_2O and applying the correction factor, C_{so} .

(6) The absorptivity of the gas mixture was determined as specified by Hottel's equations by adding the separately calculated absorptivity values for CO_2 and H_2O and applying the correction factor, C_{so} .

This regression method of estimating the gas emissivity has not been treated in the literature. This approach was also undertaken in part because the indirect-fired kiln model required the calculation of the emissivity of the inner shell gas which contained water but no CO_2 . The literature calculations of emissivity have been made only for combustion gases, which included CO_2 . The emissivities of CO_2 and H_2O could have been calculated separately also by using a gray/clear gas model. The emissivity and absorptivity of the kiln gas could then be calculated as suggested by Hottel. This would require knowledge of the weighting factors for CO_2 and H_2O . (See Section 4.5). The method for determining these factors had not been found during the model development but later was found reported in the thesis of T.R.

Johnson¹⁵. See Appendix G for the program listing of the gas data base.

4.6 Transmissivity of the Gas for Its Own Radiation

Introduction- The transmissivity of the gas for its own radiation is much lower than the absorption of radiation from a solid through the gas. The gas emission and absorption is characterized by two sharp peaks or bands in the infrared spectrum, while the black body or gray body radiation is continuous over the spectrum of interest. The absorption by the gas for gray or black body radiation will occur only within the bands or peaks in the gas spectrum, and therefore will result in lower values of gas absorptivity (and gas emissivity) than a black body. However the gas absorptivity for its own radiation is relatively high because the characteristic peaked radiation wavelength spectrum emitted by the gas is also the wavelength spectrum absorbed by the gas.

Previous Work -

The method as presented by Gorog¹ uses the weighting factors and absorption coefficients for the gray/clear gas model¹ to characterize the weighted average transmissivity of the gas for its own radiation, τ'_g , as shown in the following equation:

$$\tau'_g = \frac{\sum_{i=1}^N a_i K_i (e^{-K_i P L_m})}{\sum_{i=1}^N a_i K_i}$$

Each weighting factor, a_i , represents the fraction of black body energy in the emitting/absorbing wavenumber region associated with the absorption coefficient K_i . The term p represents the combined partial pressures of CO_2 and H_2O , and L_m is the average beam length of the gas in the enclosure. The equation has a similar form to that used to estimate the gray/clear gas emissivity. In the emission case, the weighting factors (a_i) refer to the ratio of the energy emission in the emitting wave number region of the gas to the total black body emission, and the denominator is the total black body emission which is defined equal to 1. However in this case, the denominator of the equation represents the total gas energy emission obtained by summing of the weighting factors (a_i) times the absorption coefficients (K_i). The numerator is the total gas energy transmitted through the gas and is equal to the summation of the product of $a_i K_i$ times the transmissivity ($e^{-K_i p L_m}$) for each K_i . The strong absorption of the gas for its own radiation is inherently treated in the Zone Method heat transfer analysis in the use of the gray/clear gas model weighting factors and absorption coefficients. However, the gas transmissivity for its own radiation is not discussed in studies which used the Resistive Network Method.

Current Work -

The present study does not use a gray/clear gas model to evaluate the transmissivity of the gas for its own radiation.

Rather this transmissivity (τ'_g) is determined (estimated) by a separate radiation balance (incorporated in the program) from the special case when the temperatures of the gas and all the surfaces are the same. In this situation, the heat flow from the gas to the solid surfaces can be equated to the heat flow from these surfaces to the gas so that the net gas-surface radiant heat exchange for each gas-surface pair is zero. The algebraic equations expressing this balance can be solved for the unknown transmissivity value of the gas for its own radiation when the other parameters affecting the heat balance (such as surface reflectivities, transmissivity of the gas for black body radiation, view factors, etc.) are specified.

The value of τ'_g calculated in this way can then be used in constructing heat balances for the usual cases where the solid surface temperatures do not equal the gas temperature. This approach is valid because the value of τ'_g is a function only of the gas temperature and composition and is independent of the surface temperatures.

Consider the simplified case of a single surface enclosure (kiln wall) with a participating gas (see Fig. 4.6-1). If the temperature of the wall and gas are equal, the system is at steady state, and the energy emitted from the wall and absorbed by the gas must be equal to the energy emitted by the gas and absorbed by the wall. That is

$$Q_{wg} = Q_{gw},$$



or from Fig. 4.6-1,

$$Q_{wg_1} + Q_{wg_2} + Q_{wg_3} = Q_{gw_1} + Q_{gw_2},$$

where Q_{wg_1} , Q_{wg_2} , and Q_{wg_3} are terms representing radiation from the wall absorbed by the gas, and Q_{gw_1} and Q_{gw_2} are terms representing radiation from the gas to the wall. The wall terms are,

$$Q_{wg} = ((1-\tau_{g1}) + \rho_w(\tau_{g1}-\tau_{g2}) + \rho_w^2(\tau_{g2}-\tau_{g3}))\epsilon_w A_w \xi_w$$

and for the gas,

$$Q_{gw} = (1+\tau'_g \rho_w) \alpha_w \epsilon_g A_g \xi_g.$$

The term ξ_w and ξ_g are the surface and gas emittance (σT^4), ρ_w is the surface reflectivity, α_w the surface absorptivity, ϵ_g is the gas emissivity, and τ_{g1} , τ_{g2} , and τ_{g3} are the gas transmissivities (for black body radiation) for beam lengths corresponding to the original ray, and its first and second reflections, respectively.

Noting that:

1. $\alpha_w = \epsilon_w$ for a gray body,
 2. $T_g = T_w$ so $\xi_w = \xi_g$, and finally,
 3. $A_w = A_g$, and therefore, $\epsilon_w A_w \xi_w = \alpha_w A_g \xi_g$,
 4. Noting the approximation for a real gas that $\epsilon_g = 1 - \tau_{g1}$.
- Equating $Q_{wg} = Q_{gw}$, and canceling equivalent terms:

$$\begin{aligned}
 (1-\tau_{g1}) + \rho_w(\tau_{g1}-\tau_{g2}) + \rho_w^2(\tau_{g2}-\tau_{g1}) &= (1+\tau'_g\rho_w)\epsilon_g \\
 &= \epsilon_g + \epsilon_g\tau'_g\rho_w \\
 &= 1-\tau_{g1} + \rho_w\epsilon_g\tau'_g
 \end{aligned}$$

Solving the expression for τ'_g :

$$\tau'_g = ((\tau_{g1}-\tau_{g2}) + \rho_w(\tau_{g1}-\tau_{g2}))/\epsilon_g \quad \text{Eq. 4.6-1}$$

It may be seen that Eq. 4.6-1 includes a small term involving the solid wall surface reflectivity, ρ_w . With a higher ρ_w , the reflections of the original radiation emitted by the wall would be stronger and permit more wall radiation to be absorbed by the gas. Because the radiation from the gas to the wall must equal the radiation from the wall to the gas where both are at the same temperature, the mathematical result using the Reflection Method is that τ'_g must increase to compensate for the larger fraction of reflected gas radiation which strikes the wall. (Incorporating a larger number of reflection terms in this balance does not cancel the presence of the ρ term.)

The heat balance equations for Q_{sg} , Q_{wg} , and Q_{fg} were copied and edited in the program for calculating τ'_g so that the temperature of the solid, wall, and flame used in these equations was that of the gas. (See Fig. 4.6-2). The solid-to-gas equations represent the net heat absorbed by the gas from radiation originating from the solids. The gas-to-solids equations (Q_{gs} , Q_{gw} , and Q_{gf}) represent the net heat absorbed by the solids from the radiation originating

sg	1	$-(1-TR_{gg1}) \cdot EM_s \cdot A_s$	-0.0835
	2	$-(TR_{gg1}-TR_{gg2}) \cdot F_{sw} \cdot p_w \cdot EM_s \cdot A_s$	-0.0026
	3	$-(TR_{gg2}-TR_{gg3}) \cdot F_{ww} \cdot F_{sw} \cdot p_w \cdot p_w \cdot EM_s \cdot A_s$	-0.0002
	4	$-(TR_{gg2}-TR_{gg3}) \cdot F_{ws} \cdot F_{sw} \cdot p_s \cdot p_w \cdot EM_s \cdot A_s$	-0.0001
			-0.0864
wg	1	$-(1-TR_{gg1}) \cdot EM_w \cdot A_w$	-0.3175
	2	$-(TR_{gg1}-TR_{gg2}) \cdot F_{ww} \cdot p_w \cdot EM_w \cdot A_w$	-0.0077
	3	$-(TR_{gg2}-TR_{gg3}) \cdot F_{ww} \cdot F_{ww} \cdot p_w \cdot p_w \cdot EM_w \cdot A_w$	-0.0007
	4	$-(TR_{gg2}-TR_{gg3}) \cdot F_{ws} \cdot F_{sw} \cdot p_s \cdot p_w \cdot EM_w \cdot A_w$	-0.0003
	5	$-(TR_{gg2}-TR_{gg3}) \cdot F_{ws} \cdot F_{ww} \cdot p_s \cdot p_w \cdot EM_w \cdot A_w$	-0.0002
	6	$-(TR_{gg1}-TR_{gg2}) \cdot F_{ws} \cdot p_s \cdot EM_w \cdot A_w$	-0.0026
			-0.3290
fg	1	$-(1-TR_{gg1}) \cdot EM_f \cdot A_f$	-0.1546
	2	$-(TR_{gg1}-TR_{gg2}) \cdot p_s \cdot F_{fs} \cdot EM_f \cdot A_f$	-0.0016
	3	$-(TR_{gg2}-TR_{gg3}) \cdot p_s \cdot p_w \cdot F_{fs} \cdot F_{sw} \cdot EM_f \cdot A_f$	-0.0002
	4	$-(TR_{gg1}-TR_{gg2}) \cdot p_w \cdot F_{fw} \cdot EM_f \cdot A_f$	-0.0056
	5	$-(TR_{gg2}-TR_{gg3}) \cdot p_w \cdot p_s \cdot F_{fw} \cdot F_{ws} \cdot EM_f \cdot A_f$	-0.0002
	6	$-(TR_{gg2}-TR_{gg3}) \cdot p_w \cdot p_w \cdot F_{fw} \cdot F_{ww} \cdot EM_f \cdot A_f$	-0.0005
			-0.1627
$TR_{gl1} = \frac{-(T_{fg}+T_{wg}+T_{sg}) - EM_g \cdot (A_f + AB_w \cdot A_w + AB_s \cdot A_s)}{(EM_g \cdot (p_w \cdot A_w \cdot (F_{wf} + AB_w \cdot F_{ww} + AB_s \cdot F_{ws}) + p_s \cdot A_s \cdot (F_{sf} + AB_w \cdot F_{sw})))}$			
			0.2599
$TR_{gs11} = \frac{(-t_{sg} - AB_s \cdot EM_g \cdot A_s)}{(AB_s \cdot p_w \cdot F_{ws} \cdot EM_g \cdot A_w)}$			
			0.2601
$TR_{gw11} = \frac{(-t_{wg} - AB_w \cdot EM_g \cdot A_w)}{((p_w \cdot F_{ww} \cdot A_w + p_s \cdot F_{sw} \cdot A_s) \cdot AB_w \cdot EM_g)}$			
			0.2599
$TR_{gf11} = \frac{(-t_{fg} - A_f \cdot EM_g)}{((p_w \cdot F_{wf} \cdot A_w + p_s \cdot F_{sf} \cdot A_s) \cdot EM_g)}$			
			0.2599

Figure 4.6-2. Calculation of Gas Transmissivity for Its Own Radiation

from the gas. The value of the transmissivity of the gas for its own radiation, τ'_g is the only parameter in this balance which has not been specified in this copied set of equations. These equations are solved numerically for this value, τ'_g . The value of τ'_g obtained in this manner is slightly higher than the value derived by the gray/clear gas method, and accounts for the radiation reflected by the enclosure surface.

4.7 Flame Emissivity

Previous Work -

Luminous radiation from flames occurs mainly as a result of the radiation from suspended solid particles. These particles, usually carbon, heavy hydrocarbon compounds, or ash (as in coal flames) emit significant amounts of radiation through a continuous spectrum extending into the visible range. The particles of carbon or heavy hydrocarbon compounds are termed soot, and result from thermal decomposition of fuel under oxygen deficient conditions.

The prediction of flame radiation characteristics is a complex problem on which much research work is currently being done¹¹. The emissivity of a luminous flame could be predicted satisfactorily provided one knew:

1. the distribution of soot within the flame, and
2. the optical properties of the soot in the flame.

However these properties have been measured only for a few particular flames different from that in the kiln used to test

this model. These quantities have not been calculated from theoretical considerations, but have been estimated from experimental measurements. Absorption coefficients appear to depend strongly on the chemical composition of the soot, but there is no way of knowing what these values will be at any point in the flame (Johnson)³⁵. The general theoretical prediction of flame characteristics is difficult because it involves the simultaneous characterization of turbulent fluid flow, the kinetics of the fuel burning reaction and the kinetics of the burnout of soot formed in flames, taking into account the heat and mass transfer problems involved. Each of these phenomena is affected by particular kiln operating conditions such as burner configuration, kiln configuration, firing rate, fuel type, and excess air usage.

Characterization of a flame has therefore been limited to particular flames for specific operating conditions where experimental measurements have been made. Only a few detailed experimental studies of industrial type flames have been found in the literature (Jenkins³⁸, Johnson³⁵, Weber⁴⁰, Falliot⁴¹). This is in part due to the inherent complexity of such studies.

In the absence of experimental data, the flame is commonly modeled in the literature (Brimacombe³) as a gray or black body. With the use of the gray flame model, heat transfer estimates sufficiently accurate for most practical purposes have been made. The emissivity of a gray flame is dependent on the type of fuel combusted (related to the average molecular weight of the fuel) and, to some extent on the firing rate, burner

configuration, flame diameter, and amount of air in and around the burner. Gas flames have a low emissivity in the range of 0.4 to 0.6. Coal flames have a high emissivity in the range of 0.9 to 1.0, in part due to the ash present in coal³.

Current Work -

An alternative to the gray body treatment to determine the flame emissivity is to estimate the optical properties and distribution of soot in the flame based on empirical data from other flames. However such data are scarce and of questionable applicability to the modeled flame. Due to the high emissivity of oil and coal flames (.8 to 1.0), the error introduced by treating the flame as a gray body is relatively small (Brimacombe)³. Therefore in view of the absence of reliable experimental data, and the relatively small error introduced, the flame is treated in the present model as (a modified black body which is equivalent to) a gray body with an emissivity of 0.8 which is in the range of fuel oil flames of 0.8 to 1.0 suggested by Brimacombe³ and Thring⁴.

5.0 CONVECTIVE AND CONDUCTIVE HEAT TRANSFER

Previous Work -

Convection and conduction usually account for 10% to 30% of the heat transferred in a rotary kiln (Brimacombe, Johnson, Jenkins, Weber⁴⁰, Folliot⁴¹). Values of heat transfer coefficients are reported by several authors in the literature Brimacombe, Watkinson⁴², Tscheng and Watkinson⁴⁷, and Kreith⁴³ among others.

Current Work -

Values of heat transfer coefficients (HTC) cited in the program were those reported by Brimacombe and Watkinson⁴². The coefficient values are variables which are input in the program.

An alternative would have been to use equations cited by the above authors to estimate the HTC values. However these equations are approximate, and sufficient data to apply them are not available in all cases.

The convective heat transferred from the gas to the solid bed and wall accounts for 5% to 10% of the heat transferred to the wall and bed. The value for convective HTC from the gas to the wall is based on Eq. 5.0-1 (Tscheng and Watkinson)⁴⁷.

$$h_{cvgw} = 0.036(K_g/D)Re^{0.8} P_r^{0.33} (D/L)^{0.55} \quad \text{Eq 5.0-1}$$

where

K_g = gas thermal conductivity W/m K

Re = Reynolds number = $\rho V D / \mu$

where ρ = gas density

V = gas velocity

D = kiln diameter, m

μ = viscosity, kg/m s

P_r = Prandl number = $C_p \mu / K$

where, C_p = heat capacity of the gas

K = thermal conductivity of the gas, W/m

D = kiln diameter, m

L = kiln length, m

The value obtained from this HTC varied from 3 to 5 BTU/ft² F in the results published by Tscheng and Watkinson⁴⁷.

The value for convective HTC from the gas to the solid bed is the least well known of all the heat transfer coefficients. No verified equation³ has been found in the literature to calculate the value. The equation cited by Brimacombe is

$$h_{cvgs} = 0.4 G'_g{}^{0.63}$$

where G'_g = gas mass flux Kg/m² hr

So again, the values reported by Brimacombe³ of 8 to 16 BTU/ft² F were used. Variations in the convective heat transfer coefficient will not significantly affect the overall heat transfer due to the small contribution from heat transferred by convection (5 to 10%).

The HTC between the wall and solid bed considers the heat transferred by conduction inside the kiln from the wall section covered by the solid bed to the solid bed. The following equation is cited by Tscheng and Watkinson⁴⁷ for conductive heat transfer:

$$h_{cdws} = 11.6 K_s / D \gamma_L (\omega R_I^2 \gamma_L / 30 k_s)^{0.3}$$

where,

K_s = solid thermal conductivity W/m K

k_s = solids thermal diffusivity, m^2/s

γ_L = solid bed half angle

D = kiln diameter, m

R = inner kiln radius, m

ω = rev/s

The value using this equation was not calculated for soil and again Brimacombe's estimate was used. The reported range of the value for limestone is 8 to 16 BTU/ft²F.

The suggested ranges from these literature references for the HTC values are considered acceptable because of the small effect convection and conduction heat transfer have in a rotary kiln. The program allows for the input of more reliable HTC values when they become available.

5.1 Shell Heat Loss

Shell heat loss and conduction of heat through the wall is accounted for in the model. The rate at which heat is conducted through the wall is equal to the rate at which heat is lost from the outer shell by convection and radiation. (See Fig. 5.1-1). The thermal conductivity values for the refractory materials used in the kiln modeled are a variables input to the program and are used to calculate the rate of heat conduction through the wall of the kiln by the following equation:

$$q_{\text{cond}} = h_{\text{cd}} A_3 (T_w - T_{\text{sh}})$$

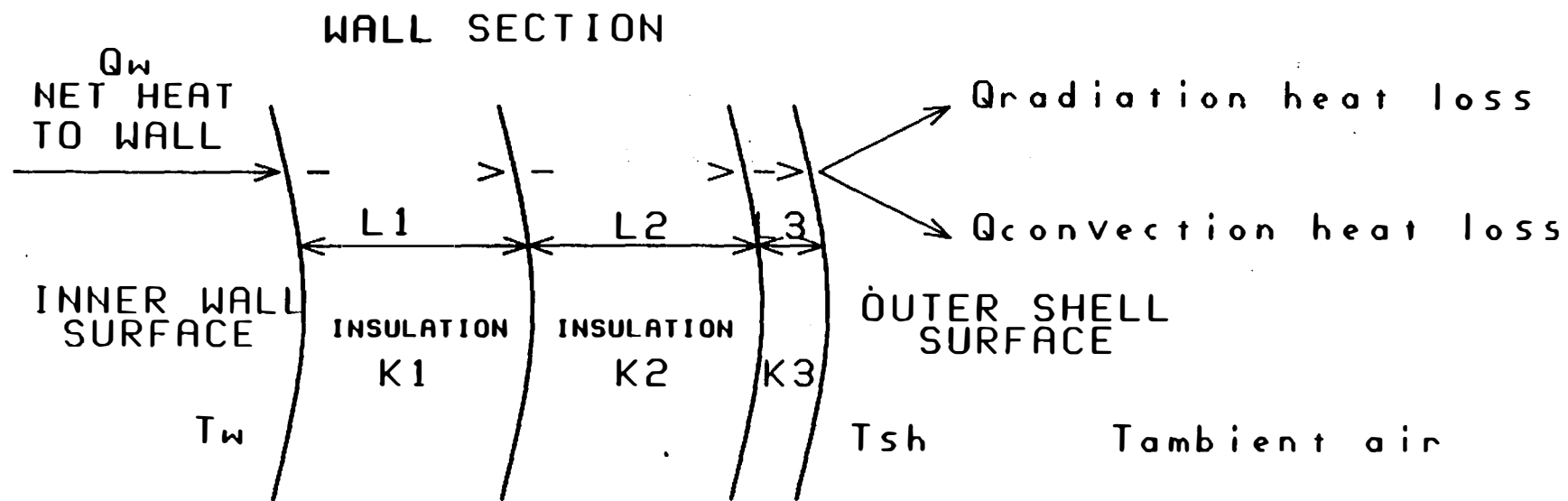


Figure 5.1-1. Shell Heat Loss

where $h_{cd} = (1/2\pi r_3) / ((r_2 - r_1) / (\pi K_1 (r_1 + r_2)) + (r_3 - r_2) / (\pi K_2 (r_2 + r_3)))$
 where,

h_{cd} = conductive heat transfer coefficient, W/m^2K

A_3 = area of second layer of refractory, m^2

T_w = temperature of inner wall surface, K

T_{sh} = temperature of outer shell surface, K

r_1 = inner kiln radius, m

r_2 = kiln radius for first layer of refractory, m

r_3 = kiln radius for second layer of refractory, m

r_4 = kiln radius for outer shell thickness, m

K_1 = thermal conductivity of refractory layer or shell, W/m^2K

The value for the shell convection coefficient was taken from the range suggested by Brimacombe³ of 3 to 5 BTU/ft².

The equation by Brimacombe is:

$$h_{cvsh} = (K_a P_r^{0.3} / D)(C)(Re)^N$$

where $C = 0.193$ for Re values of 4,000 to 40,000, and

$$N = 0.618$$

D = outer kiln diameter, m

K_a = thermal conductivity of air $W/m K$

P_r = Prandl number

Re = Reynolds number

This equation is similar to the equation cited in Perry 5th edition⁴⁶ for convective heat transfer in tube bundles:

$$hD/k = a(Re)^{.6}(Pr)^{.33}$$

where the constant a is determined by the tube bundle configuration and the amount of leakage air normal to the tube bundle.

The value for the emissivity of the outer shell was also taken from Brimacombe, and was verified using the temperature dependent equation cited by Jenkins¹⁸. The rate of heat loss from the shell is dependent on the outer shell temperature which in turn is related to the heat losses from the kiln interior by convection, radiation, and conduction. The determination of the outer wall temperature becomes a trial and error procedure in the program. The shell temperature could also be determined directly by the solution of a fourth order equation (if the inner wall temperature and K-values are specified). This shell heat balance is represented by Eqn. 5.1-1:

$$q_{\text{cond}} = q_{\text{conv}} + q_{\text{rad}} \quad \text{Eq. 5.1-1}$$

substituting,

$$h_{\text{cd}}(T_{\text{w}} - T_{\text{sh}}) = h_{\text{cvsh}}(T_{\text{sh}} - T_{\text{a}}) + h_{\text{rad}}(T_{\text{sh}} - T_{\text{amb}})$$

$$h_{\text{rad}} = \sigma \epsilon_{\text{sh}} (T_{\text{sh}}^4 - T_{\text{a}}^4) / (T_{\text{sh}} - T_{\text{a}})$$

where, h_{cd} is the conductive HTC for the wall, h_{cvsh} is the convective HTC for the outer shell, h_{rad} is the linearized radiative HTC for the outer shell, and

T_{sh} = shell temperature, K

T_{a} = ambient air temperature, K

T_{w} = inner wall surface temperature, K

σ = Boltzmann constant, $\text{W/m}^2 \text{K}^4$

ϵ_{sh} = shell emissivity

Solving for the shell temperature using Eq. 5.1-1,

$$T_{sh} = (h_{cd} A_3 T_w + A_{sh} h_{cvsh} T_a + A_{sh} h_{rad} T_a) / (h_{cd} A_3 + A_{sh} h_{cvsh} + A_{sh} h_{rad})$$

Note that h_{rad} is a function of T_{sh} , and a trial and error solution of T_{sh} is required. Beginning with an initial estimated shell temperature, the program predicts a new value for the temperature of the shell which is closer to the correct value. The new temperature is then used in the program to predict a still closer approximation to the correct value. This process is repeated until the value converges to the final correct temperature. This is a simple and rapidly converging iteration. Usually a satisfactory temperature is found after only a few iterations.

6.0 DEVELOPMENT OF A COMPUTER PROGRAM FOR THE DIRECT-FIRED KILN MODEL

Current Work -

In the forgoing chapters, the main elements of a theoretical model for heat transfer in a direct-fired kiln are discussed, including a number of modifications and improvements to the basic Reflection Method as presented by Gorog¹. In this chapter it is indicated how all of these elements are combined in an overall heat transfer model for the operation of a direct-fired kiln. A computer program was written in the LOTUS 1-2-3 worksheet language for carrying out the model calculations on a PC computer. The program listing is included in Appendix E.

The program calculates the heat transfer in the kiln for any selected set of temperatures in each section of the kiln. At steady state, the heat entering and leaving each section must balance. Radiant heat transfer among the kiln wall, hot gases, and the solid bed is the predominant mode of heat transfer, but the program also takes into account convective and conductive heat transfer within the kiln and out through the kiln wall. Heat generation by combustion of the fuel in the flame region is also accounted for. From the direction of imbalance calculated by the program on the basis of the initial set of temperatures selected by the user, the direction of adjustment of temperatures is indicated for the next set of trial temperatures. This process is repeated (usually requiring a few

dozen trial iterations) until the final temperature profile for a kiln section produces a satisfactory overall heat balance. (If this program were to be used repeatedly, then the iterative process could be simplified by the use of circular reference equations for the temperature inputs in the spreadsheet. A circular reference in an equation in LOTUS 1-2-3 is noted on the bottom of the screen with a high-lighted message, CIRC, and denotes that an equation, A, which references a second equation B, is referenced in equation B. For example,

$$A = +B, \text{ and}$$

$$B = +A + (\text{Limit-Value}) * \text{factor},$$

where A is the input and B predicts the next value of A based on the difference between a desired limit and a resulting value (which is a function of the input A) times a scaling factor. This allowance of circular references in LOTUS 1-2-3 is very useful for trial and error solutions. A circular reference is allowed only in the manual calculation mode. This circular calculation procedure would automatically estimate the new trial temperatures by (manually) recalculating the worksheet until the final temperatures are obtained within a section. Different sets of circular equations would be required for the flame region and the downstream gas region.)

The program is set-up primarily to provide equations and calculational procedures to determine all of the heat transfer phenomena which take place within a single kiln section. This involves specifying parameters such as kiln geometry, feed rates, initial temperatures, fuel firing rates, etc.. It also

involves tracking the enthalpy of the gas and solid bed from one kiln section to the next. Tracking these enthalpies and corresponding temperatures is a large part of the effort of using the program.

The intent of the LOTUS 1-2-3 program as written was not to develop the most efficient computer program for carrying out the calculations and iterations involved, but rather to demonstrate how a number of modifications and improving features could be incorporated in a computer program to model a rotary kiln. The intent of this chapter is to describe the calculational procedure and method involved. The program was written using the LOTUS 1-2-3 language because it is a good language allowing the user to see all of the interrelationships involved in the model. This kiln heat transfer model is the first which has been reported on a PC computer.

A faster language such as Fortran or even BASIC would be better suited for repeated use of the program to calculate the temperature profile without user assistance. Several hours may be required to compute the temperature profile in a kiln using the LOTUS 1-2-3 program as developed, where as in Fortran it is estimated that the same task could be completed in several minutes. The program development work done in LOTUS 1-2-3 could be used to write and structure a Fortran program using the flow diagram shown in Fig. 6.0-1.

6.1 Radiation Balance

The Reflection Method as originally developed by Succoc³⁴ is basically a set of simple algebraic equations which represent

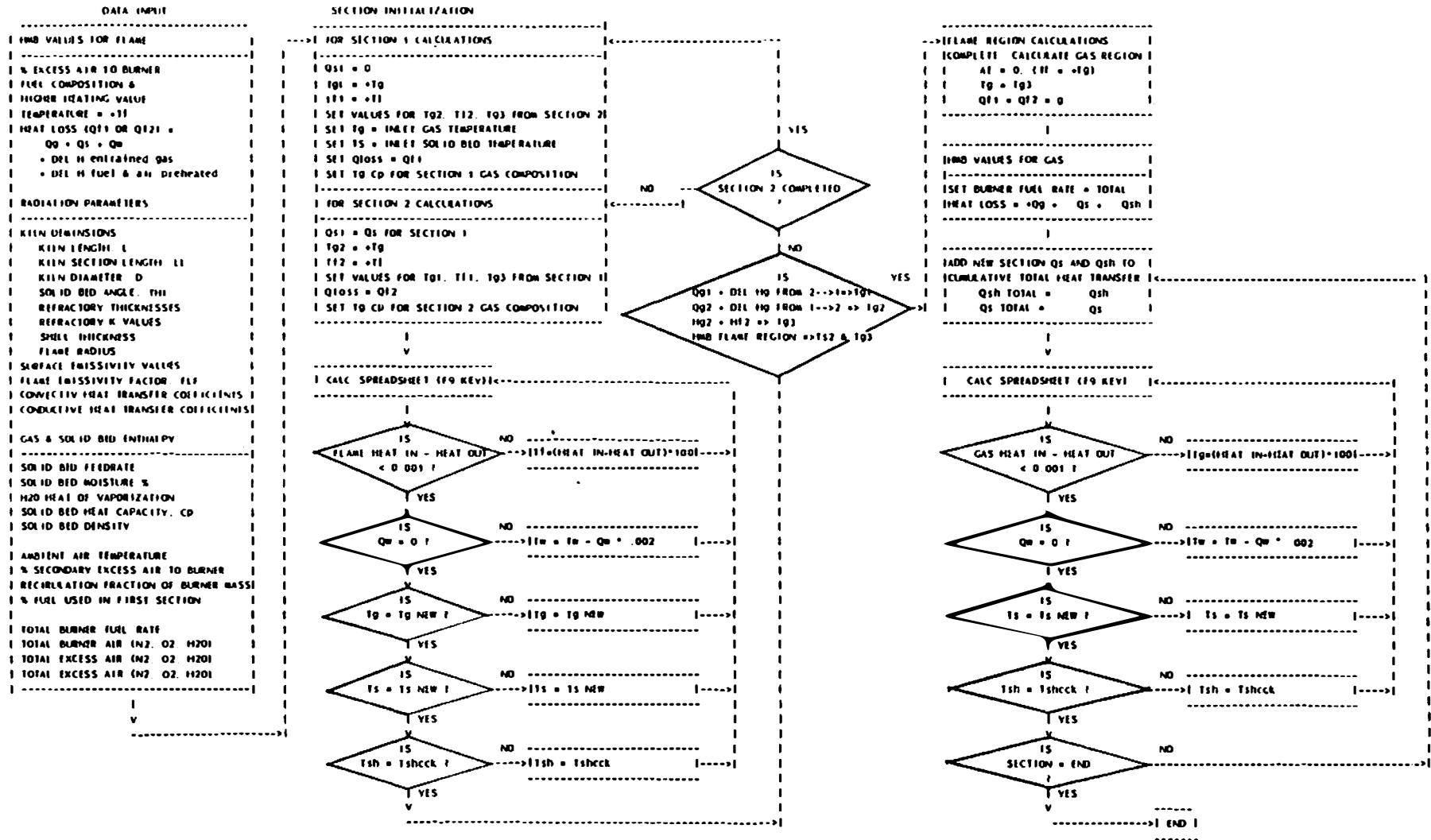


Figure 6.0-1. Computer Model Calculational Flow Diagram

the various emissions, absorptions, and reflections involved in calculating the radiation balance using the surface and gas properties and geometrical factors (view factors) required to model the kiln. (See Table 4.2-6 for list of equations in the radiation balance). The work by Gorog¹ outlines the general application of the method to a rotary kiln in which gas radiation without a flame is the principal source of heat. Gorog treated the gas as a gray/clear gas and the wall and solid bed as gray bodies. This treatment was modified in the present model to include,

- (1) the effect of the flame as a radiating and absorbing body,
- (2) the effect the re-entrainment of gases in the flame region,
- (3) the effect of conductive and convective heat transfer, and
- (4) the effect of using gas emissivity based on experimental data.

These modifications provide a more complete model of heat transfer in a direct-fired rotary kiln.

For a given set of kiln operating conditions, the modified radiation balance, using the Reflection Method, will determine the temperature profile of the gas and surfaces within the enclosure. The selection of the set of gas and surface temperatures which allows the radiation balance to be satisfied depends on the overall heat balance, including the addition of combustion heat and heat transfers by convection and conduction (Eq. 6.1-1) and any further constraints, such as steady state operation, imposed on the system by the inner kiln balance (Eq. 6.1-2)

Overall Balance

$$H_{\text{air}} + Q_{\text{comb}} = H_{\text{gas}} + H_{\text{solids}} + Q_{\text{shell loss}} \quad (\text{Eq. 6.1-1})$$

Inner Balance

$$Q_{\text{flame}} = Q_{\text{gas}} + Q_{\text{solids}} + Q_{\text{wall}} \quad (\text{Eq. 6.1-2})$$

where H is the enthalpy and Q is the heat gained or lost. Also the temperature distribution of the surfaces in the enclosure is such that at steady state the rate of energy gained is equal to the rate of energy lost for each surface in the enclosure.

Steady state constraints for the solid bed and gas, wall, and flame are discussed below in Sections 6.1.1, 6.1.2, and 6.1.3.

6.1.1 Temperature Convergence Criteria for the Solid Bed and Gas

There are two ways in which the temperature of the solid or gas can be calculated to estimate the temperatures within any section of the kiln and how it affects the temperature to be used in the next section:

- (1) The gas or solid temperature can be specified as the inlet temperature and the resulting final temperature determined by the heat absorbed by the gas or solid at the specified inlet temperatures in that section of the kiln can be used as the temperature in the next section, or
- (2) The temperature of the solid or gas in the section can be specified such that the heat absorbed by the gas or solid bed is sufficient to raise the gas or solid bed from the inlet temperatures to the specified temperature of the gas or solid.

The heat transfer is different depending on whether the heat is transferred to a hot or cold body. The latter method is thought to be better represent the actual situation, recognizing that either method is approximate. The program references the value of the heat transferred to the solid bed or gas and calculates how much the temperature of the solid bed or gas would increase or decrease. The 'average' temperature of the solid bed or gas is determined when the temperature input matches the resulting temperature of the solid bed or gas calculated by the program. The solid bed and gas will enter a given section at an initial temperature, absorb or lose heat, and exit at a different final temperature. In the first method, the inlet temperatures maybe much different than the actual gas and solid temperatures in a given section, and thus can result in unreasonably high heat transfer. The latter method is a type of average of the initial and final temperatures as calculated by the first method. The later method is preferred for the following reasons:

- (1) The gas and solid bed heat up very rapidly, and the use of the entering temperatures in the first section result in unreasonably high gas and solid bed temperatures.
- (2) The solid bed is generally modeled as a well mixed bed (Brimacombe³) even though it absorbs heat through the outer surface of the bed which is thought to be hotter than the inner portion of the bed (Watkinson)^{4,2}. That is, the bed material acts as an insulator, which allows the surface of the bed to heat up more rapidly than the interior. Thus, the use of an 'average' temperature higher than the entering

temperature models the physical behavior more closely than an initial or final temperature would.

6.1.2 Wall Balance

The assumption of steady state operation requires that the temperature for a given point in the system remains constant. From this constraint, the net rate at which the wall absorbs heat must equal the rate heat is conducted through the wall and lost to the ambient surroundings by convection and radiation (see Fig. 5.1-1). The heat lost from the shell is included in the wall balance. In this manner, the temperature of the wall is determined when the heat balance for the wall is zero. That is, the net heat to the wall from inside the kiln minus the heat lost through the wall to the outside is zero.

6.1.3 Flame Balance

Considering next the flame region in a rotary kiln, the rate at which the flame loses heat to the surrounding gas and enclosure surfaces is balanced by the net fuel combustion heat release rate in the flame. The temperature of the flame in any section is determined by the basic condition that the rate of heat entering that section is equal to the rate of heat leaving that section. The heat leaving is the net heat transferred from the flame to the surrounding gas, solid bed, and wall. The heat entering is the heat of combustion minus the heat required to heat the air and reaction products and unburned air and fuel components to the temperature of that section of the flame.

An overall heat and mass balance of the flame region developed by David Pitts of IT Corp.⁴⁴ was modified to be used as the flame balance in the present work. The heat and mass balance program is listed in Appendix E. The present calculations consider only fuel oil to be combusted in the balance, however, different fuel compositions could be treated by the balance. The balance calculates the heat of combustion for the fuel specified composition and the mass and enthalpy of the resulting combustion gases. The primary inputs used in the balance include:

- (1) fuel composition,
- (2) burner excess air,
- (3) flame heat loss,
- (4) flame temperature, and
- (5) fuel firing rate, lb/hr.

The enthalpy calculation is referred to a standard temperature of 60°F. The inputs to the balance are adjusted until the 'heat in' equals the 'heat out'. In the present work, the temperature of the flame was adjusted by the iteration process in the program to satisfy this condition.

The flame provides all the heat to the system, and the flame heat loss must include:

- (1) the heat transferred to the gas, wall, and the solid bed,
- (2) heat required to heat up the entrained air to the temperature of the flame,
- (3) the heat required to compensate for any unburned fuel or burner air remaining after the first section. (The fuel and

air in the burner not combusted in the first section is vaporized or heated to the flame temperature of the first section. The heat required to vaporize the fuel is added to the heat loss in the first section and credited to the heat loss calculation for the second section of the flame region balance), and

- (4) the heat lost from the kiln shell. (This is equal to the heat absorbed by the inner wall).

The flame heat loss is a formula in the program which sums up these above heat losses. The ''correct'' flame temperature T_{f1} is determined when:

- (1) the heat lost by the flame is equal to the heat released in that section of the flame, and
- (2) the temperature of the gas, wall, and solid bed are such that the heat lost by the flame equals the heat gained by the solid bed, wall, and gas.

6.2 Co-current and Countercurrent Kiln Operation

In industrial practice, the principal interest in developing a heat transfer model is to calculate the temperature profile of the solid bed and the exit temperature of the gas for a given length kiln, or to estimate the length of the kiln required to obtain some exit temperature of the gas and solids. The temperature profile of the solid bed is in part determined by whether the kiln solid feed is operated with co-current flow of the gas, ''co-current operation'', or with countercurrent gas flow, ''countercurrent operation''. Either mode of operation

can be treated by the model developed.

If the kiln is operated co-currently, the solid bed is heated up rapidly by the flame early in its progression through the kiln: this operation allows the solid bed to 'cook' at a high temperature for a longer section of the kiln than counter current operation would allow. However the co-current operation of a kiln is not as efficient in heating the solid bed as a countercurrent kiln because the temperature difference between the gas phase and the solid bed decreases rapidly as the solid bed is heated, resulting in poor heat transfer at the exit end of the kiln. In countercurrent operation, the temperature difference between the gas and solid bed is optimized and allows higher exit temperatures of the solid bed to be obtained more efficiently than with co-current operation. For a given kiln and firing rate, countercurrent operation will yield a higher exit temperature of the solids in the kiln. Alternatively it would allow use of less fuel to meet the same exit solids temperature, a smaller kiln, or higher through-put of solids if the gas-to-solids heat transfer is the limiting factor in the kiln.

The operation of a countercurrent kiln is controlled principally by the following variables,

- (1) kiln length,
- (2) fuel firing rate,
- (3) solid feed rate, and
- (4) exit solid bed temperature.

If the first three variables are specified, the exit solid bed

temperature (T_{sx}) is calculated by a trial and error process. An initial T_{sx} is assumed and the program calculates the inlet solid bed temperature (T_{si}). If T_{si} does not match the known T_{si} , the T_{sx} is adjusted to give a closer match of the calculated with the known T_{si} . This process is repeated until the calculated T_{si} matches the known T_{si} . In this process, the temperature profile of the kiln will have been determined. (For the indirect-fired kiln, which is operated counter-currently, calculations to estimate the temperature profile are made in the same way).

For the present calculation, the kiln was operated co-currently because the experimental data available to verify the model were taken from a kiln which operated co-currently. For co-current operation, the exit temperatures of the solid bed and gas can be calculated directly (without a trial and error process) for a given kiln geometry, firing rate, and the entering solid and gas temperatures.

6.3 Calculation of the Temperature Profile in the Flame Region

The calculation of the temperature profile in the flame region is strongly influenced by the assumptions made regarding the recirculation and entrainment of combustion gases. In section 3.1 and 3.3, reasons are given for subdividing the flame into two sections and for assuming that twice as much gas is entrained in the second section as in the first section of the flame. The ratio of the mass of gas recirculated to the mass of gas fired through the burner is determined from the Thring and

Newby correlation (see Appendix A). For other kiln designs, this ratio and the fraction of gases entrained in each section are variable inputs in the program.

The gas in the flame region surrounding the flame of the kiln is heated simultaneously by the thermal convection (mixing) due to gas recirculation and by radiation heat transfer in the kiln from the flame and wall. The exact effect of these two factors on the gas temperature calculation depends upon whether the mixing or the radiant heat transfer is calculated first. If the flame radiates heat to the gas before it is heated by mixing, the mixed gas would be hotter. It was assumed that the gases are first mixed (resulting in a 'mixed gas' temperature) and then heated by radiant heat transfer from the flame. This order of calculation maximizes the effect of gas recirculation on the gas temperature, while the opposite order would maximize heat transfer by radiation.

The final temperature of the flame and of the gas surrounding the flame in each section is determined in four steps:

- (1) The first trial temperatures of the gas surrounding the flame in each section are initially estimated.
- (2) An enthalpy balance for the section calculates an HMB (heat and mass balance) temperature based on the masses and temperatures of gases entering and exiting it (see Fig.3.1.2-1).

- (3) From this temperature, the gas is heated further by heat transfer in the kiln to reach the temperature of the gas entering the next section.
- (4) If the overall balance of the flame region is not satisfied, these new gas temperatures are adjusted, and the process is repeated.

For the first section of the gas in the flame region of the gas surrounding the flame the procedure is to:

- (1) Estimate the temperature of the gas T_{g2} in the second section and the temperature of the gas T_{g3} recirculated to the second section. An overall kiln balance for the flame region is used to provide an estimate of the temperature of the gases T_{g3} recirculated to the second section taking into account the shell heat loss and the solid bed temperature at the end of the flame region.
- (2) Calculate the enthalpy balance temperature T_{g1} of the gas mixture in the first section, and then
- (3) Calculate the heat absorbed by the gas from the radiation balance.

The resulting temperature is then used as the T_{g1} temperature going into the second gas section. (See Fig.3.1.2-1 block diagram). This procedure is illustrated by the calculational flow diagram of Fig. 6.0-1.

For the second gas section, the temperature of the gas is determined by

- (1) calculating the enthalpy balance temperature T_{g2} of the

gas mixture in the second section (the calculated gas temperature T_{g1} from section 1 and the calculated temperature of the hot recirculated gases T_{g3} from the end of the flame region),

- (2) calculating the heat absorbed by the gas from the flame and wall from the radiation balance using the mixed gas temperature T_{g2} as the initial temperature.

The resulting calculated gas temperature T_{g2} of the second section is then compared to the temperature initially estimated in the second section and the temperature of the gases T_{g3} downstream of the flame recirculated to the second section is calculated based on the mass and temperature of T_{g2} and T_{f2} exiting the flame region. If the calculated temperatures do not match those initially estimated, then the procedure is repeated using the new calculated value for the second gas temperature T_{g2} and the gas temperature T_{g3} exiting the flame region is recalculated using the overall balance for the flame region. The procedure is repeated until the trial temperatures used match the previous gas temperatures used. The entire procedure takes about five iterations of the trial gas temperature estimated in the second section before the calculated gas temperatures and previous trial gas temperatures are within a degree. This procedure is discussed in further detail in Appendix B.

Dividing the flame region into more than two sections would involve a similar procedure, but the calculational time involved would be considerably more. Two sections for the flame region

are considered sufficient in light of the accuracy of other parameters and assumptions used in such models. If one flame section is used, the (above) procedure calculates the temperature of the gas in the flame region easily with only one or two iterations of the exit gas temperature leaving the flame region. The variation in the heat transfer results caused by treating the flame region as one or two sections is discussed in Section 8.0, Results and Discussion.

6.4 Kiln Modeled with Flame Absent from View of the Enclosure

The case where a flame is not in direct view of the kiln enclosure may be modeled using the radiation balance as presented by Gorog for gas radiation only, with convective and conductive modes of heat transfer added. This case occurs when the flame is enclosed or shielded from direct view of the kiln enclosure by a flame shroud principally to ensure the solid bed is not "burnt" by direct radiation from the flame. Generally, the flame shroud/burner assembly is mounted outside of the kiln and the hot gases are fired into the kiln where heat is supplied to the kiln by the gas radiation only, without a flame, as in the gas region of a direct-fired kiln. The mass balance in the program is used to calculate the gas temperature based on the available heat released in the gas and the heat lost to the wall and solid bed, and an enthalpy balance is used (as in the gas region of the kiln) to determine the gas temperature if heat is not released. (For the gas region of the direct-fired kiln, heat is not released in the gas phase, and the temperature of

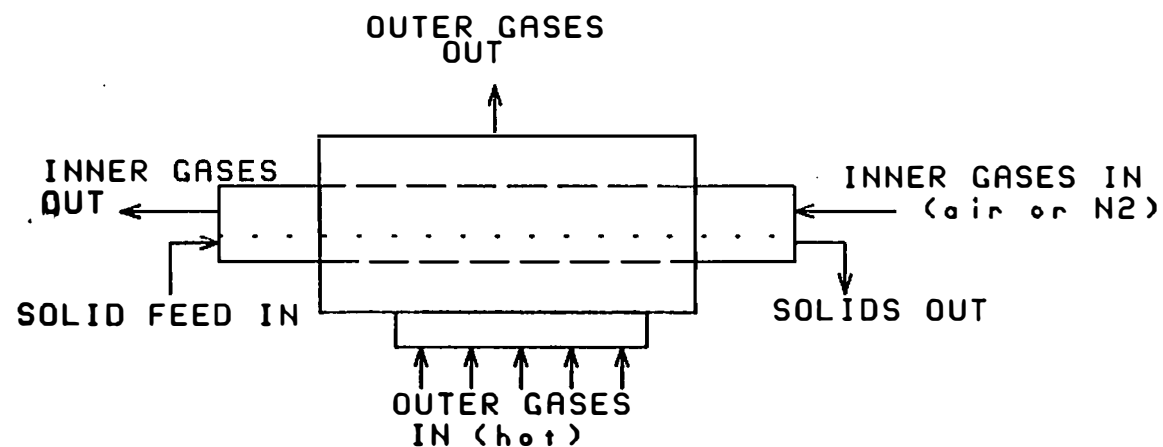
the gas is defined such that the heat lost by the gas lowers the gas temperature by the enthalpy difference between the gas temperature of the last section and the present section). The procedure to calculate the temperatures for the wall and solid bed are treated as before.

7.0 INDIRECT-FIRED KILN MODEL AND PROGRAM DEVELOPMENT

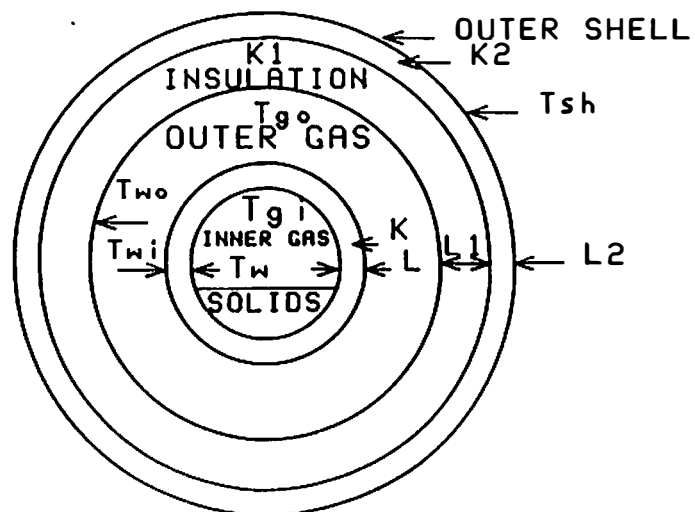
Since indirect-fired kilns are used in many industrial processes, the present heat transfer model has been extended to provide an approximate treatment of heat transfer in indirect-fired kilns. No previous heat transfer models of indirect-fired kilns have been found in the literature.

The configuration of the indirect-fired (IDF) kiln model is shown in Fig. 7.0-1a (side view) and Fig. 7.0-1b (end view). The heat transfer model used two separate heat balances (see Fig. 7.0-2). In the first balance, heat is transferred by radiation and convection from the burning fuel to the outer wall of the inner shell. Radiation heat transfer directly from the flame is neglected. About two thirds of the combustion heat is carried out by the outer shell exit combustion gas and by conduction through the outer shell wall for the typical IDF kiln. In the second heat balance, the heat entering the inner shell wall at T_{wi} leaves the inner shell wall at T_w and heats the solid bed to T_s by radiation, conduction, and convection. Thus the heat transferred to the inner shell from the outer gas is equal to the heat transferred to the solid bed (plus a small part to the inner gas).

The temperature gradient through the inner shell wall ($T_{wi} - T_w$) adjusts so that the amount of heat transferred from the outer gas to the inner shell at T_{wi} is equal to the heat transferred from the inner wall of the inner shell at T_w to the solid bed and inner shell gas. This amount of heat is also,



SIDE VIEW OF IDF KILN



CROSSSECTION OF IDF KILN

Figure 7.0-1. Side View and Crossection of IDF Kiln

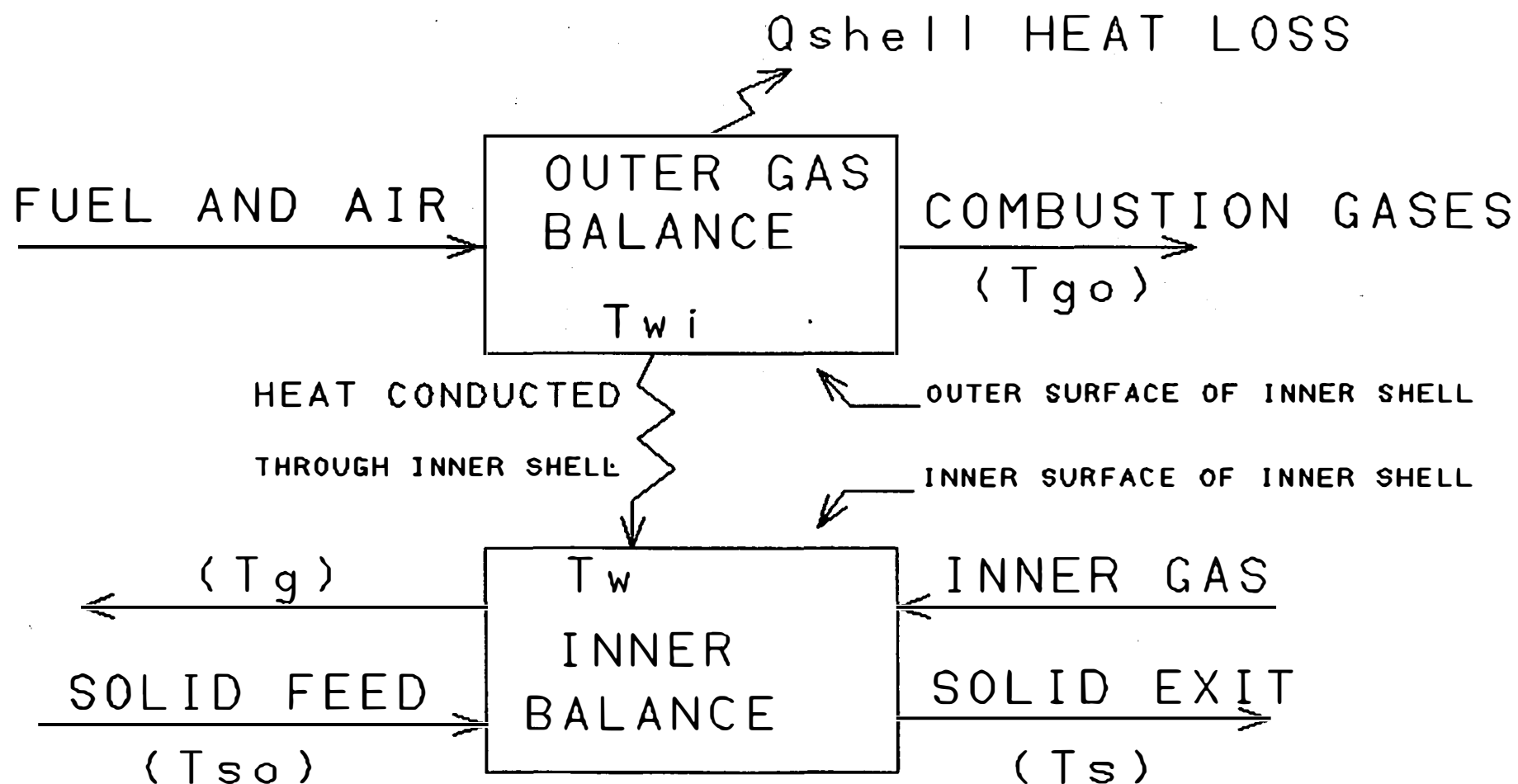


Figure 7.0-2. Indirect Fired Kiln Balances

of course, the same as the quantity moving through the inner shell under the gradient $(T_{wi}-T_w)$.

The kiln is divided into uniform longitudinal sections for each element of which (walls, gases, and solid bed) constant temperature and surface properties were assumed over the length of each zone, as with the direct-fired kiln. This treatment provides a reasonable approximation for a direct-fired kiln, but is very approximate for an IDF kiln, because of the large angular gas temperature gradient that exists in the outer gas between the bottom and top of the kiln. An IDF kiln is fired at the bottom between the inner and outer walls of the kiln, and heat is transferred to the inner shell as the hot gases rise around the sides of the inner shell.

An estimate of the gas temperature at the bottom may be based on a heat and mass balance assuming that a typical kiln is fired with approximately 25% excess air (2600°F for the adiabatic case). A vendor of IDF kilns⁴⁵ has reported that the temperature of the outer gas leaving the top of the kiln is generally in the range of 1600 to 1800°F . The resulting temperature gradient between the top and bottom of the kiln thus is 800 to 1000°F . The outer gas temperature gradient results in a corresponding inner shell temperature gradient between the top and bottom, reported by the kiln vendor to be 200 to 300°F . To make more accurate allowance for these temperature gradients, further subdivision of the axial sections into angular sections would be required. For this work, it was assumed that heat transfer from the outer gas to the inner shell could be

characterized by a single 'average' temperature of the outer gas, intermediate between the top and bottom temperatures. This intermediate gas temperature in turn was assumed to correspond to a single intermediate inner wall temperature.

Additional vendor information^{4,5} indicated (1) that, because of material considerations, the upper practical limit of the average temperature of the shell surface in contact with the outer gas was approximately 1400°F, and (2) that the exit temperature (T_{s1}) of the solid bed ranged up to within 200°F of the temperature of the inner surface of the inner shell.

The case chosen for modeling was the use of of an IDF kiln in the thermal treatment of damp soil slightly contaminated with hazardous organic chemical wastes. Kiln characteristics and operating parameters were taken to be those of a commercially available IDF kiln used primarily for heating dry solids and for which some operating characteristics were available. Unfortunately a complete set of empirical data was not available, and it was not possible to run the model computations for a realistic set of operating conditions and then compare the calculated with the actual results. Thus this model is unproven, but it is presented here as a logical extension of the direct-fired model discussed earlier. The kiln parameters and operating conditions needed for the calculation of the bed temperature profile were given selected values that appeared reasonable for thermally treating damp contaminated soil. In this example, the fuel burning rate in each kiln section was chosen to yield the same 'average' outer gas temperature (2200

F) in each section. This required a higher fuel burning rate in the solid feed end of the kiln and progressively lower rates toward the bed exit end.

The convergence method used to determine the temperature profile for the IDF kiln was similar to that used for the gas region of the direct-fired kiln with the added condition that the heat transferred to the inner shell from the outer gas equaled the heat transferred through the inner shell to the inner gas and solid bed. The temperature of the inner wall of the inner shell determined how much heat was transferred to the inner gas and solid bed. The unique set of temperatures for a given section of the kiln was again determined by a trial and error procedure like that used in the direct-fired kiln. The heat transfer calculations were performed for an IDF kiln operated with an inner gas flow countercurrent to that of the solid bed. For the reasons discussed in Section 6.7, the iteration procedure to determine the kiln temperature profile was started at the exit end of the kiln. The computer program listing for IDF kiln operation in this mode is given in Appendix F. The resulting temperature profiles are shown in Fig. 7.0-3 and Table 7.0-1. These profiles show the following:

- (1) The solid bed temperature, T_s , remains constant at 212 F until its water content has been evaporated. Then the T_s rises at an approximately constant rate to its exit temperature, 1130°F.

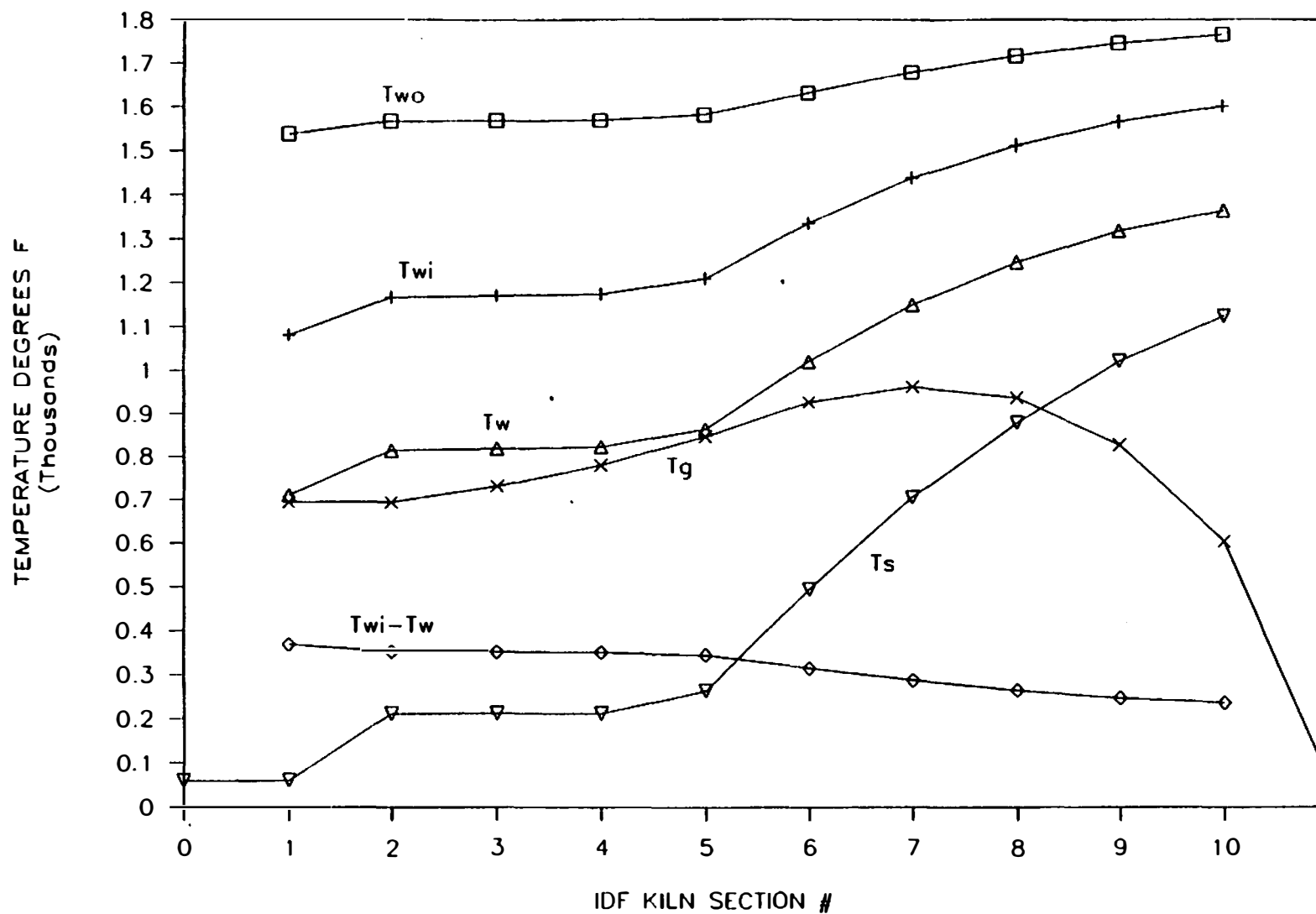


Figure 7.0-3. Calculated IDF Kiln Temperature Profiles

Table 7.0-1. Calculated IDF Kiln Temperature Profiles

SECTION #	Two	Twl	Twl-Tw	Tw	Tg
1	1540	1081	369	712	696
2	1568	1168	353	815	696
3	1569	1171	352	819	732
4	1570	1175	351	823	781
5	1583	1210	345	865	847
6	1633	1337	316	1021	927
7	1680	1439	288	1151	963
8	1717	1514	265	1248	937
9	1746	1568	248	1320	828
10	1766	1603	237	1365	606

- (2) During the drying of the solid bed in kiln sections 2 to 5, all of the other temperatures (T_{w0} , T_{wi} , and T_w) except the inner shell gas temperature also remain relatively constant, and subsequent kiln sections then rise monotonically toward their values at the solid exit end of the kiln.
- (3) The inner gas, which enters the kiln at the solid exit end at low temperature, is heated to a maximum temperature in section 7, then is cooled by the cooler solid bed as its water evaporates.
- (4) The value of $(T_{wi} - T_w)$, which is roughly proportional to the fuel burning rate, remains constant until the water content of the solid bed has been vaporized, and then decreases toward the solid exit end of the kiln.

The calculated temperature profiles agree qualitatively with what might be expected intuitively. However for the vendor-described kiln as modeled, sufficient heat could not be transferred to dry the bed and heat it to 1100°F in the assumed length of kiln without exceeding the vendor-specified limit of the inner shell temperature. For the assumed outer gas temperature of 2200°F , the calculated outer wall temperature of the inner shell rose above the allowable limit the vendor reported⁴⁵ (1400°F), reaching 1600°F at section 10. This could be avoided by lowering the outer gas temperature, but then less heat would be transferred to the solid bed and it could not be heated to the desired 1100°F . A further difficulty encountered

was that it was necessary in the model to assume unrealistically high conductive heat transfer from the inner wall of the inner shell to the solid bed in order to achieve a bed temperature of 1100° F at the exit end of the kiln for the kiln length used.

The use of dry soil feed would agree better with the vendor suggested kiln operating characteristics. The model indicates for damp soils, that either a longer kiln or a lower soil feed rate would be required to reach exit bed temperatures of 1100° F estimated by the vendor. As mentioned above, empirical (operating) data from an IDF kiln complete enough to verify the model and computer program were not found in the literature.

This example shows how the model may be used to determine the overall shape of the temperature profiles in an IDF kiln and to predict the effect of changing kiln parameters and operating conditions. No other model has been described in the literature to provide this type of design information for IDF kilns.

8.0 RESULTS AND DISCUSSION

The results are discussed in four main sections. These are: (1) verification of the basic heat transfer model, (2) the modeling of the flame region including recirculation and entrainment, (3) the derivation of gas emissivities from real gas data, and (4) the application of the model to an IDF kiln.

8.1 Overall Heat Transfer Model Verification

The heat transfer model and computer program developed were verified using data from the operation of the ERRU kiln²⁵, a direct-fired kiln used for incinerating soil contaminated with trace levels of dioxin. The operating data used for modeling the ERRU kiln are listed in Table 8.1-1 and include information on:

- (1) the physical configuration of the kiln (dimensions, refractory type and thickness, and shell thickness),
- (2) solid bed characteristics including feed rate, % moisture, heat capacity, and % fill in the kiln,
- (3) fuel (No. 2 fuel oil) and air feed rates, and
- (4) the exit temperatures of the gas and solid bed, and measured approximate shell temperatures.
- (5) the convective and conductive heat transfer coefficient values

The model predictions of the temperature profiles for the flame, wall, solid bed, and shell are shown in Fig. 8.1-1 and Table 8.1-2. The computer program listing for these calculations is

Table 8.1-1. Operating Data from ERRU Kiln

Parameter	Value
Kiln Diameter, meters	1.32
Kiln Length, meters	4.87
Fire Brick, inches	4
Fire Brick K-value, Btu/ft ² F/in	5.5
Insulating Brick, inches	2
Insulating Brick K-value, Btu/ft ² F/in	2
Radiation Parameter	

Solid Bed Solid Angle, Degrees	80
Solid Bed Emissivity	0.8
Wall Emissivity	0.8
Shell Emissivity	0.7
Conv. & Cond. Heat Transfer Coefficient	

Wall to Solid Bed, W/m ² K	50
Gas to Solid Bed, W/m ² K	50
Gas to Wall, W/m ² K	20
Shell to Ambient (conv.), W/m ² K	10
Shell to Ambient (rad.), W/m ² K	9
Operating Parameters	

Soil Feed Rate, lb/hr	1335
Soil % H ₂ O	10.1%
Soil Heat Capacity, Cp Btu/lbF	0.26
% Excess Air	65.6%
Fuel Oil Firing Rate, lb/hr	178
Solid Bed Exit Temperature, F	1600
Gas Exit Temperature, F	1840

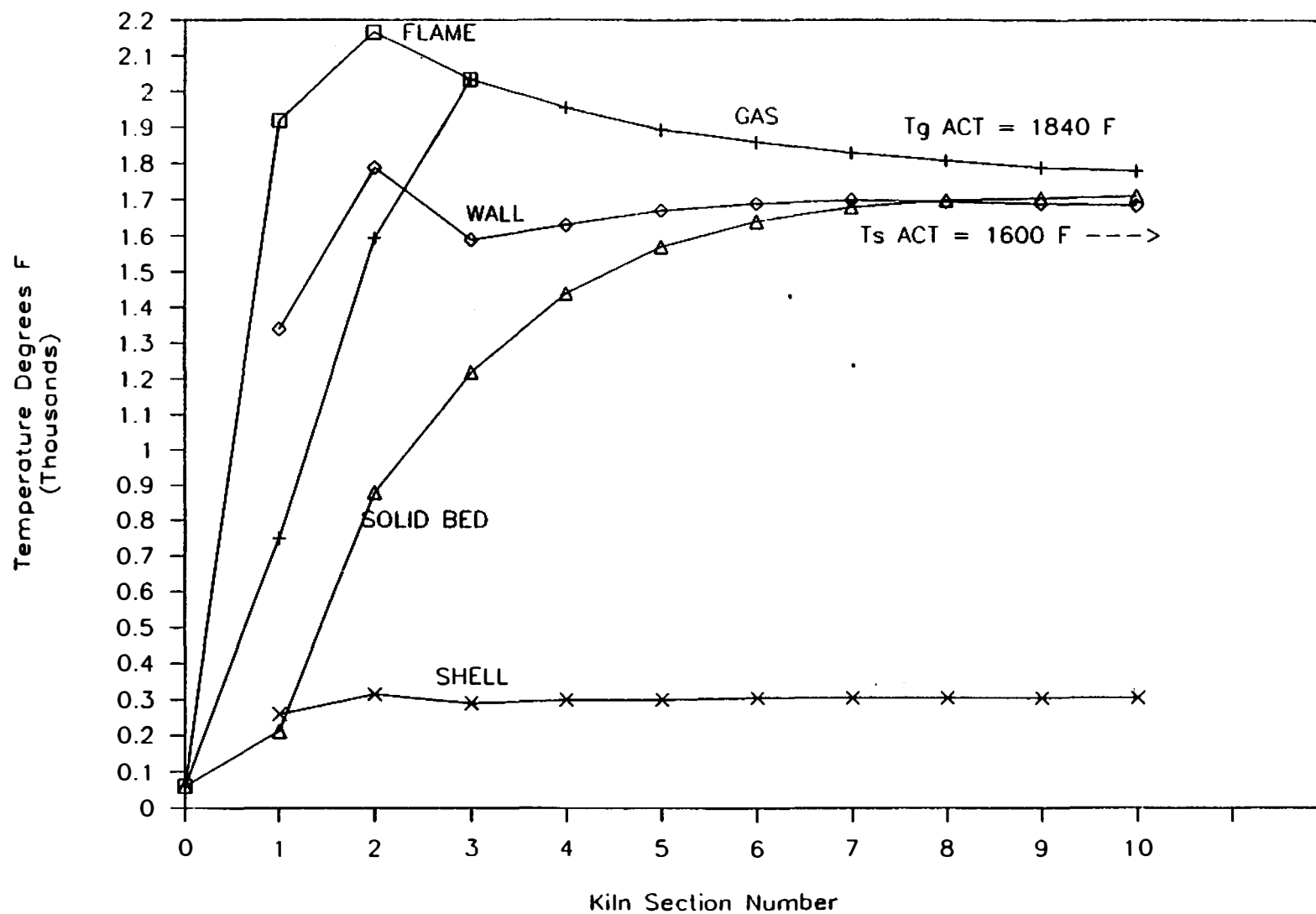


Figure 8.1-1. Calculated ERRU Kiln Temperature Profiles

Table 8.1-2. Calculated ERRU Direct Fired Kiln Temperature Profiles

SECTION #	Tf	Tg	Tw	Ts	Tsh
0	60	60		60	
1	1920	750	1340	212	260
2	2165	1595	1790	880	315
3	2035	2035	1590	1220	290
4		1955	1630	1440	300
5		1895	1670	1570	300
6		1860	1690	1640	305
7		1830	1700	1680	305
8		1810	1695	1700	305
9		1790	1690	1705	305
10		1780	1685	1710	305

given in Appendix E. The model assumes a two section flame region with the mass of recirculated gas set equal to the mass fired through the burner, in accordance with the discussion of recirculation effects given in Section 3.3. For the experimental data of the gas and solid bed, only the temperatures from the exit of the kiln were available for comparison to the model predictions. Shell temperature data were available at several points along the kiln shell.

As shown in Fig. 8.1-1, satisfactory agreement was obtained between the calculated and observed shell temperatures and the exit temperatures of the gas and solid bed. The predicted temperature profiles indicate the model slightly over-predicts the heat transferred from the freeboard gases to the solid bed, resulting in a higher solid bed temperature and lower exit gas temperature than those measured for the ERRU kiln. The shell temperatures are very close to the measured values, particularly in the flame region.

The values of all parameters used in the heat transfer model were obtained from the literature or experimental data, and are listed in Table 8.1-1. Conductive and convective heat transfer coefficient values from the gas and wall to the solid bed were selected at the lower end of ranges reported in the literature to obtain slightly better agreement between actual and predicted solid bed exit temperatures.

8.2 Heat Transfer Modeling of the Flame Region

The modeling of heat transfer in the flame region was discussed in Section 3.0. The three-foot flame region of the

EERU kiln³⁵ was modeled first considering the flame region as one section, and then as two sections. For each case, the heat transfer was treated with and without consideration of entrainment and recirculation of combustion gases. These heat transfer results are shown in Table 8.2-1.

The gas temperatures calculated with and without consideration of recirculated gases are significantly different. The temperature of the gas surrounding the flame increases as recirculation increases, while the flame temperature decreases. Also the lower flame temperature resulting from entrainment of gases results in less heat transfer to the solid bed. The gas temperature calculated for the one section case was intermediate between the gas section temperatures calculated for the two section case. Similarly, an intermediate flame temperature resulted for the single section case. However, approximately the same solid bed temperature and gas temperature leaving the flame region were obtained regardless whether one or two sections were used. This result indicates that the coarseness of kiln zoning did not strongly affect the heat transfer to the solid bed and the exit temperatures in the flame region are not strongly sensitive to segmentation and recirculation in the flame region. Clearly the two section representation of the flame region is more realistic since it can show the existence of a temperature gradient in the flame region.

**Table 8.2-1. Results of Calculations in the Flame Region with 1
or 2 Sections and with or without Recirculation of
Combustion gases**

Case Tested	Surface	Section 1	Section 2	Entering Gas Section Temp	Section 1 Qi (Btu/hr)	Section 2 Qi (Btu/hr)	Flame Region Qi total (Btu/hr)
2 Sections w/o Recirculation	Tf	2,157	2,550	1,972	386,749	584,965	971,714
	Tg	393	938		(156,681)	(277,488)	(434,169)
	Tw	1,545	1,949		(7)	0	(7)
	Ts	281	1,213		(211,964)	(283,145)	(495,109)
	Tsh	286	344		(18,112)	(24,338)	(42,450)
					(15)	(6)	(21)
2 Sections with Recirculation	Tf	1,920	2,168	2,038	265,739	287,686	553,425
	Tg	750	1,594		(86,110)	(32,434)	(118,544)
	Tw	1,339	1,790		(6)	(68)	(74)
	Ts	212	877		(164,100)	(234,000)	(398,100)
	Tsh	260	315		(15,487)	(21,188)	(36,675)
					36	(4)	32
1 Sections w/ Recirculation	Tf	2,126		1,977			765,037
	Tg	1,464					(235,059)
	Tw	1,937					177
	Ts	1,153					(484,062)
	Tsh	332					(46,098)
							0
1 Sections w/o Recirculation	Tf	2,352		1,928			1,168,683
	Tg	1,182					(563,561)
	Tw	2,127					(133)
	Ts	1,377					(554,022)
	Tsh	353					(50,967)
							0

8.3 Emissivity of Gas

In the present work the gas emissivity of CO_2 and water was calculated using Hottel's data¹⁶ for emissivity. Hottel's data were regressed using a least squares method which enabled emissivity of any partial pressure of CO_2 and H_2O to be calculated for a wide range of temperatures and beam lengths. The calculated emissivity of the combustion gases is compared to Hottel's experimental data¹⁶ in Table 4.5-4 for various temperatures and beam lengths of interest for CO_2 and H_2O . This table indicates good agreement with the data of Hottel. The data regression was carried out using the computer program listed in Appendix G.

8.4 Indirect-Fired Kiln Heat Transfer Model

Section 7.0 showed how the present model developed could be used for an approximate treatment of heat transfer in an indirect-fired kiln (IDF). The computer program listing for these calculations is shown in Appendix G. Since a sufficiently complete set of experimental data is not available for comparison, the predictive value of this model for an IDF kiln could not be accurately assessed. The model predictions of the exit bed temperature are somewhat lower than those based on vendor predictions of the performance of IDF kilns⁴⁵. The vendor's predictive model assumes that approximately 1/3 of the combustion heat is transferred to the solid bed. This assumption is unduly optimistic for the final stages of heating the bed. This accounts in part at least for the different

predictions between these two models. In spite of the very approximate nature of its modeling, the model was able to indicate the ways in which solid bed and gas temperature profiles would depend upon kiln parameters and operating conditions.

9.0 SUMMARY AND CONCLUSIONS

An improved heat transfer model has been developed for a direct-fired rotary kiln. The model can be used to verify kiln design, to optimize operating conditions, to predict the temperature history of the solids, and to evaluate if local areas of the kiln will be overheated. The treatment of radiant heat transfer was based on the Reflection Method developed by Succes and applied by Gorog, and was extended to account for radiation from a flame. Some elements of the Resistive Network Method and Zone Method were incorporated in the model. This method results in a more straightforward and flexible treatment of radiant heat transfer than other methods of analysis. The model also accounts for conductive and convective heat transfer within the kiln and heat conducted through the kiln wall and lost from the outer kiln shell to the ambient surroundings.

The model divides the kiln into a flame region where the flame is present, plus a downstream gas region. The flame and gas regions are each subdivided longitudinally into kiln sections of equal length. A new method was devised to model the grey body emissivity of an axially centered flame of given area. It was treated as equivalent to a black body of reduced area. This treatment greatly simplified the calculation of radiant heat transfer to and from the flame. A method was devised for calculating the gas transmissivity for its own radiation in the Reflection Method. The model also includes an approximate treatment of the recirculation and entrainment of combustion gas in the flame region, and assumes plug flow

downstream of the flame region. A regression method was developed for calculating the emissivity of combustion gases of varying CO_2 and H_2O concentrations based on Hottel's real gas data. The temperature and heat transferred to or from the flame, gas, wall, and solid bed in each axial section of the kiln is calculated using the Reflection Method by simultaneously solving a set of algebraic expressions involving the emissivity, area, and radiative (geometrical) view factors for the various surfaces in the kiln. The model was verified with a computer program written in LOTUS 1-2-3 using a set of operating data from a direct-fired kiln used for the incineration of lightly contaminated soil. The model yielded good agreement between the calculated and reported values of the solid and gas exit temperatures as shown in Fig. 8.1-1 and Table 8.1-1. The percent error for the estimated solids exit temperature was 6.8 and for the gas was -3.2.

The new heat transfer model was also extended to provide an approximate treatment of heat transfer in IDF kilns. The model used two separate heat balances to (1) estimate the heat transferred from burning fuel in the outer gas to the outer surface of the inner shell, and (2) the heat transferred through the inner shell and radiated to the solid bed and inner gas. As with the direct-fired kiln, the kiln was divided into uniform longitudinal sections, each with constant temperatures and surface properties. The use of a constant outer gas temperature is only approximate because of the steep temperature gradient that exists between the bottom temperature where the fuel combustion occurs and the top temperature where the combustion

gases exit. Model calculations for a hypothetical data set (no actual data were available) indicated approximate agreement with vendor reported kiln characteristics and temperature profiles.

This model is the first treatment of heat transfer in an IDF kiln reported in the literature.

9.1 General Heat Transfer Model Developments

The radiation balance developed can be applied to any enclosure with two grey surfaces (e.g., wall and solid bed) and one black body or axially centered grey body (e.g., flame) with a participating gas of varying CO_2 and H_2O concentrations. The temperatures of the three surfaces and the gas determines the heat flow within the enclosure. Convective heat transfer from the gas to both grey surfaces (the solid bed and wall), and conductive heat transfer between the grey surfaces is considered. All parameters required for calculating the heat distribution are variables which can be input in the program, and they can be modified for different geometries, fuel, air, solid bed feed rate, surface properties, and gas compositions. Heat loss by conduction through the enclosure shell is estimated for a kiln wall constructed of 2 layers of insulating material and the outer shell. Heat is lost from the outer shell by convection and radiation to the ambient surroundings.

9.2 Simplifying Assumptions

To simplify the development of the heat transfer model, a number of assumptions were necessary. These include the following: (1) the neglect of axial radiation, (2) the use of a

constant circumferential wall temperature, (3) an approximate treatment of recirculation and entrainment of combustion gases in the flame region, (4) neglect of kiln end effects, (5) a well mixed solid bed of constant temperature within each axial zone, (6) neglect of the effect of coarse kiln zoning of the kiln, (7) constant 'average' surface and gas temperatures in each zone, and (8) constant emissivity of the flame over its length. Approximate estimates were made for the effects of these assumptions on the uncertainties of results calculated by the model.

10.0 RECOMMENDATIONS FOR FURTHER WORK

- (1) While there is a great amount of information published on combustion technology and heat transfer, there is a lack of detailed information in the open literature on the physical parameters and operating conditions for direct-fired rotary kilns. It would be of great value in verifying the validity of kiln heat transfer models if such detailed experimental data were determined and reported.
- (2) The accuracy of the model could be improved by extending it to include the treatment of the effects of the following phenomena: (1) effects of soot and entrained dust concentrations on the flame and gas emissivities, (2) more detailed zoning of the flame region as it effects recirculation and entrainment, heat and mass balance, gas compositions, and temperature profile in each zone, (3) using grey/clear gas models to determine the emissivities of $\text{CO}_2\text{-H}_2\text{O}$ mixtures of varying compositions, and (4) a solid bed containing combustible material.
- (3) Carry out sensitivity analyses of all the assumptions listed above.
- (4) For extended and repeated use of the program, a FORTRAN coded version would reduce computation time required.
- (5) A heat transfer model for IDF kilns capable of treating angular surface and gas temperature gradients should be developed to provide a more accurate description of surface and gas temperatures.

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APPENDICES

APPENDIX A

FLAME REGION ENTRAINMENT MODEL DEVELOPMENT

As discussed earlier in the model development (Sections 3.1-3.3) and results and discussion (Section 8.0), the recirculation of entrained gases significantly changes the temperature of the flame and the gas surrounding the flame. This appendix provides additional information on how the amount of gas recirculated varies with different operating conditions and burner configurations.

The treatment of entrainment and recirculation of gases in the flame region is based on the correlation of Thring and Newby²⁷, as modified by Field et al.²⁶. Ricou and Spaulding³⁰ measured entrainment rates and determined that the mass flow rate (m_x) in the jet is linearly related to x according to the equation

$$m_x/m_0 = 0.32 (\rho_g/\rho_0)^{1/2} (x/d_0) \quad \text{Eq. A-1}$$

This relationship holds for all values of nozzle Reynolds number greater than 2.5×10^4 and for $x/d_0 > 6$. At $x/d_0 < 6$, the entrainment rate per unit jet length is lower, increasing progressively with distance until it stabilizes at the constant value corresponding to Eq. A1.

The correlation modified by Field et al. assumes that the the jet entrains as a free jet up to the point C (see Fig. A-1) and the total entrainment up to this point (the net recirculation flow m_r) is given by the Eq. A-2:

$$m_r = [0.32(\rho_g/\rho_0)^{1/2} (x-6d_0)/d_0 m_0] - m_0 \quad \text{Eq. A-2}$$

This is Eq. 3.2 with the terms as defined in the text. The point C is postulated to lie midway between the point x_0 where entrainment begins ($m_x = m_0$), according to Eq. A-2 and the point p (see Fig. A-1) where the envelope of an unconfined jet strikes the wall. From Eq. A-1 where $m_x = m_0$:

Fig. A-1

$$x_o = (d_o / .32) (\rho_o / \rho_a)^{1/2} \quad \text{Eq. 1.0-3}$$

Assuming the jet angle of 9.7° , the jet strikes the wall at a distance x_p diameters down the duct:

$$x_p = 2.925 D \quad \text{Eq. A-4}$$

Thus x_C is given by

$$x_C = 1/2 [x_p + d_o / 0.32 (\rho_o / \rho_a)^{1/2}] \quad \text{Eq. A1.-5}$$

A parameter ω is then defined:

$$\omega = (d_o / D) (\rho_o / \rho_a)^{1/2} \quad \text{Eq. A-6}$$

hence

$$\begin{aligned} x_C &= 1/2 (x_p + D\omega / 0.32) \\ &= D(1.467 + \omega / 0.64) \end{aligned} \quad \text{Eq. A-7}$$

and

$$m_r / m_o = 0.47 / \omega^{-0.5} \quad \text{Eq. A-8}$$

Present Work -

The correlation has been modified in the present work assuming that

$$x_p = D$$

due to the skewed burner configuration which angles the flame from the burner toward the wall, and consequently intercepts the wall earlier than one would expect in most kilns. This results in Eq. A-7 becoming:

$$x_C = D(0.5 + \omega / 0.64), \quad \text{Eq. A-9}$$

and Eq. A-8 becomes,

$$m_r / m_o = 0.16 / \omega^{-0.5} \quad \text{A-10}$$

This last equation results in about 1/3 of the net recirculated flow as proposed by the Thring and Newby correlation due to the shorter jet length used. The values used in the resulting equation, Eq. A-10, are:

$\rho_a = 0.0745 \text{ lb/ft}^3$ for the density of the ambient air
 $\rho_o = 0.0787 \text{ lb/ft}^3$ for the density of the fuel jet stream
 $D = 4 \text{ ft}$ for the diameter of the kiln
 $d_o = .5 \text{ ft}$ for the burner nozzle diameter

and

$$m_r = 0.746 m_o \quad \text{Eq. A-11}$$

As can be seen from the form of Eq. A-1, the net entrainment is proportional to the distance from the burner along the jet axis (or kiln axis in this case). This relationship relationship is valid for distances from the burner nozzle greater than 6 nozzle diameters, $6d_o$. Less than $6d_o$, the entrainment rate is less. To account for entrainment in this distance, the rate of entrainment in the first section was assumed half of the rate in the second section. The resulting block flow diagram is shown in Fig. 3.1.2-1. Note that the gases recirculated are assumed to originate from the end of the flame region.

With the specified rate of gas entrainment in each section, the balance for the flame region can be solved. The fuel and air not combusted in the first flame section are assumed to be volatilized and heated to the temperature of the first flame section and enter the second flame section as preheated fuel and air. The heat required to preheat the fuel and air is treated as a heat loss in the first flame section and as a heat 'credit' in the second flame section. By considering

- (1) the net heat release of the flame for each section
- (2) the enthalpy balance of the flame region for recirculated gases, and
- (3) the overall balance of the flame region, the temperatures in the flame region may be solved using the radiation balance as discussed earlier in program development and below.

APPENDIX B**Enthalpy Balance of the Flame Region**

Enthalpy Balance of the Flame Region

The enthalpy balance of the flame region is presented here for a flame region which is divided into two sections and considers recirculation of combusted gases. The resulting block diagram is shown in Fig. 3.1.2-1. The flame region with recirculation of combustion gases modeled as a single section is a much simpler subset of the block flow diagram below.

Note that the overall mass balance of the flame region requires that the total mass entering the balance (the sum of the excess air and the mass fired through the burner) is equal to the mass leaving the flame region (the mass of the combustion gas plus the mass of excess air). This relationship is expressed mathematically as follows:

$$M_o + M_{\text{xair}} = M_{\text{cp}} + M_{\text{xair}}$$

This equation requires that $M_o = M_{\text{cp}}$. From this balance, it is recognized that the effect of recirculated gases can be viewed qualitatively as a partial mixing of the gas and flame sections in the flame region. The primary result of considering recirculated gases in the flame region is to increase the temperature in the gas sections and decrease the temperature in the flame sections of the flame region. These temperature changes affect the heat transfer in the flame region of the kiln. There is very little effect from recirculation downstream of the flame region, where the gases are assumed to be well

mixed and of uniform temperature within each section of the gas region.

B1.0 Assumptions Required for Recirculation Calculations

The following assumptions are required to solve for the temperatures in the flame region:

- (1) The composition and mass of the secondary excess air, M_{xair} , is constant (not mixed with the recirculated gases) in each gas section, but is allowed to come to thermal equilibrium within the gas section with the recirculated gases. This assumption is made because there is no simple way to determine the fraction of excess air directly entrained in the flame or the extent of mixing, and the composition of the excess air and recirculated gases are both primarily nitrogen. Consequently, the heat capacities of these gases are nearly the same, and error from this assumption had negligible effects on the heat or mass balance.
- (2) The mass of recirculated gas, $X(M_{\text{cp}} + M_{\text{xair}})$ as seen in Fig.3.1.2-1, represented by the value m_r as calculated above in Appendix A in the modified correlation of Thring and Newby, is a variable input in the program, and is varied by specifying the fraction of the burner mass which has been estimated to be recirculated, C_r (the constant above of 0.746 in Eq. A10). The fraction X is calculated in the

program by the following equation:

$$X = C_r * M_o / (M_{cp} + M_{xair})$$

The value X represents the fraction of the total mass entering the flame region ($M_o + M_{xair}$) which is recirculated. In the present calculations, the value of the fraction, C_r , is assumed to be unity (in place of the value estimated above of 0.746) in light of the uncertainty involved in determining the value of this factor.

- (3) The gas entrained from the gas region to the flame is assumed to be at the corresponding gas region temperature, T_{g1} or T_{g2} .
- (4) The mass of recirculated gas is not effected by assumption (1), and its composition is assumed to be that of the gas exiting the flame region.

B2.0 Determination of the Gas Temperature in Each Section of the Flame Region

The gas in the flame region surrounding the flame of the kiln is heated simultaneously by the thermal convection (mixing) due to gas recirculation and by radiation heat transfer in the kiln from the flame and wall. The exact effect of these two factors on the gas temperature calculation depends upon whether the mixing or the radiant heat transfer is calculated first. If the radiant heat transfer to the gas is calculated before it is heated by mixing, the mixed gas would be hotter. It was assumed

that the gases are first mixed resulting in a 'mixed gas' temperature which was then heated by radiant heat transfer from the flame. This order of calculation maximizes the effect of gas recirculation on the gas temperature, while the opposite order would maximize heat transfer by radiation. The temperature of each gas region is determined in three steps:

- (1) The gas temperatures in each section are initially assumed.
- (2) An enthalpy balance for the section calculates an HMB temperature based on the gases entering and exiting it.
- (3) The HMB temperature is used in the radiation balance as an initial temperature of the gas to calculate the new gas temperature of the section.

Each of these steps is discussed separately below.

Step (1): An overall flame region heat and mass balance is used to estimate the temperature of the gas leaving the flame region, which is assumed to be at the same temperature as the gas recirculated (Section B.1 assumption 4 above). The temperature of the gas leaving the flame region is based on the overall heat balance for the flame region:

$$H_{\text{air}} + H_{\text{gas}} = H_{\text{gas}} + H_{\text{solids}} + Q_{\text{shell}}$$

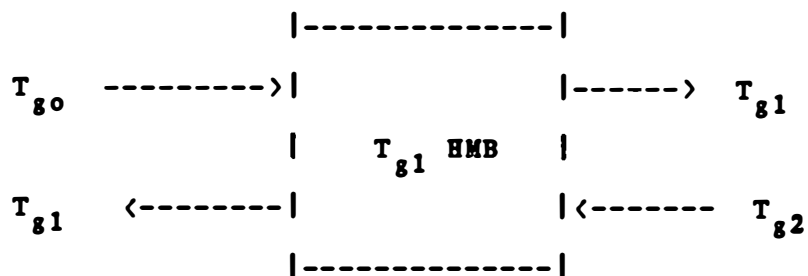
where H represents the enthalpy of air, gas, or solids, and Q represents the heat lost from the flame and shell. From the exit gas temperature (T_{g3}), determined by this balance, the temperatures of the gas sections in the flame region are assumed. The initial estimates for the gas temperatures in the flame are 'best guess' approximations as discussed below.

In the present calculations, the temperature of the gas exiting the flame region was first estimated from the overall balance using an estimated solid bed temperature of 600 F and heat loss based on a shell temperature of 300 F, which resulted in an exit gas temperature from the flame region of approximately 1900 F. The first estimate of the gas temperatures in the flame region were arbitrarily calculated assuming a uniform temperature rise in section 1, 2, and 3 (by dividing the overall flame region balance temperature by 3). The initial gas temperature assumed were: $T_{g1} = 600$ F in the first gas section and $T_{g2} = 1200$ F in the second gas section, and $T_{g3} = 1900$ F for the gas leaving the flame region.

It may be noted that this procedure could be extended to consider more than two section in the flame region.

Step (2): A heat balance is calculated for the gas temperature (shown below in the diagram) in the section of the flame region being calculated. The balance is based on the mass, composition, and assumed temperature of each stream entering the gas section. For the calculation of the first gas section, the assumed temperature of the second gas section T_{g2} is used (in this case assumed to be 1200 F). The enthalpy difference for each of the streams entering the gas section are calculated and the 'heat and mass balance' (HMB) temperature of the gas section T_{g1} is determined by a trial and error procedure of guessing the temperature of the gas section and comparing the net enthalpy difference between the entering and exiting stream enthalpy. The correct temperature of the gas

section is calculated when the net enthalpy of the entering and exiting streams are equal. This is illustrated below:



$$\Delta H_{T_{g0} \rightarrow T_{g1}} = - \Delta H_{T_{g2} \rightarrow T_{g1}}$$

Step (3): The HMB temperature T_{g1} of the gas section is used in the radiation heat transfer section of the program as the 'initial temperature to determine the temperature profile of the first section of the flame region. The high temperature of the flame and wall results in additional heat transfer to the gas (by radiation from the flame and wall, and convection from the wall).

B3.0 Flame Region Temperature Convergence Criteria

The temperature profile of the first section of the kiln is calculated as described above (for the flame, solid bed, wall, and gas), and yields a new estimate of the gas temperature T_{g1} in the first section (say 800 F). The temperature profile of the second section of the flame region is calculated in a similar fashion. This procedure is summarized below:

Step (1): The HMB gas temperature of the second gas section is calculated based on the new estimated gas temperature $T_{g1} = 800$ F of the first section and the gas temperature exiting the flame region $T_{g3} = 1900$ F as calculated by an overall balance of the flame region (Step 1 above). For example let the resulting HMB temperature $T_{g2} = 1400$ F.

Step (2): The new HMB gas temperature of the second gas section $T_{g2} = 1400$ F is used as the initial gas temperature to calculate the heat transferred by radiation within the kiln. For example, let the new value of T_{g2} including radiation heat transfer be 1650 F. The trial temperature profile of the second section of the kiln includes: (1) a new gas temperature $T_{g2} = 1650$ F for the second section, (2) the temperature of the flame combustion gases, say $T_{f2} = 2000$ F, (3) the solid bed temperature which exits the flame region, say $T_{s2} = 1000$ F and (4) the shell heat loss in the second section, say $Q_{sh} = 0.2$ MM Btu/hr.

Step (3): An enthalpy balance of the gases leaving the flame region (the flame combustion gases $T_{f2} = 2000$ F and second gas section gases $T_{g2} = 1650$) is calculated to determine the combined temperature of the gases T_{g3} , say 1850 F. If the calculated temperatures equal the estimated temperatures used in the overall balance of the flame region, the flame region gas temperatures assumed are correct.

If the exit gas temperatures are not equal, a new (second) estimate of the gas temperature T_{g3} leaving the flame region can be calculated using the overall balance for the flame region

with the new values for the shell heat loss in the flame region, and solid bed temperature $T_{s2} = 1000$ F exiting the flame region. For example say the overall balance predicted $T_{g3} = 1950$ F. The procedure of calculating the temperature profile of the kiln in the flame region has now come full circle, and a new (second) set of trial temperatures for the gas temperatures of the second section $T_{g2} = 1650$ F and third section $T_{g3} = 1950$ F can be used to repeat the procedure. This entire procedure is repeated until the calculated temperatures (T_{g2} and T_{g3}) are the same as the previous trial values used.

It may be noted that the program continuously calculates in a section the values of the HMB gas temperature for the 'other' gas section in the flame region and the exit gas leaving the flame region, based on the corresponding enthalpy balances. These gas temperatures may be used to indicate whether a particular set of gas temperatures are likely to result in the same exit gas temperature as calculated by the overall balance of the flame region. The mass and composition of each stream for the flame region balance remains fixed for a particular set of operating parameters and the estimated combustion gas fraction recirculated. The enthalpy difference between the second gas temperature and the first gas temperature must be constant because there is only one set of 'correct' temperatures which allows the balance of the flame region to be satisfied. Lowering the second gas temperature or raising the first section gas temperature, lowers this enthalpy difference. The temperatures of the gas and flame in the second section

determines the exit gas temperature, and the heat released in each flame section is fixed. Consequently, the range of temperatures which allows the temperature profile in the flame region to be determined is restricted.

Using these observations, the user is often able to 'abort' the procedure, and choose a new set of gas temperatures which will converge more quickly. The first few iterations of this procedure may be performed rapidly by using 'loose' convergence criteria for a given section of the flame region, recognizing that the assumed temperatures used in the first few iterations are not the final values.

For instance, on the second iteration say the resulting gas temperature of the second section $T_{g2} = 1800$ F and the resulting flame temperature of the second section $Tf_2 = 2000$ F, and the calculated combined gas temperature of these two resulted in 2000 F. Then, from the overall flame region balance temperature of $T_{g3} = 1950$ F, one would know that the second gas temperature $T_{g2} = 1800$ F was too high and a lower gas temperature for the second section, say 1500 F, would be required to give the estimated overall flame region balance temperature of 1950 F. This lower gas temperature of the second section would also likely result in a lower gas temperature for the first section T_{g1} as well, say 700 F. The gas temperatures assumed include the heat transferred by both convection and radiation.

Within several complete iterations of the flame region, the gas temperature of section 1 and 2 begin to get closer to their final values. The overall balance gas temperature leaving the flame region varies less each iteration of the flame region as the solid bed and shell heat loss exiting the flame region get closer to their final values. With greater confidence in the overall balance gas temperature leaving the flame region, the gas temperatures in the flame region may be 'fine tuned' to determine the temperature profile of the flame region.

APPENDIX C
CALCULATIONS FOR MODELING THE FLAME
AS A GRAY BODY IN THE FLAME RADIATION BALANCE.

C1.0 Radiation Model of the Flame

The flame is modeled as an axial flame and is treated in the radiation balance as a black body surface of a cylindrical shape. This simplification significantly reduces the equations required to trace the emitted and reflected radiation within the enclosure for constructing the radiation balance. A real flame is different from a gray solid surface because some of the radiation is transmitted through the flame. The flame is here treated as a black body of reduced area to avoid the complications otherwise involved in calculating the radiation balance of the flame treated as a partially transparent gray body. The flame is treated as an opaque black body of reduced area such that the radiation emitted or absorbed is equivalent to that of the partially transparent flame with the actual flame area. With the reduced area, less volume is occupied by the flame, which therefore intercepts less radiation in the kiln and is effectively more 'transparent'.

The mathematical relations involved in this model are given in the following. The heat emitted to the kiln wall by the flame, considered as a grey body with emissivity ϵ_f and area A_f , is equated to that emitted by a reduced area flame considered as a black body with emissivity ϵ'_f and area A'_f , i.e.,

$$Q_{f \rightarrow w} = Q'_{f \rightarrow w}$$

Substituting the general expression for radiation heat transfer,

$$\sigma A_f \epsilon_f F_{fs} T_f^4 = \sigma A'_f \epsilon'_f F'_{fs} T_f^4$$

The view factors F_{fw} and F'_{fw} are equal because of the cylindrical geometry of the kiln. Therefore,

$$A_f \epsilon_f = A'_f \epsilon'_f, \quad \text{Eq. C1.0-1}$$

where ϵ'_f equals 1 since the reduced area flame is considered to be a black body.

Now using Kirchhoff's law for the radiation between the wall and the flame for the actual area case,

$$A_w F_{wf} = A_f F_{fw}.$$

For the reduced area case,

$$A_w F'_{wf} = A'_f F'_{fw}$$

Eliminating F_{fw} between these equations yields

$$A_w F'_{wf} = A'_f (A_w F_{wf} / A_f).$$

Simplifying,

$$F_{wf} / F'_{wf} = A_f / A'_f$$

Therefore, using Eq C1.0-1,

$$F_{wf} / F'_{wf} = \epsilon_f = \alpha_f.$$

Therefore,

$$F_{wf} - F'_{wf} = (1 - \alpha_f) F_{wf} \quad \text{Eq. C1.0-2}$$

From this last equation and Eqns. C1.1-3 and C1.1-6, it follows that:

$$F_{wf} (1 - \alpha_f) = (F'_{ws} - F_{ws}) + (F'_{ww} - F_{ww}) \quad \text{Eq. C1.0-3}$$

This derivation shows that the fraction of energy radiated by the wall which is transmitted through the flame (treated as a gray body) is equal to the difference between the view factor F_{wf} for the gray body case and the black body view factor F'_{wf} .

Such treatment of the flame has not been discussed in the literature.

The reduced area of the black body flame causes a reduction of the operative view factors ($F'_{wf}F'_{sf}$) which determine the fraction of radiation which will be emitted by each of the two surfaces to the black body flame. This treatment compensates for the energy that would have been transmitted through the flame as if it were a gray (partially transparent) body. This treatment greatly simplifies the calculation of the radiation balance. Treating the flame as a gray body would double the number of equations required to calculate the radiation absorbed by the gas because the additional equations would be required to account for radiation which passed through the flame.

The difficulty involved in considering the flame as a gray body is that the flame is a partially transparent surface. For a partially transparent surface, part of the emitted radiation (from the solid bed or wall) which is 'viewed' by the (flame) surface is transmitted through the partially transparent (flame) body. The radiation emitted from the solid bed which is transmitted through the flame is intercepted by the wall (and partly reflected). For the radiation emitted by the wall to the flame, the radiation transmitted through the flame may be intercepted by either the solid bed or the wall. (See Fig. C1.0-1) Some reflected radiation (originally emitted from the flame, wall, solid bed, and gas) also would pass through the flame. The difficulty in accounting for the radiation transmitted through the flame is complicated further by the fact

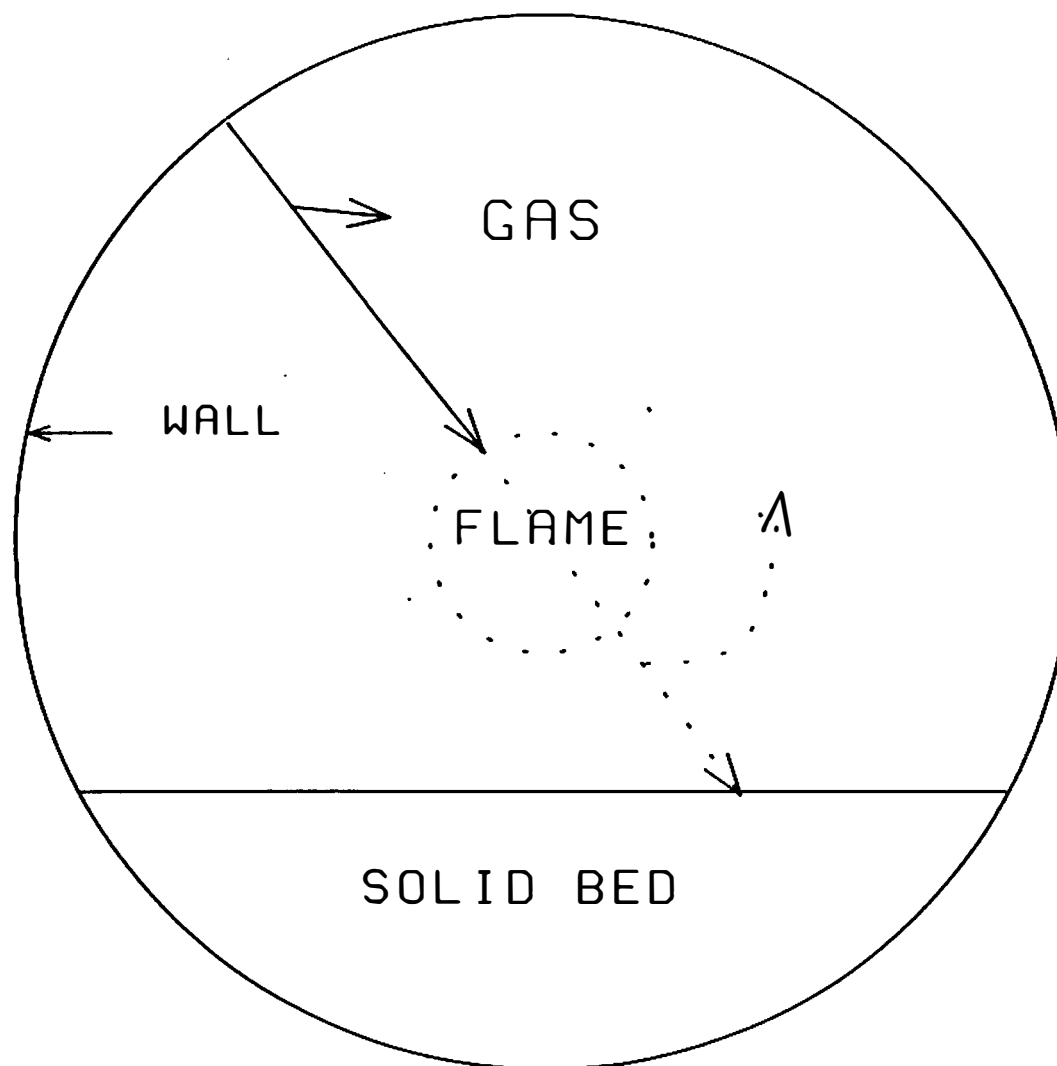


Figure C1.0-1. Radiation Transmitted Through the Flame with Gas
Absorption Before and After the Flame

that the gas would also absorb some fraction of each of the radiation rays. Two gas absorption terms would be required to describe each ray which intercepts the flame, one before intercepting the flame and one after passing through the flame before the ray is intercepted by another solid surface (see Fig. C1.0-1)

C1.1 Numerical Comparison of the Gray Flame and Reduced Area Flame Treatments -

The calculation of the view factors and heat transfer for the gray flame method and the reduced area flame method is illustrated in the following numerical example. The following numerical values for the parameters of interest were chosen:

$$\begin{aligned}\beta_s &= 90^\circ = \pi/2 \text{ radians} = \text{the angle subtended by the solid bed} \\ D_f &= 2 \text{ feet} = \text{the diameter of the flame (actual)} \\ D_k &= 10 \text{ feet} = \text{kiln ID} \\ \epsilon_f &= \alpha_f = 0.8 = \text{emissivity and absorptivity of the} \\ &\quad \text{flame (actual or gray body)}\end{aligned}$$

From these numerical values, the following quantities are calculated:

$$\begin{aligned}F_{fw} &= F'_{fw} = (2\pi - \pi/2)/2\pi = 3/4 = \text{fraction of flame radiation} \\ &\quad \text{intercepted by the wall} \\ F_{fs} &= F'_{fs} = (\pi/2)/2\pi = 1/4 = \text{the fraction of flame radiation} \\ &\quad \text{intercepted by the solid bed} \\ A_f &= \pi D_f = \text{area of the flame per unit length of kiln} \\ &\quad = 6.28 \text{ ft}^2/\text{ft} \\ A_s &= \text{SIN}(\beta_s/2) D_k = (2^{.5}/2) 10 \\ &\quad = \text{area of solid bed per unit length of kiln} = 7.07 \text{ ft}^2/\text{ft}\end{aligned}$$

$$A_w = (\pi - \beta_s/2) D_k = (3/4) \pi 10$$

$$= \text{area of wall per unit length of kiln} = 23.56 \text{ ft}^2/\text{ft}$$

The treatment of the gray flame will be considered first and compared to the treatment of the flame as a black body of reduced area. Several mathematical relationships for these calculations need to be defined:

(1) All radiation leaving a surface i within an enclosure must be intercepted by the enclosure surfaces. This results in the following mathematical relationships between the view factors:

$$\sum_{j=1}^N F_{ij} = 1 \quad \text{Eq. C1.1-1}$$

From this it follows that,

$$\text{flame} - \quad F_{fs} + F_{fw} = 1 \quad \text{Eq. C1.1-2}$$

$$\text{wall} - \quad F_{ws} + F_{ww} + F_{wf} = 1 \quad \text{Eq. C1.1-3}$$

$$\text{solid bed} - \quad F_{sw} + F_{sf} = 1 \quad \text{Eq. C1.1-4}$$

Similar equations can be written for the reduced area case:

$$\text{flame} - \quad F'_{fs} + F'_{fw} = 1 \quad \text{Eq. C1.1-5}$$

$$\text{wall} - \quad F'_{ws} + F'_{ww} + F'_{wf} = 1 \quad \text{Eq. C1.1-6}$$

$$\text{solid bed} - \quad F'_{sw} + F'_{sf} = 1 \quad \text{Eq. C1.1-7}$$

The axial radiation and end effects from the kiln end surfaces have been neglected in this treatment.

(2) Kirchoff's law is a useful relationship between the view factor from one surface to a second surface within an enclosure:

$$A_i F_{ij} = A_j F_{ji} \quad \text{Eq. C1.1-8}$$

(3) The total radiation which is intercepted by a partially transparent surface which does not reflect radiation is either absorbed or transmitted through the medium, as represented by

the following expression:

$$\tau_1 + \alpha_1 = 1 \quad \text{Eq. C1.1-9}$$

Determination of F_{wf} and F'_{wf} -

Solving Kirchoff's law for F_{wf} ,

$$\begin{aligned} A_w F_{wf} &= A_f F_{fw} \\ \text{or, } F_{wf} &= A_f F_{fw} / A_w \\ &= (\pi D_f) F_{fw} / (\pi - \beta_s/2) D_k \\ &= (2 \pi) (3/4) / (\pi - \pi/4) 10 \\ &= 0.20 \end{aligned}$$

Going through a similar calculation for F'_{wf} ,

$$\begin{aligned} A_w F'_{wf} &= A'_f F_{fw} \\ \text{or, } F'_{wf} &= A'_f F_{fw} / A_w \\ &= \epsilon_f (\pi D_f) F_{fw} / (\pi - \beta_s/2) D_k \\ &= (0.8)(2 \pi) (3/4) / (\pi - \pi/2) 10 \\ &= (0.8)(1/5) = 0.16 \end{aligned}$$

The fraction of energy transmitted through the flame is given by the following formula (from Eq. C1.1-9):

$$\tau_f = 1 - \alpha_f \quad \text{Eq. C1.1-10}$$

The fraction of radiation emitted by the wall which is transmitted through the flame (to the solid bed or wall) is given by the product of the fraction of energy transmitted through the flame times the view factor, F_{wf} :

$$F_{wf} (1 - \alpha_f) \quad \text{Eq. C1.1-11}$$

which equals

$$0.20(1-0.8) = 0.04$$

It is seen that this is equal to the quantity

$$F_{wf} - F'_{wf} = 0.2 - 0.16 = 0.04$$

This equality is consistent with the relationship derived above (Eq. C1.0-2),

$$F_{wf} - F'_{wf} = F_{wf}(1 - \alpha_f) \quad .$$

C2.0 Evaluation of the Other View Factors

The determination of the view factors involves the use of Kirchhoff's law and Eq. C1.1-1,

$$\sum_{j=1, n} F_{ij} = 1 \quad .$$

These view factors will be used in the solution of Eq. C1.1-4,

$$F_{ws} + F_{ww} + F_{wf} = 1$$

Determination of F_{ws} and F'_{ws} -

By Eq. C1.1-4,

$$F_{sw} = 1 - F_{sf}$$

By Kirchhoff's Law, this yields,

$$\begin{aligned} F_{sw} &= 1 - A_f F_{fs} / A_s \\ &= 1 - (\pi D_f) F_{fs} / \text{SIN}[(\beta_s/2) D_k] \\ &= 1 - 0.2221 = 0.7781 \end{aligned}$$

Now, the view factor F_{ws} may be determined using Kirchhoff's law as follows:

$$\begin{aligned} A_w F_{ws} &= A_s F_{sw} \\ \text{and } F_{ws} &= A_s F_{sw} / A_w \\ &= [\text{SIN}(\beta_s/2) D_k F_{sw}] / (\pi - \beta_s/2) D_k \\ &= (2^{.5}/2)(10)(0.7781) / (3/4)\pi 10 \\ F_{ws} &= 0.2335 \end{aligned}$$

Alternately, a direct solution can be written to solve for F_{ws} which does not include the intermediate solutions of the F_{sf} and F_{sw} :

$$\begin{aligned}
 F_{ws} &= A_s F_{sw} / A_w \\
 &= A_s (1 - F_{sf}) / A_w \\
 &= A_s (1 - A_f F_{fs} / A_s) / A_w \\
 &= \text{SIN}(\beta_s/2) (1 - (\pi D_f) F_{fs} / [\text{SIN}(\beta_s/2) D_k]) / (\pi - \beta_s/2) / D_k
 \end{aligned}$$

Determination of the View Factors F'_{sw} and F'_{ws} -

By Kirchoff's law,

$$A_w F'_{ws} = A_s F'_{sw}$$

By Eq C1.1-7,

$$F'_{sw} = 1 - F'_{sf}$$

By Kirchoff's Law,

$$\begin{aligned}
 F'_{sf} &= A'_f F'_{fs} / A_s \\
 &= \epsilon_f (\pi D_f) F'_{fs} / [\text{SIN}(\beta_s/2) D_k] \\
 &= (0.8) (2\pi) (1/4) / [\text{SIN}(\pi/4) 10]
 \end{aligned}$$

$$F'_{sf} = (0.8)(0.2221) = 0.1777$$

Therefore,

$$\begin{aligned}
 F_{sw} &= 1 - 0.1777 \\
 &= 0.8223
 \end{aligned}$$

Now, the view factor F'_{ws} may be determined using Kirchoff's law as follows:

$$\begin{aligned}
 F'_{ws} &= A_s F'_{sw} / A_w \\
 F'_{ws} &= \text{SIN}(\beta_s/2) F'_{sw} / (\pi - \beta_s/2) D_k \\
 &= (2^{.5}/2) (10) (0.7781) / (3/4) \pi 10 \\
 F'_{ws} &= 0.2468
 \end{aligned}$$

$$\begin{aligned}
 \text{or alternatively, } F'_{ws} &= A_s F'_{sw} / A_w \\
 &= (A_s (1 - F'_{sf})) / A_w \\
 &= [A_s (1 - A'_f F_{fs} / A_s)] / A_w \\
 &= (\sin(\beta_s/2) (1 - \epsilon_f (\pi D_f) F_{fs} / [\sin(\beta_s/2) D_k])) / (\pi - \beta_s)
 \end{aligned}$$

Calculation of $F'_{ws} - F_{ws}$ -

From the values of F'_{ws} and F_{ws} calculated above,

$$F'_{ws} - F_{ws} = 0.2468 - 0.2335 = 0.0133$$

As discussed above (Eq. C1.0-3), F'_{ws} minus F_{ws} is equal to the radiation emitted from the wall and transmitted through the flame to the solid bed.

Determination of F_{ww} and F'_{ww} -

We now have the values to determine F_{ww} from the equation,

$$F_{ws} + F_{ww} + F_{wf} = 1$$

and,

$$F_{ww} = 1 - F_{ws} - F_{wf}$$

$$F_{ww} = 1 - 0.2335 - .2$$

$$F_{ww} = 0.5665$$

Similarly, F'_{ww} is determined:

$$F'_{ww} = 1 - F'_{ws} - F'_{wf}$$

$$F'_{ww} = 1 - 0.2468 - 4/25$$

$$F'_{ww} = 0.5932$$

Calculation of $F'_{ww} - F_{ww}$ -

From the values of F'_{ws} and F_{ws} calculated above,

$$F'_{ww} - F_{ww} = 0.5932 - 0.5665 = 0.0267$$

As discussed above (Eq. C1.0-3), F'_{ww} minus F_{ww} is equal to the radiation emitted from the wall and transmitted through the flame to the solid bed.

The sum of the differences between F'_{ws} minus F_{ws} and F'_{ww} minus F_{ww} equals the difference F_{wf} minus F'_{wf} and is consistent with Eq. C1.0-3,

$$F_{wf}(1-\alpha_f) = (F'_{ws} - F_{ws}) + (F'_{ww} - F_{ww}) \quad .$$

Appendix D

Operating Data from the ERRU Kiln

TITLE _____

Project No. _____

Book No. _____

From Page No. _____ 11/8/84

Test 1 Clarksburg Soil

waste oil on
water spray offStart 15 ~~min~~ 16 charge 20 sec dwell
935 AM940 reduce dwell to 10 seconds - corbel look
fine - No ash jams

945 ash temp 740°C 1364°F

1005 ash temp 785°C

1025 John Deere shut down - restarted

1125 ash temp 810°C

1135

Drum Cooling Data

Drum #	Time removed	Fullness	Core Temp °C
1	935	232 1/3 (55)	685
2	955	244 1/3	730
3	10:10	313 1/2	800
4	1025	311 1/2	800
5	1055	258 1/2	795
6	1110	306 1/2	810
7	1125	349 2/3	820
8	1140	286 1/2	812
9	1150	348 2/3	less than 800

1208/16/12
dry1142 Changing CHEAF media tripped out
IB Fan vacuum interlock1145 informed by YSC that they ~~are~~ ^{have not}
sampled last point before CHEAF
upset.We decided that we would conclude
test without last point since it
is a very low velocity zone and would
not give significantly effect results

To Page: _____

Reviewed by	Entered by	Date
	Recorded by	

Project No. _____

12

Book No. _____ TITLE _____

From Page No

Soil Moisture

Dry Missouri Soil in Bag 17% H_2O
 " " on ground 13.7%
 Dry Chisholm soil 10.1% H_2O
 " " 5.7% H_2O

210 Test 2 start
 20 lb charge 10 sec dwell 1.07 KPM

243 1 min 23 sec per RMM cycle
 303 1 min 7 sec per RMM cycle

255 ash temp 722°C

4 PM hooked up 4-20 ma output from solids feed
 to Galton recorder in monitoring
 trailer

415 ash temp 740°C
 418 Test 2 completed

time	drum wts	net wt
230	281	278
250	278	267
310	286	283
330	192	190
350	286	283
410	353	350
420	215	213

mixed 208

To Page No..

Witnessed & Understood by me.

Date

Invented by

Date

Project No. _____

Book No. _____

13

on Page No. _____

6 PM Test 3 start Mondmorillonite
20 lb/chg 10 sec dwell
40 sec cycle BSM

7:04 pm Ash temp from 6:51 pm 738°C

There is no indication of dusting as the ash falls out into the ash drum. Material comes out red and quickly cools on surface.

7⁴² pm Ash T = 735°C Drum 7³⁵ pm

time	Drum weight	net wt
6:25		255
6:38		210
6:51		224
7:02		231
7:13		214
7:25		227
7:35		212
7:45		227
7:54		208

Test 3 complete 8:10⁵ pm 11/8/84

8:00	210
8:11	196
8:17	153

To Page No. _____

Read & Understood by me.

Date

Invented by

Date

14

Project No. _____

Book No. _____ TITLE _____

From Page No

$$55 \frac{\text{gal}}{\text{min}} \cdot \frac{\text{ft}^3}{7.48 \text{ gal}} \times 62 \frac{\text{lb}}{\text{ft}^3} = 456 \text{ lb/min}$$

add 5 gal to get 18% loading 10% 14.0
46 lb

11/9/84

Test # 4

11:10 PM

Wet Clarksburg Soil @ 5 gal H₂O
 added to each drum ~ 18% moisture
 Initial conditions

~ 2000 lb/hr.

SCFM rich Air = 1050

WC = 126 lb/hr

FO = 4 gal/min

rich T = 1850

PO₂ = 7.5

<u>Time</u>	<u>Solids Temp</u>	<u>rich T</u>	<u>Air SCFM</u>	<u>WC</u>	<u>PO₂</u>	<u>net drum wt</u>
1:35 PM	775	1850	1050	126	7.57	377.5
2:07 PM	725	1830	1000	112	7.82	355.5
2:40 PM	717	1800	1050	111.7	7.70	371.8
2:58 PM	760	1800	1050	111.7	7.46	405
3:15 PM	750	1790	1050	110.6	7.98	378.5
3:30	750					368
4:2						

Witnessed & Understood by me.

Date

Invented by

Date

To Page No. _____

Recorded by

TITLE

Book No.

From Page No.

11/9/84 Dry Clarksburg Soil

355	ash temp	750°C	(454)
410	ash temp	770°C	(463)
430	ash temp	790°C	(426)
445	ash temp	770°C	(498)
500	ash temp	710°C	(460)

To Page N

Invented by me

Date

Invented by

Date

Recorded by

DATE: 11/8/04

SHIFT: DAY

OPERATOR: CT/MSP

ITEM	TAG #	UNITS	TIME											
			9:00AM	10:00A	11:00A	12:00P	1:00P	2:00P	3:00P	4:00P	5:00P	6:00P	7:00P	8:00P
Kiln Temperature	TIC-101	°F	1840	1850	1840	1840	1820	1850	1840	1820	1800	1800	1830	1800
Kiln Comb Air Flow	FI-102	SCFH	1200	1250	1250	1200	1200	1250	1250	1250	1200	1200	1300	1250
SCC Temperature	TIC-201	°F	2090	2080	2160	2100	2140	2165	2160	2150	2170	2160	2170	2150
Waste Solids Flow Rate		LBS/CHG	10	15	15	15	-	20	20	20	-	-	20	20
Ambient Temperature		°F	45	49	51	52	50	58	56	55	55	45	43	43
Kiln Comb Air Temp		°F	70	72	74	75	72	77	80	80	80	76	74	74
Kiln Water Flow	FI-106	GPM	-	-	-	-	-	-	-	-	-	-	-	-
Kiln Blower Pressure		In H2O	31.5	31	30.5	30.5	31	30.5	30.5	31	32	32	31.5	32
Waste Oil Flow Rate	FI-150	LBS/HR	152.6	147.4	136.4	163.5	-	107.9	133.4	116	114	125	139.8	157.6
Burner 2 Fuel Flow	FI-104D	GPH	3.5	4	4	4	15	4	4	4	4	4	4	4
Burner 4 Fuel Flow	FI-204B	GPH	25	25	24	24	23	23.5	24	24	24	23	24	24
Total SCC Gas Flow	FI-202	in ³ /s	0.15	0.07	0.28	-	-	-	0.57	-	-	0.60	0.63	-
Burner 1 Fuel Flow	FI-104A	GPH	-	-	-	-	15	-	-	-	-	-	-	-
Water Atom Pressure	PI-112	PSI	25	24.5	24	25	25	26	26	25	-	25	25	25
Waste Oil Atom Press		PSI	25	25	24	25	25	26	25	25	-	25	25	25
Kiln Vacuum		In H2O	1.7	1.2	1.1	1.0	0.5	1.3	1.4	1.3	1.2	1.5	1.5	1.7
SCC Vacuum		In H2O	2.5	2.0	1.5	1.5	0.5	1.6	1.8	1.3	-	2.6	2.0	2.3
SCC Blower Pressure		In H2O	25.5	25.5	25	24.5	24	25	25	25	25	25	25.5	25
Burner 3 Fuel Flow	FI-201A	GPH	25	24.5	24	24	23	24	23.5	24	-	24	24	24
SCC Comb Air Temp	TI-203	°F	68	69	74	74	76	78	77	76	74	73	75	74
SCC Comb Air Flow	FI-201	SCFH	1250	1200	1200	1250	1200	1200	1200	1200	1200	1200	1250	1250
Kiln Drive Flow		GPM	3.2	3.2	3.2	3.2	3.2	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Operator Comments: Test #1 Checkup, Set Start @ 9:35 AM. Increased kiln drive to 5 gpm @ 2:00

to increase rpm

Test #2 Missouri Clay @ 2:10 PM

Test #3 Kist Litter @ 6:06 PM

TEST ENDED @ 10:00 PM

TABLE 7 AIR POLLUTION CONTROL EQUIPMENT OPERATING LOG SHEET

HOURLY LOG

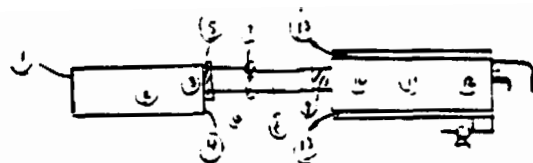
DATE: 11/1/84

SHIFT: DAY

OPERATOR: CT/MP/2B

ITEM	TAG #	UNITS	TIME													
			9:00AM	10:00	11:00	12:00P	1:00P	2:00P	3:00P	4:00P	5:00P	6:00P	7:00P	8:00P		
Quench Water Temp.	TI-335	°F	170	171	170	170	172	171	171	172	170	170	170	170		
Quench H2O Press DNST	PI-335	PSI	46	40	40	41	45	40	46	40	46	40	46	46		
Quench Recycle Flow	FI-335	GPM	52	48	50	45	50	44	51	47	46	44	51	51		
Quenched Gas Temp.	TSH-336	°F	210	210	210	215	215	215	215	215	215	210	215	220		
CHEAF Exit Temp.		°F	170	170	170	168	170	171	170	168	168	170	170	170		
CHEAF Water Flow	FI-355	GPM	14	14	14	14	14	14	14	14	14	15	15	15		
CHEAF Water Temp.	TI-355	°F	130	129	130	129	132	130	131	131	130	131	132	130		
CHEAF Filter Differ	DPI-356	In H2O	25	23.6	23.5	24	24	25	24	27.6	23.5	23	24.5	23		
CHEAF Outlet Press	PI-358	In H2O	30	28	28.5	28.5	27.5	28	28.5	28	28	27	29	27		
CHEAF Inlet Press	PI-357	In H2O	5.5	4.6	4.5	4	3.6	4.0	4.5	4	4.5	4.5	3	4.5		
CHEAF H2O Press DNST		PSI	24.5	21	24	25	25	25	25.5	25.5	25	25	24.5	25		
Scrubber Water Temp.	TI-375	°F	160	162	162	162	163	161	162	163	161	162	161	161		
Scrubber Water Press	PI-375	PSI	22	21.5	22	22	22.5	23	22	22.6	22.6	22.5	23	23		
Scrubber Water Flow	FI-375	GPM	145	146	150	146	142	145	140	142	140	140	138	130		
ID Fan Inlet Press	PI-376	In H2O	31.5	31	31	31.5	30.5	30.5	31	32	31	31	32	32		
Quench Water pH	PHIC-335		7.8	7.5	7.4	7.4	7.6	7.5	7.5	7.5	7.4	7.4	7.8	8		
CHEAF Water pH	PHIC-354		7.8	7.9	7.9	8.5	7.5	7.7	8.9	8.0	8.1	8.0	8.0	8		
Scrubber Water pH	PHIC-374		8.7	8.7	8.7	8.7	8.6	8.6	8.7	8.6	8.8	8.8	8.6	8.5		
ID Fan Vibration		mil	0.7	0.7	0.8	0.8	0.9	1.0	1.0	0.9	0.8	0.6	0.8	0.7		
Stack Temperature	TI-376	°F	176	171	171	178	174	170	168	172	168	175	178	175		
ID Fan Drive Speed		RPM	1850	1760	1750	1750	1750	1700	1725	1750	1750	1800	1800	1800		
Makeup Water Press	PI-304	PSI	30	30	30	30	30	30	29	29	29	28	29	28		
Makeup Water Flow	FCV-372	GPM	11	10	10	10	10	10	10	10	10	10	10	10		

REMARKS:



5

JSC

5-10-10

Resolution Issues

System Surface Temps & Ambient Parameters

Test	1	2	3	4
Date	3/31	4/1	4/1	4/1
Time	6-8 AM	5-8 AM	1-3 pm	8-10 pm
Ambient Temp				
Relative humidity				
6 WU./16 DG.				
RA/SCC Temp (°F)	1674/2070	1643/2113	1680/2477	1680/2153
Estimated Rotary Kew Surf Temp (°F)				
1	875	815	900	900
2	340	340	350	350
3	340	340	350	350
4	730	730	760	760
RA/SCC				
Assumption	1640	1643	1680	1680
Assumed Temp	1600	1600	1610	1610
Assumed Temp	1600	1600	1640	1640
SCC				
10				
11				
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ERRA Data

$$D = 52"$$

$$L = 16'$$

$$\text{shell, in} = 44$$

$$\text{ins 1} = 4 \quad KK1 = 4.0$$

$$\text{ins 2} = 2 \quad KK2 = 2.0$$

9:55 AM 11/8 ^{DRY} from 2-6 - checks bag soil 1200 lb/hr @ 10.1% wet
 from 2-7 missouri dry @ 4% loading
 2-8 @ 7% loading

$$2-6 \quad T_3 = 1004^\circ\text{C} (1840^\circ\text{F})$$

firing rate ~ 3.4 mm 80/hr

$$2-7 \quad 1025 \text{ lb/hr Dry } 11\% \text{ wet } \text{in} = 3.1 \text{ mm } \underline{\underline{\text{wet}}}$$

11/8 ^{before} Can ~~30~~ 30 p 75 6"

11/8 Jade Pak 38-P 4" p 55 $E_g'' = 1.5 - 2.0$

$$k = 4.5$$

$$1.5 / 1800^\circ\text{F} / 2$$

7/8 shell

$$C_{\text{shell}} = ?$$

2" masonry line IFB Green int 30

$$E_g'' = 3.0$$

$$k = \frac{2.0}{1000^\circ\text{F}}$$

overall

$$\text{overall } 10^\circ\text{F} / \text{ft}^2 = \text{hr}$$

Appendix E

Program Listing for Direct Fired Kiln

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	PRIMARY BURNER AND CHAMBER MASS AND HEAT BALANCE RESULTS																
2																	
3			(1)			(2)			(3)			(4)			(5)		
4			TOTAL WASTE + FUEL			AUX FUEL TO BURNER			WASTE TO BURNER			WASTE TO CHAMBER			PYROLYSIS PRODUCTS		
5			LB/HR LB-M/HR			LB/HR LB-M/HR			LB/HR LB-M/HR			LB/HR LB-M/HR			LB/HR LB-M/HR		
6																	
7	C		155.23	12.94		155.23	12.94		0.00	0.00		0.00	0.00		0.00	0.00	
8	H2		22.46	11.23		22.46	11.23		0.00	0.00		0.00	0.00		0.00	0.00	
9	O2		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00	
10	N2		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00	
11	WATER		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00	
12	CL		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00	
13	S		0.30	0.01		0.30	0.01		0.00	0.00		0.00	0.00		0.00	0.00	
14	BR		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00	
15	F		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00	
16	SALT		0.00	----		0.00	----		0.00	----		0.00	----		0.00	----	
17	ASH		0.00	----		0.00	----		0.00	----		0.00	----		0.00	----	
18																	
19	TOTAL		178.00	24.16		178.00	24.16		0.00	0.00		0.00	0.00		0.00	0.00	
20																	
21	SCFM														0		
22	ACFM														0		
23	TEMP F		ERR			60			ERR			ERR			2353		
24	ENTHALPY		0.000			0.000			0.000			0.000			0.000		
25	HEAT REL		3.415			3.415			0.000			0.000			0.000		
26																	
27	MM BTU/HR		3.415			3.415			0.000			0.000			0.000		
28																	
29	PRIMARY CHAMBER																
30	HEAT BALANCE			WASTE		AUX FUEL		IN		AIR					TOTAL		
31	MM BTU/HR			0.000		3.415				0.037					3.452		
32	FMB PROGRAM FOR PRIMARY AND SECONDARY COMBUSTION SYSTEMS INCL PYROLYSIS																
33	FILE:	FMB.WKS				BY: D. M. PITIS			TEMPLATE 2			PRIMARY BURNER AND CHAMBER COMBUSTION CONDITIONS/CALCULATION					
34			INPUT TEMPLATE 1 PRIMARY CHAMBER WASTE DATA														
35		PRIMARY	BURNER WASTES----			CHAMBER WASTES----											
36	NAME: AUX FUEL		WASTE 1	WASTE 2	WASTE 3	WASTE 4	WASTE 5	WASTE 6									
37	% C	87.21	0.00	0.00	0.00	0.00	0.00	0.00				% EXCESS AIR FOR FUELS TO BURNER	10.00				
38	% H2	12.62	0.00	0.00	0.00	0.00	0.00	0.00				% EXCESS AIR FOR WASTES TO CHAMBER	0.00				
39	% O2	0.00	0.00	0.00	0.00	0.00	0.00	0.00				RADIATION LOSS (MM BTU/HR)	1.17	←=QT UQ00			
40	% N2	0.00	0.00	0.00	0.00	0.00	0.00	0.00				AIR TEMP F	69.92				
41	% WATER	0.00	0.00	0.00	0.00	0.00	0.00	0.00				AIR HUMIDITY (LB/LB DRY AIR)	0.01				
42	% CL	0.00	0.00	0.00	0.00	0.00	0.00	0.00				% ASH IN EXIT	0.00				
43	% S	0.17	0.00	0.00	0.00	0.00	0.00	0.00				% SALT IN EXIT	0.00				
44	% BR	0.00	0.00	0.00	0.00	0.00	0.00	0.00				PYROLYSIS (1 = YES, 0 = NO)	0				
45	% F	0.00	0.00	0.00	0.00	0.00	0.00	0.00				HEAT OF PYROLYSIS BTU/LB	360.00				
46	% SALT	0.00	0.00	0.00	0.00	0.00	0.00	0.00				AVG MOL WEIGHT OF PYROLYSIS PRODUCTS	50.00				
47	% ASH	0.00	0.00	0.00	0.00	0.00	0.00	0.00				% FIXED CARBON IN ASH	0.00				
48												SPECIFIC HEAT OF ASH (BTU/LB F)	0.26				
49	TOTAL	100.00	0.00	0.00	0.00	0.00	0.00	0.00				DESIRED ASH DISCHARGE TEMPERATURE F	0.00	←- USED IF INPUT			
50	LB/HR	----	0.00	0.00	0.00	0.00	0.00	0.00				DISIRED OR "GUESS" TEMPERATURE F	2352.50	←=11			
51	BTU/LB	19188	0	0	0	0	0	0				1BS/HR AUX FUEL	178.00	521.16			
52	TEMP F	60	60	60	60	60	60	60				HEAT IN =	3.452	HEAT OUT =	3.452		Δ H = 0.00026
53	BTU/LB F	0.50	0.50	0.50	0.50	0.50	0.50	0.50									
54																	
55	PAUX LB/HR =		178.00			% FUEL COMB SECT 1 =	100%	29-feb	MM		0.00						

	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
1																			
2																			
3	(6)					(7)			(8)			(9)			(10)			(11)	
4	SOLIDS OUT BOTTOM					TOTAL AIR			AIR TO BURNER			AIR TO CHAMBER			COMBUSTION PRODUCT			TOTAL OFF-GAS	
5	LB/HR LB-M/HR					LB/HR LB-M/HR			LB/HR LB-M/HR			LB/HR LB-M/HR			LB/HR LB-M/HR			LB/HR LB-M/HR	
6																			
7	0 00 0 00			CO2		0 00 0 00			0 00 0 00			0 00 0 00			569 19 12 94			569 19 12 94	
8	0 00 0 00			PYRO GAS		0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00	
9	0 00 0 00			O2		653 37 20 42			653 37 20 42			0 00 0 00			59 40 1 86			59 40 1 86	
10	0 00 0 00			N2		2163 23 77 26			2163 23 77 26			0 00 0 00			2163 23 77 26			2163 23 77 26	
11	0 00 0 00			WATER		28 17 1 56			28 17 1 56			0 00 0 00			230 34 12 80			230 34 12 80	
12	0 00 0 00			HCL		0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00	
13	0 00 0 00			SO2		0 00 0 00			0 00 0 00			0 00 0 00			0 61 0 01			0 61 0 01	
14	0 00 0 00			HBR		0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00	
15	0 00 0 00			HF		0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00	
16	0 00 0 00			SALT		0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00	
17	0 00 0 00			ASH		0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00			0 00 0 00	
18																			
19	0 00 0 00			TOTAL		2844 76 99 24			2844 76 99 24			0 00 0 00			3022 76 104 86			3022 76 104 86	
20																			
21				SCFM		628			628			0			663			663	
22				ACFM		640			640			0			3588			3588	
23	2353			TEMP F		70			70			70			2353			2353	
24	0 000			ENTHALPY		0 037			0 037			0 000			2 283			2 283	
25	0 000			HEAT REL		0 000			0 000			0 000			0 000			0 000	
26																			
27	0 000			MM BTU/HR		0 037			0 037			0 000			2 283			2 283	
28																			
29						OUT									HEAT IN - HEAT OUT				
30	OFF-GAS			ASH		HEAT OF PYROLYSIS			HEAT LOSS			TOTAL							
31	2 283			0 000		0 000			1 169			3 452			0 000				
32																			
33				TEMPLATE 8		COMPONENT HEAT BALANCE BTU/HR													
34																			
35						(5)	(7)	(8)	(9)	(10)	(11)	PRIMARY COMBUSTION CHAMBER 5			LBS/HR			MM BTU/HR	
36						PYROLYS	TOTAL	AIR TO	AIR TO	COMBUST	TOTAL OFF	TEMP = 2353 F			IN	OUT		IN	OUT
37	A	B	C			PRODUCTS	AIR	BURNER	CHAMBER	PRODUCTS	GAS								
38																			
39	0 20	0 00	-0 00	CO2	0	0	0	0	0	367424	367424	AUX FUEL			178 00	---		3 415	---
40	0 44	0 00	-0 00	PYRO GAS	0	0	0	0	0	0	0	WASTE TO BURNER			0 00	---		0 000	---
41	0 24	0 00	-0 00	O2	0	1546	1546	0	0	36317	36317	646 WASTE TO CHAMBER			0 00	---		0 000	---
42	0 24	0 00	-0 00	N2	0	5252	5252	0	0	1353674	1353674	0 STOIC AIR TO BURNER			2560 54	---		0 006	---
43	0 44	0 00	-0 00	WATER	0	29979	29979	0	0	525473	525473	611 XS AIR TO BURNER			256 05	---		0 001	---
44	0 19	0 00	-0 00	HCL	0	0	0	0	0	0	0	626 STOIC AIR TO CHAMBER			0 00	---		0 000	---
45	0 15	0 00	-0 00	SO2	0	0	0	0	0	302	302	2281 XS AIR TO CHAMBER			0 00	---		0 000	---
46	0 08	0 00	-0 00	HBR	0	0	0	0	0	0	0	0 AIR HUMIDITY			28 17	---		0 030	---
47	0 35	0 00	0 00	HF	0	0	0	0	0	0	0	498 PYRO PRODUCTS			0 00	0 00		0 000	0 000
48				SALT	INCL	0	0	0	0	0	0	0 COMBUSTION GAS			0 00	3022 76		0 000	2 283
49				ASH	INCL	0	0	0	0	0	0	0 SOLIDS OUT BOTTOM			0 00	0 00		0 000	0 000
50												0 HEAT OF PYROLYSIS			---	---		---	0 000
51												0 HEAT LOSS			---	---		---	1 169
52						TOTAL	0	36778	36778	0	2283190	TOTAL			3022 76	3022 76		3 452	3 452
53												AIR SCFM:			BURNER =	627 80	CHAMBER =	0 00	OVERALL = 627 80
54												% XS AIR OVERALL =			10 00%	OFF-GAS ACFM =		3588	
55																			

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
56	HEAT IN =	3 452	HEAT Out =		3 452		DELTA H =	0 00028									
57					11.1	19.7	DELTA Hg	BIU			H2Og1	500 00	1000 00	1500 00	2000 00	2500 00	
58		1 F	1. K	1 NEW	2351 9	69 9	0	0 80									
59		11a	2351 9	1562 2	1562 17	2351 9	1102 0	563 500	AI =	2 45		0 19	0 14	0 11	0 08	0 06	
60		19a	1182 0	912 2	912 20	1.927	1927 5	b AS =	0 8269			0 14	0 14	0 14	0 13	0 12	
61		1wa	2127 6	1437 6	1437 58	Xmo =	0 00	Aw =	3 1434			-0 01	-0 02	-0 01	-0 01	-0 01	
62		1sa	1377 6	1020 9	1 021	Fsw =	0 34176	Aq =	6 4198			Y=Emg	X=1				
63		1stin	353 4	451 9		Fws =	0 08990	0 00000	ws m =	0 8485		1a	0 31		Y=Emg	X=1	X^2
64	1sh check =		451 89			Fww =	0 30404	0 00000	AI =	3 06		500 00	0 24	500 00	0 24	500 00	*****
65		350 00	449			F1w =	0 77778		Area3 =	4 97481		750 00	0 19	750 00	0 19	750 00	*****
66	Qs + Qw + Qg + Ql =		14.929	50 967		F1s =	0 22222		As1t =	5 09146		1000 00	0 18	1000 00	0 18	1000 00	*****
67	Qs =		(162.2801)			Fst =	0 65824					1500 00	0 15	1500 00	0 15	1500 00	*****
68	Qw =		(39)*			Fwt =	0 60606		r11 m =	0 66000		2000 00	0 12	2000 00	0 12	2000 00	*****
69	Qg =		(165.074)	(563.561)	DS =	0 20			r12 m =	0 76160		2500 00	0 09	2500 00	0 09	2500 00	*****
70	Ql =		342.322			DW =	0 20		r13 m =	0 81240		3000 00	0 07	3000 00	0 07	3000 00	*****
71	Qwcd =		14.928			PQ =	0 00		rsh m =	0 83145		3500 00	0 06	3500 00	0 06	3500 00	*****
72	DIL 1s. K =	731.91	1020 91			ABS =	0 80		r1 m =	0 50000		4000 00	0 05	4000 00	0 05	4000 00	*****
73	DIL 1g. K =	ERR	ERR			ABW =	0 80										
74	DIL 1g. f =	ERR	ERR			ABI =	1 00		D m =	1 32		500 00			1 16	18750 00	*****
75	1Rq1 =		0 7840			1msh =	0 7		L m =	4 87					Y	X	X#2
76	1Rq2 =		0 7414			1ms =	0 80		LL m =	0 97							
77	1Rq3 =		0 7022			1mm =	0 80										
78	1Rq1 =		0 8517			1ml =	1 00		1hr =	80 00							
79	1Rq2 =		0 8025			1s =	61.588		1hrad =	1 39626							
80	1Rq3 =		0 7624			1m =	242.162		0 95*8Q28*(1-8Q29)								
81						1g =	39 260		1/D =	0 117							
82	1ag =		0 2321			1l =	337 671										
83	1Rq11=(ABg2+A	ERR	0 1870			sigma =	0 000000		Inst. in	4 0							
84	ABg11 =		0 8130			notes total	105		Inst2 in	2 0							
85						Pco2 =	0 07544		shell. in	0 8							
86	TRg11 =		0 9072			PH2O =	0 12375		kk1. 81u/	5 5		500 00	0 12	500 00	0 12	500 00	*****
87	TRg12 =		0 8984			PCO2 + PH2O	0 19919		kk2. 81u/	2 0		1000 00	0 09	1000 00	0 09	1000 00	*****
88	TRg13 =		0 8895						kw1. w/m*	0 79251		1500 00	0 11	1500 00	0 11	1500 00	*****
89						Lm= 66*D*(1-FD)			kw2. w/m*	0 28618		2000 00	0 11	2000 00	0 11	2000 00	*****
90	TRgg1 =		0 7679			Lm. m =	0 77										
91	TRgg2 =		0 7274			2Lm. m =	1.53858	(PH2O+PCO2)*(r11-r1) =	0 032			500 00			0 43	5000 00	*****
92	TRgg3 =		0 6897			3Lm. m =	2.30787	(PH2O+PCO2)*(r11-r1)*2 =	0 064						Y	X	X#2
93	ABg1 = 1 - TRgg1		0 2321					(PH2O+PCO2)*(r11-r1)*3 =	0 096								
94	ABg2 = TRgg1 - TRgg2		0 0405			hcdwsh =	1/((2*OP1+r13)*((r12-r1)/(OP1*kw1*(r11+r12))+((r13-r12)/(OP1*										
95	ABg3 = TRgg2 - TRgg3		0 0377				3.04423					2500 00	0 09	2500 00	0 09	2500 00	*****
96						hrsha =	sigma*(1msh*(Tsh*Tsh*Tsh-Ta*Ta*Ta*Ta)/(Tsh-Ta)					3000 00	0 07	3000 00	0 07	3000 00	*****
97	% excess air =		10.00				8 61594					3500 00	0 06	3500 00	0 06	3500 00	*****
98	1a =	71	294			Tsh check =	(hcdwsh*Area3*Tw+Ash*hcvsha*Ta+Ash*hrsha*Ta)/(hcdwsh*Area3+AS					4000 00	0 05	4000 00	0 05	4000 00	*****
99	hcvws =		50				452										
100	hcvgs =		50			Qwcd =	Qshcv + Qshr					500 00			0 26	13000 00	*****
101	hcvgw =		20			Qwcd =	Area3*hcdwsh*(1w-Tsh)								Y	X	X#2
102	hcvsha =		10				14928										
103	1r sha =		9			Qshcv =	Ash*hcvsha*(Tsh-Ta)										
104							8019										
105	(PH2O+PCO2)*Lm =		0 1532			Qshr =	Ash*hrsha*(Tsh-Ta)										
106	(PH2O+PCO2)*Lm2 =		0 306				6909										
107	(PH2O+PCO2)*Lm3 =		0 460			Qshcv+Qshr	14928										
108																	
109																	
110	Qss+Qsw+Qsg+Qsl =		(10)			1ms =	0 80		del l								

	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
56	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
57	3000.00	3500.00	4000.00	750.00															
58	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
59	0.04	0.03	0.02	0.15															
60	0.10	0.08	0.07	0.15															
61	-0.01	-0.01	-0.01	-0.02															
62	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
63	X'3	X'4	XY	X'2Y	N														
64	-----	-----	117.92	58961.06	1.00														
65	-----	-----	145.99	109492.10	1.00														
66	-----	-----	179.67	179695.66	1.00														
67	-----	-----	228.35	342529.50	1.00														
68	-----	-----	242.77	485530.82	1.00														
69	-----	-----	233.01	582516.95	1.00														
70	-----	-----	223.34	670034.19	1.00														
71	-----	-----	208.92	731232.58	1.00														
72	-----	-----	186.67	746675.14	1.00														
73	-----	-----	-----	-----	-----														
74	-----	-----	1766.64	3906638.01	9.00														
75	X#3	X#4	XY	X#2Y	N														
76	-----	-----	-----	-----	-----														
77	3000.00	3500.00	4000.00																
78	-----	-----	-----	-----	-----														
79	-----	-----	-----	-----	-----														
80	0.06	0.05	0.04																
81	0.06	0.05	0.04																
82	-0.01	-0.01	-0.01																
83	-----	-----	-----	-----	-----														
84	-----	-----	-----	-----	-----														
85	X'3	X'4	XY	X'2Y	N														
86	-----	-----	60.09	30045.38	1.00														
87	-----	-----	94.37	94373.92	1.00														
88	-----	-----	159.13	238697.72	1.00														
89	-----	-----	211.04	422084.39	1.00														
90	-----	-----	-----	-----	-----														
91	-----	-----	524.64	783200.41	4.00														
92	X#3	X#4	XY	X#2Y	N														
93	-----	-----	-----	-----	-----														
94	X'3	X'4	XY	X'2Y	N														
95	-----	-----	222.80	556946.45	1.00														
96	-----	-----	215.80	647386.30	1.00														
97	-----	-----	202.66	709308.35	1.00														
98	-----	-----	183.38	733524.90	1.00														
99	-----	-----	-----	-----	-----														
100	-----	-----	824.63	2647216.00	4.00														
101	X#3	X#4	XY	X#2Y	N														
102	-----	-----	-----	-----	-----														
103	-----	-----	-----	-----	-----														
104	3000.00	3500.00	4000.00	750.00															
105	-----	-----	-----	-----	-----														
106	-----	-----	-----	-----	-----														
107	0.04	0.03	0.02	0.15															
108	0.10	0.08	0.07	0.15															
109	-0.01	-0.01	-0.01	-0.02															
110	-----	-----	-----	-----	-----														

EMGO1 = (E(CO2) + (CH2O)) / (1 - Csol)

0.23

Y Calc Y Actstg
 X=1 Y=0.00 500.00 0.12 0.12
 X=2 Y=0.00 1000.00 0.10 0.09
 X=3 Y=0.11 1500.00 0.10 0.11
 X=4 Y=0.15 2000.00 0.11 0.11
 X=5 Y=0.21 2500.00 0.09 0.09
 X=6 Y=0.21 3000.00 0.07 0.07
 X=7 Y=-0.00 3500.00 0.06 0.06
 X=8 Y=0.00 4000.00 0.05 0.05
 X=9 Y=0.00 4500.00 0.05 0.05
 X=10 Y=0.00 5000.00 0.10 0.10

	AI	AW	AN	AO	AP	AQ	AR	AS	AT	AIU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	
56																				
57																				
58	H2OW1	500.00	1000.00	1500.00	2000.00	*****	3000.00	3500.00	*****	750.00										
59																				
60	a	0.19	0.14	0.11	0.08	0.06	0.04	0.03	0.02	0.15										
61	b	0.14	0.14	0.14	0.13	0.12	0.10	0.08	0.07	0.15										
62	c	-0.01	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02										
63		Y=Eg	X=T																	
64	L=	0.49		Y=Eg	X=T	X^2	X^3	X^4	XY	X^2Y	N	A =	0.00	X=T	Y	Calc	Y	Act=Eg		
65	500.00	0.26	500.00	0.26	500.00	*****	64747.54	1.00				B =	-0.00	500.00	0.25	0.26				
66	750.00	0.22	750.00	0.22	750.00	*****	1.00					C =	4400.00	1000.00	0.21	0.20				
67	1000.00	0.20	1000.00	0.20	1000.00	*****	1.00					D =	0.26	1500.00	0.17	0.18				
68	1500.00	0.18	1500.00	0.18	1500.00	*****	1.00					E =	*****	2000.00	0.14	0.14				
69	2000.00	0.14	2000.00	0.14	2000.00	*****	1.00							2500.00	0.11	0.11				
70	2500.00	0.11	2500.00	0.11	2500.00	*****	1.00					a =	0.30	3000.00	0.09	0.09				
71	3000.00	0.09	3000.00	0.09	3000.00	*****	1.00					b =	-0.00	3500.00	0.07	0.07				
72	3500.00	0.07	3500.00	0.07	3500.00	*****	1.00					C =	0.00	4000.00	0.06	0.06				
73	4000.00	0.06	4000.00	0.06	4000.00	*****	1.00							2587.64	0.11					
74																				
75	500.00			1.33	16750.00	*****	9.00													
76				Y	X	X#2	X#3	X#4	XY	X#2Y	N									
77																				
78																				
79	CO2W1	500.00	1000.00	1500.00	2000.00	*****	3000.00	3500.00	*****											
80																				
81	a	0.11	0.09	0.10	0.09	0.08	0.06	0.05	0.04											
82	b	0.04	0.05	0.05	0.06	0.06	0.06	0.05	0.04											
83	c	-0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.00	-0.00											
84																				
85		Y=Eg	X=T																	
86	L=	0.21		Y=Eg	X=T	X^2	X^3	X^4	XY	X^2Y	N	A =	0.00	A =	0.00	X=T	Y	Calc	Y	Act=Eg
87	500.00	0.12	500.00	0.12	500.00	*****	60.51	30253.61	1.00			B =	-0.00	B =	-0.00	500.00	0.12	0.12		
88	1000.00	0.10	1000.00	0.10	1000.00	*****	95.34	95343.59	1.00			C =	2500.00	C =	6500.00	1000.00	0.10	0.10		
89	1500.00	0.11	1500.00	0.11	1500.00	*****	1.00					D =	0.12	D =	0.16	1500.00	0.10	0.11		
90	2000.00	0.11	2000.00	0.11	2000.00	*****	1.00					E =	*****	E =	*****	2000.00	0.11	0.11		
91																2500.00	0.09	0.09		
92	500.00			0.43	5000.00	*****	4.00					a =	0.15	a =	0.21	3000.00	0.07	0.07		
93				Y	X	X#2	X#3	X#4	XY	X#2Y	N	b =	-0.00	b =	-0.00	3500.00	0.06	0.06		
94												c =	0.00	c =	0.00	4000.00	0.05	0.05		
95	L=	0.21		Y=Eg	X=T	X^2	X^3	X^4	XY	X^2Y	N					2587.64	0.09			
96	2500.00	0.09	2500.00	0.09	2500.00	*****	1.00													
97	3000.00	0.07	3000.00	0.07	3000.00	*****	1.00													
98	3500.00	0.06	3500.00	0.06	3500.00	*****	1.00													
99	4000.00	0.05	4000.00	0.05	4000.00	*****	1.00													
100																				
101	500.00			0.27	13000.00	*****	4.00													
102				Y	X	X#2	X#3	X#4	XY	X#2Y	N									
103																				
104																				
105	H2OS2	500.00	1000.00	1500.00	2000.00	*****	3000.00	3500.00	*****	750.00										
106																				
107	a	0.19	0.14	0.11	0.08	0.06	0.04	0.03	0.02	0.15										
108	b	0.14	0.14	0.14	0.13	0.12	0.10	0.08	0.07	0.15										
109	c	-0.01	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02										
110		Y=Eg	X=T																	

	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
111	X'J	X'4	XY	X'2Y	N	A =	0 00	X=I	Y Calc	Y Act=Eq									
112	.....	.....	137 71	68853 70	1 00	B =	-0 00	500 00	0 27	0 28									
113	.....	.....	176 63	132474 76	1 00	C =	4400 00	1000 00	0 22	0 22									
114	.....	.....	219 96	219956 46	1 00	D =	0 28	1500 00	0 19	0 19									
115	.....	.....	287 40	431096 15	1 00	E =	.....	2000 00	0 16	0 16									
116	.....	.....	315 69	631381 21	1 00			2500 00	0 13	0 13									
117	.....	.....	315 08	787697 13	1 00	A =	0 31	3000 00	0 10	0 10									
118	.....	.....	307 93	923786 35	1 00	B =	-0 00	3500 00	0 08	0 08									
119	.....	.....	291 53	1020363 37	1 00	C =	0 00	4000 00	0 07	0 07									
120	.....	.....	270 48	1081919 70	1 00			1641 97	0 18										
121	-----	-----	-----	-----	-----														
122	.....	.....	2322 40	5297528 84	9 00	ABgg2 = (ABC02,ABH20)*(1-C501)													
123	X#3	X#4	XY	X#2Y	N														
124	.....	.....	.....	.....	.....	0 2726													
125	.....	.....	.....	.....	.....	ABC02 = ((EMC02 @ I\$ P*(L*I\$/I\$)*(I\$/I\$) .65													
126	3000 00	3500 00	4000 00	.....	.....	0 11													
127	-----	-----	-----	-----	-----	ABH20 = ((EMH20 @ I\$ P*(L*I\$/I\$)*(I\$/I\$) .45													
128	0 06	0 05	0 04	.....	.....	0 16													
129	0 06	0 05	0 04	.....	.....	I\$ =	1641 97	pio2 =	0 38										
130	-0 01	-0 00	-0 00	.....	.....	I\$ =	1641 97	C50g2 =	0 0512										
131	.....	.....	.....	.....	.....														
132	.....	.....	.....	.....	.....														
133	X'3	X'4	XY	X'2Y	N	A =	0 00	A =	0 00	X=I	Y Calc	Y Act=Eq							
134	.....	.....	63 52	31758 50	1 00	B =	-0 00	B =	-0 00	500 00	0 12	0 13							
135	.....	.....	102 34	102337 14	1 00	C =	2500 00	C =	6500 00	1000 00	0 11	0 10							
136	.....	.....	171 74	257607 59	1 00	D =	0 12	D =	0 18	1500 00	0 11	0 11							
137	.....	.....	232 22	464445 00	1 00	E =	.....	E =	.....	2000 00	0 12	0 12							
138	-----	-----	-----	-----	-----					2500 00	0 10	0 10							
139	.....	.....	569 82	856148 23	4 00	A =	0 15	A =	0 22	3000 00	0 08	0 08							
140	X#3	X#4	XY	X#2Y	N	B =	-0 00	B =	-0 00	3500 00	0 07	0 07							
141	.....	.....	.....	.....	.....	C =	0 00	C =	0 00	4000 00	0 05	0 05							
142	X'3	X'4	XY	X'2Y	N					1641 97	0 11								
143	.....	.....	249 74	624355 40	1 00														
144	.....	.....	245 74	737212 64	1 00														
145	.....	.....	231 37	809789 01	1 00														
146	.....	.....	209 36	837450 63	1 00														
147	-----	-----	-----	-----	-----														
148	.....	.....	936 21	3008807 67	4 00														
149	X#3	X#4	XY	X#2Y	N														
150	.....	.....	.....	.....	.....														
151	.....	.....	.....	.....	.....														
152	3000 00	3500 00	4000 00	750 00	.....														
153	-----	-----	-----	-----	-----														
154	0 04	0 03	0 02	0 15	.....														
155	0 10	0 08	0 07	0 15	.....														
156	-0 01	-0 01	-0 01	-0 02	.....														
157	.....	.....	.....	.....	.....														
158	X'3	X'4	XY	X'2Y	N	A =	0 00	X=I	Y Calc	Y Act=Eq									
159	.....	.....	156 04	78018 03	1 00	B =	-0 00	500 00	0 30	0 31									
160	.....	.....	204 75	153563 25	1 00	C =	4400 00	1000 00	0 26	0 26									
161	.....	.....	257 05	257046 12	1 00	D =	0 32	1500 00	0 22	0 23									
162	.....	.....	342 11	513163 19	1 00	E =	.....	2000 00	0 19	0 19									
163	.....	.....	383 22	766439 03	1 00			2500 00	0 16	0 16									
164	.....	.....	391 00	977510 85	1 00	A =	0 35	3000 00	0 13	0 13									
165	.....	.....	386 49	1159467 98	1 00	B =	-0 00	3500 00	0 11	0 11									

	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD
111	L=	0.70		Y=FMG	X=1	X^2	X^3	X^4	XY	X^2Y	N	A =	0.00	X=1	Y Calc	Y Act=EQ			
112	500.00	0.28	500.00	0.28	500.00	*****	71103.60				1.00	B =	-0.00	500.00	0.28	0.28			
113	750.00	0.24	750.00	0.24	750.00	*****					1.00	C =	4400.00	1000.00	0.23	0.23			
114	1000.00	0.23	1000.00	0.23	1000.00	*****					1.00	D =	0.29	1500.00	0.20	0.20			
115	1500.00	0.20	1500.00	0.20	1500.00	*****					1.00	E =	*****	2000.00	0.16	0.17			
116	2000.00	0.17	2000.00	0.17	2000.00	*****					1.00			2500.00	0.13	0.13			
117	2500.00	0.13	2500.00	0.13	2500.00	*****					1.00	a =	0.32	3000.00	0.11	0.11			
118	3000.00	0.11	3000.00	0.11	3000.00	*****					1.00	b =	-0.00	3500.00	0.09	0.09			
119	3500.00	0.09	3500.00	0.09	3500.00	*****					1.00	c =	0.00	4000.00	0.07	0.07			
120	4000.00	0.07	4000.00	0.07	4000.00	*****					1.00			1837.60	0.17				
121																			
122	500.00			1.53	18750.00	*****					9.00	ABG52 =	{ABCO2+ABH2O}{1-C5O1}						
123				Y	X	X#2	X#3	X#4	XY	X#2Y	N		0.26						
124												ABCO2 =	{ E=ACO2 @ 1s P*L*Ts/Ig }*(Iq/Ig) 65						
125													0.11						
126	CO252	500.00	1000.00	1500.00	2000.00	*****	3000.00	3500.00	*****			ABH2O =	{ E=H2O @ 1s P*L*Ts/Ig }*(Iq/Ig) 45						
127													0.17						
128	a	0.11	0.09	0.10	0.09	0.08	0.06	0.05	0.04			Iq =	1641.97	PL2*Ts/Ig	0.70				
129	b	0.04	0.05	0.05	0.06	0.06	0.06	0.05	0.04			Is =	1837.60	Cso2 =	0.05				
130	c	-0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.00	-0.00										
131																			
132		Y=FMG	X=1																
133	L=	0.43		Y=FMG	X=1	X^2	X^3	X^4	XY	X^2Y	N	A =	0.00	A =	0.00	X=1	Y Calc	Y Act=EQ	
134	500.00	0.13	500.00	0.13	500.00	*****	64.31	32155.14			1.00	B =	-0.00	B =	-0.00	500.00	0.13	0.13	
135	1000.00	0.10	1000.00	0.10	1000.00	*****					1.00	C =	2500.00	C =	6500.00	1000.00	0.11	0.10	
136	1500.00	0.12	1500.00	0.12	1500.00	*****					1.00	D =	0.12	D =	0.18	1500.00	0.11	0.12	
137	2000.00	0.12	2000.00	0.12	2000.00	*****					1.00	E =	*****	E =	*****	2000.00	0.12	0.12	
138																2500.00	0.10	0.10	
139	500.00			0.47	5000.00	*****					4.00	a =	0.15	a =	0.22	3000.00	0.08	0.08	
140				Y	X	X#2	X#3	X#4	XY	X#2Y	N	b =	-0.00	b =	-0.00	3500.00	0.07	0.07	
141												c =	0.00	c =	0.00	4000.00	0.05	0.05	
142	L=	0.43		Y=FMG	X=1	X^2	X^3	X^4	XY	X^2Y	N					1837.60	0.12		
143	2500.00	0.10	2500.00	0.10	2500.00	*****					1.00								
144	3000.00	0.08	3000.00	0.08	3000.00	*****					1.00								
145	3500.00	0.07	3500.00	0.07	3500.00	*****					1.00								
146	4000.00	0.05	4000.00	0.05	4000.00	*****					1.00								
147																			
148	500.00			0.31	13000.00	*****					4.00								
149				Y	X	X#2	X#3	X#4	XY	X#2Y	N								
150	*****																		
151																			
152	H2O2w	500.00	1000.00	1500.00	2000.00	*****	3000.00	3500.00	*****	750.00									
153																			
154	a	0.19	0.14	0.11	0.08	0.06	0.04	0.03	0.02	0.15									
155	b	0.14	0.14	0.14	0.13	0.12	0.10	0.08	0.07	0.15									
156	c	-0.01	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02									
157		Y=FMG	X=1																
158	L=	0.99		Y=FMG	X=1	X^2	X^3	X^4	XY	X^2Y	N	A =	0.00	X=1	Y Calc	Y Act=EQ			
159	500.00	0.32	500.00	0.32	500.00	*****	79346.16				1.00	B =	-0.00	500.00	0.31	0.32			
160	750.00	0.28	750.00	0.28	750.00	*****					1.00	C =	4400.00	1000.00	0.27	0.26			
161	1000.00	0.26	1000.00	0.26	1000.00	*****					1.00	D =	0.33	1500.00	0.23	0.23			
162	1500.00	0.23	1500.00	0.23	1500.00	*****					1.00	E =	*****	2000.00	0.19	0.20			
163	2000.00	0.20	2000.00	0.20	2000.00	*****					1.00			2500.00	0.16	0.16			
164	2500.00	0.16	2500.00	0.16	2500.00	*****					1.00	a =	0.36	3000.00	0.13	0.13			
165	3000.00	0.13	3000.00	0.13	3000.00	*****					1.00	b =	-0.00	3500.00	0.11	0.11			

[illegible]

[illegible]

	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
221									0 04										
222	0 06	0 05	0 04																
223	0 06	0 05	0 04																
224	-0 01	-0 00	-0 00																
225																			
226																			
227	X^3	X^4	XY	X^2Y	N														
228			58 21	29105.97	1 00	A =	0 00	A =	0 00	X=I	Y Calc	Y Act=Eg							
229			89 99	89985.63	1 00	B =	-0 00	B =	-0 00	500 00	0 11	0 12							
230			152 21	228318.87	1 00	C =	2500 00	C =	6500 00	1000 00	0 10	0 09							
231			199 38	398766.98	1 00	D =	0 11	D =	0 15	1500 00	0 09	0 10							
232						E =		E =		2000 00	0 10	0 10							
233			499 79	746177.44	4 00					2500 00	0 08	0 08							
234	X#3	X#4	XY	X#2Y	N	a =	0 14	a =	0 21	3000 00	0 07	0 07							
235						b =	-0 00	b =	-0 00	3500 00	0 05	0 05							
236	X^3	X^4	XY	X^2Y	N	c =	0 00	c =	0 00	4000 00	0 04	0 04							
237			208 00	519992.24	1 00					2811 90	0 07								
238			199 37	598110.54	1 00														
239			186 96	654344.56	1 00														
240			169 21	676843.28	1 00														
241																			
242			763 53	2449290.62	4 00														
243	X#3	X#4	XY	X#2Y	N														
244																			
245																			
246	3000.00	3500.00	4000.00	750.00															
247																			
248	0.04	0.03	0.02	0.15															
249	0.10	0.08	0.07	0.15															
250	-0.01	-0.01	-0.01	-0.02															
251																			
252	X^3	X^4	XY	X^2Y	N	A =	0 00	X=I	Y Calc	Y Act=Eg									
253			109 04	54518.32	1 00	B =	-0 00	500 00	0 21	0 22									
254			132 15	99109.14	1 00	C =	4400 00	1000 00	0 17	0 16									
255			161 50	161499.73	1 00	D =	0 22	1500 00	0 13	0 13									
256			201.84	302760.87	1 00	E =		2000 00	0 10	0 11									
257			210.01	420013.24	1 00			2500 00	0 08	0 08									
258			196.12	490291.89	1 00	a =	0 25	3000 00	0 06	0 06									
259			185.42	556261.01	1 00	b =	-0.00	3500 00	0 05	0 05									
260			171.93	601759.73	1 00	c =	0 00	4000 00	0 04	0 04									
261			149.07	596286.10	1 00			2811 90	0 07										
262																			
263			1517.07	3282500.02	9.00	ABgg3 =	{ABC02+ABH20}{1-CS01}												
264	X#3	X#4	XY	X#2Y	N														
265																			
266																			
267	3000.00	3500.00	4000.00																
268																			
269	0.06	0.05	0.04																
270	0.06	0.05	0.04																
271	-0.01	-0.00	-0.00																
272																			
273																			
274	X^3	X^4	XY	X^2Y	N	A =	0 00	A =	0 00	X=I	Y Calc	Y Act=Eg							
275			59 88	29940.85	1 00	B =	-0 00	B =	-0 00	500 00	0 12	0 12							

	AI	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD
221															0.20				
222 a		0.11	0.09	0.10	0.09	0.08	0.06	0.05	0.04										
223 b		0.04	0.05	0.05	0.06	0.06	0.06	0.05	0.04			Tg =	1641.97	Pl =	0.57				
224 c		-0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.00	-0.00			Is =	1837.60	Cso =	0.06				
225																			
226		Y=Emg	X=1																
227	L =	0.64		Y=Emg	X=1	X^2	X^3	X^4	XY	X^2Y	N	A =	0.00	A =	0.00	X=1	Y Calc	Y Act=Emg	
228 500.00		0.14	500.00	0.14	500.00					67.92	33958.33	1.00	B =	-0.00	B =	-0.00	500.00	0.13	0.14
229 1000.00		0.11	1000.00	0.11	1000.00							1.00	C =	2500.00	C =	6500.00	1000.00	0.12	0.11
230 1500.00		0.13	1500.00	0.13	1500.00							1.00	D =	0.13	D =	0.20	1500.00	0.12	0.13
231 2000.00		0.13	2000.00	0.13	2000.00							1.00	E =		E =		2000.00	0.13	0.13
232																2500.00	0.11	0.11	
233		500.00		0.50	5000.00						4.00	a =	0.16	a =	0.23	3000.00	0.09	0.09	
234				Y	X	X#2	X#3	X#4	XY	X#2Y	N	b =	-0.00	b =	-0.00	3500.00	0.08	0.08	
235												C =	0.00	C =	0.00	4000.00	0.06	0.06	
236	L =	0.64		Y=Emg	X=1	X^2	X^3	X^4	XY	X^2Y	N					1837.60	0.13		
237 2500.00		0.11	2500.00	0.11	2500.00						1.00								
238 3000.00		0.09	3000.00	0.09	3000.00						1.00								
239 3500.00		0.08	3500.00	0.08	3500.00						1.00								
240 4000.00		0.06	4000.00	0.06	4000.00						1.00								
241																			
242		500.00		0.35	13000.00						4.00								
243				Y	X	X#2	X#3	X#4	XY	X#2Y	N								
244																			
245																			
246 H2O3W	500.00	1000.00	1500.00	2000.00	*****	3000.00	3500.00	*****	750.00										
247																			
248 a		0.19	0.14	0.11	0.08	0.06	0.04	0.03	0.02	0.15									
249 b		0.14	0.14	0.14	0.13	0.12	0.10	0.08	0.07	0.15									
250 c		-0.01	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02									
251		Y=Emg	X=1																
252	L =	1.48		Y=Emg	X=1	X^2	X^3	X^4	XY	X^2Y	N	A =	0.00	X=1	Y Calc	Y Act=Emg			
253 500.00		0.37	500.00	0.37	500.00					92135.95	1.00	B =	-0.00	500.00	0.36	0.37			
254 750.00		0.33	750.00	0.33	750.00						1.00	C =	4400.00	1000.00	0.32	0.31			
255 1000.00		0.31	1000.00	0.31	1000.00						1.00	D =	0.39	1500.00	0.28	0.28			
256 1500.00		0.28	1500.00	0.28	1500.00						1.00	E =		2000.00	0.24	0.24			
257 2000.00		0.24	2000.00	0.24	2000.00						1.00			2500.00	0.20	0.20			
258 2500.00		0.20	2500.00	0.20	2500.00						1.00	a =	0.41	3000.00	0.17	0.17			
259 3000.00		0.17	3000.00	0.17	3000.00						1.00	b =	-0.00	3500.00	0.14	0.14			
260 3500.00		0.14	3500.00	0.14	3500.00						1.00	C =	0.00	4000.00	0.11	0.12			
261 4000.00		0.12	4000.00	0.12	4000.00						1.00			2587.64	0.20				
262																			
263		500.00		2.17	18750.00						9.00	ABgw3 =	(ABC02+ABH20)*(1-CS01)						
264				Y	X	X#2	X#3	X#4	XY	X#2Y	N		0.24						
265												ABC02 =	({MC02 @ Tw. P*L*Tw/Tg }*(Tg/Tw).65						
266													0.09						
267 C02W3	500.00	1000.00	1500.00	2000.00	*****	3000.00	3500.00	*****				ABH20 =	({w120 @ Tw. P*L*Tw/Tg }*(Tg/Tw).45						
268													0.16						
269 a		0.11	0.09	0.10	0.09	0.08	0.06	0.05	0.04										
270 b		0.04	0.05	0.05	0.06	0.06	0.06	0.05	0.04			Tg =	1641.97	Pl =	0.57				
271 c		-0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.00	-0.00			Tw =	2587.64	Cso =	0.06				
272																			
273		Y=Emg	X=1																
274	L =	0.90		Y=Emg	X=1	X^2	X^3	X^4	XY	X^2Y	N	A =	0.00	A =	0.00	X=1	Y Calc	Y Act=Emg	
275 500.00		0.14	500.00	0.14	500.00					72.06	36032.35	1.00	B =	0.00	B =	-0.00	500.00	0.14	0.14

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
276	9 00	-fww*TRgm3*fws*fww*fs	-0 0001								1000 00	0 09	1000 00	0 09	1000 00	*****
277	10 00	-fwl*TRgm3*fws*fww*fs	-0 0001								1500 00	0 11	1500 00	0 11	1500 00	*****
278	11 00	-fsi*TRgm3*fws*fws*fs	-0 0000								2000 00	0 10	2000 00	0 10	2000 00	*****
279			-1 4040	(140.001)	(1160.765)											
280												500 00		0 42	5000 00	*****
281	Iq q1	-At*Emg	-0 5684											Y	X	X#2
282		2 00 -TRgl11*pm*fwl*Aw*Emg	-0 0165													
283	Q1 <= Qg	3 00 -TRgl11*ps*fsi*As*Emg	-0 0047													
284			-0 5897	(23.150)	(79.035)											
285																
286	I1 I1	-Em1*At	2 4494													
287		2 00 -TRgl2*ps*fsi*fs*Em1	-0 0644													
288		3 00 -TRgl3*ps*pm*fs*fsm*	-0 0040													
289	Q1 <= Q1	4 00 -TRgl2*pm*fwl*fwl*Em1	-0 2075													
290		5 00 -TRgl3*pm*pm*fwl*fwl*	-0 0125													
291		6 00 -TRgl3*pm*ps*fwl*fwl*	-0 0040													
292		7 00 -TRgl3*pm*pm*pm*fwl*	-0 0008													
293		8 00 -TRgl3*pm*pm*ps*fwl*	-0 0003													
294		9 00 -TRgl3*ps*pm*pm*fs*	-0 0002													
295		10 00 -TRgl3*pm*pm*ps*fwl*	-0 0002													
296		11 00 -TRgl3*ps*ps*pm*fs*	-0 0001													
297			2 1555	727 852	2 464 867											
298	Q1 >=															
299				342 322	1 168 687											
300																
301																
302																
303		Qs =	(162.280)	(554.025)												
304		Qw =	(39)	(134)												
305		Qg =	(165.074)	(563.561)												
306		Q1 =	342 322	1 168 687												
307																
308																
309																
310																
311	sg	-(1-TRgg1)*Em*As	-0 1535													
312		2 00 -(TRgg1-TRgg2)*Fsm*pm	-0 0018													
313		3 00 -(TRgg2-TRgg3)*Fsm*fs	-0 0001													
314		4 00 -(TRgg2-TRgg3)*Fws*fs	-0 0000													
315			-0 1555													
316																
317	wg	-(1-TRgg1)*Em*Aw	-0 5836													
318		2 00 -(TRgg1-TRgg2)*Fsm*pm	-0 0062													
319		3 00 -(TRgg2-TRgg3)*Fsm*fw	-0 0004													
320		4 00 -(TRgg2-TRgg3)*Fws*fs	-0 0001													
321		5 00 -(TRgg2-TRgg3)*Fws*fw	-0 0001													
322		6 00 -(TRgg1-TRgg2)*Fws*ps	-0 0018													
323			-0 5922													
324																
325																
326	Iq	1 0-(1-TRgg1)*Em*At	-0 5684													
327		2 00 -(TRgg1-TRgg2)*ps*fs	-0 0044													
328		3 00 -(TRgg2-TRgg3)*ps*pm*	-0 0003													
329		4 00 -(TRgg1-TRgg2)*pm*fwl*	-0 0154													
330		5 00 -(TRgg2-TRgg3)*pm*ps*	-0 0003													

BASIS	GAS ENTHALPY	SEC 4	FEED COMBST
FEED LB/HR	1335 00 CO2 LB/HR =	569 19	569 19
% H2O	10.10% O2 LB/HR	446 72	389 33 59 40
CD BTU/LB*F DRY	0.2600 N2 LB/HR	3452 25	1289 02 2163 23
	185 H2O/HR	381 96	151 62 230 34
F/D FEEL RATIO	10.00 TOTAL LB/HR	4852 12	1829 96 3022 15
% EXCESS AIR SEC. =	65.58% MOLES H2O	21 22	8 42 12 80
AIR DENSITY, LB/FT3	0.0811 MOLES GAS	171 47	6 6 63 104 85
MOLE VOL FT3/MOL	355 65 MOL % H2O	0 1238	CO2 LB/HR 12 94
Lat. F	70 00 MOL % CO2	0 0754	O2 LB/HR 1 86
HEAT OF VAPOR, BTU/L	1060 00		N2 LB/HR 77 26
HCWS BTU/FT2*F =	8.80		H2O LB/HR 12 80
	T ABM.K =	294 40	
BASIS : SOIL ENTHALPY			
SOIL DRY BASIS, LB2/HR		1200 17	
BTU/HR*F =		312 04	
DEL TS, K =		731.91	
QS BTU/HR =	554025	Qs1 BTU/HR =	0
BTU/HR UP TO 212 =	47431		
DEL HV H2O, BTU/HR =	142925		
BTU/HR ABOVE 212 =	363669		
DEL TS, F =	1317		
DEL TS, C =	731.91		
DEL TS, K =	731.91		
HEAT LOSS CALC FOR FLAME HWS			
-QS SOLID, BTU/HR =	554025	<====INCLUDES HEAT OF VAPOR, OF WATER IN	
-QW WALL, BTU/HR =	134		
-QG GAS, BTU/HR =	563561		
SHELL LOSS BTU/HR =	50967		
Q11 OR Q12 BTU/HR =	0	<==== ENTHALPY CALC FOR RECIRC GAS	
		OR FELA & AIR PREHEATED	
TOTAL MM BTU/HR =	1 1687		

R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
276		93.89	93885.44	1.00			C =	6500.00	1000.00	0.10	0.09							
277		158.36	237543.23	1.00			D =	0.16	1500.00	0.10	0.11							
278		209.75	419492.92	1.00			E =		2000.00	0.11	0.10							
279									2500.00	0.09	0.09							
280		521.88	780862.43	4.00			A =	0.21	3000.00	0.07	0.07							
281	X#3	X#4	X#2Y	N			B =	-0.00	3500.00	0.06	0.06							
282							C =	0.00	4000.00	0.05	0.05							
283	X*3	X*4	X*2Y	N					2811.90	0.08								
284		221.15	552881.40	1.00														
285		213.97	641904.21	1.00														
286		200.91	703188.23	1.00														
287		181.80	727207.93	1.00														
288																		
289		817.83	2625181.77	4.00														
290	X#3	X#4	X#2Y	N														
291																		
292	COMBUSTION GAS ENTHALPY CALC.																	
293		11 =	2331.90			Tg	IN =	2251.90										
294			Cp			Tg												
295			BTU/LB*F			BTU/HR												
296						OUT												
297		CO2	0.2816	367.314	0.2797	348.998												
298		O2	0.2667	36.307	0.2656	34.985												
299		N2	0.2730	1.353.287	0.2718	1.288.998												
300		H2O	0.5327	525.387	0.5287	511.112												
301																		
302			2.282.295			2.183.693												
303		DEL H GAS.	BTU/HR =	98602														
304		WATTS	28862	Cp IN =	0.5442													
305		BTU/F =	986.02	Cp OUT =	0.5444													
306		DEL Tg. K =	317.53															
307			A	B	C													
308																		
309		0.20	0.00	-0.00	CO2													
310		0.24	0.00	-0.00	O2													
311		0.24	0.00	-0.00	N2													
312		0.44	0.00	-0.00	H2O													
313																		
314	FEED GAS ENTHALPY CALC USED																	
315		Tg =	1181.97			Tg	IN =	69.92										
316			Cp			Tg												
317			BTU/LB*F			BTU/HR												
318						OUT												
319	ERR	CO2	0.2508	0	0.2029													
320	284.23	O2	0.2533	110.658	0.2386	921												
321	290.89	N2	0.2593	374.967	0.2447	3.130												
322	1605.29	H2O	0.4860	243.392	0.4411	161.379												
323																		
324				779.017		165.430												
325		DEL H GAS.	BTU/HR =	563587														
326		WATTS	165081	Cp IN =	0.3351													
327		BTU/F =	506.80	Cp OUT =	9.1130													
328		DEL Tg. K =	617.78															
329			A	B	C													
330																		

Y=BTU/LB X=PL
2088.000 400.00
2467.000 500.00
2942.000 600.00

	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	
331			0.20	0.00	-0.00	CO2			3425.000	700.00										
332			0.24	0.00	-0.00	O2			3944.000	800.00										
333			0.24	0.00	-0.00	N2			7814.000	1500.00										
334			0.44	0.00	-0.00	H2O														
335									22680.000	4500.00										
336			AVG DENSITY OF SOLID BED, LB/FT ³ =			100.00			Y	X										
337			SOLID FEED RATE, FT ³ /HR =			13.35														
338			RESIDENCE TIME FOR SOLID BED, HR =			1.155														
339																				
340			Tg1-Tg0 BTU/HR =			0														
341			MCP*MXAIR*(Tg1-Tg2) BTU/HR =			0			1. Q1A ENTH CALC 1/3*(MCP*MXAIR)*(Tf-Tg) 1/3X=					2 Q1B ENTH CALC 1/3X(MCP*MXAIR)*(Tf2-Tf1)						
342			-Qg1 BTU/HR =			0			Tf =	2351.90	Tg =	1181.97			Tf2 =	2351.90	Tf1 =	2351.90	1/3X=	0.00
343									Cp	Tg				Tg			Cp	Tg		Tg
344			Tg2-Tg1 BTU/HR =			563560			1/3X(MCP*MXAIR) BTU/LB*F					BTU/HR	1/3X(MCP*MXAIR) BTU/LB*F			BTU/HR		BTU/HR
345			MCP*MXAIR*(Tg2-Tg3) BTU/HR =			0			LB/HR	(X)				IN	LB/HR			OUT		IN
346			-Qg2 BTU/HR =			563560			0	CO2	0.2816	0	0.2508	0	0	CO2	0.2816	0	0.2816	0
347						0			O2	0.2667	0	0.2533	0	0	O2	0.2667	0	0.2667	0	
348			Tg2-Tg3 BTU/HR =			-413861			0	N2	0.2730	0	0.2593	0	0	N2	0.2730	0	0.2730	0
349			X(MCP*MXAIR)-(Tg3-Tf2) BTU/HR =			413867			0	H2O	0.5327	0	0.4860	0	0	H2O	0.5327	0	0.5327	0
350			0 =			6														
351						0			0	0				0	0					
352									DEL H GAS, BTU/HR =	0				DEL H GAS, BTU/HR	0					
353			DEL H GAS, BTU/HR =			0			WATTS	0				WATTS	0			CP IN =	0.0000	
354			BTU/F =			0			CP IN =	ERR				BTU/F =	ERR			CP OUT =	0.0000	
355			Qg BTU/HR = -563561						DEL Tg, K =	ERR				DEL Tg, K =	ERR					
356																				
357						A	B	C						A	B	C				
358						0.20	0.00	-0.00	CO2					0.20	0.00	-0.00	CO2			
359						0.24	0.00	-0.00	O2					0.24	0.00	-0.00	O2			
360						0.24	0.00	-0.00	N2					0.24	0.00	-0.00	N2			
361						0.44	0.00	-0.00	H2O					0.44	0.00	-0.00	H2O			
362																				
363																				
364																				
365																				
366																				
367																				
368																				
369																				
370			XAIR = 1/3X(MCP*MXAIR)			B	Tg2 COMBUSTION GAS ENTHALPY CALC.: MXAIR * X(MCP*MXAIR)													
371			69.92				Tg2 = 1181.97			Tg1MB =	69.92									
372			Tg			MXAIR =	Cp			Tg										
373			BTU/HR			X(MCP*MXAIR)	BTU/LB*F			BTU/HR										
374			IN			LB/HR	OUT			IN										
375			0			0	CO2			0	0.2029	0								
376			921			389	O2			110631	0.2386	921								
377			3.130			1289	N2			374967	0.2447	3130								
378			161.381			152	H2O			243394	0.4411	161.381								
379																				
380			165.431			1830				728992		165431								
381							DEL H GAS, BTU/HR =			563560										
382			ERR				WATTS			165073		CP IN =	ERR							
383			ERR				BTU/F =			507		CP OUT =	ERR							
384							DEL Tg, K =			-0										
385																				

	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD
331	2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00	0 09 2500 00
332	3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00	0 08 3000 00
333	3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00	0 06 3500 00
334	4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00	0 05 4000 00
335																			
336		500.00		0 28 13000.00															
337				Y	X	X#2	X#3	X#4	XY	X#2Y	N								
338																			
339																			
340	IN F F I A O I I																		
341	Y=BIU/LB	X=PL	X^2	X^3	X^4	XY		X^2Y	N	A =	0 00		X=T	Y CALC					
342	259	400							1 00	B =	0 66		400 00	255 57					
343	306	500							1 00	C =	1964 52		600 00	366 86					
344	365	600							1 00	D =	-23 01		700 00	425 61					
345	425	700							1 00	E =			800 00	486 43					
346	489	800							1 00				1500 00	970 02					
347	970	1500							1 00	a =	57 7904		2351 90	1695 20					
348										b =	0 4531								
349	2815	4500							6 00	c =	0 0001								
350	Y	X	X#2	X#3	X#4	XY		X#2Y	N										
351								X#2Y	N										
352													SP GR =	0 97					
353													LB/FI3 =	60 27					
354													LB/CAL =	8 06					
355																			
356																			
357	C501 PC02/(PH2O*PC02) = .35																		
358	Y=C50	X=PL	X^2	X^3	X^4	XY		X^2Y	N	A =	-0 02		X=T	Y CALC	Y ACT=C50				
359	0 016	0 10	0 01	0 00	0 00	0 00		0 00	1 00	B =	0 03		0 10	0 02	0 02				
360	0 030	0 25	0 06	0 02	0 00	0 01		0 00	1 00	C =	2 05		0 75	0 05	0 05				
361	0 052	0 75	0 56	0 42	0 32	0 04		0 03	1 00	D =	0 02		1 00	0 06	0 06				
362	0 059	1 00	1 00	1 00	1 00	0 06		0 06	1 00	E =	-0 60		1 50	0 07	0 07				
363	0 065	1 50	2 25	3 38	5 06	0 10		0 15	1 00				2 00	0 07	0 07				
364	0 068	2 00	4 00	8 00	16 00	0 14		0 27	1 00	a =	0 0122			0 01	C=C50				
365										b =	0 0660								
366	0 290	5 60	7 89	12 81	22 38	0 34		0 51	6 00	c =	-0 0193								
367	Y	X	X#2	X#3	X#4	XY		X#2Y	N										
368																			
369																			
370																			
371																			
372																			
373																			
374																			
375																			
376																			
377																			
378																			
379																			
380																			
381																			
382																			
383																			
384																			
385																			

	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
386					A	B	C												
387	CO2				0.20	0.00	-0.00	CO2											
388	O2				0.24	0.00	-0.00	O2											
389	N2				0.24	0.00	-0.00	N2											
390	H2O				0.44	0.00	-0.00	H2O											
391																			
392																			
393	T02 --> T03				10. T02 HMB ENTHALPY CALC	MCP + λ(MCP+MxΔT)	T12 --> T03												
394	1927.46				T12 = 2351.90		T03 = 1927.46												
395	T0				MCP + Cp	T0	T0												
396	BTU/HR				λ(MCP+MxΔT)	BTU/LB°F	BTU/HR												
397	IN				LB/HR		OUT												
398	0				569	CO2	0.2816	367.314	0.2728	289.929	569	CO2	0.2816	367.314	0.2816	367.314			
399	190.517				59	O2	0.2667	363.09	0.2621	29.075	59	O2	0.2667	363.09	0.2667	36.309			
400	645.563				2163	N2	0.2730	1353.288	0.2682	1083.382	2163	N2	0.2730	1353.288	0.2730	1353.288			
401	306.773				230	H2O	0.5327	525.391	0.5158	466.048	230	H2O	0.5327	525.391	0.5327	525.391			
402																			
403	1.142.853				3022		2282301		1868433	3022		2282301		2282301		2282301			
404					DEL H GAS. BTU/HR =		413867					DEL H GAS. BTU/HR =		0					
405	ERR				WATTS		121227		Cp IN =	ERR		WATTS		0		Cp IN =	ERR		
406	ERR				BTU/F =		975		Cp OUT =	ERR		BTU/F =		ERR		Cp OUT =	ERR		
407					DEL T0. K =		0					DEL T0. K =		ERR					
408																			
409					A	B	C					A	B	C					
410	CO2				0.20	0.00	-0.00	CO2				0.20	0.00	-0.00	CO2				
411	O2				0.24	0.00	-0.00	O2				0.24	0.00	-0.00	O2				
412	N2				0.24	0.00	-0.00	N2				0.24	0.00	-0.00	N2				
413	H2O				0.44	0.00	-0.00	H2O				0.44	0.00	-0.00	H2O				
414																			

FullM.WMI FLOW REGION MODELED AS ONE SECTION
General Information - Locus 123 Spreadsheet
Source Path C:\LOTUS\5\FULLM.WMI
Active Range A1..B6436
Iteration Count 1
Recalculation manual
Recalc Order natural

Principal Window cursor at E60
Global Col Width 9
Global Format IF2

Column Widths individually specified as follows:
A B C E F 6 I J K L M N O P Q R S T U V W X Y Z AA AB AC AE AF AG AH AI
13 9 12 11 11 9 11 10 20 11 11 10 8 10 10 10 11 9 11 11 10 12 12 9 8 11 9 1 8 6 6

Named Ranges

1	A3A..053
106	I331..Y414
116	Z393..0E408
16	V341
2	J33..052
26	08341
3	0E3A..AJ53
36	A370
4	A1..T28
40	U2..A128
46	G370
50	V39
50A	V49
50S	V48
56	A393
66	G393
76	K370
8	U33..AJ54
86	I370
9	K3A..A185
96	K393
08	F74
0861	C33
08611	C84
0862	C94
0863	C55
08671	052
08672	063
08673	064
08681	002
08682	004
08683	066
08691	003
08692	065
08693	067
086	F72
08A	F73
0D	R39
0D12	075
08	I59
06	I62
0A20	0A3

PHILM.M1 ** Range Report **
 Page 2
 PHILM.M1 FLOW REGION MODELED AS ONE SECTION

PHB	R46
PHL	R44
PH	R47
PH	R42
PH2	R42
PH1	R41
AD	165
AS	160
ASH	166
ASD	R45
AW	161
BDX	R23
BD	S39
BD20	S43
BD8	S46
BDL	S44
BF	S47
BM	S42
BD	S41
BD	S45
C	R55
CLC	G122
CC	PH1B..R426
CD	139
CD20	T43
CD8	T46
CDL	T44
CF	T47
CH	T42
CD	T41
CD61	AS..J109
CD	T45
CD1	AL37
D	174
DITE	F129
DLH	AL37
DEP	D52
DELS	G122
E	A109..E128
EC	A370..L365
ED	M370..Y365
ED9	A393..L408
ED7	M392..Y408
EF	F82
EB	F81
EN	AL..808
DF	F78
D6	A01
D62	AS1
D63	A01
D6	F76
D6H	F75
EN11	AL..80339
EN12	AS..R271
DM	F77
EN	M311..80332
ES	F79
EM	F80

PAULUMI ** Range Report **
Page 3
PAULUMI FLAME REGION MODELED AS ONE SECTION

F	AL357
FD	181
FF	B286
FFS	F66
FTM	F65
F6	B2A3
FL	AL357
FLA	1340..0352
FLA1	0341..0356
FLF	159
FD	AL357
FS	B158
FSF	F67
FSU	F62
FV	B200
FAF	F69
FAS	F63
FM	F64
G	H56
GF	B281
GS	B236
GA	B154
H	B155
	L282..0340
KOVSH	F95
KOVES	C100
KOVU	C101
KOVSH	C102
KOVMS	D99
IL	L320
MESH	F97
HS	L306
I	B34
I161	183
I162	184
KK1	186
KK2	187
KKK1	A129
KKK2	A129
L	175
LL	176
LH	F90
LK2	F91
LK3	F92
ML101	F84
PKU1	D51
PKU2	F85
PK	F71
PK20	F86
PK20	F86
PL1	C105
PL2	C106
PL3	C107
PLF1	J91
PLF2	J92
PLF3	J93
PS	F69
PI	D50

FMILM1 FLAME REGION MODELED AS ONE SECTION

PM	F70
P15	P35
P15B	Q35
P15C	Q36
Q1A	M349
Q1B	Y352
Q2C	AE352
Q2CV	F104
QF	F299
QF1	J355
QF2	J359
QFF	F297
QFG	F249
QFS	F165
QFV	F211
QG	F254
QGF	F284
QGG	F241
QGS	F156
QGN	F198
QS	F170
QSF	F266
QSG	F226
QSH	F106
QSL	B0318
QSS	F144
QSW	F181
QW	F217
QWC	F102
QWF	F279
QWG	F234
QWS	F152
QWV	F193
R	A129
R90	A129..6307
RC	M352
RF	I72
RR1	I68
RR2	I69
RR3	I70
RSH	I71
S	B0318
SF	B259..C262
SG	B222..C225
SHELL	I85
SIGNA	F83
SS	B139..C143
SW	B175..C180
T	A309..F344
TA	C98
TC	Q340
TF	C59
TF6	E332
TG	C68
TERII	B335
THI	I78
THIRAO	I79
TITLE	G122

FKILNWK1 ** Range Report **

Page 5

FKILNWK1 FLAME REGION MODELED AS ONE SECTION

TAG11	B335
TAGF1	C86
TAGF11	B344
TAGF2	C87
TAGF3	C88
TAGS1	C90
TAGS2	C91
TAGS3	C92
TAGS1	C75
TAGS11	B338
TAGS2	C76
TAGS3	C77
TAGM1	C78
TAGM11	B341
TAGM2	C79
TAGM3	C80
TS	C62
TS6	E315
TS1	C63
TSNOX	F99
TW	C61
TWG	E323
W	I63
WF	B268
WG	B228
WS	B146
WM	B183
TAIR	C97
Z	A261
VA	G130
VC	J115
VE	G128
VF	G116
VH	G119
VP	G122
VR	G125
VS	O125
VT	G111
VZ	B0318

Print range Z393..AE408

Print style formatted

Global Protection not enabled

Setup string \015

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0 240 0 0 66

Label Prefix * (double quote)

* Graphs *

(Current) line graph

no data ranges specified

** End of range report **

FILENAME: ** Range 1 INLA..0531 **VRL **
 Page 6
 FILENAME: FUME REGION MODELED AS ONE SECTION
 -8-
 34 1 1
 35 1 1
 36 1 1
 37 1 1
 38 1 1
 39 1 1
 40 1 1
 41 1 1
 42 1 1
 43 1 1
 44 1 1
 45 1 1
 46 1 1
 47 1 1
 48 1 1
 49 1 1
 50 1 1
 51 1 1
 52 1 1
 53 1 1

PRILAM1 ** Range 1 (0.0..0.53) *VL **
 Page 7
 PRILAM1 FLAME REGION MODELED AS ONE SECTION

34	1" INPUT TEMPERATURE 1	-C-	-0-
35	1" WASTE 1		1" BURER WASTES----
36	1" WASTE 2		1" WASTE 2
37	10		10
38	10		10
39	10		10
40	10		10
41	10		10
42	10		10
43	10		10
44	10		10
45	10		10
46	10		10
47	10		10
48	1" WASTE 1		1" WASTE 1
49	1" WASTE 2		1" WASTE 2
50	10		10
51	11 ((C37/100)+(1/121))*((C38/100)+(0.5/21))*((C39/100)+(1/321))*((C40/100)+(1/131))*((C43/100)+(1/321))*B4003.25		160
52	160		160
53	10.5		10.5

225

FRILN.WK1 ** Range 1 (R34..053) +VR. **

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107-9-18 13: 1

FRILN.WK1 FLAME REGION MODELED AS ONE SECTION

	-H-	-J-	-K-	-L-
34				
35	1*CHAMBER WASTES----	1* EXCESS AIR FOR FUELS TO BURNER		
36	1*WASTE 5	1* EXCESS AIR FOR WASTES TO CHAMBER		
37	10	1* RADIATION LOSS (MM BTU/HR)		
38	10	1* AIR TEMP F		
39	10	1* AIR HUMIDITY (LB/LB DRY AIR)		
40	10	1* ASH IN EXIT		
41	10	1* % SALT IN EXIT		
42	10			
43	10	1* PYROLYSIS (1 = YES, 0 = NO)		
44	10	1* HEAT OF PYROLYSIS BTU/LB		
45	10	1* AVG MOL WEIGHT OF PYROLYSIS PRODUCTS		
46	10	1* % FIRED CARBON IN ASH		
47	10	1* SPECIFIC HEAT OF ASH (BTU/LB F)		
48	1* -----	1* DESIRED ASH DISCHARGE TEMPERATURE F		
49	1*SUM(636..648) (0)	1*SUM(436..448) (0)		
50	1*100.95 (0)	1* DESIRED OR "GUESS" TEMPERATURE F		
51	1* ((637/100) * ((1/12) * ((638/100) * (0.5/21) * ((639/100) * (1-1/32) * ((640/100) * (1/14) * ((643/100) * (1/32) * 104403.25 (0) 10	1* LBS/HR AIR FUEL		
52	160	1* HEAT IN =	1* C27+427 (3.452154976912) 1*	HEAT OUT =
53	10.5			

FKILM.WK1 ** Range 4 (01..126) *VRL **

age 12

FKILM.WK1 FLAME REGION MODELED AS ONE SECTION

	-G-	-H-	-I-	-J-	-K-	-L-	-M-	-N-
1	|	|	|	|	|	|	|	|
2	|-----|	|-----|	|-----|	|-----|	|-----|	|-----|	|-----|	|-----|
3	|	|** (13)	|	|	|** (14)	|	|	|**
4	|	|** WASTE TO BURNER	|	|	|** WASTE TO CHAMBER	|	|	|**
5	|*LB-W/MR	|**LB-W/MR	|	|*LB-W/MR	|**LB-W/MR	|	|*LB-W/MR	|**
6	|*-----|	|**-----|	|	|*-----|	|**-----|	|	|*-----|	|**
7	|*F7/12 (12.93615)	|** (IC37+BC150+D37+DE150+E37+HE150)/100 (0)	|	|*17/12 (0)	|** (IF37+BF150+G37+H37+MH50)/100 (0)	|	|*L7/12 (0)	|**
8	|*F8/2 (111.2318)	|** (IC38+BC150+D38+DE150+E38+HE150)/100 (0)	|	|*18/2 (0)	|** (IF38+BF150+G38+H38+MH50)/100 (0)	|	|*L8/2 (0)	|**
9	|*F9/32 (0)	|** (IC39+BC150+D39+DE150+E39+HE150)/100 (0)	|	|*19/32 (0)	|** (IF39+BF150+G39+H39+MH50)/100 (0)	|	|*L9/32 (0)	|**
10	|*F10/28 (0)	|** (IC40+BC150+D40+DE150+E40+HE150)/100 (0)	|	|*110/28 (0)	|** (IF40+BF150+G40+H40+MH50)/100 (0)	|	|*L10/28 (0)	|**
11	|*F11/18 (0)	|** (IC41+BC150+D41+DE150+E41+HE150)/100 (0)	|	|*111/18 (0)	|** (IF41+BF150+G41+H41+MH50)/100 (0)	|	|*L11/18 (0)	|**
12	|*F12/35.5 (0)	|** (IC42+BC150+D42+DE150+E42+HE150)/100 (0)	|	|*112/35.5 (0)	|** (IF42+BF150+G42+H42+MH50)/100 (0)	|	|*L12/35.5 (0)	|**
13	|*F13/32 (0.00945625)	|** (IC43+BC150+D43+DE150+E43+HE150)/100 (0)	|	|*113/32 (0)	|** (IF43+BF150+G43+H43+MH50)/100 (0)	|	|*L13/32 (0)	|**
14	|*F14/79.9 (0)	|** (IC44+BC150+D44+DE150+E44+HE150)/100 (0)	|	|*114/79.9 (0)	|** (IF44+BF150+G44+H44+MH50)/100 (0)	|	|*L14/79.9 (0)	|**
15	|*F15/19 (0)	|** (IC45+BC150+D45+DE150+E45+HE150)/100 (0)	|	|*115/19 (0)	|** (IF45+BF150+G45+H45+MH50)/100 (0)	|	|*L15/19 (0)	|**
16	|*-----|	|** (IC46+BC150+D46+DE150+E46+HE150)/100 (0)	|	|*-----|	|** (IF46+BF150+G46+H46+MH50)/100 (0)	|	|*-----|	|**
17	|*-----|	|** (IC47+BC150+D47+DE150+E47+HE150)/100 (0)	|	|*-----|	|** (IF47+BF150+G47+H47+MH50)/100 (0)	|	|*-----|	|**
18	|*-----|	|**-----|	|	|*-----|	|**-----|	|	|*-----|	|**
19	|PSUM(65..618) 124.17740625|	|**PSUM(15..118) (0)	|	|PSUM(75..718) (0)|	|**PSUM(15..118) (0)	|	|PSUM(85..818) (0)|	|**
20	|-----|	|-----|	|	|-----|	|-----|	|	|-----|	|-----|
21	|	|**	|	|	|**	|	|	|**
22	|	|**	|	|	|**	|	|	|**
23	|	|** (1124+1000000)/(IC51+CS0+D51+DE50+E51+HE50)+60 (ERR)	|	|	|** (1124+1000000)/(IF51+FS0+G51+H51+MH50)+60 (ERR)	|	|	|**
24	|	|** (IC53+CS0+IC52-60+D53+DE50+DE52-60+E53+ES0+ES2-60)/100000 (0)	|	|	|** (IF53+FS0+IF52-60+G53+H51+H52-60+H53+MH50+MH2-60)/100000 (0)	|	|	|**
25	|	|** (IC50+CS1+D50+DE1+ES0+ES1)/100000 (0)	|	|	|** (IF50+FS1+G51+H51+MH50+MH1)/100000 (0)	|	|	|**
26	|	|**-----|	|	|	|**-----|	|	|	|**
27	|	|**PSUM(124..126) (0)	|	|	|**PSUM(124..126) (0)	|	|	|**
28	|-----|	|-----|	|	|-----|	|-----|	|	|-----|	|-----|

FRILM.WRI ** Range 4 (R1..128) WRL **

age 13

FRILM.WRI FLAME REGION MODELED AS ONE SECTION

	-O-	-P-	IO-I	-R-	-S-	II-I
1	I	I	I	I	I	I
2	I	I	I	I	I	I
3	I* (5)	I	I*II* (5)	I	I	I*II
4	I*PYROLYSIS PRODUCTS	I	I*II* SOLIDS OUT BOTTOM	I	I	I*II
5	I*LB/MR	I*LB-M/MR	I*II*LB/MR	I	I*LB-M/MR	I*II
6	I	I	I	I	I	I
7	I*IF(10043=0,0,C7-F7-17-R7) (0)	I*07/12 (0)	I*II*100.1 (0)	I	I*07/12 (0)	I*II
8	I*IF(10043=0,0,LB) (0)	I*08/2 (0)	I*II0	I	I*08/2 (0)	I*II
9	I*IF(10043=0,0,L9) (0)	I*09/32 (0)	I*II0	I	I*09/32 (0)	I*II
10	I*IF(10043=0,0,L10) (0)	I*010/28 (0)	I*II0	I	I*010/28 (0)	I*II
11	I*IF(10043=0,0,L11) (0)	I*011/18 (0)	I*II0	I	I*011/18 (0)	I*II
12	I*IF(10043=0,0,L12) (0)	I*012/35.5 (0)	I*II0	I	I*012/35.5 (0)	I*II
13	I*IF(10043=0,0,L13) (0)	I*013/32 (0)	I*II0	I	I*013/32 (0)	I*II
14	I*IF(10043=0,0,L14) (0)	I*014/79.9 (0)	I*II0	I	I*014/79.9 (0)	I*II
15	I*IF(10043=0,0,L15) (0)	I*015/19 (0)	I*II0	I	I*015/19 (0)	I*II
16	I*IF(10043=0,0,L16+10041/100) (0)	I*---	I*II+C16-C16+10041/100 (0)	I	I*---	I*II
17	I*IF(10043=0,0,L17+10040/100) (0)	I*---	I*II+C17-C17+10040/100 (0)	I	I*---	I*II
18	I*-----	I*-----	I*II*-----	I	I*-----	I*II
19	I*SUM(05..018) (0)	I*SUM(PS..P18) (0)	I*II*SUM(RS..R18) (0)	I	I*SUM(S5..S18) (0)	I*II
20	I	I	I	I	I	I
21	I*AJB*10.73*520/(14.7*60) (0)	I	I*II	I	I	I*II
22	I*AJB*10.73*(023+460)/114.7*60) (0)	I	I*II	I	I	I*II
23	I*PT (2352.501166339)	I	I*II*IF(1048)0,048,PT) (2352.501166339)	I	I	I*II
24	I*((019-016-017)+1020+1020*(023-60)+020*(023-60)*211+((016+017)+047))*(023-60)/1000000 (0)	I	I*II*19*047+1020*(023-60)/1000000 (0)	I	I	I*II
25	IO	I	I*II0	I	I	I*II
26	I*-----	I	I*II*-----	I	I	I*II
27	I*SUM(024..026) (0)	I	I*II*SUM(R24..R26) (0)	I	I	I*II
28	I	I	I	I	I	I

FRILM.WK1 ** Range 40 (02..020) +VRL **
age 14

(02 03 00 13:51 P

FRILM.WK1 FLAME REGION MODELED AS ONE SECTION

	-U-	-V-	-W-	-X-	-Y-	-Z-
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	1	1	1	1	1	1
7	1	1	1	1	1	1
8	1	1	1	1	1	1
9	1	1	1	1	1	1
10	1	1	1	1	1	1
11	1	1	1	1	1	1
12	1	1	1	1	1	1
13	1	1	1	1	1	1
14	1	1	1	1	1	1
15	1	1	1	1	1	1
16	1	1	1	1	1	1
17	1	1	1	1	1	1
18	1	1	1	1	1	1
19	1	1	1	1	1	1
20	1	1	1	1	1	1
21	1	1	1	1	1	1
22	1	1	1	1	1	1
23	1	1	1	1	1	1
24	1	1	1	1	1	1
25	1	1	1	1	1	1
26	1	1	1	1	1	1
27	1	1	1	1	1	1
28	1	1	1	1	1	1

FKILNWK1 ** Range 4A 102..AJ20) *VAL **
age 15
FKILNWK1 FLAME REGION MODELED AS ONE SECTION

000 000 000 000

	-AA-	LABI	-AC-		-AD-	IAE1
2	|	|	|	|	|	|
3	|	I*11*	(9)	|	|	I*11
4	|	I*11*	AIR TO DRYER	|	|	I*11
5	I*LB-N/HR	I*11*LB/HR		I*LB-N/HR		I*11
6	I*-----	I*11-----		I*-----		I*11
7	10	I*11*AD7+44 (0)		10		I*11
8	10	I*11*AD8+40945 (0)		10		I*11
9	1*((67+J7)+(68+J8-0.5*(612+614+615+J12+J14+J15))/2)+613+J13)-(69+J9)+((1+P1SB/100)) (20.417656875)	I*11*AD9+32 (0)		10IF1043=0, 11N7+(10B-0.5*(N12+N14+N15))/2)+N13+M9)+((1+P1SC/100)) (0)		I*11
10	1*AD9+3.78389 (77.25816767274)	I*11*AD10+28 (0)		10IF1043=0,AD9+3.78389 (0)		I*11
11	1*Z11/10 (1.56477428602)	I*11*AD139*(AC9+AC10) (0)		1*AC11/10 (0)		I*11
12	10	I*11*AD12+36.5 (0)		10		I*11
13	10	I*11*AD13+6A (0)		10		I*11
14	10	I*11*AD14+80.9 (0)		10		I*11
15	10	I*11*AD15+20 (0)		10		I*11
16	I*-----	I*11-----		I*-----		I*11
17	I*-----	I*11-----		I*-----		I*11
18	I*-----	I*11-----		I*-----		I*11
19	10SUM(ACS..AD18) (99.24059843376)	I*11SUM(ACS..AC18) (0)		10SUM(AD5..AD18) (0)		I*11
20	|	|	|	|	|	|
21	|	I*11*AD19+10.73+520/114.7460 (0)		|		I*11
22	|	I*11*AD19+10.73+(AC23+4601/114.7460) (0)		|		I*11
23	|	I*11*Q38 (69.92)		|		I*11
24	|	I*110SUM(Y39..Y49)/1000000 (0)		|		I*11
25	|	I*110		|		I*11
26	|	I*11*-----		|		I*11
27	|	I*110SUM(AC24..AC25) (0)		|		I*11
28	|	|	|	|	|	|

FRILNWKI ** Range on (U2..AJ:8) *VAR **
age 16

01/09/88 12:21 1

FRILNWKI FLAME REGION MODELED AS ONE SECTION

	-RF-	-RG-	-RH-	-RI-	-RJ-
2	|-----|	|-----|	|-----|	|-----|	|-----|
3	1" (10)		1"1" (11)		
4	1"COMBUSTION PRODUCTS		1"1" TOTAL OFF-GAS		
5	1"LB/HR	1"LB-N/HR	1"1"LB/HR		1"LB-N/HR
6	|-----|	|-----|	|-----|	|-----|	|-----|
7	1*RG7+44 (569.1906)	1*07-P7-57 (12.93615)	1"11*AJ7+44 (569.1906)		1*RG7 (12.93615)
8	1*RG8+10945 (0)	10	1"11*019-016-017 (0)		1*RG8/80145 (0)
9	1*RG9+32 (59.39602)	1*09+19-P9-RG7-RG13-(108-P8)/2-0.5*(RG12+RG14+RG15)/2 (1.856150625)	1"11*AJ9+32 (59.39602)		1*RG9 (1.856150625)
10	1*RG10+28 (2163.228694036)	1*010-P10+110 (77.25816767274)	1"11*AJ10+28 (2163.228694036)		1*RG10 (77.25816767274)
11	1*RG11+18 (230.3383371483)	1*011-P11+111-(108-P8)-(RG12+RG14+RG15)/2 (12.79657428602)	1"11*AJ11+18 (230.3383371483)		1*RG11 (12.79657428602)
12	1*RG12+36.5 (0)	1*012-P12 (0)	1"11*AJ12+36.5 (0)		1*RG12 (0)
13	1*RG13+64 (0.6052)	1*013-P13 (0.00945625)	1"11*AJ13+64 (0.6052)		1*RG13 (0.00945625)
14	1*RG14+80.9 (0)	1*014-P14 (0)	1"11*AJ14+80.9 (0)		1*RG14 (0)
15	1*RG15+20 (0)	1*015-P15 (0)	1"11*AJ15+20 (0)		1*RG15 (0)
16	1*01F(80143+0,C16+10941/100,(C16-L16)+80141/100) (0) 1"----		1"11*016+RF16 (0)		1"-----
17	1*01F(10143+0,C17+80140/100,(C17-L17)+80140/100) (0) 1"-----		1"11*017+RF17 (0)		1"-----
18	1"-----	1"-----	1"11"-----		1"-----
19	1*SUM(RF5..RF18) (3022.759651985)	1*SUM(RG5..RG18) (104.8564988337)	1"11*SUM(AJ5..AJ18) (3022.759651985)		1*SUM(RJ5..RJ18) (104.8564988337)
20	|-----|	|-----|	|-----|	|-----|	|-----|
21	1*RG19+10.73+520/(114.7+60) (663.3302957969)		1"11*AJ19+10.73+520/(114.7+60) (663.3302957969)		
22	1*RG19+10.73+(RF23+460)/(114.7+60) (3587.725443456)		1"11*AJ19+10.73+(RJ23+460)/(114.7+60) (3587.725443456)		
23	1*PT (2352.501166339)		1"11*PT (2352.501166339)		
24	1*SUM(RJ39..RJ49)/1000000 (2.283189605792)		1"11*SUM(AJ39..AJ49)/1000000 (2.283189605792)		
25	10		1"110		
26	1"-----		1"11"-----		
27	1*SUM(RF24..RF25) (2.283189605792)		1"11*SUM(AJ24..AJ25) (2.283189605792)		
28	|-----|	|-----|	|-----|	|-----|	|-----|

FRILANKI FLAME REGION MODELLED AS ONE SECTION

FRILANKI FLAME REGION MODELLED AS ONE SECTION

[illegible]

FRILM.MK1 ** Range 8 (UJJ..RJ54) *VR **

100-00 00 1.3.5.1.1

age 19

FRILM.MK1 FLAME REGION MODELLED AS ONE SECTION

	-AA-	-AB-	-AC-	-AD-
33	|	|	|	|
34	|-----|	|	|PRIMARY COMBUSTION CHAMBER SUMMARY|	|
35	|*(11)|	|	|*TEMP =	|*P1 (2352.5)1166339|
36	|*TOTAL OFF	|	|-----|	|
37	|*BAS	|	|*AUX FUEL	|
38	|*-----	|	|*WASTE TO BURNER	|
39	| (A17)*(ACD*BCD*(A1023-60)*CD*(A1023-60)*211*(A1023-60) (367424.3364215)	| IF (A17=0,0,*AA39/A17) (645.52*7384337)	|*WASTE TO CHAMBER	|
40	| (A18)*(AR40*BS40*(A1023-60)*BT40*(A1023-60)*211*(A1023-60) (0)	| IF (A18=0,0,*AA40/A18) (0)	|*STOIC AIR TO BURNER	|
41	| (A19)*(AD*BD*(A1023-60)*CD*(A1023-60)*211*(A1023-60) (36316.95065798)	| IF (A19=0,0,*AA41/A19) (611.4292*88024)	|*XS AIR TO BURNER	|
42	| (A110)*(AH*BH*(A1023-60)*CH*(A1023-60)*211*(A1023-60) (1353673.764995)	| IF (A110=0,0,*AA42/A110) (625.7654441374)	|*STOIC AIR TO CHAMBER	|
43	| (A111)*(I060)*((A111)*(AH*CH*BD*CD*(A1023-60)*CD*BD*(A1023-60)*211*(A1023-60) (525472.9758147)	| IF (A111=0,0,*AA43/A111) (2281.309235449)	|*XS AIR TO CHAMBER	|
44	| (A112)*(HDL*BDL*(A1023-60)*CDL*(A1023-60)*211*(A1023-60) (0)	| IF (A112=0,0,*AA44/A112) (0)	|*AIR HUMIDITY	|
45	| (A113)*(ASD*BSD*(A1023-60)*CSD*(A1023-60)*211*(A1023-60) (301.5779030761)	| IF (A113=0,0,*AA45/A113) (498.3111*10971)	|*PYRO PRODUCTS	|
46	| (A114)*(ABR*BRBR*(A1023-60)*CBR*(A1023-60)*211*(A1023-60) (0)	| IF (A114=0,0,*AA46/A114) (0)	|*COMBUSTION GAS	|
47	| (A115)*(AHF*BF*(A1023-60)*CF*(A1023-60)*211*(A1023-60) (0)	| IF (A115=0,0,*AA47/A115) (0)	|*SOLIDS OUT BOTTOM	|
48	| (A116)*(H0447*(A1023-60)) (0)	| IF (A116=0,0,*AA48/A116) (0)	|*HEAT OF PYROLYSIS	|
49	| (A117)*(H0447*(A1023-60)) (0)	| IF (A117=0,0,*AA49/A117) (0)	|*HEAT LOSS	|
50	|*-----	|	|	|
51	|PSUM(AA38..AA50) (2283189.605792)	|	|*TOTAL	|
52	|	|	|*AIR SECN:	|
53	|	|	|*XS AIR OVERALL	|*OVERALL =
54	| (.....|	|	|	|

FILED.MMS 00 Range 8 (U33..A)5A) VWR 00

Age 20

FILED.MMS FLAME REGION MODELED AS ONE SECTION

	-06-	-06-	-06-	-06-
33	I	I	I	I
34	I	I	I	I
35	I*	(BS/HR	I	I
36	I	I	I	I
37	I	I	I	I
38	I	I	I	I
39	I	I	I	I
40	I	I	I	I
41	I	I	I	I
42	I	I	I	I
43	I	I	I	I
44	I	I	I	I
45	I	I	I	I
46	I	I	I	I
47	I	I	I	I
48	I	I	I	I
49	I	I	I	I
50	I	I	I	I
51	I	I	I	I
52	I*	BURKE *	I	I
53	I	I	I	I
54	I	I	I	I

age 21

FRILANKI FLARE REGION MODELED AS ONE SECTION

```

33 |
34 | " MM BTU/HR
35 | "IN
36 | -----
37 | 1#27 (3.415377474895)
38 | 1#27 (0)
39 | 1#27 (0)
40 | 1#1F1F40=0,0,(1Y51-Y43)+(1F40/1F40+1F41)/1000000 (0.006180326903)
41 | 1#1F1F41=0,0,(1Y51-Y43)+(1F41/1F41+1F40)/1000000 (0.00618032691)
42 | 1#1F1F42=0,0,(1Y51-Y43)+1F42/1F42+1F43)/1000000 (0)
43 | 1#1F1F43=0,0,(1Y51-Y43)+(1F43/1F43+1F42)/1000000 (0)
44 | 1#W43/1000000 (0.029979142422)
45 | 10
46 | 10
47 | 10
48 | " ----
49 | " ----
50 | -----
51 | 1#SUM(A136..A150) (3.452154976912)
52 | 1#OVERALL =
53 | 1#A122 (3587.725443456)
54 |
55 |

```

FRILUMK1 ** Range (CONS) 1955.. J109) *VRL **

age 22

FRILUMK1 FLAME REGION MODELED AS ONE SECTION

	-A-	-B-	-C-	-D-	-E-
55	I*PAU LB/Hr =		1178*(11340) (1178)		I*FFLB COMB. SEC' 1 =
56	I*HEAT IN =	I*KS2 (3.452154976912)	I*HEAT OUT =		I*KS2 (3.451876479273)
57					I*Tr, F
58	I	I*Tr, F	I*Tr, K	I*Tr, NEW	I*Tr+1.8-460 (2351.901166339)
59	I*Tr+ =	I*Tr+1.8-460 (2351.901166339)	I*Tr+ =	I*Tr+1.8-460 (2351.901166339)	I*Tr+1.8-460 (2351.901166339)
60	I*Tr- =	I*Tr-1.8-460 (1181.966459613)	I*Tr- =	I*Tr-1.8-460 (1181.966459613)	I*Tr-1.8-460 (1181.966459613)
61	I*Tr= =	I*Tr=1.8-460 (2127.636437027)	I*Tr= =	I*Tr=1.8-460 (2127.636437027)	I*Tr=1.8-460 (2127.636437027)
62	I*Tr+ =	I*Tr+1.8-460 (1377.601452302)	I*Tr+ =	I*Tr+1.8-460 (1377.601452302)	I*Tr+1.8-460 (1377.601452302)
63	I*Tr- =	I*Tr-1.8-460 (1353.4076297979)	I*Tr- =	I*Tr-1.8-460 (1353.4076297979)	I*Tr-1.8-460 (1353.4076297979)
64	I*Tr check =				I*Tr check =
65	I*KS0	I*KS0 (11465-321/1.8)+272.2 (440.866666666)			
66	I*Os + Os + Og + Of =		I*Os+Os+Og+Of 114928.79651721)	I*Os+Os+Og+Of 114928.79651721)	
67	I*Os =		I*Os (-162280.1989821)	I*Os (-162280.1989821)	
68	I*Og =		I*Og (-39.21852042004)	I*Og (-39.21852042004)	
69	I*Of =		I*Of (-165073.6507062)	I*Of (-165073.6507062)	
70	I*Of =		I*Of (342321.872726)	I*Of (342321.872726)	
71	I*Omd =		I*Omd (114927.61128344)	I*Omd (114927.61128344)	
72	I*DEL Ts, K =	I*DEL Ts, K =	I*DEL Ts, K =	I*DEL Ts, K =	I*DEL Ts, K =
73	I*DEL Tg, K =	I*DEL Tg, K =	I*DEL Tg, K =	I*DEL Tg, K =	I*DEL Tg, K =
74	I*DEL Tg, F =	I*DEL Tg, F =	I*DEL Tg, F =	I*DEL Tg, F =	I*DEL Tg, F =
75	I*Trgs1 =		I*Trgs1 (0.7837506968)	I*Trgs1 (0.7837506968)	
76	I*Trgs2 =		I*Trgs2 (0.741371890936)	I*Trgs2 (0.741371890936)	
77	I*Trgs3 =		I*Trgs3 (0.70244207241)	I*Trgs3 (0.70244207241)	
78	I*Trgs1 =		I*Trgs1 (0.85173160014)	I*Trgs1 (0.85173160014)	
79	I*Trgs2 =		I*Trgs2 (0.802473016424)	I*Trgs2 (0.802473016424)	
80	I*Trgs3 =		I*Trgs3 (0.762393143624)	I*Trgs3 (0.762393143624)	
81					
82	I*Erg =		I*Erg (0.232058836923)	I*Erg (0.232058836923)	
83	I*Trg11 = (ABg2+ABg3+(fms+par+furs+ps))/ABg1 (894+895+(E64+E70+E63+E63))/893 (ERR)		I*Trg11 (0.106977006897)	I*Trg11 (0.106977006897)	
84	I*ABg11 =		I*ABg11 (0.813022993102)	I*ABg11 (0.813022993102)	
85					
86	I*Trg1 =		I*Trg1 (0.907204005692)	I*Trg1 (0.907204005692)	
87	I*Trg12 =		I*Trg12 (0.898390115044)	I*Trg12 (0.898390115044)	
88	I*Trg13 =		I*Trg13 (0.899486178792)	I*Trg13 (0.899486178792)	
89					
90	I*Trg1 =		I*Trg1 (0.767941163076)	I*Trg1 (0.767941163076)	
91	I*Trg2 =		I*Trg2 (0.721439798465)	I*Trg2 (0.721439798465)	
92	I*Trg3 =		I*Trg3 (0.689730941602)	I*Trg3 (0.689730941602)	
93	I*ABg1 = I - Trg1		I*ABg1 (0.232058836923)	I*ABg1 (0.232058836923)	
94	I*ABg2 = Trg1 - Trg2 =		I*ABg2 (0.04050136461)	I*ABg2 (0.04050136461)	
95	I*ABg3 = Trg2 - Trg3 =		I*ABg3 (0.03770885663)	I*ABg3 (0.03770885663)	
96					
97	I* excess air =				
98	I*Ta =	I*Ta (1978-273)+1.8+32 (70.52)	I*Ta =	I*Ta =	I*Ta =
99	I*hcvs =		I*hcvs =	I*hcvs =	I*hcvs =
100	I*hcvs =		I*hcvs =	I*hcvs =	I*hcvs =
101	I*hcvs =		I*hcvs =	I*hcvs =	I*hcvs =
102	I*hcvs =		I*hcvs =	I*hcvs =	I*hcvs =
103	I*hrsha =		I*hrsha (8.615937694191)	I*hrsha (8.615937694191)	
104					
105	I*(PH20+Pro2)*Lm =		I*(PH20+Pro2)*Lm 10.153235702897)	I*(PH20+Pro2)*Lm 10.153235702897)	
106	I*(PH20+Pro2)*Lm2 =		I*(PH20+Pro2)*Lm2 (0.306471405794)	I*(PH20+Pro2)*Lm2 (0.306471405794)	
107	I*(PH20+Pro2)*Lm3 =		I*(PH20+Pro2)*Lm3 (0.459707108691)	I*(PH20+Pro2)*Lm3 (0.459707108691)	
108					
109					

FKILM.MK1 ** Range CONST (ASS..J109) +VAL **
age 23

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FKILM.MK1 FLAME REGION MODELED AS ONE SECTION

	-F-	-G-	-H-	-I-
55	I	I+U340 (1)	I0INT(0NOM) (J2202)	I*Imo =
56	I	I*DELTA H =	I*DELP (0.000278497632)	I
57	I' Tg, F	I*DEL Hg, BTU/HR	I-----I	I
58	I+TR=1.8-460 (69.92)	I+U340+U341 (0)	I	I+U, B
59	I+TR=1.8-460 (1181.966459613)	I+U344+U345 (56.3560.3450.351)	I*RF =	I+FLF=164 (2.4494369015)
60	I+EG0 (1927.461489724)	I+U348+U349 (6.220902404747)	I*Ra =	I+HML (0.826928261808)
61	I0	I'	I*Ra =	I(RP1-THIRAD/2)+D+ML (3.14344409886)
62	I1-FSF (0.341757502792)	I'	I*Ra =	I+RA+RS+RF (6.419809320819)
63	I(PSIN+THIRAD/2)/(RP1-THIRAD/2)+FSH (0.089904235113)	I0IF(+J59=0,0,(12+J72+J76)/J60)+G62 (0)	I*Wg, m =	I+D+PSIN+THIRAD/2 (0.848479644786)
64	I1-FHS-FHF (0.304035158825)	I0IF(+J59=0,0,(12+J72+J76)/J61)+G61 (0)	I*RA' =	I(RP1+RF+2)+LL (3.8617962001881)
65	I(2+RP1-THIRAD)/(2+RP1) (0.777777777777)	I'	I*Area3 =	I2+RP1+R23+LL (4.974806466066)
66	I1-FFW (0.222222222222)	I'	I*Ash =	I2+RP1+R23+ML (5.091460901293)
67	I0IF(+RF=0,0,1(RF)/R5)+FFS (0.658242497707)	I'	I	I
68	I0IF(+RF=0,0,1(RF)/R6)+FFW (0.60606060606)	I'	I*rr1, m =	I+D/2 (0.66)
69	I1-RBS (0.2)	I'	I*rr2, m =	I+RR1+INS1+0.0254 (0.7616)
70	I1-RBW (0.2)	I'	I*rr3, m =	I+RR2+INS2+0.0254 (0.8124)
71	I0	I'	I*rrsh, m =	I+RR3+SHLL=0.0254 (0.83145)
72	I+QIS (0.8)	I'	I*rrf, m =	I0.5
73	I+EMW (0.8)	I'	I	I
74	I+EMF (1)	I'	I'D, m =	I1.32
75	I0.7	I'	I'L, m =	I4.873
76	I0.8	I'	I*LL, m =	I4.75 (0.9746)
77	I0.8	I'	I	I
78	I1	I'	I*Thi =	I180
79	I+SIEM+IS+IS+IS (61588.31752571)	I'	I*Thirad =	I+THI/180)+RP1 (1.356263401595)
80	I+SIEM+IS+IS+IS+IS (242162.0419811)	I'	I*0.95+0.028+(1-B029)	I
81	I+SIEM+IS+IS+IS+IS (33259.98819782)	I'	I*F/D =	I0.5+11-PCOS(THIRAD/2) (0.116977778441)
82	I+SIEM+IF*4 (337670.59728011)	I'	I	I
83	I56.7/IE9 (5.67E-8)	I'	I*ins1, in =	I4
84	I+RJ19 (104.8564988337)	I'	I*ins2, in =	I2
85	I+Q302 (0.075441246375)	I'	I*sho11, in =	I0.75
86	I+Q301 (0.123754099113)	I'	I*sh1, BTU/hr+ft+02+in =	I15.5
87	I+PC02+H020 (0.199191345488)	I'	I*sh2, BTU/hr+ft+02+in =	I12
88	I	I'	I*ku1, W/m+02+K/m =	I+KK1/6.94 (0.79250720461)
89	I	I'	I*ku2, W/m+02+K/m =	I+KK2/6.94 (0.28818443804)
90	I0.66+D+11-FD (0.769288959422)	I'	I	I
91	I+LM+2 (1.538577918845)	I'	I*(H020+PCu2)+1rr1-rf) =	I
92	I+LM+3 12.307866878267)	I'	I*(H020+PCu2)+1rr1-rf)+2 =	I
93	I	I'	I*(H020+PCu2)+1rr1-rf)+3 =	I
94	I' 1/(2+RP1+rr31+((rr2-rr1)/(RP1+ku1)+1rr1+rr2))+((rr3-rr2)/(RP1+ku2)+1rr2+rr3)))	I'	I	I
95	I1/(12+RP1+RR3)+((RR2-RR1)/(RP1+188+(RR1+RR2))+((RR3-RR2)/(RP1+189+(RR3+RR2)))) (3.044226807653)	I'	I	I
96	I' sigmah+EMsh+11sh+11sh+11sh-Ta+Ta+Ta+Ta/(1sh-Ta)	I'	I	I
97	I+SIEM+EMsh+11sh+11sh+11sh-TA*41/11SH-TA (8.615937694191)	I'	I	I
98	I' (hcdsh+Area3+1w+Ash+hcvsh+1a+Ash+hcvsh+1a)/(hcdsh+Area3+Ash+hcvsh+1a+Ash+hcvsh+1a)	I'	I	I
99	I' (HCDSH+AREA3)+1w+ASH+HCVSH+1a+ASH+HCVSH+1a/1HCDSH+AREA3+ASH+HCVSH+ASH+HCVSH (451.8935591416)	I'	I	I
100	I	I'	I	I
101	I' Area3+hcdsh+(Tw-Tsh)	I'	I	I
102	I' AREA3+HCDSH+(TW-TSH) (14927.61128344)	I'	I	I
103	I' Ash+hcvsh+11sh-Ta)	I'	I	I
104	I' ASH+HCVSH+11SH-TA (8018.701017314)	I'	I	I
105	I' Ash+hcvsh+11sh-Ta)	I'	I	I
106	I' ASH+HCVSH+(1SH-TA) (6908.862833353)	I'	I	I
107	I+QD+CV+BSH (14927.56385266)	I'	I	I
108	I	I'	I	I
109	I-----I	I'	I	I

```

FILIN.W1 ** Range CONST (055..J103) WVL **
Age 24
FILIN.W1 FLAME REGION MODELED AS ONE SECTION
      -J-
55 1461 00
56 1"
57 1"
58 1"
59 1"
60 1"
61 1"
62 1"
63 1"
64 1"
65 1"
66 1"
67 1"
68 1"
69 1"
70 1"
71 1"
72 1"
73 1"
74 1"
75 1"
76 1"
77 1"
78 1"
79 1"
80 1"
81 1"
82 1"
83 1"
84 1"
85 1"
86 1"
87 1"
88 1"
89 1"
90 1"
91 146204021*081-051 0.031076615270
92 146204021*081-0512 0.06371235561
93 146204021*081-0513 0.095611045031
94 1
95 1"
96 1"
97 1"
98 1"
99 1"
100 1"
101 1"
102 1"
103 1"
104 1"
105 1"
106 1"
107 1"
108 1"
109 1"

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FKILN.MR1 ** Range E (A109...E128) *VRL **

Age 25

FKILN.MR1 FLAME REGION MODELED AS ONE SECTION

	-A-	-B-	-C-	-D-	-E-
109	|-----|-----|-----|-----|-----|				
110	1*Qss+Qsm+Qsg+Qsf =		1*QSS+QSM+QSG+QSF (-5.456968210637E-12)*EMs =		1*EMS (0.8)
111	1*Qms+Qsm+Qmg+Qmf =		1*QMS+QSM+QMG+QMF (-3.637978807091E-11)*EMs =		1*EMM (0.8)
112	1*Qgs+Qgm+Qgg+Qgf =		1*QGS+QGM+QGG+QGF (5.456968210637E-12)*FLF =		1*FLF (0.8)
113	1*Qfs+Qfm+Qfg+Qff =		1*QFS+QFM+QFG+QFF (2.910383045673E-11)*EMF =		1*EMF (1)
114	|		|		|
115	1*Ts = Tm = Tg		|		|
116	|-----|		|		|
117	1*Qms = Qsm	1*QMS (-39623.04440461)	1*QSM (-9277.160936659)		1*C117-B117 (30345.88346795)
118	1*Qgs = Qsg	1*QGS (-6104.24178883)	1*QSG (-8929.722165155)		1*C118-B118 (-2825.480376324)
119	1*Qgm = Qmg	1*QGM (-23248.45635983)	1*QMG (-92802.59797963)		1*C119-B119 (-69554.1416198)
120	1*Qfs = Qsf	1*QFS (-142433.3176775)	1*QSF (-22378.49950583)		1*C120-B120 (120054.8181717)
121	1*Qfm = Qmf	1*QFM (-507096.3850739)	1*QMF (-340001.4623277)		1*C121-B121 (167094.9227462)
122	1*Qfg = Qgf	1*QFG (-78322.45963568)	1*QGF (-23150.32782764)		1*C122-B122 (55172.13180804)
123	1*Qs	1*QMS (-162280.1989821)			
124	1*Qm	1*QSM (-39.21852042004)		1*all s	
125	1*Qg	1*QGS (-165073.6587062)		1*/FSA:FKILN*R/FSC:FKILN*RI	
126	1*Qf	1*QF (342321.872726)			
127		1*B125+B124+B123+QF (14928.79651721)			
128					

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FILN.MK1 ** Range FLA (11340..13621) *VAL **
age 26

FILN.MK1 FLAME REGION MODELED AS ONE SECTION

	-I-	-J-	-K-	-L-	-M-	-N-
340	1*PREHEAT OF FUEL AND AIR			1*% FUEL USED SECT 1 =	11	
341	1*TF1 =	1*ES0 (2.351, 901166339)	1*TDIAL	1*SE1.1, 1 COMBUSTED	1*PREHEATED	
342			1*LB/HR	1*LB/HR	1*LB/HR	1*BTU/HR
343	1*FUEL LB/HR =		1178	1*MS340+MS343 (178)	1*MS343-L343 (0)	1*MS366+MS343 (0)
344	1*CO2 LB/HR =					
345	1*BURNER O2, LB/HR =		1653.37	1*MS340+MS345 (653.37)	1*MS345-L345 (0)	1*1298+(0.0341-60)*MS345
346	1*BURNER N2, LB/HR =		12163.23	1*MS340+MS346 (2163.23)	1*MS346-L346 (0)	1*1299+(0.0341-60)*MS346
347	1*BURNER H2O, LB/HR =		128.17	1*MS340+MS347 (28.17)	1*MS347-L347 (0)	1*1300+(0.0341-60)*MS347
348						
349				1*SUM(MS347..MS343) (3022.77)	1*SUM(L347..L343) (3022.77)	1*SUM(MS347..MS343) (0)
350						
351	1*RECIRCULATION FRAC. =			1*Mo = X(Mcp + Mair)		
352	1*X =		1*F61 (0)	1*Mo/(Mcp + Mair) =	1*F61+MS349/0349 (0)	
353						
354	1*QF1 TOTAL = (1-SCOMB)Mo(Tf1-To) + 1/31(Mcp+Mair)(Tf1-Tg1)					
355	1*QF1 =	1*Q1A+Q1B (0)	1*Q1A (0)	1*Q1B (0)		
356						
357	1*QF2 TOTAL = -(1-SCOMB)Mo(Tf1-To) + 1/31(Mcp+Mair)(Tf2-Tf1) + 211/31(Mcp+Mair)(Tf2-Tg2) + Mcp1(Tf2-Tf1)					
358	1*QF2 =	1*Q1A (0)	1*Q2C (0)	1*Q1B+2 (0)		1*Q2C+Q4 (0)
359	1*QF2 =	1*Q1A+2*Q1B+Q2C+MS50 (0)				
360						
361	1*QF TOTAL BTU/HR = X(Mcp + Mair)*(Tf-Tg) = 311/31(Mcp + Mair)					
362	1*QF =	1*L355+3 (0)				

FILENAME: 00 Range FLA (1344..0362) +VRL 00
Age 27

FRILUMMI FLOWE REGION MODELED AS ONE SECTION

	-0-	-0-	-0-	-R-	-5-	-T-	-U-
340		101M1 (NEM) (2202)					
341	1" ID/RL	1" ID/RL	1" J. Hair		1" Ig1-Ig0 BTU/HR =	1-DJ1 (0)	
342	1" Ncp/Hair	1" Hair	1" A. 1/31 (Ncp/Hair)		1" Ig1-Ig2 BTU/HR =	1-DJ1 (0)	
343	1" LB/HR	1" LB/HR			1" Ig1 BTU/HR = *	1-DJ1 (0)	
344	156.194344 (569.19)	10	1" S. Hair		1" Ig2-Ig1 BTU/HR =	1-DJ1 (0)	
345	156.449345 (448.63)	1369.23	1" S. 1 (Ncp/Hair)		1" Ig2-Ig3 BTU/HR =	1-DJ1 (0)	
346	12163.2349346 (3482.25)	11289.02			1" Ig2 BTU/HR = *	1-DJ1 (0)	
347	1230.3449347 (381.96)	1151.62				1-DJ1 (0)	
348			1" S. Hair		1" Ig2-Ig3 BTU/HR =	1-DJ1 (0)	
349	1625M1 (0347..0343) (4852.03) 1625M1 (P347..P343) (1625.67)	1" 10. Ncp/Hair	1" 10. Ncp/Hair		1" Ig3-Ig2 BTU/HR =	1-DJ1 (0)	
350						1-DJ1 (0)	
351						1-DJ1 (0)	
352						1-DJ1 (0)	
353						1-DJ1 (0)	
354						1-DJ1 (0)	
355						1-DJ1 (0)	
356						1-DJ1 (0)	
357						1-DJ1 (0)	
358						1-DJ1 (0)	
359						1-DJ1 (0)	
360						1-DJ1 (0)	
361						1-DJ1 (0)	
362						1-DJ1 (0)	

	-V-	-W-	-I-	-Y-	-Z-
341		"I. OFA EXPL. ORC. 1/311 (Kp=Harr) (11-fg)			
342		"OIT =	10F01.8-460 12351.9011663399		
343		"CP			10F01.8-460 11181.966457812
344		"BU/ABF			
345	"1/31 (Kp=Harr)	"BU/ABF			
346	"B/HR	"BU/HR			
347	"1/31 (Kp=Harr) (0)	"O2	10F59.1259011342-601 1259011342-601 21 00.2815687633	10F349.1346+1346+1346+1346-601 (0)	10F359.1259011342-601 1259011342-601 21 00.25049493626291
348	"1/31 (Kp=Harr) (0)	"O2	10F59.1259011342-601 1259011342-601 21 00.286762037563	10F349.1346+1346+1346+1346-601 (0)	10F359.1259011342-601 1259011342-601 21 00.2531323078191
349	"1/31 (Kp=Harr) (0)	"O2	10F59.1259011342-601 1259011342-601 21 00.2775552901271	10F349.1346+1346+1346+1346-601 (0)	10F359.1259011342-601 1259011342-601 21 00.2582760879351
350	"1/31 (Kp=Harr) (0)	"O2	10F59.1259011342-601 1259011342-601 21 00.532717118953	10F349.1346+1346+1346+1346-601 106501 (0)	10F359.1259011342-601 1259011342-601 21 00.48650122544801
351	"1/31 (Kp=Harr) (0)	"O2	10F59.1259011342-601 1259011342-601 21 00.532717118953	10F349.1346+1346+1346+1346-601 (0)	10F359.1259011342-601 1259011342-601 21 00.48650122544801
352	"DEL. H. GMS. BU/HR =	"O2	10F59.1259011342-601 1259011342-601 21 00.532717118953	10F349.1346+1346+1346+1346-601 (0)	10F359.1259011342-601 1259011342-601 21 00.48650122544801
353	"BU/HR =	"O2	10F59.1259011342-601 1259011342-601 21 00.532717118953	10F349.1346+1346+1346+1346-601 (0)	10F359.1259011342-601 1259011342-601 21 00.48650122544801
354	"DEL. Ig. K =	"O2	10F59.1259011342-601 1259011342-601 21 00.532717118953	10F349.1346+1346+1346+1346-601 (0)	10F359.1259011342-601 1259011342-601 21 00.48650122544801
355		"O2	10F59.1259011342-601 1259011342-601 21 00.532717118953	10F349.1346+1346+1346+1346-601 (0)	10F359.1259011342-601 1259011342-601 21 00.48650122544801

FRILUM.M1 ** Range FLOW (V3A1..REISS) *AL **
age 29

FRILUM.M1 FLOW REGION MODELED AS ONE SECTION

		-00-	-00-	-00-	-00-	-00-	-00-
341	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
342	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
343	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
344	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
345	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
346	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
347	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
348	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
349	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
350	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
351	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
352	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
353	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
354	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
355	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=
356	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=	I1/31=

```

FILLUM1  ** Range FLOW (W-1: 98 to 10) **
498 30
FILLUM1 FLOW REGION MODELLED AS ONE SECTION
-#-
341 |
342 | 11/31*
343 |
344 |
345 |
346 | 140.359+0E+350+0E+342-601+0E+358+10E+342-601+21 0.28156874631 140.346+0E+346+0E+342-601 00
347 | 140.359+0E+359+0E+342-601+0E+359+10E+342-601+21 0.25670207568 140.347+0E+347+0E+342-601 00
348 | 140.350+0E+350+0E+342-601+0E+350+10E+342-601+21 0.27255290127 140.348+0E+348+0E+342-601 00
349 | 140.351+0E+351+0E+342-601+0E+351+10E+342-601+21 0.53271131896 140.349+0E+349+0E+342-601+1060 00
350 |
351 |
352 |
353 | *Cp IN =
354 | *Cp OUT =
355 |
356 |

```

FILLUMK1 ** Range H (L292..M340) +VAL **
 Age 31
 FILLUMK1 FLAME REGION MODELED AS ONE SECTION

-L-		-H-	-H-
292	1* BASIS : GAS ENTHALPY		
293	-----		
294	1* FEED LB/HR	11335	1* O2 LB/HR =
295	1* % H2O	10.101	1* O2 LB/HR
296	1* Cp BTU/LB*F, DRY	10.26	1* N2 LB/HR
297	1		1* LBS H2O/HR
298	1* F/D FILL RATIO	110	1* TOTAL LB/HR
299	1* % EXCESS AIR SEC. =	10.6558	1* MOLES H2O
300	1* AIR DENSITY, LB/FT3	128.84/M301 (0.081090730676)	1* MOLES GAS
301	1* MOLAR VOL. FT3/MOL	1360*(1+1.81)/536.4 (355.6510067114)	1* MOL % H2O
302	1* Tair, F	170	1* MOL % CO2
303	1* HEAT OF VAPOR, BTU/LB	11060	
304	1* hcvms BTU/FT2*F =	1* hcvms/5.68 (8.082016901408)	
305	1	1* T ABMLK =	1* TA (294.4)
306	1* BASIS : SOIL ENTHALPY		
307	-----		
308	1* SOIL DRY BASIS, LB2/HR		1* (1-M295)*M294 (1200.165)
309	1* BTU/HR*F =		1* M296*M308 (312.1429)
310	1* DBL TS, K =		1* M318 (731.9141398062)
311	1		
312	1* OS BTU/HR =	1* OS*3.414*P312 (554024.599325)	
313	1* BTU/HR UP TO 212 =	1* (212-60)*M309 (47430.5208)	
314	1* DEL HW H2O, BTU/HR =	1* M295*M294*M303 (112925.1)	
315	1* BTU/HR ABOVE 212 =	1* IF((1+M312-M313)*M314, M312-M313-M314, 0) (363664.978525)	
316	1* DEL TS, F =	1* IF((1+M312-M313)*M314, M315/M309*(212-60), 0) IF((1+M312-M313)*0, 212-60, M312/M309) (1317.44541651)	
317	1* DEL TS, C =	1* (M316)/1.8 (731.9141398062)	
318	1* DEL TS, K =	1* M317 (731.9141398062)	
319	1		
320	1* HEAT LOSS CALC FOR FLAME HWB		
321	-----		
322	1* -Qs SOLID, BTU/HR =	1* OS*3.414 (554024.599325)	1* (==== INCLUDES HEAT OF VAPOR OF WATER IN FEED SOLID)
323	1* -Qw WALL, BTU/HR =	1* QW*3.414 (133.892028714)	
324	1* -Qg GAS, BTU/HR =	1* OS*3.414 (563561.470823)	
325	1* SHELL LOSS BTU/HR =	1* Q66*3.414 (50966.91130977)	
326	1* QF1 OR QF2 BTU/HR =	1* QF1*QF2 (0)	1* (==== ENTHALPY CALC FOR REACT GAS OR FEED & AIR PREHEATED)
327	-----		
328	1* TOTAL HW BTU/HR =	1* SUM(M326..M322)/1000000 (1.168686873486)	
329	1		
330	-----		
331	1		
332	1* CROSSSECTIONAL AREA OF BED =		
333	1* = 1*(D/2)^2*(THIRAD/2-ACOS(THIRAD/2))/SIN(THIRAD/2)		
334	1* % FILL =		
335	1* SOLID BED VOLUME, m^3 =		
336	1* FT^3 =		
337	1* CORRECT. AREA OF FREEBOARD, Awt, M^2 =		
338	1* FREEBOARD VOLUME, M^3 =		
339	-----		
340	1* % FEED USED SECT 1 =	11	

FXILUM.M1 ** Range H (L292..M340) +VAL **

107-09-88 13:46 P

age J2

FXILUM.M1 FLAME REGION MODELED AS ONE SECTION

	-D-	-P-	-Q-	-R-	-S-
292		I*SEC. 4			I*COMBUSTION GAS ENTHALPY CALC.
293	I*SUM	I*FEED	I*COMBST.		I*TF =
294	I*P294+Q294 (569.1906)		I*AF7 (569.1906)		
295	I*P295+Q295 (448.72272048)	I (67.68/2)*32+P299 (389.32590048)	I*AF9 (59.39682)		
296	I*P296+Q296 (3452.249278708)	I (67.68/2)*3.78389+28+P299 (1209.020583871)	I*AF10 (2163.228694836)		
297	I*P297+Q297 (381.9568019918)	I*Q39+ (P296+P295)+P295+P294 (151.6184648435)	I*AF11 (230.3383371483)		I*CO2
298	I*P298+Q298 (4852.11940118)	I*P296+P295+P297+P294 (1829.964949194)	I*Q296+Q295+Q297+Q294 (3022.154451985)		I*O2
299	I*P299+Q299 (21.21982233288)	I*P297/18 (8.423248046861)	I*Q297/18 (12.79657428602)		I*H2
300	I*P300+Q300 (171.4731744446)	I*P299+P295/32+P296/28 (66.62613186083)	I*Q300 (Q304..Q301) (104.8470425837)		I*H2O
301	I*Q299/Q300 (0.123750099113)	I*CO2 Lbm/hr	I*AF7 (12.93615)		
302	I (Q294/44)/Q300 (0.075441246375)	I*O2 Lbm/hr	I*AF9 (11.856150625)		
303		I*H2 Lbm/hr	I*AF10 (77.25816767274)		I*DEL H GAS, BTU/hr =
304		I*H2O Lbm/hr	I*AF11 (12.79657428602)		
305					I*BTU/F =
306					I*DEL Tg, K =
307					
308					
309					
310					
311					
312	I*O2 BTU/hr =	10			
313					
314					I*FEED GAS ENTHALPY CALC USED
315					I*Tg =
316					
317					
318					
319				I*U319/P294 (ERR)	I*CO2
320				I*U320/P295 (284.2304422669)	I*O2
321				I*U321/P296 (290.8929036278)	I*H2
322				I*U322/P297 (1605.289448497)	I*H2O
323					
324					
325					I*DEL H GAS, BTU/hr =
326					
327					I*BTU/F =
328					I*DEL Tg, K =
329					
330					
331					
332		I ((10/2)*2)*(TH(ROD/2-PCOS(TH(ROD/2)+SIN(TH(ROD/2))) (0.089615040261)			
333					
334		I*P332/P337 (0.070074010982)			
335		I*L*P332 (0.436694091193)			
336		I*P335/O.028317 (15.4216227423)			I*AVG. DENSITY OF SOLID BED, LB/FT^3 =
337		I*RR1*2*OP1-P332 (1.278862719642)			I*SOLID FEED RATE, FT^3/hr =
338		I*P337*L (6.231898032816)			I*RESIDENCE TIME FOR SOLID BED, hr =
339					
340		I*INT(RNDM) (32202)	I*3. Mzair		I*Tg1-Tg0 BTU/hr =

FRILUMI ** Range M (L292..M344) *VR**

Age 33

FRILUMI FLAME REGION MODELED AS ONE SECTION

	-T-	-U-	-V-	-W-
292				
293	I*F=1.8-460 (2351.901166339)		I*lg IN =	I*1293-100 (2251.9+1166.339)
294	I*Cp	I*lg		I*lg
295	I*BTU/LB*F	I*BTU/HR		I*BTU/HR
296		I*OUT		I*IN
297	I*1309+U309*(101293-60)+V309*(101293-60)^2 (0.281568674631)	I*Q294+I*297*(101293-60) (367314.3889226)	I*1309+U309*(101293-60)+V309*(101293-60)^2 (0.279733298113)	I*Q294+V297*(101293-60) (348997.9313852)
298	I*1310+U310*(101293-60)+V310*(101293-60)^2 (0.266702057568)	I*Q295+I*298*(101293-60) (36306.58876423)	I*1310+U310*(101293-60)+V310*(101293-60)^2 (0.265644881755)	I*Q295+V298*(101293-60) (34584.82756334)
299	I*1311+U311*(101293-60)+V311*(101293-60)^2 (0.272955290127)	I*Q296+I*299*(101293-60) (1353286.77131)	I*1311+U311*(101293-60)+V311*(101293-60)^2 (0.271849788267)	I*Q296+V299*(101293-60) (1288998.470331)
300	I*1312+U312*(101293-60)+V312*(101293-60)^2 (0.532717131896)	I*Q297+I*300*(101293-60)+10601 (525386.778711)	I*1312+U312*(101293-60)+V312*(101293-60)^2 (0.528746437943)	I*Q297+V300*(101293-60)+10601 (511111.5414022)
301				
302		IPSUM(U301..U297) (2282294.527708)		IPSUM(U301..U297) (2183692.770682)
303		I*U302-M302 (98601.75702628)		
304	I*WATTS	I*U303/3.414 (28881.59256774)	I*Cp IN =	I*U302/P298/(1293-60) (0.544168040804)
305		I*U303/(1293-M293) (986.0175702628)	I*Cp OUT =	I*U302/P298/(M293-60) (0.544412135074)
306		I*-Q293.414/(U305+1.8) (317.5295405023)		
307	I*A	I*B	I*C	
308				
309	10.202394171692	10.000051475613	1-7.387E-9	I*CD2
310	10.2384537361	10.0000141588	1-8E-10	I*Q2
311	10.2446041076	10.0000137453	1-6E-10	I*H2
312	10.4407080267	10.000046037	1-2E-10	I*H2O
313				
314				
315	I*F=1.8-460 (1181.966459613)		I*lg IN =	I*TA=1.8-460 (69.92)
316	I*Cp	I*lg		I*lg
317	I*BTU/LB*F	I*BTU/HR		I*BTU/HR
318		I*OUT		I*IN
319	I*1331+U331*(11315-60)+V331*(11315-60)^2 (0.250849262829)	I*P294+I*319*(101315-60) (0)	I*1331+U331*(11315-60)+V331*(11315-60)^2 (0.202904082844)	I*P294+V319*(11315-60) (0)
320	I*1332+U332*(11315-60)+V332*(11315-60)^2 (0.253332387819)	I*P295+I*320*(101315-60) (110658.2728793)	I*1332+U332*(11315-60)+V332*(11315-60)^2 (0.23859411267)	I*P295+V320*(11315-60) (921.477408269)
321	I*1333+U333*(11315-60)+V333*(11315-60)^2 (0.259270587935)	I*P296+I*321*(101315-60) (374966.9404783)	I*1333+U333*(11315-60)+V333*(11315-60)^2 (0.244740401932)	I*P296+V321*(11315-60) (3129.516124691)
322	I*1334+U334*(11315-60)+V334*(11315-60)^2 (0.486012254488)	I*P297+I*322*(101315-60)+10601 (243391.5218107)	I*1334+U334*(11315-60)+V334*(11315-60)^2 (0.441110795722)	I*P297+V322*(11315-60)+10601 (161379.0277075)
323				
324		IPSUM(U323..U319) (729016.7351684)		IPSUM(U323..U319) (165430.0212404)
325		I*U324-M324 (563586.713928)		
326	I*WATTS	I*U325/3.414 (165081.0527029)	I*Cp IN =	I*U324/P298/(11315-60) (0.355070713144)
327		I*U325/(11315-M315) (506.8014101892)	I*Cp OUT =	I*U324/P298/(M315-60) (9.112968769611)
328		I*-Q293.414/(U327+1.8) (617.7759171899)		
329	I*A	I*B	I*C	
330				
331	10.202394171692	10.000051475613	1-7.387E-9	I*CD2
332	10.2384537361	10.0000141588	1-8E-10	I*Q2
333	10.2446041076	10.0000137453	1-6E-10	I*H2
334	10.4407080267	10.000046037	1-2E-10	I*H2O
335				
336				
337				I100
338				I*(P294/100) (13.35)
339				I*P336/U337 (1.155177735061)
340		I-D381 (0)		

FAIL.MNI ** Range MOD (R1C9..GJ07) *VRL **

age 34

FAIL.MNI FLAME REGION MODELLED AS ONE SECTION

	-A-	-B-	-C-	-D-	-E-
129	I'Ds = sEs + uEs + gEs + fEs + hves(Tm - Ts) + hcvgs(Tg - Ts)				
130					
131	I'Du = sEs + uEs + gEs + fEs + hcvgs(Tg - Ts) + hcvgs(Tg - Ts)				
132					
133	I'Dg = sEs + uEs + gEs + fEs + hcvgs(Tg - Ts) + hcvgs(Tg - Ts)				
134					
135	I'Df = sEs + uEs + gEs + fEs				
136	I'Ds				
137	*****	*****	*****	*****	*****
138					
139	I'Es	I'Es			I'Es (0.66154260946)
140	12	I'Es			I'Es (0.66154260946)
141	13	I'Es			I'Es (0.66154260946)
142	14	I'Es			I'Es (0.66154260946)
143	15	I'Es			I'Es (0.66154260946)
144	I'Ds (= Ds)				I'Ds (0.66154260946)
145					
146	I'Eu	I'Eu			I'Eu (0.66154260946)
147	12	I'Eu			I'Eu (0.66154260946)
148	13	I'Eu			I'Eu (0.66154260946)
149	14	I'Eu			I'Eu (0.66154260946)
150	15	I'Eu			I'Eu (0.66154260946)
151	16	I'Eu			I'Eu (0.66154260946)
152	I'Ds (= Ds)				I'Ds (0.66154260946)
153					
154	I'Eq	I'Eq			I'Eq (0.66154260946)
155	12	I'Eq			I'Eq (0.66154260946)
156	I'Ds (= Ds)				I'Ds (0.66154260946)
157					
158	I'Ef	I'Ef			I'Ef (0.66154260946)
159	12	I'Ef			I'Ef (0.66154260946)
160	13	I'Ef			I'Ef (0.66154260946)
161	14	I'Ef			I'Ef (0.66154260946)
162	15	I'Ef			I'Ef (0.66154260946)
163	16	I'Ef			I'Ef (0.66154260946)
164	17	I'Ef			I'Ef (0.66154260946)
165					
166					
167	I'hves	I'hves			I'hves (0.66154260946)
168	I'hvgs	I'hvgs			I'hvgs (0.66154260946)
169					
170	I'Ds (=)				
171					
172	I'Du				I'Du (0.66154260946)
173	*****	*****	*****	*****	*****
174					
175	I'su	I'su			I'su (0.66154260946)
176	12	I'su			I'su (0.66154260946)
177	I'Es	I'Es			I'Es (0.66154260946)
178	14	I'Es			I'Es (0.66154260946)
179	15	I'Es			I'Es (0.66154260946)
180	16	I'Es			I'Es (0.66154260946)
181	I'Du (= Ds)				I'Du (0.66154260946)
182					
183	I'Eu	I'Eu			I'Eu (0.66154260946)
184	12	I'Eu			I'Eu (0.66154260946)
185	I' = f u 13	I' = f u 13			I' = f u 13 (0.66154260946)

607

[illegible][illegible]

100-47488 12-2-61 6

FILM-WAX FLAME REGION MODELED AS ONE SECTION

253

FILED.MK) ** Range RND (M25..G307) WVL **
Age 37
FILED.MK) FLUME REGION MODELED AS ONE SECTION

	-A-	-B-		-C-		-D-		-E-	
300	|	|	|	|	|	|	|	|	|
301	|	|	|	|	|	|	|	|	|
302	|	|	|	|	|	|	|	|	|
303	|	|	|	|	|	|	|	|	|
304	|	|	|	|	|	|	|	|	|
305	|	|	|	|	|	|	|	|	|
306	|	|	|	|	|	|	|	|	|
307	|	|	|	|	|	|	|	|	|

```

FRILN.MK1 ** Range RAD (4129..6307) *VLE **
age 38
FRILN.MK1 FLAME REGION MODELED AS ONE SECTION
      -6-
129 IPRINT(RNDM) (32202)
130 |
131 |
132 |
133 I*FLF = |
134 I*ENL = |
135 I*ENL = |
136 I*ENL = |
137 I*Watts |
138 |
139 |
140 |
141 |
142 |
143 |
144 I*SUM(E143..E139)*ES (40565.38260765) |
145 |
146 |
147 |
148 |
149 |
150 |
151 |
152 I*SUM(E151..E146)*EN (-39623.04440461) |
153 |
154 |
155 |
156 I*SUM(E155..E154)*EG (-6104.24178883) |
157 |
158 |
159 |
160 |
161 |
162 |
163 |
164 |
165 I*E165*EF (-142433.3176775) |
166 |
167 I*E167 (-19199.51731661) |
168 I*E168 (4493.780679249) |
169 |
170 I*SUM(F168..F144) (-162280.1989821) |
171 |
172 |
173 |
174 |
175 |
176 |
177 |
178 |
179 |
180 |
181 I*SUM(E180..E175)*ES (-9277.160936659) |
182 |
183 |
184 |
185 |

```

FK11N.MK1 ** Range 180 18129.63071 *VRL **

Age 39

FK11N.MK1 FLAME REGION MODELED AS ONE SECTION

-f-

-6-

```
186 |
187 |
188 |
189 |
190 |
191 |
192 |
193 | (PSUM(E192..E183)*EM (472427.1047119) | *QAM*3.414 (1612866.135486)
194 |
195 |
196 | ""
197 |
198 | (PSUM(E197..E195)*EG (-23248.45635983) | *QAM*3.414 (-79370.23001246)
199 |
200 |
201 |
202 |
203 |
204 |
205 |
206 |
207 |
208 |
209 |
210 |
211 | *E211*EF (-507096.3850739) | *QFM*3.414 (-1731227.058642)
212 |
213 | *E213 (19199.51731661) | *F213*3.414 (65547.15211893)
214 | *E214 (33029.56344412) | *F214*3.414 (112762.9295982)
215 | *E215 (14927.61128344) | *F215*3.414 (50962.86492166)
216 |
217 | (PSUM(F215..F179) (-39.21852042004) | *QAM*3.414 (-133.892028714)
218 |
219 |
220 | (PRINT(RNDM) (32202)
221 |
222 |
223 |
224 |
225 |
226 | *E226*ES (-8929.722165155) | *QSE*3.414 (-30486.07147184)
227 |
228 |
229 |
230 |
231 |
232 |
233 |
234 | (PSUM(E233..E228)*EM (-92802.59797963) | *QME*3.414 (-316828.0695824)
235 |
236 |
237 |
238 |
239 |
240 |
241 | (PSUM(E240..E236)*EG (52503.0259763) | *QEG*3.414 (179245.3306831)
242 |
```

107 09-88 13:511 F

FKJ(LN,MK) ** Range RRD (R129..6307) *VFL **

age 4)

FKJ(LN,MK) FLARE REGION MODELED AS ONE SECTION

```

      |               -F-               |               -G-               |
243 |               |               |               |
244 |               |               |               |
245 |               |               |               |
246 |               |               |               |
247 |               |               |               |
248 |               |               |               |
249 |PSUM(E248..E243)*EF (-78322.45963568) |+OFF+3.414 (-267392.8771962) |
250 |               |               |               |
251 |+E251 (-4493.780679249) |+F251+3.414 (-15341.76723895) |
252 |+E252 (-33029.563444121) |+F252+3.414 (-112762.92959821) |
253 |+E253 (-33029.563444121) |+F253+3.414 (-112762.92959821) |
254 |PSUM(F252..F224) (-165073.6587062) |+OF+3.414 (-563561.470823) |
255 |               |               |               |
256 |               |               |               |
257 |POINT(RNOM) (32202) |               |
258 |               |               |               |
259 |               |               |               |
260 |               |               |               |
261 |               |               |               |
262 |               |               |               |
263 |               |               |               |
264 |               |               |               |
265 |               |               |               |
266 |PSUM(E265..E259)*ES (-22378.49950583) |+OFF+3.414 (-76400.19731292) |
267 |               |               |               |
268 |               |               |               |
269 |               |               |               |
270 |               |               |               |
271 |               |               |               |
272 |               |               |               |
273 |               |               |               |
274 |               |               |               |
275 |               |               |               |
276 |               |               |               |
277 |               |               |               |
278 |               |               |               |
279 |PSUM(E278..E268)*EW (-340001.4623277) |+OF+3.414 (-1160764.992386) |
280 |               |               |               |
281 |               |               |               |
282 |               |               |               |
283 |               |               |               |
284 |PSUM(E283..E281)*EE (-23150.32782764) |+OF+3.414 (-79035.21920358) |
285 |               |               |               |
286 |               |               |               |
287 |               |               |               |
288 |               |               |               |
289 |               |               |               |
290 |               |               |               |
291 |               |               |               |
292 |               |               |               |
293 |               |               |               |
294 |               |               |               |
295 |               |               |               |
296 |               |               |               |
297 |+E297*EF (27852.1623872) |+OFF+3.414 (2484887.282389) |
298 |+E298 (-342321.872726) |+F298+3.414 (1168686.873486) |
299 |PSUM(F298..F262) (342321.872726) |+OF+3.414 (1168686.873486) |

```

10/19/88 13:52 P

FRULMK1 ** Range T (A309..F344) *VAL **
 age 42
 FRULMK1 FLAME REGION MODELED AS ONE SECTION

-A-

```

309 |
310 |
311 |
312 |
313 |
314 |
315 |
316 |
317 |
318 |
319 |
320 |
321 |
322 |
323 |
324 |
325 |
326 |
327 |
328 |
329 |
330 |
331 |
332 |
333 |
334 | *TRgII = (- (Tfg+Tmg+Tsg) *Ehg*(Af+ABu+Am+ABs+As)) / (Ehg*(pw*Am*(Fuf+ABu*Fum+ABs*Fus)+ps*As*(Fs*(ABu*Fsu))) |
335 | * = |
336 |
337 | *TRgsII = |
338 | * = |
339 |
340 | *TRgml = |
341 | * = |
342 |
343 | *TRgfl = |
344 | * = |

```

-B-

```

|
| *CALCULATION OF GAS TRANSMISSIVITY FOR ITS OWN RADIATION
|
| *sg
| 12
| 13
| 14
|
|
| *mg
| 12
| 13
| 14
| 15
| 16
|
|
| *fg 1.00
| 12
| 13
| 14
| 15
| 16
|
|
| *
|
| * (- (TFG+TMG+TSG) *ENG*(Af+ABu+Am+ABs+As)) / (ENG*(Pw*Am*(Fuf+ABu*Fum+ABs*Fus)+PS*AS*(FSF+ABu*FSM))) (0.186977006897) |
|
| * (- (Tsg-ABs*Ehg*As)) / (ABs*(pw*Fus*Ehg*Am))
| IF (PA=0,0, (-TSG-ABS*ENG*AS) / (ABS*PA*(FUS*ENG*AM))) (0.187333376444)
|
| * (- (Tmg-ABu*Ehg*Am)) / ((pw*Fum+ps*Fs*As)*(ABu*ENG))
| (-TMG-ABU*ENG*AM) / ((PA*FUM+PS*FS*AS)*(ABU*ENG)) (0.186946345394)
|
| * (- (Tfg-Af*Ehg)) / ((pw*Fuf+ps*Fs*As)*(ENG))
| IF (FLF=0,0, (-TFG-AF*ENG) / ((PA*FUF+PS*FS*AS)*(ENG))) (0.186956514263)
|

```

FRILUM.MK1 ** Range 1 (R3)9...1344) *VRL **

age 43

FRILUM.MK1 FLAME REGION MODELLED AS ONE SECTION

```

1          -C-          |          -E-          |
309 |          |          |          |
310 |          |          |          |
311 | 1*-(1-TRgg1)*ENs*As | 1-(1-TRG61)*ENs*AS (-0.153516A08523) |
312 | 1*-(TRgg1-TRgg2)*Fsw*ps*ENs*As | 1-(TRG61-TRG62)*FSM*PW*ENs*AS (-0.001831367618) |
313 | 1*-(TRgg2-TRgg3)*Fsw*ps*ps*ENs*As | 1-(TRG62-TRG63)*FSM*PW*PS*ENs*AS (-0.000103681923) |
314 | 1*-(TRgg2-TRgg3)*Fsw*ps*ps*ENs*As | 1-(TRG62-TRG63)*FMS*PS*PW*ENs*AS (-0.000030659099) |
315 |          | 1ESUM(E314..E311) (-0.155482517164) |
316 |          |          |          |
317 | 1*-(1-TRgg1)*ENr*Am | 1-(1-TRG61)*ENr*AM (-0.583571185211) |
318 | 1*-(TRgg1-TRgg2)*Fsw*ps*ENr*Am | 1-(TRG61-TRG62)*FSM*PW*ENr*AM (-0.006193258236) |
319 | 1*-(TRgg2-TRgg3)*Fsw*ps*ps*ENr*Am | 1-(TRG62-TRG63)*FSM*PW*PS*ENr*AM (-0.000350620068) |
320 | 1*-(TRgg2-TRgg3)*Fsw*ps*ps*ENr*Am | 1-(TRG62-TRG63)*FMS*PS*PW*ENr*AM (-0.000116545979) |
321 | 1*-(TRgg2-TRgg3)*Fsw*ps*ps*ENr*Am | 1-(TRG62-TRG63)*FMS*PW*PS*ENr*AM (-0.000103681923) |
322 | 1*-(TRgg1-TRgg2)*Fsw*ps*ENr*Am | 1-(TRG61-TRG62)*FMS*PS*ENr*AM (-0.001831367618) |
323 |          | 1ESUM(E322..E317) (-0.592166667057) |
324 |          |          |          |
325 |          |          |          |
326 | 1*-(1-TRgg1)*ENf*Af | 1-(1-TRG61)*ENf*AF (-0.568413492089) |
327 | 1*-(TRgg1-TRgg2)*ps*Ffs*ENf*Af | 1-(TRG61-TRG62)*PS*FFS*ENf*AF (-0.004409135085) |
328 | 1*-(TRgg2-TRgg3)*ps*ps*Ffs*ENf*Af | 1-(TRG62-TRG63)*PS*PW*FFS*ENf*AF (-0.000280591924) |
329 | 1*-(TRgg1-TRgg2)*ps*Ffs*ENf*Af | 1-(TRG61-TRG62)*PW*FFS*ENf*AF (-0.015431972797) |
330 | 1*-(TRgg2-TRgg3)*ps*ps*Ffs*ENf*Af | 1-(TRG62-TRG63)*PW*PS*FFS*ENf*AF (-0.00025834812) |
331 | 1*-(TRgg2-TRgg3)*ps*ps*Ffs*ENf*Af | 1-(TRG62-TRG63)*PW*PW*FFS*ENf*AF (-0.00087367311) |
332 |          | 1ESUM(E331..E326) (-0.589667213117) |
333 |          |          |          |
334 |          |          |          |
335 |          |          |          |
336 |          |          |          |
337 |          |          |          |
338 |          |          |          |
339 |          |          |          |
340 |          |          |          |
341 |          |          |          |
342 |          |          |          |
343 |          |          |          |
344 |          |          |          |

```

07/07/85 11:25:15

FX11A.W1 ** Range 1 (03A..053) WRL 40

49 41

FX11A.W1 FLAME REGION MODELED AS ONE SECTION

LEGEND: f formula i Integer r Real

! Text Left ~ Text Center - Text Right \ Text

b blank

m macro

ACCTEHIJDUWDPQ

34 1b . . |

35 | *fb |

36 | |

37 | *f |

38 | *f |

39 | *f |

40 | |

41 | *bb . |

42 | b |

43 | *bb . |

44 | *bb . |

45 | *bb . |

46 | *bb . |

47 | |

48 | |

49 | f |

50 | f |

51 | f |

52 | f |

53 | f |

FKILN.MK1 ** Range 40 (12..,A128) *VAL **

age 46

FKILN.MK1 FLAME REGION MODELED AS ONE SECTION

LEGEND: F Formula . Integer * Real # macro b blank

' Text Left ~ Text Center * Text Right \ Repeat

A

```

UNITZABCDEFGHIJ
2 11111111111111111111
3 | ** ** ** ** |
4 | ** ** ** ** |
5 | .....|
6 1\^*\^*\^*\^*\^*\^|
7 1**FF*F.*F.*FF*FF1
8 1**FF*F.*F.*FF1
9 1**FF*FF*FF*FF*FF1
10 1**FF*FF*FF*FF*FF1
11 1**FF*FF*FF*FF*FF1
12 1**FF*F.*F.*FF*FF1
13 1**FF*F.*F.*FF*FF1
14 1**FF*F.*F.*FF*FF1
15 1**FF*F.*F.*FF*FF1
16 1*****F*F*F*F*F*F1
17 1*****F*F*F*F*F*F1
18 1 .....|
19 1**FF*FF*FF*FF*FF1
20 11111111111111111111
21 1**F *F *F *F *F 1
22 1**F *F *F *F *F 1
23 1**F *F *F *F *F 1
24 1**fb*fb*fb*fb*fb1
25 1**..b*.b*.b*.b1
26 1b**b**b**b**b1
27 1**fb*fb*fb*fb*fb1
28 11111111111111111111

```

LEGEND: F Formula . Integer + Real @ macro b blank
 ' Text Left ^ Text Center * Text Right \ Repeat

UNCLAS//~~FOUO~~

33 1. 1

34 ||||| • • •

35 16 ~~_____~~ of the 21

36 | 11 1'61'1

37 | Page • FBF-1

38 1800000 • F'6F'1

39 1°. FFFFF° F°BF°1

40 1°FFFFF° F°bF°1

41 1°.FFFFFF° F°BF°1

42 1".FFFFFF° F"BF"1

43 1°.FFFFF°6BF°BF°1

44 1°.FFFFFF° F°bF°I

45 1".JF1FFF" .fb.FI

46 1°.FFFFFFF° .Fb.FI

47 1°.FFFFF° .Fb,Fi

4B 1°FFFFFF° °°b°FI

49 1"FFFFFF"bb"" "F1

50 | ~~REDACTED~~ | 10b101

50 10FFFFFF * FF FF1

52 | b6b7c - F*F*F1

53 | b6 b7C "F "b5 |

50 |||||

FILENAME 00 Range CONST (ABS..J109) +WZ 00
48P 49
FILENAME FLOW REGION MODELO AS ONE SECTION
LEBNO: f Formula . Integer * Real m macro
 ' Test Left ^ Test Center * Test Right \ Repeat o blank

AC00000000
109 1111111111111111

PRINT:ARI 00 Range E (A109..E128) *VRL 00
Age 50
PRIMALVAL FLAME REGION MODELED AS ONE SECTION
LEBDO: F Formula Integer Real
 : Test Left Test Center Test Right Repeat b blank

RECODE

109	111A7A
110	1* F*F1
111	1* F*F1
112	1* F*F1
113	1* F*F1
114	1
115	1
116	1A
117	1*F1
118	1*F1
119	1*F1
120	1*F1
121	1*F1
122	1*F1
123	1F
124	1F
125	1F
126	1F
127	1F
128	1

```

FILM.MK1  00 Range FILA (1340..1032) +VRL 00
49F 51
FILM.MK1 FLAME REGION MODELED AS DIE SECTION
LEGEND:  f Formula      . Integer  + Real      = Macro      b Blank
          ' Text Left  - Text Center  * Text Right  \ Repeat

[RLJNDPQRSTU
340 1'  .  f'  *  f1
341 1'  .  .  .  .  .  *  f1
342 1'  .  .  .  .  .  *  f1
343 1'  .  .  .  .  .  *  f1
344 1'  .  .  .  .  .  *  f1
345 1'  .  .  .  .  .  *  f1
346 1'  .  .  .  .  .  *  f1
347 1'  .  .  .  .  .  *  f1
348 1'  .  .  .  .  .  *  f1
349 1'  .  .  .  .  .  *  f1
350 1'  .  .  .  .  .  *  f1
351 1'  .  .  .  .  .  *  f1
352 1'  .  .  .  .  .  *  f1
353 1'  .  .  .  .  .  *  f1
354 1'  .  .  .  .  .  *  f1
355 1'  .  .  .  .  .  *  f1
356 1'  .  .  .  .  .  *  f1
357 1'  .  .  .  .  .  *  f1
358 1'  .  .  .  .  .  *  f1
359 1'  .  .  .  .  .  *  f1
360 1'  .  .  .  .  .  *  f1
361 1'  .  .  .  .  .  *  f1
362 1'  .  .  .  .  .  *  f1

```

```

FILM.WK1  ** Range F1A1 (V341..AGJ56) v9L **
age 52

```

(07-10-88 13:57) P

```

FILM.WK1 FLAME REGION MODELED AS ONE SECTION

```

```

LEGEND: F Formula      . Integer      * Real      # macro      b blank
         ' Text Left    ^ Text Center  " Text Right  \ Repeat

```

```

      A
      WXYZABCDEFG
341 | . ' " |
342 | *F*F *F*F*F|
343 | ** * ** *|
344 | ' ** " ** -|
345 | " * ** * *|
346 |F*FFFF*FFFF:
347 |F*FFFF*FFFF|
348 |F*FFFF*FFFF|
349 |F*FFFF*FFFF|
350 | \ \ \ \ \ \
351 |F F FF F F|
352 | * F * F |
353 | *F*F *F*F|
354 |b* F*F * F*F|
355 |b* F * F |
356 |//////////|

```

FXILNWK1 00 Range H (L292..W340) +VRL 00
age 33

FXILNWK1 FLAME REGION MODELED AS ONE SECTION

LEGEND: F Formula . Integer * Real m macro b blank
 ! Text Left ^ Text Center * Text Right \ Repeat

UNDERSTAND

```

292 I"  * ** I
293 I\  ****F *FI
294 I".*Fb* ** *I
295 I".*FFF* ** *I
296 I".*FFF* * *I
297 I b*FFF*FFFFI
298 I".*FFF*FFFFI
299 I".*FFF*FFFFI
300 I"F*FFF*FFFFI
301 I"F*F*F* \ \ I
302 I".*F*F* F FI
303 I". *F** F I
304 I"F *F* *F*FI
305 I *F ** F*FI
306 I" ** F I
307 I\ \  * ** I
308 I" F  * I
309 I" F  * ***I
310 I" F  * ***I
311 I  * ***I
312 I"F * . * ***I
313 I"F b * \ \ \ \ \ I
314 I"F b ** I
315 I"F **F *FI
316 I"Fb b * ** *I
317 I"F  * ** *I
318 I"F  * * *I
319 I  F*FFFFI
320 I" F*FFFFI
321 I\ \  bF*FFFFI
322 I"F* bF*FFFFI
323 I"Fb b* \ \ I
324 I"Fb b* F FI
325 I"F b** F I
326 I"F* b* *F*FI
327 I\ \ * b** F*FI
328 I"F b** F I
329 I  b* *** I
330 I \ \ \ \ \ \ \ I
331 I  ***I
332 I" F ***I
333 I" b ***I
334 I" F ***I
335 I" F  I
336 I" F  * .I
337 I" F  * FI
338 I" F  * FI
339 I \ \ \ \ \ \ \ \ \ \ I
340 I". F* * F I

```

(07-03) 88 1:5:5d) 1

FILENAME 00 Range 000 00123.0000 000
age 54
FILENAME FILE REGION MODELED AS ONE SECTION
LEGEND: F Formula I Integer R Real
 L Left C Center R Right b blank
 e echo \ Repeat

RESULTS

129 1.1 F 1
130 1.1 bl
131 1.1 I
132 1.1 I
133 1.1 F1
134 1.1 F1
135 1.1 F1
136 1.1 F1
137 1.1 F1
138 1.1 I
139 1.1 F 1
140 1.1 F 1
141 1.1 F 1
142 1.1 F 1
143 1.1 F 1
144 1.1 F1F1
145 1.1 b 1
146 1.1 F 1
147 1.1 F1F1
148 1.1 F 1
149 1.1 F 1
150 1.1 F 1
151 1.1 F 1
152 1.1 F1F1
153 1.1 I
154 1.1 F 1
155 1.1 F 1
156 1.1 F1F1
157 1.1 I
158 1.1 F 1
159 1.1 F 1
160 1.1 F 1
161 1.1 F 1
162 1.1 F 1
163 1.1 F 1
164 1.1 F 1
165 1.1 F1F1
166 1.1 I
167 1.1 F1F1
168 1.1 F1F1
169 1.1 I
170 1.1 F1
171 1.1 I
172 1.1 F 1
173 1.1 F1F1
174 1.1 I
175 1.1 F 1
176 1.1 F 1
177 1.1 F1F1
178 1.1 F 1
179 1.1 F 1
180 1.1 F 1
181 1.1 F1F1
182 1.1 b 1

PRILMNH ** Range 880 (0125..6307) *VRL **

app 55

PRILMNH FLOWE REGION MODELED AS ONE SECTION

LEEND: F Formula * Integer * Real

 * Test Left ^ Test Center * Test Right

m macro

\ Repeat

b blank

AB00376

183 1''' F I
184 1'' F I
185 1'' F I
186 1'' F I
187 1'' F I
188 1'' F I
189 1'' F I
190 1'' F I
191 1'' F I
192 1'' F I
193 1' FFF
194 1 b
195 1''' F I
196 1'' F I
197 1'' F I
198 1' FFF
199 1
200 1''' F I
201 1'' F I
202 1'' F I
203 1'' F I
204 1'' F I
205 1'' F I
206 1'' F I
207 1'' F I
208 1'' F I
209 1'' F I
210 1'' F I
211 1' FFF
212 1
213 1'' FFF
214 1'' FFF
215 1'' FFF
216 1 \ I
217 1' FFI
218 1
219 1'
220 1''' F I
221 1
222 1''' F I
223 1'' F I
224 1'' F I
225 1'' F I
226 1' FFF
227 1
228 1''' F I
229 1'' F I
230 1'' F I
231 1'' F I
232 1'' F I
233 1'' F I
234 1' FFI
235 1
236 1''' F I

FRILANKI ** Range RAD 1A129..G3071 +VAL **

age 56

FRILANKI FLAME REGION MODELED AS ONE SECTION

LEGEND: F Formula . Integer * Real @ macro b blank
! Test Left ^ Test Center * Test Right \ Repeat

ABCD/6
237 | . F |
238 | . F |
239 | . F |
240 | ! F |
241 | FFF |
242 | b |
243 | ! F |
244 | . F |
245 | . F |
246 | . F |
247 | . F |
248 | . F |
249 | FFF |
250 | |
251 | ! FFF |
252 | ! FFF |
253 | \ |
254 | ! F |
255 | |
256 | ! |
257 | ! F |
258 | |
259 | ! F |
260 | . F |
261 | ! F |
262 | . F |
263 | . F |
264 | . F |
265 | . F |
266 | FFF |
267 | |
268 | ! F |
269 | . F |
270 | . F |
271 | ! F |
272 | . F |
273 | . F |
274 | . F |
275 | . F |
276 | . F |
277 | . F |
278 | . F |
279 | FFF |
280 | |
281 | ! F |
282 | . F |
283 | ! F |
284 | FFF |
285 | |
286 | ! F |
287 | . F |
288 | . F |
289 | ! F |
290 | . F |

(07-09-88 11:58) P

REC'D

291	1	F	1
292	1	F	1
293	1	F	1
294	1	F	1
295	1	F	1
296	1	F	1
297		FF	1
298	1		111
299			FF
300			1
301	1		11111
302	1		1
303	1		FF
304	1		FF
305	1		FF
306	1		FF
307			11111

FRILN.WK1 ** Range 1 (A301..F344) «VWL»
 age 58

10/03/88 13:59:11

FRILN.WK1 FLAME REGION MODEL CD AS ONE SECTION

LEGEND: F Formula . Integer + Real @ macro b blank
 ! Text Left ^ Text Center * Text Right \ Repeat

ABCODEF
 309 | * |
 310 | |
 311 | ** F |
 312 | , F |
 313 | , F |
 314 | , F |
 315 | F |
 316 | b |
 317 | ** F |
 318 | , F |
 319 | , F |
 320 | , F |
 321 | , F |
 322 | , F |
 323 | F |
 324 | b |
 325 | b |
 326 | ** F |
 327 | , F |
 328 | , F |
 329 | , F |
 330 | , F |
 331 | , F |
 332 | F |
 333 | |
 334 | * |
 335 | * F |
 336 | |
 337 | ** |
 338 | * F |
 339 | b |
 340 | ** |
 341 | * F |
 342 | b |
 343 | ** |
 344 | * F |

Appendix F

Program Listing for Indirect Direct Fired Kiln

V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ
1																					
2																					
3	(4)		(5)		(6)		(7)		(8)		(9)		(10)								
4	WASTE TO CHAMBER		PYROLYSIS PRODUCTS		SOLIDS OUT BOTTOM		TOTAL AIR		AIR TO BURNER		AIR TO CHAMBER		COMBUSTION PRODUCTS								
5	LB/HR LB-M/HR		LB/HR LB-M/HR		LB/HR LB-M/HR		LB/HR LB-M/HR		LB/HR LB-M/HR		LB/HR LB-M/HR		LB/HR LB-M/HR								
6																					
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	223.84	5.09		
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	PYRO GAS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O2	256.94	8.03	256.94	8.03	0.00	0.00	0.00	0.00	23.36	0.73		
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	N2	850.71	30.38	850.71	30.38	0.00	0.00	0.00	0.00	830.71	30.38		
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	WATER	11.08	0.62	11.08	0.62	0.00	0.00	0.00	0.00	90.58	5.03		
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	HCL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	SO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00		
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	HBR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	HF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
16	0.00	----	0.00	----	0.00	----	0.00	----	SALT	----	----	----	----	----	----	----	----	0.00	----		
17	0.00	----	0.00	----	0.00	----	0.00	----	ASH	----	----	----	----	----	----	----	----	0.00	----		
18																					
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	TOTAL	1118.73	39.03	1118.73	39.03	0.00	0.00	0.00	0.00	1188.73	41.24		
20																					
21			0						SCFM	247		247		0				261			
22			0						ACFM	247		247		0				1335			
23	ERR		2201		60				TEMP F	60		60		60				2201			
24	0.000		0.000		0.000				ENTHALPY	0.012		0.012		0.000				0.839			
25	0.000		0.000		0.000				HEAT REL	0.000		0.000		0.000				0.000			
26																					
27	0.000		0.000		0.000				MB BTU/HR	0.012		0.012		0.000				0.839			
28																					
29																					
30	TOTAL				OFF-GAS		ASH		OUT		HEAT OF PYROLYSIS		HEAT LOSS		TOTAL		HEAT IN				
31	1.355				0.839		0.000		0.000		0.000		1.164		2.003		-0.648				
32																					
33																					
34	TEMPLATE 8		COMPONENT HEAT BALANCE		BTU/HR																
35																					
36			(5)		(7)		(8)		(9)		(10)		(11)								
37			PYROLYS		TOTAL		AIR TO		AIR TO		COMBUST		TOTAL OFF								
38	C		PRODUCTS		AIR		BURNER		CHAMBER		PRODUCTS		GAS								
39																					
40	-0.00	CO2	CO2	0	0	0	0	0	133555	133555											
41	-0.00	PYRO GAS		0	0	0	0	0	0	0											
42	-0.00	O2	O2	0	0	0	0	0	13255	13255											
43	-0.00	N2	N2	0	0	0	0	0	494004	494004											
44	-0.00	H2O	WATER	0	11741	11741	0	0	198146	198146											
45	-0.00		HCL	0	0	0	0	0	0	0											
46	-0.00		SO2	0	0	0	0	0	109	109											
47	-0.00		HBR	0	0	0	0	0	0	0											
48	0.00		HF	0	0	0	0	0	0	0											
49			SALT	0	0	0	0	0	0	0											
50			ASH	0	0	0	0	0	0	0											
51																					
52			TOTAL	0	11741	11741	0	0	839069	839069											
53																					
54																					
55																					

	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ
1										
2										
3			(11)							
4	PRODUCTS		TOTAL OFF-GAS							
5	LB-M/HR		LB/HR	LB-M/HR						
6	-----		-----	-----						
7	5.09		223.84	5.09						
8	0.00		0.00	0.00						
9	0.73		23.36	0.73						
10	30.38		850.71	30.38						
11	5.03		90.58	5.03						
12	0.00		0.00	0.00						
13	0.00		0.24	0.00						
14	0.00		0.00	0.00						
15	0.00		0.00	0.00						
16	----		0.00	----						
17	----		0.00	----						
18	-----		-----	-----						
19	41.24		1188.73	41.24						
20	-----		-----	-----						
21			261							
22			1335							
23			2201							
24			0.839							
25			0.000							
26			-----							
27			0.839							
28	-----		-----	-----						
29	HEAT IN - HEAT OUT		-----							
30										
31	-0.648									
32										
33										
34	@sum({Up},{End}{Up})"									
35										
36	/c".{End}{Down}"									
37										
38	/c"(Right){Right}"(Right){Right}{Edit}{Home}{Del}"(Left){Left}"									
39										
40	IRg{?}									
41										
42	o \w									
43	ppq									
44			all s							
45	agrCONST2"	ALT R	/ppqx"agppq							
46										
47			ALT I							
48	gppq		/PPRI"AGLLRII"CPPQ							
49										
50										
51	pq									
52	gppq									
53	agrCONST2"AGppq									
54										
55										


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AQ      AR      AS      AT      AU      AV      AW      AX      AY      AZ
-----
56
57 {GoTo}xx~/lcccx~{PgDn}\~/c~ {Right}{Right}{Right}{Right}{Right}{Right}{Right}{Right}{Right}{Down}/rnx~"/rncx~" {GoTo}xqst~{Left}{End}{Down}{Right}{End}{Up}{Down}{?}-QS*3 414~/?~ {GoTo}c~{Right}{Right}{Down}
58
59
60 Down{Down}{Down}{Down}{Down}/rncy~{Bs}. {Right}{Right}{Right}{Right}{Right}{Right}{Right}{Right}{Right}{Right}{Right}{Right}{End}{Down}{Left}{Left}{End}{Up}{Right}{?}/ppry~agppq~ {GoTo}c~
61
62 rnx~"/PgUp){Up}{?}/rncx~" {GoTo}c~{Right}{Right}{Down}{Down}{Down}{Down}
63
64
65 =      70.00
66 I 355      HEAT OUT =      1.481      DELTA H = -0.126J
67 LL GAS -----OUTSIDE COMBUSTION GAS -----
68 T. F      T. K      OLD Ig      1.760      T. F      T. K |
69 603      590.0      400.0 Ig =      2.101      1422.2 |
70 1.144      891.0      Two =      1.701      1200.1 |
71 1.340      999.9 |      Tw =      1.547      1114.7 |
72 157      87.20 | <==      Tsh =      293      418.0 |
73 |      <==      87.2 |
74 207      114.76 |      999.88 <=== Tw |
75 1588.32 {104.884}|
76 {77.384}|      Qwo = 0      {19}|
77 = Qg+Qs == 182.268 °      Qwi = Qcdw+Q = Qw {182.179}|
78 w = Qw 182.268 °      Qgo =      199.330 |
79 Qg = 0      0 |      Qcdwosh =      17.132 |
80 601      588.84 °      Qwi + Qwo + Qgo =      17.132 |
81 1.146      891.68 °      hcvws =      566.00 |
82 1200.60      922.56 |
83 340      188.84 |      Tsho check. K =      418.51 |
84 55      30.54 |      Tw-Tg =      410 |
85 -----
86 =      70.00
87 I 355      HEAT OUT =      1.503      DELTA H = -0.1486
88 LL GAS -----OUTSIDE COMBUSTION GAS -----
89 T. F      T. K      OLD Ig      1.760      T. F      T. K |
90 824      713.0      588.0 Ig =      2.101      1422.2 |
91 1.067      848.0      Two =      1.688      1193.0 |
92 1.310      983.0 |      Tw =      1.524      1101.8 |
93 168      93.10 | <==      Tsh =      293      418.0 |
94 |      <==      93.1 |
95 214      118.78 |      983.08 <=== Tw |
96 1588.32 {70.948}|
97 {117.705}|      Qwo = 0      44 |
98 = Qg+Qs == 188.653 °      Qwi = Qcdw+Q = Qw {188.922}|
99 w = Qw 188.653 °      Qgo =      205.855 |
100 Qg = 0      {0}|      Qcdwosh =      16.977 |
101 826      714.31 °      Qwi + Qwo + Qgo =      16.977 |
102 1.062      845.23 °      hcvws =      566.00 |
103 1145.63      892.02 |
104 226      125.47 |      Tsho check. K =      417.56 |
105 139      76.99 |      Tw-Tg =      270 |
106 -----
107 =      70.00
108 I 355      HEAT OUT =      1.546      DELTA H = -0.1912
109 LL GAS -----OUTSIDE COMBUSTION GAS -----
110 T. F      T. K      OLD Ig      1.760      T. F      T. K |

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	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ
111	941	778 0	714 3	Igo =	2.101	1422.2				
112	943	779 0		Iw =	1.663	1179.3				
113	1 249	949 2		Iw1 =	1.478	1076.1				
114	190	105 10	I <=	Ish =	288	415.0				
115			I <=	105.3						
116	228	126 94		949 19	<=	Iw				
117	1588 32	(137 943)								
118		(163.678)		Qw = 0		10				
119	Qg+Qs =	201.621		Qw1 = Qcdw1w = Qw		(201.612)				
120	w1 = Qw	201.621		Qgo =		218.345				
121	Qg = 0	(0)		Qcdwosh =		16.743				
122	946	780 79		Qw1 = Qw0 + Qgo =		16.743				
123	946	780 64		hcvws =	566.00					
124	1062 02	845 56								
125	120	66 48		Tsho check. K =		416.33				
126	255	141 59		Iw-Ig =		171				
127										
128		70.00								
129	1 355	HEAT OUT =	1 598	DELTA H =	-0 2435					
130	LL GAS		OUTSIDE COMBUSTION GAS							
131	T. F	T. K	OLD Ig	1.760	T. F	T. K				
132	984	802 0	780 8	Igo =	2.101	1422.2				
133	801	700 0		Iw =	1.633	1162.2				
134	1 171	905 6		Iw1 =	1.417	1042.4				
135	220	122 30	I <=	Ish =	288	415.0				
136			I <=	122.3						
137	246	136 80		905 60	<=	Iw				
138	1588.32	(12.349)								
139		(204.927)		Qw = 0		13				
140	Qg+Qs =	217.276		Qw1 = Qcdw1w = Qw		(217.287)				
141	w1 = Qw	217.275		Qgo =		233.643				
142	Qg = 0	(0)		Qcdwosh =		16.369				
143	985	802 35		Qw1 = Qw0 + Qgo =		16.369				
144	800	699 76		hcvws =	566.00					
145	945.75	780.97								
146	39	21.56		Tsho check. K =		414.04				
147	408	222.46		Iw-Ig =		104				
148										
149		70.00								
150	1 355	HEAT OUT =	1 664	DELTA H =	-0 3096					
151	LL GAS		OUTSIDE COMBUSTION GAS							
152	T. F	T. K	OLD Ig	1.760	T. F	T. K				
153	964	790.6	802.4	Igo =	2.101	1422.2				
154	626	603.0		Iw =	1.593	1140.1				
155	1.063	846.0		Iw1 =	1.332	995.3				
156	266	147.70	I <=	Ish =	288	415.0				
157			I <=	147.7						
158	269	149.31		845.99	<=	Iw				
159	1588 32	6.417								
160		(243 565)		Qw = 0		7				
161	Qg+Qs =	237.148		Qw1 = Qcdw1w = Qw		(237.131)				
162	w1 = Qw	237.148		Qgo =		253.006				
163	Qg = 0	(0)		Qcdwosh =		15.882				
164	965	791.13		Qw1 = Qw0 + Qgo =		15.882				
165	627	603.64		hcvws =	566.00					

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
166 Qs => Qm					-0.5360	15.4551	(18.623)			Qm => Qm				-2.7572	(237.842)	(811.992)				
167																				
168 lg	s3	-ABS*lg*As			-0.397					lgo	w3	-ABw*lg*Aw		-0.6107						
169		2.00 -ABS*fsw*pm*TRg11*lg*			-0.018							2.00 -ABw*fsw*pm*TRg11		-0.0616						
170 Qs => Qg					-0.415	(3.998)	(13.648)			Qm => Qg				-0.6724	(181.817)	(620.722)				
171																				
172	hcvws	+hcvws*(THrad*D/2)*(f			318489	(318.489)	*****			hcvws	+hcvws*(THrad*D/2)*(f	hw-Tw			(0)	0				
173	hcvgs	+hcvgs*As*(Tg-Ts)			22575	(22.575)	(77.072)			hcvgs	+hcvgs*Aw*(Tg-Tw)			17842	(17.842)	(60.914)				
174														17842	*****					
175 Qs =>						(350.134)	*****			Qm =>					(325.507)	(1.111.281)				
176																				
177													5.7374	1.0000	7.4311					
178 Qw					1.00					Qw			5.7374	0.7721	5.7374					
179																				
180																				
181 w1		-ABw*TRgs1*fsw*ems*As			-0.5110					w1		-ABw*TRgwi1*fsw*em		-2.4315						
182		2.00 -ABw*TRgs2*fsw*fsw*pm*			-0.0882							2.00 -ABw*TRgwi2*fsw*fsw		-0.1019						
183 ls		3.00 -ABw*TRgs3*fsw*fsw*fsw			-0.0182					lwi		3.00 -ABw*TRgwi3*fsw*fsw		-0.0043						
184		4.00 -ABw*TRgs3*fsw*fsw*fsw			-0.0074							4.00 -ABw*TRgwi3*fsw*fsw		-0.0956						
185		5.00 -fsw*TRgs3*fsw*fsw*fsw			-0.0055							5.00 -fsw*TRgwi3*fsw*fsw		-0.0002						
186		6.00 -2*fsw*TRgs3*fsw*fsw*fsw			-0.0045							6.00 -2*fsw*TRgwi3*fsw*fsw		-0.0109						
187 Qm => Qs					-0.6347	(251)	(857)			Qm => Qm				-2.6444	(80.430)	(274.587)				
188																				
189 w2		+Em*Aw			2.983					w2		+Em*Aw		5.9449						
190 lwi		2.00 -ABw*TRgwi1*fsw*em*Aw			-0.894					lwi		2.00 -ABw*TRgwi1*fsw*em		-0.8550						
191 f * fsw		3.00 -ABw*TRgwi2*fsw*fsw*pm*			-0.136					f * fsw		3.00 -ABw*TRgwi2*fsw*fsw		-0.0357						
192		4.00 -ABw*TRgwi2*fsw*fsw*pm*			-0.056							4.00 -ABw*TRgwi2*fsw*fsw		-0.7961						
193		5.00 -ABw*TRgwi3*fsw*fsw*fsw			-0.033							5.00 -ABw*TRgwi3*fsw*fsw		-0.0015						
194		6.00 -2*ABw*TRgwi3*fsw*fsw*fsw			-0.027							6.00 -2*ABw*TRgwi3*fsw*fsw		-0.0671						
195		7.00 -fsw*TRgwi3*fsw*fsw*fsw			-0.010							7.00 -fsw*TRgwi3*fsw*fsw		-0.0001						
196		8.00 -2*fsw*TRgwi3*fsw*fsw*fsw			-0.008							8.00 -2*fsw*TRgwi3*fsw*fsw		-0.0038						
197		9.00 -fsw*TRgwi3*fsw*fsw*fsw			-0.004							9.00 -fsw*TRgwi3*fsw*fsw		-0.0019						
198		10.00 -fsw*TRgwi3*fsw*fsw*fsw			-0.002							10.00 -fsw*TRgwi3*fsw*fsw		-0.0426						
199 Qm => Qm					1.812	18.444	62.967			Qm => Qm				4.1410	357.213	1.219.525				
200																				
201 lg	w3	-ABw*lg*Aw			-1.157					lgo	w3	-ABw*lg*Aw		-0.9041						
202		2.00 -ABw*fsw*pm*TRg11*lg*			-0.037							2.00 -ABw*fsw*pm*TRg11		-0.0208						
203		3.00 -ABw*fsw*pm*TRg11*lg*			-0.011							3.00 -ABw*fsw*pm*TRg11		-0.1057						
204 Qm => Qg					-1.205	(11.604)	(39.617)			Qm => Qg				-1.0305	(278.656)	(951.330)				
205																				
206	hcvws	+hcvws*(THrad*D/2)*(f			318489	318.489	*****			hcvws	+hcvws*(THrad*D/2)*(f	hw-Tw		0		0				
207	hcvgw	+hcvgw*Aw*(Tg-Tw)			-379	379				hcvgw	+hcvgw*Aw*(Tg-Tw)			13642	(13.642)					
208	hcdwsh	+hcdwsh*((Aw*Aw)/2)*(			-325456	*****	NOT ADDED			hcdwsh	+hcdwsh*Aw*(Tg-Tw)			15522	15.522					
209														29165	*****					
210 Qm =>						325.457	*****			Qm =>					7	25				
211																				
212 Qg										Qg										
213																				
214																				
215 ls	g1	-(1-TRgs1)*fsw*ems*As			-0.293					lwi	g1	-(1-TRgwi1)*fsw*em		-0.9767						
216		2.00 -(TRgs1-TRgs2)*fsw*pm*			-0.039							2.00 -(TRgwi1-TRgwi2)*fsw		-0.0492						
217		3.00 -(TRgs2-TRgs3)*fsw*fsw			-0.001							3.00 -(TRgwi2-TRgwi3)*fsw		-0.0019						
218		4.00 -(TRgs2-TRgs3)*fsw*fsw			-0.000							4.00 -(TRgwi2-TRgwi3)*fsw		-0.0099						
219 Qg => Qs					-0.333	(132)	(450)			Qg => Qm				-1.0378	(31.564)	(107.759)				
220																				

	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP
166																					OLD TS =
167 H2O1W	500.00	1000.00	1500.00	2000.00	2500.00	3000.00	3500.00	*****	750.00												DEL Tg. K
168 a	0.13	0.08	0.06	0.04	0.03	0.02	0.01	0.01	0.09												DEL TS. K
169 b	0.30	0.29	0.27	0.22	0.20	0.16	0.15	0.12	0.29												-----
170 c	-0.08	-0.08	-0.07	-0.05	-0.05	-0.04	-0.04	-0.03	-0.08												PAUX LB/Hr
171																					HEAT IN =
172	Y=EMg	X=I																			INSIDE SHE
173 L=	0.23		Y=EMg	X=I	X^2	X^3	X^4	XV	X^2V	N		A =	0.00	X=I	Y calc	Y act=Eq					
174 500.00	0.19	500.00	0.19	500.00	*****	95.40	47699.99	1.00				B =	-0.00	500.00	0.18	0.19					Tg =
175 750.00	0.16	750.00	0.16	750.00	*****	117.11	87810.49	1.00				C =	4400.00	1000.00	0.15	0.14					TS =
176 1000.00	0.14	1000.00	0.14	1000.00	*****	141.39	*****	1.00				D =	0.19	1500.00	0.12	0.12					Tw =
177 1500.00	0.12	1500.00	0.12	1500.00	*****	175.94	*****	1.00				E =	*****	2000.00	0.09	0.09					Two-Tw =
178 2000.00	0.09	2000.00	0.09	2000.00	*****	184.50	*****	1.00						2500.00	0.07	0.07					
179 2500.00	0.07	2500.00	0.07	2500.00	*****	175.04	*****	1.00				a =	0.22	3000.00	0.05	0.05					Twl-Tw =
180 3000.00	0.05	3000.00	0.05	3000.00	*****	163.38	*****	1.00				b =	-0.00	3500.00	0.04	0.04					Qg = 0
181 3500.00	0.04	3500.00	0.04	3500.00	*****	147.41	*****	1.00				c =	0.00	4000.00	0.03	0.03					QS =
182 4000.00	0.03	4000.00	0.03	4000.00	*****	132.21	*****	1.00						1999.09	0.09						Qw' = Qcd
183																					Qcdw = Q
184 500.00			0.90	18750.00	*****					9.00											QS = Qw' =
185			Y	X	X#2	X#3	X#4	XV	X#2V	N											NW Tg =
186																					NW TS =
187																					OLD TS =
188 CO2I	500.00	1000.00	1500.00	2000.00	2500.00	3000.00	3500.00	*****													DEL Tg. K
189																					DEL TS. K
190 a	0.08	0.07	0.08	0.07	0.06	0.04	0.04	0.03													-----
191 b	0.11	0.10	0.10	0.12	0.11	0.10	0.08	0.07													PAUX LB/Hr
192 c	-0.03	-0.03	-0.03	-0.03	-0.03	-0.02	-0.02	-0.02													HEAT IN =
193																					INSIDE SHE
194	Y=EMg	X=I																			
195 L=	0.23		Y=EMg	X=I	X^2	X^3	X^4	XV	X^2V	N		A =	0.00	A =	0.00	X=I	Y calc	Y act=Eq			Tg =
196 500.00	0.11	500.00	0.11	500.00	*****	53.89	26942.90	1.00				B =	-0.00	B =	-0.00	500.00	0.11	0.11			TS =
197 1000.00	0.09	1000.00	0.09	1000.00	*****	87.63	87633.53	1.00				C =	2500.00	C =	6500.00	1000.00	0.09	0.09			Tw =
198 1500.00	0.10	1500.00	0.10	1500.00	*****	146.23	*****	1.00				D =	0.10	D =	0.15	1500.00	0.09	0.10			Two-Tw =
199 2000.00	0.10	2000.00	0.10	2000.00	*****	192.02	*****	1.00				E =	*****	E =	*****	2000.00	0.10	0.10			
200																					Twl-Tw =
201 500.00			0.39	5000.00	*****	479.78	*****	4.00				a =	0.13	a =	0.18	3000.00	0.07	0.07			Qg = 0
202			Y	X	X#2	X#3	X#4	XV	X#2V	N		b =	-0.00	b =	-0.00	3500.00	0.05	0.05			QS =
203												c =	0.00	c =	0.00	4000.00	0.04	0.04			Qw = Qcd
204 L=	0.23		Y=EMg	X=I	X^2	X^3	X^4	XV	X^2V	N											Qcdw = Q
205 2500.00	0.08	2500.00	0.08	2500.00	*****	201.85	*****	1.00													QS = Qw' =
206 3000.00	0.07	3000.00	0.07	3000.00	*****	197.23	*****	1.00													NW Tg =
207 3500.00	0.05	3500.00	0.05	3500.00	*****	183.79	*****	1.00													NW TS =
208 4000.00	0.04	4000.00	0.04	4000.00	*****	164.15	*****	1.00													OLD TS =
209																					DEL Tg. K
210 500.00			0.24	13000.00	*****	747.02	*****	4.00													DEL TS. K
211			Y	X	X#2	X#3	X#4	XV	X#2V	N											-----
212																					PAUX LB/Hr
213																					HEAT IN =
214 H2O2S	500.00	1000.00	1500.00	2000.00	2500.00	3000.00	3500.00	*****	750.00												INSIDE SHE
215 a	0.13	0.08	0.06	0.04	0.03	0.02	0.01	0.01	0.09												Tg =
216 b	0.30	0.29	0.27	0.22	0.20	0.16	0.15	0.12	0.29												TS =
217 c	-0.08	-0.08	-0.07	-0.05	-0.05	-0.04	-0.04	-0.03	-0.08												Tw =
218																					Two-Tw =
219	Y=EMg	X=I																			
220 L=	0.35		Y=EMg	X=I	X^2	X^3	X^4	XV	X^2V	N		A =	0.00	X=I	Y calc	Y act=Eq					

	AQ	AR	AS	AT	AU	AV	AW	AX	AZ
166	800.17	700.10							
167	1201	-11.22							
168	573	318.58							
169									
170		70.00							
171	1.355	HEAT OUT =	1.737						
172	11 GAS								
173	1	1	1	1	1	1	1	1	1
174	901	756.0	791.1	190 =	2.101	1422.2			
175	430	494.0		190 =	1.548	1115.0			
176	933	773.5		191 =	1.226	936.4			
177	328	182.30	<==	15h =	279	410.0			
178			<==	182.3					
179	293	162.89		773.52	<==	1w			
180	1588.32	19.417							
181		(278.136)		Qw0 = 0		50			
182	QU-QS ==	258.719		Qw1 = Qcdw1w = Qw	(258.838)				
183	w1 = Qw	258.719		Qq0 =	274.232				
184	Qq = 0	0		Qcdwosh =	15.444				
185	903	757.00		Qw1 = Qw0 + Qq0 =	15.444				
186	430	493.86		hcvws =	566.00				
187	627.15	603.97							
188	(61)	-34.13		fsno check. K =	408.62				
189	771	428.35		1w-1g =	18				
190									
191		70.00							
192	1.355	HEAT OUT =	1.815						
193	11 GAS								
194	1	1	1	1	1	1	1	1	1
195	811	706.0	757.0	190 =	2.101	1422.2			
196	212	373.0		190 =	1.502	1089.9			
197	780	688.3		191 =	1.099	865.7			
198	412	228.70	<==	15h =	271	406.0			
199			<==	228.7					
200	319	177.43		688.37	<==	1w			
201	1588.32	28.646							
202		(310.462)		Qw0 = 0		(29)			
203	QU-QS ==	281.816		Qw1 = Qcdw1w = Qw	(281.997)				
204	w1 = Qw	281.815		Qq0 =	297.006				
205	Qq = 0	(0)		Qcdwosh =	14.980				
206	812	706.29		Qw1 = Qw0 + Qq0 =	14.980				
207	213	373.33		hcvws =	566.00				
208	433.14	496.19							
209	(91)	-50.71		fsno check. K =	405.93				
210	0	0.00		1w-1g =	-18				
211									
212		70.00							
213	1.355	HEAT OUT =	1.818						
214	11 GAS								
215	1	1	1	1	1	1	1	1	1
216	747	670.0	706.3	190 =	2.101	1422.2			
217	212	373.0		190 =	1.501	1088.9			
218	773	684.6		191 =	1.093	862.7			
219	415	230.80	<==	15h =	271	406.0			
220			<==	230.8					

	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ

221	321	178.09		684.62	====	Tw				
222	1588.32	20.726								
223		(303.595)		Qwo = 0					(23)	
224	= Qg+Qs ==	282.669 *		Qwi = Qcdwim = Qw		(282.899)				
225	wi = Qw	282.868 *		Qgo =		297.881				
226	Qg = 0	(0)		Qcdwosh =		14.959				
227	74b	669.41 *		Qwi + Qwo + Qgo =		14.959				
228	213	373.33 *		hcvws =		566.00				
229	428.2b	493.48								
230	(66)	-3b.88		Tsho check. K =		405.79				
231	0	0.00		Tw-Tg =		15				
232	-----									
233	=	70.00								
234	I.355		HEAT OUT =	1.820		DELTA H =	-0.4650			
235	LI GAS		-----OUTSIDE COMBUSTION GAS-----							
236	T. F	T. K	OLD Tg	1.760	T. F	T. K				
237	698	643.0	669.4	Tgo =	2.101	1422.2				
238	212	373.0		Two =	1.499	1088.1				
239	768	682.0		Twl =	1.089	860.5				
240	418	232.30		Tsh =	271	406.0				
241					232.3					
242	321	178.48		682.03	====	Tw				
243	1588.32	15.239								
244		(298.730)		Qwo = 0		(159)				
245	= Qg+Qs ==	283.491 *		Qwi = Qcdwim = Qw		(283.524)				
246	wi = Qw	283.491 *		Qgo =		298.526				
247	Qg = 0	(0)		Qcdwosh =		14.942				
248	697	642.18 *		Qwi + Qwo + Qgo =		14.942				
249	213	373.33 *		hcvws =		566.00				
250	424.81	491.56								
251	(49)	-27.23		Tsho check. K =		405.69				
252	0	0.00		Tw-Tg =		39				
253	-----									
254	=	70.00								
255	I.355		HEAT OUT =	1.868		DELTA H =	-0.5131			
256	LI GAS		-----OUTSIDE COMBUSTION GAS-----							
257	T. F	T. K	OLD Tg	1.760	T. F	T. K				
258	621	600.0	642.2	Tgo =	2.101	1422.2				
259	61	289.0		Two =	1.471	1072.3				
260	656	619.6		Twl =	993	807.2				
261	487	270.50		Tsh =	264	402.0				
262					270.5					
263	338	187.56		619.61	====	Tw				
264	1588.32	20.054								
265		(317.965)		Qwo = 0		(37)				
266	= Qg+Qs ==	297.911 *		Qwi = Qcdwim = Qw		(297.909)				
267	wi = Qw	297.910 *		Qgo =		312.628				
268	Qg = 0	(0)		Qcdwosh =		14.682				
269	632	606.13 *		Qwi + Qwo + Qgo =		14.682				
270	(6)	251.84 *		hcvws =		566.00				
271	219.78	377.66								
272	(65)	-3b.05		Tsho check. K =		404.23				
273	219	121.49		Tw-Tg =		20				
274	-----									
275										

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
176	C	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
177																				
178																				
179																				
180																				
181																				
182																				
183																				
184																				
185																				
186																				
187																				
188																				
189																				
190																				
191	10 H2O1W	500.00	750.00	1000.00	1250.00	1500.00	1750.00	2000.00												
192																				
193	A	0.41	0.37	0.36	0.35	0.34	0.30	0.29												
194	B	0.02	0.02	0.02	0.02	0.02	0.02	0.02												
195	C	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00												
196																				
197																				
198																				
199																				
200																				
201																				
202																				
203																				
204																				
205																				
206																				
207																				
208																				
209																				
210	10 H2O2S	500.00	750.00	1000.00	1250.00	1500.00	1750.00	2000.00												
211																				
212	A	0.41	0.37	0.36	0.35	0.34	0.30	0.29												
213	B	0.02	0.02	0.02	0.02															

[illegible]

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
386 ID H2O42	500.00	750.00	1000.00	1250.00	1500.00	1750.00	2000.00													
387																				
388 a	0.41	0.37	0.36	0.35	0.34	0.30	0.29													
389 b	0.02	0.02	0.02	0.02	0.02	0.02	0.02													
390 c	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00													
391																				
392	Y=Emg	X=I																		
393	L =	6.50	Y=Emg	X=I	X^2	X^3	X^4	XV	X^2V	N	A =	-0.00	X=I	Y Calc	Y Act=Emg					
394	500.00	0.53	500.00	0.53	500.00			265.78	132888.42	1.00	B =	0.01	500.00	0.23	0.53					
395	750.00	0.00	750.00	0.00	750.00			0.00	0.00	0.00	C =	1000.00	0.40	0.48						
396	1000.00	0.48	1000.00	0.48	1000.00			475.51	475508.75	1.00	D =	-8.49	1250.00	0.45	0.47					
397	1250.00	0.47	1250.00	0.47	1250.00			584.91	731132.74	1.00	E =	1500.00	0.46	0.46						
398	1500.00	0.46	1500.00	0.46	1500.00			691.17		1.00		1155.60	0.44							
399	1750.00	0.45	1750.00	0.45	1750.00			780.54		1.00	A =	-0.06								
400	2000.00	0.42	2000.00	0.42	2000.00			839.89		1.00	b =	0.00	ABH2O = (EmH2O @ Tw. P*L*Tw/Ig)*(Ig/Iw) .45							
401											C =	-0.00	0.44							
402			2.80	8750.00				3637.79		6.00	PL2 =	6.50								
403			Y	X	X#2	X#3	X#4	XV	X#2V	N	Tgl =	1155.60	Tgl =	1155.60						
404																				
405 ID H2O43	500.00	750.00	1000.00	1250.00	1500.00	1750.00	2000.00													
406																				
407 a	0.41	0.37	0.36	0.35	0.34	0.30	0.29													
408 b	0.02	0.02	0.02	0.02	0.02	0.02	0.02													
409 c	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00													
410																				
411	Y=Emg	X=I																		
412	L =	9.75	Y=Emg	X=I	X^2	X^3	X^4	XV	X^2V	N	A =	-0.00	X=I	Y Calc	Y Act=Emg					
413	500.00	0.58	500.00	0.58	500.00			291.90	145952.47	1.00	B =	0.01	500.00	0.25	0.58					
414	750.00	0.00	750.00	0.00	750.00			0.00	0.00	0.00	C =	1000.00	0.44	0.52						
415	1000.00	0.52	1000.00	0.52	1000.00			521.03	521026.32	1.00	D =	-9.20	1250.00	0.49	0.52					
416	1250.00	0.52	1250.00	0.52	1250.00			645.50	806878.00	1.00	E =	1500.00	0.51	0.51						
417	1500.00	0.51	1500.00	0.51	1500.00			761.85		1.00		1155.60	0.48							
418	1750.00	0.49	1750.00	0.49	1750.00			862.88		1.00	A =	-0.07								
419	2000.00	0.47	2000.00	0.47	2000.00			942.62		1.00	b =	0.00	ABH2O = (EmH2O @ Tw. P*L*Tw/Ig)*(Ig/Iw) .45							
420											C =	-0.00	0.48							
421			3.09	8750.00				4025.79		6.00	PL3 =	9.75								
422			Y	X	X#2	X#3	X#4	XV	X#2V	N	Tgl =	1155.60	Tgl =	1155.60						
423																				
424 H2O43	500.00	1000.00	1500.00	2000.00	2500.00	3000.00	3500.00	4000.00	750.00											
425 a	0.13	0.08	0.06	0.04	0.03	0.02	0.01	0.01	0.09											
426 b	0.30	0.29	0.27	0.22	0.20	0.16	0.15	0.12	0.29											
427 c	-0.08	-0.08	-0.07	-0.05	-0.05	-0.04	-0.04	-0.03	-0.08											
428																				
429	Y=Emg	X=I																		
430	L =	0.91	Y=Emg	X=I	X^2	X^3	X^4	XV	X^2V	N	A =	0.00	X=I	Y Calc	Y Act=Emg					
431	500.00	0.33	500.00	0.33	500.00			165.69	82846.06	1.00	B =	-0.00	500.00	0.33	0.33					
432	750.00	0.29	750.00	0.29	750.00			220.05	165039.51	1.00	C =	4400.00	1000.00	0.28	0.28					
433	1000.00	0.28	1000.00	0.28	1000.00			276.91	276906.83	1.00	D =	0.35	1500.00	0.24	0.24					
434	1500.00	0.24	1500.00	0.24	1500.00			367.40	551102.02	1.00	E =	2000.00	0.20	0.20						
435	2000.00	0.20	2000.00	0.20	2000.00			405.91	811815.95	1.00		2500.00	0.17	0.17						
436	2500.00	0.17	2500.00	0.17	2500.00			415.64		1.00	A =	0.37	3000.00	0.14	0.14					
437	3000.00	0.14	3000.00	0.14	3000.00			404.58		1.00	b =	-0.00	3500.00	0.11	0.11					
438	3500.00	0.11	3500.00	0.11	3500.00			398.57		1.00	C =	0.00	4000.00	0.09	0.09					
439	4000.00	0.09	4000.00	0.09	4000.00			369.41		1.00		2660.00	0.16							
440																				

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
441		500 00			I 06 18750 00															
442					Y	X	X#2	X#3	X#4	XV	X#2V									
443																				
444																				
445	(QJ5J)	500 00	1000 00	1500 00	2000 00	2500 00	3000 00	3500 00	4000 00											
446																				
447	a	0 08	0 07	0 06	0 05	0 04	0 04	0 04	0 03											
448	b	0 11	0 10	0 10	0 11	0 10	0 10	0 08	0 07											
449	c	-0 03	-0 03	-0 03	-0 03	-0 02	-0 02	-0 02	-0 02											
450																				
451		Y=Emg	X#1																	
452		L=	0 91		Y=Emg	X#1	X'2	X'3	X'4	XV	X'2V	N								
453	500 00	0 16	500 00	0 16	500 00					77 84	38921 48	1 00								
454	1000 00	0 14	1000 00	0 14	1000 00					135 04	135037 73	1 00								
455	1500 00	0 14	1500 00	0 14	1500 00					214 73	322092 47	1 00								
456	2000 00	0 15	2000 00	0 15	2000 00					303 45	608891 48	1 00								
457																				
458		500 00			0 59	5000 00				731 05		4 00								
459					Y	X	X#2	X#3	X#4	XV	X#2V	N								
460																				
461		L=	0 91		Y=Emg	X#1	X'2	X'3	X'4	XV	X'2V	N								
462	2500 00	0 14	2500 00	0 14	2500 00					339 89	849212 78	1 00								
463	3000 00	0 11	3000 00	0 11	3000 00					342 17		1 00								
464	3500 00	0 09	3500 00	0 09	3500 00					323 70		1 00								
465	4000 00	0 07	4000 00	0 07	4000 00					295 31		1 00								
466																				
467		500 00			0 42	13000 00				1300 87		4 00								
468					Y	X	X#2	X#3	X#4	XV	X#2V	N								
469																				

$$ABG5J = (ABC02+ABH20)(1-CS01)$$

$$ABH20 = (EMC02 * TS, P*1*TS/Tg)*(Tg/TS) 65$$

$$ABH20 = (EMC02 * TS, P*1*TS/Tg)*(Tg/TS) 45$$

$$Tg = 2660.00 \quad plo3 = 0.91$$

$$Tg = 2660.00 \quad C5003 = 0.08$$

$$A = 0.00 \quad A = 0.00 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$B = -0.00 \quad B = -0.00 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$C = 2500.00 \quad C = 6500.00 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$D = 0.15 \quad D = 0.24 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$E = 0.15 \quad E = 0.24 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$F = 0.15 \quad F = 0.24 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$G = 0.15 \quad G = 0.24 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$H = 0.15 \quad H = 0.24 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$I = 0.15 \quad I = 0.24 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$J = 0.15 \quad J = 0.24 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$K = 0.15 \quad K = 0.24 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$L = 0.15 \quad L = 0.24 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$M = 0.15 \quad M = 0.24 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

$$N = 0.15 \quad N = 0.24 \quad X#1 \quad V \quad G \quad A \quad C \quad V \quad act = fg$$

Appendix G

Program Listing for Gas Database Regression Analysis

	O	P	Q	R	S	T	U	V	W	X	Y
1											
2											
3											
4											
5											
6											
7											
8	CONST	500	1000	1500	2000	2500	3000	3500	4000	750	
9											
10	a	0.193360	0.136173	0.109983	0.082221	0.057915	0.044245	0.034452	0.024206	0.150427	
11	b	0.140591	0.144277	0.139809	0.129614	0.116838	0.099847	0.083375	0.074278	0.146890	
12	c	-0.01491	-0.01638	-0.01478	-0.01381	-0.01258	-0.01027	-0.00838	-0.00771	-0.01723	
13											
14		Y=EMg	X=T								
15	L=	5	Y=EMg	X=T	X^2	X^3	X^4	XY	X^2Y	N	
16	500	0.523517	500	0.523517	500	250000	1.3E+08	6.2E+10	261.7587	130879.3	1
17	750	0.453961	750	0.453961	750	562500	4.2E+08	3.2E+11	340.4708	255353.1	1
18	1000	0.447921	1000	0.447921	1000	1000000	1.0E+09	1.0E+12	447.9210	447921.0	1
19	1500	0.439369	1500	0.439369	1500	2250000	3.4E+09	5.1E+12	659.0545	988581.8	1
20	2000	0.385022	2000	0.385022	2000	4000000	8.0E+09	1.6E+13	770.0440	1540088.	1
21	2500	0.327484	2500	0.327484	2500	6250000	1.6E+10	3.9E+13	818.7107	2046776.	1
22	3000	0.286547	3000	0.286547	3000	9000000	2.7E+10	8.1E+13	859.6425	2578927.	1
23	3500	0.241829	3500	0.241829	3500	12250000	4.3E+10	1.5E+14	846.4041	2962414.	1
24	4000	0.202614	4000	0.202614	4000	16000000	6.4E+10	2.6E+14	810.4573	3241829.	1
25											
26		500	3.308267	18750	51562500	1.6E+11	5.5E+14	5814.464	14192772	9	
27			Y	X	X#2	X#3	X#4	XY	X#2Y	N	
28											
29	A =	-0.00000				X=T	Y calc	Y act=Eg		Y calc	
30	B =	-0.00008				500	0.501608	0.523517		0.338609	
31	C =	4400				750	0.481372	0.453961		0.290875	
32	O =	0.547211				1000	0.460928	0.447921		0.250150	
33	E =	-3437500				1500	0.419410	0.439369		0.216436	
34						2000	0.377054	0.385022		0.175279	
35	a =	0.541449				2500	0.333860	0.327484		0.145563	
36	b =	-0.00007				3000	0.289827	0.286547		0.120009	
37	c =	-0.00000				3500	0.244957	0.241829		0.098618	
38						4000	0.199248	0.202614			
39											

	A	B	C	O	E	F	G	H	I	J
1										
2										
3										
4	H2O		. (?) (Down) / XG \ A -							
5										
6	T, R	Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y		N
7	500	0.19	0.2	0.04	0.008	0.0016	0.038	0.0076		1
8		0.23	0.3	0.09	0.027	0.0081	0.069	0.0207		1
9		0.25	0.4	0.16	0.064	0.0256	0.1	0.04		1
10		0.29	0.6	0.36	0.216	0.1296	0.174	0.1044		1
11		0.31	0.8	0.64	0.512	0.4096	0.248	0.1984		1
12		0.33	1	1	1	1	0.33	0.33		1
13		0.38	1.5	2.25	3.375	5.0625	0.57	0.855		1
14		0.41	2	4	8	16	0.82	1.64		1
15		0.46	3	9	27	81	1.38	4.14		1
16		0.53	5	25	125	625	2.65	13.25		1
17										
18	500	3.38	14.8	42.54	165.202	728.637	6.379	20.5861		10
19		Y	X	X#2	X#3	X#4	XY	X#2Y		N
20										
21	A = -0.01491		T		X=Lm	Y calc	Y act=Eg			
22	B = 0.066708		500		0.2	0.220882	0.19			
23	C = 4.954584				0.3	0.234195	0.23			
24	O = 0.239271	Y=A+B*X=C*X*X			0.4	0.247211	0.25			
25	E = -3.07878				0.6	0.272346	0.29			
26					0.8	0.296289	0.31			
27	a = 0.193360				1	0.319039	0.33			
28	b = 0.140591				1.5	0.370695	0.38			
29	c = -0.01491				2	0.414895	0.41			
30					3	0.480926	0.46			
31	P*L	EMg			5	0.523517	0.53			
32	0.05	0.200352			2.5	0.451638				
33										
34										
35	T, R	Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y		N
36	1000	0.13	0.2	0.04	0.008	0.0016	0.026	0.0052		1
37		0.175	0.3	0.09	0.027	0.0081	0.0525	0.01575		1
38		0.19	0.4	0.16	0.064	0.0256	0.076	0.0304		1
39		0.235	0.6	0.36	0.216	0.1296	0.141	0.0846		1
40		0.26	0.8	0.64	0.512	0.4096	0.208	0.1664		1
41		0.28	1	1	1	1	0.28	0.28		1
42		0.325	1.5	2.25	3.375	5.0625	0.4875	0.73125		1
43		0.35	2	4	8	16	0.7	1.4		1

	A	B	C	D	E	F	G	H	I	J
44			0.4	3	9	27	81	1.2	3.6	1
45			0.455	5	25	125	625	2.275	11.375	1
46										
47	1000		2.8	14.8	42.54	165.202	728.637	5.446	17.6886	10
48			Y	X	X#2	X#3	X#4	XY	X#2Y	N
49										
50	A = -0.01638			T		X=Lm	Y calc	Y act=Eg		
51	B = 0.063093			1000		0.2	0.164373	0.13		
52	C = 4.954584					0.3	0.177982	0.175		
53	D = 0.186621		Y=A+B*X=C*X*X			0.4	0.191263	0.19		
54	E = -3.07878					0.6	0.216841	0.235		
55						0.8	0.241108	0.26		
56	a = 0.136173					1	0.264065	0.28		
57	b = 0.144277					1.5	0.315722	0.325		
58	c = -0.01638					2	0.359186	0.35		
59						3	0.421535	0.4		
60	P*L	EMg				5	0.447921	0.455		
61	0.05	0.200352								
62										
63										
64										
65										
66	T, R		Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y	N
67	1500		0.115	0.2	0.04	0.008	0.0016	0.023	0.0046	1
68			0.14	0.3	0.09	0.027	0.0081	0.042	0.0126	1
69			0.165	0.4	0.16	0.064	0.0256	0.066	0.0264	1
70			0.2	0.6	0.36	0.216	0.1296	0.12	0.072	1
71			0.23	0.8	0.64	0.512	0.4096	0.184	0.1472	1
72			0.25	1	1	1	1	0.25	0.25	1
73			0.295	1.5	2.25	3.375	5.0625	0.4425	0.66375	1
74			0.32	2	4	8	16	0.64	1.28	1
75			0.38	3	9	27	81	1.14	3.42	1
76			0.445	5	25	125	625	2.225	11.125	1
77										
78	1500		2.54	14.8	42.54	165.202	728.637	5.1325	17.00155	10
79			Y	X	X#2	X#3	X#4	XY	X#2Y	N
80										
81	A = -0.01478			T		X=Lm	Y calc	Y act=Eg		
82	B = 0.066548			1500		0.2	0.137354	0.115		
83	C = 4.954584					0.3	0.150595	0.14		
84	D = 0.155507		Y=A+B*X=C*X*X			0.4	0.163541	0.165		
85	E = -3.07878					0.6	0.188546	0.2		
86						0.8	0.212367	0.23		

	A	B	C	D	E	F	G	H	I	J
87	a = 0.109983					1	0.235006	0.25		
88	b = 0.139809					1.5	0.286428	0.295		
89	c = -0.01478					2	0.330456	0.32		
90						3	0.396333	0.38		
91	P*L EMg					5	0.439369	0.445		
92	0.05 0.200352									
93										
94										
95										
96	T, R		Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y	N
97	2000		0.088	0.2	0.04	0.008	0.0016	0.0176	0.00352	1
98			0.115	0.3	0.09	0.027	0.0081	0.0345	0.01035	1
99			0.135	0.4	0.16	0.064	0.0256	0.054	0.0216	1
100			0.16	0.6	0.36	0.216	0.1296	0.096	0.0576	1
101			0.19	0.8	0.64	0.512	0.4096	0.152	0.1216	1
102			0.21	1	1	1	1	0.21	0.21	1
103			0.25	1.5	2.25	3.375	5.0625	0.375	0.5625	1
104			0.285	2	4	8	16	0.57	1.14	1
105			0.33	3	9	27	81	0.99	2.97	1
106			0.39	5	25	125	625	1.95	9.75	1
107										
108	2000		2.153	14.8	42.54	165.202	728.637	4.4491	14.84717	10
109			Y	X	X#2	X#3	X#4	XY	X#2Y	N
110										
111	A = -0.01381			T		X=Lm	Y calc	Y act=Eg		
112	B = 0.061187			2000		0.2	0.107592	0.088		
113	C = 4.954584					0.3	0.119863	0.115		
114	D = 0.124742				Y=A+B*X=C*X*X	0.4	0.131858	0.135		
115	E = -3.07878					0.6	0.155018	0.16		
116						0.8	0.177074	0.19		
117	a = 0.082221					1	0.198025	0.21		
118	b = 0.129614					1.5	0.245569	0.25		
119	c = -0.01381					2	0.286207	0.285		
120						3	0.346767	0.33		
121	P*L EMg					5	0.385022	0.39		
122	0.05 0.200352									
123										
124										
125	T, R		Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y	N
126	2500		0.065	0.2	0.04	0.008	0.0016	0.013	0.0026	1
127			0.088	0.3	0.09	0.027	0.0081	0.0264	0.00792	1
128			0.105	0.4	0.16	0.064	0.0256	0.042	0.0168	1
129			0.13	0.6	0.36	0.216	0.1296	0.078	0.0468	1

	A	B	C	D	E	F	G	H	I	J
130			0.155	0.8	0.64	0.512	0.4096	0.124	0.0992	1
131			0.17	1	1	1	1	0.17	0.17	1
132			0.21	1.5	2.25	3.375	5.0625	0.315	0.4725	1
133			0.23	2	4	8	16	0.46	0.92	1
134			0.29	3	9	27	81	0.87	2.61	1
135			0.33	5	25	125	625	1.65	8.25	1
136										
137	2500		1.773	14.8	42.54	165.202	728.637	3.7484	12.59582	10
138			Y	X	X#2	X#3	X#4	XY	X#2Y	N
139										
140	A = -0.01258			T		X=Lm	Y calc	Y act=Eg		
141	B = 0.054485			2500		0.2	0.080779	0.065		
142	C = 4.954584					0.3	0.091834	0.088		
143	D = 0.096661			Y=A+B*X=C*X*X		0.4	0.102637	0.105		
144	E = -3.07878					0.6	0.123487	0.13		
145						0.8	0.143331	0.155		
146	a = 0.057915					1	0.162168	0.17		
147	b = 0.116838					1.5	0.204857	0.21		
148	c = -0.01258					2	0.241252	0.23		
149						3	0.295166	0.29		
150	P*L	EMg				5	0.327484	0.33		
151	0.05	0.200352								
152										
153										
154	T, R		Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y	N
155	3000		0.05	0.2	0.04	0.008	0.0016	0.01	0.002	1
156			0.07	0.3	0.09	0.027	0.0081	0.021	0.0063	1
157			0.083	0.4	0.16	0.064	0.0256	0.0332	0.01328	1
158			0.108	0.6	0.36	0.216	0.1296	0.0648	0.03888	1
159			0.125	0.8	0.64	0.512	0.4096	0.1	0.08	1
160			0.14	1	1	1	1	0.14	0.14	1
161			0.177	1.5	2.25	3.375	5.0625	0.2655	0.39825	1
162			0.2	2	4	8	16	0.4	0.8	1
163			0.24	3	9	27	81	0.72	2.16	1
164			0.29	5	25	125	625	1.45	7.25	1
165										
166	3000		1.483	14.8	42.54	165.202	728.637	3.2045	10.88871	10
167			Y	X	X#2	X#3	X#4	XY	X#2Y	N
168										
169	A = -0.01027			T		X=Lm	Y calc	Y act=Eg		
170	B = 0.048927			3000		0.2	0.063804	0.05		
171	C = 4.954584					0.3	0.073275	0.07		
172	D = 0.075887			Y=A+B*X=C*X*X		0.4	0.082540	0.083		

	A	B	C	D	E	F	G	H	I	J
173	E = -3.07878					0.6	0.100454	0.108		
174						0.8	0.117546	0.125		
175	a = 0.044245					1	0.133815	0.14		
176	b = 0.099847					1.5	0.170893	0.177		
177	c = -0.01027					2	0.202831	0.2		
178						3	0.251291	0.24		
179	P*L	EMg				5	0.286547	0.29		
180	0.05	0.200352								
181										
182	T, R	Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y		N
183	3500	0.039	0.2	0.04	0.008	0.0016	0.0078	0.00156		1
184		0.053	0.3	0.09	0.027	0.0081	0.0159	0.00477		1
185		0.067	0.4	0.16	0.064	0.0256	0.0268	0.01072		1
186		0.088	0.6	0.36	0.216	0.1296	0.0528	0.03168		1
187		0.105	0.8	0.64	0.512	0.4096	0.084	0.0672		1
188		0.115	1	1	1	1	0.115	0.115		1
189		0.15	1.5	2.25	3.375	5.0625	0.225	0.3375		1
190		0.16	2	4	8	16	0.32	0.64		1
191		0.2	3	9	27	81	0.6	1.8		1
192		0.245	5	25	125	625	1.225	6.125		1
193										
194	3500	1.222	14.8	42.54	165.202	728.637	2.6723	9.13343		10
195		Y	X	X#2	X#3	X#4	XY	X#2Y		N
196										
197	A = -0.00838		T		X=Lm	Y calc	Y act=Eg			
198	B = 0.041855		3500		0.2	0.050792	0.039			
199	C = 4.954584				0.3	0.058711	0.053			
200	D = 0.060253		Y=A+B*X=C*X*X		0.4	0.066462	0.067			
201	E = -3.07878				0.6	0.081461	0.088			
202					0.8	0.095790	0.105			
203	a = 0.034452				1	0.109448	0.115			
204	b = 0.083375				1.5	0.140661	0.15			
205	c = -0.00838				2	0.167683	0.16			
206					3	0.209159	0.2			
207	P*L	EMg			5	0.241829	0.245			
208	0.05	0.200352								
209										
210										
211										
212										
213										
214										
215										

	A	B	C	D	E	F	G	H	I	J
216										
217										
218										
219										
220										
221										
222										
223										
224										
225										
226										
227										
228										
229										
230	T, K		Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y	N
231	4000		0.03	0.2	0.04	0.008	0.0016	0.006	0.0012	1
232			0.042	0.3	0.09	0.027	0.0081	0.0126	0.00378	1
233			0.053	0.4	0.16	0.064	0.0256	0.0212	0.00848	1
234			0.07	0.6	0.36	0.216	0.1296	0.042	0.0252	1
235			0.085	0.8	0.64	0.512	0.4096	0.068	0.0544	1
236			0.098	1	1	1	1	0.098	0.098	1
237			0.12	1.5	2.25	3.375	5.0625	0.18	0.27	1
238			0.14	2	4	8	16	0.28	0.56	1
239			0.17	3	9	27	81	0.51	1.53	1
240			0.205	5	25	125	625	1.025	5.125	1
241										
242	4000		1.013	14.8	42.54	165.202	728.637	2.2428	7.67606	10
243			Y	X	X#2	X#3	X#4	XY	X#2Y	N
244										
245	A = -0.00771			T		X=Lm	Y calc	Y act=Eg		
246	B = 0.036032			4000		0.2	0.038753	0.03		
247	C = 4.954584					0.3	0.045795	0.042		
248	D = 0.047972					0.4	0.052682	0.053		
249	E = -3.07878			Y=A+B*X=C*X*X		0.6	0.065994	0.07		
250						0.8	0.078688	0.085		
251	a = 0.024206					1	0.090765	0.098		
252	b = 0.074278					1.5	0.118255	0.12		
253	c = -0.00771					2	0.141885	0.14		
254										
255	P*L	EMg								
256	0.05	0.200352								
257										
258	T, K		Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y	N

	A	B	C	D	E	F	G	H	I	J
259	750		0.15	0.2	0.04	0.008	0.0016	0.03	0.006	1
260			0.185	0.3	0.09	0.027	0.0081	0.0555	0.01665	1
261			0.205	0.4	0.16	0.064	0.0256	0.082	0.0328	1
262			0.25	0.6	0.36	0.216	0.1296	0.15	0.09	1
263			0.275	0.8	0.64	0.512	0.4096	0.22	0.176	1
264			0.3	1	1	1	1	0.3	0.3	1
265			0.34	1.5	2.25	3.375	5.0625	0.51	0.765	1
266			0.36	2	4	8	16	0.72	1.44	1
267			0.42	3	9	27	81	1.26	3.78	1
268			0.46	5	25	125	625	2.3	11.5	1
269										
270	750		2.945	14.8	42.54	165.202	728.637	5.6275	18.10645	10
271			Y	X	X#2	X#3	X#4	XY	X#2Y	N
272										
273	A = -0.01723			T		X=Lm	Y calc	Y act=Eg		
274	B = 0.061489			750		0.2	0.179115	0.15		
275	C = 4.954584					0.3	0.192942	0.185		
276	D = 0.203495					0.4	0.206425	0.205		
277	E = -3.07878					0.6	0.232356	0.25		
278						0.8	0.256908	0.275		
279	a = 0.150427					1	0.280080	0.3		
280	b = 0.146890					1.5	0.331980	0.34		
281	c = -0.01723					2	0.375261	0.36		
282						3	0.435968	0.42		
283						5	0.453961	0.46		

	M	N	O	P	Q	R	S	T	U	V
1	CONST	500	1000	1500	2000	2500	3000	3500	4000	4500
2										
3 a	0.113014	0.085994	0.097287	0.094390	0.077821	0.061488	0.049351	0.039099	0.072831	
4 b	0.038437	0.045063	0.047224	0.059833	0.060663	0.056025	0.045795	0.036061	0.140905	
5 c	-0.00432	-0.00570	-0.00544	-0.00743	-0.00717	-0.00637	-0.00480	-0.00344	-0.04336	
6										
7										
8										
9										
10										
11										
12	Y=EMg	X=T								
13	L= 5	Y=EMg	X=T	X^2	X^3	X^4	XY	X^2Y		
14	500 0.197053	500 0.197053	500	250000	1.3E+08	6.2E+10	98.52694	49263.47		
15	1000 0.168575	1000 0.168575	1000	1000000	1.0E+09	1.0E+12	168.5753	168575.3		
16	1500 0.197184	1500 0.197184	1500	2250000	3.4E+09	5.1E+12	295.7766	443664.9		
17	2000 0.207588	2000 0.207588	2000	4000000	8.0E+09	1.6E+13	415.1764	830352.9		
18										
19	500	0.770401	5000	7500000	1.3E+10	2.2E+13	978.0554	1491856.		
20		Y	X	X#2	X#3	X#4	XY	X#2Y		
21										
22	L= 5	Y=EMg	X=T	X^2	X^3	X^4	XY	X^2Y		
23	2500 0.201876	2500 0.201876	2500	6250000	1.6E+10	3.9E+13	504.6909	1261727.		
24	3000 0.182318	3000 0.182318	3000	9000000	2.7E+10	8.1E+13	546.9544	1640863.		
25	3500 0.158272	3500 0.158272	3500	12250000	4.3E+10	1.5E+14	553.9544	1938840.		
26	4000 0.133189	4000 0.133189	4000	16000000	6.4E+10	2.6E+14	532.7577	2131031.		
27										
28	500	0.675656	13000	43500000	1.5E+11	5.3E+14	2138.357	6972462.		
29		Y	X	X#2	X#3	X#4	XY	X#2Y		
30										
31	A = 0.000000		A = -0.00000	X=T	Y calc	Y act=Eg				
32	B = 0.000012		B = -0.00004	500	0.193289	0.197053				
33	C = 2500		C = 6500	1000	0.179869	0.168575				
34	D = 0.177547		D = 0.318483	1500	0.185890	0.197184				
35	E = -1250000		E = -1.0E+07	2000	0.211352	0.207588				
36				2500	0.202048	0.201876				
37	a = 0.226150		a = 0.261851	3000	0.181800	0.182318				
38	b = -0.00008		b = -0.00001	3500	0.158790	0.158272				
39	c = 0.000000		c = -0.00000	4000	0.133016	0.133189				

CO₂

	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	
1			ALT Z												
2			/CL~LM~(Calc)(GoTo)LL~/RVC~~(GoTo)L~(Down)/RNCL~(Bs)~												
3			{GoTo)LL~/M(End)(Down)~(Down)~(Down)												
4			ALT X /M~(End)(Right)(Right)~												
5			{Down)/M(End){Down)~(Up)~(Up)												
6			/RNCLL~(Bs)~												
7			EMISSION OF CO2: ACTUAL VS ESTIMATED												
8			FT*ATM	TEMPERATURE DEGREES R											
9			P*L	500	500	500	1000	1000	1000	1500	1500	1500	2000	2000	2000
10															
11		LL		ACTUAL	ESTIMATED	DELTA	ACTUAL	ESTIMATED	DELTA	ACTUAL	ESTIMATED	DELTA	ACTUAL	ESTIMATED	DELTA
12															
13			0.2	0.108	0.118045	-9.30%	0.085	0.102230	-20.27%	0.095	0.099063	-4.28%	0.095	0.108543	-14.26%
14			0.3	0.12	0.121737	-1.45%	0.095	0.106256	-11.85%	0.108	0.103707	3.97%	0.108	0.114090	-5.64%
15			0.4	0.13	0.125339	3.58%	0.105	0.110180	-4.93%	0.12	0.108231	9.81%	0.12	0.119492	0.42%
16			0.6	0.14	0.132272	5.52%	0.115	0.117720	-2.37%	0.127	0.116917	7.94%	0.13	0.129861	0.11%
17			0.8	0.15	0.138843	7.44%	0.125	0.124850	0.12%	0.135	0.125120	7.32%	0.145	0.139650	3.69%
18			1	0.152	0.145052	4.57%	0.132	0.131571	0.32%	0.145	0.132840	8.39%	0.155	0.148860	3.96%
19			1.5	0.165	0.158993	3.64%	0.142	0.146577	-3.22%	0.16	0.150029	6.23%	0.17	0.169349	0.38%
20			2	0.17	0.170673	-0.40%	0.152	0.159021	-4.62%	0.17	0.164202	3.41%	0.18	0.186215	-3.45%
21			3	0.18	0.187253	-4.03%	0.162	0.176221	-8.78%	0.18	0.183498	-1.94%	0.2	0.209083	-4.54%
22			5	0.2	0.193289	3.36%	0.171	0.179869	-5.19%	0.2	0.185890	7.05%	0.21	0.211352	-0.64%
23															
24						4.33%			6.17%			6.03%			3.71%
25															
26		L	2500	2500	2500	3000	3000	3000	3500	3500	3500	4000	4000	4000	
27															
28				ACTUAL	ESTIMATED	DELTA	ACTUAL	ESTIMATED	DELTA	ACTUAL	ESTIMATED	DELTA	ACTUAL	ESTIMATED	DELTA
29															
30			0.2	0.08	0.089610	-12.01%	0.064	0.072608	-13.45%	0.052	0.058148	-11.82%	0.04	0.046230	-15.58%
31			0.3	0.09	0.095346	-5.94%	0.074	0.077808	-5.15%	0.06	0.062571	-4.29%	0.048	0.049636	-3.41%
32			0.4	0.1	0.100937	-0.94%	0.083	0.082884	0.14%	0.067	0.066896	0.15%	0.053	0.052974	0.05%
33			0.6	0.119	0.111687	6.15%	0.096	0.092661	3.48%	0.079	0.075247	4.75%	0.062	0.059445	4.12%
34			0.8	0.128	0.121859	4.80%	0.108	0.101941	5.61%	0.087	0.083203	4.36%	0.069	0.065645	4.86%
35			1	0.138	0.131453	4.74%	0.119	0.110723	6.96%	0.094	0.090763	3.44%	0.076	0.071573	5.82%
36			1.5	0.158	0.152912	3.22%	0.133	0.130499	1.88%	0.11	0.107929	1.88%	0.088	0.085202	3.18%
37			2	0.168	0.170762	-1.64%	0.148	0.147164	0.56%	0.12	0.122620	-2.18%	0.097	0.097132	-0.14%
38			3	0.185	0.195630	-5.75%	0.163	0.171157	-5.00%	0.138	0.144577	-4.77%	0.11	0.115892	-5.36%
39			5	0.205	0.202048	1.44%	0.185	0.181800	1.73%	0.16	0.158790	0.76%	0.135	0.133016	1.47%
40															
41						4.66%			4.40%			3.84%			4.40%

	A	B	C	D	E	F	G	H	I	J
1	C02		.(?) (Down)/XG\A-							
2										
3	T, R	Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y		N
4	500	0.108	0.2	0.04	0.008	0.0016	0.0216	0.00432		1
5		0.12	0.3	0.09	0.027	0.0081	0.036	0.0108		1
6		0.13	0.4	0.16	0.064	0.0256	0.052	0.0208		1
7		0.14	0.6	0.36	0.216	0.1296	0.084	0.0504		1
8		0.15	0.8	0.64	0.512	0.4096	0.12	0.096		1
9		0.152	1	1	1	1	0.152	0.152		1
10		0.165	1.5	2.25	3.375	5.0625	0.2475	0.37125		1
11		0.17	2	4	8	16	0.34	0.68		1
12		0.18	3	9	27	81	0.54	1.62		1
13		0.2	5	25	125	625	1	5		1
14										
15	500	1.515	14.8	42.54	165.202	728.637	2.5931	8.00557		10
16		Y	X	X#2	X#3	X#4	XY	X#2Y		N
17										
18	A = -0.00432		T		X=Lm	Y calc	Y act=Eg			
19	B = 0.017004		500		0.2	0.120529	0.108			
20	C = 4.954584				0.3	0.124156	0.12			
21	D = 0.126333		Y=A+B*X=C*X*X		0.4	0.127697	0.13			
22	E = -3.07878				0.6	0.134520	0.14			
23					0.8	0.140996	0.15			
24	a = 0.113014				1	0.147126	0.152			
25	b = 0.038437				1.5	0.160938	0.165			
26	c = -0.00432				2	0.172586	0.17			
27					3	0.189394	0.18			
28	P*L	EMg			5	0.197053	0.2			
29	0.05	0.114925			2.5	0.182071				
30										
31										
32	T, R	Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y		N
33	1000	0.085	0.2	0.04	0.008	0.0016	0.017	0.0034		1
34		0.095	0.3	0.09	0.027	0.0081	0.0285	0.00855		1
35		0.105	0.4	0.16	0.064	0.0256	0.042	0.0168		1
36		0.115	0.6	0.36	0.216	0.1296	0.069	0.0414		1
37		0.125	0.8	0.64	0.512	0.4096	0.1	0.08		1
38		0.132	1	1	1	1	0.132	0.132		1
39		0.142	1.5	2.25	3.375	5.0625	0.213	0.3195		1

	A	B	C	D	E	F	G	H	I	J
40			0.152	2	4	8	16	0.304	0.608	1
41			0.162	3	9	27	81	0.486	1.458	1
42			0.171	5	25	125	625	0.855	4.275	1
43										
44	1000		1.284	14.8	42.54	165.202	728.637	2.2465	6.94265	10
45			Y	X	X#2	X#3	X#4	XY	X#2Y	N
46										
47	A = -0.00570			T		X=Lm	Y calc	Y act=Eg		
48	B = 0.016775			1000		0.2	0.094778	0.085		
49	C = 4.954584					0.3	0.098999	0.095		
50	D = 0.103572		Y=A+B*X=C*X*X			0.4	0.103105	0.105		
51	E = -3.07878					0.6	0.110976	0.115		
52						0.8	0.118390	0.125		
53	a = 0.085994					1	0.125348	0.132		
54	b = 0.045063					1.5	0.140742	0.142		
55	c = -0.00570					2	0.153283	0.152		
56						3	0.169799	0.162		
57	P*L	EMg				5	0.168575	0.171		
58	0.05	0.114925								
59										
60										
61										
62										
63	T, R		Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y	N
64	1500		0.095	0.2	0.04	0.008	0.0016	0.019	0.0038	1
65			0.108	0.3	0.09	0.027	0.0081	0.0324	0.00972	1
66			0.12	0.4	0.16	0.064	0.0256	0.048	0.0192	1
67			0.127	0.6	0.36	0.216	0.1296	0.0762	0.04572	1
68			0.135	0.8	0.64	0.512	0.4096	0.108	0.0864	1
69			0.145	1	1	1	1	0.145	0.145	1
70			0.16	1.5	2.25	3.375	5.0625	0.24	0.36	1
71			0.17	2	4	8	16	0.34	0.68	1
72			0.18	3	9	27	81	0.54	1.62	1
73			0.2	5	25	125	625	1	5	1
74										
75	1500		1.44	14.8	42.54	165.202	728.637	2.5486	7.96984	10
76			Y	X	X#2	X#3	X#4	XY	X#2Y	N
77										
78	A = -0.00544			T		X=Lm	Y calc	Y act=Eg		

	A	B	C	D	E	F	G	H	I	J
79	B = 0.020226		1500			0.2	0.106514	0.095		
80	C = 4.954584					0.3	0.110964	0.108		
81	D = 0.114064		Y=A*B*X=C*X*X			0.4	0.115305	0.12		
82	E = -3.07878					0.6	0.123660	0.127		
83						0.8	0.131580	0.135		
84	a = 0.097287					1	0.139063	0.145		
85	b = 0.047224					1.5	0.155864	0.16		
86	c = -0.00544					2	0.169940	0.17		
87						3	0.189920	0.18		
88	P*L	EMg				5	0.197184	0.2		
89	0.05	0.114925								
90										
91										
92										
93	T, R	Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y		N
94	2000	0.095	0.2	0.04	0.008	0.0016	0.019	0.0038		1
95		0.108	0.3	0.09	0.027	0.0081	0.0324	0.00972		1
96		0.12	0.4	0.16	0.064	0.0256	0.048	0.0192		1
97		0.13	0.6	0.36	0.216	0.1296	0.078	0.0468		1
98		0.145	0.8	0.64	0.512	0.4096	0.116	0.0928		1
99		0.155	1	1	1	1	0.155	0.155		1
100		0.17	1.5	2.25	3.375	5.0625	0.255	0.3825		1
101		0.18	2	4	8	16	0.36	0.72		1
102		0.2	3	9	27	81	0.6	1.8		1
103		0.21	5	25	125	625	1.05	5.25		1
104										
105	2000	1.513	14.8	42.54	165.202	728.637	2.7134	8.47982		10
106		Y	X	X#2	X#3	X#4	XY	X#2Y		N
107										
108	A = -0.00743		T		X=Lm	Y calc	Y act=Eg			
109	B = 0.022977		2000		0.2	0.106060	0.095			
110	C = 4.954584				0.3	0.111671	0.108			
111	D = 0.117293		Y=A*B*X=C*X*X		0.4	0.117134	0.12			
112	E = -3.07878				0.6	0.127613	0.13			
113					0.8	0.137497	0.145			
114	a = 0.094390				1	0.146785	0.155			
115	b = 0.059833				1.5	0.167404	0.17			
116	c = -0.00743				2	0.184303	0.18			
117					3	0.206942	0.2			

	A	B	C	D	E	F	G	H	I	J
118	P*L	EMg				5	0.207588	0.21		
119	0.05	0.114925								
120										
121										
122	T, R	Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y		N
123	2500	0.08	0.2	0.04	0.008	0.0016	0.016	0.0032		1
124		0.09	0.3	0.09	0.027	0.0081	0.027	0.0081		1
125		0.1	0.4	0.16	0.064	0.0256	0.04	0.016		1
126		0.119	0.6	0.36	0.216	0.1296	0.0714	0.04284		1
127		0.128	0.8	0.64	0.512	0.4096	0.1024	0.08192		1
128		0.138	1	1	1	1	0.138	0.138		1
129		0.158	1.5	2.25	3.375	5.0625	0.237	0.3555		1
130		0.168	2	4	8	16	0.336	0.672		1
131		0.185	3	9	27	81	0.555	1.665		1
132		0.205	5	25	125	625	1.025	5.125		1
133										
134	2500	1.371	14.8	42.54	165.202	728.637	2.5478	8.10756		10
135		Y	X	X#2	X#3	X#4	XY	X#2Y		N
136										
137	A = -0.00717		T		X=Lm	Y calc	Y act=Eg			
138	B = 0.025136		2500		0.2	0.089667	0.08			
139	C = 4.954584				0.3	0.095375	0.09			
140	D = 0.099897		Y=A+B*X=C*X*X		0.4	0.100939	0.1			
141	E = -3.07878				0.6	0.111638	0.119			
142					0.8	0.121763	0.128			
143	a = 0.077821				1	0.131314	0.138			
144	b = 0.060663				1.5	0.152682	0.158			
145	c = -0.00717				2	0.170466	0.168			
146					3	0.195277	0.185			
147	P*L	EMg			5	0.201876	0.205			
148	0.05	0.114925								
149										
150										
151	T, R	Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y		N
152	3000	0.064	0.2	0.04	0.008	0.0016	0.0128	0.00256		1
153		0.074	0.3	0.09	0.027	0.0081	0.0222	0.00666		1
154		0.083	0.4	0.16	0.064	0.0256	0.0332	0.01328		1
155		0.096	0.6	0.36	0.216	0.1296	0.0576	0.03456		1
156		0.108	0.8	0.64	0.512	0.4096	0.0864	0.06912		1

	A	B	C	D	E	F	G	H	I	J
157			0.119	1	1	1	1	0.119	0.119	1
158			0.133	1.5	2.25	3.375	5.0625	0.1995	0.29925	1
159			0.148	2	4	8	16	0.296	0.592	1
160			0.163	3	9	27	81	0.489	1.467	1
161			0.185	5	25	125	625	0.925	4.625	1
162										
163	3000		1.173	14.8	42.54	165.202	728.637	2.2407	7.22843	10
164			Y	X	X#2	X#3	X#4	XY	X#2Y	N
165										
166	A = -0.00637			T		X=Lm	Y calc	Y act=Eg		
167	B = 0.024455			3000		0.2	0.072438	0.064		
168	C = 4.954584					0.3	0.077722	0.074		
169	D = 0.081106			Y=A+B*X=C*X*X		0.4	0.082879	0.083		
170	E = -3.07878					0.6	0.092809	0.096		
171						0.8	0.102230	0.108		
172	a = 0.061488					1	0.111141	0.119		
173	b = 0.056025					1.5	0.131189	0.133		
174	c = -0.00637					2	0.148051	0.148		
175						3	0.172217	0.163		
176	P*L	EMg				5	0.182318	0.185		
177	0.05	0.114925								
178										
179	T, R		Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y	N
180	3500		0.052	0.2	0.04	0.008	0.0016	0.0104	0.00208	1
181			0.06	0.3	0.09	0.027	0.0081	0.018	0.0054	1
182			0.067	0.4	0.16	0.064	0.0256	0.0268	0.01072	1
183			0.079	0.6	0.36	0.216	0.1296	0.0474	0.02844	1
184			0.087	0.8	0.64	0.512	0.4096	0.0696	0.05568	1
185			0.094	1	1	1	1	0.094	0.094	1
186			0.11	1.5	2.25	3.375	5.0625	0.165	0.2475	1
187			0.12	2	4	8	16	0.24	0.48	1
188			0.138	3	9	27	81	0.414	1.242	1
189			0.16	5	25	125	625	0.8	4	1
190										
191	3500		0.967	14.8	42.54	165.202	728.637	1.8852	6.16582	10
192			Y	X	X#2	X#3	X#4	XY	X#2Y	N
193										
194	A = -0.00480			T		X=Lm	Y calc	Y act=Eg		
195	B = 0.022002			3500		0.2	0.058318	0.052		

	A	B	C	D	E	F	G	H	I	J
196	C = 4.954584					0.3	0.062657	0.06		
197	O = 0.064136		Y=A+B*X=C*X*X			0.4	0.066901	0.067		
198	E = -3.07878					0.6	0.075099	0.079		
199						0.8	0.082914	0.087		
200	a = 0.049351					1	0.090344	0.094		
201	b = 0.045795					1.5	0.107239	0.11		
202	c = -0.00480					2	0.121733	0.12		
203						3	0.143517	0.138		
204	P*L	EMg				5	0.158272	0.16		
205	0.05	0.114925								
206										
207										
208										
209	T, K	Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y		N
210	4000	0.04	0.2	0.04	0.008	0.0016	0.008	0.0016		1
211		0.048	0.3	0.09	0.027	0.0081	0.0144	0.00432		1
212		0.053	0.4	0.16	0.064	0.0256	0.0212	0.00848		1
213		0.062	0.6	0.36	0.216	0.1296	0.0372	0.02232		1
214		0.069	0.8	0.64	0.512	0.4096	0.0552	0.04416		1
215		0.076	1	1	1	1	0.076	0.076		1
216		0.088	1.5	2.25	3.375	5.0625	0.132	0.198		1
217		0.097	2	4	8	16	0.194	0.388		1
218		0.11	3	9	27	81	0.33	0.99		1
219		0.135	5	25	125	625	0.675	3.375		1
220										
221	4000	0.778	14.8	42.54	165.202	728.637	1.543	5.10788		10
222		Y	X	X#2	X#3	X#4	XY	X#2Y		N
223										
224	A = -0.00344		T		X=Lm	Y calc	Y act=Eg			
225	B = 0.018974		4000		0.2	0.046173	0.04			
226	C = 4.954584				0.3	0.049607	0.048			
227	D = 0.049717		Y=A+B*X=C*X*X		0.4	0.052972	0.053			
228	E = -3.07878				0.6	0.059495	0.062			
229					0.8	0.065741	0.069			
230	a = 0.039099				1	0.071712	0.076			
231	b = 0.036061				1.5	0.085432	0.088			
232	c = -0.00344				2	0.097428	0.097			
233										
234	P*L	EMg								

	A	B	C	D	E	F	G	H	I	J
235	0.05	0.114925								
236										
237	T, K		Y=EMg	X=P*L	X^2	X^3	X^4	XY	X^2Y	N
238	4500		0.045	0.1	0.01	0.001	0.0001	0.0045	0.00045	1
239			0.075	0.15	0.0225	0.003375	0.000506	0.01125	0.001687	1
240			0.1	0.2	0.04	0.008	0.0016	0.02	0.004	1
241			0.155	0.6	0.36	0.216	0.1296	0.093	0.0558	1
242			0.155	1	1	1	1	0.155	0.155	1
243			0.155	0.4	0.16	0.064	0.0256	0.062	0.0248	1
244			0.155	0.8	0.64	0.512	0.4096	0.124	0.0992	1
245			0.155	0.3	0.09	0.027	0.0081	0.0465	0.01395	1
246			0.155	1.5	2.25	3.375	5.0625	0.2325	0.34875	1
247			0.2	2	4	8	16	0.4	0.8	1
248										
249	4500		1.35	7.05	8.5725	13.20637	22.63760	1.14875	1.503637	10
250			Y	X	X#2	X#3	X#4	XY	X#2Y	N
251										
252	A = -0.04336			T		X=Lm	Y calc	Y act=Eg		
253	B = 0.054688			4500		0.1	0.086488	0.045		
254	C = 1.988413					0.15	0.092992	0.075		
255	D = 0.096444		Y=A+B*X=C*X*X			0.2	0.099278	0.1		
256	E = -0.54458					0.6	0.141765	0.155		
257						1	0.170377	0.155		
258	a = 0.072831					0.4	0.122256	0.155		
259	b = 0.140905					0.8	0.157806	0.155		
260	c = -0.04336					0.3	0.111201	0.155		
261						1.5	0.186630	0.155		
262						2	0.181203	0.2		
263										

Appendix H
Nomenclature

Nomenclature

a	constant determined by the tube bundle configuration and the amount of leakage air normal to the tube bundle
a_i	weighting factor represents the fraction of black body energy in the emitting/absorbing wavenumber region associated with the absorption coefficient K_i
A	bounding surface area of the kiln volume
A_1	radiating surface area upon which F_{12} is based, sq. ft.
A_3	area of second layer of refractory, m^2
A'_f	new 'effective' area in the equation for radiant heat from the flame
A_i	surface area
C	0.193 for Re values of 4,000 to 40,000
C_p	heat capacity of the gas
d_o	burner nozzle diameter, ft
D	kiln diameter, ft.
D	outer kiln diameter, m
F	solid bed depth (of fill)
F/D	fill ratio of F divided by D
F_{12}	view factor between surface 1 and surface 2
F_{ij}	view factor from one surface area to another

F_{ij}	the fraction of radiation leaving the first surface which is intercepted by the second surface
G'_g	gas mass flux $\text{Kg/m}^2\text{hr}$
h_{cd}	conductive heat transfer coefficient, $\text{W/m}^2\text{K}$
h_{cdws}	HTC between the wall and solid bed
h_{cvgs}	convective HTC from the gas to the solid bed
h_{cvgw}	convective HTC from the gas to the wall (Eq. 5.0-1)
h_{cvsh}	outer shell convection HTC
h_r	radiant heat transfer coefficient (Eqn. 2-3.1), in Btu/hr sq ft R
h_{rad}	linearized radiative HTC for the outer shell
H_{air}	enthalpy of the entering combustion gas and excess air
ΔH_{solids}	change in enthalpy of the solids
ΔH_{gas}	change in enthalpy of the combustion gas and excess air
$I_{absorbed}$	amount of energy attenuated by the gas for each ray
$I_{initial}$	energy initially emitted or reflected
$I_{transmitted}$	energy that is transmitted through the gas to a solid surface.
k_s	solids thermal diffusivity, m^2/s
K	thermal conductivity of the gas, W/m K
K_a	thermal conductivity of air W/m K
K_g	gas thermal conductivity W/m K

K_i	absorption coefficient (depends on the pressure and temperature of the gas)
K_s	solid thermal conductivity W/m K
K_i	thermal conductivity of refractory layer or shell, W m/m ² K
L	kiln length, m
L_m	<u>mean</u> beam length,, is an approximate representation of the geometry of an isothermal gas volume. Physically, the mean beam length is the radius of an equivalent gas hemisphere which radiates a flux to the center of its base equal to the average flux radiated to the area of interest by the actual volume of gas. (see Section 4.5)
m_o	mass fired through the burner lb/hr
m_r	additional flow at distance x due to recirculation and entrainment
N	constant equal to 0.618
P or p	represents the specific or combined partial pressures of CO ₂ and H ₂ O
P_r	Prandl number = $C_p \mu / K$
q_{cond}	heat conducted through kiln wall
q_r	radiant heat flow, Btu/hr
Q_{comb}	heat of combustion of the fuel
$Q_{shell loss}$	heat conducted through the wall and lost from the outer shell
Q_{gi}	heat absorbed by surface i from the gas

Q_i	rate at which the total radiation is emitted from a surface i
Q_i absorbed	heat absorbed by a surface i
Q_{ig}	energy originally emitted by surface i which is absorbed by the gas
Q_{ij}	energy originally emitted by surface i
Q_{ji}	heat absorbed by surface i from the other surfaces j
ΔQ_i	net radiant heat change for a surface (or the gas), (Eq. 4.2-2)
r_1	inner kiln radius, m
r_2	kiln radius for first layer of refractory, m
r_3	kiln radius for second layer of refractory, m
r_4	kiln radius for outer shell thickness, m
R	inner kiln radius, m
Re	Reynolds number = $\rho V D / \mu$
T_a	ambient air temperature, K
T_i	surface temperature
T_{sh}	outer shell temperature, K
T_w	inner wall surface temperature, K
T_1	temperature of surface 1, R
T_2	temperature of surface 2, R
V	volume in the kiln, ft ³
V	gas velocity
x	distance from the burner nozzle, ft

Greek Letters

α_i	fraction of incident radiation which is absorbed by a surface i or gas
α'_g	absorptivity of the gas for its own radiation
γ_L	solid bed half angle
ϵ_i	surface or gas emissivity
ϵ'_f	new 'effective' emissivity in the equation for radiant heat from the flame
ϵ_{sh}	shell emissivity
ϵ_1	emissivity of surface 1
ϵ_2	emissivity of surface 2
ρ_i	surface or gas reflectivity defines the fraction reflected by an opaque solid, which is equal to $1-\alpha_i$.
ρ_a	density of gas entrained in the jet, lb/ft ³
ρ_o	density of jet stream, lb/ft ³
ρ	gas density
τ_g	transmissivity of the gas is the fraction of radiation transmitted equal to $1-\alpha_g$.
τ_{gi}	gas transmissivities (for black body radiation) for beam lengths corresponding to the original ray, and its first and second reflections
τ'_g	transmissivity of the gas for its own radiation, given by $= 1-\alpha'_g$
τ_{g1}	gas transmissivity for the solid radiation,
σ	Stefan-Boltzmann radiation constant, W/m ² K ⁴
μ	viscosity, kg/m s
ω	rev/s

APPENDIX I**GLOSSARY**

GLOSSARY

Absorptivity - The fraction of total radiation incident on a surface that is absorbed.

Black body - Idealized body that absorbs all radiant energy incident upon it and emits maximum possible radiation at a given temperature.

Black body radiation - Theoretical rate of radiation from a black body at a given temperature.

Banded radiation - The change in energy level due to changes in vibrational frequency or rotation which manifest themselves in a strong peak at the wavelength corresponding to the vibrational transformation, with multiple rotational energy changes slightly above or below the peak. This type of radiation is characteristic of radiating gases.

Diffuse radiation - When the reflected radiation from a surface is reflected uniformly in all angular directions.

Diffusivity - A measure of the rate with which heat diffuses through a material, evaluated as K/C_p , conductivity divided by specific heat.

Emissivity - Measure of the ability of a substance to radiate energy equal to the ratio (expressed as a decimal fraction) of

the radiating ability of a given material to that of a black body.

Emittance - The ability of a surface to emit or radiate energy as compared with that of a black body.

Flux method - A heat transfer method of analysis described in Section 2.2.

Gray body - When at a given temperature the ratio of the monochromatic emissive power of a body to the monochromatic emissive power of a black body at the same wavelength is constant over the entire wavelength spectrum.

Kirchhoff's Law - The monochromatic emittance is equal to the monochromatic absorptance for any surface.

Radiosity - The rate at which radiation leaves a surface per unit area. The radiosity is the sum of radiation emitted, reflected, and transmitted.

Reciprocity theorem - $A_1 F_{12} = A_2 F_{21}$ where A_i is the area of a surface and F_{ij} is the view factor for surface i to surface j .

Reflection method - A heat transfer method of analysis described in Section 2.4.

Reflectivity - The fraction of total radiation incident on a surface which is reflected, $\rho = (1-\alpha-\tau)$.

Resistive Network Method - A heat transfer method of analysis described in Section 2.3.

Specular radiation - When the angle of reflected radiation is equal to the angle of incident radiation.

Theoretical air - (Stoichiometric air) The chemically correct amount of air required for complete reaction or combustion of a given quantity of material.

Thermal conductivity - Measure of the ability of a material to conduct heat. Typical units are $\text{Btu-in./ft}^2\text{-hr-F}$.

Transmissivity - The fraction of incident radiation which is transmitted through a body $\tau = (1-\alpha-\rho)$.

View Factor - (Shape Factor) The total diffuse radiation leaving one surface which is intercepted by another surface

Zone Method - A heat transfer method of analysis described in Section 2.1.

VITA

Steven Joel Kirsliis was born in Oak Ridge, Tennessee on January 26, 1957. He attended elementary schools in that city and graduated from Oak Ridge High School in January, 1975. He completed his Bachelor of Science degree in Chemical Engineering in 1981. He worked at American Can Company in Shelbyville for two years before returning to the University of Tennessee to begin the Master's degree program in the Fall of 1983. He has worked at IT Corporation in the Thermal Incineration Group since 1984. The work at IT Corporation has been the process design of incineration systems for disposing of hazardous wastes. He received his Master's Degree in Chemical Engineering in June of 1989.