

**DEVELOPMENT OF AIR/FUEL RATIO CONTROL AND
SECONDARY COMBUSTION FOR A COMMERCIAL-SCALE
BIOMASS-FUELED BOILER**

by

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ABSTRACT

The development, testing, and modeling of a multi-fuel biomass combustion system is described. The system is developed by adding air/fuel ratio control and catalytic secondary combustion to a commercially available 150 kW biomass-fueled boiler. The basis of the air/fuel ratio control system is an inexpensive electrochemical oxygen sensor. A catalytic secondary combustion system is developed from monolithic noble metal catalytic combustor segments commonly used on domestic wood burning equipment. The development and understanding of the combustion system is supported by both experimental measurements and theoretical modeling of the combustion process. Experimentally measured variables include gas temperatures, combustion air and exhaust gas flow rates, exhaust gas CO and CO₂ concentrations, and useful heat output. Both equilibrium and chemical kinetic models of the gas-phase combustion process are developed. In the kinetic model, mixing is modeled by assuming the combustion passages behave as a series of perfectly mixed reactors.

The modified boiler reduces CO output to about 10 to 15 percent of the CO produced by the baseline unit in steady operation. Results of the combustion modeling indicate that the combustion proceeds nearly to equilibrium except when operating with fuel/air equivalence ratios less

than about 0.7 and immediately after addition of a batch of fuel. Under these conditions the gas temperatures are usually low enough to impose a kinetic limit on the combustion process. Equilibrium calculations reveal that more than one-half of the total heat transfer from the combustion products occurs in the combustion zone, indicating that there may be opportunity to reduce kinetic limitations by restricting heat losses from the combustion zone.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

Direct combustion of biomass is a potentially large source of useful energy in rural areas of the southeastern United States. The economics of the use of biomass fuel indicate that in many cases the most economical method is combustion in scattered, small-scale boilers, at the site of fuel generation, rather than centralized collection, storage, and combustion in large facilities. However, small scale combustion equipment which economically incorporates fuel-air equivalence ratio control is not presently available; consequently, this equipment often operates with low efficiency and high emissions.

The present research project is an attempt to meet the need for a clean and economical, small scale combustion system. Part of the technology by which this can be accomplished became available as a result of increasingly strict federal regulation of automobile exhaust emissions. In response to these requirements, the automobile industry developed the zirconia oxygen sensor which is used as a feedback element for closed loop fuel-air ratio control. The sensor distinguishes lean vs. rich mixtures but is not capable of indicating how lean or rich. Its use in the products of biomass combustion was successfully documented in previous research [1]. The same project also demonstrated the use of the sensor as a feedback element in the control of secondary combustion air on a prototype biomass combustor of approximately 2 to 3 dry g/s maximum combustion rate.

The present work is an attempt to apply the inexpensive exhaust gas oxygen sensor to a commercially available, 150 kW (500,000 Btu/hr) biomass-fired boiler to obtain clean efficient combustion of the biomass

fuels. Apart from simple performance evaluation there are two distinct areas of development work involved in this project:

1. determine how to configure the admission of secondary combustion air (preheated vs. nonheated).
2. develop a strategy for control of the secondary combustion air flow.

The principal issue involved in configuring the secondary combustion air inlet is whether or not to preheat the secondary combustion air using the products of combustion as the heat source. The combustion process in the boiler will be modeled in support of the experimental effort to evaluate schemes for admission of secondary combustion air.

The final objective of this research is to develop the overall combustion system and evaluate its performance.

2. LITERATURE REVIEW

2.1 Wood Combustion Mechanism

Investigators have developed several schemes for subdividing the very complex process of wood combustion [2,3,4]. For purposes of the present review a combination of these schemes will be used, in which wood combustion takes place in five phases:

1. heating and drying the solid wood,
2. pyrolysis of the solid wood,
3. char oxidation,
4. oxidation of gas phase products of pyrolysis, and
5. post-flame reactions.

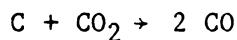
Along with the subdivisions of the wood combustion process, some basic knowledge of wood composition and structure is necessary to understand wood combustion. Wood is composed of water, cellulose, hemicelluloses, lignin, extractives, and minerals. The cellulose and hemicelluloses are bound together by lignin to form the cell walls. These three components along with the free and adsorbed water form more than 98 percent, by mass, of most wood [3,4].

The process of wood combustion is begun when the wood is subjected to an external heat flux, raising the internal wood temperature by heat conduction and convection [5]. Up to about 100°C the only effect is the removal of water. Phase one ends at about 100°C when all water has been removed.

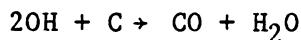
Phase two, solid wood pyrolysis, begins at about 200 to 280°C [5]. In this phase, first the hemicelluloses, then the celluloses are

broken down and release gaseous, volatile, and tarry products. What remains is mostly lignin, which has been transformed into the solid char and is significantly richer in carbon than the virgin wood [2,4]. The temperature at which the pyrolysis proceeds will significantly affect the yield of char and volatiles tars, with higher temperatures ($> 300^{\circ}\text{C}$) favoring tar production and reducing char and volatiles yields [4]. A typical char was found to contain 81 percent carbon, 3 percent hydrogen, and 16 percent oxygen by mass compared with an average wood composition of about 50 percent carbon, 6 percent hydrogen, and 44 percent oxygen [3]. The yield from wood pyrolysis after heating at 400°C for 10 minutes was typically 25 percent char and 75 percent combustible volatiles [3].

Phase three, char oxidation, begins when all volatile and tarry products have been driven off. Being a heterogeneous reaction, the oxidation of the char is strongly dependent on diffusion of O_2 to the char and counter diffusion of the primary products, CO and CO_2 . The proportions of CO and CO_2 produced in this phase of wood combustion vary with prevailing conditions of heat and mass transfer. Due to the large differences in heat of reaction to form CO and CO_2 , the heat evolved varies strongly with the proportions of CO and CO_2 [3,5]. Two mechanisms have been proposed in the literature for the heterogeneous reaction of CO oxidation. The first is the classical Boudouard reaction



Since CO is the only product, all CO₂ that appears would be a result of gas phase conversion from CO [2,6]. The second mechanism involves chemisorption of oxygen on the char surface with products of both CO₂ and CO resulting from the heterogeneous reaction [7]. A third proposed mechanism proceeds through



with no CO₂ resulting from the heterogeneous reaction [2].

The consensus appears to be articulated in the observation that CO and not CO₂ is the primary product of char oxidation at the solid surface and that any CO₂ that appears is due to gas phase conversion [6,8,9]. This gas phase conversion is obviously influenced strongly by many external conditions.

The fourth phase of the wood combustion is the gas phase oxidation of the products of pyrolysis. These gaseous products include H₂O, CO, CO₂, CH₄, CH₃OH, along with a wide variety of other hydrocarbons and organic molecules [2,3,4,5]. In one experimental investigation into this phase of wood combustion, several compounds were selected as "model" pyrolysis products and were burned in a 15 ms residence time stirred reactor to obtain combustion rate information [10,11]. The compounds selected were α -pinene (C₁₀H₁₆), methyl ethyl ketone (C₄H₈O), and acetaldehyde (C₂H₄O), with pentane (C₅H₁₂) being burned as a reference compound. Results indicated essentially complete combustion of all compounds above 1000°C. Above about 930°C, carbon in the original compounds was more than 95 percent converted to CO and CO₂ and above 1000°C the conversion exceeds 99 percent.

Phase five, the post-flame reaction zone consists chiefly of the oxidation of CO. Wood and hydrocarbon combustion are no different in this zone, at least on the level of the present discussion, therefore the reader is referred to Section 2.3 for the review of this zone.

2.2 Wood and Solid Fuel Combustion Models

Due to the complexity of the wood combustion process relatively few models which attempt to predict it in real equipment have been developed. Gross assumptions are necessary in order to model even the simplest of real systems.

One simple model is the calculation of the adiabatic flame temperature and composition. Several researchers have used the NASA equilibrium code [12] for this calculation. Inputs include

- 1) an empirical chemical formula for wood
- 2) pressure
- 3) higher heating value of the wood
- 4) equivalence ratio

Jaasma used this calculation to predict potential pollutant emissions from fuel-rich combustion in a woodstove catalyst [13]. Wood of composition $C_{4.14}H_{6.49}O_{2.69}$ was assumed with a higher heating value of 20 MJ/kg for bone dry wood. Calculated flame temperatures range from 1527°C for 30% moisture content (mc) wood at 0.8 equivalence ratio to 1897°C for 9% mc wood at 1.0 equivalence ratio. Equilibrium concentrations of HCN, NH₃, and C₂N₂ were reported but that of CO was not.

Another feature of Jaasma's work was to investigate the effects of an assumption of uniform burning. The uniform burning condition is that in which the material released in combustion is in precisely the same atomic C₁H₁O proportions as unburned wood. It is known that charcoal remaining near the end of burn out of a batch of wood contains a larger fraction of carbon than the unburned wood. In light of this, it is clear that wood does not burn uniformly in batch mode.

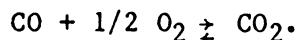
Jaasma investigated the effect of this phenomena on pollutant emissions by calculating air-fuel equilibrium compositions of fuel of pure H and fuel of pure C. These two cases represent the limiting cases for the early part of the batch cycle and late part of the batch cycle respectively.

Tillman and Anderson [14] also report equilibrium calculations for products of wood combustion. In this work adiabatic flame temperature, but not composition, was calculated for five species of wood at moisture contents of 15%, 30%, and 50%, and equivalence ratios of 0.5 to 1.0. Significant results include: 1) Douglas fir flame temperature is up to 160°C higher than Black Oak under the same moisture and equivalence ratio conditions, 2) peak flame temperature occurs at 1.0 equivalence ratio and zero moisture.

Adams developed two models of wood combustion applicable to various industrial biomass-fueled boilers. His earlier model [15] is for combustion of dry, devolatilized char particles in an updraft furnace. The particles are assumed to be pure carbon and the particle surface is modeled as a CO source. Conversion of CO to CO₂ is assumed to take place in the gas phase and is modeled by a one step global kinetic mechanism for moist CO oxidation.

Turton et al. [16] used the same one step global kinetic mechanism as Adams did. It was used as part of a model of a wood char particle combustor.

Adams' later model [17] is of the char layer in a fixed bed, updraft, on-grate wood combustion system. Again the product of the heterogeneous reaction on the char surface is taken to be CO. Conversion of CO to CO₂ is modeled by assuming equilibrium of



Mackend modeled CO oxidation in the secondary combustion zone of a hand fired lump coal combustor [18]. The model considered the secondary combustion zone to be a plug flow reactor so combustion rate is kinetically controlled. Rather than a global reaction, an elementary reaction mechanism is used. A measured temperature profile is used to describe the plug flow reactor model temperature profile.

The results of the model calculation were compared with measurements. The model showed CO oxidation, while the measurements showed slight CO production. The investigator believed that a strong factor in the disagreement was the steep profiles of CO concentration and gas temperature across the actual reactor. The plug flow assumption was thus obviously invalid and measured "averaged" concentrations were suspect, being very sensitive to probe positioning.

Other models of wood combustion have been done which attempt to predict primarily the rate of combustion of pieces of wood with well defined geometry and environmental conditions. Models of this type are

not of great interest in the present work as the concern here is with completeness of combustion rather than overall rate of consumption.

2.3 Hydrocarbon Combustion Kinetics

Hydrocarbon combustion has been studied a great deal and is fairly well understood and kinetically quantified for the lower hydrocarbon fuels. In addition, it bears similarity to the gas phase reactions in wood combustion so this review will shed light on the process of wood combustion as well.

The aspects of hydrocarbon combustion to be reviewed herein are limited to chemical considerations. Fluid mechanical considerations are not reviewed. As compared to wood combustion, the detailed chemistry of hydrocarbon combustion is well understood.

It is commonly accepted that the elementary mechanisms of hydrocarbon combustion can be viewed as a group of subsets of elementary reactions [19-24]. The subsets are used as building blocks for the various mechanisms. These subsets include the H₂/O₂ mechanism, CO, and CH₄ which are each part of the mechanism for all hydrocarbon fuels. Higher hydrocarbons will each add more subsets to the total mechanism.

CO is one of the principle intermediate and final products of hydrocarbon combustion [6, 19-24]. Its role in hydrocarbon combustion may be described, in part, as follows. At the onset of hydrocarbon combustion, CO is produced in large quantities as an intermediate product. Immediately, conversion of CO to CO₂ begins, but at a very low rate until all hydrocarbons are consumed [6, 19-24].

The reason for the low rate of conversion with hydrocarbons present is the role of OH in conversion of CO to CO₂. This conversion proceeds largely through CO + OH → CO₂ + H [6, 19-24], so that CO can only oxidize to the extent that OH is present. But hydrocarbons also consume OH in their breakdown and at a much faster rate than CO can consume it. Thus, the presence of even small quantities of hydrocarbons holds the OH concentration to such a low level that CO oxidation is essentially stopped [6,19,24]. Once the hydrocarbons are fully consumed, the OH concentration rises and CO oxidation proceeds. It has been found that the hydrocarbon oxidation phase is very short compared to the CO oxidation phase [24].

To date, comprehensive mechanisms have been developed at least for H₂/O₂, CO, CH₄ [19], C₂H₆ [24], C₂H₄ [24], and CH₃OH [21]. The current frontier in the development of comprehensive hydrocarbon combustion mechanisms is in the C₃ and higher hydrocarbons [24]. The term "comprehensive" means a detailed mechanism which has been shown to accurately reproduce experimental data in a variety of combustion environments and experimental setups (e.g., both flow reactors and shock tubes.)

It has been observed that even though the detailed kinetic mechanisms have proven reliable under a wide variety of conditions, they become impractical for multidimensional problems due to the huge amount of computational time required [22-24]. For example, a detailed mechanism for methanol oxidation involves 84 elementary reactions, each with both forward and reverse rates, and 26 species [22]. To reduce the computational requirements and to extend to fuels without known detailed

mechanisms, a number of global and quasi-global mechanisms for both CO and hydrocarbon oxidation have been proposed [22-24].

A global mechanism is one in which the kinetics of the entire hydrocarbon combustion mechanism are represented by one or more reactions which each encompass many elementary steps. The rate expression is developed as a fit to experimental data for combustion of the hydrocarbon involved. The four-step global mechanism of reference [23] is an example of this type.

A quasi-global mechanism is one in which the actual elementary reaction mechanism is represented as one or more global steps from the hydrocarbon to simpler compounds for which an elementary mechanism is well established.

The major disadvantage of the global and quasi-global methods is that the rate expressions are valid only under the conditions in which the data were collected. Extrapolation beyond these conditions can lead to gross errors. The quasi-global mechanism gets around part of this difficulty by using a comprehensive elementary mechanism for parts of the overall reaction [20].

2.4 Wood Combustion Control and Improvement

Among the important goals of any combustion system are high combustion efficiency and low emissions. Various design modifications have been used in attempts to achieve these goals. Among the most significant devices to be introduced in recent years to attain these goals in small scale wood combustion equipment is the catalytic combustor [13,25,26].

Catalytic combustors have been shown to reduce creosote by up to 98%, polycyclic organic matter (POM) by up to 76%, non-POM organics by up to 90% [27], carbon monoxide by up to 98% [13], and to increase energy efficiency by up to 11 percent [26,27] as compared to standard non-catalytic equipment. The improvements in efficiency and emissions are most dramatic under low temperature, fuel-lean conditions when kinetic limitations have prevented combustibles from burning. Obviously a catalytic combustor cannot substantially reduce emissions in fuel-rich exhaust.

An earlier study by Dody attempted to make use of the catalytic combustor to clean up the exhaust from a biomass-fuel combustor under those conditions when the catalyst is most effective [1]. Control of equivalence ratio was employed in order to maintain the equivalence ratio in such a range that the catalyst would be effective. The system, which incorporated both equivalence ratio control and catalytic secondary combustion, achieved reductions of CO emissions of about 75% compared to the noncatalytic uncontrolled configuration. The novel feature of the combustor was that it was capable of obtaining relatively clean combustion on fuels as variable as cordwood, corn fodder, and baled slash and that this was obtained with relatively inexpensive equipment.

Dody's work is significant in that it demonstrated the feasibility of an inexpensive combustion system which combined equivalence ratio control with catalytic combustor technology. However, it was limited to a prototype of approximately 1/10th of the power output of the boiler to be used in the present research. To the author's knowledge, this type

of inexpensive equivalence ratio control has never been applied to a solid fuel boiler similar to the Eshland E500.

3. APPARATUS AND PROCEDURES

3.1 Boiler Description

The Eshland model E500 boiler, shown in Figs. 1-4, is a non-catalytic, 150 kW capacity, wood-fired unit with thermostatic control. A thermostatic switch opens when the water temperature at the outlet from the boiler exceeds the operating set point, thus closing the primary air dampers and stopping the fan. Fuel may be either batch loaded or, if appropriately sized, continuously and automatically augered into the 71 cm wide x 94 cm high x 142 cm long fuel magazine. Batch loading was used for all tests discussed in this paper. It is expected that experimental results would be different if the boiler was fueled continuously. The combustion arrangement is downdraft with induced air flow provided by a fixed-speed, 0.56 kW centrifugal fan. Power output is controlled by fully opening or closing the two primary air inlet dampers. The fan stops with the closing of the air inlets.

Figures 1-4 show the boiler with its access doors open and the original equipment fan dismounted to show the gas flow passages. Primary combustion air enters the boiler through the two intakes (Fig. 1), enters the fuel magazine, and passes through the fuel bed and into the row of holes connecting the fuel magazine to the primary combustion tunnel. The gases then (now products of gasification and combustion) flow through the primary tunnel to the plenum at the rear of the boiler where the flow splits, turns 180 degrees, and enters the two secondary combustion tunnels. The front plenum, which is at the secondary tunnel outlets, is the end of the firebox portion of the boiler and the

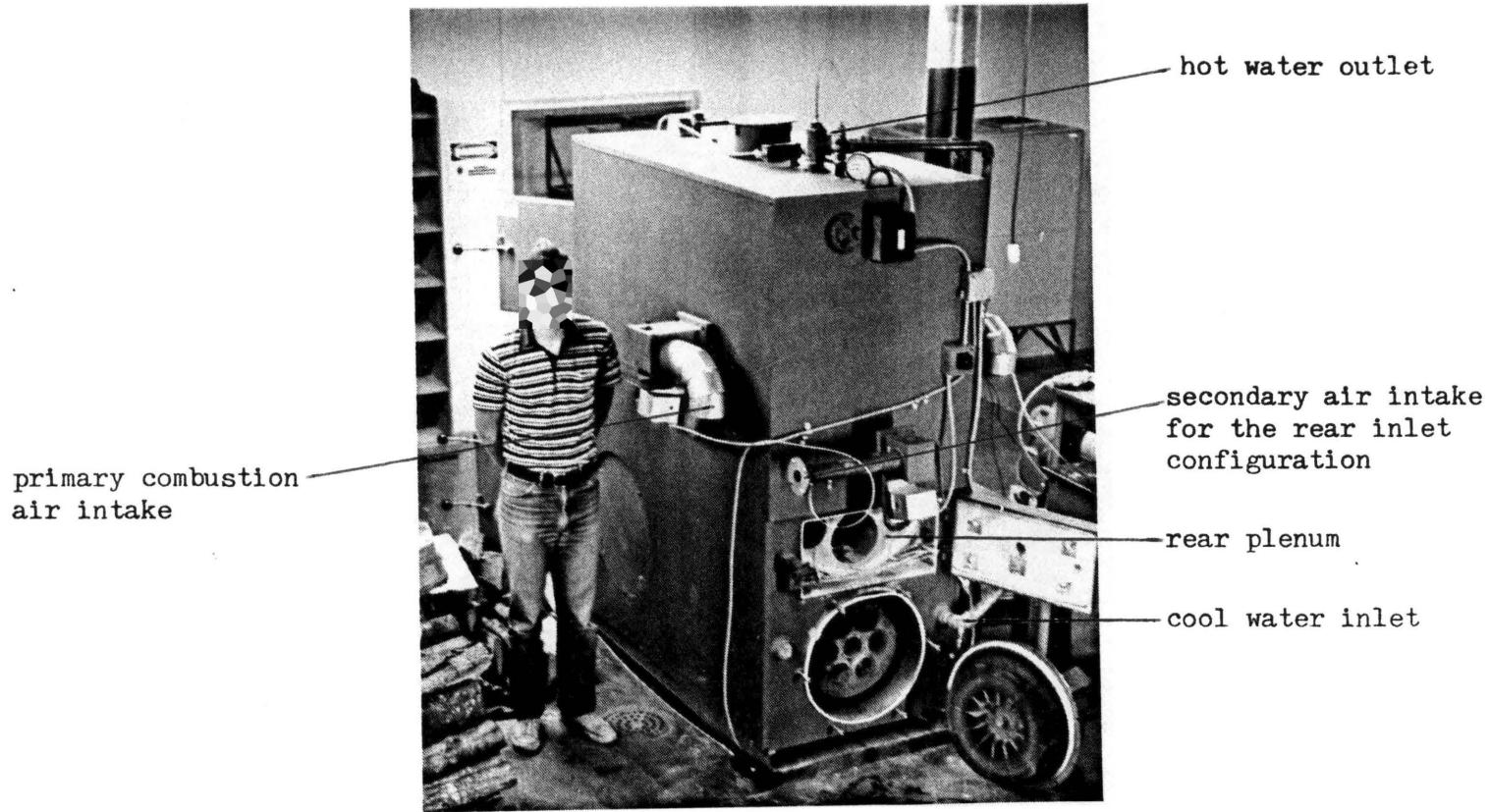


Figure 1. Eshland Enterprises, Inc. Model E 500 Biomass-Fueled Boiler, Rear View. (The Boiler Is Shown in the Rear Inlet Secondary Air Configuration.)

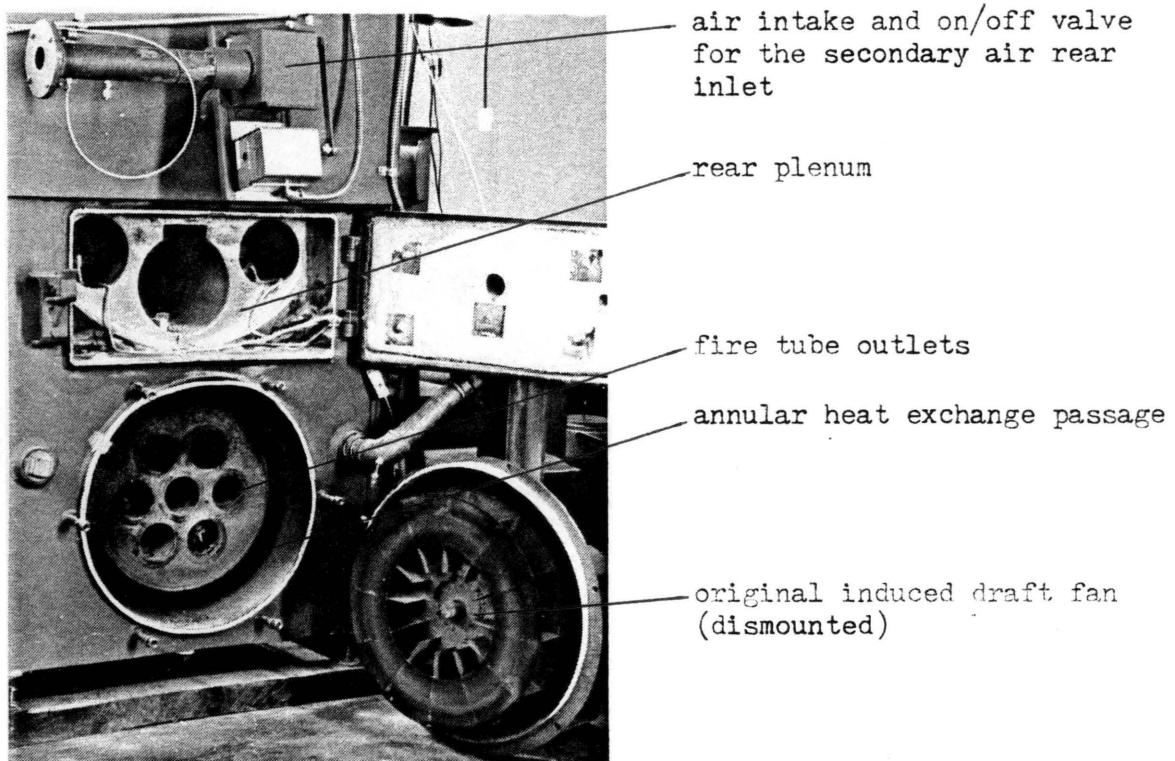
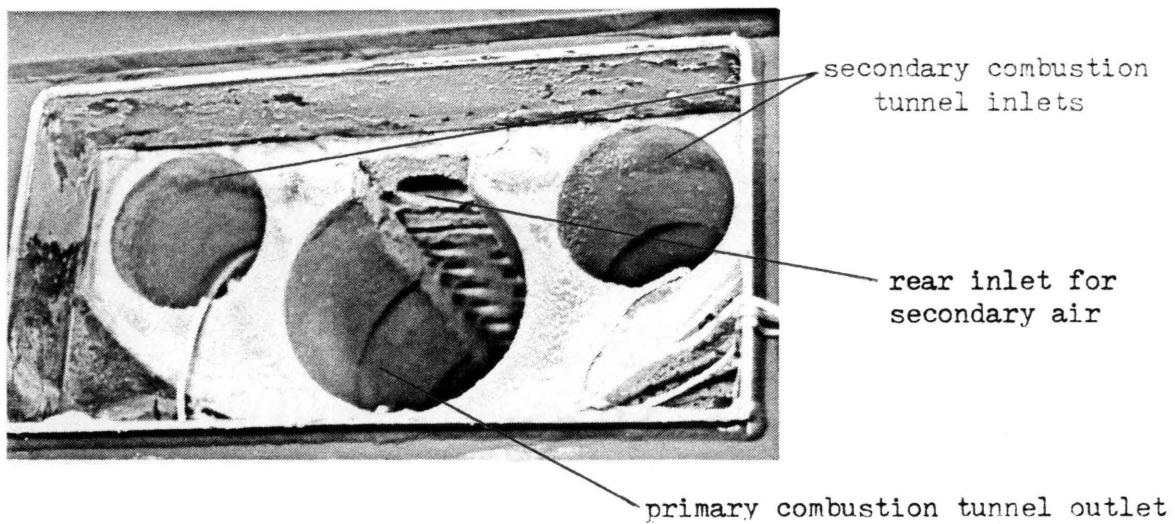


Figure 2. Lower-Rear Side of the E500 Boiler (below) and Close-Up View of the Rear Plenum (above). Both Views Show the Boiler in the Rear Inlet Secondary Air Configuration.

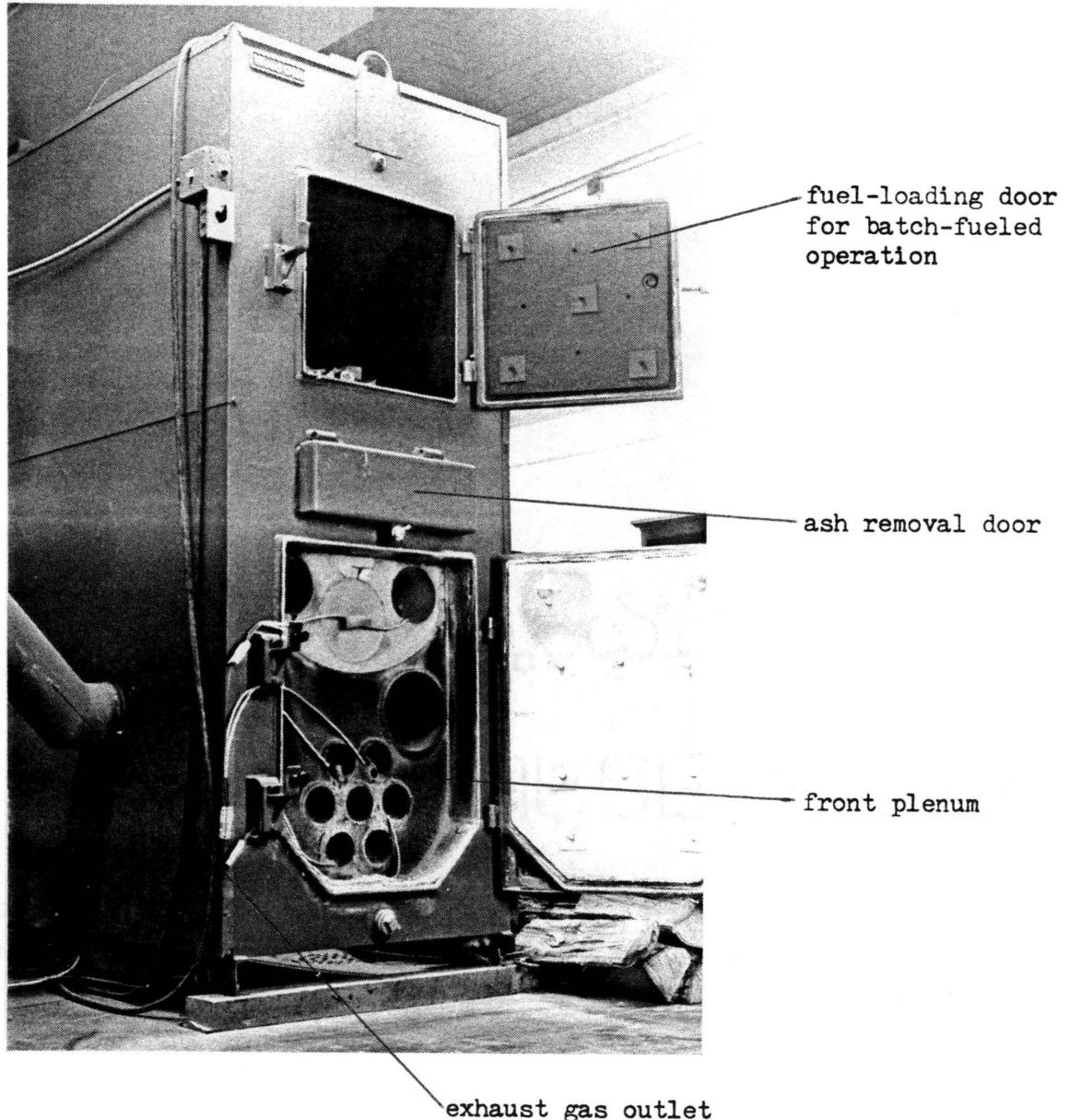


Figure 3. Eshland Enterprises, Inc. Model E500 Boiler, Front View

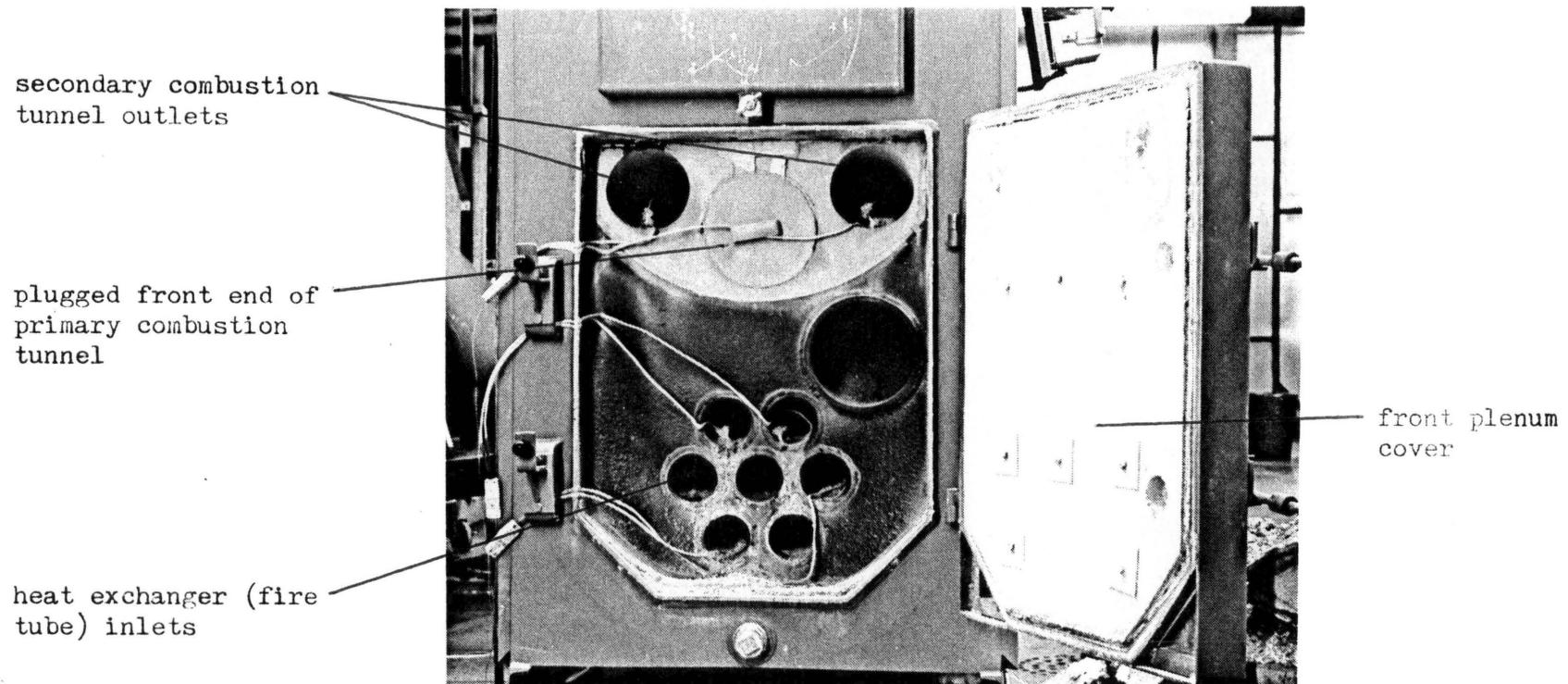


Figure 4. Front Plenum of the E500 Boiler

beginning of the heat exchanger. The firebox portion of the boiler (i.e., the fuel magazine and combustion passages) is shown schematically in Fig. 5.

As originally equipped, the boiler had an on/off port for adding secondary air but had no means of varying the flow rate to control equivalence ratio. This rear inlet for secondary air, with which the boiler was equipped at the factory, is shown in Figs. 1 and 2. The air enters through a damper and is routed through refractory passages to the primary tunnel (Figs. 2 and 5) 7.5 cm upstream of where the tunnel ends at the rear plenum.

After splitting at the rear plenum, the gas flows through the secondary combustion tunnels and into the front plenum (Figs. 3 and 4) where the two streams are mixed. The flow then splits again and enters the seven 7.6 cm diameter fire tubes of the heat exchanger. The gas emerges from the tubes at the rear of the boiler (Figs. 1 and 2) and enters the fan, which discharges it into the annular passage of the heat exchanger. The flow then leaves the boiler through the side, passes through the particulate removal cyclone and goes up the 3.6 m high stack. In the current test setup, the gases mix with ambient air at the outlet of the stack and are drawn into the dilution tunnel which conveys them outdoors via the main lab stack. The firebox portion of the gas flow path is shown schematically in Fig. 5.

Due to the physical arrangement of the primary and secondary air inlets and the induced draft fan, the gas flows cannot be independently controlled. Opening the secondary air inlet damper has the effect of reducing the primary air flow, though not by the full amount of the

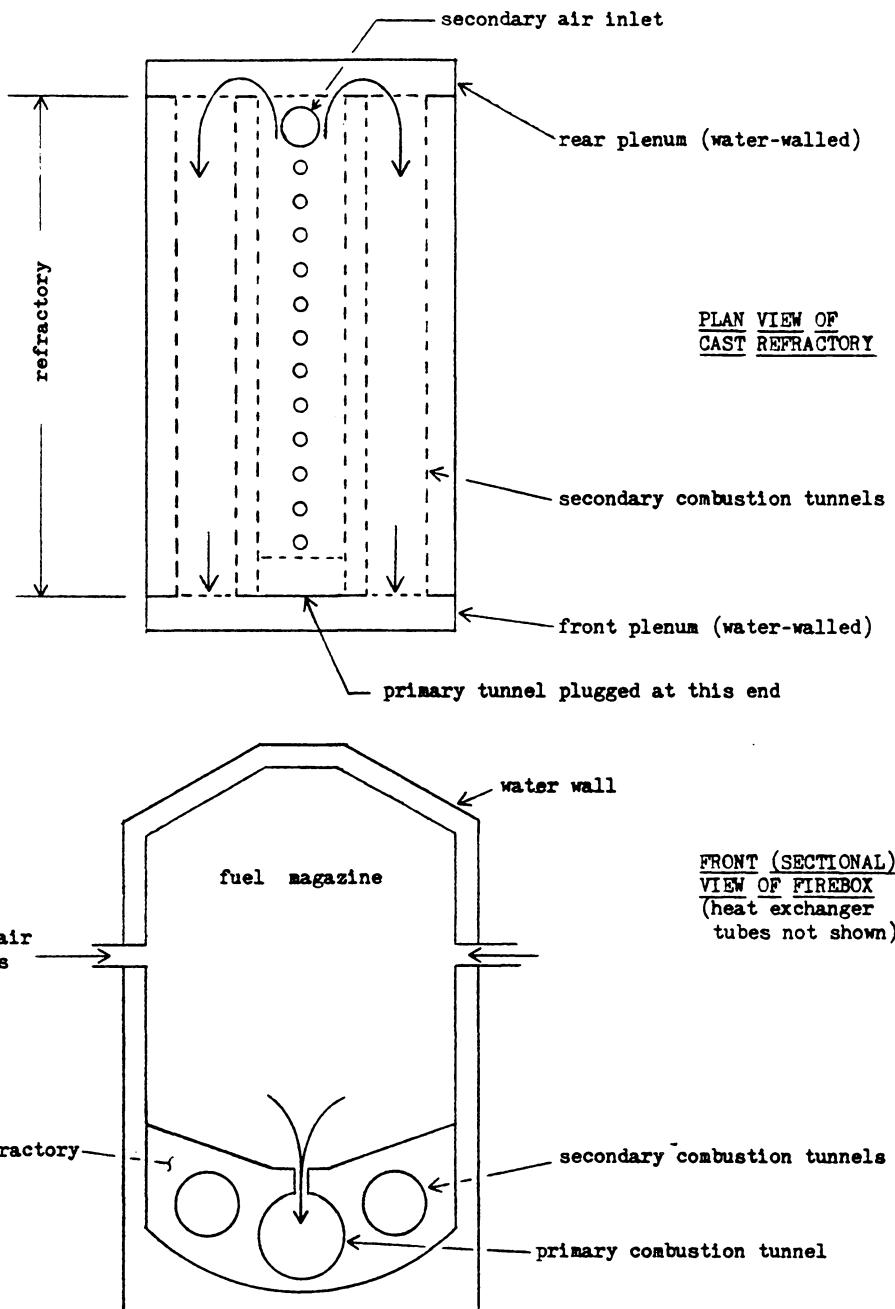


Figure 5. Diagram of the Eshland Model E500 Boiler Firebox with the Rear-Inlet Secondary Air Configuration. Arrows Show Flow Path of Air and Combustion Products.

secondary air flow. Also note that the primary combustion air flow is a strong function of the gas temperature (density) at the fan.

The water flow path in the boiler is very roughly a counter-flow arrangement. Water enters at the bottom of the boiler, flowing parallel to and in the same direction as the final gas pass from fan to cyclone. The water then turns and flows into the fire-tube portion of the heat exchanger in a U-pattern then flows up around the sides of the fuel magazine in the water walls and then out the top of the boiler (Fig. 1). The boiler can be arranged for either hot water or saturated steam service. In the present work it is arranged for hot water.

Development testing was begun with the boiler and instrumentation configured as described in this section. However, at various times during the test program the boiler, its accessories, and the instrumentation were modified as required to meet the objectives of the research. These modifications are documented in the order in which they were made, at the appropriate places in Chapter 5, with the major changes noted in Table 6. This approach of documenting the modifications in the results sections of the report makes clear the purpose of each modification, however, it provides an inadequate description of the final configuration because the description is scattered throughout the results section in small pieces. For this reason, the final configuration of the secondary combustion air system, including both hardware and software, is documented in Section 3.5.

3.2 Instrumentation

The boiler was instrumented for exhaust gas analysis and measurements of temperatures, exhaust and secondary air mass flow rates, cooling water flow rate and oxygen sensor output. The exhaust gas analyzer was an Infrared Industries model IR-702 (infrared) which measured CO and CO₂ concentrations. The CO measurement range was 0 to 3 mole percent, dry basis and the CO₂ range was 0 to 20 mole percent, dry basis. Sample gas was continually drawn from the stack and cooled in an ice-packed condensing coil to reduce the moisture content.

Gas temperatures were measured using type K thermocouples located as follows: one near the primary combustion tunnel outlet (just upstream of where secondary air is added), one in the inlet of each secondary tunnel with the two signals averaged, one in the outlet of each secondary tunnel with the two signals averaged, two in the inlets of the fire-tubes, with signals averaged, two in the outlets of the fire-tubes with signals averaged, and one in the stack. Inlet and outlet water temperatures were also measured. Testing began with all bare thermocouples but following test 13 these were replaced by 1/8 in. diameter inconel-sheathed probes to improve durability. Errors due to radiative cooling of the thermocouples in the combustion tunnels were believed to be small since the refractory surrounding them would be at a temperature similar to the gas. Therefore, radiation corrections were not made.

The Bosch heated oxygen sensor was selected, as opposed to an unheated sensor, due to the low gas temperatures in the stack (usually less than 200°C). Previous research results [28] had shown that the

heated sensor performed much better than unheated sensors at low temperatures.

Part way through the test program another type of inexpensive oxygen sensor became available and was used, in addition to the Bosch sensor, for the remainder of the test program. Since its primary function was to provide the feedback signal for closed loop secondary combustion air control, it is described more completely in Section 3.5.

The mass flow rates of exhaust gas and secondary combustion air were measured using calibrated orifice meters. The orifice for the exhaust gas was located in the stack 145 cm downstream from the outlet (top) of the cyclone. For the secondary combustion air, the intake opening was designed and used as the orifice. Differential pressures were measured by electronic differential pressure transmitters.

Data acquisition and storage was done with an IBM PC equipped with the hardware and software necessary to interpret the analog input signals. Thermocouple thermometry was accomplished with a software package that performed the conversions between voltages and temperatures, measured the cold junction temperature and accordingly computed the desired temperatures. Data collection, reduction and storage to a magnetic disc were performed every 30 seconds.

The instrumentation described in this section was the basic package with which testing was begun. However, as development testing proceeded, various modifications and additions were made to the instrumentation in order to provide more thorough understanding of the processes occurring in the boiler. These changes are documented at the appropriate points in Chapter 5.

3.3 Test Procedures

In preparation for each test run the gas sample line filters were changed, gas analyzers were zeroed and spanned, the zero level voltage of the pressure transducers was measured, the gas sampling system was packed with ice and leak-checked, and the fuel loads were weighed. Fuel moisture content was determined by oven drying of fuel samples.

All tests were run with the fuel batch-loaded. In each test the first fuel load was relatively small, contained about 7-11% moisture and was loaded with the largest pieces on the bottom, using progressively smaller wood toward the top of the load and covering the entire load with a layer of several pounds of wadded newspapers¹. Combustion was initiated by starting the dilution tunnel fan, starting the boiler exhaust gas fan and lighting the newspaper in several locations with a propane torch. The door was left open slightly for several minutes to quickly establish combustion. After combustion of the start-up load was well established and boiler temperatures were near those obtained in steady operation the first main fuel load was added.

3.4 Data Reduction

Calculated values include equivalence ratio, CO/CO₂ ratio, exhaust gas density and moisture content, burn rate, primary air mass flow rate, and useful power output. The calculations are based on the following assumptions 1) uniform combustion (i.e., at any time in the burn cycle,

¹After installing the catalytic combustor, common charcoal lighter fluid was used to start the fire instead of newspaper, which clogged the catalytic combustor.

the fuel being burned has the average as-fired composition), 2) the mass of carbon contained in the total unburned combustibles in the effluent is 2.0 times the mass of carbon in the CO in the effluent¹, 3) the dry fuel has the empirical chemical formula C_{4.24} H_{6.61} O_{2.68}, and 4) the quantity [CO₂] + 1/2 [CO] + [O₂] is a constant and equals 19.8 (this is actually true only for complete, stoichiometric combustion of fuel of the assumed composition).

Based on the above approximations, equivalence ratio can be calculated from the measured variables as:

$$\phi = ([CO_2] + 2.0 * [CO]) / 19.8$$

where

ϕ = fuel/air equivalence Ratio

[x] = dry basis molar concentration of x
in the effluent (%)

With this definition of ϕ , values less than 1 indicate fuel-lean effluent.

Exhaust gas density is calculated by assuming ideal gas behavior with molecular weight 28.8 as follows:

$$\rho = PM/RT$$

where

$$\rho = \text{exhaust gas density (kg/m}^3\text{)}$$

¹This has been found to be approximately true, on average, for domestic woodstove effluent. However, for the Eshland Boiler with its much better mixing, this assumption will result in the total carbon in the effluent being overestimated.

P = barometric pressure (kPa)

M = molecular weight (kg/kmol)

\bar{R} = universal gas constant (8.3143 kJ/kmol/K)

T = stack gas temperature (K)

Exhaust gas moisture content is calculated as:

$$[\text{H}_2\text{O}] = ([\text{CO}_2] + 2.0 * [\text{CO}] * (3.3 + 5.56 * \text{MC}/(100-\text{MC})) / 4.24 - 0.75 [\text{CO}]$$

where

$[\text{H}_2\text{O}]$ = exhaust gas moisture content (mole %, dry basis)

MC = fuel moisture content (mass %, wet basis)

Burn rate is calculated as:

$$\text{BR} = 2 * \dot{m}_e * (2[\text{CO}] + [\text{CO}_2]) * 12 / ([\text{H}_2\text{O}] + 100) * 28.8$$

where

BR = burn rate (dry g/s)

\dot{m}_e = mass flow rate of effluent (g/s)

Primary combustion air flow rate is calculated as stack flow less secondary air and the rate of consumption of wet fuel:

$$\dot{m}_p = \dot{m}_e - \dot{m}_s - \text{BR} \left(1 + \frac{\text{MC}}{(100-\text{MC})} \right)$$

where

\dot{m}_p = mass flow rate of primary combustion air (g/s)

\dot{m}_s = mass flow rate of secondary combustion air (g/s)

Useful power output is the heat transferred to the cooling water which is calculated as:

$$\text{POWER} = Q_w \rho_w (T_{\text{OUT}} - T_{\text{IN}}) C_p$$

where

POWER = useful output power (kw)

Q_w = cooling water volumetric flow (m^3/s)

ρ_w = cooling water density (kg/m^3)

T_{OUT} = temperature of water at outlet ($^{\circ}\text{C}$)

T_{IN} = temperature of water at inlet ($^{\circ}\text{C}$)

C_p = specific heat of water (kJ/kg· K)

For simplicity the molar CO/CO₂ ratio is used as an indication of the completeness of combustion. From the review in section 2.3, it is clear that when the CO concentration is low, essentially no hydrocarbons are present if the flow is well-mixed, as is the case in the Eshland boiler. On the other hand, when the CO concentration is high the concentration of unburned hydrocarbons could be anywhere from negligible to very large. Thus, when CO is low combustion efficiency can be fairly accurately determined from CO measurements alone. At high CO levels, CO concentration is only a qualitative indicator of combustion efficiency.

3.5 Secondary Combustion Air System - Final Design

The purpose of the secondary combustion air control system is to maintain the equivalence ratio at a specified value by providing secondary combustion air at the required flow rate. A schematic diagram of the system, showing its elements and the flow of information between

them, is presented in Fig. 6. Information supplied to the controller (an IBM PC) consists of the oxygen sensor output and the secondary tunnel inlet temperature. The controller output is a series of voltage pulses used to drive the valve to a position calculated by the controller.

The oxygen sensor (G-cell) is a noncatalytic electro-chemical cell¹ which produces a voltage which is proportional to the partial pressure of oxygen in the sample gas. In atmospheric air, the output corresponding to the 21 mole % oxygen present is about 25 mV. This sensor provides more information than the Bosch sensor with which the project was begun. Given a completely burned sample, it is not only capable of distinguishing between lean and rich mixtures, but also measures how lean a lean mixture is. Even though it provides more information than the Bosch sensor, the G-cell has several disadvantages:

1. It requires a separate incinerator or catalytic combustor to completely burn the sample gas upstream of the G-cell if the output is to be used as an indication of equivalence ratio;
2. It requires a gas sample which has been cooled to room temperature and had condensed water separated, and
3. It is inherently slower responding than the Bosch sensor and is further slowed in practice by the gas sample residence time in the incinerator and conditioning systems. As used in the

¹Model 33-570 G-cell oxygen sensor, G.C. Industries Inc., 20361 Prairie St., Unit 4, Chatsworth, CA, 91311, Phone (818) 701-7072. This sensor cost \$60 in 1987.

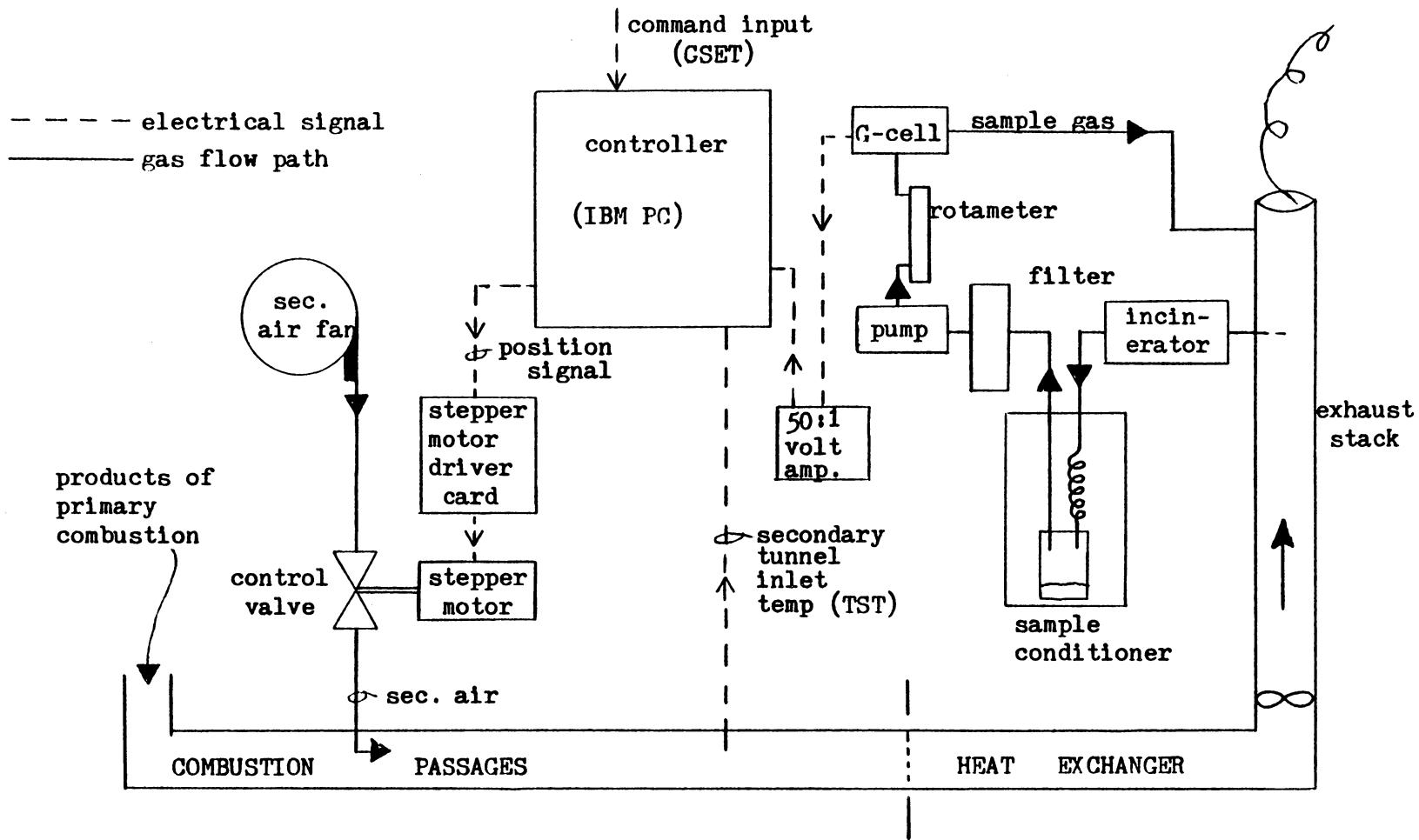


Figure 6. Schematic Diagram of the Final Secondary Combustion Air System

present apparatus, the Bosch sensor response time was of the order of 1 second or less while the G-cell system response was of the order of 20 to 20 seconds.

In the order of the sample flow path, the G-cell system includes a sample port on the boiler exhaust stack, a catalytic combustor (incinerator), gas cooler/condenser (sample conditioner), particulate filter, sample pump, rotameter, and the G-cell sample chamber. Because the data acquisition system did not have onboard amplification, a 50:1 voltage amplifier was used to boost the G-cell output voltage before transmission to the data acquisition system (controller). The catalytic combustor is a stainless steel cylinder 18 cm long by 2 cm in diameter (inside dimensions). The cylinder is hollow and filled with catalytic beads (taken from an automotive catalytic converter). Heaters are embedded in the wall of the cylinder and are controlled to maintain the combustor temperature at or near 450°C. Gas sample enters the pellet-filled hollow from the top, flows through the pellet bed and out the bottom. The sample conditioner is a copper condensing coil fabricated from 1/4 inch diameter copper tubing, followed by a beaker which allows the condensed moisture to drop out before the gas sample goes to the particulate filter.

The secondary combustion tunnel inlet temperature used in the control system is the average of the measurements from four thermocouples--two located in the inlet to each of the two tunnels. Though the present configurations uses this average temperature, a commercial system could obtain entirely adequate information from a single well-placed thermocouple located either on the rear plenum door or in the secondary tunnel inlet.

The controller is an IBM PC personal computer equipped with analog and digital input and output (I/O) capability. Since this is the same computer and I/O system used for data acquisition and storage, the controller cannot operate when these functions are being performed. However, since data acquisition and storage takes only about 4 seconds on a 30 second interval this time limitation proves not to be significant. The primary result of using one computer to do all three functions is a more complex program.

The secondary air supply system consists of the fan, the control valve, and the associated ducting. The fan is a 1/4 hp shop vacuum with the ducting connected to provide pressure rather than suction. The control valve is a 1 1/4 inch (nominal) bronze gate valve. The packing was removed to reduce the actuating torque required and the stem was spring loaded in tension to eliminate positioning errors caused by the loose stem threads. The valve is actuated by a stepper motor which is interfaced to the controller through a stepper motor driver card. A stepper motor (200 pulses per revolution) is used to eliminate the need for a valve position feedback signal. By counting pulses (and their associated direction) the controller can always know exactly how far open the valve is, to the nearest 1/200 of a revolution. There is also an orifice meter in the secondary air duct, downstream of the control valve which is used for measurement, but not control, and so is not shown in Fig. 6.

The final form of the strategy for control of secondary combustion air is presented in the flow diagram of Fig. 7, which shows the flow diagram of only those parts of the strategy relevant to control.

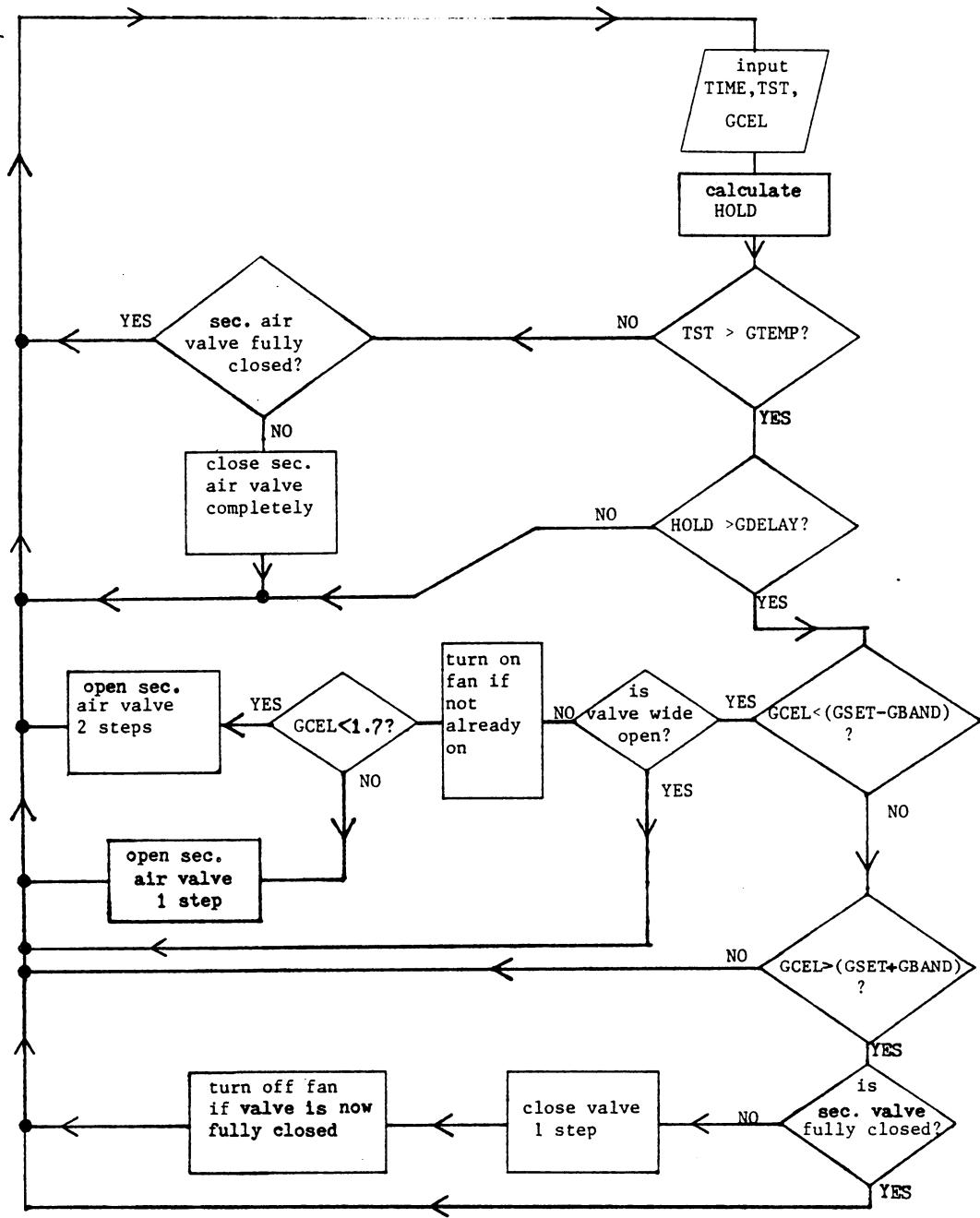


Figure 7. Abridged Flow Diagram of the Final Secondary Air Control Strategy. Parameters and Variables Are Defined in Table 1.

Provisions for redundant safety features are omitted, for clarity. These provisions are included however, in the complete flow diagram presented in Fig. 8. The parameters and variables appearing in this strategy are shown in Table 1. The inputs to the controller are GCEL, TST, and PFL0 while the outputs are the position of the secondary combustion air valve and the setting of a relay (open or closed contacts) which controls the vacuum cleaner which supplies secondary combustion air. The controller changes the valve position in steps, which change secondary combustion air flow rate by about 5 g/s per step.

The only inputs and outputs (I/O) required from a control standpoint are input of GCEL and TST and output of the valve position. The remaining I/O is for safety features. These safety features could be incorporated in a commercial system by other means of less cost and complexity. This control strategy is implemented in the IBM PC BASIC-A language as part of the code presented in Appendix A. The remainder of the code implements the data acquisition, reduction, and storage functions.

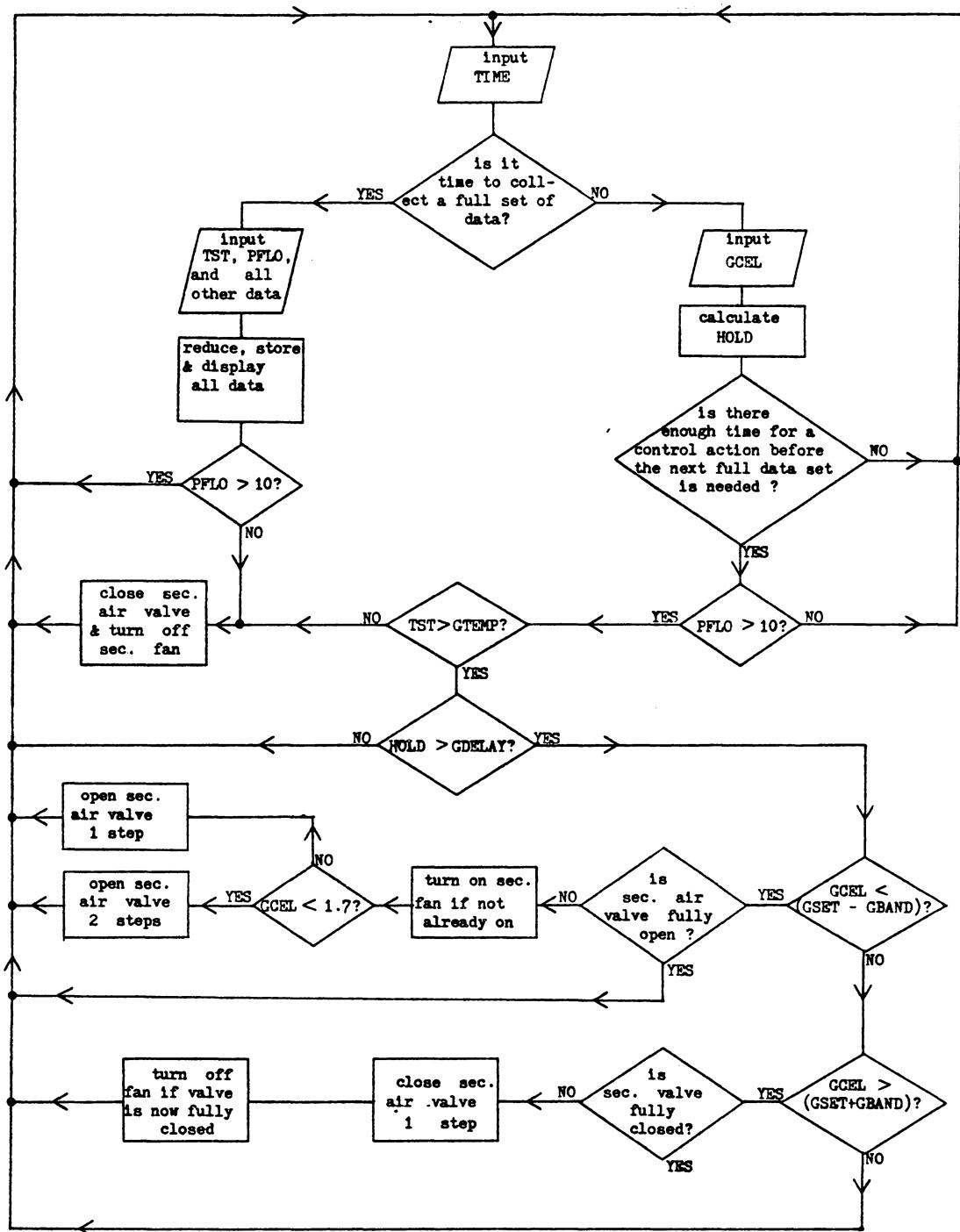


Figure 8. Complete Flow Diagram of the Final Secondary Air Control Strategy. Parameters and Variables Are Defined in Table 1.

Table 1. Definitions of Parameters and Variables Used in the Secondary Air Control Strategy

<u>Parameter</u>	<u>Definition</u>	<u>Final Value</u>
GSET	the controller target or setpoint value for the G-cell output	4.5 mV
GTEMP	the secondary tunnel inlet Temperature(TST) below which secondary air flow is stopped	700°C (600 for litter)
GBAND	half-width of the deadband surrounding GSET; no control action is taken when GCEL is within the range GSET ± GBAND	0.6 mV
GDELAY	the minimum time between changes of valve position	30 seconds

<u>Variable</u>	<u>Definition</u>
GCEL	output from the G-cell oxygen sensor (mV)
TST	secondary tunnel inlet temperature (°C)
PFL0	primary combustion air flow rate (g/s)
HOLD	elapsed time since last change of valve position (seconds)

4. COMBUSTION MODELING

4.1 Introduction

The wood combustion process occurring in the Eshland boiler is an extremely complex phenomena involving chemical reaction in gas, liquid, and solid phases, heat transfer by conduction, convection and radiation, mass transfer by diffusion and convection, and numerous chemical species (certainly well in excess of 100) with many of these processes being strongly three dimensional, unsteady, and coupled. Obviously it is not possible, given the present state of knowledge, to mathematically model such a process in its entirety. Though, if one could successfully do this, the optimum combustion system could be designed before touching even the first piece of hardware.

Knowing then, what we would like to be able to do, but cannot, we attempt to determine what modeling can be done to explain why the boiler behaves the way it does. To do this, we must first decide what are the most important determinants of the completeness of combustion. There are three categories of such determinants relative to the gas-phase processes:

1. Fuel-air equivalence ratio (equilibrium considerations).
2. Temperature and residence time (chemical kinetics).
3. Mixing/mass transfer.

Equilibrium calculations give an indication of the maximum temperature attainable and the extent to which combustion would proceed given perfect mixing and enough time, for any given combination of wood moisture and equivalence ratio. Chemical kinetic modeling would

indicate the extent to which residence time limited the attainment of equilibrium. If radial and circumferential mixing are incomplete both the chemical kinetic and the equilibrium calculations are invalidated. Mathematical treatment of the radial mixing problem is beyond the scope of the present work but axial species gradients will be at least partially accounted for in the kinetic model to be discussed.

For the Eshland boiler gas phase combustion process occurring in the primary tunnel, secondary tunnels, and rear plenum, the assumption of perfect radial and circumferential mixing will be made. This assumption is justifiable based on the turbulent flow ($30,000 < Re_D < 100,000$) and the cross-wise injection of the gases into the primary tunnel. Thus, equilibrium and chemical kinetic aspects of the gas phase combustion are modeled with the kinetic model accounting for axial species concentration gradients.

Even though only a relatively small part of the actual combustion process was modeled, the models are expected to produce helpful results. Specifically, the modeling should reveal and help explain trends of gas phase combustion behavior as affected by equivalence ratio, temperature, fuel moisture content, and axial gradients of species concentration. It appears reasonable to exclude the solid phase from the modeling if for no other reason than that its primary effect appears to be that of controlling the equivalence ratio. There is little problem in controlling the equivalence ratio but sometimes there are great problems obtaining complete combustion given the proper equivalence ratio.

4.2 Equilibrium Calculations

This is among the simplest of models for any combustion process since its prediction of the composition of the products of combustion depends only on the relative numbers of atoms involved in the process and on the final temperature. The final temperature may be determined by either of two means,

1. solve the energy equation or,
2. specify a temperature.

For the present modeling, two series of calculations will be done using the first option, i.e., solving for adiabatic flame temperatures, and a third series will be done with specified temperatures.

The following assumptions form the basis of these equilibrium calculations:

1. fuel and air are both initially at 25°C,
2. the empirical chemical formula of dry wood is $C_{4.24}H_{6.61}O_{2.68}$ (typical of hardwood),
3. air has molar composition of 78.11% N₂, 20.96% O₂, 0.93% A_r, and
4. the product species are H, O, N, H₂, OH, CO, NO, O₂, H₂O, CO₂, N₂, and A_r.

The equilibrium calculations were performed, based on these assumptions, using a computer code [29].

Three series of adiabatic calculations were performed. First, the equivalence ratio was held constant at 0.85 and calculations were performed for fuel moisture contents from 0 to 50%. Second, the fuel moisture was held constant at 20%, wet basis (a reasonable average value

for actual fuel) and equivalence ratio was varied from 0.2 to 2.0. The third series of calculations used specified temperatures from 500 to 1200°C and equivalence ratios from 0.2 to 1.3. The equilibrium composition was found for each combination of equivalence ratio and temperature.

4.3 Gas-Phase Chemical Kinetic Model

4.3.1 Introduction

This calculation attempts to model only phases 4 and 5 of the phases of wood combustion discussed in section 2.1. The entire solid phase is neglected and an equivalence ratio is specified instead. This is a reasonable approach because the main effect of the solid phase and heterogeneous processes of wood combustion within the framework of other assumptions¹ of the present model, is to determine the equivalence ratio. In the present experimental program it has been established that the major problem is not controlling the equivalence ratio, ϕ , but getting the mixture (which is already at an apparent optimum value of ϕ) to burn completely. Therefore, it appears reasonable to concentrate on the gas phase processes.

¹Particularly those introduced in section 4.3.2.3 regarding inlet composition.

4.3.2 Model Definition

4.3.2.1 General

The assumed structure of the gas phase combustion system is as shown in Figs. 9 and 10. In the model, the gas phase combustion process is assumed to occur in a series of 11 perfectly mixed reactors. Obviously, radial mixing is assumed perfect in this approach though axial gradients of species concentration are accounted for. The primary combustion tunnel is divided into five reactors, the rear plenum is one reactor and the secondary tunnels are modeled as five reactors. The figure shows the sources and rate of mass influx to each reactor. Each stirred reactor is defined by its volume, mass flow rate and temperature.

4.3.2.2 Reactor Volumes and Flow Rates

For the five primary tunnel reactors, the primary tunnel was divided into five equal length segments. Each reactor was assigned the actual volume available in its segment for combustion gases to occupy (i.e., each reactor was assigned 1/5 of the primary tunnel volume, less the volume of the secondary air inlet tube, its refractory support and normal ash accumulation). The volume assigned to reactor No. 6 (plenum reactor) was the actual plenum volume less normal ash accumulation and the volume of the secondary air tube. The volume assigned to reactors No. 7 through 11 was 1/5 of the total volume of both secondary tunnels. Numerical values of the volume of each reactor are shown in Figs. 9 and 10.

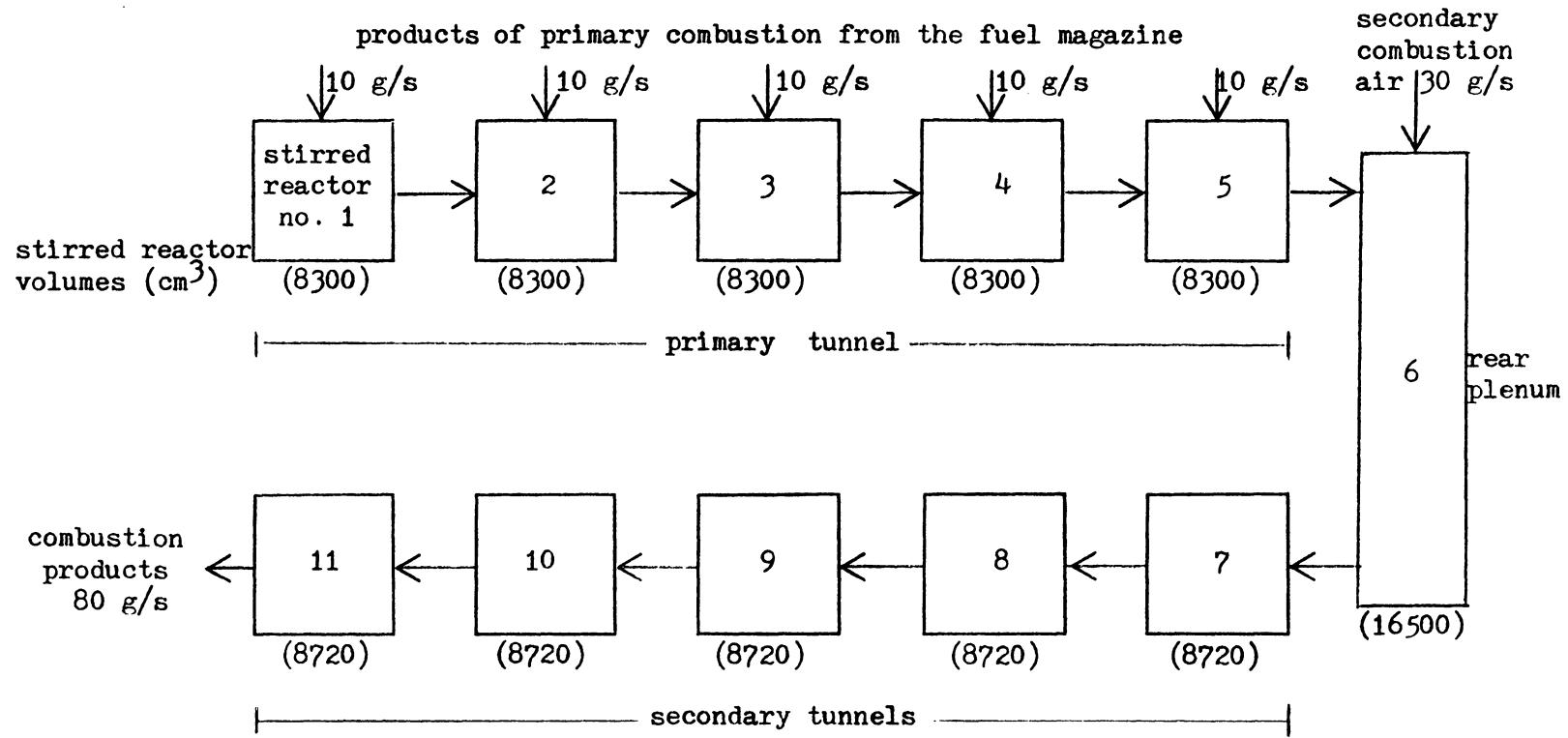


Figure 9. Schematic Diagram of the Eshland Boiler Gas-Phase Combustion System, with Rear Secondary Air Inlet, as Structured in the Stirred Reactor Kinetic Model

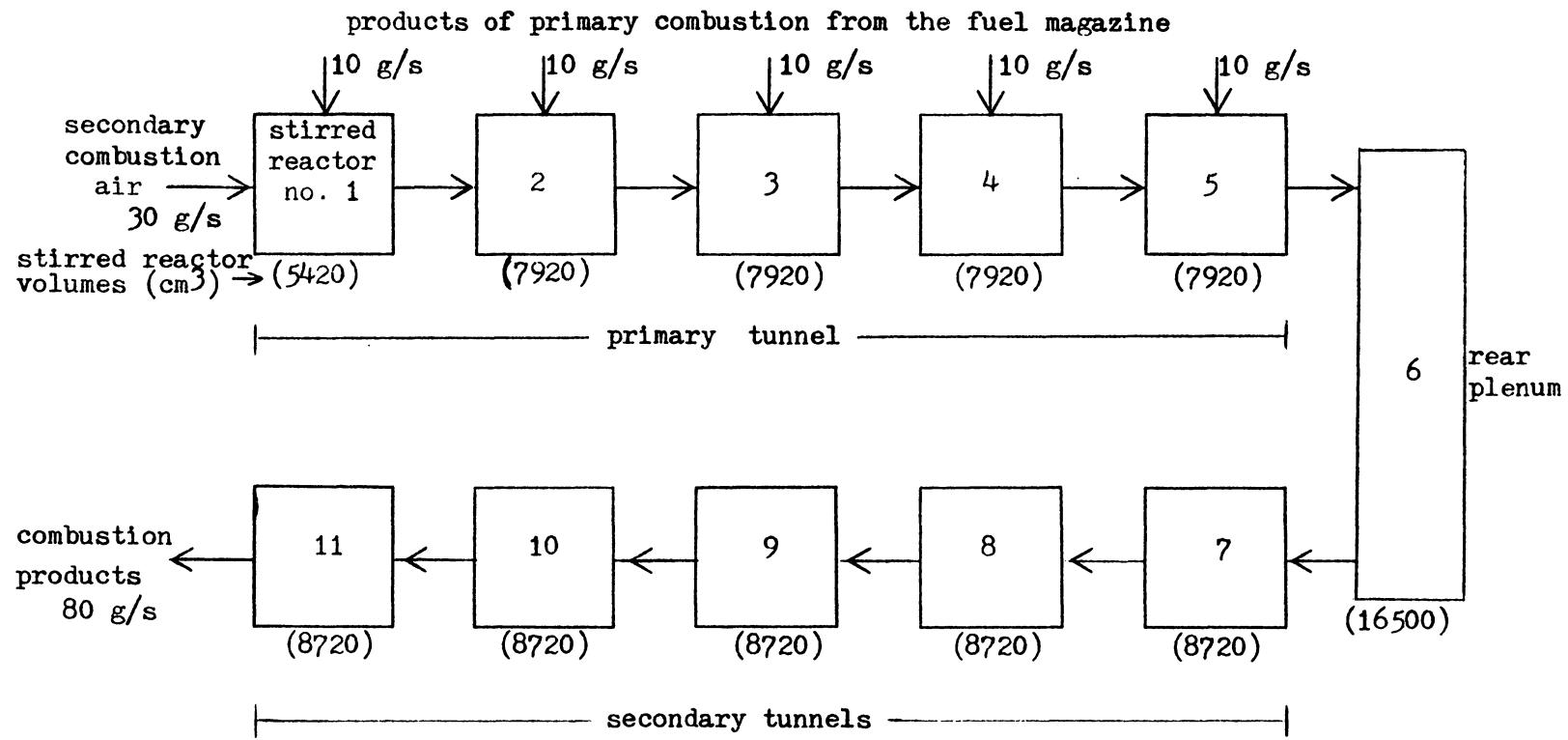


Figure 10. Schematic Diagram of the Eshland Boiler Gas-Phase Combustion System, with Tube Secondary Air Inlet, as Structured in the Stirred Reactor Kinetic Model

The exhaust gas flow rate used in the model was 80 g/s while the secondary air flow rate was 30 g/s. Thus, the total flow rate of products of primary combustion was 50 g/s. This was divided such that 10 g/s entered each of the first five reactors. The mass flow rate of each reactor is shown in Figs. 9 and 10.

4.3.2.3 Inlet Temperature and Composition

The inlet temperature and composition were determined using the following steps: 1) assigning an exhaust gas equivalence ratio, 2) estimating the primary combustion equivalence ratio (which is different from the exhaust gas equivalence ratio any time secondary air is being added), and 3) calculating the species mole fractions for adiabatic equilibrium. The exhaust gas equivalence ratio was taken to be 0.84, a value representative of much of the test data since it was the setpoint value for the secondary air control system. It would be desirable to explore a range of equivalence ratios from say 0.5 to 1.0 and thus examine the effect of ϕ on the chemical kinetics of the process, but time constraints prevented this.

In step 2 the primary combustion equivalence ratio was calculated assuming the same fuel composition used for the equilibrium calculations and 20 percent moisture content. Given this fuel composition (which uniquely determines the stoichiometric air/fuel ratio), as well as the exhaust gas equivalence ratio and the secondary combustion air and exhaust gas flow rates, the primary combustion equivalence ratio was determined to be 1.50.

In step 3 the inlet temperature and composition were then estimated to be those corresponding to adiabatic equilibrium, i.e., the adiabatic flame temperature and composition, at the primary combustion equivalence ratio of 1.50. The first two assumptions used in Section 4.2 were used, as well as:

3. the molar composition of air is 79 percent N₂ and 21 percent O₂, and
4. the product species are H, O, OH, H₂, HO₂, H₂O₂, H₂O, CO, CO₂, O₂, and N₂.

The set of species in item 4 is different from that used in Section 4.2 for two reasons. First, Ar, N, and NO are not included here because their effects on CO oxidation are negligible for the temperatures investigated. Each species deleted reduces the number of nonlinear simultaneous equations in the stirred reactor model by one, thus, reducing the computation time. Second, HO₂ and H₂O₂ are included because they are potentially significant in the CO oxidation process and thus are part of the chemical kinetic mechanism. The inlet composition thus calculated is shown in Table 2. The inlet tempeature resulting from this calculation is 1407.9°C.

4.3.2.4 Reactor Temperatures

The reactor temperatures used in the model were defined by either one of two methods:

1. by specifying a single temperature to apply to all reactors (this is called the isothermal model), or

Table 2. Inlet Composition¹ for the Gas-Phase Chemical Kinetic Model. This is the Adiabatic Equilibrium Composition for 20% Moisture Fuel Burned at 1.5 Equivalence Ratio.

<u>Species</u>	<u>mole fraction</u>
CO	0.099877
CO ₂	0.10865
O	0.22944 x 10 ⁻⁸
O ₂	0.37448 x 10 ⁻⁸
H	0.28205 x 10 ⁻⁴
H ₂	0.049380
OH	0.48705 x 10 ⁻⁵
H ₂ O	0.17758
HO ₂	0.26698 x 10 ⁻¹¹
H ₂ O ₂	0.55590 x 10 ⁻¹¹
N ₂	0.56448

¹These inputs were used for all model runs.

2. by solving the energy equation based on the assumption of constant pressure combustion (this is called the energy method or model).

The isothermal method neglects an important aspect of the difference between the rear inlet and tube inlet secondary air configurations--the possibly very different axial temperature profiles in the primary tunnel. For this reason the isothermal case will add little or no information to the comparison between the two secondary air configurations. However, the isothermal tests should demonstrate the effect of temperature on the reaction kinetics and thus yield some qualitative insight into the combustion behavior of the boiler. To do this, a series of isothermal model runs were done for temperatures from 400 to 800°C in increments of 100°C and 1000 to 1400°C in increments of 200°C.

In the energy method, the temperature of the influx to each reactor and the rate of heat transfer from each reactor are required to solve the energy equation and thus determine each reactor's temperature. As seen in Figs. 9 and 10, there were three possible sources of influx to each reactor.

- 1) products of primary combustion at 1407.9°C,
- 2) secondary combustion air at 830°C (temperature determination to be discussed in a subsequent paragraph), and
- 3) efflux from the previous reactor (temperature equal to that of the previous reactor).

For reactors with a single influx, the temperature of the influx was as specified in the list above. For reactors with two sources of influx the temperature of the influx was assumed to be the temperature which would result from a constant pressure, adiabatic, steady-flow process of mixing the two streams without chemical reaction.

The heat transfer from each reactor was determined as follows. For all reactors in the rear inlet configuration and reactors 7-11 in the tube inlet configuration, the process was assumed adiabatic. For reactors 1-6 in the tube inlet configuration the heat loss from each reactor was taken to be $\dot{Q}_A/6$ with \dot{Q}_A being the heat transfer rate required to raise the temperature of the secondary air flow from 40°C (the measured temperture at the outlet from the vacuum cleaner) to 830°C (the estimated secondary air temperature at the outlet of the tube).

The temperature of 830°C at the tube outlet was estimated using a turbulent convective heat transfer solution for a fully developed velocity profile with thermal entry length. The boundary conditions used were constant wall temperature of 1200°C and initial temperature of 40°C. The constant wall temperature boundary condition was chosen for simplicity and on the basis of a comparison of the three components of the total heat transfer. The three components are the internal convection, the wall conduction, and the external convection resistances. Simple calculations showed the internal convective resistance to be from 6 to 10 times as large as the wall conduction resistance. Intuitively, it was expected that the external convective resistance would be small compared to the internal resistance since the jets of primary combustion products issuing from the fuel magazine were

impinging in crossflow on the outside of the tube. It was on the basis of these simple arguments then, and for the sake of simplicity, that the external convection and wall conduction resistances were assumed negligible. Given this assumption then, a constant wall temperature was the most defensible boundary condition to choose, even though it contradicts the uniform heat flux assumed in dividing the heat transfer equally among the six reactors. The contradiction was allowed because its effect was believed to be small compared to the effect of neglecting heat loss from the primary tunnel reactors to the water jacket.

4.3.2.5 Chemical Kinetic Mechanism

The chemical kinetic mechanism selected is a comprehensive mechanism for moist CO oxidation [24] and is presented in Table 3. The most significant shortcoming of the mechanism is the omission of hydrocarbon species. There are several reasons for this.

First, even a very simple hydrocarbon such as methane would require as many as 30 species and 100 elementary reactions [24], as compared to the 11 species and 23 reactions in the selected CO mechanism. The size of the mechanism increases rapidly for more complex hydrocarbons. Clearly the added complexity and computational cost of including any hydrocarbon species would be significant.

Second, given adequate patience, computing time, and elementary reaction rate data, the significant question of which hydrocarbon species to include remains. In the actual combustion process the number of hydrocarbon species present is quite large, so one could not include them all. However, one of the important effects of the presence of hydrocarbons in the combustion environment under study is that they

Table 3. Chemical Kinetic Mechanism [24] Used in the Gas-Phase Chemical Kinetic Model. The Forward Rate Expression for each Elementary Reaction is of the Form

$K_F = AT^\beta \exp(-E/RT)$
 Reverse rates are given by $K_{rev} = \frac{K_F}{K_c}$
 where K_c is the thermodynamic equilibrium constant, in concentration units, for the given reaction.

<u>Reaction</u>	<u>A</u>	<u>β</u>	<u>E</u>
$H+O_2 \rightleftharpoons O+OH$	5.13×10^{16}	-0.816	16510
$O+H_2 \rightleftharpoons H+OH$	1.82×10^{10}	1.0	8900
$H_2+OH \rightleftharpoons H_2O+H$	2.19×10^{13}	0	5150
$O+H_2O \rightleftharpoons OH+OH$	6.76×10^{13}	0	18360
$H+H+M \rightleftharpoons H_2+M^\dagger$	3.02×10^{15}	0	0
$O+O+M \rightleftharpoons O_2+M$	1.91×10^{13}	0	-1790
$O+H+M \rightleftharpoons OH+M$	1.00×10^{16}	0	0
$H+OH+M \rightleftharpoons H_2O+M$	1.41×10^{23}	-2.0	0
$H+O_2+M \rightleftharpoons HO_2+M$	1.51×10^{15}	0	-1000
$H+HO_2 \rightleftharpoons H_2+O_2$	2.51×10^{13}	0	700
$H+HO_2 \rightleftharpoons OH+OH$	2.51×10^{14}	0	1900
$H+HO_2 \rightleftharpoons H_2O+O$	5.01×10^{13}	0	1000
$HO_2+OH \rightleftharpoons H_2O+O_2$	5.01×10^{13}	0	1000
$HO_2+O \rightleftharpoons O_2+OH$	5.01×10^{13}	0	1000
$HO_2+HO_2 \rightleftharpoons H_2O_2+O_2$	1.00×10^{13}	0	1000
$H_2O_2+OH \rightleftharpoons H_2O+HO_2$	1.00×10^{13}	0	1800
$H_2O_2+H \rightleftharpoons H_2O+OH$	3.16×10^{14}	0	8940
$H_2O_2+H \rightleftharpoons HO_2+H_2$	1.70×10^{12}	0	3750
$H_2O_2+M \rightleftharpoons OH+OH+M$	1.20×10^{17}	0	45500
$CO+O+M \rightleftharpoons CO_2+M$	5.89×10^{15}	0	4100
$CO+O_2 \rightleftharpoons CO_2+O$	2.51×10^{12}	0	47690
$CO+OH \rightleftharpoons CO_2+H$	1.51×10^7	1.3	-770
$CO+HO_2 \rightleftharpoons CO_2+OH$	5.75×10^{13}	0	22930

[†]For all reactions in which the arbitrary third body, M, appears, all species present are assumed to act with equal efficiency so that the molar concentration of M is taken to be simply the molar density of the mixture.

inhibit CO oxidation by consuming OH much more rapidly than CO can in its cominant conversion reaction $\text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H}$ [6,24]. This effect might be qualitatively modeled by including the mechanism for one simple hydrocarbon and including it as a product of primary combustion. Such a model would, however, leave uncertainty as to how the species selection affects the results. For the present modeling effort it was decided to use the relatively simple CO mechanism since it is not clear that significantly more useful results would be obtained in return for the large added effort and expense of including even simple hydrocarbon species.

4.3.3 Conditions Modeled

In order to compare the two different secondary air inlet configurations studied experimentally, the model was configured both ways. The two configurations are the tube inlet and the rear inlet. In the rear inlet configuration the secondary air is added as an input to reactor number 6 (Fig. 9) while in the tube inlet, it is an input to reactor number 1 (Fig. 10).

It is conjectured that the tube inlet will provide more complete combustion in the actual process for the following reasons:

1. better fuel/air mixing due to the longer mixing path.
2. longer time available for noncatalytic secondary combustion.
3. higher temperature of the secondary air due to heat transfer through the tube.

These calculations along with the experimental program should give some insight into whether the difference between the two configurations in

the areas stated in item 2 and 3 above is significant and in either case, help explain why.

The conditions for which the simulation was run are presented in Table 4.

4.3.4 Implementation

The model is implemented as a modified and extended version of a Fortran production code [30], developed at Sandia National Laboratories for modeling perfectly stirred reactors (PSRs). The portions of the model code that are not direct from the PSR production code are presented in Appendix B. The model was run on a VAX 11/780 computer, entirely in double precision. In order to run, the code must be linked with the CHEMKIN package [31].

Table 4. Summary of Conditions Modeled with the Gas Phase Chemical Kinetic Model

<u>Run No.</u>	<u>Temp. (°C)</u>	<u>Sec. Air Configuration^a</u>
1	E [†]	R
2	E	T
3	1400	T
4	1200	T
5	1000	T
6	800	T
7	700	T
8	600	T
9	500	T
10	400	T
11	1400	R
12	1200	R
13	1000	R
14	800	R
15	700	R

^a R = rear inlet, T = tube inlet

[†] E = obtained by solving the energy equation

5. EXPERIMENTAL RESULTS

5.1 Baseline Testing

5.1.1 General

The results of tests 1, 2, and 7 are presented and discussed in this section. Unlike the remainder of the tests discussed in this report, tests 1 and 2 were not run under the author's direction¹ and were not equipped with all of the instrumentation described in section 3.2. However, for the purpose of establishing the baseline performance as discussed in this section, their results are entirely comparable to the author's tests run with the more extensive instrumentation.

All three tests were run without a catalytic secondary combustor and (except for the latter part of test 7) without secondary combustion air. This setup is called the unmodified, or baseline, condition, and these test are referred to as baseline tests. In addition, even though intermittent operation might more realistically simulate important aspects of actual field use, the boiler was run continuously in these tests in order to reduce the number of variables. Tests 1, 2, and 7 were fueled with cordwood of 8, 27, and 19 percent moisture content, respectively. The purpose of these tests was to document the performance of the baseline boiler in terms of emissions (CO/CO₂ ratio), equivalence ratio and, in a rough way, the effects of fuel moisture.

¹These tests were originally reported in reference 28.

5.1.2 Tests 1, 2, and 7

The results of tests 1, 2, and 7 reveal similar trends in equivalence ratio, CO/CO₂ ratio, and character of the batch fuel cycle. Due to the similarities, only the results of test 2 are presented. These results are presented as plots of equivalence ratio and CO/CO₂ ratio vs time in Fig. 11, and secondary tunnel inlet temperature in Fig. 12 and serve to illustrate the important characteristics of the baseline boiler performance as seen in all three baseline tests.

The primary result is clear from Fig. 11 -- the boiler sometimes runs fuel-rich and with high emissions for extended periods. Specifically, the average equivalence ratio and CO/CO₂ ratio were at least 1.20 and 0.18, respectively, during the 400 minutes run time¹. The actual values are higher because the CO analyzer was above its full scale value of 5 percent for about 40 minutes².

The results also show that the boiler is capable of running quite cleanly, as it did from 145 to 153 minutes and from 320 to 350 minutes. During these time windows the CO/CO₂ ratio was less than 0.012 and equivalence ratio was between 0.60 and 0.95. The average combustion efficiency during these periods is estimated to be about 99 percent.

¹The period from 20 min to about 420 min elasped time is considered the run time--in field use, the boiler would have been refueled no later than about 420 min to maintain a useful level of power output.

²All CO measurements exceeding instrument full scale were reduced to the full scale measurement of 5 percent, thus reflecting lower than actual values of equivalence ratio and CO/CO₂ ratio.

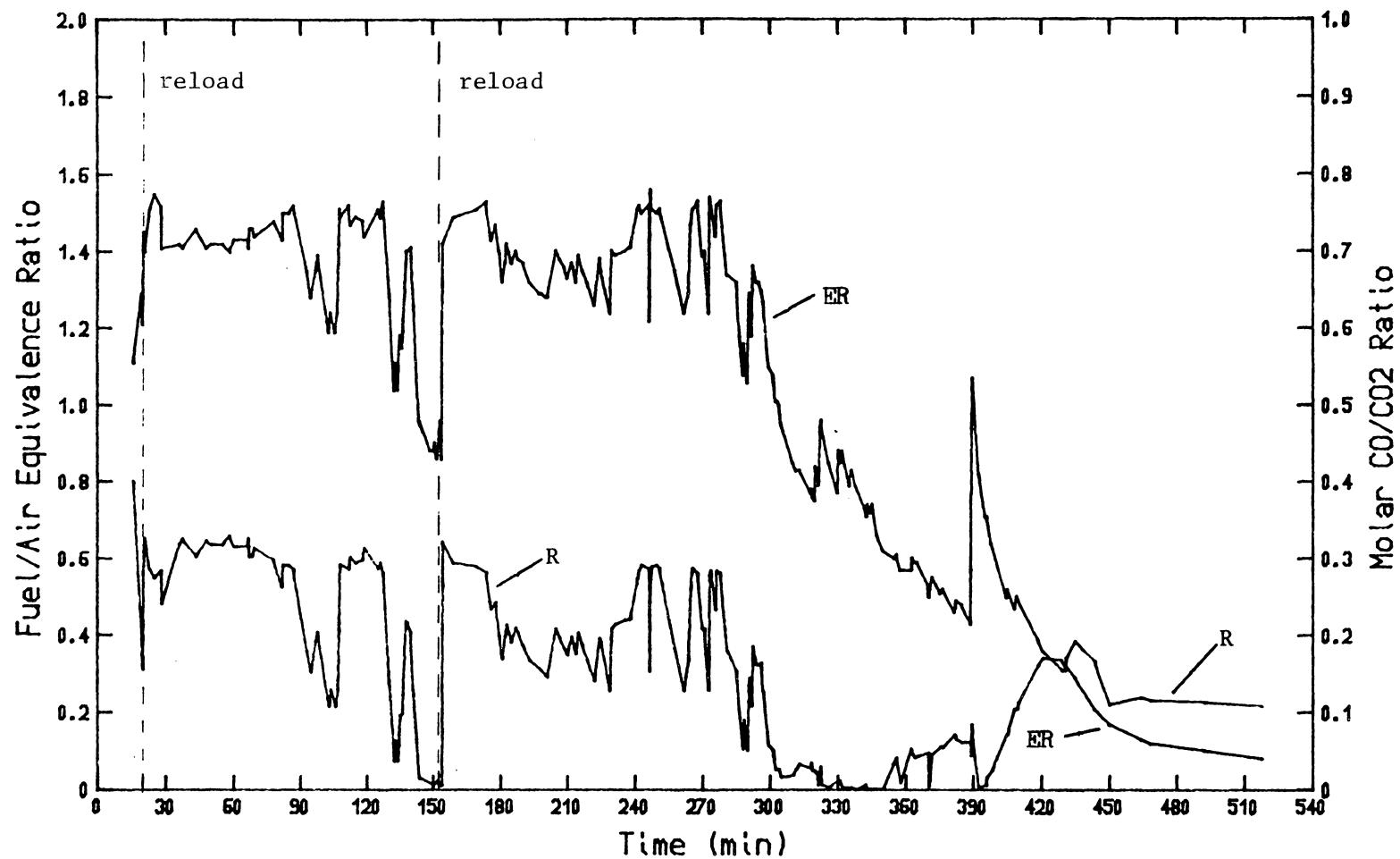


Figure 11. Equivalence Ratio (ER) and Molar CO/CO₂ (R) Ratio During Test 2

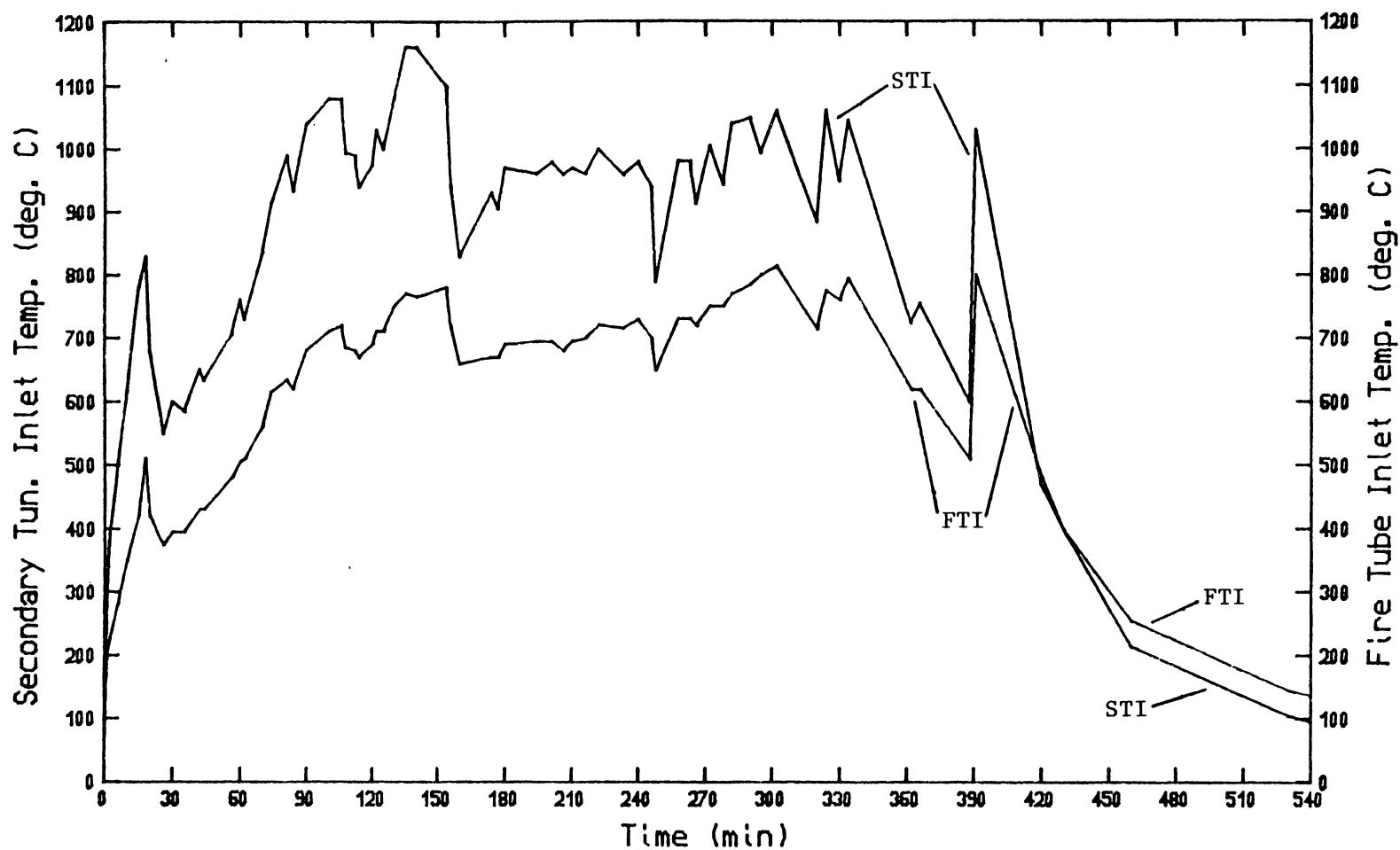


Figure 12. Secondary Tunnel Inlet (STI) and Fire Tube Inlet (FTI) Temperatures During Test 2

The character of the batch fuel cycle can also be seen in the plot of equivalence ratio. A new cycle begins each time a batch of fuel is loaded. The two batch fuel reload times for this test are indicated on the figure. Immediately following the reload at 153 minutes, the equivalence ratio increased abruptly from 0.8 to above 1.5 and remained between 1.3 and 1.5 until about 280 minutes. At that time the equivalence ratio began a downward trend which it followed to the end of the test except for a dramatic but brief increase caused by stirring the fuel at 390 minutes. By the end of the test, the equivalence ratio had dropped to 0.1.

Significantly, the two periods of low emissions which were discussed earlier each occurred in the middle¹ of their respective batch cycles with $0.60 < \phi < 0.95$ (during the period of decreasing equivalence ratio). On the other hand, the periods of high emissions occurred both early in the batch cycle, with $\phi > 1$, and late in the batch cycle with $\phi < 0.6$, and thus a rough correlation between equivalence ratio and emissions is seen, as one would expect. The correlation is clear upon examining Fig. 13 in which CO/CO₂ ratio is plotted as a function of ϕ .

Tests 1 and 7 provide confirmation of the results of test 2. Cycles of equivalence ratio and emissions similar to those in test 2 were observed, with similar maximum and minimum values of these variables. The primary differences between the three tests were the fuel moistures which were 8 percent, 27 percent, and 19 percent for

¹The reader rightfully asks how it is that the low emissions period from 145 to 153 minutes is in the middle of its batch cycle which ends at 153 minutes. The answer is that the reload at 153 minutes prematurely terminated the cycle.

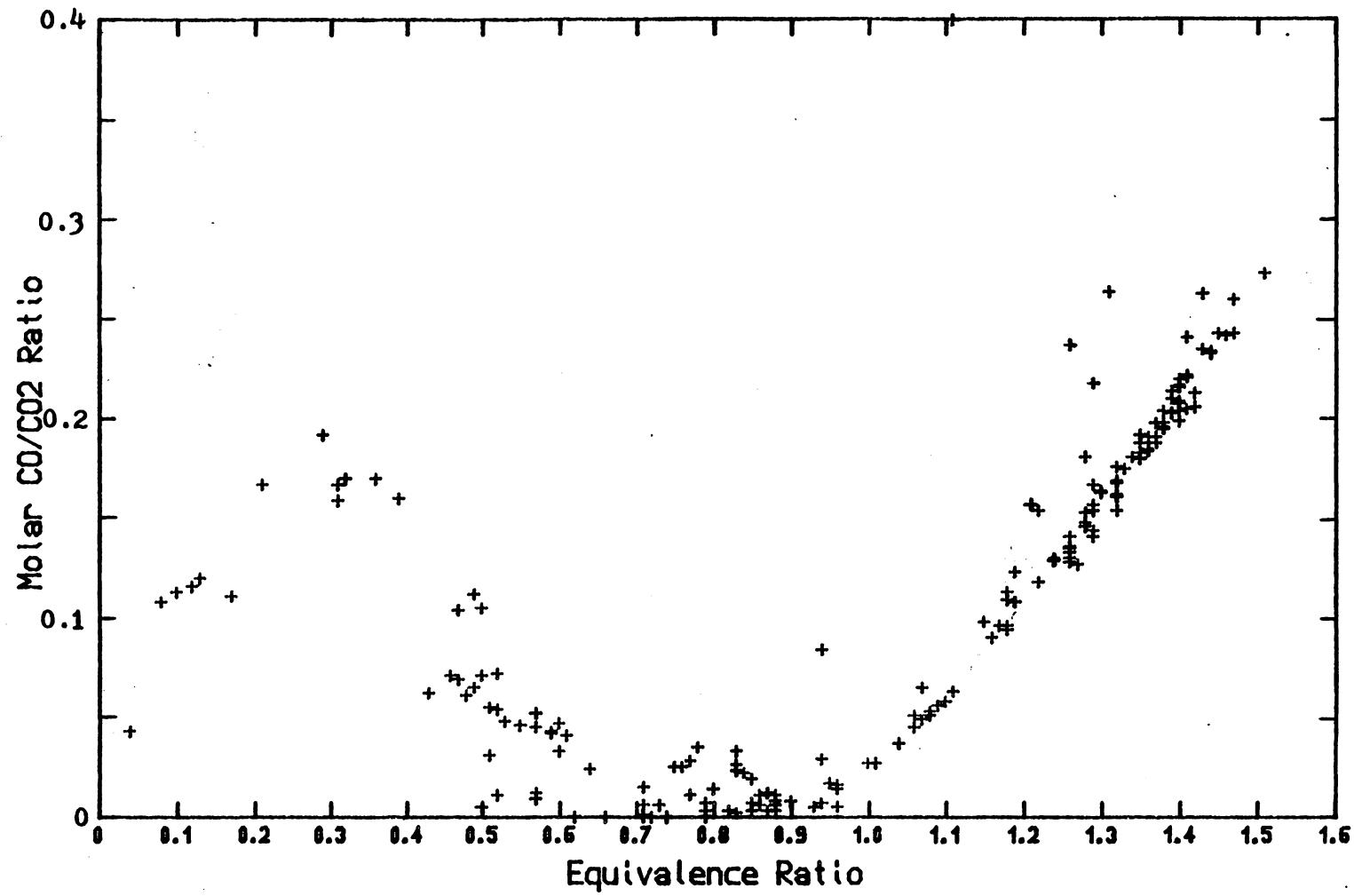


Figure 13. Molar CO/CO₂ Ratio as a Function of Equivalence Ratio During Test 2

tests 1, 2, and 7 respectively. A summary of the baseline tests including fuel type, fuel moisture content, and mass and elapsed time of each reload is presented in Table 5. Since the results of the three tests were essentially the same in spite of the differing fuel moistures, it is concluded that for this range of moisture contents, fuel moisture is not a major variable in regard to its effect on the results discussed in the present section.

On the basis of the foregoing discussion of tests 1, 2, and 7, five conclusions may be drawn. For the boiler in its baseline condition, operated continuously with cordwood fuel in a batch-fueled mode:

1. the CO/CO₂ ratio is in excess of 0.1 for the majority of the operating time,
2. uncontrolled, usually fuel rich, equivalence ratio is the major cause of the high emissions,
3. given an equivalence ratio in the range of 0.6 to 0.95, the boiler is capable of operating with CO/CO₂ < 0.01,
4. the given range of fuel moisture contents does not significantly affect the overall equivalence ratio or emissions behavior, and
5. the batch fuel cycle, which begins when a batch of fuel is loaded, is characterized by a period of relatively steady equivalence ratio in excess of 1.2 followed by a period of gradually declining equivalence ratio which ends when the fuel is completely consumed; the decline is briefly interrupted any time the fuel is stirred.

Table 5 Summary of Baseline Tests¹

	Test Number		
	1	2	7
fuel mc (%)	8	27	19
load 1 mass (kg)			74
load 2 time (min mass (kg)	24	20	78 227
load 3 time (min)	--	153	--
estimated avg. CO/CO ₂ ratio	0.13	0.18	--

¹ All tests shown were fueled with cordwood.

5.1.3 Test 3

This test was run using poultry litter as at 50 percent moisture content. In order to accommodate the fine size of the poultry litter¹, a bridge of refractory blocks was installed over the two rows of openings between the fuel magazine and primary combustion tunnel.

Two features of the data are of particular interest. First, in contrast to runs one and two, the unit ran fuel-lean and with low emissions through the majority of the test. Second, the minimum secondary tunnel inlet temperature corresponding to clean burning (low CO/CO₂ ratio) was only 550°C which is significantly lower than for the cordwood tests. The estimated minimum equivalence ratio corresponding to periods of low CO/CO₂ ratio was also low, being only 0.40. However, the uncertainty in this value is large because of the unknown chemical composition and proximate analysis of the litter. The reasons for these differences are unknown, though speculatively, differences in fuel chemistry could account for them.

5.2 Development Testing

5.2.1 General

Prior to test five, the boiler was shipped back to the manufacturer. A modified version of the boiler was received later, incorporating the rear inlet for admitting secondary combustion air. The boiler was then outfitted with the more extensive instrumentation

¹Litter is a mixture of wood shavings and poultry manure.

described in section 3.2 for tests 5 and 6. However, nearly every test after number 5 resulted in a change in either the boiler, its accessories, or the instrumentation. These changes are documented in detail in the discussion of results of each test, as applicable. To summarize these discussions of apparatus modifications and to make clear the configuration of the entire apparatus for each test, the status of major items is shown in Table 6. This table also provides a summary of the fuel history of each test (consisting of moisture content, mass and elapsed time of each fuel load) and indicates which figures, if any, present data from any given test.

All development tests were cordwood fueled and run continuously (except for occasional forced shutdowns caused by high circulating water temperature or equipment failures). Cordwood was chosen as the single development fuel because it is easy to handle and store and was readily available. It was decided to use the alternate fuels after the final configuration had been shown to work satisfactorily on cordwood. This procedure eliminated a variable during development and thus simplified the process of developing the final boiler configuration.

5.2.2 Tests 5 and 6

These tests had two primary purposes. First, the Bosch heated oxygen sensor was to be tested in the relatively low temperature environment of the boiler stack to determine if it could accurately detect fuel-rich conditions. The same sensor had been shown to work for cordwood, baled slash, and corn fodder fuels in an earlier study [27]. However, in that application, the sensor was located in a significantly

higher temperature area than in the present apparatus. Results of that study showed that the reliability of the sensor is a strong function of temperature below 400°C. Second, it was desired to determine whether maintaining the equivalence ratio below 0.95 would in fact result in significantly lower emissions as one would predict based on results of the baseline tests.

The discussion of results is facilitated by presenting the data in Figs. 14-17. The first two figures present equivalence ratio, emissions, and gas flow rates for test 5 and are discussed in the present section. The last two figures present temperature data for test 5 and are included for later reference. Due to the similarities between tests 5 and 6, the results of test 6 are not presented.

Bosch Sensor

The reliability of the Bosch oxygen sensor in detecting fuel-rich exhaust gas during test 5 can be evaluated by examining Fig. 14 at the points where the mixture switches from lean to rich. The times of interest are 30, 34, 42, 62, 97, 120, 160, and 177 minutes. At all of the times listed, except the one at 34 minutes, the oxygen sensor output exceeds 450 mV, thus agreeing with the calculated equivalence ratio and affirming the reliability of the sensor for indicating fuel-rich conditions. This result is confirmed by all later tests.

The discrepancy in the event of 34 minutes can be plausibly explained. Out of all the "fuel-rich" events listed above, the one at 34 minutes shows the lowest peak equivalence ratio -- 1.04. Also, The oxygen sensor shows a distinct rise in output at 34 minutes but not

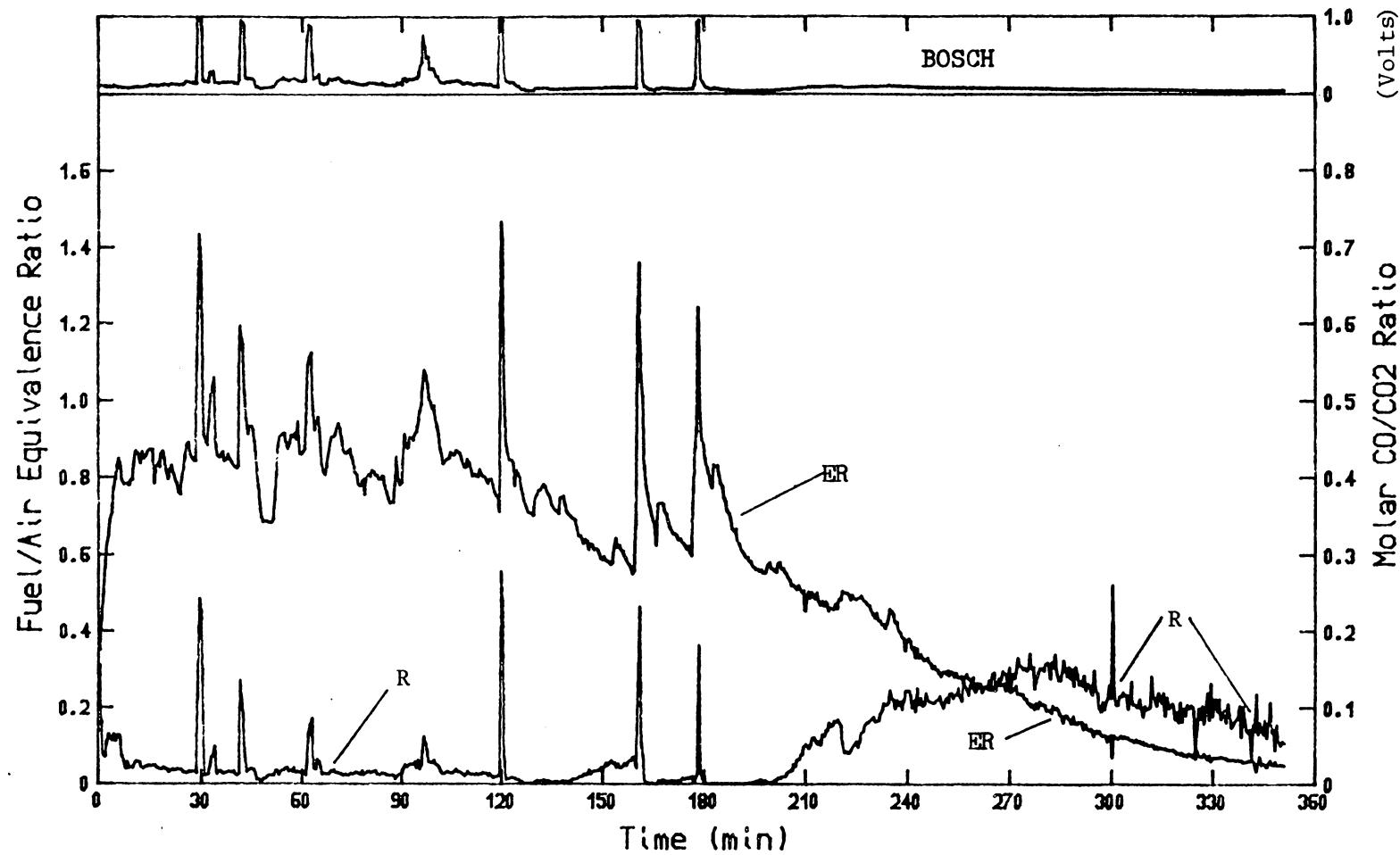


Figure 14. Equivalence Ratio (ER), Molar CO/CO₂ Ratio (R), and Bosch Oxygen Sensor Output (BOSCH) During Test 5

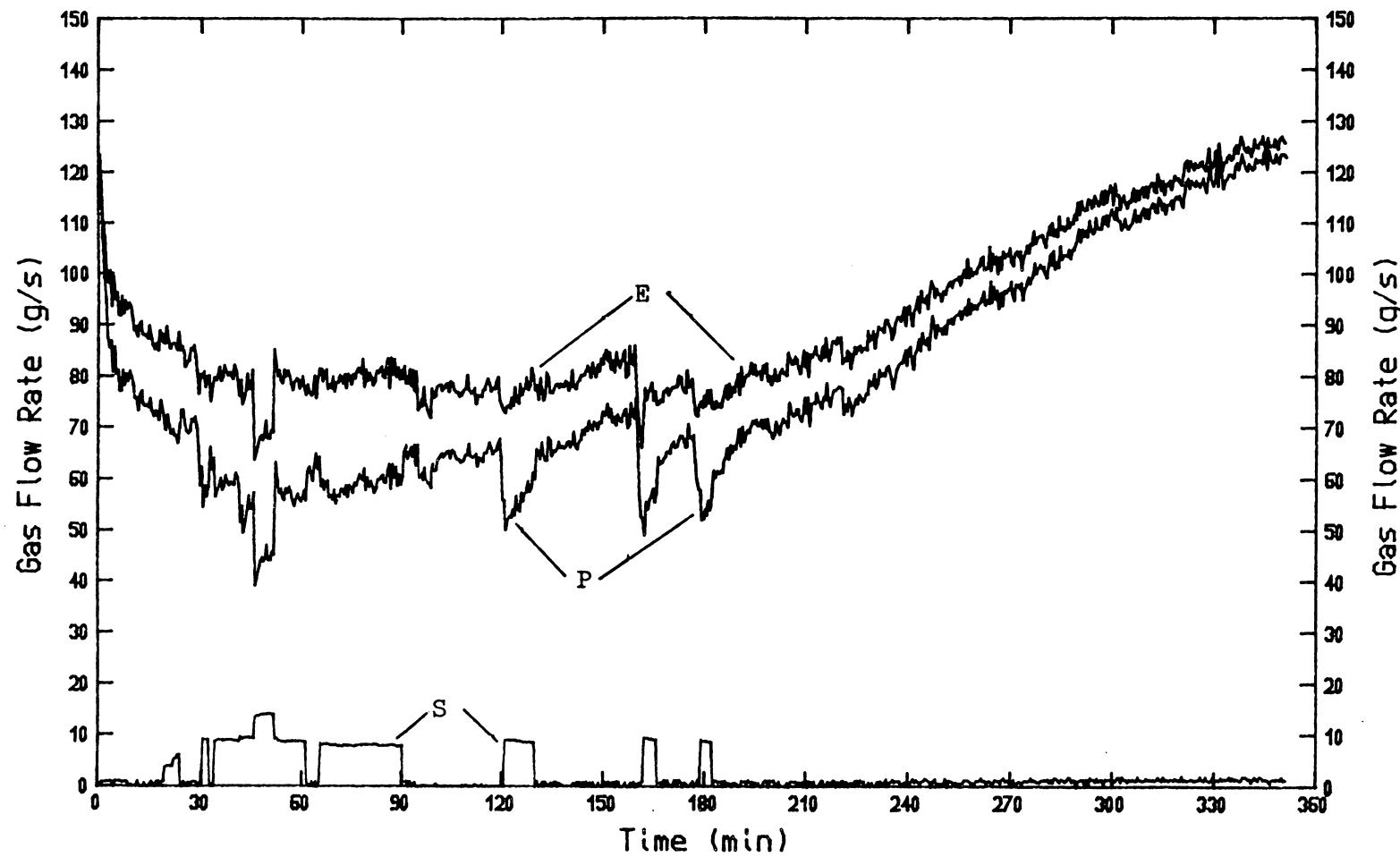


Figure 15. Exhaust Gas Flow Rate (E), Primary Combustion Air Flow Rate (P), and Secondary Combustion Air Flow Rate (S) During Test 5

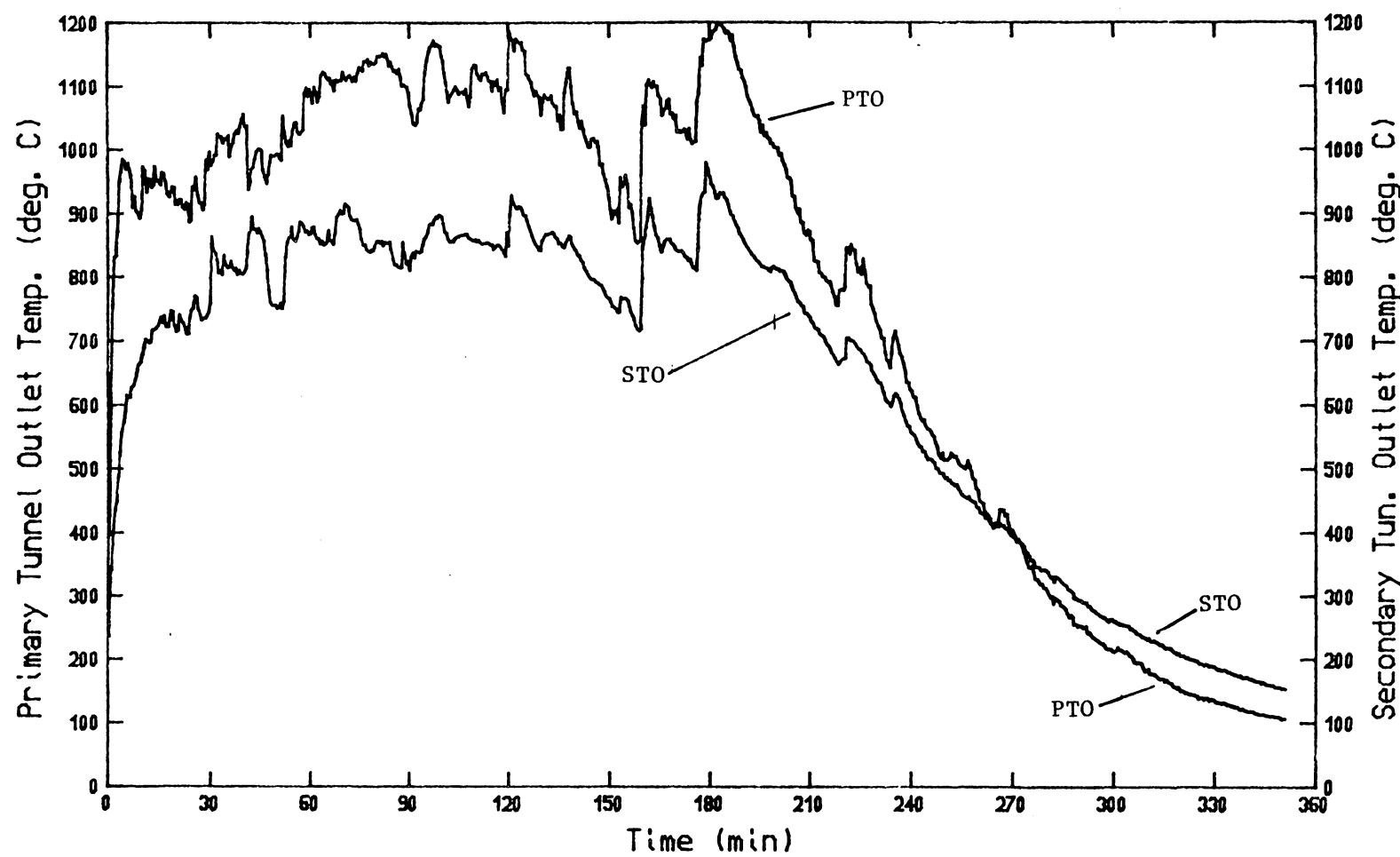


Figure 16. Primary Tunnel Outlet (PTO) and Secondary Tunnel Outlet (STO) Temperatures During Test 5

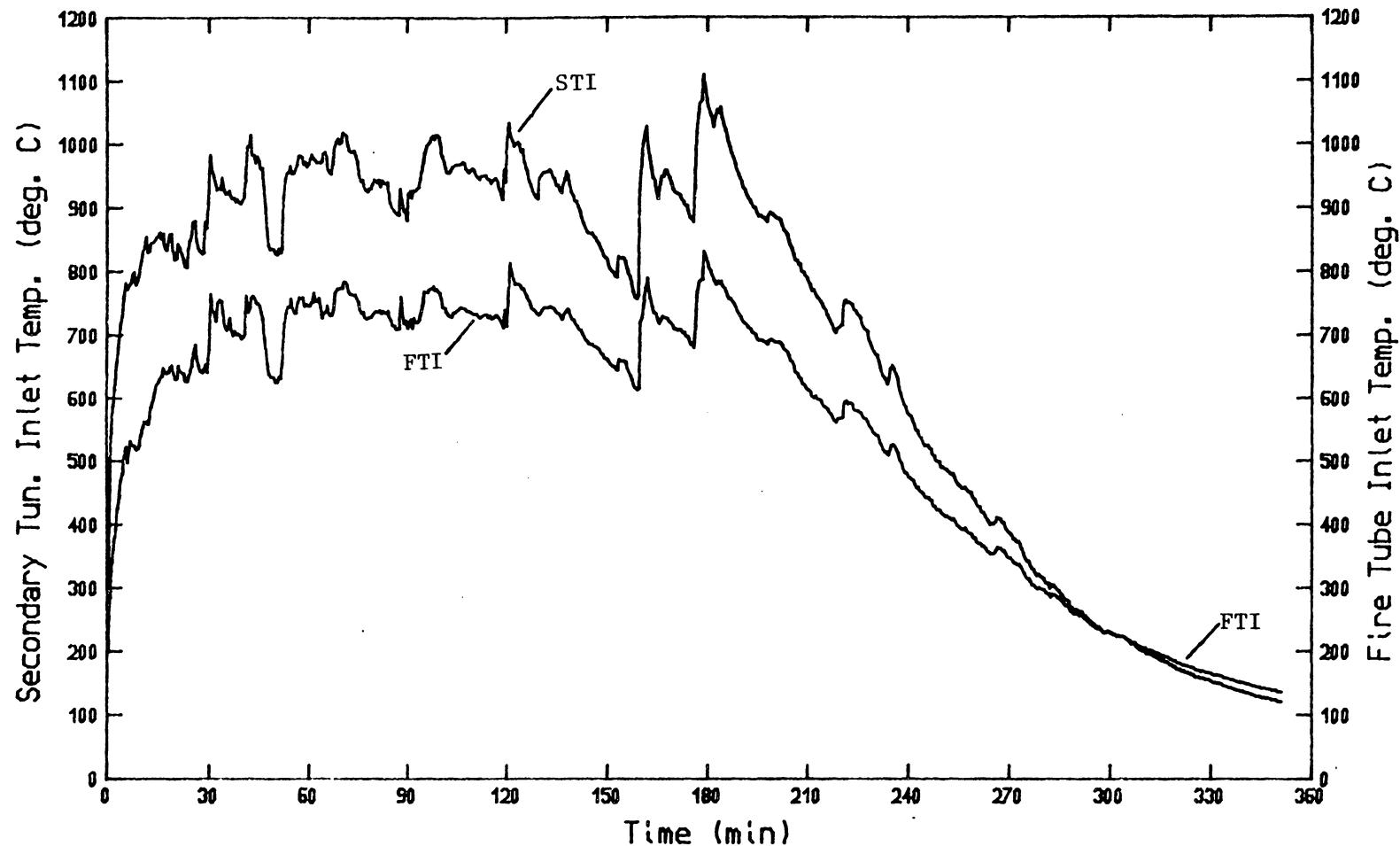


Figure 17. Secondary Tunnel Inlet (STI) and Fire Tube Inlet (FTI) Temperatures During Test 5

TABLE 6. Summary of Development Tests¹

	Test Number									
	5	6	8	9	10	11	12	13	16	17
Fuel mc (%) ²	32	32	18	12	12	11	10	10	7	7
Load 1 mass (kg)	101	46	65	48	64	27	58	48	50	52
Load 2 time (min) mass (kg)	42 98	65 165	46 227	31 112	35 98	15 93	42 110	43 54	65 20	51 98
Load 3 time (min) mass (kg)	-- --	-- --	263 90	-- --	-- --	175 106	250 107	60 56	97 97	144 107
Load 4 time (min) mass (kg)	-- --	-- --	-- --	-- --	-- --	-- --	-- --	265 135	-- --	-- --
sec. air config. ³	R	R	T	T	T	T	R	T	T	T
sec air cap.(g/s)	10	11	22	30	30	30	30	30	30	30
catalytic? ⁴	N	N	N	N	N	N	Y	Y	Y	Y
fan ⁵	OE	OE	OE	D	D	D	D	D	D	D
control ⁶	N	N	N	N	N	N	N	N	G	G
figure numbers	14-17	--	--	19-21	--	22-26	27-31	32-36	38-43	44-48

¹All tests shown here were cordwood fueled²The specified moisture contents apply to loads 2 and later.

Load no. 1 was 7 to 9% moisture on all tests.

³N = no secondary air, R = rear inlet, T = tube inlet.⁴N = no catalytic combustor installed, Y = catalytic combustor installed⁵OE = original equipment fan, D = Dayton fan, installed externally.⁶N = no automatic control, G = G-cell controlled

enough to call the flow rich, indicating that it senses that the equivalence ratio is near, but less than, 1.0. Thus, the two instruments agree that equivalence ratio is near 1.0. The resulting discrepancy easily falls within the uncertainty of the equivalence ratio calculation. Thus, one is inclined to accept the determination of the Bosch sensor. Another possible explanation for the discrepancy is that the quick responding Bosch sensor actually did sense a rich mixture for some short time which just happened not to occur at the time data was collected. This is quite possible as the equivalence ratio measured 1.01 at two data points and 1.04 at only one point.

Emissions

The plots of equivalence ratio, CO/CO₂ ratio and the gas flow rates for test 5, which are presented in Figs. 14 and 15 will serve as the basis of evaluating the boiler's emission performance with manually controlled secondary combustion air. For purposes of this evaluation the run time is somewhat arbitrarily picked to begin at light off (0 minutes) and end when the equivalence ratio drops below 0.4 (236 minutes). The cut-off of 0.4 equivalence ratio is not entirely arbitrary; by the time it gets about that low the boiler would have to be refueled to maintain a reasonable power level.

For this time window, from 0 to 236 minutes, the average CO/CO₂ ratio is about 0.025 while the average equivalence ratio is about 0.75. Comparing these results to those of test 2 it is found that they represent an 86 percent reduction in emissions while equivalence ratio dropped from 1.2 to 0.75. In addition, we find from the plot of

secondary combustion air flow rate in Fig. 15 that the secondary air was on during about 30 percent of the test 5 run time. The test 6 data (not presented) reveals a result similar to test 5, though with slightly higher average equivalence ratio and emissions.

While the tests discussed up to this point have not been sufficiently controlled to permit a meaningful quantitative assessment of the effects of using secondary combustion air, they do lead to an obvious qualitative conclusion -- controlled addition of secondary combustion air can maintain the burning mixture fuel-lean most of the time and thus substantially reduce emissions below those of the baseline unit. This conclusion is in some way confirmed by every remaining test in the current research project.

Resulting Modifications

A review of the results of tests 5, 6, and 7 revealed that a greater secondary combustion air capacity would be needed to adequately provide for future development. Therefore, prior to test 8 a fan was incorporated into the secondary air system, increasing the capacity to about 22 g/s.

The instrumentation in place on the boiler during tests 5 and 6 enabled an evaluation of the level of emissions from the boiler and gave some information which would help explain why the boiler emissions were what they were. Measurements of equivalence ratio, combustion area temperature, and flow rates of primary air, secondary air, and exhaust gas were all available to help explain the performance. Significantly though, no indication was available of the extent to which the burning

gases flowing through the refractory combustion tunnels were radially and circumferentially mixed.

To address this situation, provision for additional temperature measurements was made prior to test 8. Three bare thermocouples were installed at the primary tunnel outlet and three were installed at the left secondary tunnel inlet with each group being in about the same plane as the previous single thermocouples. The three thermocouples in each location were arranged, with roughly equal spacing, on a vertical line intersecting the tunnel axis. It was hoped that we would be able, with this arrangement, to detect radial temperature gradients and infer from their behavior over periods of changing emissions whether inadequate mixing was contributing to higher emissions.

5.2.3 Synopsis of Results and Next Steps

To this point in the test program, it had been established that the unmodified boiler runs dirty as a result of poor control over equivalence ratio. Later, it was shown that controlled addition of secondary combustion air via the rear inlet: 1) could be used to better control the equivalence ratio, and 2) resulted in significantly reduced emissions. With these results the project had a start toward achieving its goal of developing a combustion system which would burn cleanly throughout the fuel cycle and on a variety of biomass fuels.

While the boiler has been shown to run relatively clean with secondary air, it is desired to make it run still more cleanly. It was the original intent in this project to accomplish this with a secondary catalytic combustor. However, economics dictate that if the goal can be

achieved with a simpler, less costly configuration requiring less maintenance, then it should be. It was on this basis that the decision was made to experiment with a simple configuration for preheating the secondary air and mixing it more completely with the products of primary combustion. This configuration is the tube inlet. The important features of the tube inlet are shown in Fig. 18. The mechanism by which secondary combustion might be improved is twofold: First, by increasing the residence time and the length of the flow patch of the secondary combustion air with the products of primary combustion the mixing should be improved and second, the counterflow heat exchanger arrangement (secondary air flow in the tube counter to the primary tunnel flow) provides for the potential of achieving super-adiabatic flame temperatures¹ in the primary tunnel and thus accelerating the chemical reaction rates. An example of how this higher-than-adiabatic flame temperature might be achieved is provided in the results of the chemical kinetic model discussed in section 6.2.2.

5.2.4 Test 8

For test eight, the material selected for the tube inlet was quartz due to its ready availability. However, it was known that the quartz tube would be exposed to temperatures near the limits of its durability so the test was primarily directed to the goal of assessing its durability in this application.

¹i.e., temperatures higher than the adiabatic flame temperature of the final mixture.

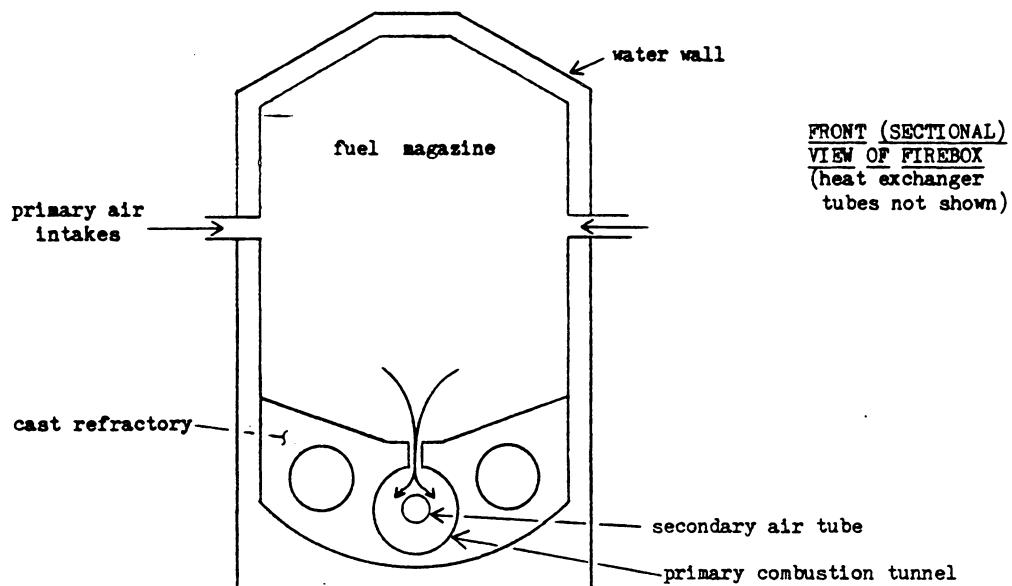
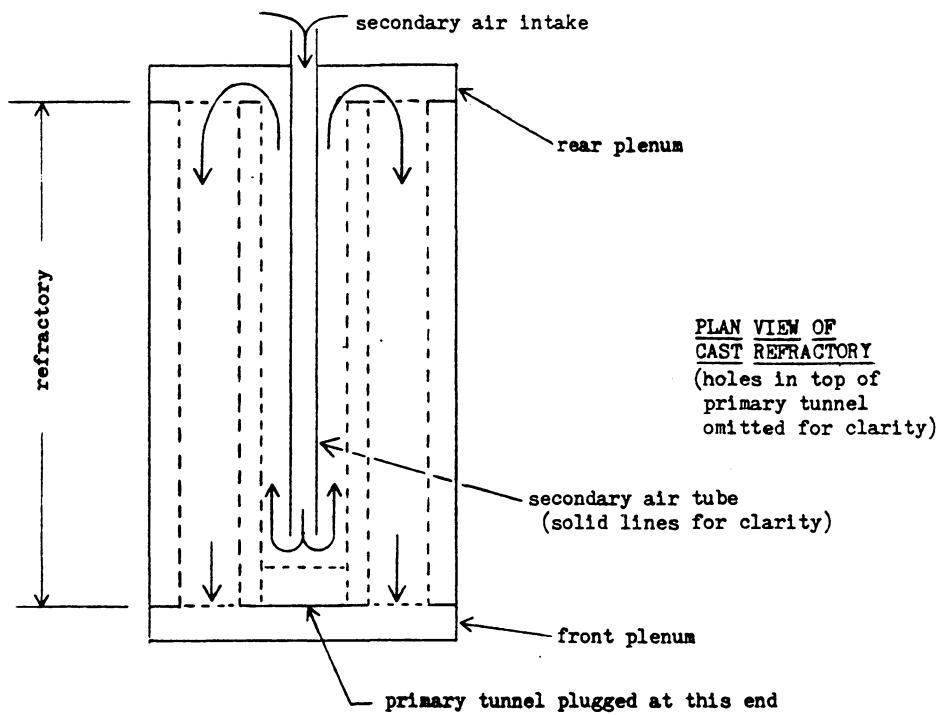


Figure 18. Diagram of Boiler Firebox with the Tube-Inlet Secondary Air Configuration. Arrows Show Flow Path of Air and Combustion Products.

The test ran about seven hours at a normal combustion rate. At the end of the test the quartz tube was found broken into three pieces. Additionally, the entire outside surface of the tube was blistered and discolored. The inner surface was essentially unchanged from before its use in the boiler. Apparently the chemical environment of the combustion tunnel contributed to the deterioration of the exterior while the inside, with air flowing through it, was protected. The conclusion is clear -- a material more durable than quartz would be required for the secondary combustion air tube inlet.

5.2.5 Tests 9 and 10

Prior to these tests, three changes were made. First, a mullite refractory tube¹ was installed as the secondary air tube inlet, for better resistance to the harsh environment². The tube dimensions were 4.45 cm outside dia x 0.32 cm thick wall x 152 cm long. Second, a larger capacity fan (a shop vacuum) was used to supply the secondary combustion air such that a maximum secondary combustion air flow rate of about 30 g/s was obtainable. Third, the original exhaust gas fan, which was an integral part of the heat exchanger, was replaced by an external fan installed at the point where the exhaust gases leave the boiler. The purpose of the new fan was to reduce the potential for erosion of the monolithic catalyst segments which would later be located directly

¹Coor's Porcelain Co., 600 9th St., Golden, CO, 80401, Phone (303-278-4000).

²The mullite tube survived these as well as all subsequent tests with no indication whatever of deterioration. It is concluded, at least for the limited operating times of this test program, that mullite is a suitably durable tube material for the present application.

in the discharge of the original fan and to simplify access to the catalyst segments for cleaning and inspection.

Both tests were aborted due to problems with the new exhaust fan -- test 9 after 130 min and test 10 after 50 minutes. In spite of this, however, useful information was obtained about 1) improvements resulting from the secondary air tube inlet configuration and 2) the relationship between equivalence ratio, secondary tunnel inlet temperature, and CO/CO₂ ratio. Due to the short duration of test 10 and the similarities between tests 9 and 10, only data from test 9 are presented (Figs. 19-21).

In order to gain insight into the relationship between temperature, equivalence ratio, and emissions, it will be helpful to examine the six instances, in test 9, when secondary combustion air flow was started, as shown in Fig. 20. The data will be examined to determine why secondary combustion was strongly initiated at 14, 32, 67, and 95 min, but little or none occurred at 39 and 48 minutes. Several possibilities can be suggested. First, the secondary tunnel inlet temperature¹ may be a critical factor in determining whether or not adding secondary combustion air results in significant secondary combustion. The cases of strong secondary combustion, evidenced by a drop in CO/CO₂ ratio and an increase in secondary tunnel inlet temperature, had secondary tunnel inlet temperatures in excess of 630° while the instances of no secondary combustion occurred with temperatures less than 590°C. Based on these instances, to initiate secondary combustion the minimum required secondary tunnel inlet temperature is above 590°C and below 630°C.

¹As measured just prior to adding the secondary air.

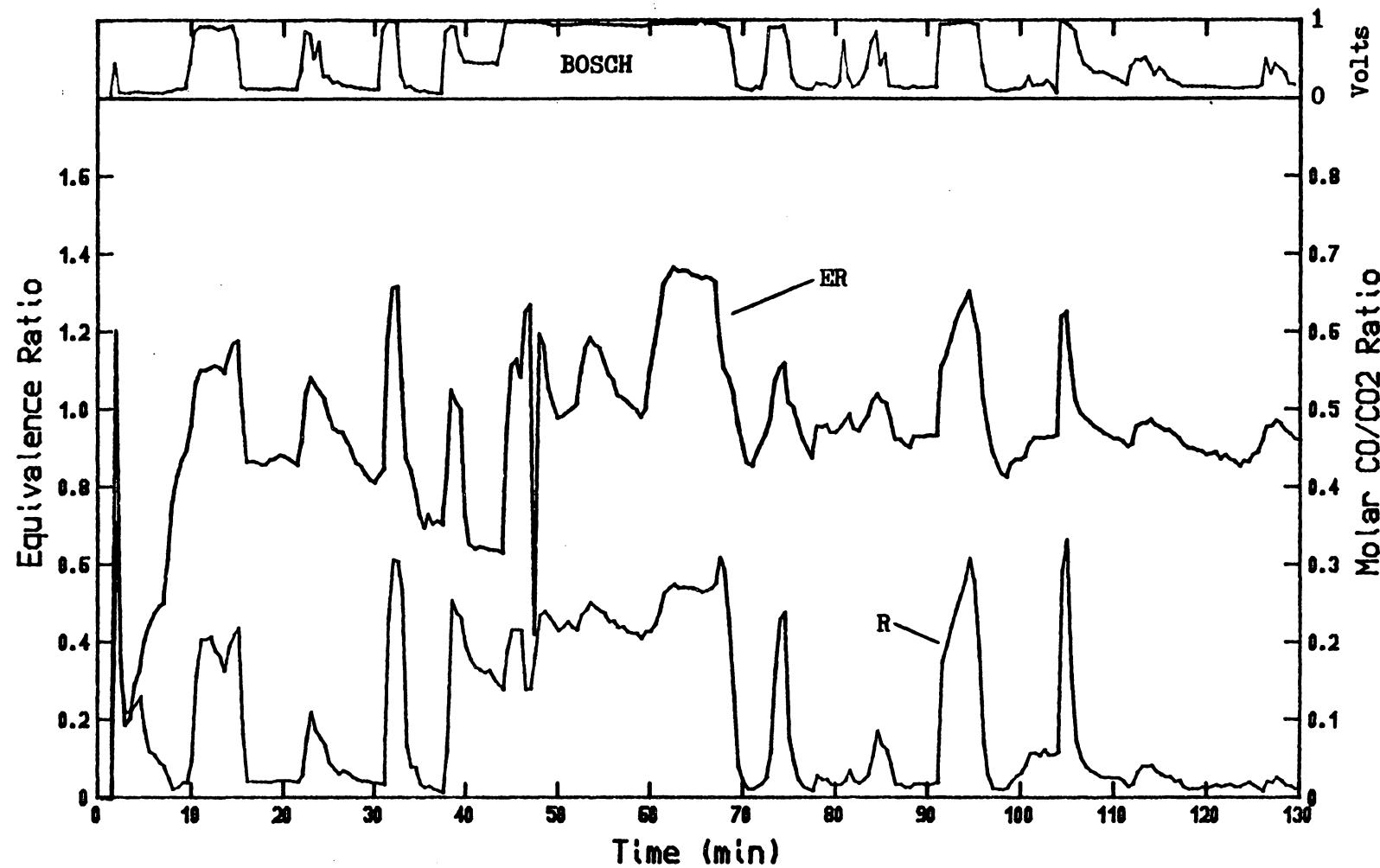


Figure 19. Equivalence Ratio (ER), Molar CO/CO₂ Ratio (R), and Bosch Oxygen Sensor Output (BOSCH) During Test 9

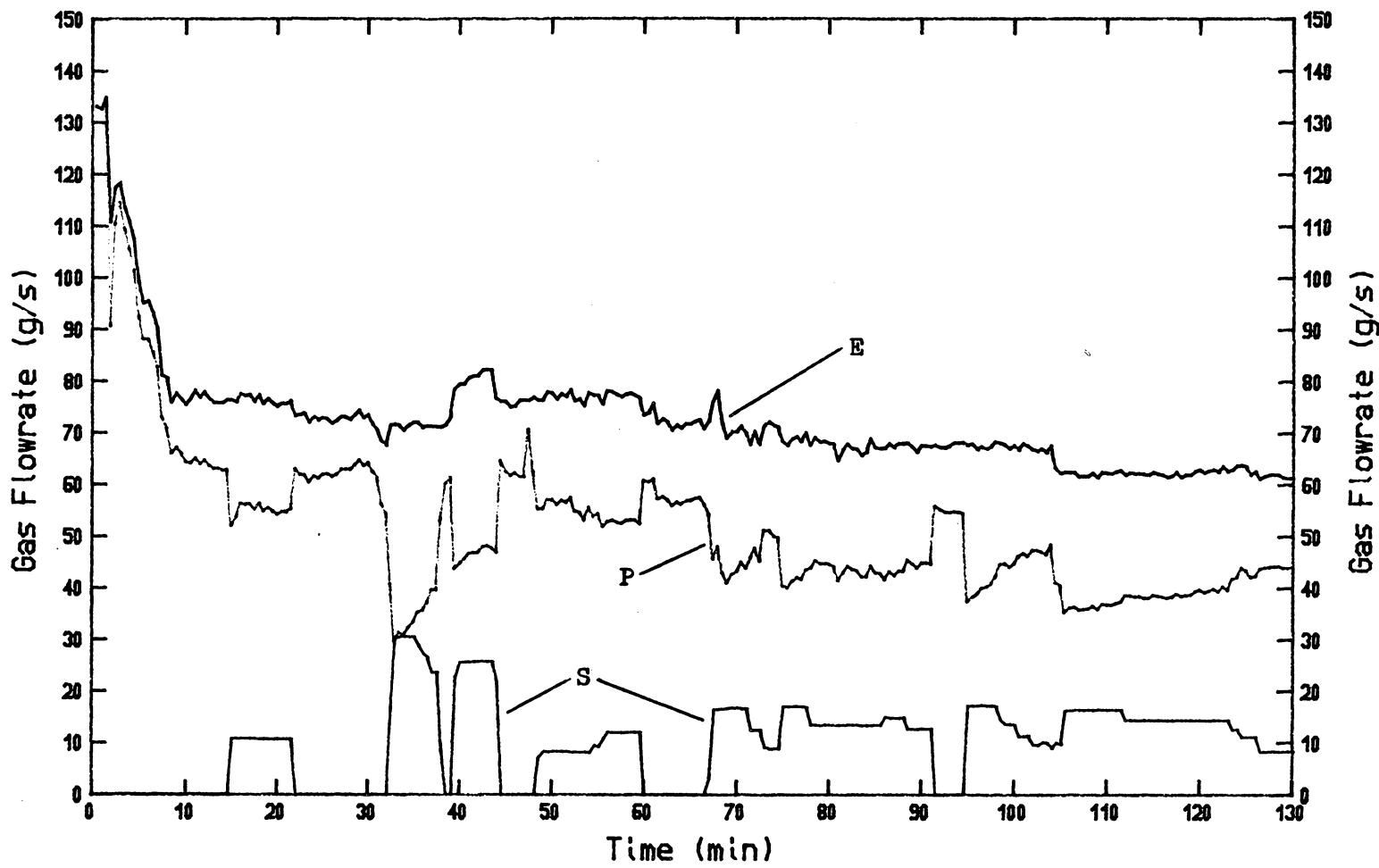


Figure 20. Exhaust Gas Flow Rate (E), Primary Combustion Air Flow Rate (P), and Secondary Combustion Air Flow Rate (S) During Test 9

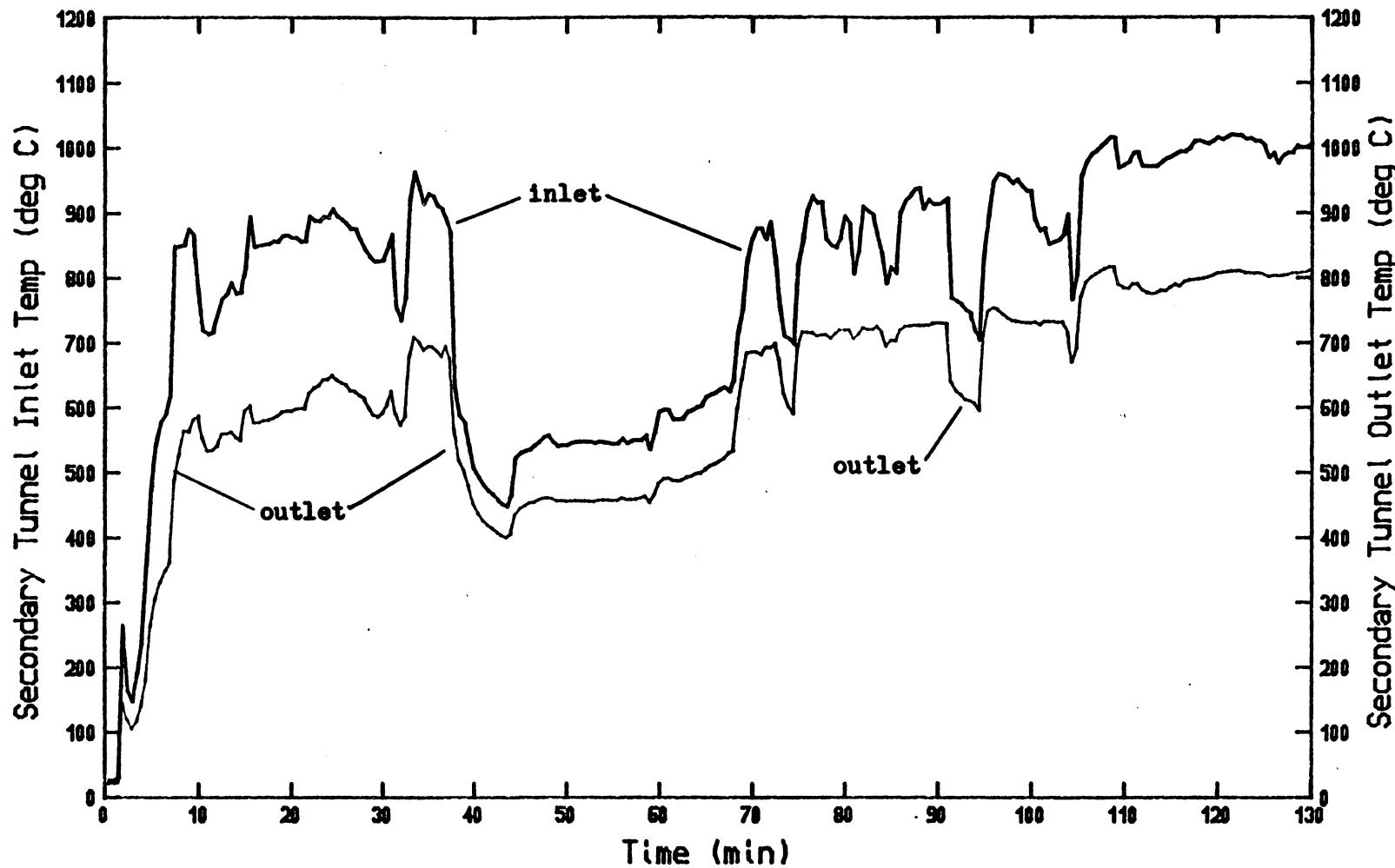


Figure 21. Secondary Combustion Tunnel Inlet and Outlet Temperatures During Test 9

Clearly though, other variables such as the secondary air flow rate and the equivalence ratio could also affect this "minimum" temperature.

A second possible explanation is the equivalence ratio resulting from the addition of secondary combustion air. For strong secondary combustion the equivalence ratio was between 0.7 and 0.9 while for no secondary combustion it was below 0.65 or above 1.0. These results indicate that an equivalence ratio control setpoint should be between 0.7 and 0.9. Since the higher equivalence ratios result from a higher burn rate and thus higher power output, the upper end of this range would be the more desirable.

5.2.6 Test 11

Test 11 was run in order to verify and further explore the secondary combustion effects observed in test 10 with the tube inlet configuration for secondary air. Results are presented in Figs. 22-26.

Addition of secondary combustion air was effective in maintaining a fuel-lean mixture following batch loads and at least modestly successful in reducing the CO/CO₂ ratio as compared to the baseline condition. For 30 minutes following the first reload (at 15 minutes elapsed time), equivalence ratio and CO/CO₂ ratio averaged 0.75 and 0.025 respectively with secondary combustion air flow ranging from 20 to 30 g/s. Similar results were obtained following the second reload (at 176 minutes). Equivalence ratio and CO/CO₂ ratio averaged 0.70 and 0.008 respectively for the 60 minutes following the second reload, while secondary combustion air flow was 30 g/s during the same period. In contrast, the baseline unit typically had greater than 1.4 equivalence ratio and 0.2 CO/CO₂ ratio for an hour or more following batch loading.

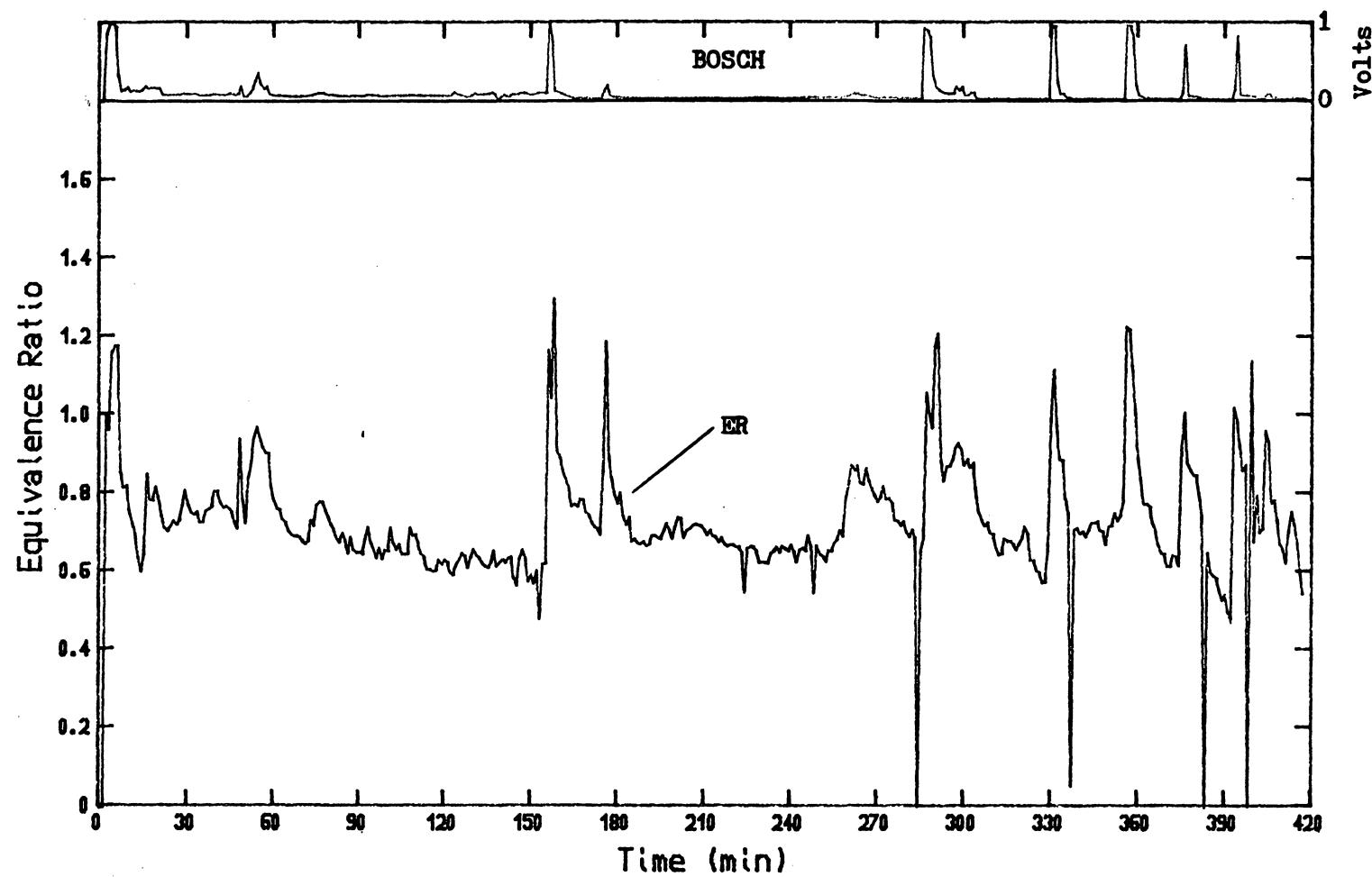


Figure 22. Equivalence Ratio (ER) and Bosch Oxygen Sensor Output (BOSCH) During Test 11

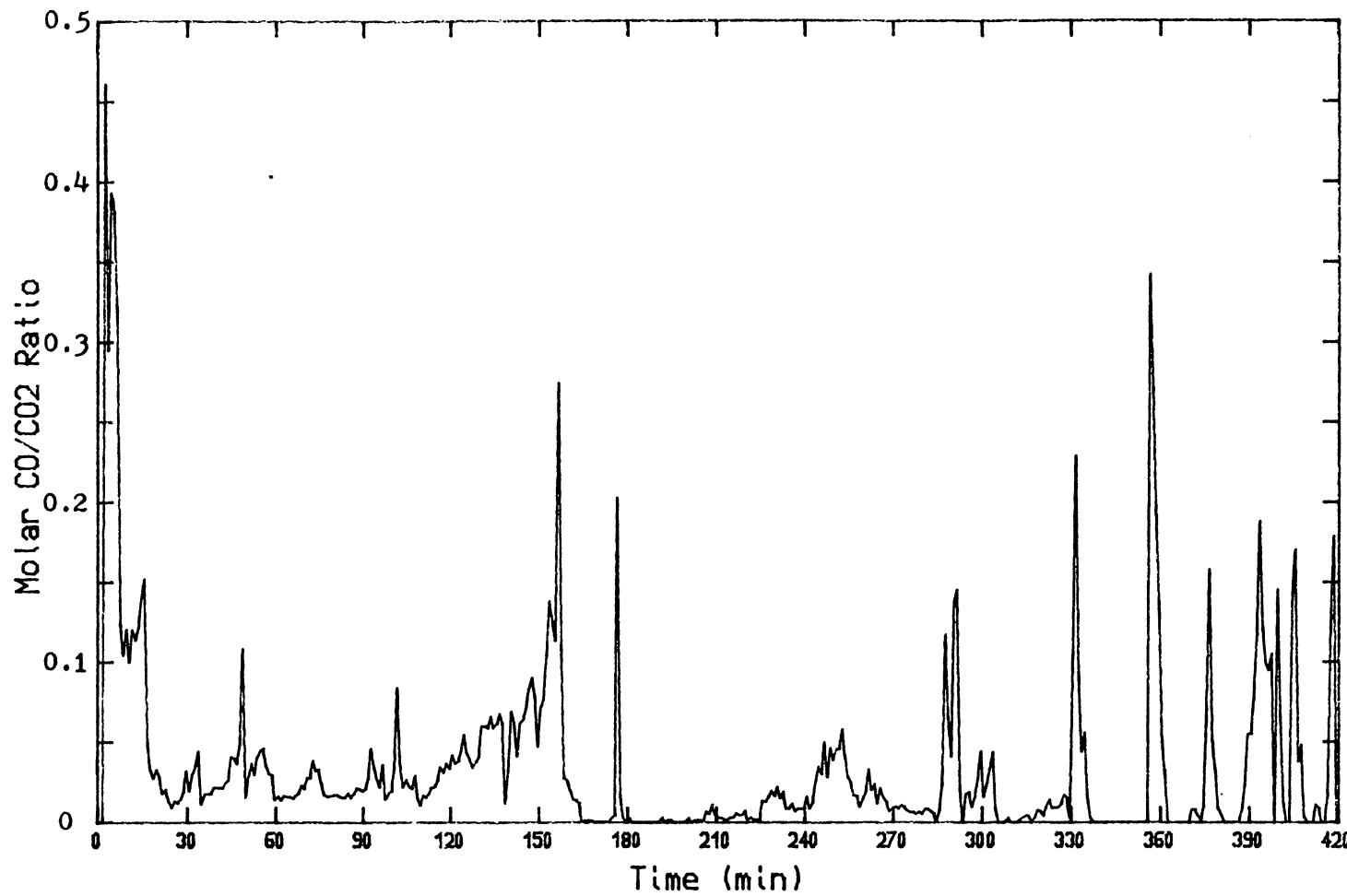


Figure 23. Molar CO/CO₂ Ratio During Test 11

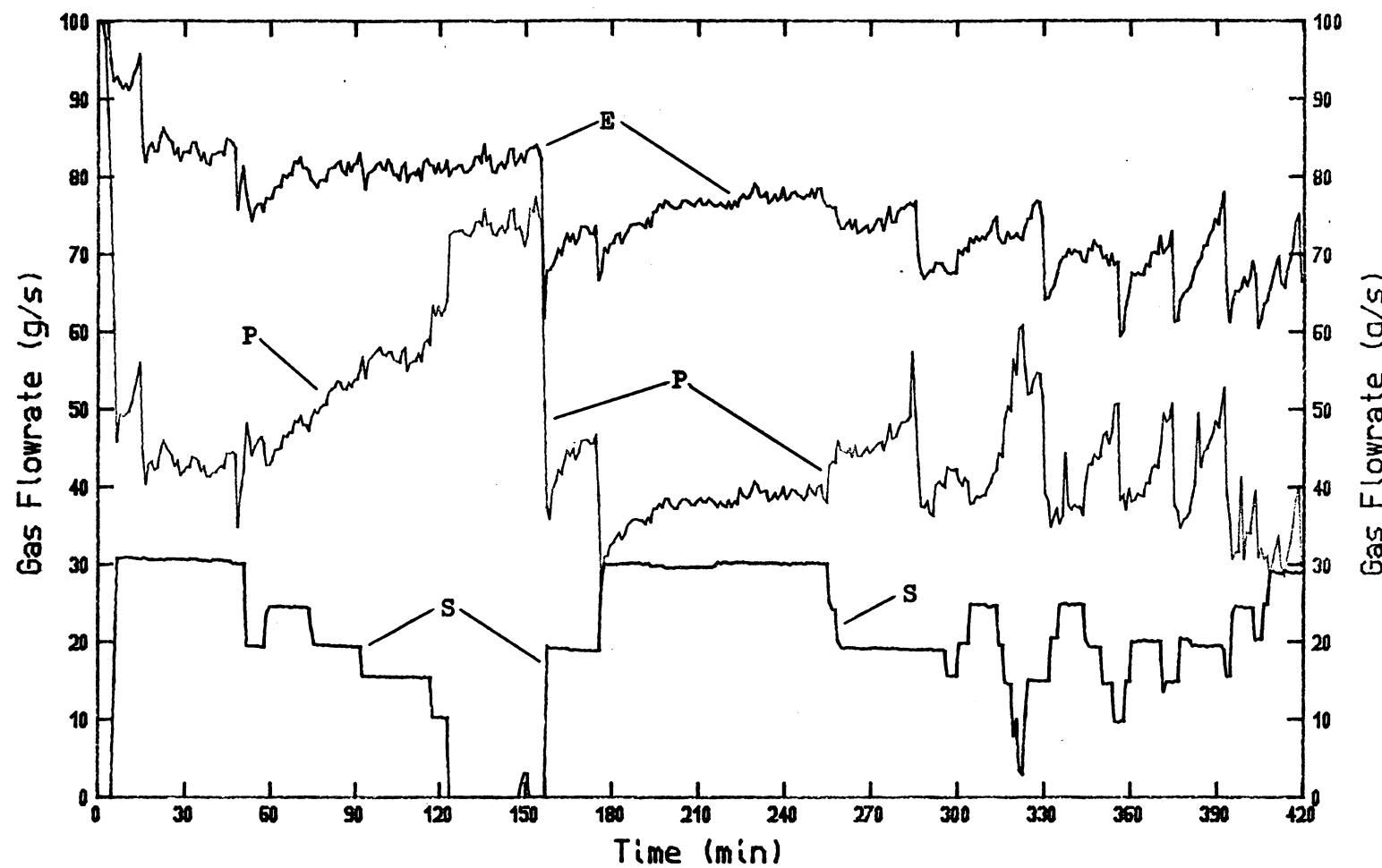


Figure 24. Exhaust Gas Flow Rate (E), Primary Combustion Air Flow Rate (P), and Secondary Combustion Air Flow Rate (S) During Test 11

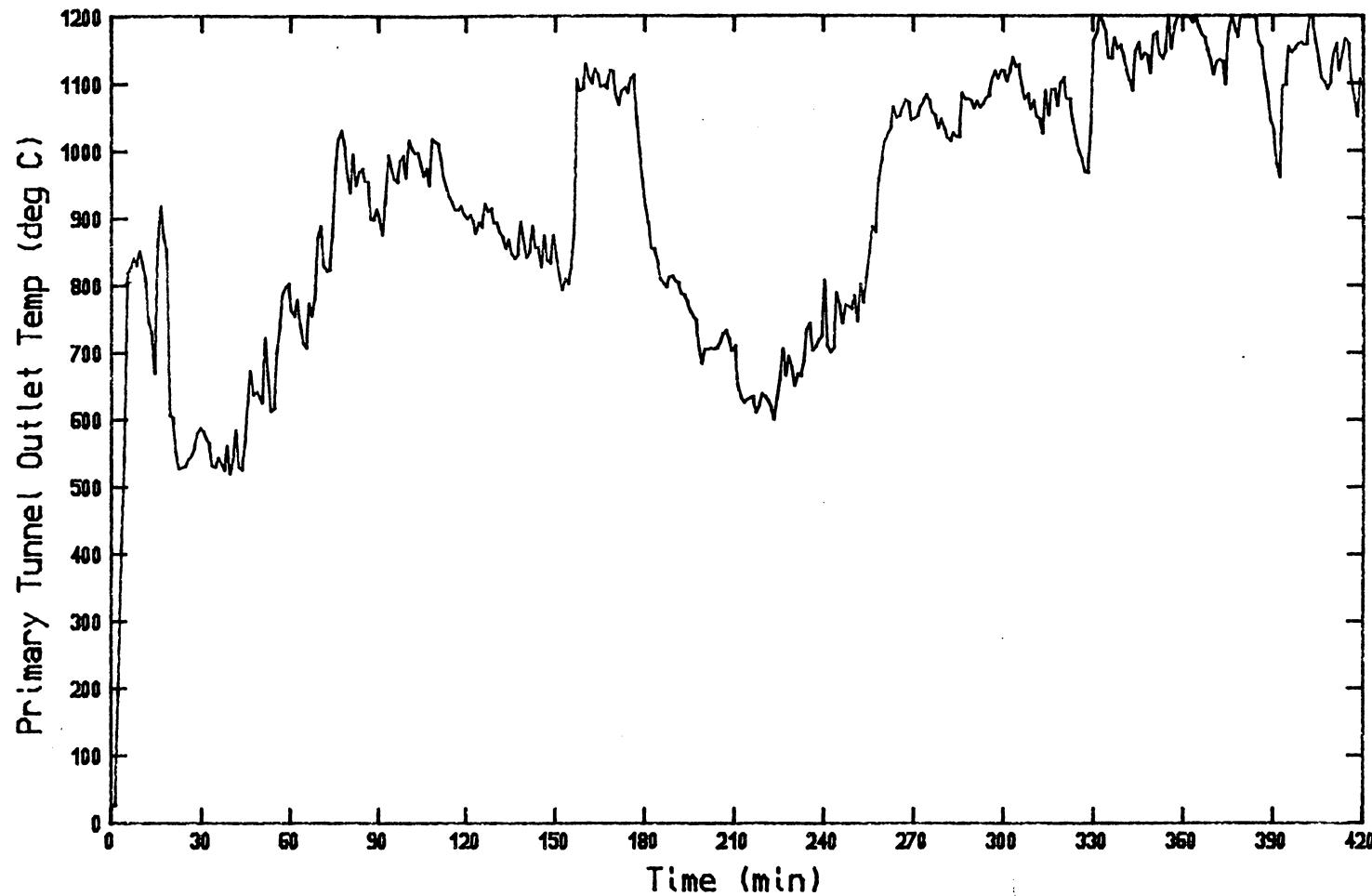


Figure 25. Primary Combustion Tunnel Outlet Temperature During Test 11

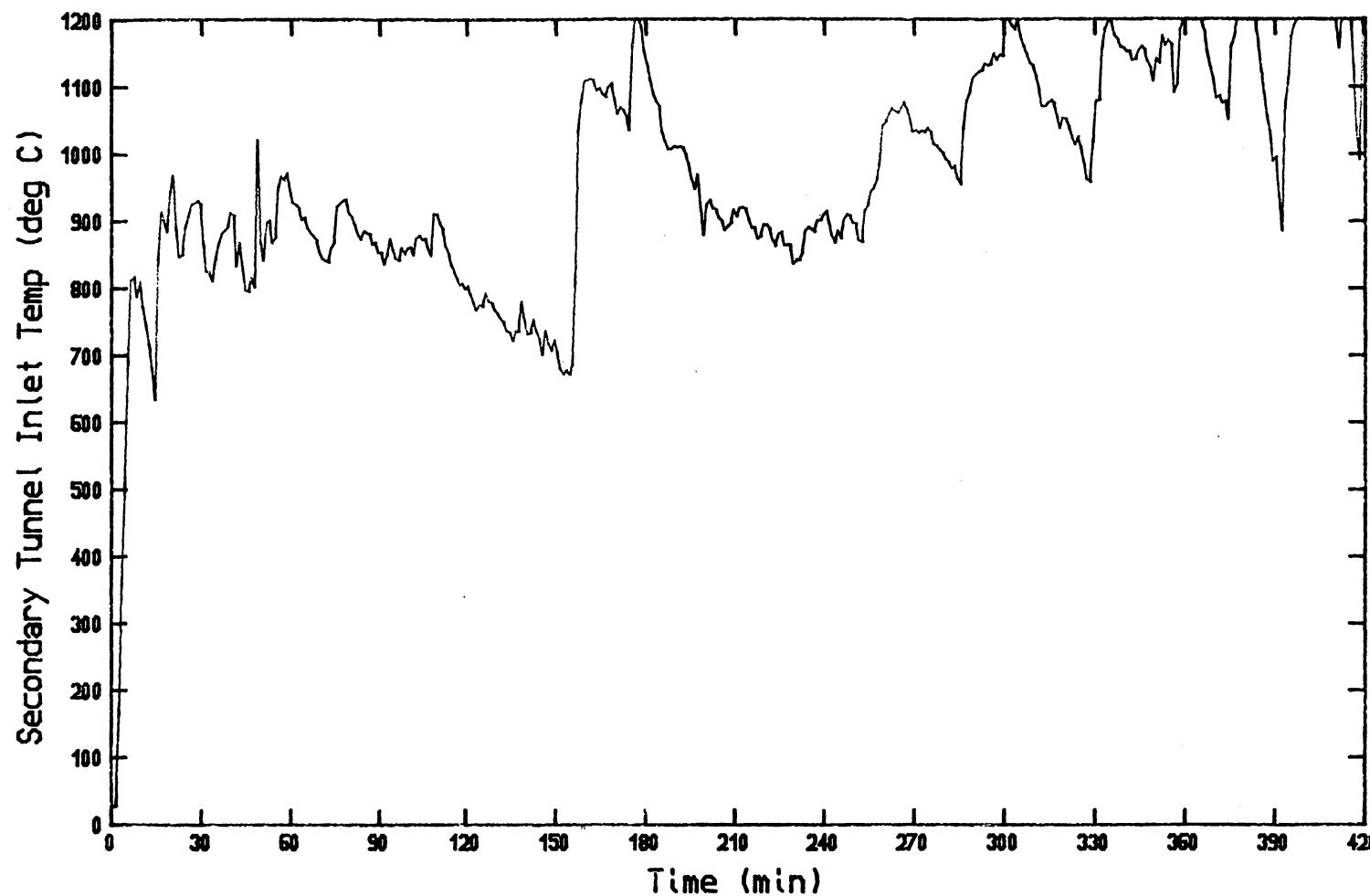


Figure 26. Secondary Combustion Tunnel Inlet Temperature During Test 11

It will also be useful to examine the periods of relatively high emissions to determine what conditions caused them. During the period from 120 to 155 minutes the CO/CO₂ ratio gradually increased from about 0.02 to a peak of 0.14. This period was later in the batch cycle than the clean 30 minutes period immediately following reload. Also, there was no secondary combustion air flow since the equivalence ratio of the primary combustion products had fallen to about 0.65, whereas immediately following reload, 30 g/s secondary air flow was required to keep the equivalence ratio at about 0.75. Secondary tunnel inlet temperatures were also different. During the dirty period they ranged from 680 to 790 °C, while during the clean period the range was 800 to 970°C. Differences in how well the burning mixtures were mixed can be inferred from the uniformity of the primary tunnel outlet and secondary tunnel inlet temperature profiles. A flow with a uniform temperature profile is judged to be better mixed than a flow with a very non-uniform profile. On this basis, the dirty flow is better mixed than the clean flow immediately following reload, thus either the measured temperature profile is not a good indicator of the extent of mixing or mixing was unimportant, relative to other variables, in affecting emissions.

These results indicate that higher temperature was the only measured variable that would explain the better performance during the 30 minutes immediately following the first reload. However, unmeasured variables could contribute to the differences as well. One possibility is the difference in chemical composition of the fuel between early in the batch cycle and late in the batch cycle. This is probably not an important variable though, since the fuel was stirred at 156 minutes

without adding new fuel. The period immediately following the stirring is characterized by secondary tunnel inlet temperature rising in several minutes from 680°C to 1100°C, a secondary air flow of 20 g/s, equivalence ratio ranging from 0.90 to about 0.70, and CO/CO₂ ratio dropping to 0.02 immediately and then down below the resolution of the gas analyzer to about 0.001. This was an extremely clean period, thus changes in the chemical composition of the fuel being consumed cannot explain the deteriorating performance from 120 to 155 minutes.

Following test 11, several changes were made to the boiler and instrumentation. First, one row of monolithic catalyst segments¹ was installed in the inlet to the annulus of the heat exchanger. Each segment measured roughly 4.5 cm x 7.5 cm in cross-section and 5.0 cm long in the flow direction. Each segment was individually "canned" in a stainless steel band after being wrapped with a layer of flexible refractory¹. The canned segments were then fit together in the annular space and the open spaces around and between them were packed with flexible refractory to prevent combustion products from bypassing the catalyst segments. Installed together, these segments form the catalytic combustor. A thermocouple was installed immediately downstream of the catalytic combustor so that, in combination with the existing fire tube outlet temperature, a temperature rise across the catalyst could be obtained.

¹"Long-Life" ceramic rectangular catalytic combustor; 25 cells/square inch, purchased from Corning Glass Works, Technical Products Division.

¹Interam-B, Minnesota Mining and Manufacturing Co.

Also following test 11, the Infrared Industries gas analyzer was replaced with a Horiba model PIR 2000 CO₂ and CO analyzers. Data taken up to this point indicated that the span of the Infrared Industries IR702 CO₂ analyzer was drifting down during tests. The estimated maximum drift in the CO₂ span on the analyzer (Infrared Industries model IR702) was down 10% of full scale. This will have little effect on the evaluation of the boiler performance made up to this point, though.

Since the catalyst segments were in place it was decided that the air inlet should be the simplest possible, since the catalyst would improve the combustion efficiency. Therefore, the rear inlet configuration was chosen for the next test.

5.2.7 Test 12

The purposes of test 12 were to begin evaluating the catalytic combustor and to investigate the rear inlet configuration with the higher secondary air flow capacity now available. Results are presented in Figs. 27-31.

The most notable feature of test 12 was the loss of noncatalytic secondary combustion at about 52 minutes followed by an extended period of high emissions and subsequent re-establishment of noncatalytic secondary combustion at about 102-105 minutes. Noncatalytic secondary combustion had been established following reload, as evidenced by the .008 CO/CO₂ ratio and the secondary tunnel inlet temperature of between 870 and 950°C (up from 800°C prior to reload) during the period from 45 to 52 minutes. At 51.5 minutes, however, the CO/CO₂ ratio suddenly increased from 0.01 to 0.10 while the secondary tunnel inlet temperature

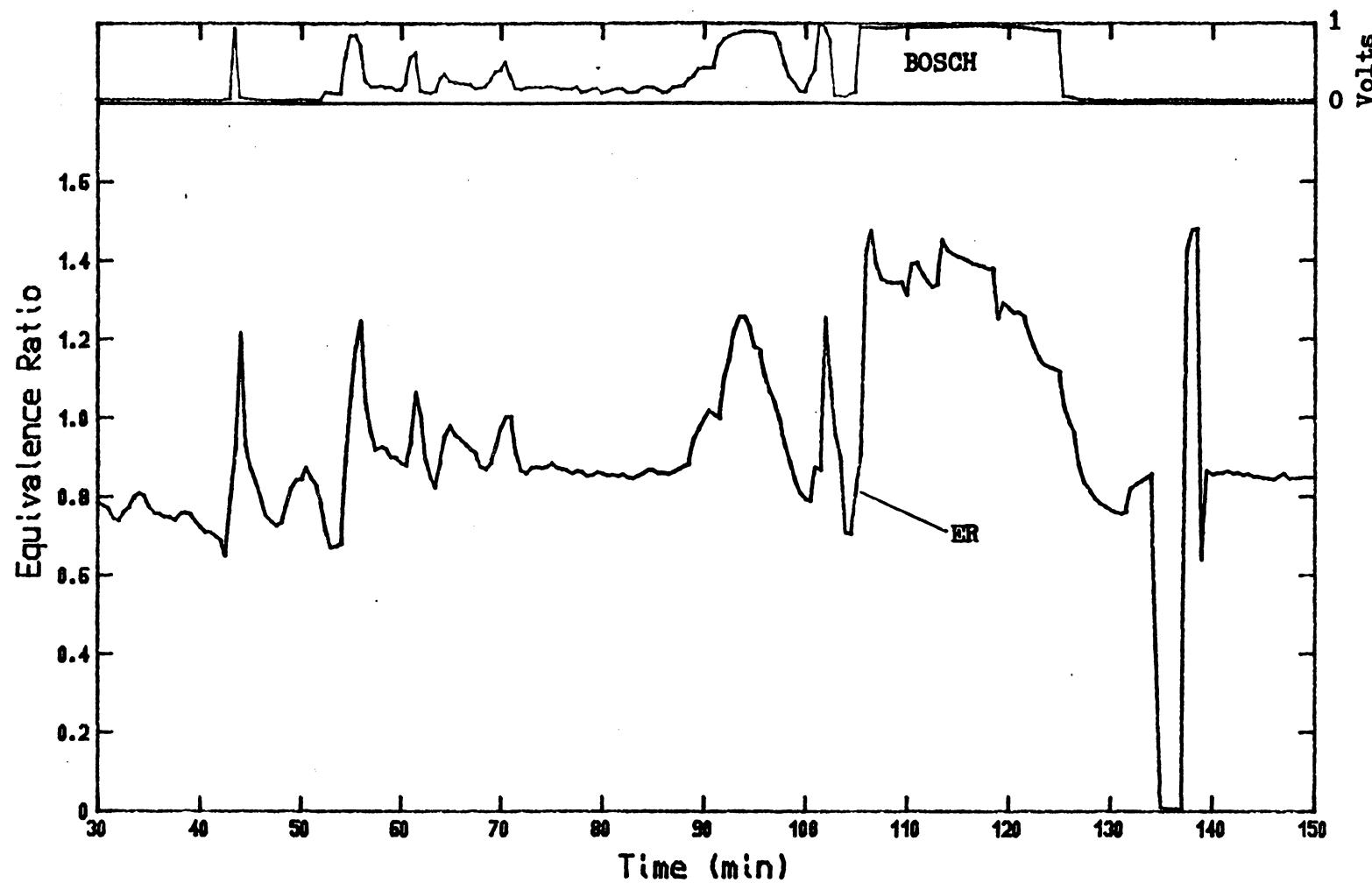


Figure 27. Equivalence Ratio (ER) and Bosch Oxygen Sensor Output (BOSCH) During Test 12

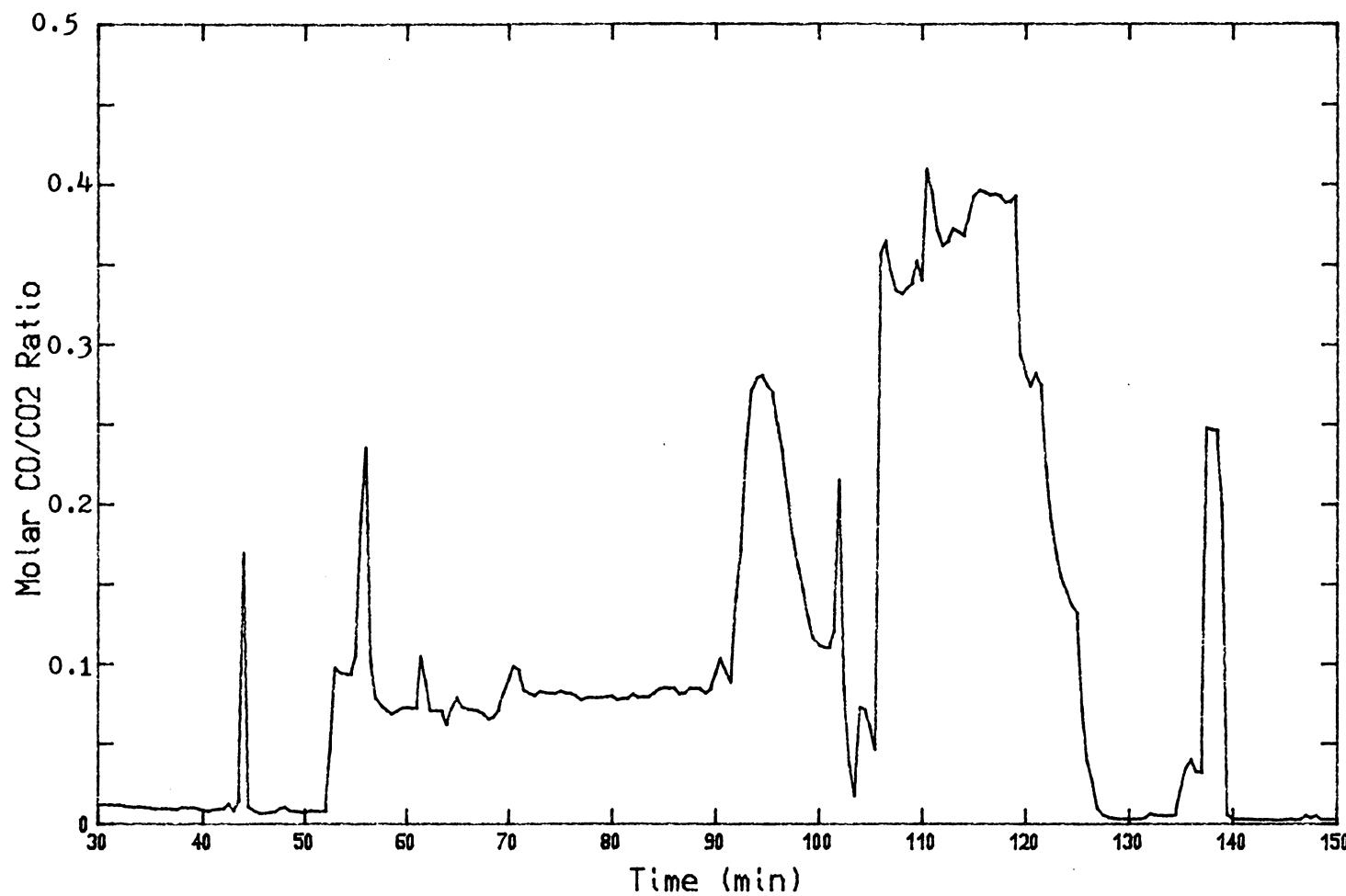


Figure 28. Molar CO/CO₂ Ratio During Test 12

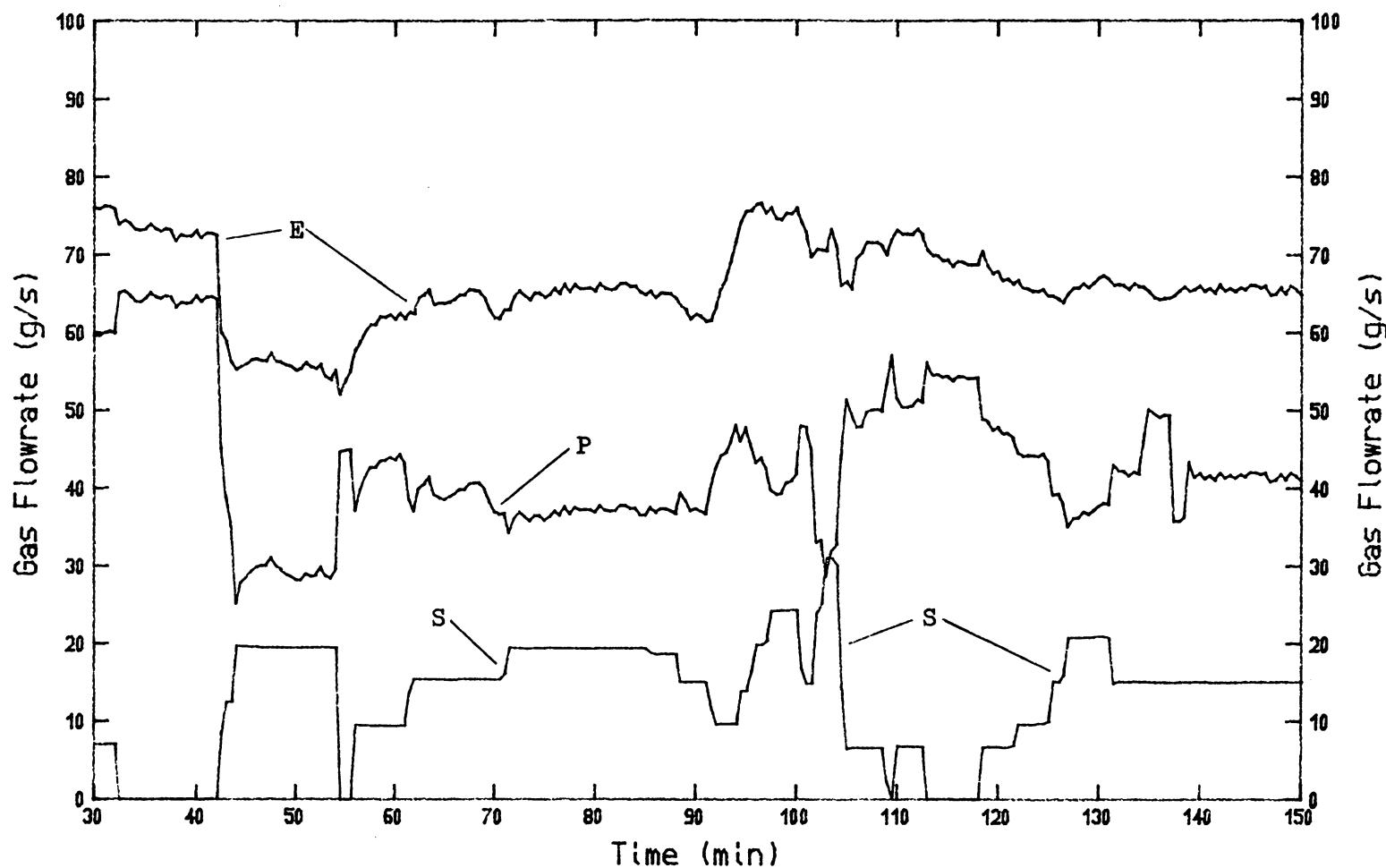


Figure 29. Exhaust Gas Flow Rate (E), Primary Combustion Air Flow Rate (P), and Secondary Combustion Air Flow Rate (S) During Test 12

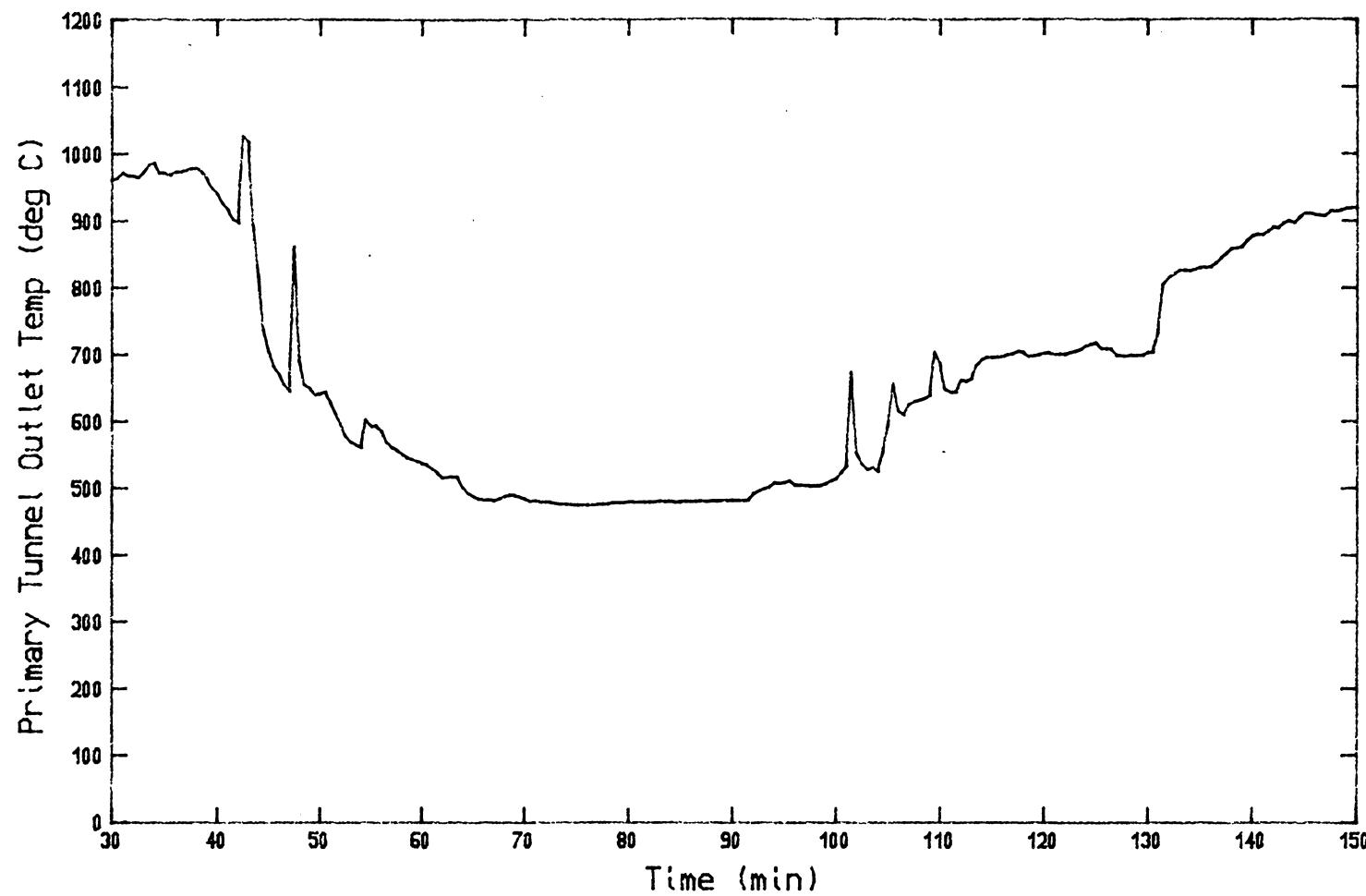


Figure 30. Primary Combustion Tunnel Outlet Temperature During Test 12

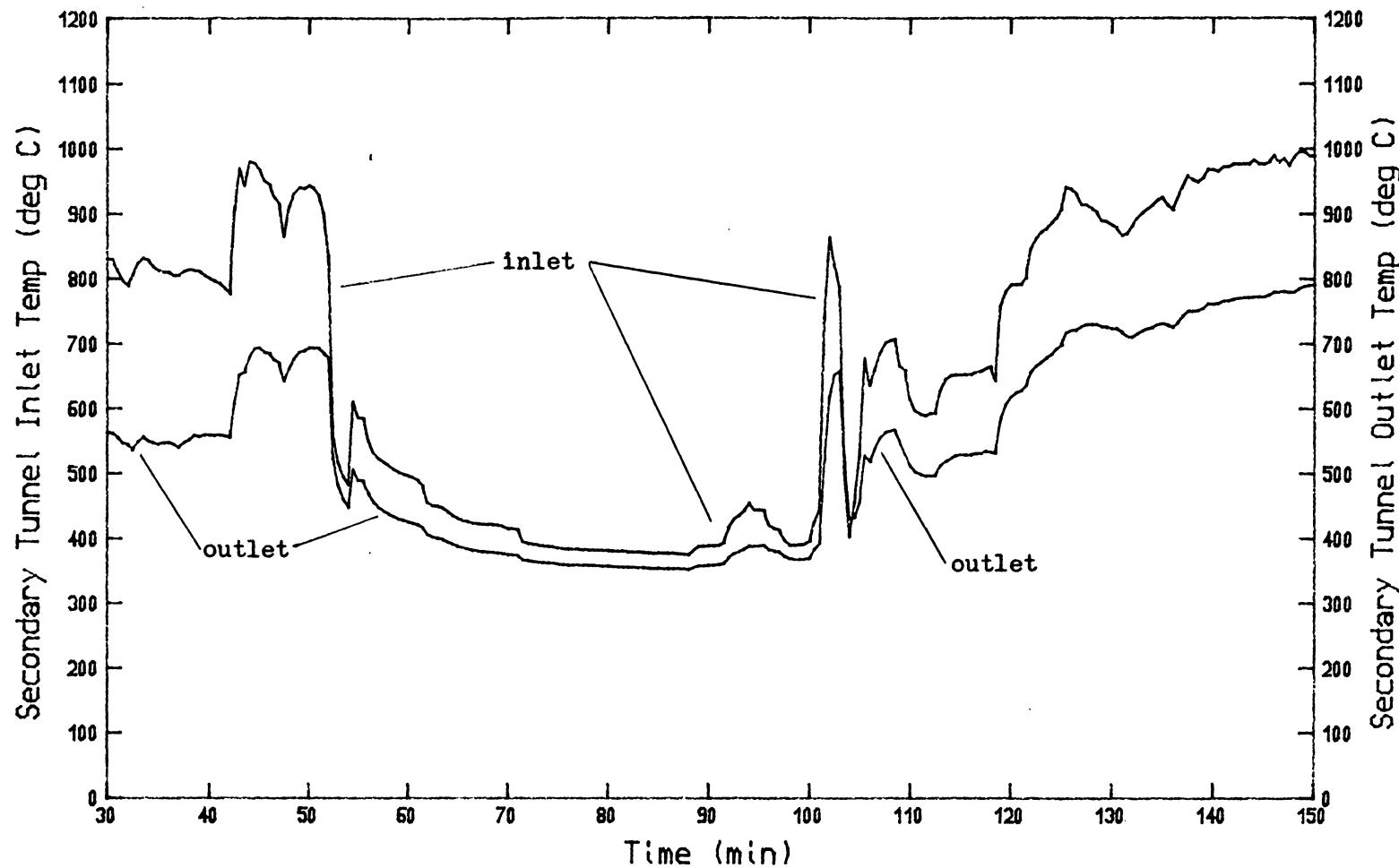


Figure 31. Secondary Combustion Tunnel Inlet and Outlet Temperatures During Test 12

dropped from 850°C to 550°C. This indicates that the noncatalytic secondary combustion came to an abrupt end. The actual reduction in noncatalytic conversion of CO to CO₂ was more than was indicated by the CO and CO₂ measurements, since they also reflect CO conversion occurring in the catalytic combustor.

It is especially notable that the equivalence ratio and the secondary combustion air and exhaust gas flow rates were essentially constant through this incident. It appears then, that the heat released by the noncatalytic secondary combustion process was not being transferred back into the process enough to maintain itself. This observation is significant in indicating a weakness of the rear inlet configuration -- it appears to require a higher temperature than the tube inlet configuration, in order to sustain itself.

The catalytic combustor could not be evaluated from the results of test 12. The placement of the upstream and downstream thermocouples was such that thermal boundary layer effects on the temperatures completely overshadowed the temperature rise caused by catalytic combustion.

In preparation for test 13, the secondary combustion air system was reconfigured to add secondary air through the refractory tube and into the front of the primary tunnel. Also, the upstream and downstream thermocouples for the catalytic combustor were relocated to provide a better temperature rise measurement.

5.2.8 Test 13

During the first part of test 13, up to about 123 minutes, there were problems with the exhaust gas flow rate dropping gradually and

reaching a low of 32 g/s. Between 100 and 123 minutes the boiler was shut down and restarted two times. The second time apparently removed the cause of the blockage and brought the flow rate back up to a more normal level of about 80 g/s. Therefore, only data after 123 minutes are useful. Results are presented in Figs. 32-36.

The period from 123 minutes (which is immediately after the boiler startup) to 200 minutes is characterized by a CO/CO₂ ratio of less than 0.02, indicating very complete combustion. Figure 36, showing fire tube outlet and catalyst outlet temperatures, indicates little or no catalytic activity until 195 minutes, when the fire tube outlet temperature begins to drop while the catalyst exit temperature holds constant. The conclusion then, is that noncatalytic secondary combustion is highly effective during the period from 123 to 195 minutes. Conditions prevailing during this period are secondary combustion air flow from 31 to 5 g/s, equivalence ratio between 0.92 and 0.65, and secondary tunnel inlet temperatures from 950°C to 1080°C.

From 195 to 214 minutes, the CO/CO₂ ratio climbed from 0.01 to 0.04 with the level of catalytic combustion increasing as well, indicating that the noncatalytic secondary combustion was becoming much less effective. The conditions during this period were equivalence ratio from 0.5 to 0.7, secondary tunnel inlet temperature from 720°C to 920°C and secondary combustion air flow 0 to 5 g/s.

The remainder of the test is characterized by a series of cycles. Each cycle begins with either a stirring of the fuel bed or addition of a batch of fuel (which includes a stirring), which causes the equivalence ratio to rise to well above 1.0. Subsequently, secondary

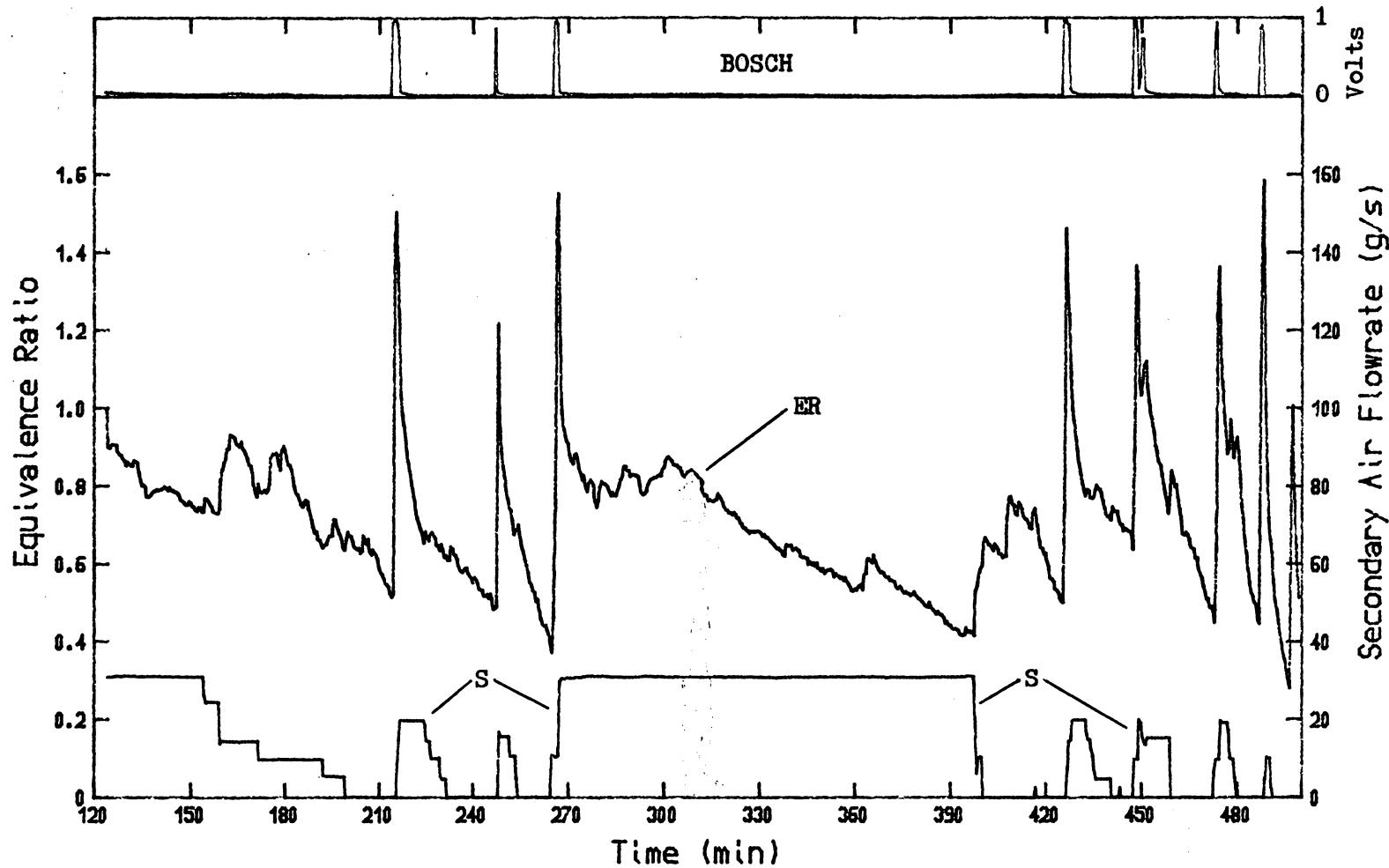


Figure 32. Equivalence Ratio (ER), Secondary Combustion Air Flow Rate (S), and Bosch Oxygen Sensor Output (BOSCH) During Test 13

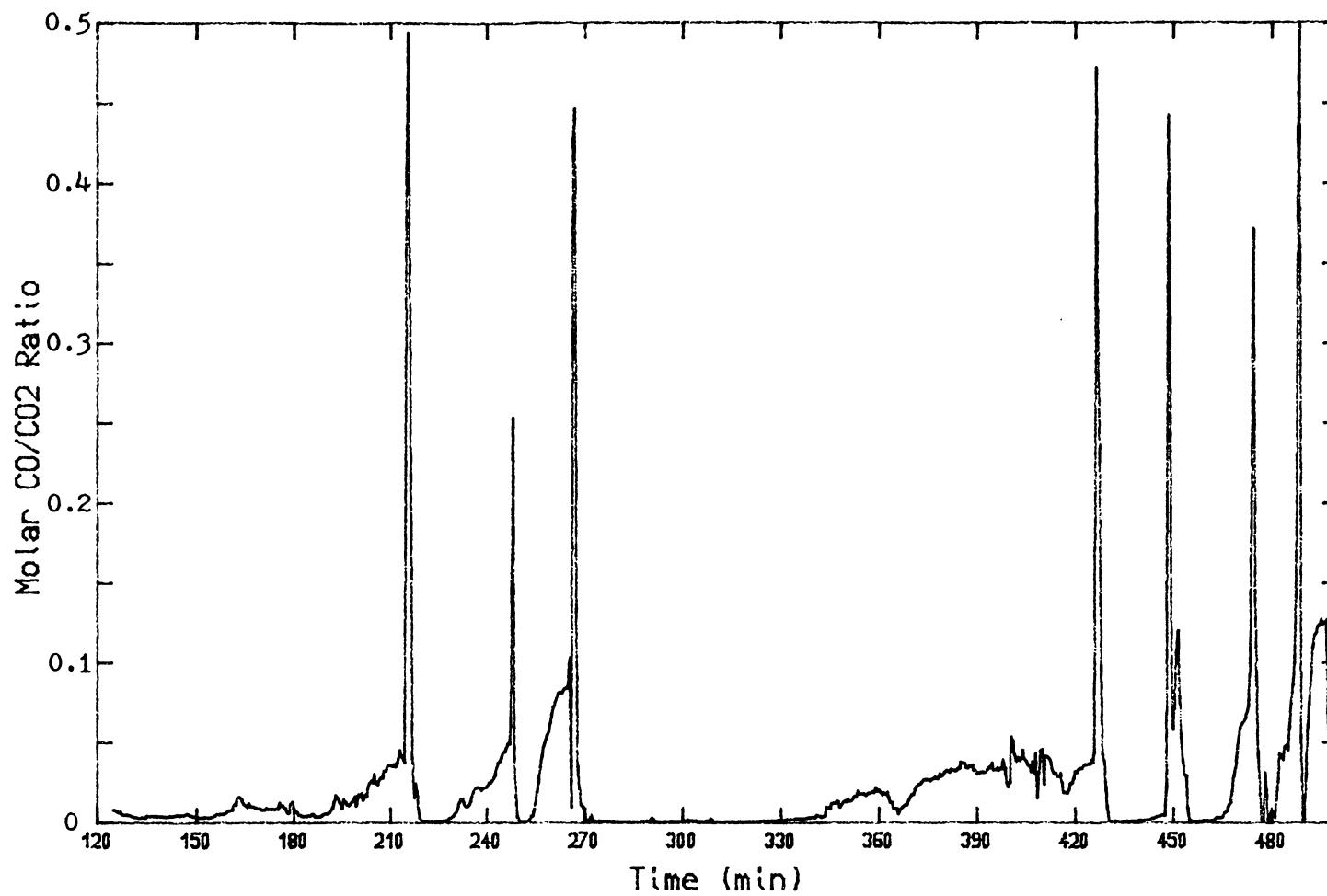


Figure 33. Molar CO/CO₂ Ratio During Test 13

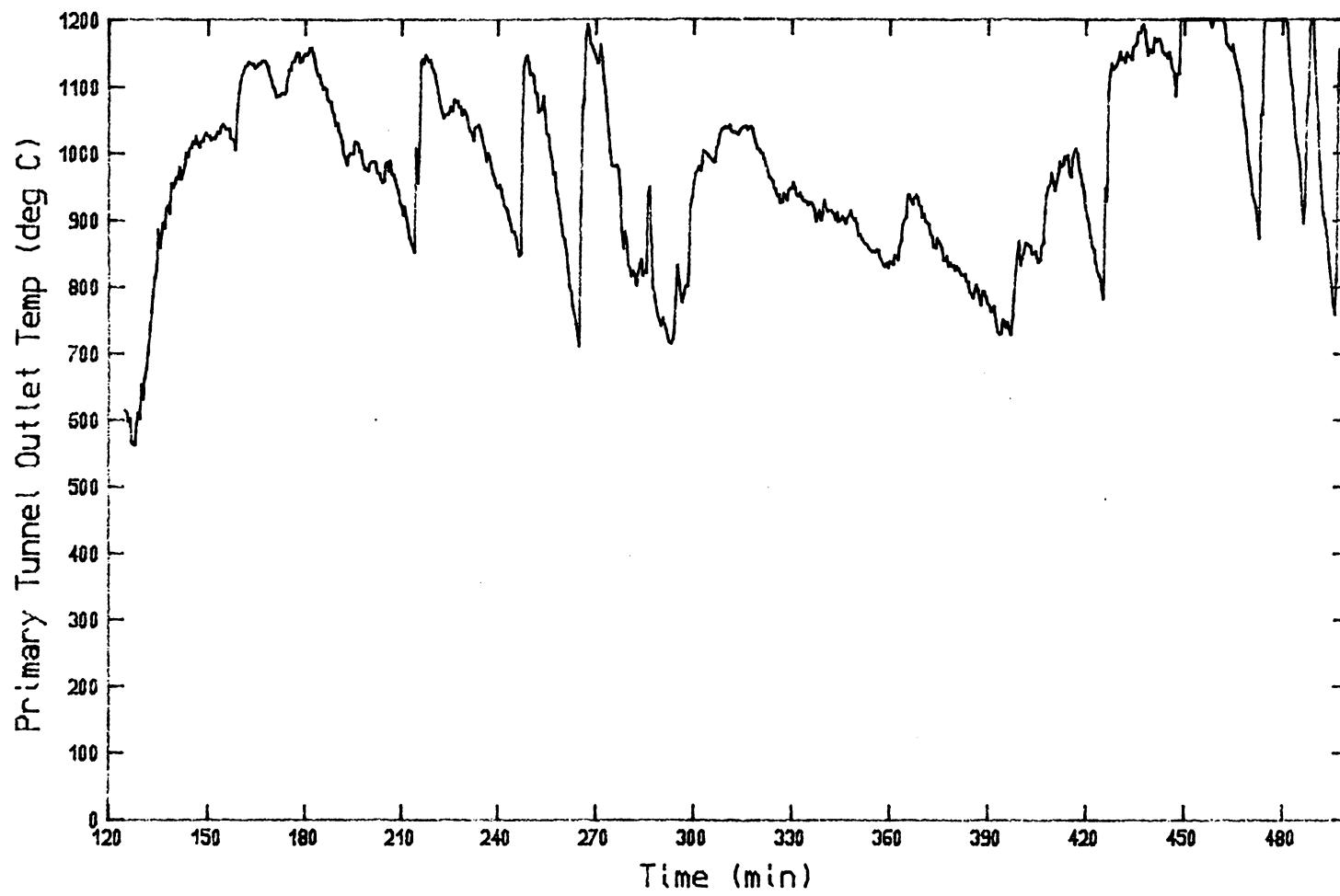


Figure 34. Primary Combustion Tunnel Outlet Temperature During Test 13

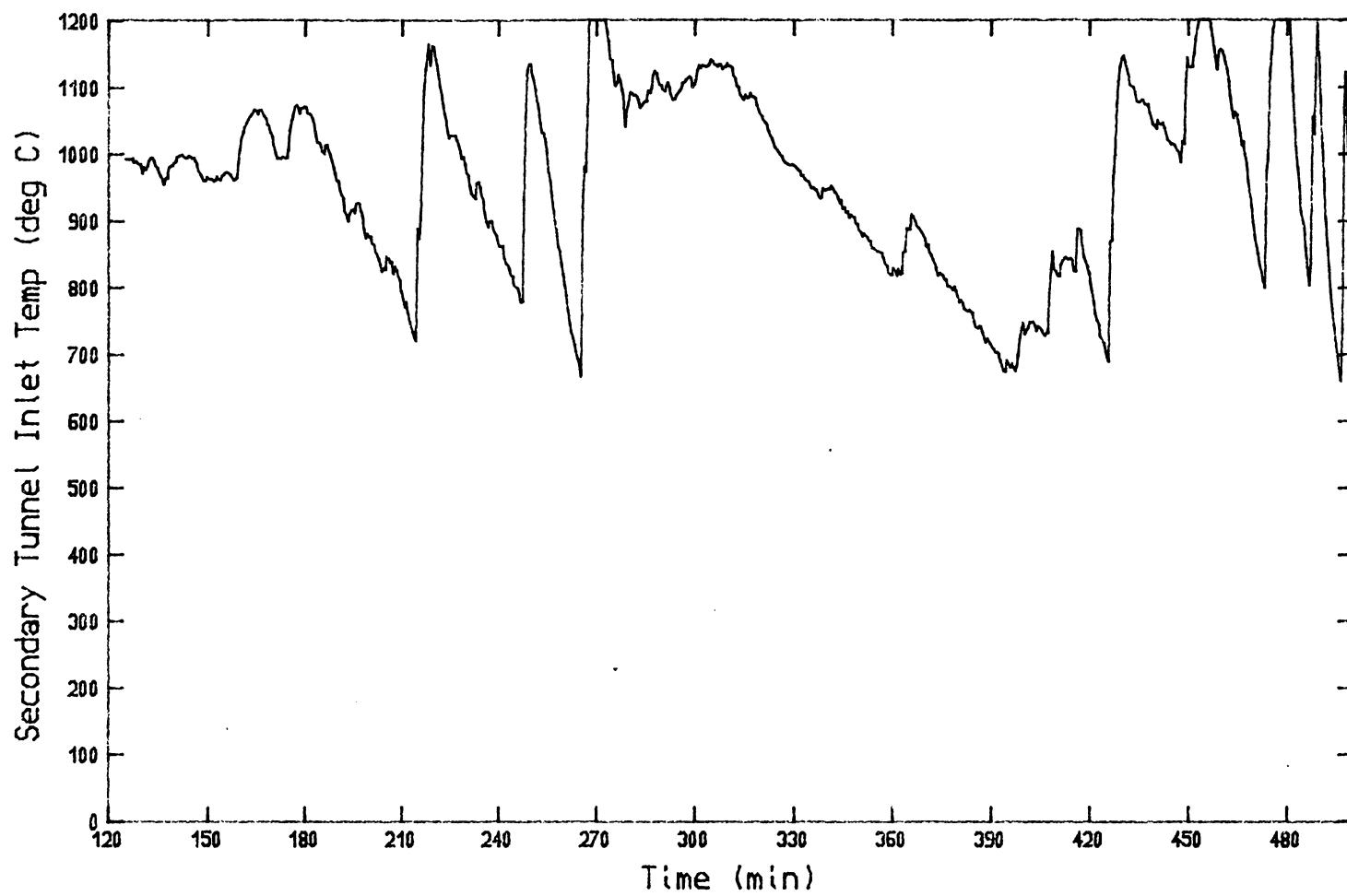


Figure 35. Secondary Combustion Tunnel Inlet Temperature During Test 13

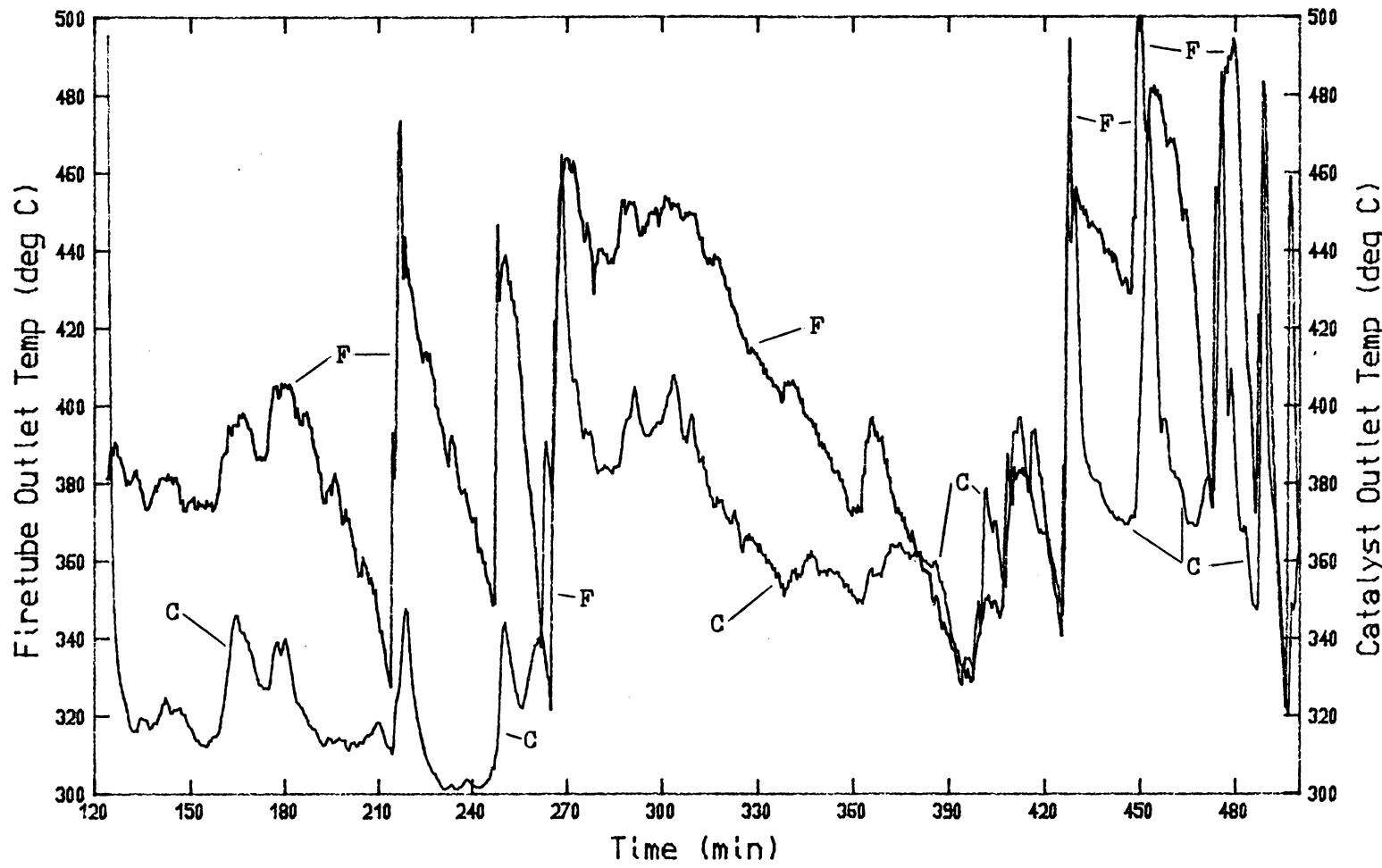


Figure 36. Firetube Outlet (F) and Catalyst Outlet (C) Temperatures During Test 13

combustion air is admitted, reducing the equivalence ratio to 0.8 to 0.95 within a few minutes. When the equivalence ratio has fallen below about 0.9, the CO/CO₂ ratio drops below 0.02, an indication of relatively complete combustion. At this time, the combustion temperatures reach their peak. For the secondary tunnel inlet, this peak normally exceeds 1000°C, and sometimes is as high as 1260°C.

Following the initial peak of primary combustion equivalence ratio and secondary combustion air flow, the equivalence ratio gradually drops. Since it was desired to learn about the combustion behavior under a variety of conditions, sometimes the secondary air flow was reduced to compensate and sometimes the equivalence ratio was left uncontrolled. In either case, the equivalence ratio of the primary combustion products continues to drop. When the exhaust gas equivalence ratio drops below about 0.60 to 0.65, the secondary tunnel inlet temperature drops below about 825°C and the CO/CO₂ ratio rises above 0.02.

The role of the catalytic combustor in these cycles is not completely clear due to the limited data available but qualitative observations can be made. Early in each cycle, the catalyst activity is low, indicating that the low level of exhaust emissions is primarily due to noncatalytic secondary combustion. Moving through the cycle however, the combustion temperatures gradually drop and the level of catalyst activity increases. The catalyst must be converting some CO to CO₂ but clearly the residence time in the catalyst is inadequate to effect complete conversion.

Following test 13 two changes were made in the instrumentation to increase the amount of information available regarding the catalyst activity. First, the Infrared Industries model IR702 combination CO and CO₂ infrared gas analyzer was installed such that the gas sample to it was multiplexed every 15 seconds between the exhaust gas at the stack and the gases immediately upstream of the catalytic combustor. This data would give a more complete picture of the activity of the catalytic combustor, as well as indicating what the combustion performance would be without the catalytic combustor. Second, the fire tube outlet thermocouples were relocated so as to obtain a better measure of the catalyst inlet temperature--that is, they were placed one to two cm upstream of the catalytic combustor inlet.

5.2.9 Tests 14 and 15

Tests 14 and 15 are the first tests in which automatic, closed loop control of equivalence ratio was attempted. The feedback to close the control loop was provided by the Bosch oxygen sensor mounted on the stack and by the secondary tunnel inlet thermocouples. These two tests were important in that they clarified the deficiencies inherent in a control scheme based on the Bosch oxygen sensor. These deficiencies have been noted in previous research [1]. Also several problems in the sample gas multiplexing scheme for the IR702 analyzer were encountered and corrected and it was discovered during these tests that the newspaper used to start the fire was plugging the catalytic combustor and thereby reducing the exhaust gas flow rate. Thus all tests after these were started with common charcoal lighter fluid and a larger

batch of dry kindling wood. Following test 15 a superior yet still inexpensive oxygen sensor became available to use as the feedback element in the control system. Because the new sensor required an entirely new strategy, no further discussion of the results of tests 14 and 15 is presented.

5.2.10 Test 16

Test 16 was the first test run under control of the G-cell. A flow diagram of the control strategy used in test 16 is presented in Fig. 37. The parameters and variables shown in the flow diagram are defined in Table 1. This strategy is the same as the final control strategy presented in Section 3.5 (Fig. 7), with the following exceptions:

- 1) no condition is set that secondary tunnel inlet temperature be above the parameter GTEMP in order to allow any secondary air flow and
- 2) when a rich signal (i.e., G-cell voltage less than GSET-GBAND) is encountered when the secondary air valve is closed, the valve opens 4 steps, resulting in about 20 g/s secondary combustion air flow rate.

Before examining the results of tests 16 and 17, we must have the purpose of the secondary combustion air system in view. It's purpose is to provide secondary air in quantities that will promote complete combustion. Based on results seen to this point, this means maintaining the equivalence ratio between about 0.7 and 0.9. With this in mind, the results can be evaluated.

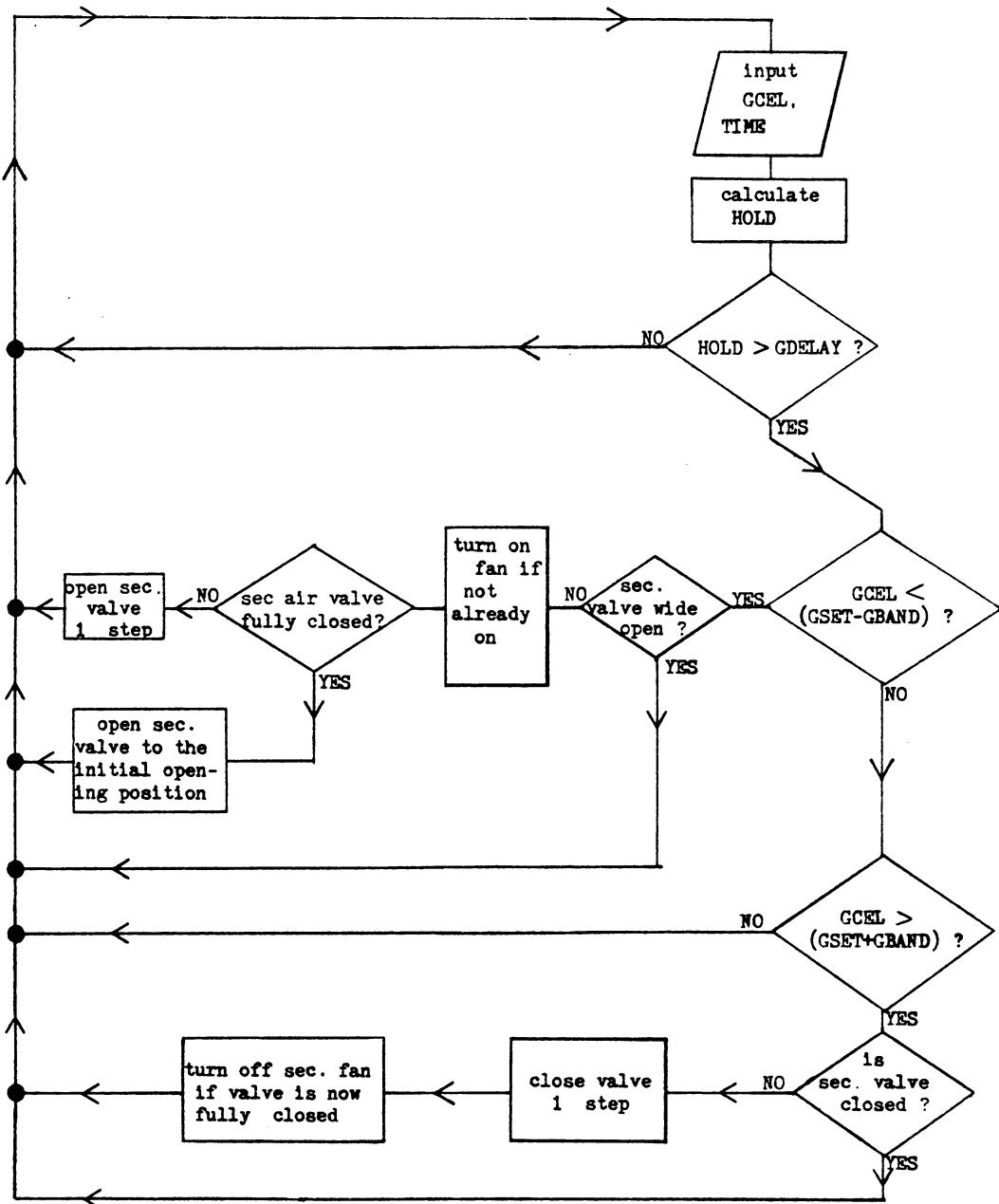


Figure 37. Abridged Flow Diagram of the Initial Secondary Air Control Strategy. Parameters and Variables Are Defined in Table 1.

Results of test 16 are presented in Figs. 38-43. Due to an error in the data acquisition and control program, the control function was inoperable prior to about 80 minutes. By the time the error was corrected (which was done with the boiler online) the equivalence ratio had dropped to about 0.7, so the fuel was stirred at 83 minutes to initiate control activity. Richness was immediately indicated by both the Bosch sensor and the calculated equivalence ratio and the secondary combustion air valve immediately opened to provide 20 g/s of secondary air, the specified initial opening position. This was too much air and caused the equivalence ratio to drop quickly to 0.6.

Ideally the secondary combustion air supply would have been reduced immediately once equivalence ratio dropped below the set point of 0.8. However, three features of the control system interacted to delay the response by about 4 minutes. First, the response time of the G-cell to changes in stack conditions is of the order of 1 minute -- the time required for sample gas to flow through the incinerator, the tubing, the condenser, and the condensate flask, plus the time required for G-cell output to respond to the new oxygen content of the sample gas at the cell. This delay is fixed by the sample conditioning system and the sensor selection and could be shortened somewhat if desired. Second, the dead band surrounding the controller set point required that the equivalence ratio (as measured by the G-cell) drop to about 0.7 before the controller would even begin to respond. This is the effect of the GBAND parameter. In order to correct the problem, GBAND could be reduced. There is a possibility, however, that if the deadband is reduced too much the control system would oscillate between two valve positions rather than settling on one position.

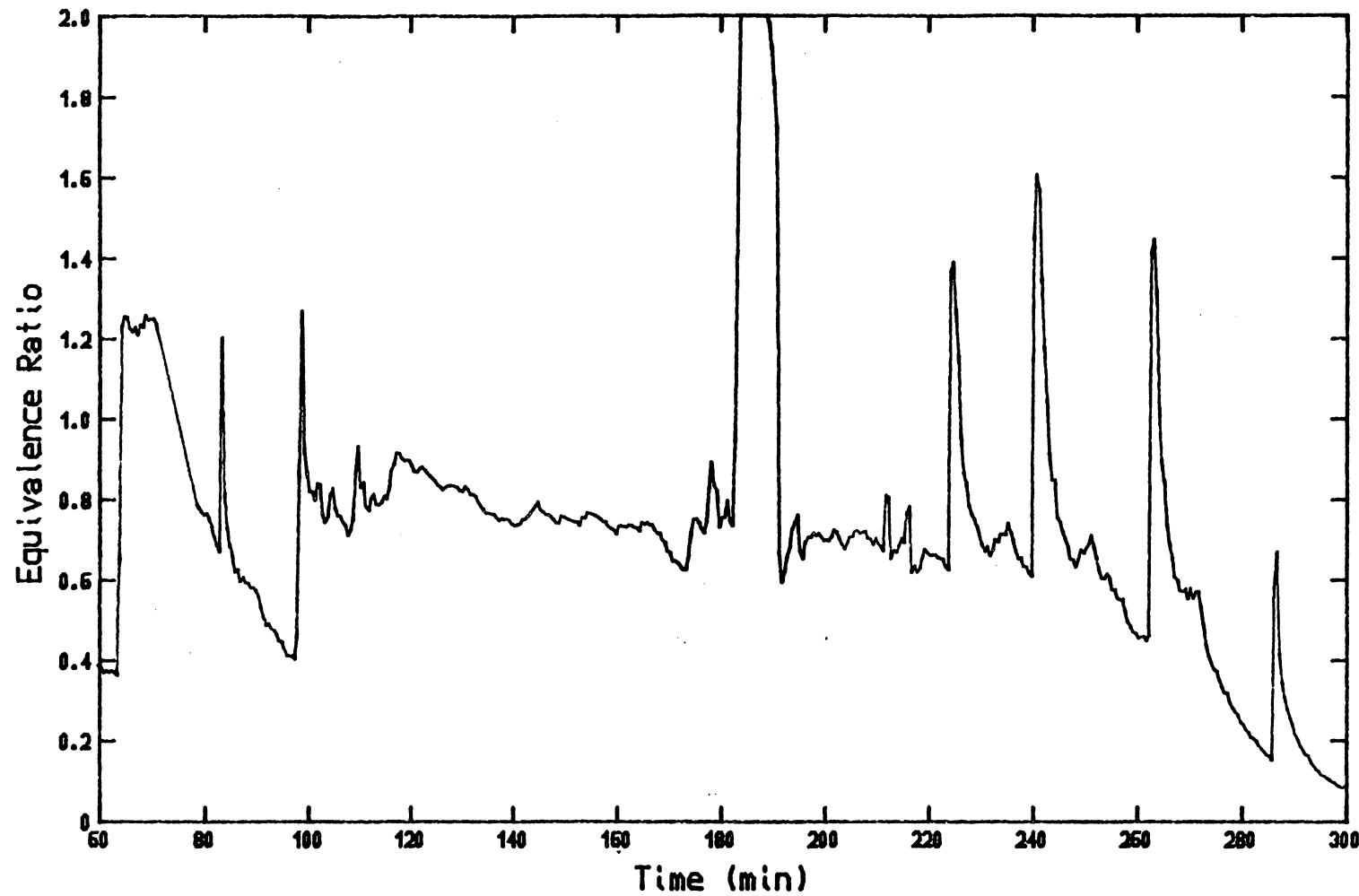


Figure 38. Equivalence Ratio During Test 16

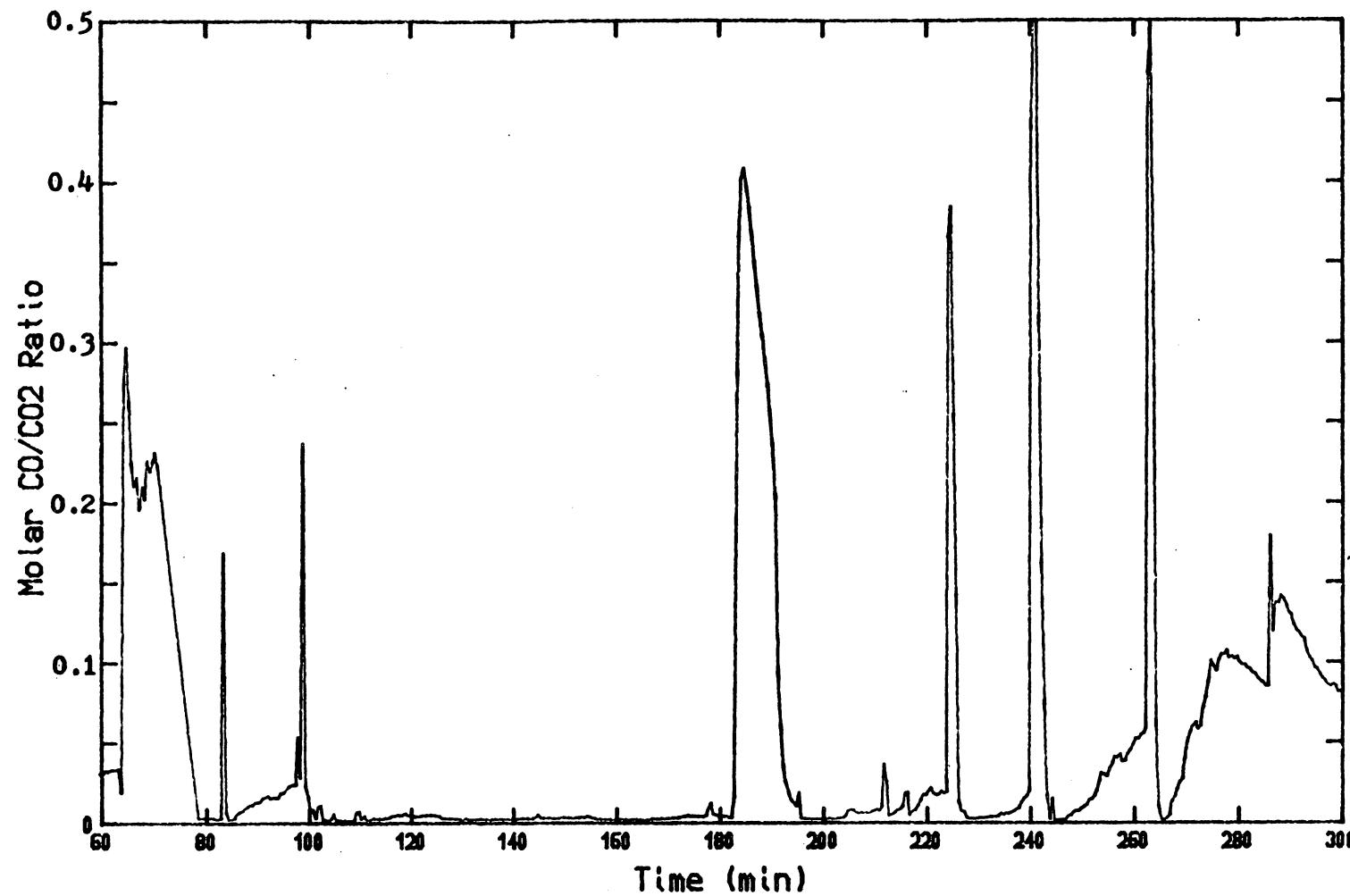


Figure 39. Molar CO/CO₂ Ratio During Test 16

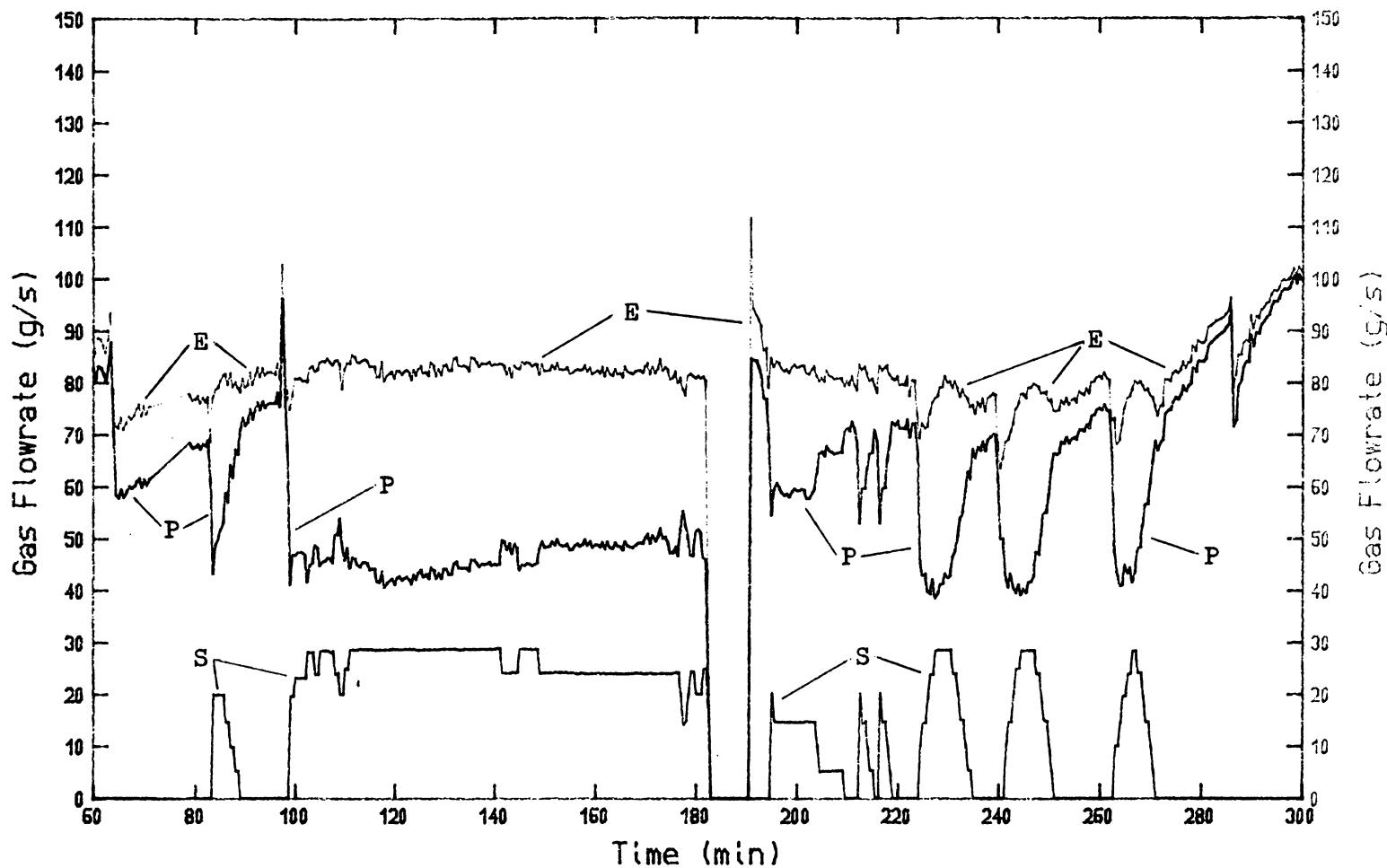


Figure 40. Exhaust Gas Flow Rate (E), Primary Combustion Air Flow Rate (P), and Secondary Combustion Air Flow Rate (S) During Test 16

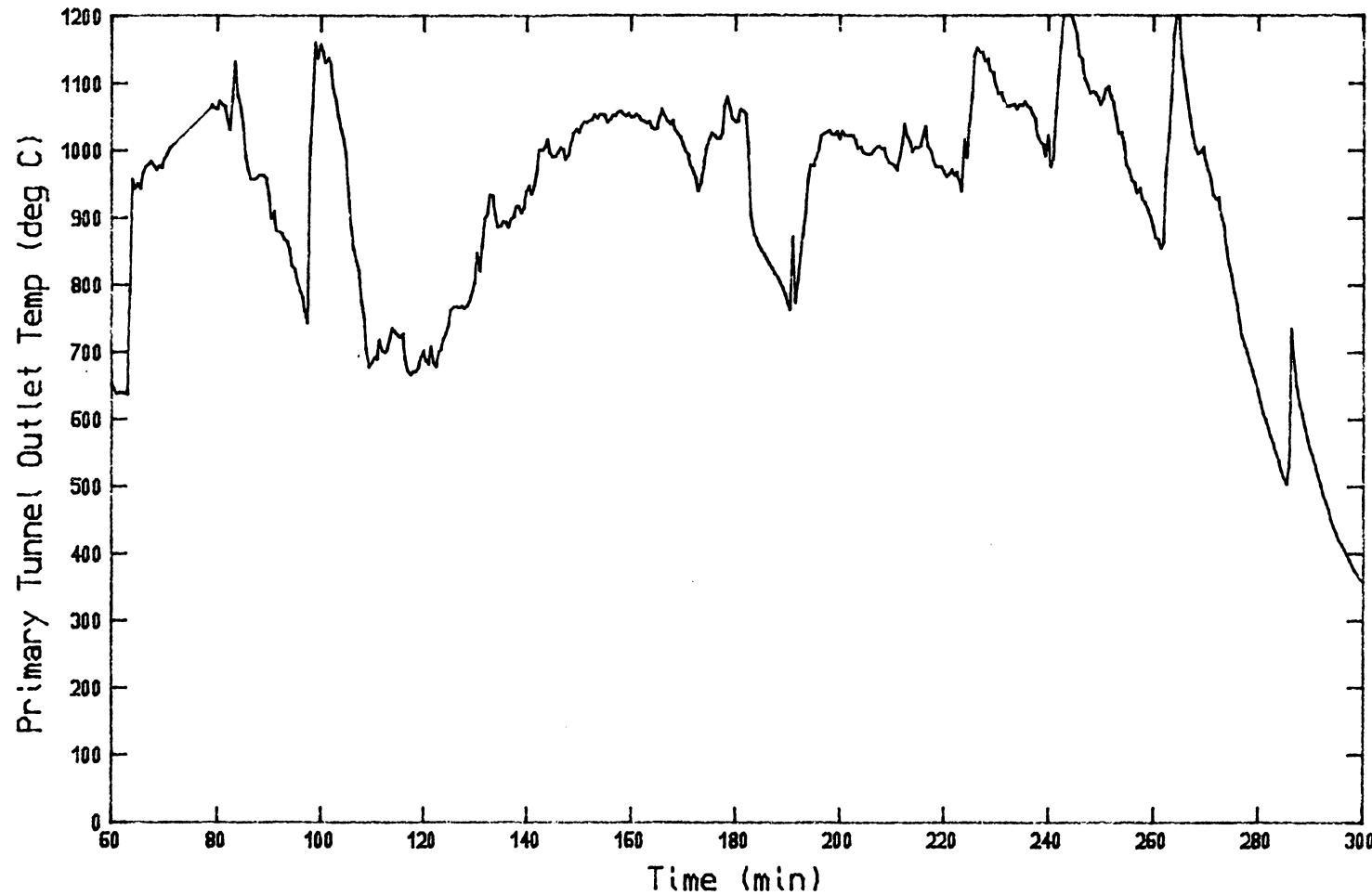


Figure 41. Primary Combustion Tunnel Outlet Temperature During Test 16

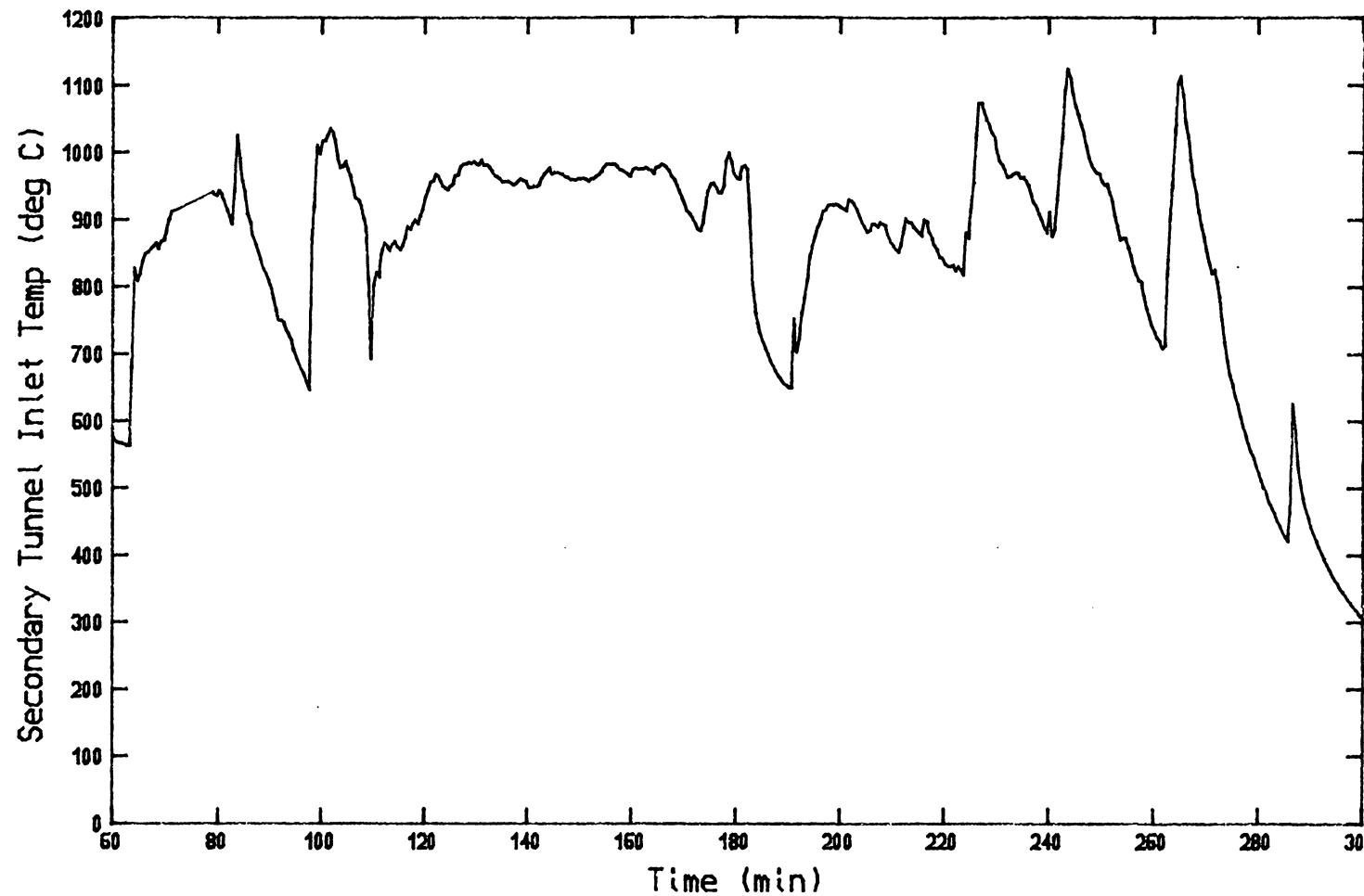


Figure 42. Secondary Combustion Tunnel Inlet Temperature During Test 16

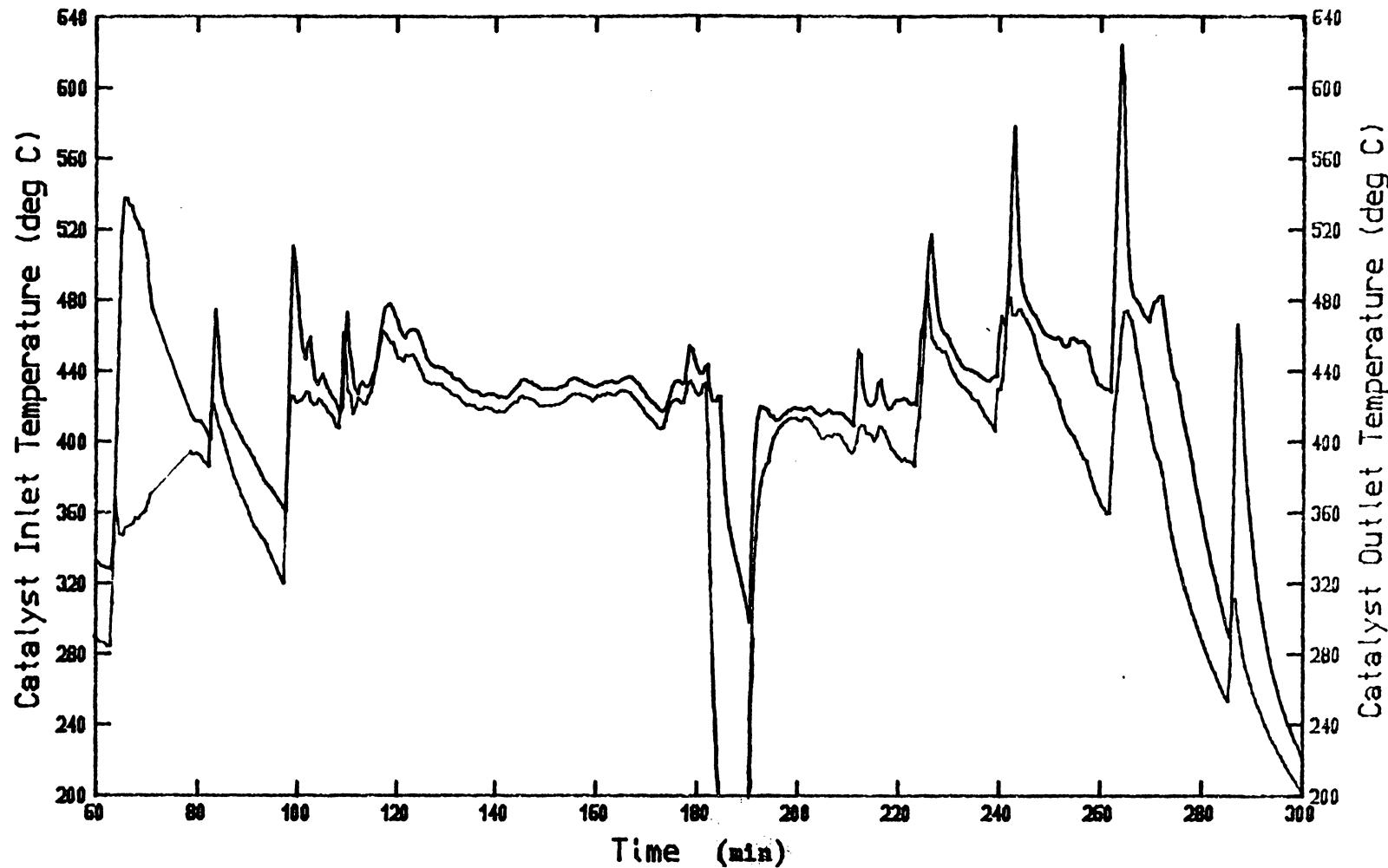


Figure 43. Catalyst Inlet and Outlet Temperatures During Test 16. In This Figure, Outlet Temperature Is Always the Higher of the Two.

Third, the programmed time delay in the controller response, as set by the GDELAY parameter, causes the controller to take 3.5 minutes to close the valve 4 steps. Each step takes a minimum time equal to GDELAY, regardless of whether the G-cell output indicates an equivalence ratio so low that secondary air should be stopped entirely. A solution to this might be to have the controller move the valve a number of steps that is proportional to the difference between actual equivalence ratio and the equivalence ratio setpoint.

Immediately after these problems were observed during the test, GBAND was changed from 2.0 to 1.0 mV and GDELAY was changed from 45 to 30 seconds. No attempt was made to provide for multi-step valve closing since potentially troublesome program changes would be required which would be too risky to attempt on-line.

Once the equivalence ratio became high enough for the control system to step in, it supplied secondary air in apparently optimum or near optimum quantities, as shown by the CO/CO₂ ratio from about 100 to 183 minutes, which averaged about 0.006. The drop in equivalence ratio between 166 and 176 minutes was not caused by problems inherent in the control strategy. During that time, the gas sample system supplying the G-cell was off-line and the secondary air valve position was held fixed while clogging in the sample train was tracked down and corrected. At 177 min the G-cell sample system was re-connected and automatic control resumed, quickly bringing the equivalence ratio back into a better range.

At 211.5 minutes, the GBAND parameter was reduced from 1.0 to 0.6 mV, causing immediate opening of the secondary air valve 4 steps. The

unstable behavior in the next 10 minutes lead to a reduction of the initial valve opening parameter from 4 steps to 2 steps, to prevent over-opening the secondary air valve when the fuel is stirred.

Several problems in the instrumentation were noted during this test. First, it was discovered that the data acquisition system was resolving the G-cell output only to the nearest 0.6 mV (which is equivalent to 0.5 percent O₂). This is unsatisfactory since it is the same magnitude as the GBAND parameter and could therefore cause undesirable oscillations in the valve position. The problem was solved by installing a 50:1 linear voltage amplifier between the G-cell and the data acquisition system prior to the next test.

The second problem discovered was that the analyses of the pre-catalyst and exhaust gases were inconsistent. During several periods of the test, one of which was nearly 90 minutes long, the gas analysis showed a drop in CO₂ across the catalytic combustor. In contrast one would expect the CO₂ to at least hold constant if there was no increase due to hydrocarbon and CO combustion. After investigating a number of possible causes of this obvious discrepancy it was determined that the most likely was a vacuum leak in the exhaust gas sample train, causing the sample to be diluted with room air and thus reducing the measured CO₂ concentration.

In an attempt to correct the pre-catalyst/exhaust gas sample problem, both sample trains were thoroughly tested for leaks and all potential sources of leakage fixed. No leaks were found during this check, which was done several hours after the test, but it was speculated that the higher temperatures experienced by the sample system

during testing may have caused greater leakage to occur than during the post-test leak check.

The obviously erroneous multiplexed CO₂ measurements fails to provide what would otherwise be valuable information about the catalytic combustion process. However, beginning with the present test better measurements of catalyst inlet and outlet temperatures were made than in previous tests. A comparison of these measurements against the multiplexed precatalyst/exhaust CO and CO₂ measurements indicates that the temperatures do provide at least a qualitative indication of the level of combustion activity in the catalyst.

Control strategy changes were also made after test 16. In order to eliminate the overshoot of secondary air flow sometimes caused by initially opening the valve a predetermined number of steps, that procedure was eliminated, making the initial valve opening step no different from any other.

5.2.11 Test 17

Results of test 17 are presented in Figs. 44-48. Initial control strategy parameters for test 17 were: GSET = 4.0 mV, GBAND = 0.4 mV, and GDELAY = 20 seconds. These parameter values resulted in unstable control as seen in the unsteady secondary air flow rate and equivalence ratio from about 10 to 30 minutes. The unsteadiness was detrimental to emission control as seen in the CO/CO₂ ratio during this period. The parameters were changed to GBAND = 0.6 mV, GDELAY = 30 seconds, and GSET = 4.5 mV to obtain steadier control and a slightly lower average equivalence ratio. Following these changes, the control stabilized and

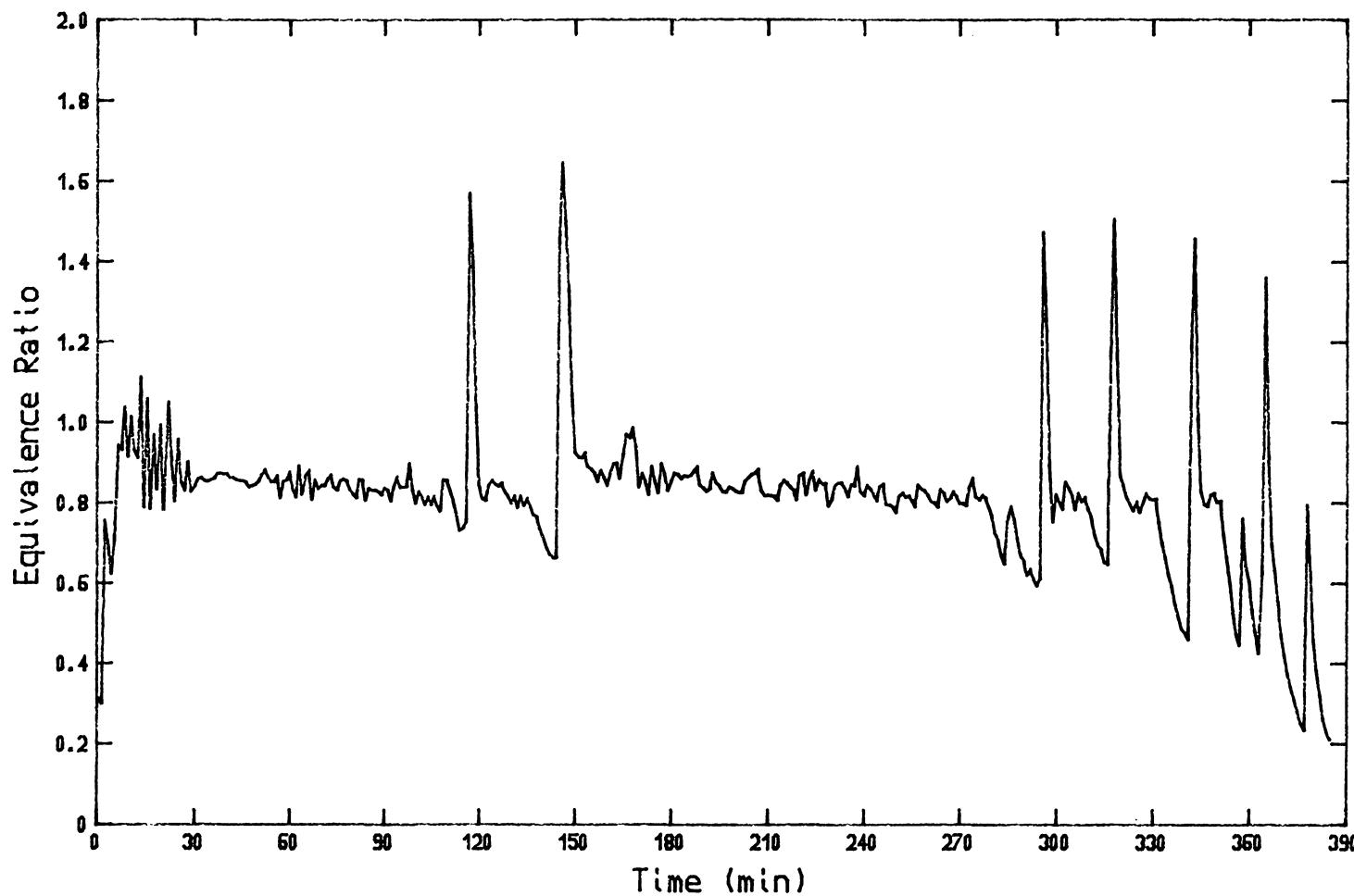


Figure 44. Equivalence Ratio During Test 17

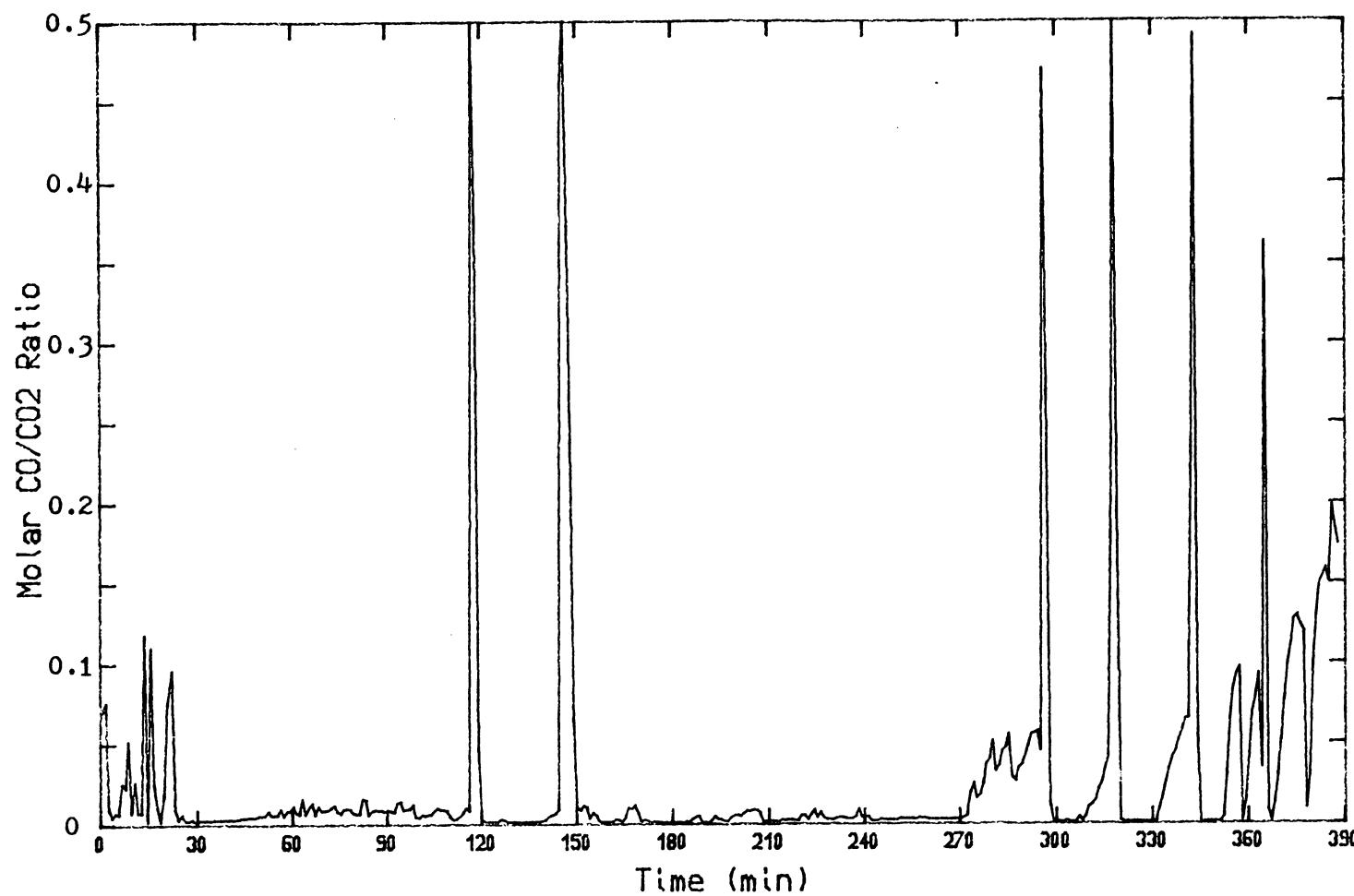


Figure 45. Molar CO/CO₂ Ratio During Test 17

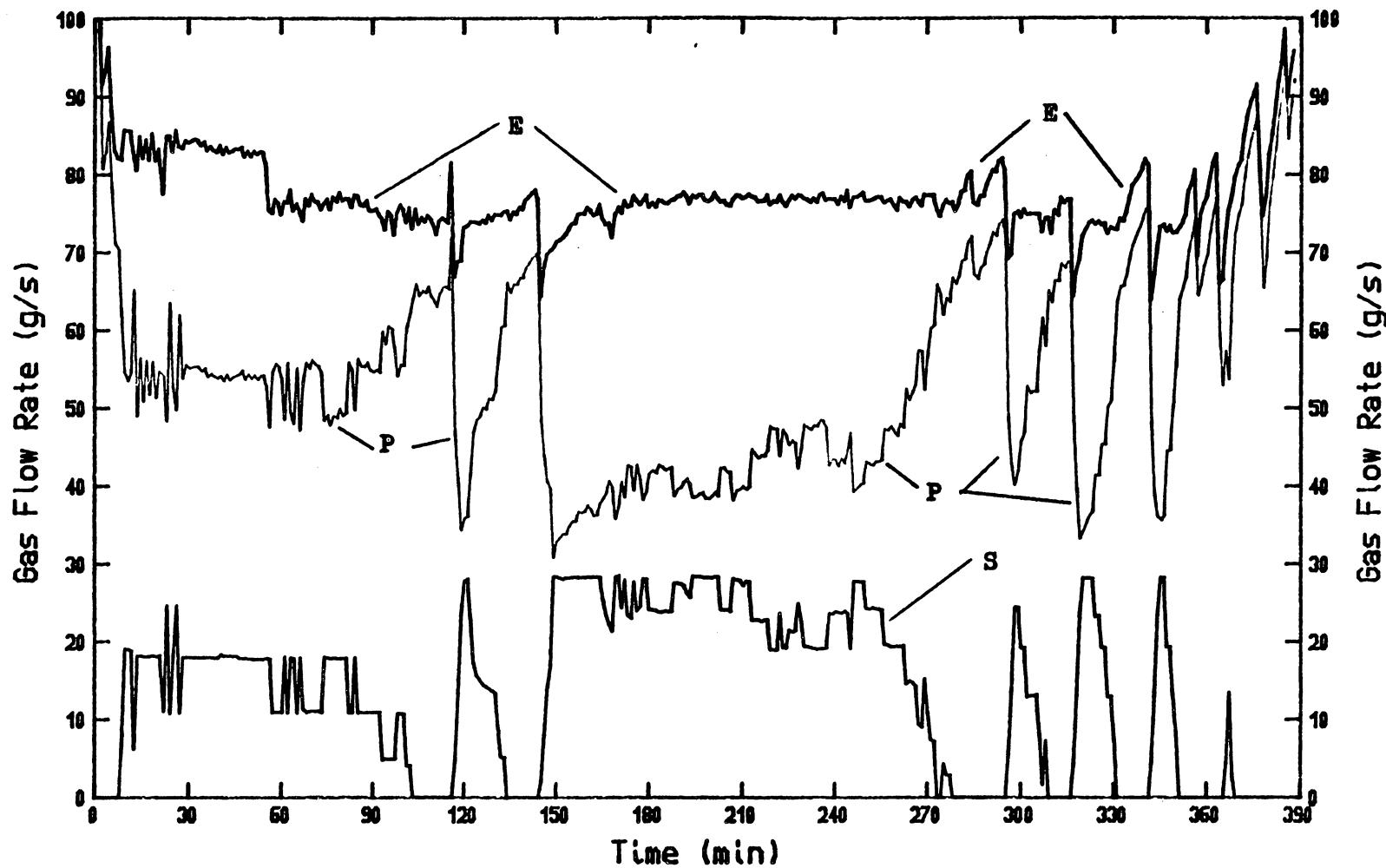


Figure 46. Exhaust Gas Flow Rate (E), Primary Combustion Air Flow Rate (P), and Secondary Combustion Air Flow Rate (S) During Test 17

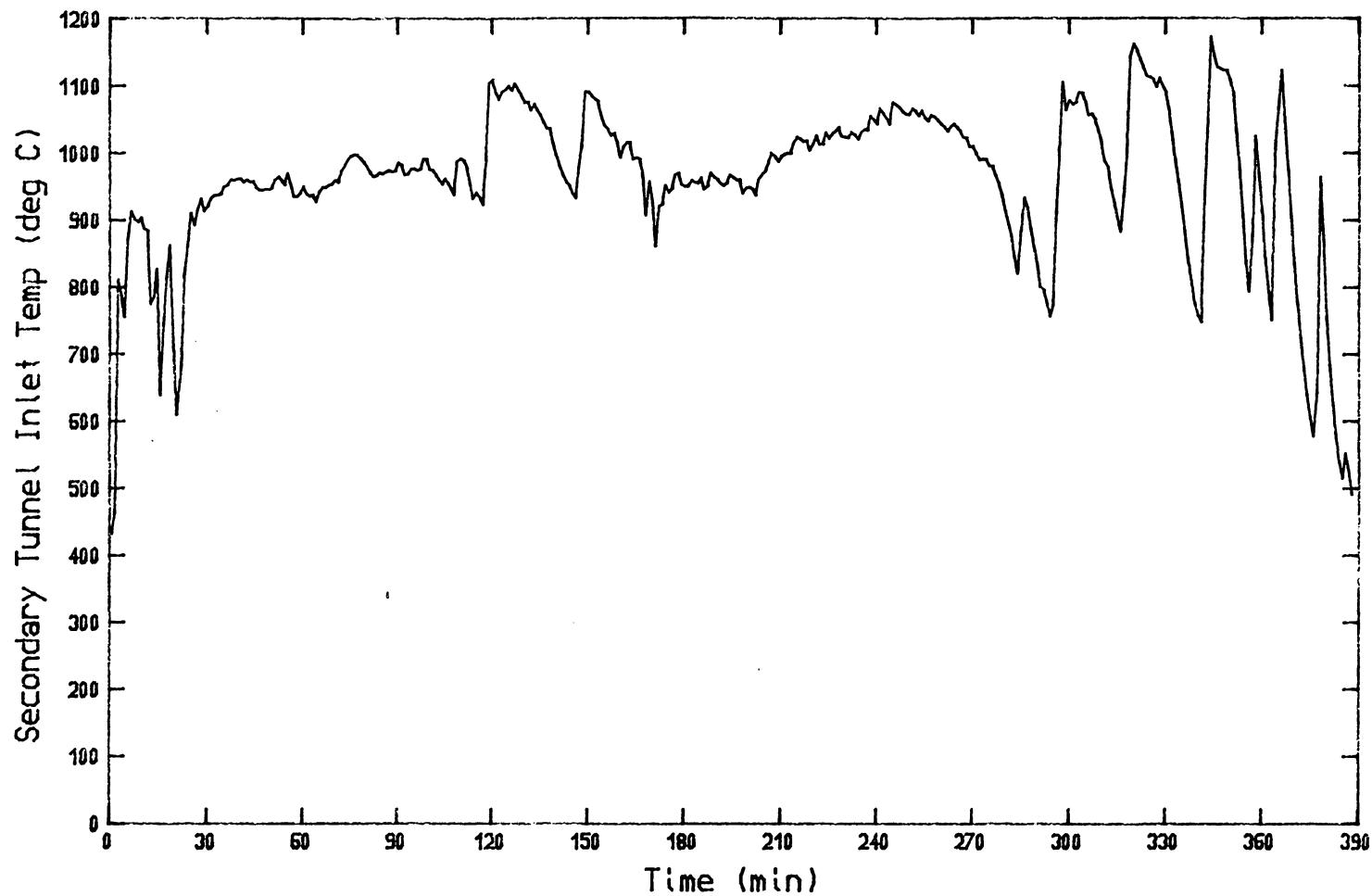


Figure 47. Secondary Combustion Tunnel Inlet Temperature During Test 17

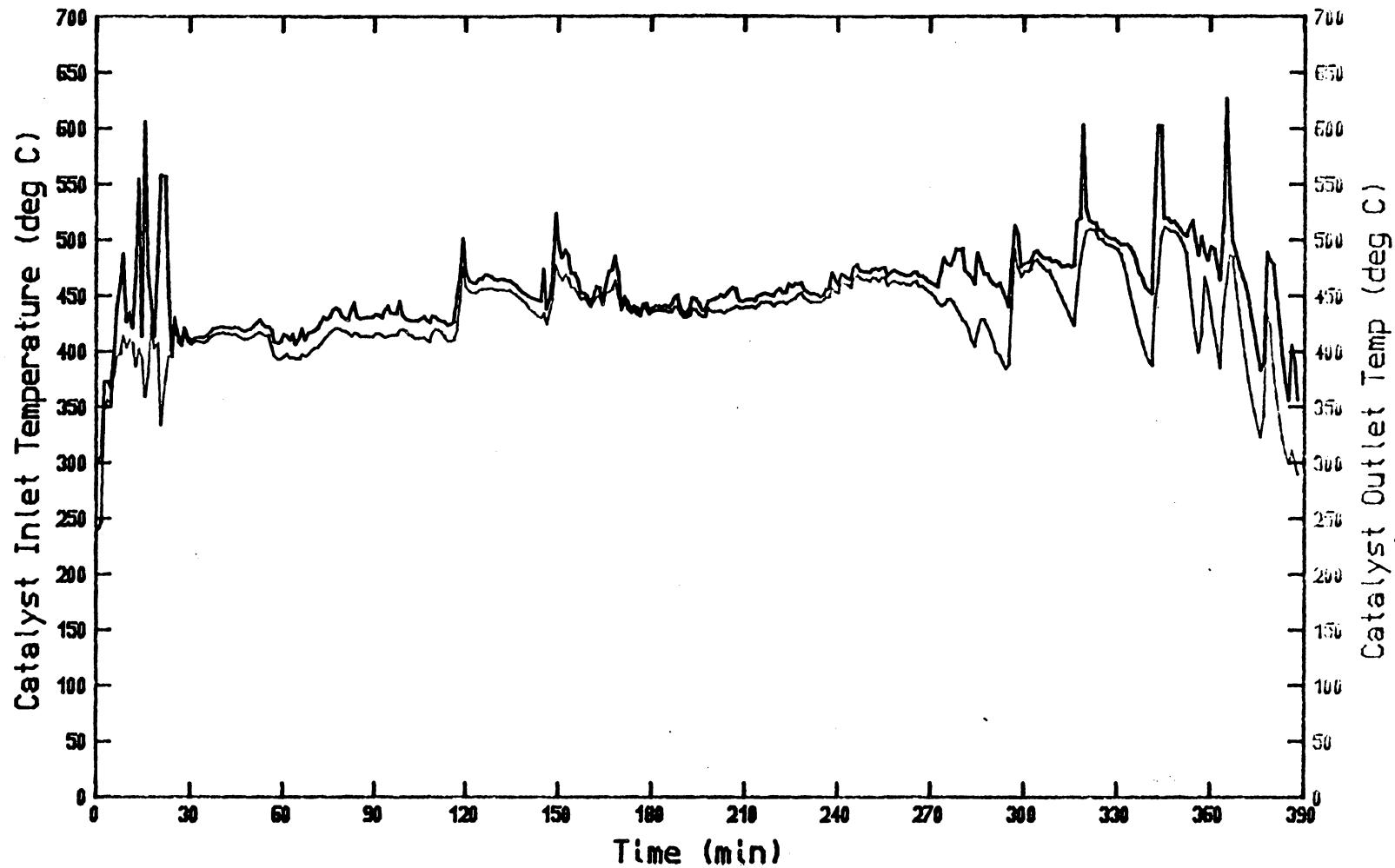


Figure 48. Catalyst Inlet and Outlet Temperatures During Test 17. In This Figure, Outlet Temperature Is Always the Higher of the Two.

the boiler ran for about 250 minutes with CO/CO₂ ratio always less than 0.02 and averaging about 0.007 except for brief periods following a stirring at 116 minutes and reload at 144 minutes. Clearly this is a significant success of the secondary combustion air control and catalytic combustion systems. This success is documented in Table 7, which compares emissions from two baseline (uncontrolled) tests [28] with the present test. It is significant that the baseline test and test 17 time periods are related in a very similar way to their respective batch fuel reload times.

The long period of extremely clean running was ended by the dropping equivalence ratio, which obviously can no longer be controlled once the secondary air flow rate has been driven to zero. Here a shortcoming of the present catalytic combustor design shows up -- even though catalyst temperatures were high enough (in excess of 400°C) and excess oxygen was present, the rate of conversion of CO to CO₂ was not adequate to hold emissions as low as during the period of higher equivalence ratio. The multiplexed gas analysis showing change in CO and CO₂ across the catalyst reveals a reduction of CO from about 0.8 mole %, dry basis (db) to 0.5 mole % db. So the catalyst is active, but the gas residence time in the catalytic combustor is apparently not long enough to complete the combustion as much as desired.

This problem occurs periodically in the boiler operation as follows. Based on the results of this and other tests, the interaction between the secondary combustion air control activity, the refuelings or stirrings, and the boiler emissions can be described as an equivalence ratio cycle. This cycle consists of 1) refueling or stirring of the

TABLE 7 Boiler Emissions in Tests Run Before and After Implementing the Controlled Secondary Combustion Air System. All Tests Cordwood Fueled with Steady Operation

	Test Number		
	1	2	17
secondary air (controlled)	No	No	Yes
time period (min) from	25	10	24
to	120	290	275
estimated avg. CO/CO ₂ ratio during time period	0.2	0.22	0.007
fuel load times (min)	23	15	5
	160	144	

fuel, 2) controlled equivalence ratio with low emissions, followed by 3) loss of equivalence ratio control as the equivalence ratio of the products of primary combustion drops, resulting in high emissions. It is during this third phase that catalytic combustion becomes most important. This cycle was repeated three times at the end of the present test (from 270 minutes on). Each time the third phase occurs, the catalyst becomes significantly more active (as measured both by temperature rise and CO drop across the catalytic combustor, but the combustion is not completed enough to maintain the CO/CO₂ ratio below 0.02.

This problem of high emissions at low equivalence ratio may be approached in two ways. First, a larger catalytic combustor could be installed, which would provide enough residence time to complete the combustion. The logical first step to accomplish this in the present boiler would be to install a second row of catalyst segments downstream of the existing row. A more effective though more costly design would be an insulated catalytic combustion chamber added to the outlet of the fire tubes. This would make better use of existing heat exchange surface while also permitting a design for lower velocity through the catalytic combustor and taking better advantage of the heat release during combustion to raise temperatures and further accelerate the combustion process. None of these changes were made, however, due to time constraints. Further investigation of the benefits provided by an improved catalytic combustor design would be a logical next step after the present research.

A second possible solution to the problem would be to prevent the conditions which lead to a low equivalence ratio. Test results have shown clearly that stirring the fuel always increases the equivalence ratio. A solution then, might be to provide automatic stirring of the fuel bed. A method that would provide either continuous stirring or frequent short stirs would be required in order to minimize disturbance to the combustion process, as compared to the less frequent stirrings done manually during the present testing. As an alternative to stirring, if the bottom of the fuel magazine was steeply sloped toward the openings to the primary tunnel, the fuel would possibly settle toward the openings and at least partly stir itself as it burned down. This approach would have the major advantage of requiring no new moving parts.

A third possible solution would be to simply refuel the boiler every time the equivalence ratio dropped below an acceptable level. This would require refueling at up to twice the frequency required to simply maintain the power output. An extension of this third solution would be to operate the boiler with continuous, automatic fuel feed. One could argue that such a condition would be analogous to a batch fed operation with frequent refueling and would thus always be within the controllable domain of the secondary combustion air system, i.e., the boiler would operate continuously in phase two of the aforementioned equivalence ratio cycle.

The results of test 17 reveal an opportunity for improving equivalence ratio control and reducing CO emissions by incorporating the Bosch sensor into the control strategy. The reasoning is as follows.

Figures 44 and 45 show that a significant fraction of the total CO emitted during the test was produced during the 2 to 6 minute long period following each fuel reload and stirring when the equivalence ratio was above 1.0. These equivalence ratio spikes are an unavoidable result of the fuel stirrings and reloads but could be shortened considerably -- possibly to as little as 5 seconds duration at equivalence ratios above 1.0 -- by taking advantage of the quick response of the Bosch sensor.

A possible strategy by which these equivalence ratio spikes could be shortened would simply drive the secondary combustion air valve open as long as the Bosch sensor showed a fuel-rich mixture. The controller would then stop driving the valve open at the first fuel-lean signal from the Bosch sensor and wait 20 to 30 seconds at which time normal control based on the G-cell would resume. A control strategy of this type was not implemented during the present experimental program however, due to time constraints and the need to completely evaluate the simpler strategy already in use.

In test 17, the gas analyses were again inconsistent, as indicated by the measured reduction of CO₂ across the catalyst. It appears likely that air leakage into the stack gas sample line was again responsible for the problem.

Following test 17, the secondary combustion air capacity was increased from 30 to about 38 g/s. The reason was that during significant portions of the test the secondary air flow was at full capacity. Although there were no instances in which inadequate secondary air was available, later tests with baled slash or other fuels

would certainly require more secondary air and thus be beyond the capability of the present system.

The control strategy was also modified after test 17. Some periodic oscillation in the controlled output was seen, possibly indicating that the step size of 5 g/s was too large or that the deadband (i.e., the GBAND parameter) was too small. As an attempt to correct this, the step size was reduced to 2.5 g/s. The problem of response time, however, is aggravated by having this smaller step size, so further modifications to the strategy was required.

In order to increase the speed of response of the secondary air system, another modification was made to the strategy which will permit multiple-step opening of the valve when

$$GCEL < (GSET - 1 - GBAND)$$

The number of steps to open is determined by

$$STEPS = (GSET - GCEL) * 1.08$$

where STEPS takes on an integer value obtained by rounding the RHS. Clearly, this scheme will speed the opening of the secondary combustion air valve when the exhaust gas undergoes a relatively large step increase of equivalence ratio. The modification is limited, however, to a maximum single opening of 5 steps, or 12.5 g/s, since the G-cell output does not go below zero, but remains near zero for all fuel-rich mixtures.

Tests 5-17 have resulted in numerous equipment modifications and many figures in which experimental data are presented. A summary of these tests, their configurations and the figure numbers for their data is presented in Table 6.

5.3 Combustion-Controlled Performance Testing

As a result of tests 1 through 17, a reasonably successful secondary air control system has been developed for steady operation on cordwood, as documented in Table 7. This system included both the hardware and the software required for a complete system. It remained to test and document the system's performance both for unsteady operating conditions (i.e., less than full power output required) and for various fuels. The tests discussed in Section 5.3 met these goals.

Specifically, the fuels used included dry cordwood, wet cordwood, and baled slash. Part-load performance was simulated by operating the boiler in a two hour cycle with approximately one hour on and one hour off after initially bringing the boiler up to a steady, clean operating condition. A summary of the fuel type and moisture, fuel load mass, elapsed time at each refueling, data figure numbers for each test and combustion performance is presented in Table 8.

5.3.1 TEST 18

Test 18 was the first in which unsteady or on/off behavior was tested. The results, presented in Figs. 49-55 reveal problem areas as well as some success. Problem areas were: 1) incomplete combustion in the catalytic combustor in spite of fuel-lean equivalence ratios, 2) an instance of apparent self-extinguishment of noncatalytic secondary combustion, and 3) poor noncatalytic secondary combustion during the period following each restart.

The emissions resulting from the first and third problems can be completely eliminated by an improved catalytic combustor design, as dis-

Table 8. Summary of Combustion-Controlled Performance Tests

	TEST NUMBER			
	18	19	20	21
fuel ¹	C	S	C	L
fuel mc (%) ²	8	20	28	27
load 1 mass (kg)	54	60	73	22
load 2 time (min)	44	30	52	23
mass (kg)	122	58	136	72
load 3 time (min)	340	150	421	93
mass (kg)	103	101	140	82
load 4 time (min)	----	----	----	205
mass (kg)	----	----	----	64
Figure numbers	49-55	56-62	63-69	71-75
Estimated avg.	0.03	0.06	0.015	0.04
CO/CO ₂ ratio				

¹ C = cordwood, L = poultry litter, S = baled slash (simulated)

² The specified moisture contents apply to loads 2 and later.
Load no. 1 was 7 to 9% moisture on all tests.

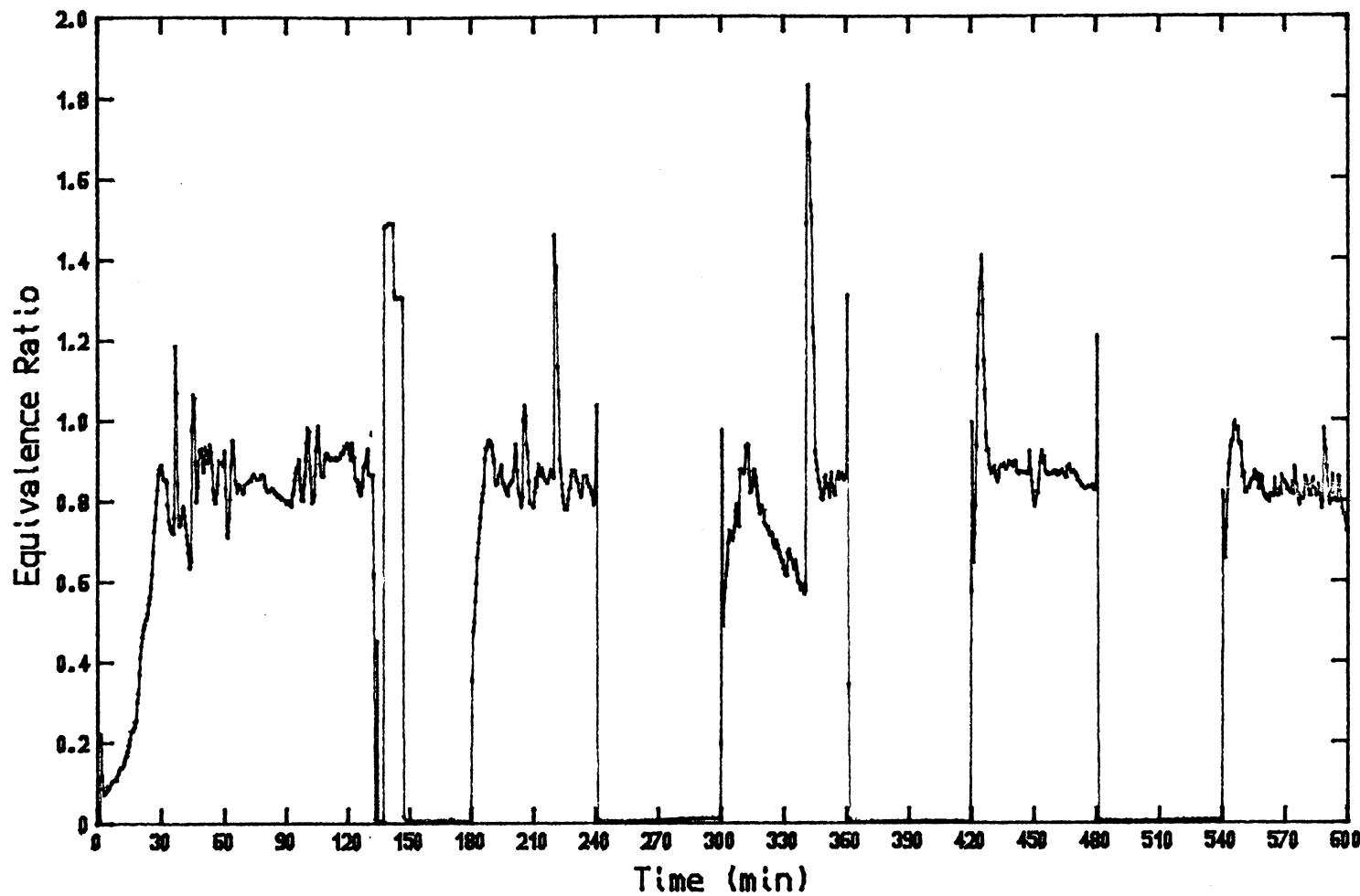


Figure 49. Equivalence Ratio During Test 18

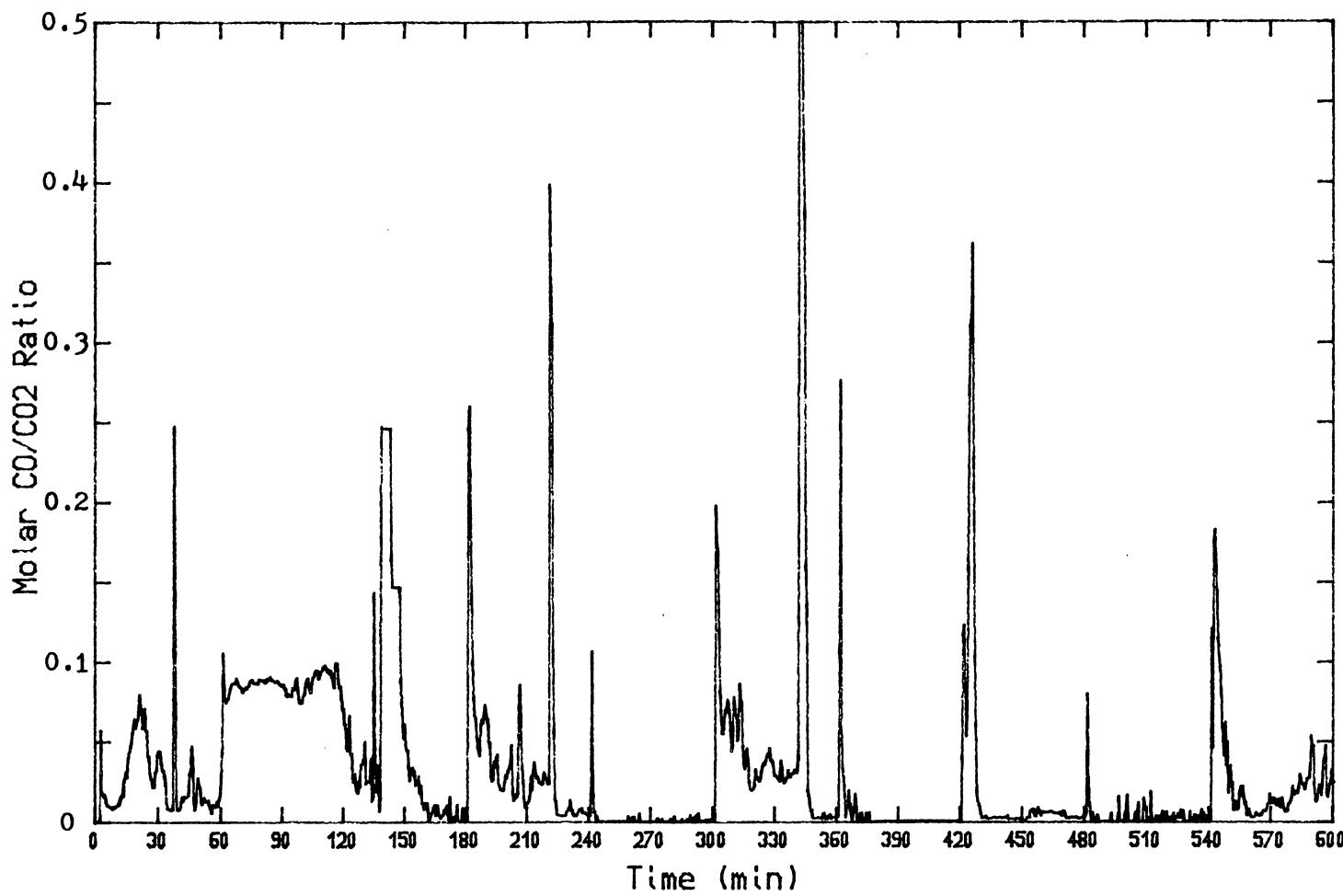


Figure 50. Molar CO/CO₂ Ratio During Test 18

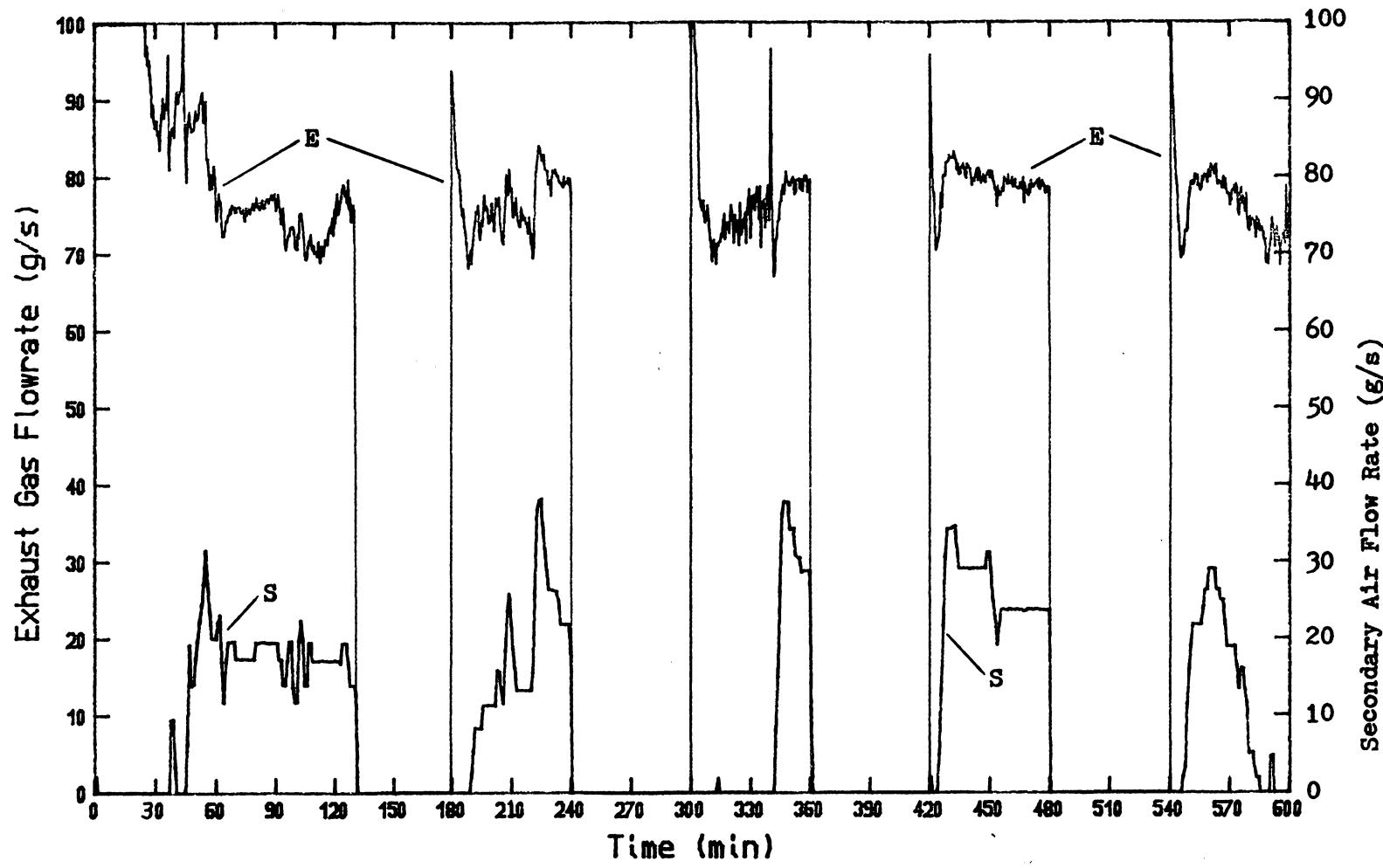


Figure 51. Exhaust Gas Flow Rate (E) and Secondary Combustion Air Flow Rate (S)
During Test 18

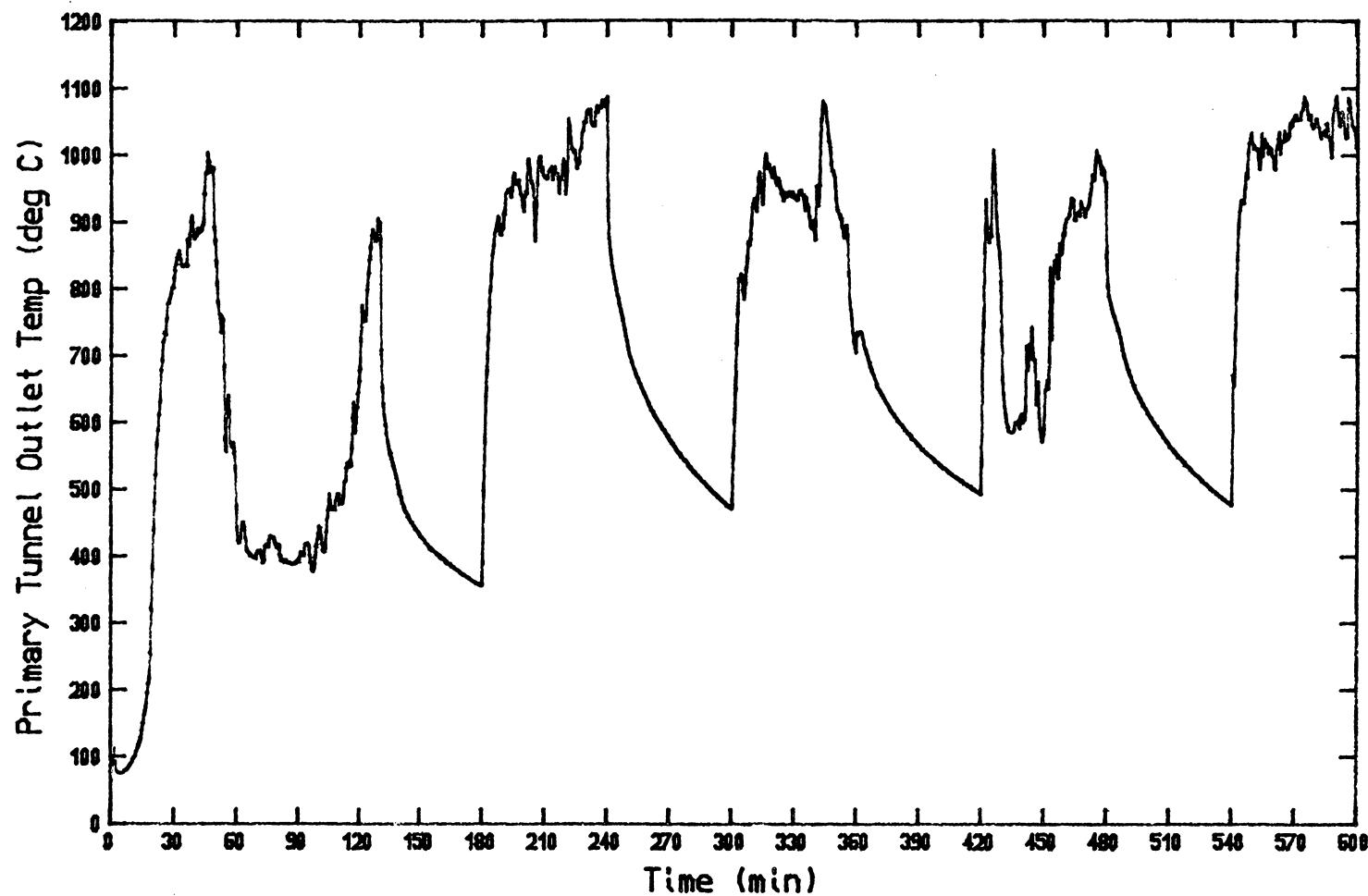


Figure 52. Primary Combustion Tunnel Outlet Temperature During Test 18

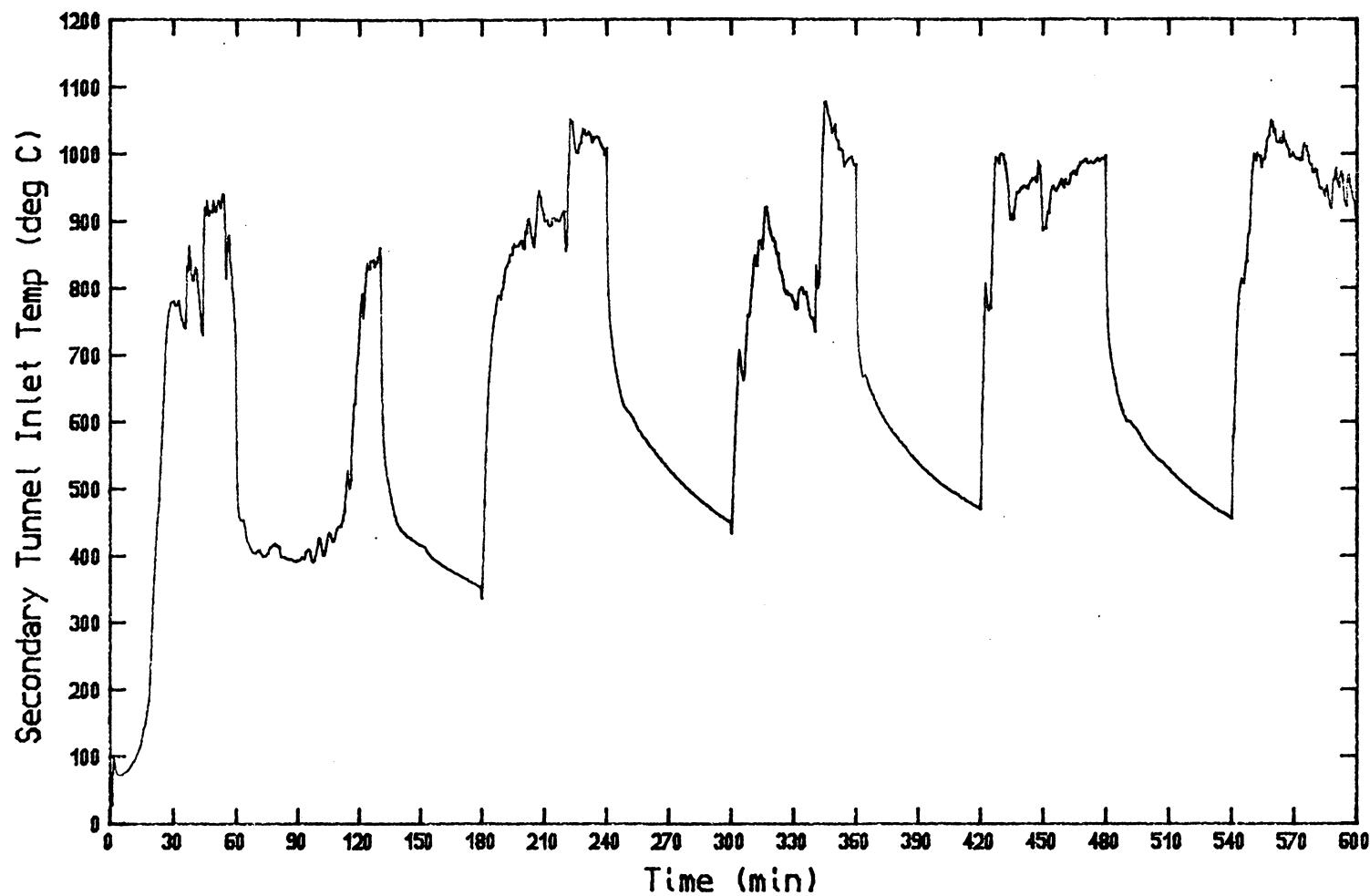


Figure 53. Secondary Combustion Tunnel Inlet Temperature During Test 18

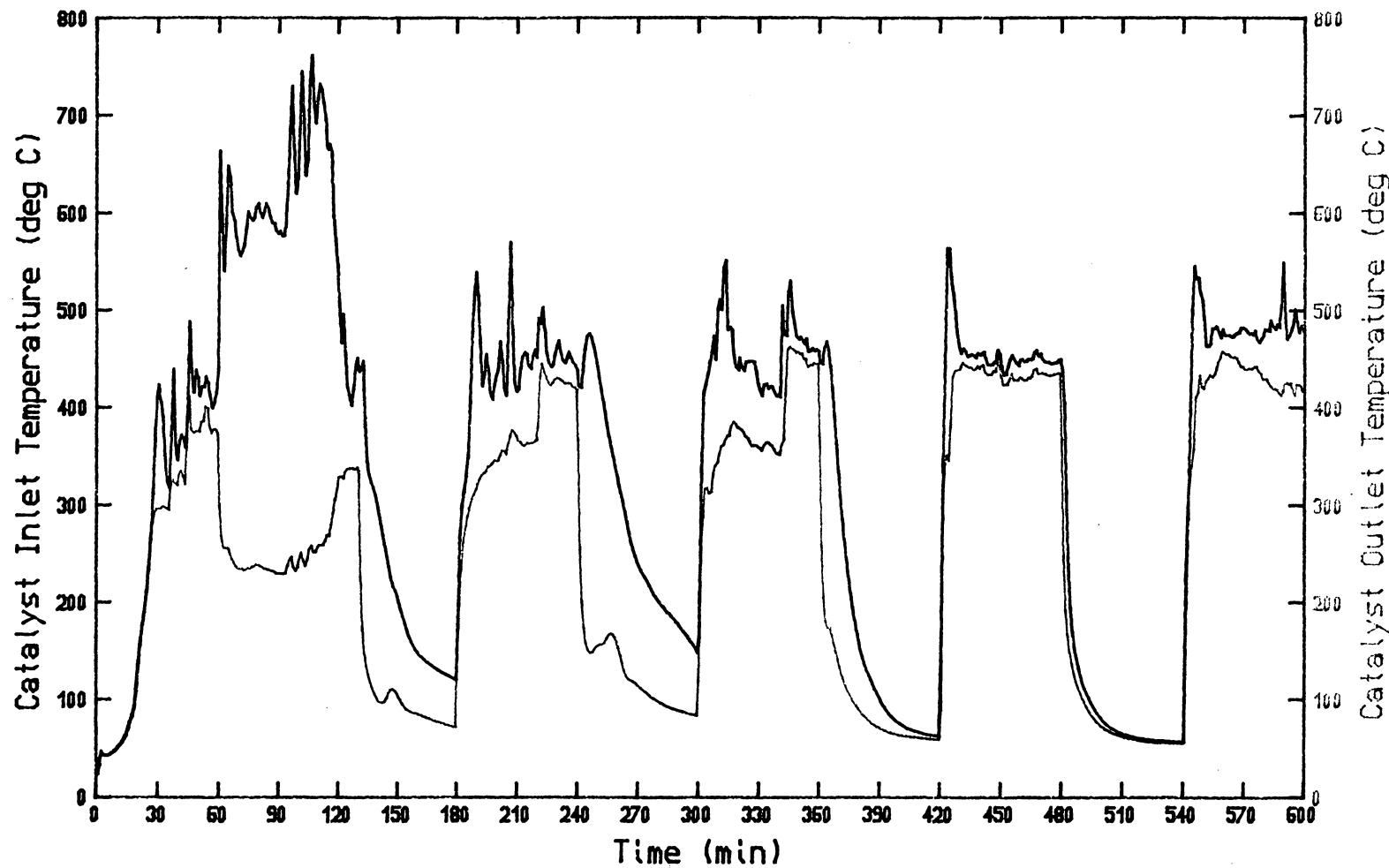


Figure 54. Catalyst Inlet and Outlet Temperatures During Test 18. In This Figure, Outlet Temperature Is Always the Higher of the Two.

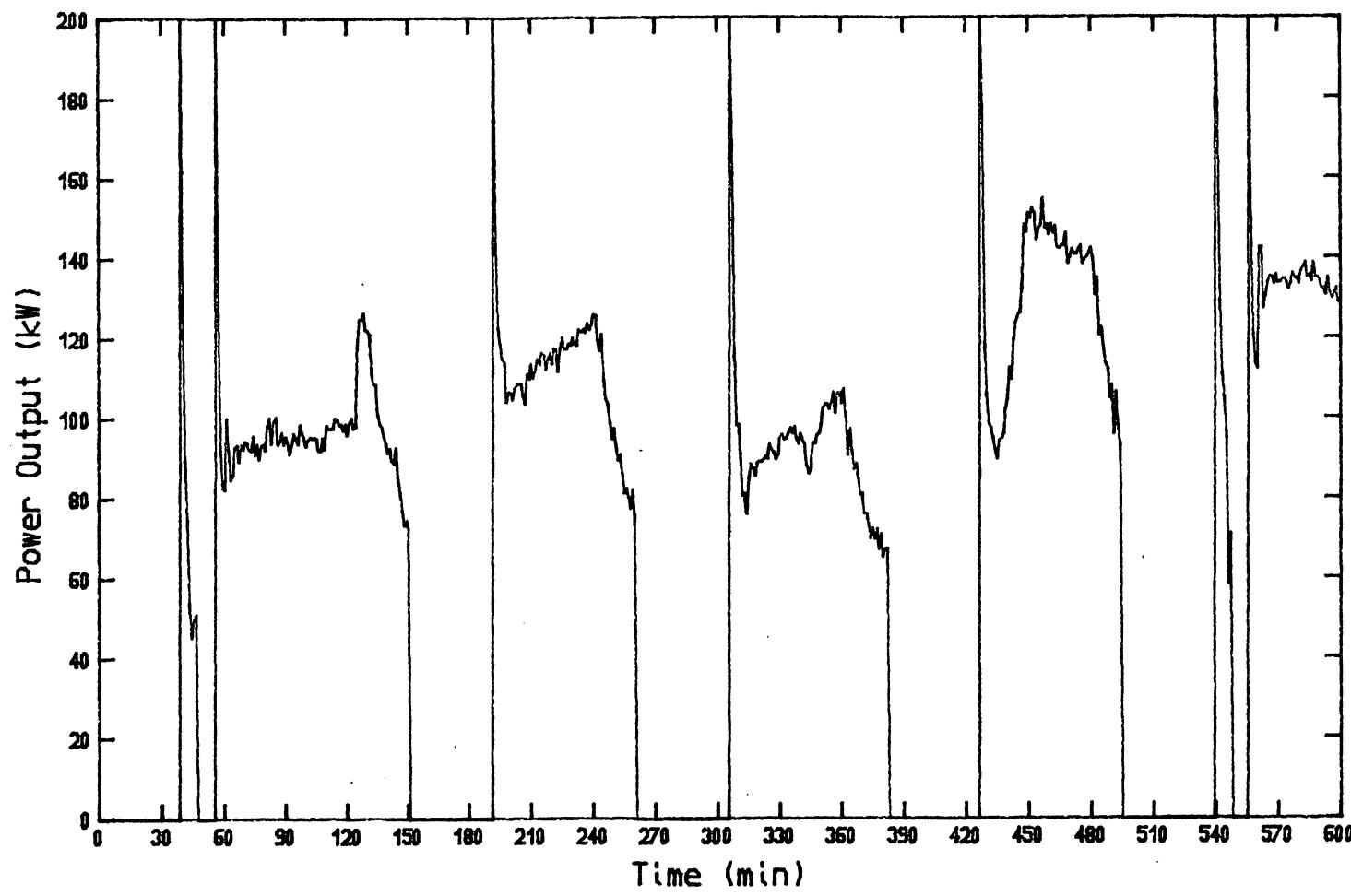


Figure 55. Useful Heat Output During Test 18

cussed earlier. However, due to the second problem such a high chemical energy level enters the catalytic combustor that a simple redesign of the catalytic combustor may not solve the problem -- even if all of the chemical energy were released in an improved combustor (which would probably have to be inordinately large), the temperature rise would be prohibitively high and severely shorten the catalyst life. Also, experience has shown that these periods of poor non-catalytic secondary combustion severely foul the heat exchange surfaces, especially the tubes which are upstream of the catalytic combustor. Therefore, it would be much more desirable to prevent self-extinguishment than to attempt to deal with its consequences.

On the positive side of the results, there were periods of low emissions. During about 50% of the operating time, the CO/CO₂ ratio was less than 0.02, the arbitrarily chosen value denoting low emissions. Further, during about 25% of the total operating time, the CO/CO₂ ratio was below 0.005 - corresponding to a combustion efficiency in excess of 99.5 percent.

5.3.2 Test 19

Prior to test 19, no changes were made to the control strategy. Finely split cordwood was used in this test in order to simulate slash (logging residual). The results of test 19, presented in Figs. 56-62, reveal performance similar to test 18. However, during test 19, a possible solution to the self-extinguishing noncatalytic secondary combustion was found.

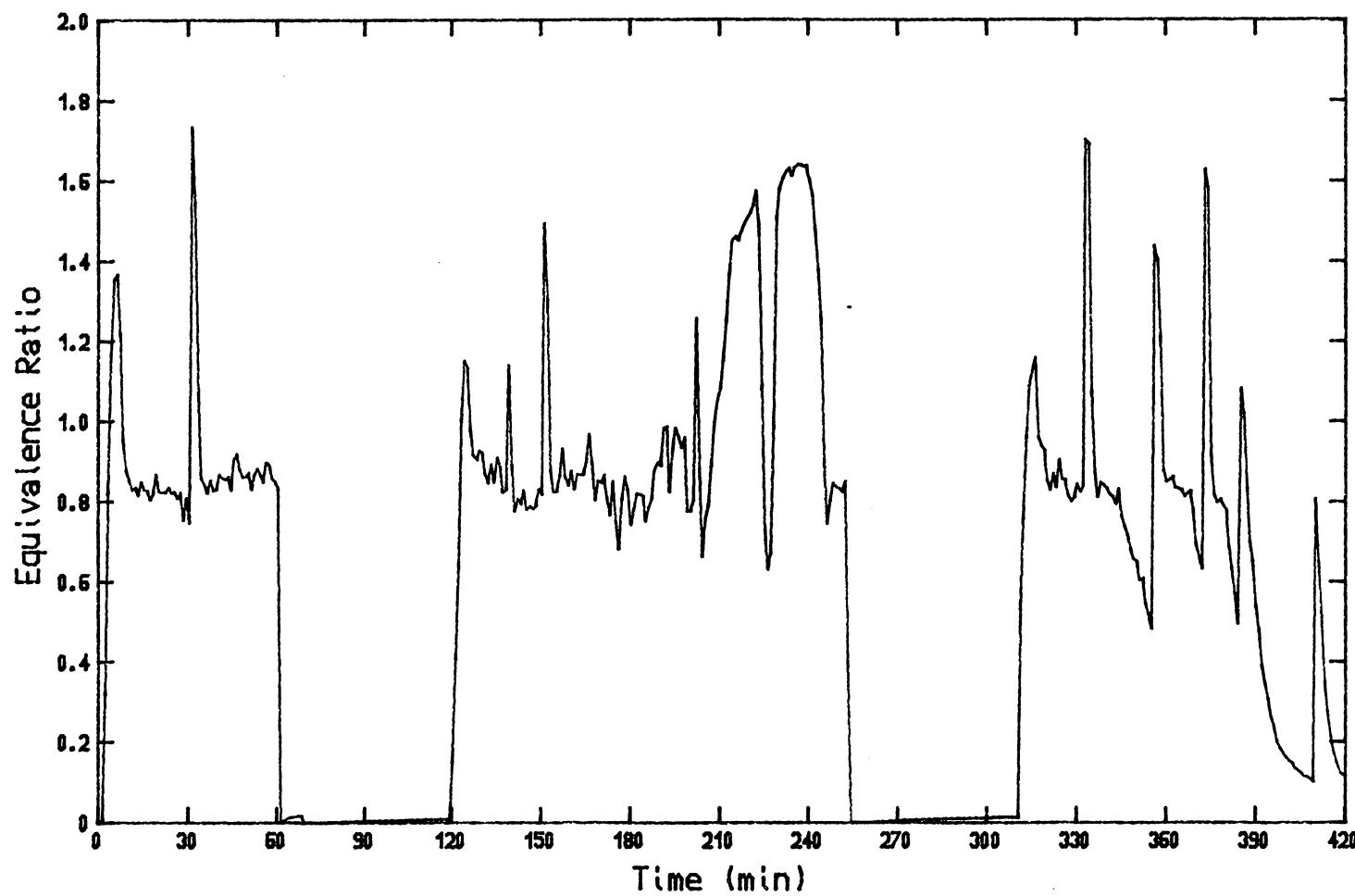


Figure 56. Equivalence Ratio During Test 19

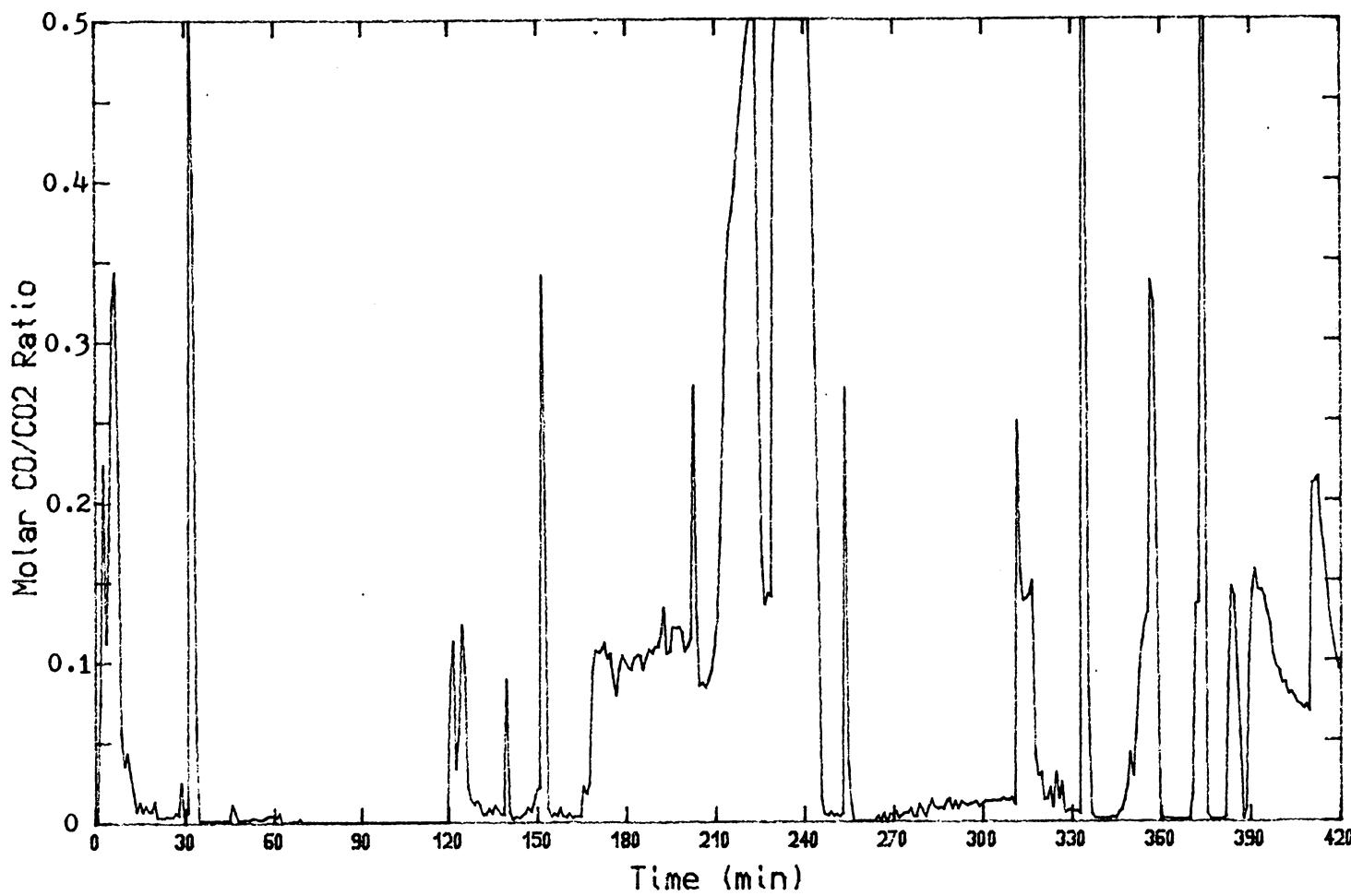


Figure 57. Molar CO/CO₂ Ratio During Test 19

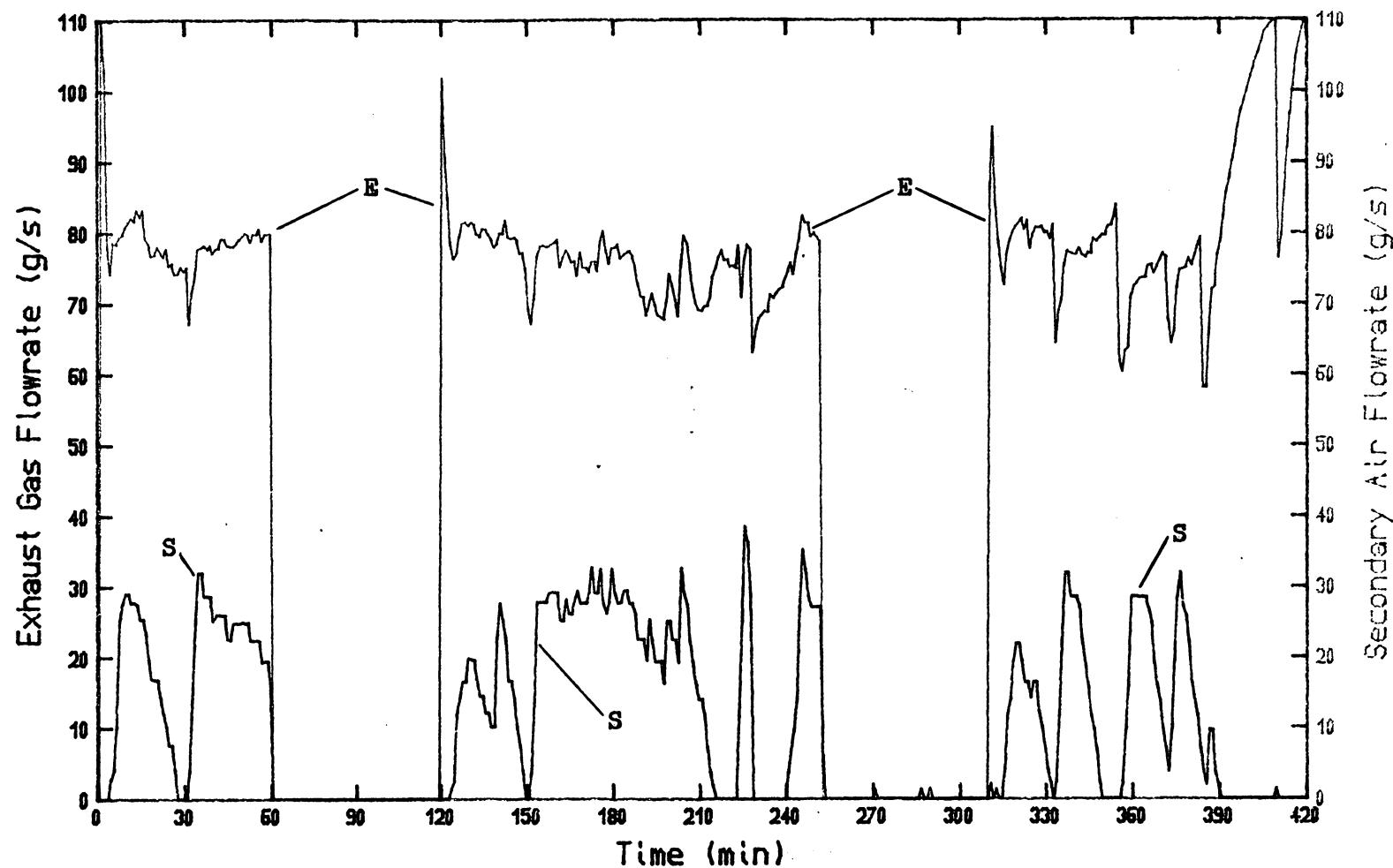


Figure 58. Exhaust Gas Flow Rate (E) and Secondary Combustion Air Flow Rate (S)
During Test 19

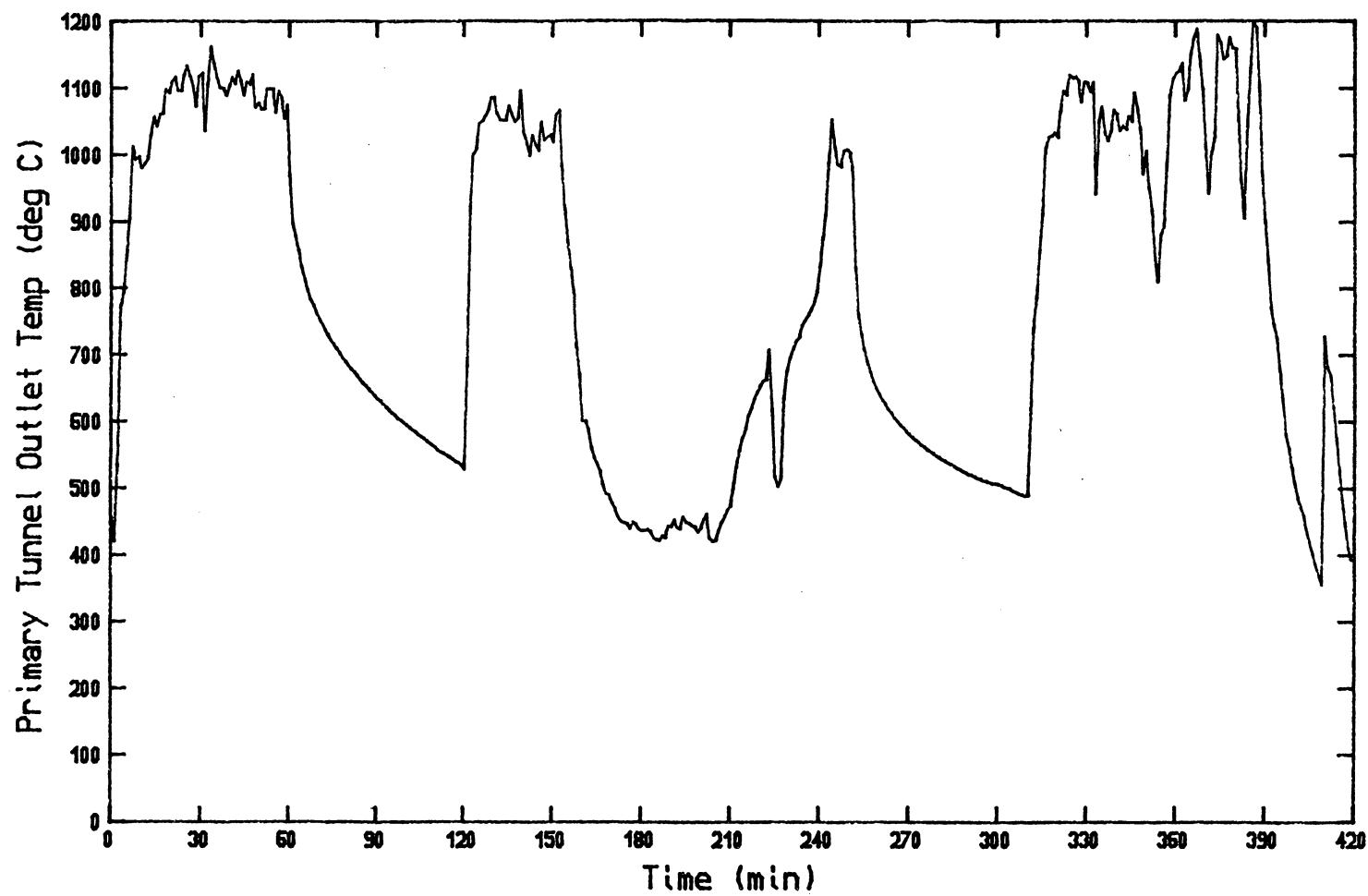


Figure 59. Primary Combustion Tunnel Outlet Temperature During Test 19

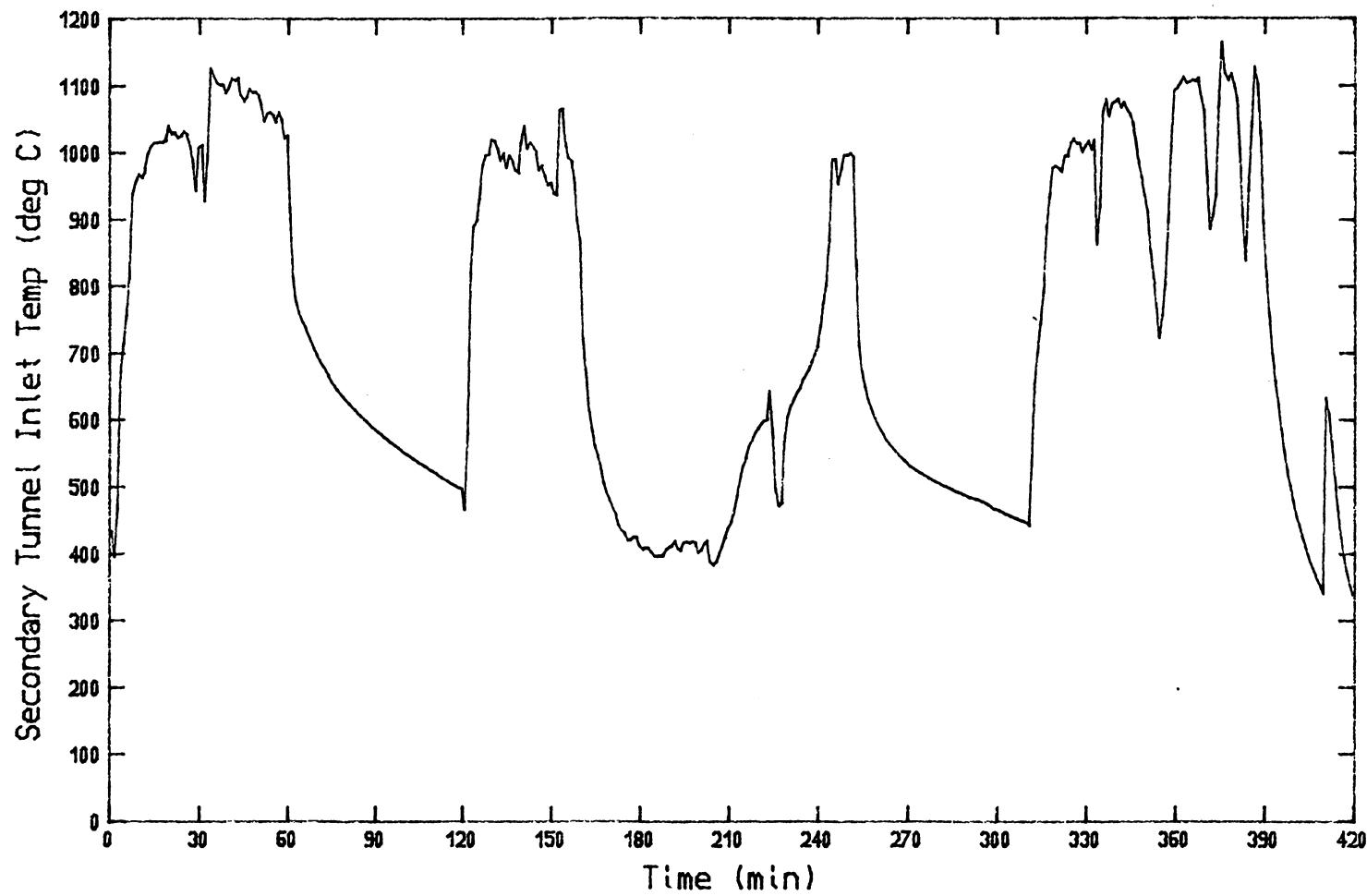


Figure 60. Secondary Combustion Tunnel Inlet Temperature During Test 19

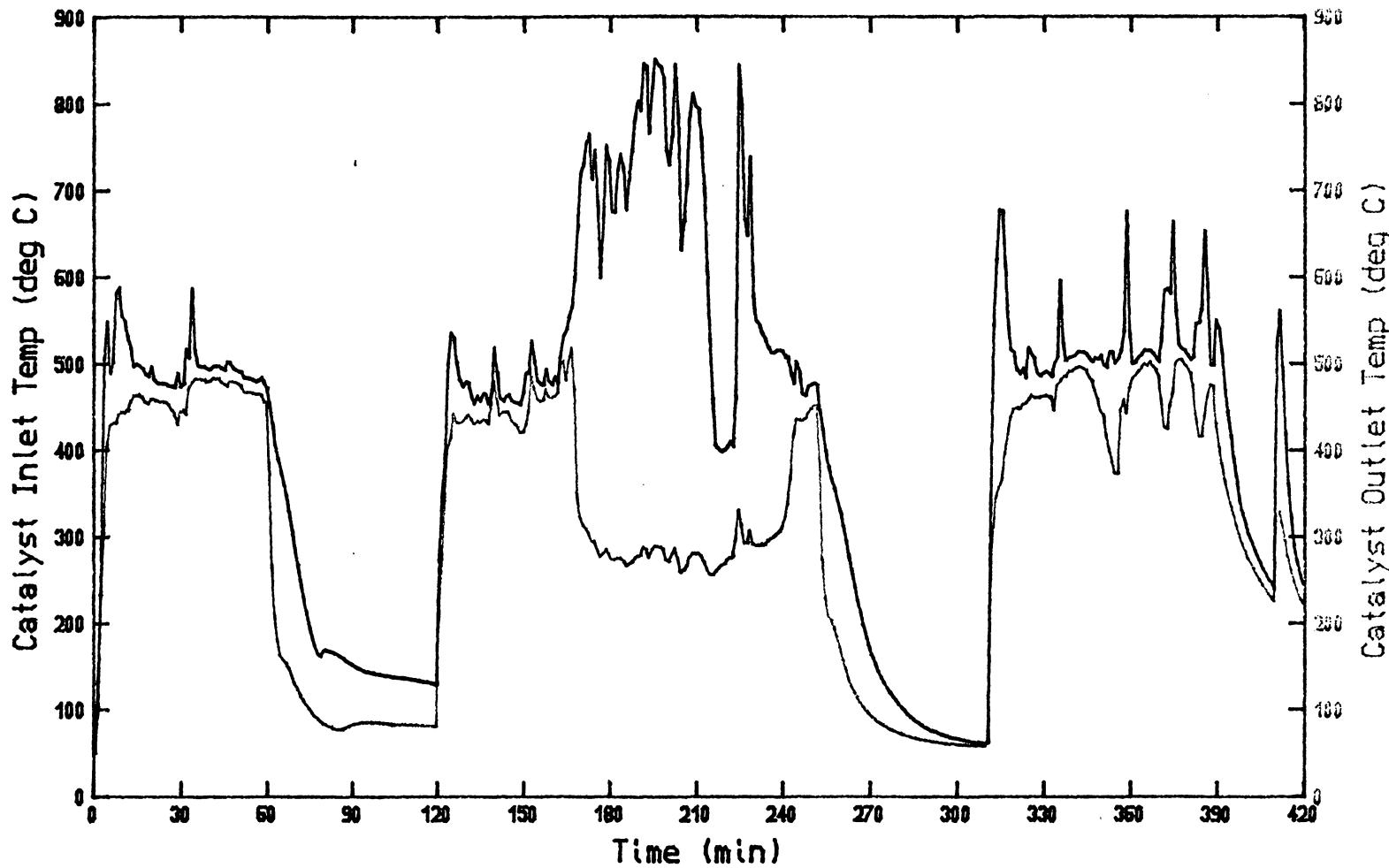


Figure 61. Catalyst Inlet and Outlet Temperatures During Test 19. In This Figure, Outlet Temperature Is Always the Higher of the Two.

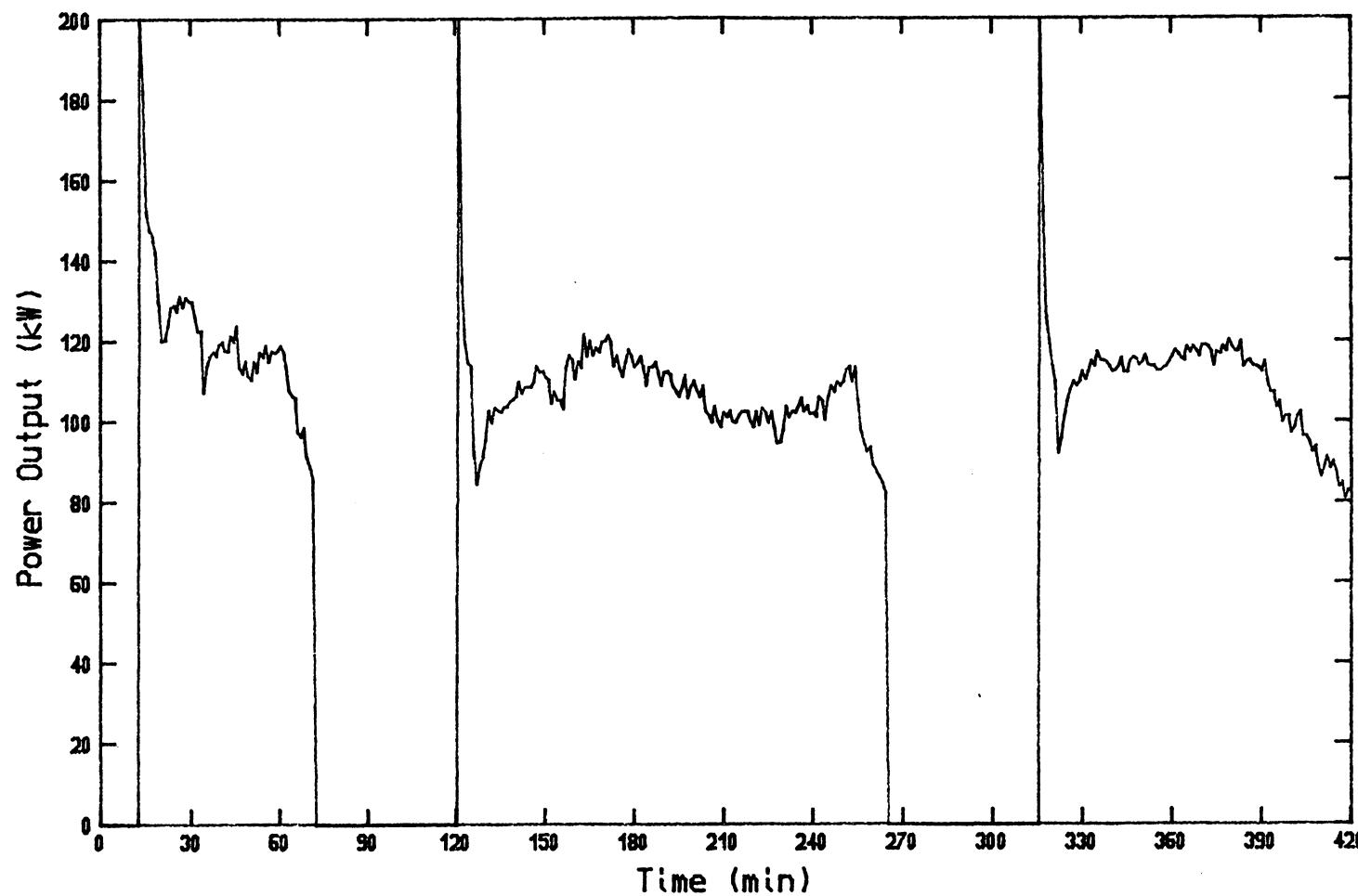


Figure 62. Useful Heat Output During Test 19

The process of developing and checking this possible solution were as follows. During the period from 187 to 198 minutes the secondary air flow was reduced below that which would have been set by the control system. The reasoning behind this was that without the noncatalytic secondary combustion to release heat in the refractory combustion passages of the boiler, the secondary combustion air probably served only as a coolant and gradually caused the boiler temperature to drop -- locking the boiler into a stable but dirty combustion mode. In this mode, the emissions could be reduced to acceptably low levels by having a sufficiently large catalytic combustor. However, given the present location of the catalytic combustor, no heat would be transferred back to the areas of noncatalytic combustion -- thus the poor noncatalytic combustion would continue. Since the secondary air was only cooling the combustion passages it was believed that reducing secondary air flow would cause the temperatures of the combustion passages to rise, resulting eventually in high enough temperatures to again add secondary air with high efficiency of noncatalytic secondary combustion.

Following this strategy for 187 to 198 min, the secondary air flow was reduced from about 30 g/s to 20 g/s. The combustion temperatures rose only about 10°C during this period, so the normal secondary air flow was resumed, bringing the equivalence ratio back to that dictated by control based on the G-cell output. Then beginning at about 210 minutes the GSET parameter (set point) was set to -1 mV, so that the controller would drive the secondary air valve entirely shut. From this point forward, the strategy was adopted of inhibiting the secondary air flow entirely until the secondary tunnel inlet temperature (henceforth

to be referred to as STI) rose above the value of a parameter designated as GTEMP. GTEMP was initially taken to be 600°C.

Immediately upon initiating this new strategy, STI began to increase from its steady value of about 400°C. Within about 10 minutes, STI rose above 600°C so the control system was once again given complete control of the secondary air. However, all noncatalytic combustion temperatures immediately plunged 150 to 200°C indicating that the secondary air was not reacting with the rich products of primary combustion.

Because of this, the GTEMP parameter was increased to 700°C, so that secondary air flow was inhibited unless STI was above 700°. Once again the noncatalytic combustion temperature climbed, in 10 to 15 minutes, to above 700°C and normal secondary air control was resumed. The required flow of about 30 g/s was added, causing STI this time to climb within 1 or 2 minutes to about 1000°C. Clearly, in this instance noncatalytic secondary combustion was initiated and sustained until the boiler was shut down at 252 minutes.

On the basis of these results then, the validity of the GTEMP strategy is clearly established at least for the present boiler conditions. Use of the GTEMP modification was continued through the remainder of test 19.

Upon restart of the boiler at 310 min, the GTEMP strategy held off secondary air for about 6 to 7 minutes, during which time the equivalence ratio was above 1.0. As in the previous instance, when STI topped 700°C and secondary air was added, noncatalytic combustion temperatures rose sharply, and CO/CO₂ ratio dropped to below 0.02,

clearly indicating the onset of noncatalytic secondary combustion. The remainder of the test was marked by generally very low emissions, except during periods immediately prior to stirring the fuel bed when the equivalence ratio dropped off due to burn out of the fuel bed. The high emissions period beginning at about 390 minutes was caused by an extremely low burn rate resulting from insufficient fuel in the magazine -- in short, the boiler was ready for refueling. For this reason, the dirty period from 390 to 430 minutes is of no practical concern.

Following test 19, the control strategy modification involving GTEMP was automated by incorporating it into the secondary combustion air control subroutines of the data acquisition and control code. Also, the secondary combustion air step size was increased to 5 g/s in an effort to speed the response of the control system.

5.3.3 Test 20

Results of test 20, presented in Figs. 63-69, may be summarized as follows:

- 1) CO/CO₂ ratio was less than 0.02 during about 68% of the operating time.
- 2) Secondary combustion air was required during less than 30% of the operating time.
- 3) When secondary air was on, its average rate was about 5 to 7 g/s.
- 4) The average reduction in CO attributable to the catalytic combustor was about 0.2% CO which amounts to roughly half of the CO entering the catalytic combustor.

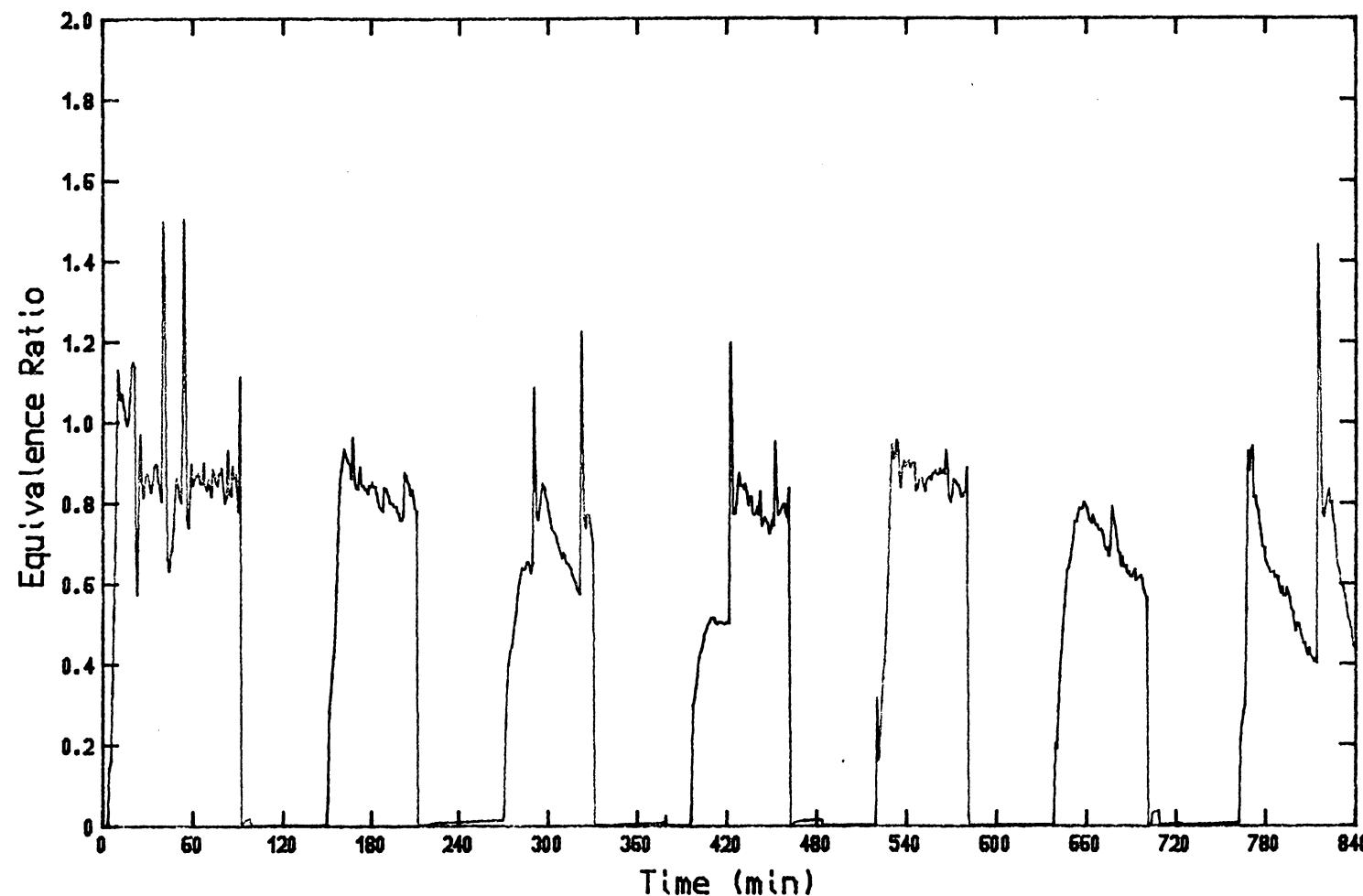


Figure 63. Equivalence Ratio During Test 20

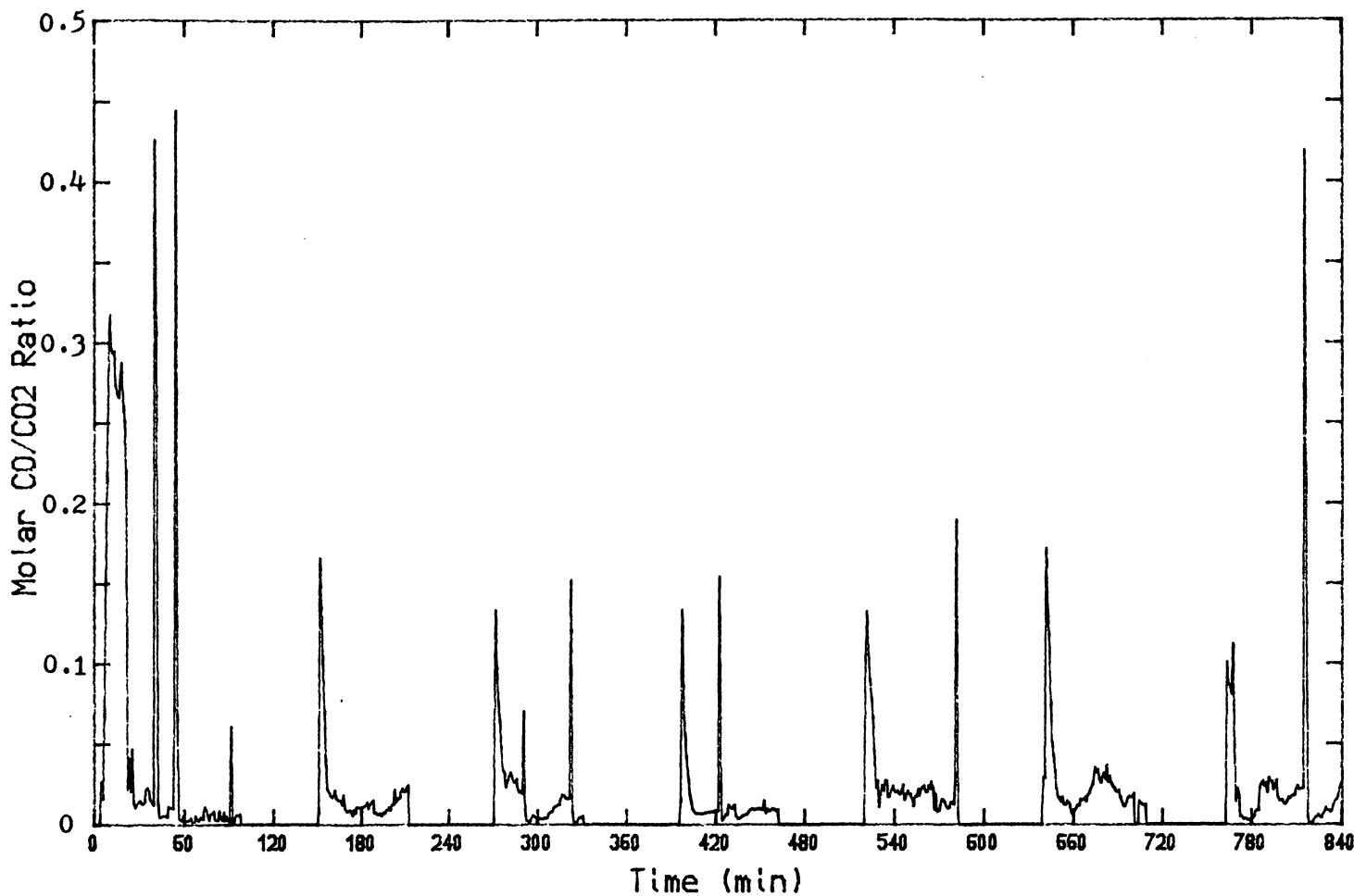


Figure 64. Molar CO/CO₂ Ratio During Test 20

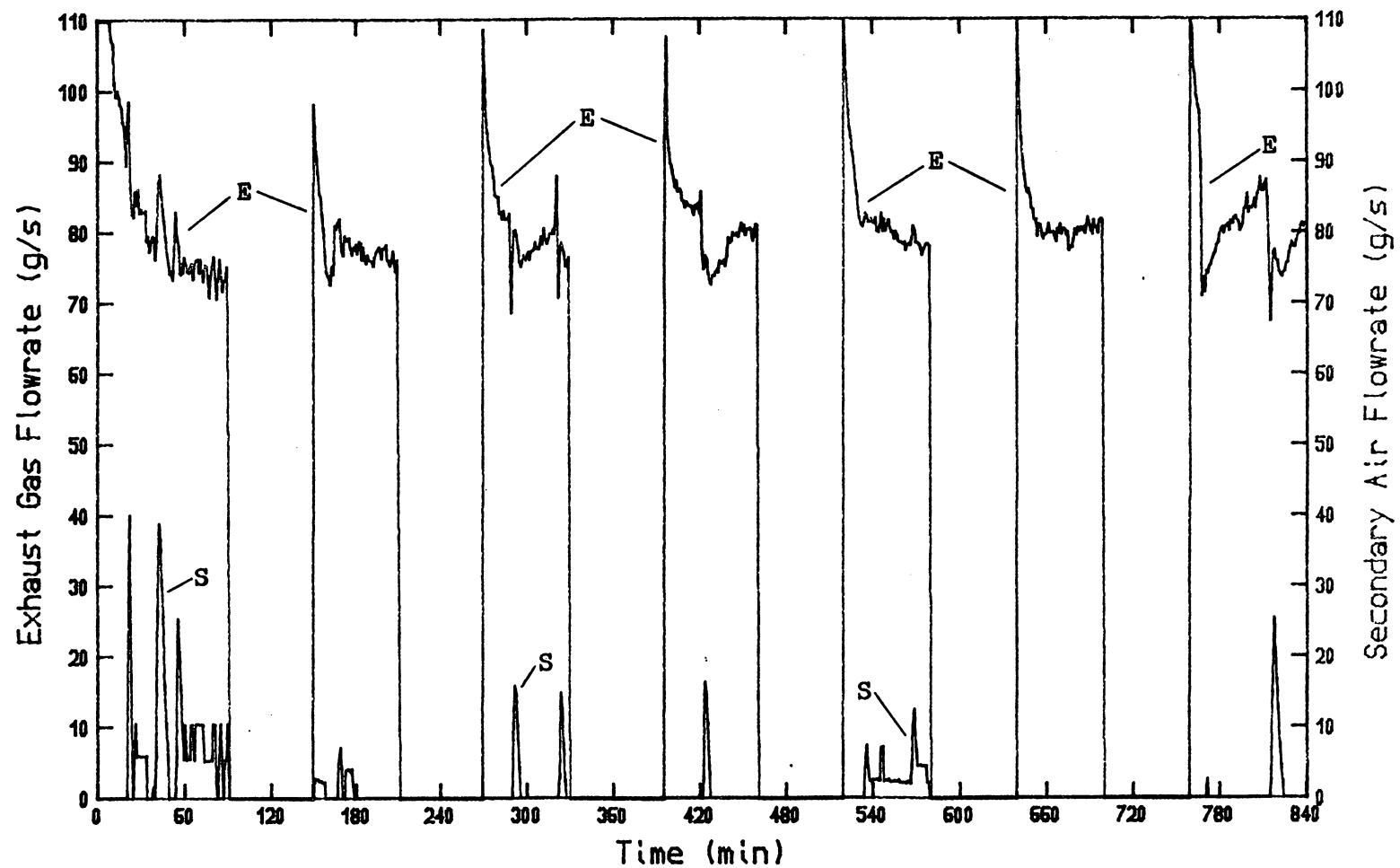


Figure 65. Exhaust Gas Flow Rate (E) and Secondary Combustion Air Flow Rate (S)
During Test 20

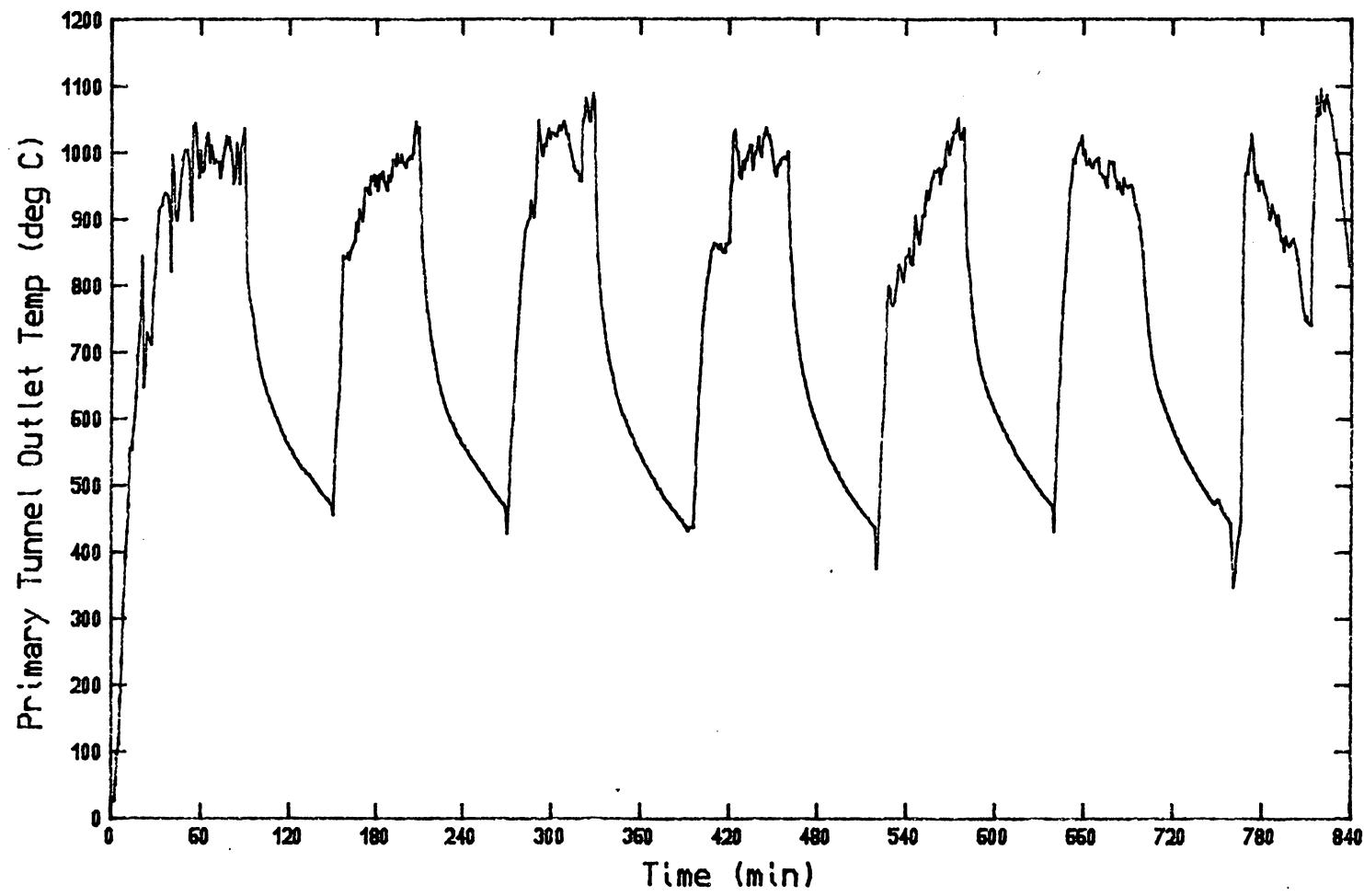


Figure 66. Primary Combustion Tunnel Outlet Temperature During Test 20

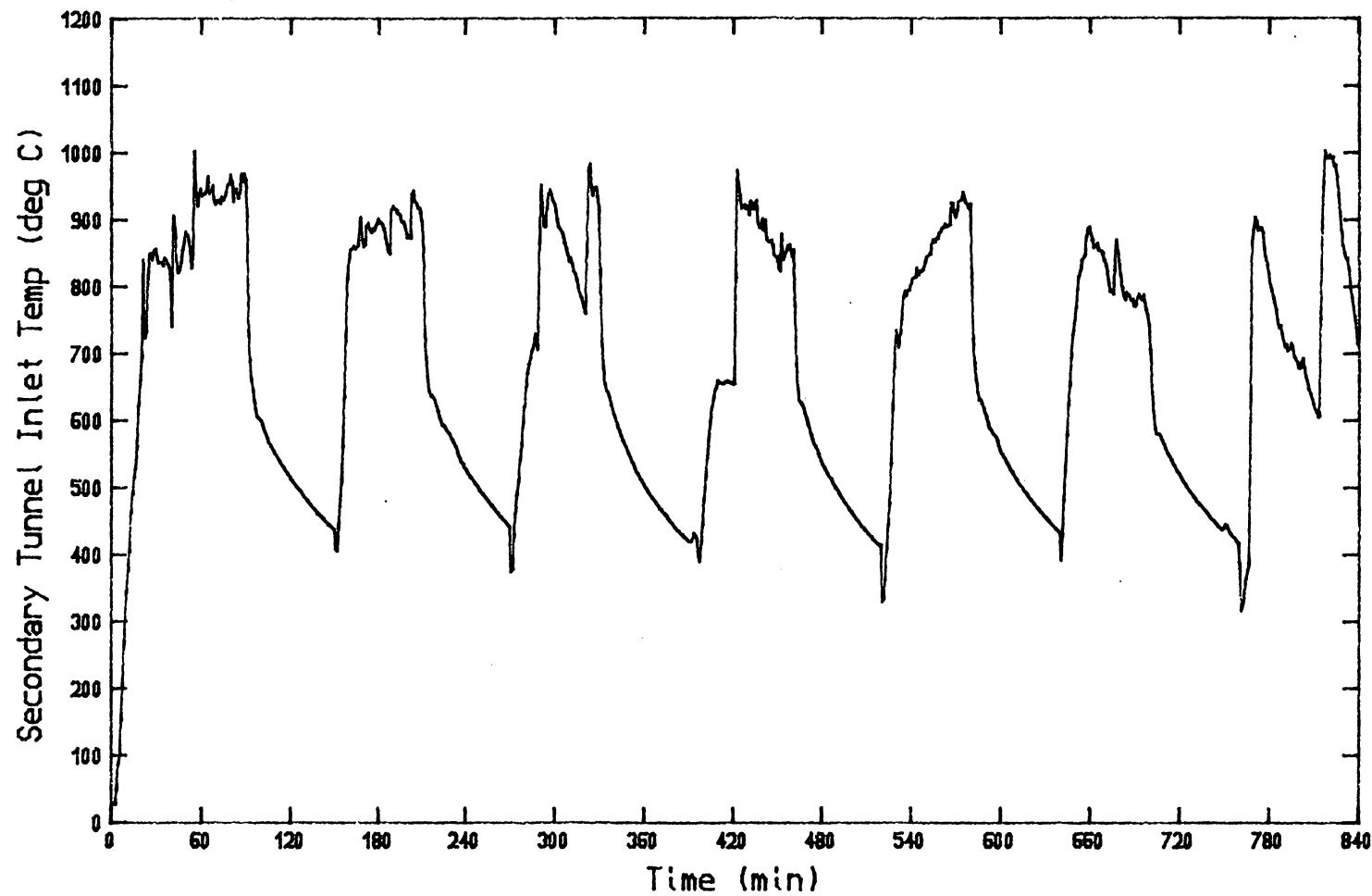


Figure 67. Secondary Combustion Tunnel Inlet Temperature During Test 20

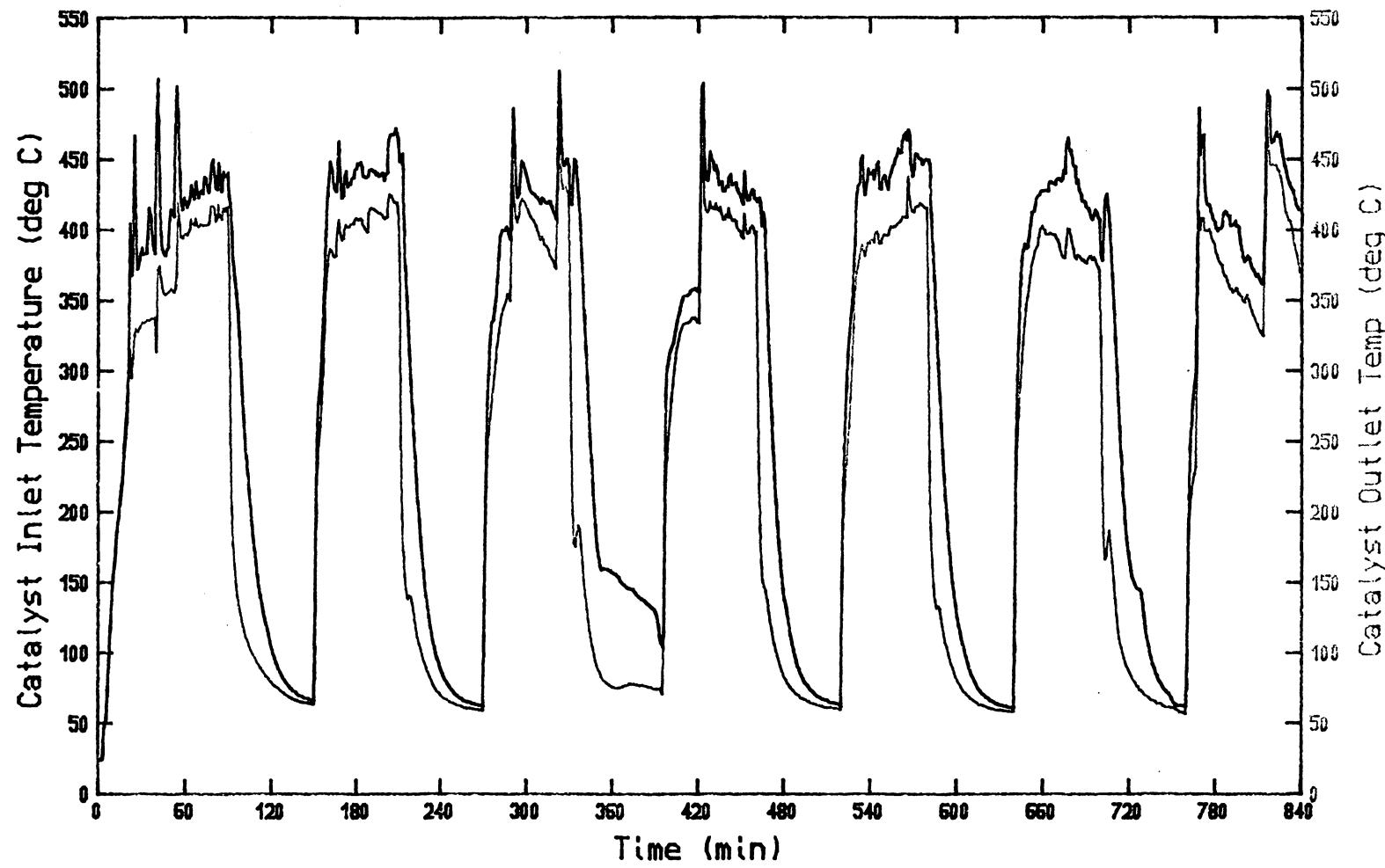


Figure 68. Catalyst Inlet and Outlet Temperatures During Test 20. In This Figure, Outlet Temperature Is Always the Higher of the Two.

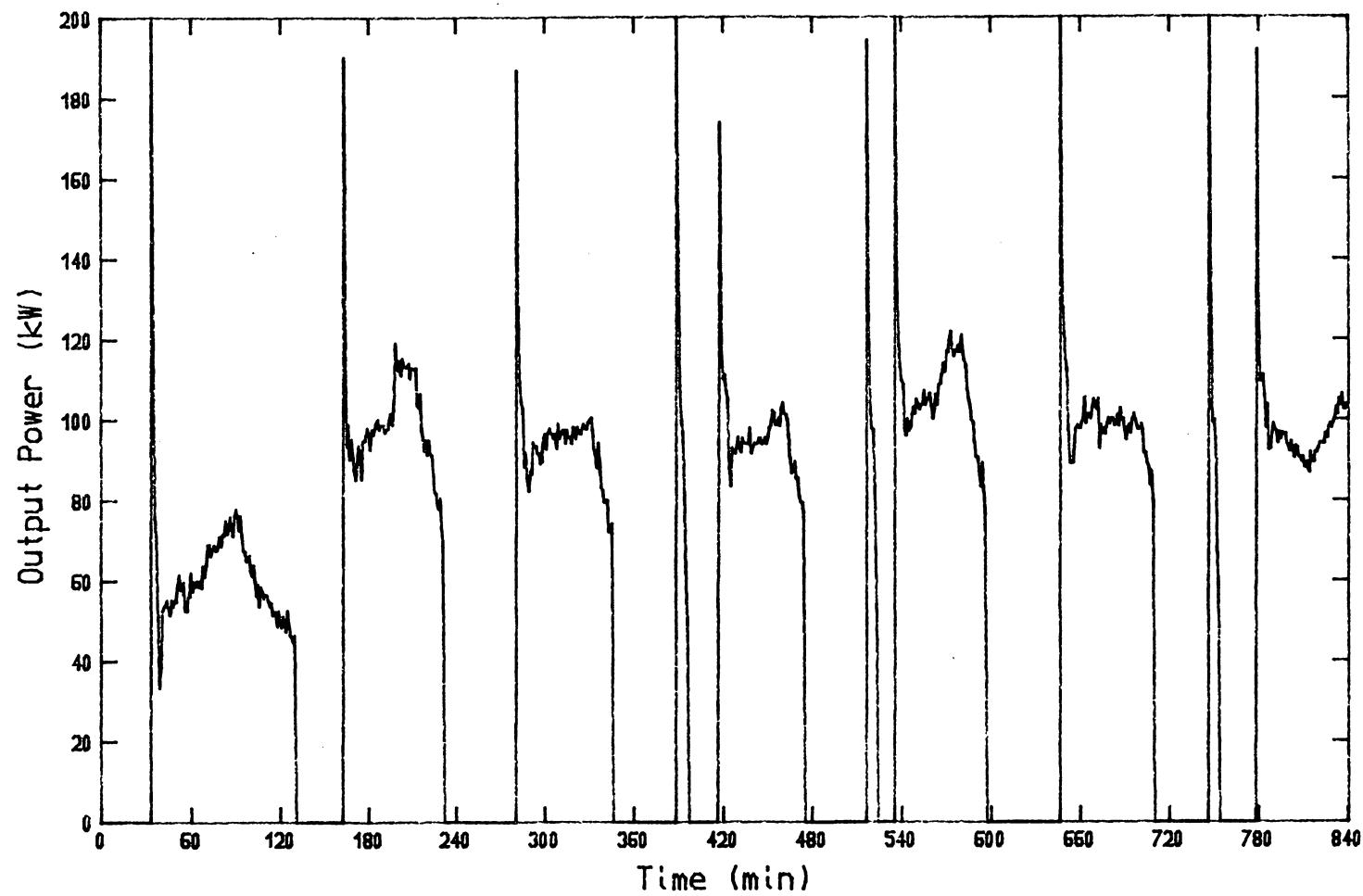


Figure 69. Useful Heat Output During Test 20

It is worthy to note that extremely low emissions could have been obtained during the test with a reasonable improvement in catalytic combustor design. In other words, the present catalytic combustor reduced CO by about 50%, on average. If a combustor was used which could increase this to say 80% -- a reasonable goal -- then the CO/CO₂ ratio would have been less than 0.02 during the entire operating time with the exception of periods when the controller was catching up with a disturbance such as a fuel stirring or reload and the equivalence ratio was near or above 1.0.

The relatively high moisture fuel used in test 20 appears to be the reason for the low secondary combustion air requirement. The energy used to drive off the fuel moisture was unavailable for gasification of the wood, thus less combustible gas was produced, yielding overall leaner products of primary combustion.

5.3.4 Test 21

Test 21 was the final performance test and was run with turkey litter fuel. In order to burn the litter with a minimum of ash carryover from the fuel magazine to the combustion passages and heat exchanger, a system of steel framed grates with Inconel screen decking was fabricated and installed prior to the test, as shown in Fig. 70, along with an "ash hood". The purpose of the grates and ash hood was twofold:

- 1) to reduce the maximum air velocity through the fuel bed and create an ash settling zone beneath the grates, and

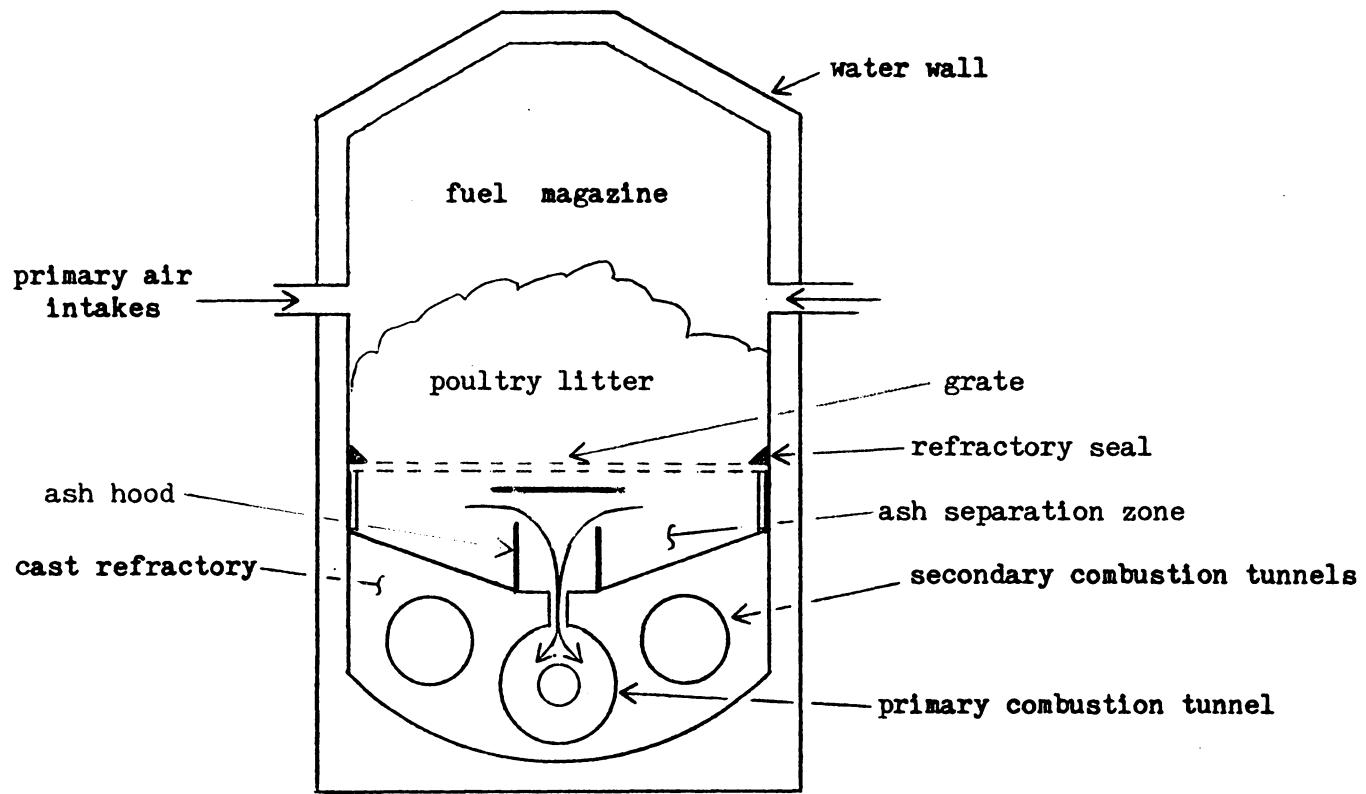


Figure 70. Diagram of Boiler Firebox Showing Raised Grates and Ash Hood for Burning Poultry Litter in Test 21. Arrows Show Flow Path of Air and Combustion Products.

- 2) to reduce the tendency for air tunneling through the fuel to occur and thus increase the average equivalence ratio of the products of primary combustion.

The development of this grate system as well as several other techniques of handling poultry litter in the Eshland model E500 boiler is covered in detail elsewhere [32].

Previous testing [32] has also shown that when litter is being fired in this raised grate configuration, the GTEMP parameter can be reduced from the 700°C required for cordwood to 600°C or possibly less. Thus, for test 21, GTEMP was assigned a value of 600°C.

Test 21 results are presented in Figs. 71-75. The test ran for about 5 1/2 hours on litter of 25 to 30% moisture with an average equivalence ratio of 0.8 to 0.85. At the end of the test, virtually no ash had passed through the inconel screened grate deck. All ash remaining at the end of the test was found fused into a brittle, fragile, porous, coral-like mass on top of the grates. No similar behavior had been noted in any earlier tests using chicken litter-fuel. The reason for the ash fusion cannot be determined with certainty, but the high temperatures reached in test 21 are probably the cause. This test saw secondary tunnel inlet temperatures in excess of 1000°C while earlier litter tests using this raised grate configuration peaked below 950°C.

It is clear that significant noncatalytic secondary combustion took place during test 21. Since the secondary air flow averaged 15 to 20 g/s during the test (which means the products of primary combustion were fuel rich), much combustion activity had to occur following addition of

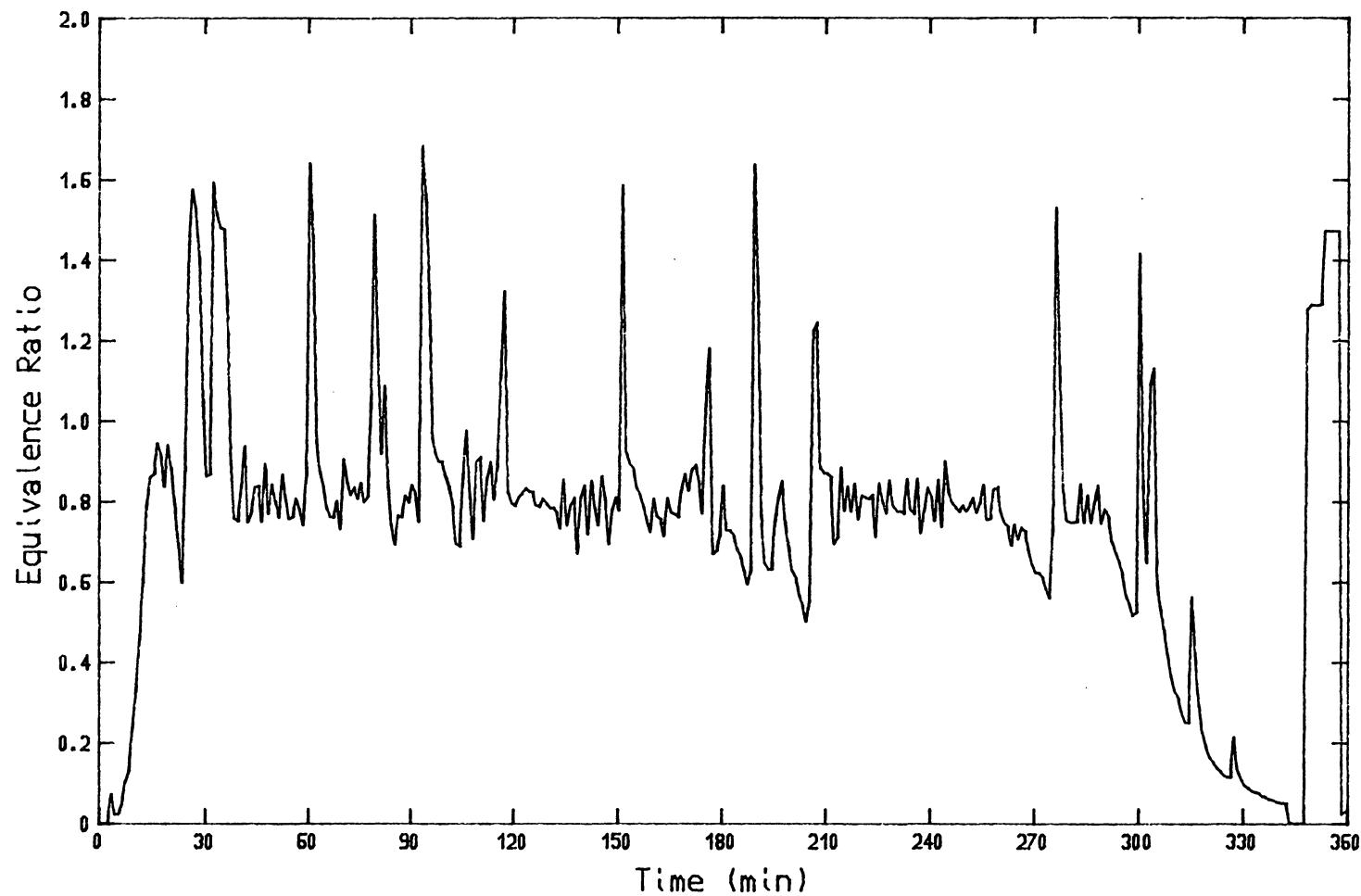


Figure 71. Equivalence Ratio During Test 21

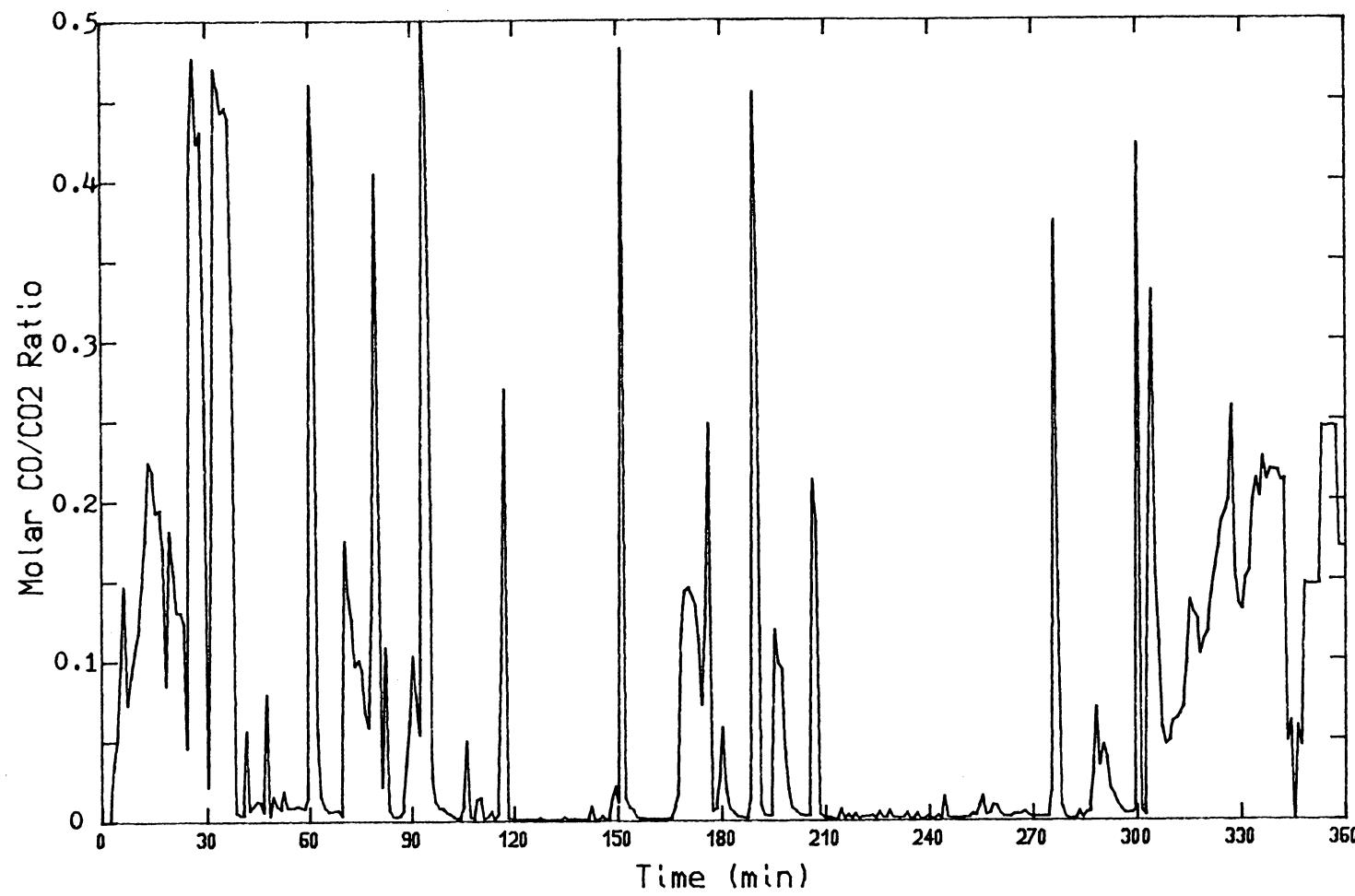


Figure 72. Molar CO/CO₂ Ratio During Test 21

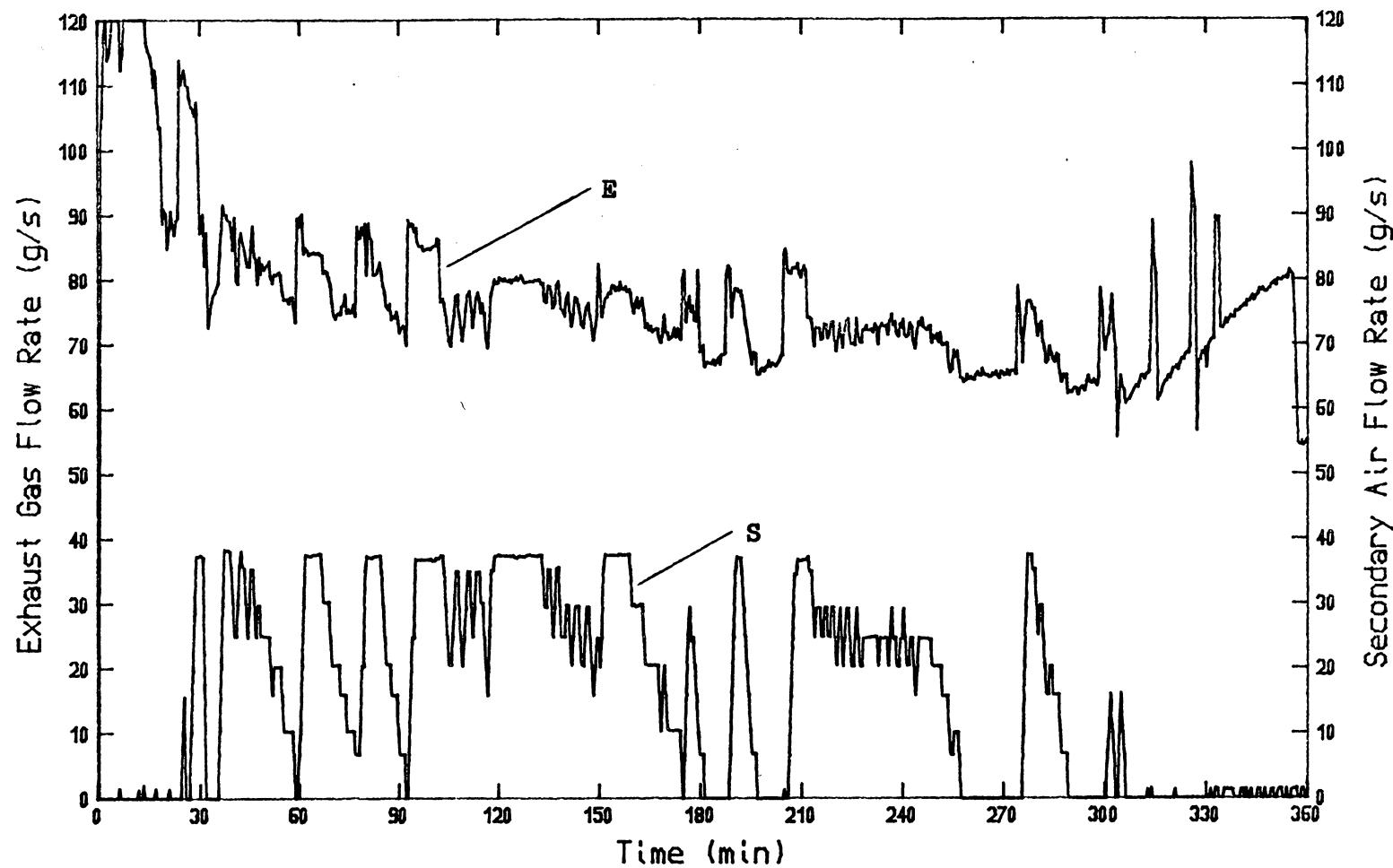


Figure 73. Exhaust Gas Flow Rate (E) and Secondary Combustion Air Flow Rate (S)
During Test 21

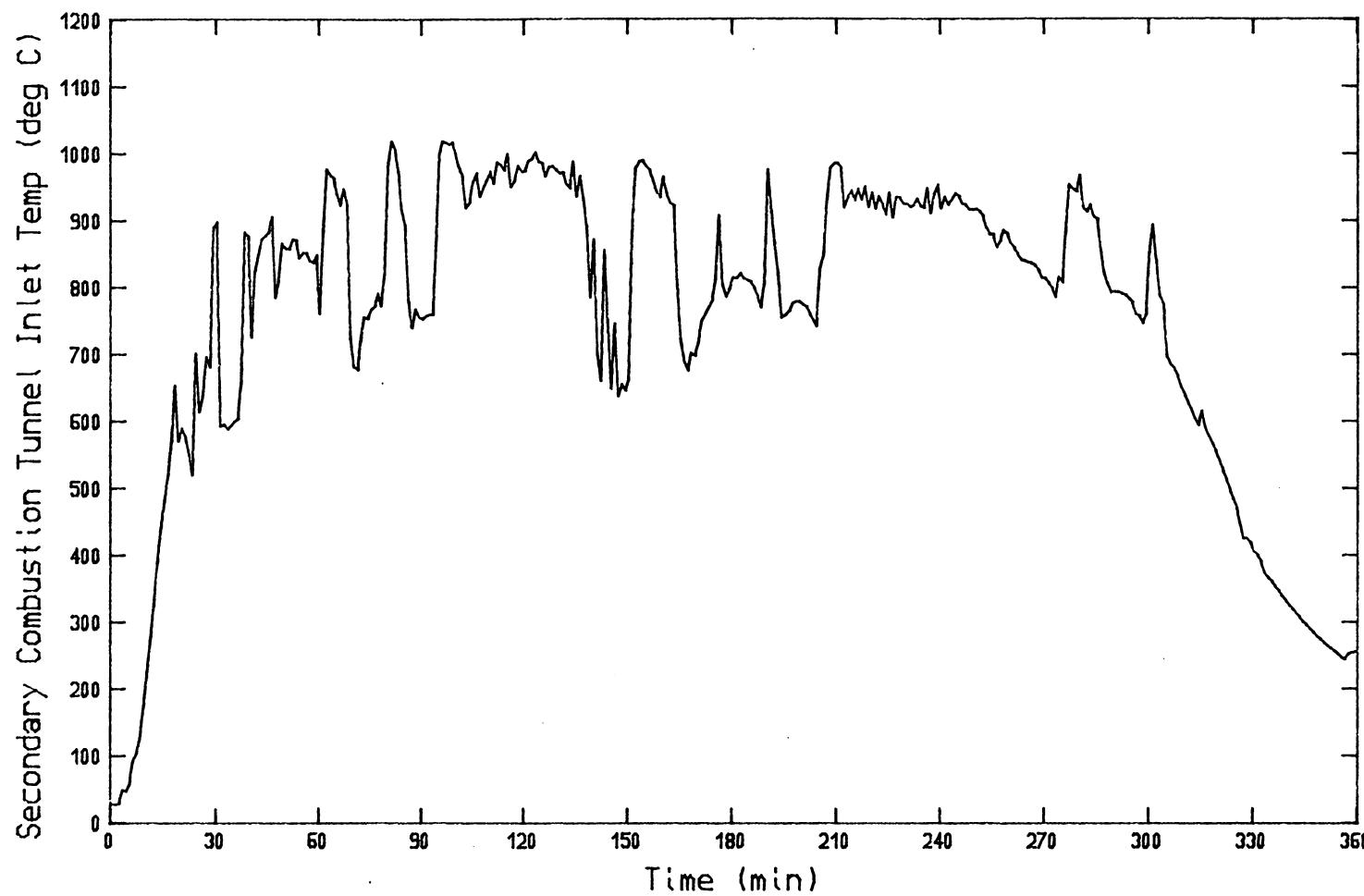


Figure 74. Secondary Combustion Tunnel Inlet Temperature During Test 21

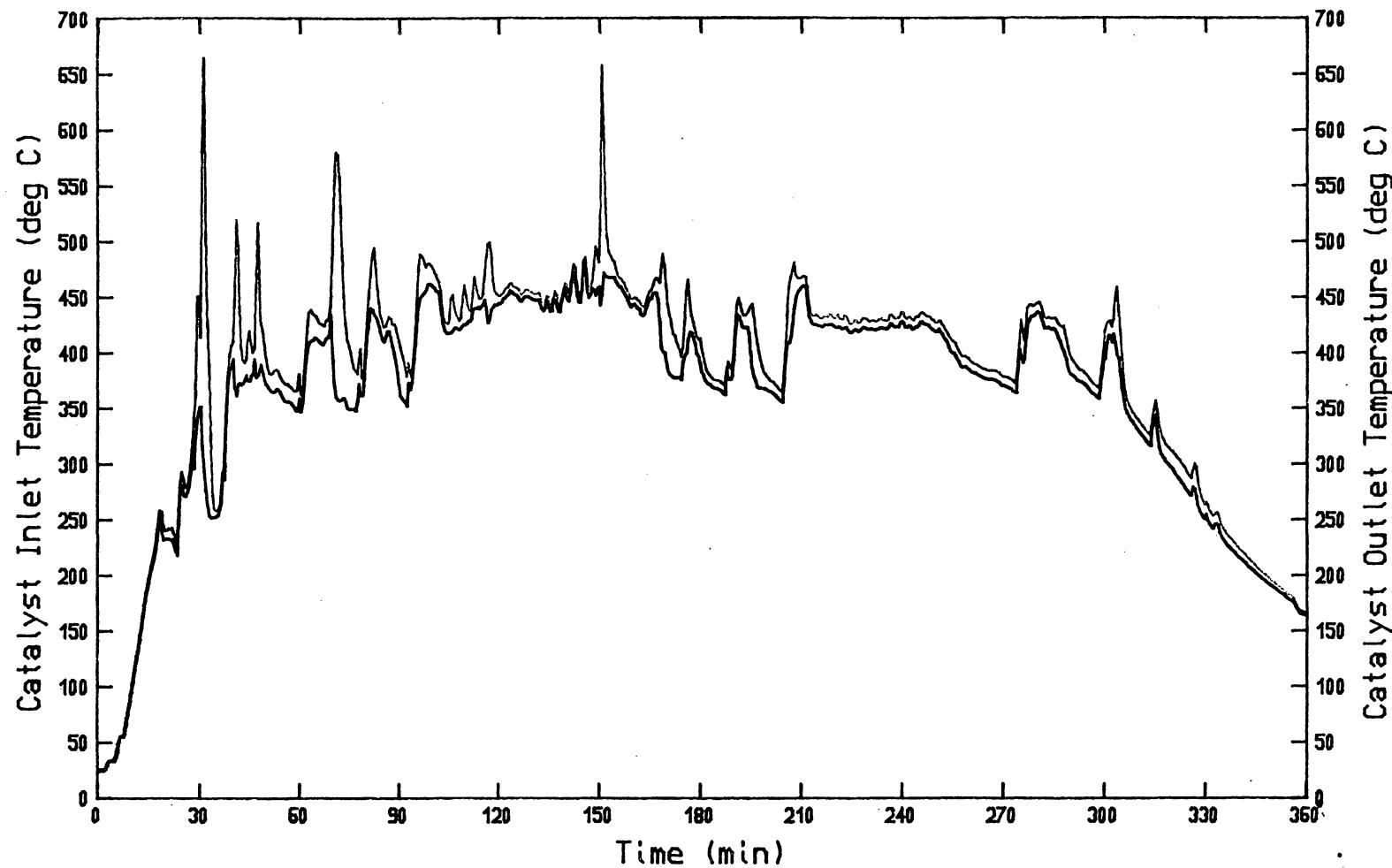


Figure 75. Catalyst Inlet and Outlet Temperatures During Test 21. In This Figure, Outlet Temperature Is Always the Higher of the Two.

secondary air in order to obtain the extremely low emissions (extended periods below 0.007 CO/CO₂ ratio) found in this test. Since the catalyst activity was very small during these periods, it must be concluded that noncatalytic secondary combustion was highly effective.

One specific event also indicated the onset of noncatalytic secondary combustion. A fuel load was added early in the test when the boiler had not yet warmed up. Immediately the equivalence ratio exceeded 1.0, but due to the low temperature, the control system did not add secondary air. In several minutes the secondary tunnel inlet temperature rose above the 600°C lower temperature limit (GTEMP) of the control system, causing secondary air flow to be initiated. Immediately, the stack puffed and the appearance of the emissions changed from thick haze to clear, giving evidence of noncatalytic secondary combustion. Also, catalyst activity dropped significantly at the time of the stack puff, reinforcing the conclusion that the very complete combustion was achieved noncatalytically.

Test 21 successfully demonstrated the grate configuration for burning litter under equivalence ratio control. The litter burned at high enough equivalence ratio for the control system to be effective, ash was retained on the grate, and combustion efficiency in excess of 99% was achieved for extended periods. However, longevity of the steel and Inconel grates in the severe combustion environment remains to be seen and ash removal must be performed manually.

6. MODEL RESULTS

6.1 Equilibrium Model

The final results of the three series of equilibrium calculations are in the form of adiabatic flame temperatures and molar CO/CO₂ ratio of the equilibrium mixture, which can be compared directly with the CO/CO₂ ratio reported in the plots of experimental data. Clearly, the assumptions of the equilibrium model are so sweeping that quantitative agreement with the experimental results is not expected. However, qualitative information about trends in the combustion process may be gleaned from the results.

The results of the variable moisture adiabatic series at 0.85 equivalence ratio, presented in Fig. 76, simply reveal, as expected, that adiabatic flame temperature falls with increasing fuel moisture. This is primarily due to the latent heat of vaporization of the fuel moisture and the dilution of the products of combustion with the vaporized moisture. Though the molar CO/CO₂ ratio increases with decreasing moisture, the peak value of 0.013 which occurs at 1797°C and 0 percent moisture is still a low value and would be considered clean since it is below 0.02. Therefore, even if the product composition was frozen at the adiabatic equilibrium value (for combustion at 0.85 equivalence ratio), the exhaust emissions would still be low.

The adiabatic flame temperature range of 1500-1800°C for 0.85 equivalence ratio and moistures under 32 percent¹ is of interest

¹Fuels used in the current test program have ranged from 7 to 32% moisture.

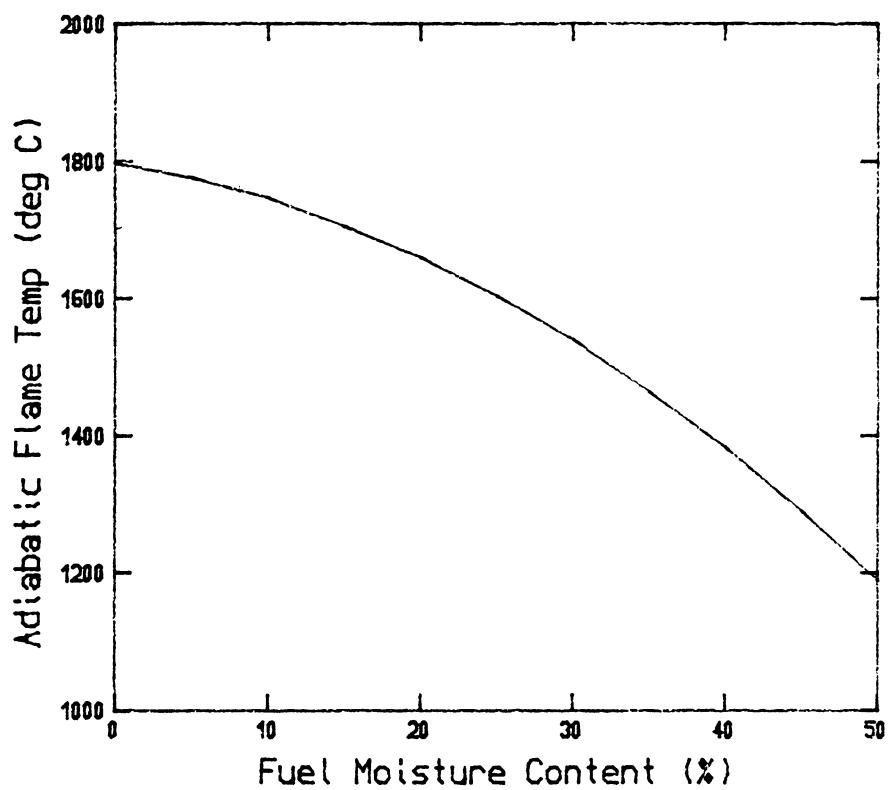


Figure 76. Equilibrium Model Results -- Effect of Fuel Moisture on Adiabatic Flame Temperature of Wood at 0.85 Equivalence Ratio

compared to the measured temperatures for the same moisture range and equivalence ratio which have not exceeded 1310°C and have only occasionally exceeded 1200°C. This discrepancy indicates that the combustion products are losing much of their available energy before they enter the heat exchanger. A simple calculation and comparison with experimental data will verify this. In test 18, at 462 minutes, with a fuel moisture of 8 percent, equivalence ratio of 0.87 (which yields an adiabatic flame temperature of about 1781°C), a secondary combustion tunnel outlet temperature of 870°C, and an estimated¹ heat exchanger outlet temperature of 330°C about 2/3 of the "available" energy² leave the products of combustion before they exit from the refractory combustion passages. Results similarly calculated and based on data from other tests is presented in Table 9. For the cases tabulated, these calculations show that 57 to 66 percent of the total heat transfer from the products of combustion occurs before they leave the secondary combustion tunnels.

This conclusion is reinforced by comparing the experimentally determined boiler heat output to the estimated heat transfer required to cool the products of combustion from their adiabatic flame temperature to the heat exchanger outlet temperature.¹ The additional experimental data (also from test 18, 462 minutes) is: exhaust gas flow rate 80 g/s and equivalence ratio 0.87. Under these conditions, the heat transfer

¹heat exchanger outlet temperature is estimated to be 60°C above the stack temperature.

²i.e., adiabatic enthalpy less the enthalpy at the estimated exhaust temperature.

Table 9. Comparison of Calculated Heat Transfer from Combustion Passages (\dot{Q}_{comb}) with Calculated Total Heat Transfer from the Products of Combustion (\dot{Q}_{total}).

<u>Test</u>	<u>Time (min)</u>	<u>$\dot{Q}_{\text{comb}} (\text{kW})$</u>	<u>$\dot{Q}_{\text{total}} (\text{kW})$</u>	<u>$(\dot{Q}_{\text{comb}} / \dot{Q}_{\text{total}})$</u>
11	190	63.4	110.5	57%
18	462	100.9	153.9	66%
20	450	73.4	120.0	61%
20	660	78.6	124.5	63%

rate required to cool the products of combustion from the adiabatic flame temperature to the exhaust temperature is 154 kW (using properties for the actual gas composition). Results similarly calculated for other tests are presented in Table 10 along with the experimentally determined useful heat outputs. Taken as a group, the calculated results show reasonable agreement with experiment, especially when it is considered that the calculated results assume 100 percent combustion efficiency (at all times shown in Table 10, actual combustion efficiencies were 98 to 99.5 percent) and take no account of stray heat losses from the boiler (though they do account for losses from the exhaust ducting cyclone and external induced-draft fan). Some scatter is also to be expected since changes in the useful power output always lag changes in the combustion process. The time since last fuel reload, also noted in Table 10 is another possible source of scatter. This is because a batch fuel load, especially a high-moisture load, could drastically reduce the actual useful heat transfer since the load acts as a large heat sink early in the batch cycle. The results shown in Table 10 then lend credibility to the earlier assertion that the majority of the heat transfer from the combustion products occurs before the heat exchanger. This large heat loss from the combustion zone has ramifications involving both the chemical kinetic modeling (see section 4.3) and the design of modifications to the boiler for combustion improvement.

The existence of large heat losses from the firebox implies that some opportunity exists for reducing these losses and thereby increasing the combustion temperatures. Since one of the major causes of high emissions (given the secondary combustion air control system developed

Table 10. Comparison Between Calculated (\dot{Q}_c) and Measured (\dot{Q}_m) Rates of Heat Transfer from Combustion Products

Test	Fuel mc(%) ¹	Time (min)	\dot{Q}_m (kW)	\dot{Q}_c (kW)	\dot{Q}_c/\dot{Q}_m	τ^2 (min)	ϕ^3
5	32	74.4	123	131	1.07	37	.80
5	32	167	120	113	.94	125	.72
6	32	135	108	133	1.23	66	.78
9	12	82	140	147	1.05	50	.96
11	11	190	115	111	.96	15	.68
18	8	462	147	154	1.05	120	.87
20	28	450	98	120	1.22	30	.76
20	28	660	100	125	1.25	240	.79

¹Fuel moisture content

²Time since last fuel load was added.

³Fuel-air equivalence ratio

in this project) is low combustion temperatures which place kinetic limits on the combustion process (see section 6.2), there must also exist some opportunity to improve the boiler's combustion performance. Probably the most useful modifications to test would be insulating the water walls of the rear plenum (where the primary tunnel flow splits and enters the secondary tunnels) and placing a layer of insulating refractory between the refractory mass which forms the combustion passages and the water cooled wall it now rests on. These modifications would increase combustion temperatures while still allowing the water cooled wall of the fuel magazine to perform its function of cooling the fuel and thus controlling the gasification rate. If the steps outlined above do not raise temperatures significantly, then insulating parts of the water wall in the fuel magazine could be tried.

Results of the constant 20 percent moisture, variable equivalence ratio adiabatic flame temperature calculations are presented in Figs. 77 and 78. The molar CO/CO₂ ratio is entirely negligible, compared to those experimentally measured in this investigation, for equivalence ratios up to about 0.70. For equivalence ratios above 0.70 and up to 0.96, the CO/CO₂ ratio remains below 0.02. Above 0.96 equivalence ratio the CO/CO₂ increases rapidly from 0.02. As expected, the adiabatic flame temperature peaks near 1.0 equivalence ratio. A comparison of the CO/CO₂ ratio results with experimental data is shown in Fig. 79. Though the experimental data show some scatter, the trend appears to be that, for $\phi > 7$, the combustion results are controlled by equilibrium, rather than kinetic processes.

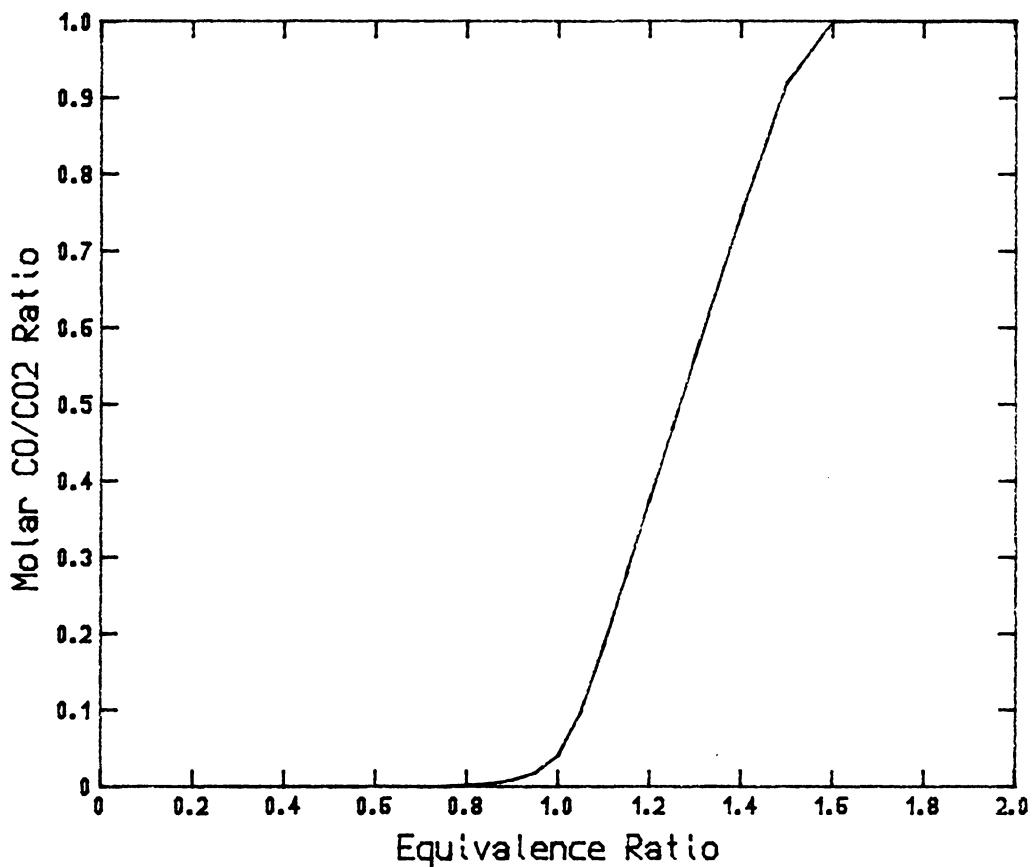


Figure 77. Equilibrium Model Results -- Effect of Equivalence Ratio on CO/CO₂ Ratio at 20% Fuel Moisture

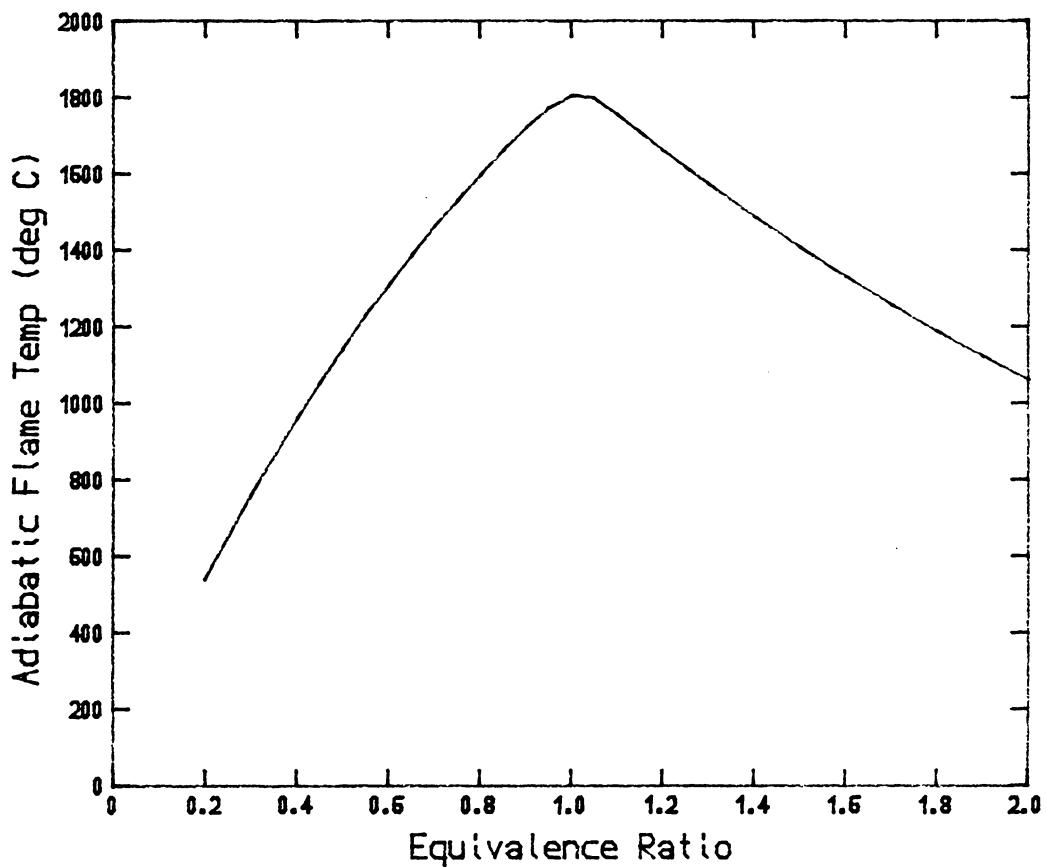


Figure 78. Equilibrium Model Results -- Effect of Equivalence Ratio on Adiabatic Flame Temperature at 20% Fuel Moisture

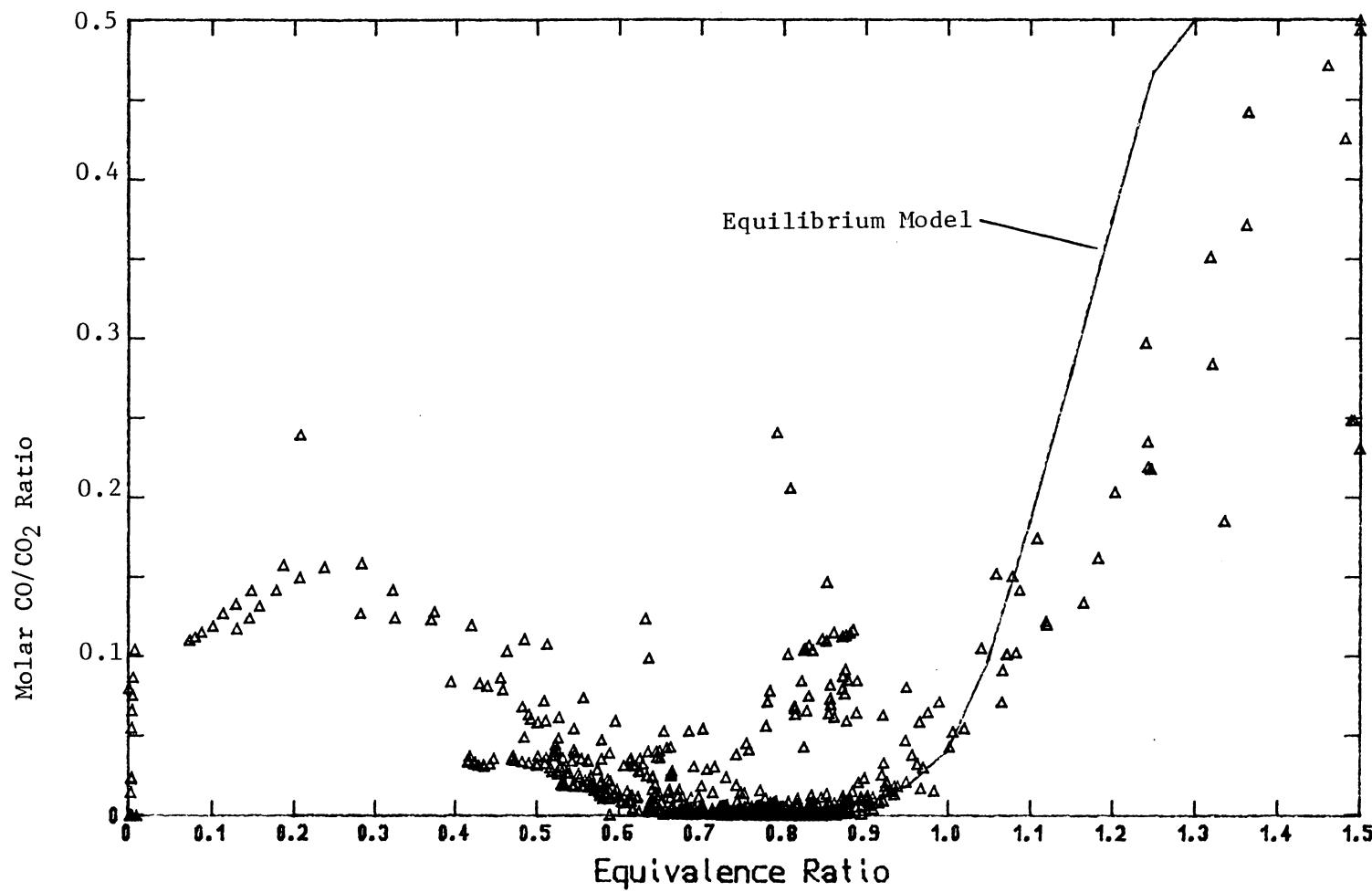


Figure 79. Comparison of Equilibrium Model Results For 20% Fuel Moisture With Test 13 Experimental Results -- The Effect of Equivalence Ratio on Molar CO/CO₂ Ratio

The final equilibrium calculations presented are those in which mixture composition is calculated for a range of specified temperatures and equivalence ratios all for 20 percent fuel moisture. These results are more nearly comparable to experimental measurements since they allow for the effects of heat transfer which has been shown to be large in earlier paragraphs. The results are presented in Fig. 80. At temperatures of 1500°C and less, the CO/CO₂ ratio is less than 0.005 for equivalence ratios under 1.0. As equivalence ratio increases above 1.0, the CO/CO₂ ratio rises sharply. At all equivalence ratios, the CO/CO₂ ratio increases as temperature increases. The effect of temperature becomes much stronger above 1500°C.

6.2 Gas-Phase Chemical Kinetic Model

6.2.1 Isothermal Model with Tube Inlet

The purpose of these runs was to obtain an understanding of the effect of temperature on the rate of conversion of CO to CO₂ for a typical operating equivalence ratio. The results are presented in Table 11 as the final CO/CO₂ ratio and specified temperature for each run (all were at 0.84 equivalence ratio).

There are two important features of these results. First, the rate of conversion of CO to CO₂ drops off rapidly between 600°C and 700°C. At 700°C it is high enough to yield virtually no CO and greater than 99.9 percent combustion efficiency. At 600°C and below, CO conversion is essentially stopped.

The second feature of the results is that at 700°C and above, the CO conversion proceeds virtually to equilibrium. Thus, there is a

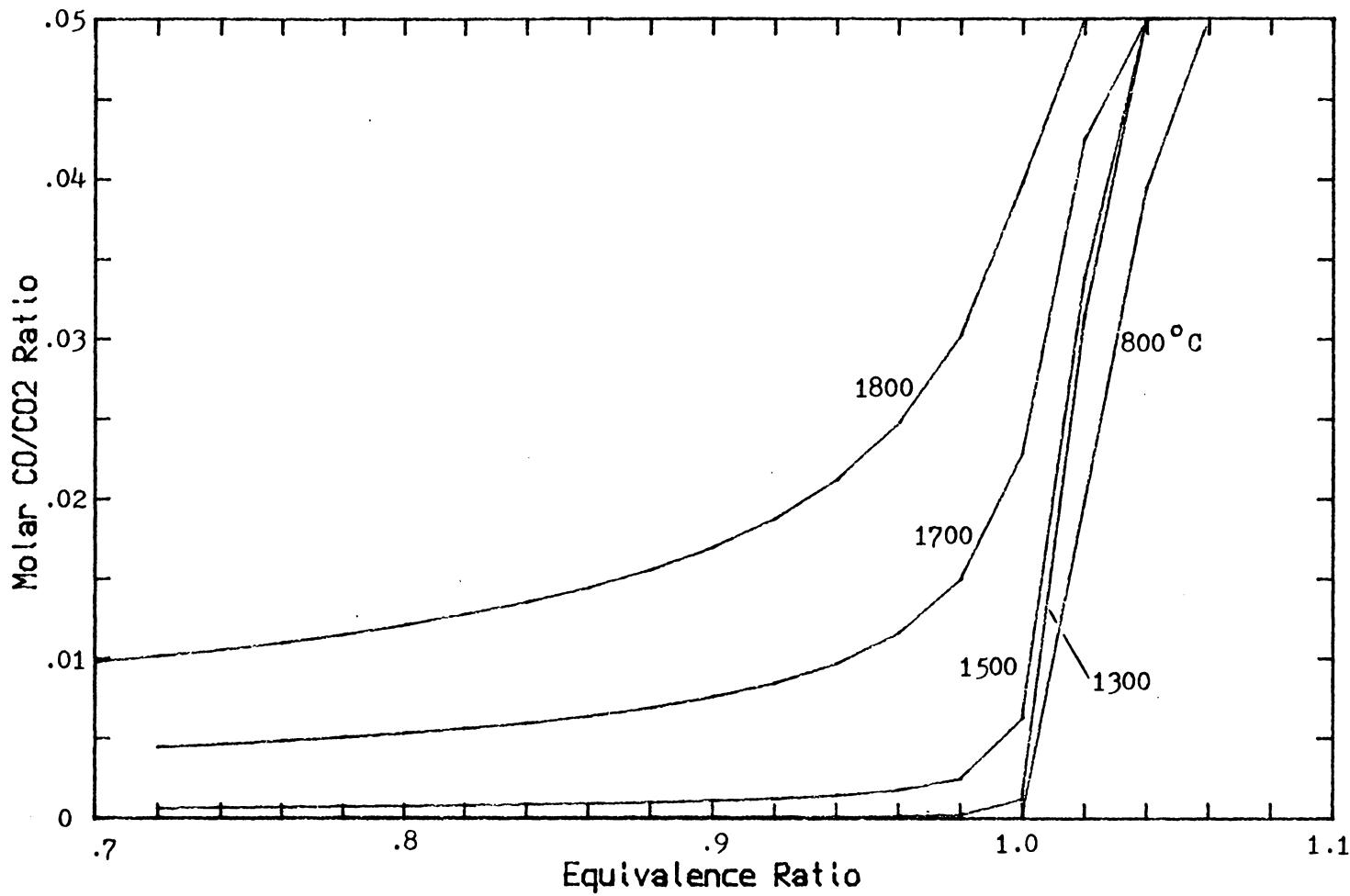


Figure 80. Equilibrium Model Results -- Effect of Temperature and Equivalence Ratio on CO/CO₂ Ratio at 20% Fuel Moisture. The 800°C Line Corresponds With the X-Axis For Equivalence Ratio Less Than 1.0.

Table 11. Isothermal Kinetic Model Results -- Molar CO/CO₂ Ratio at Secondary Tunnel Outlet for Tube Inlet Configuration

Temperature (°C)	CO/CO ₂ at Outlet
1400	.0003
1200	.0001
1000	.0000
800	.0001
700	.0009
600	.56
500	.92
400	.92

threshold temperature range, somewhere between 600 and 700°C in which the process changes from being equilibrium-controlled to being strongly kinetically limited.

6.2.2 Energy Model - Run 1 & 2

The purpose of these model runs was to compare the tube (Fig. 10) with the rear (Fig. 9) secondary air inlet configuration on the basis of combustion performance. Results are presented as plotted values of the temperature (Fig. 81), equivalence ratio (Fig. 82) and molar CO/CO₂ ratio (Fig. 83) of each stirred reactor. Both configurations are shown in each figure for comparison.

The results of these model runs show no difference between the two configurations, based on final combustion efficiency -- the combustion proceeds to equilibrium in both configurations, with a resulting CO/CO₂ ratio of 0.004. However, results of both the equilibrium (section 6.1) and the isothermal kinetic (section 6.2.1) models shed light on the present model results.

First, it was shown in section 6.1 that the combustion process in the Eshland boiler is far from adiabatic, thus the combustion efficiency result of the model is not expected to be valid. However, the temperature and equivalence ratio profiles shown in Figs. 81 and 82, do contribute to understanding the problem in that they reveal large differences between the internal processes of the two configurations even though the final results are identical.

The tube inlet was introduced in section 5.2.3 and at that time the possibility of achieving a super-adiabatic temperature in the primary

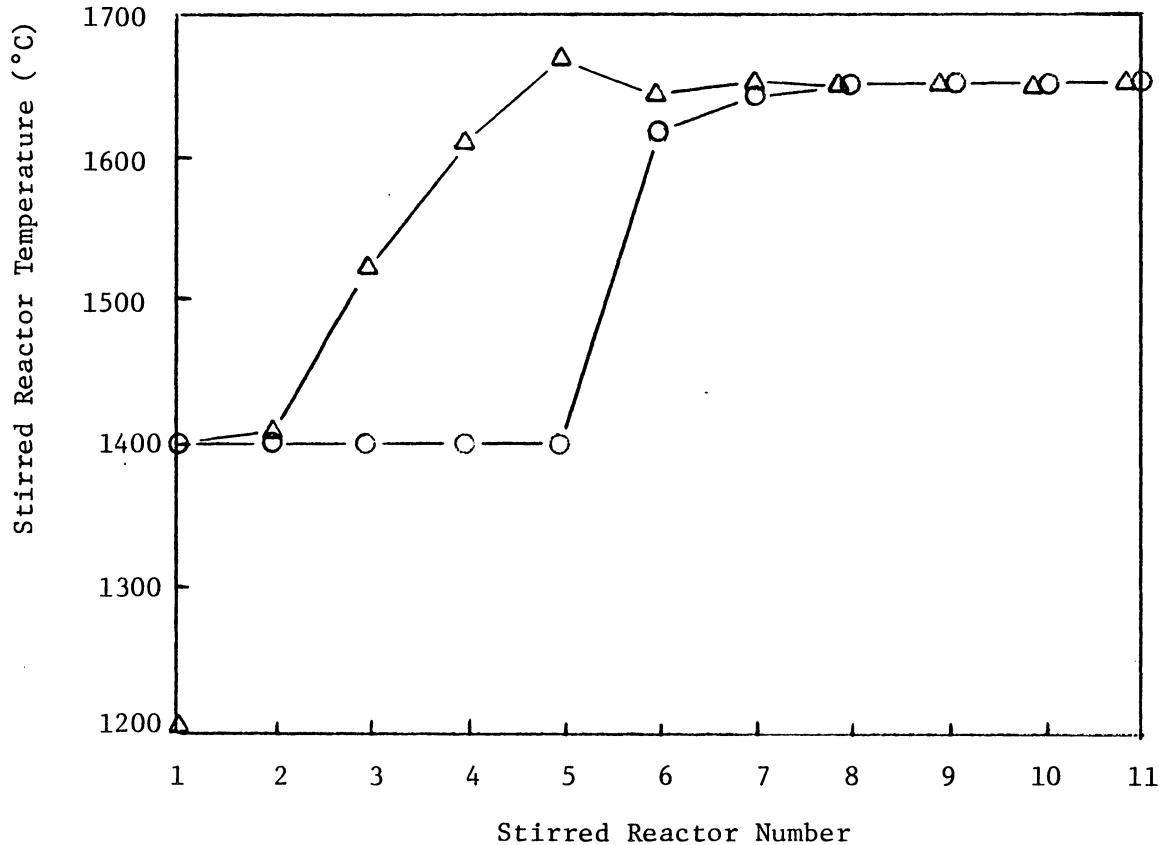


Figure 81. Results of Energy Method Kinetic Model -- Profiles of Reactor Temperature For Rear Inlet (O) and Tube Inlet (Δ) Configurations

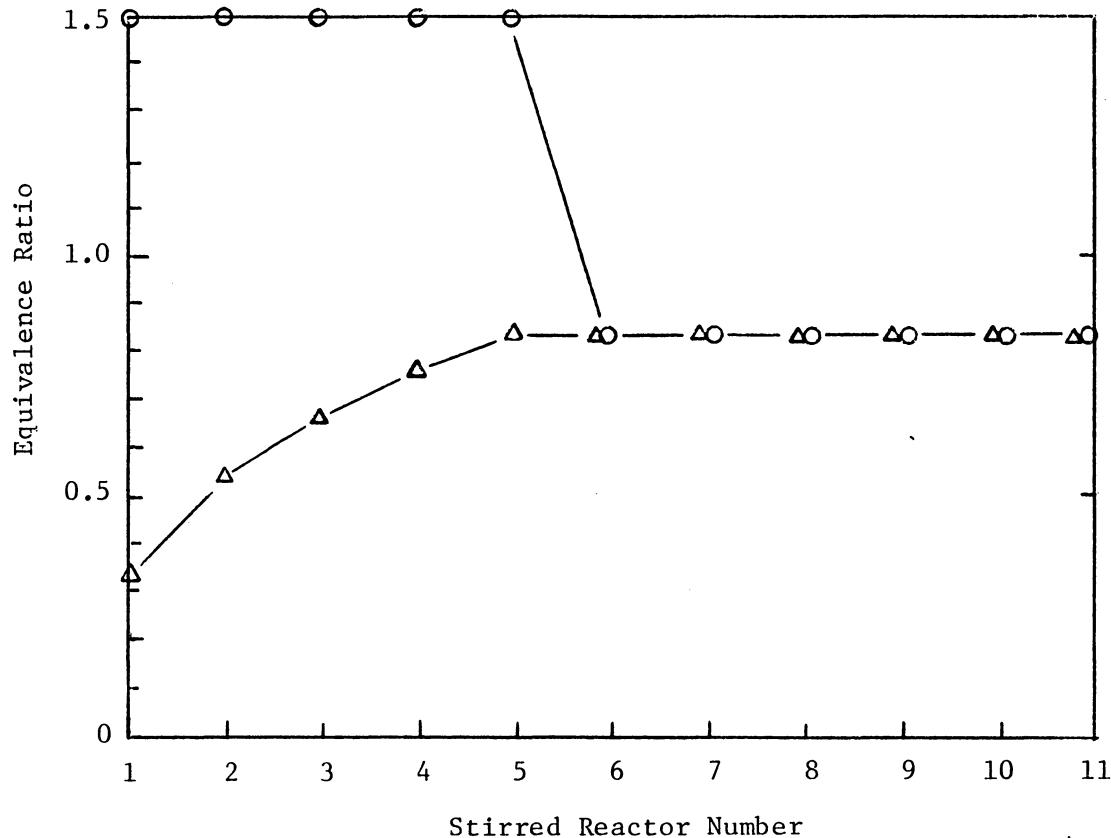


Figure 82. Results of Energy Method Kinetic Model -- Equivalence Ratio Profiles
For Rear Inlet (O) and Tube Inlet (Δ) Configurations

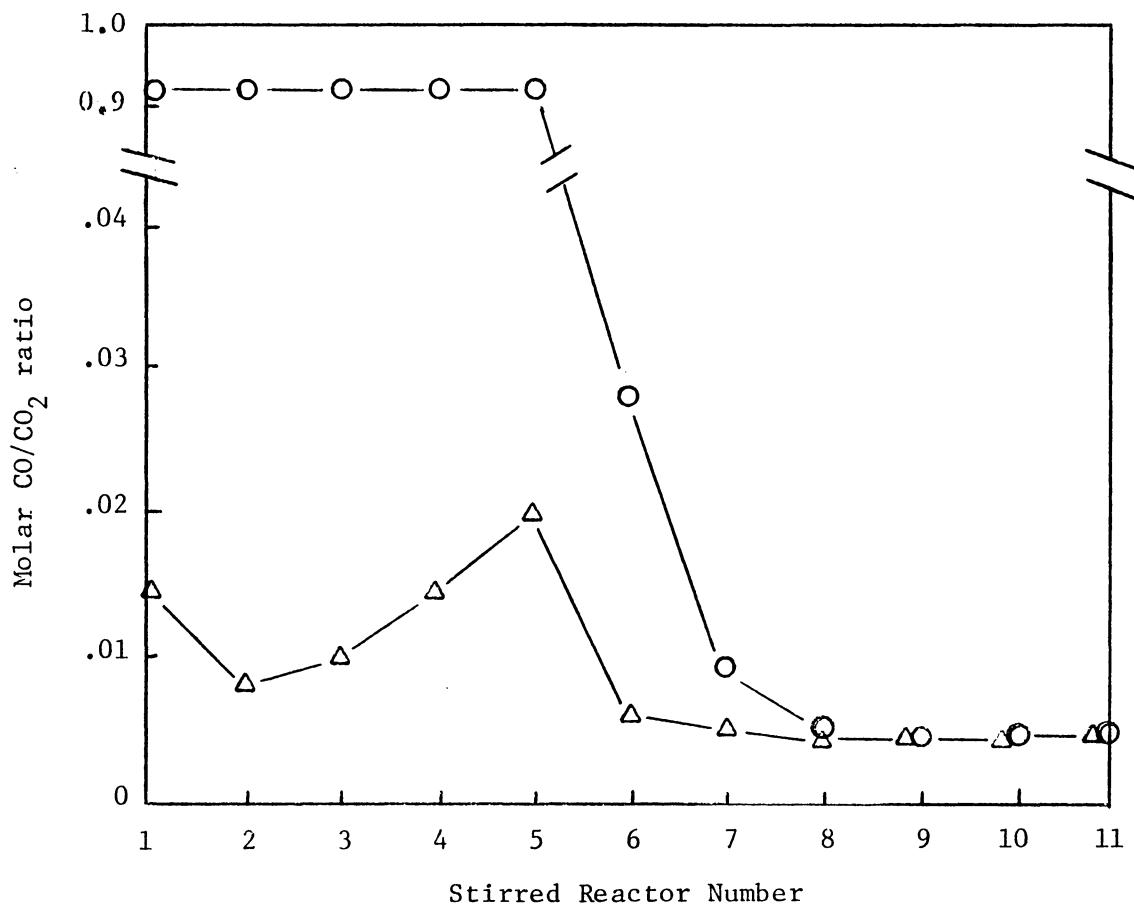


Figure 83. Results of Energy Method Kinetic Model -- Profiles of Molar CO/CO₂ Ratio For Rear Inlet (O) and Tube Inlet (Δ) Configurations

tunnel was thought to be a potential benefit of the tube configuration relative to the rear inlet. The temperature profile shows, however, that the effect is very short-lived, with reactor 5 being the only one with the desired super-adiabatic temperature, which even then is only 14°C above adiabatic. The more dilute mixtures in the first 4 reactors, as seen in the equivalence ratio profile, are primarily responsible for this. But even though reactors nos. 1-4 are not above the final adiabatic flame temperature of about 1651°C , they are above what they would have been without the counterflow heat transfer from the gases in the primary tunnel to the secondary combustion air.

The temperature profile in the actual process, however, is the result of a complex balance between heat transfer from the fuel bed, heat transfer from the primary tunnel, heat transfer from combustion products to the secondary air, the flow rates of primary combustion products and secondary air, and heat release due to chemical reactions. To further complicate the problem, most of these factors are strongly coupled to the resulting temperature. Thus, any further modeling would probably best proceed in conjunction with detailed measurements of temperatures in the primary combustion tunnel, which could then be used to model the process with a given temperature for each reactor, rather than attempting to understand the heat transfer problem along with the reaction problem.

In spite of these complexities, one result is clear from the energy model -- if the temperature in the primary tunnel can be maintained above about 700°C , the tube inlet has a distinct advantage over the rear inlet in that the low equivalence ratio in the primary tunnel will

contribute to increasing the reaction rate. In the rear inlet configuration however, the primary combustion products can react very little (in the model, none at all) until only half of their residence time in the combustion tunnels remains. Thus, externally heating the secondary air, in the tube inlet configuration, during periods of low combustion temperatures (as occur following batch fuel loading) could significantly improve combustion efficiency. Experience in operating and monitoring the boiler shows that this external heating would be required only for very short periods (possibly for 5-10 minutes following each batch fuel loading and boiler start-up).

In the absence of either external preheat or augmented heat transfer, from the products of primary combustion, for the tube inlet configuration the model does not suggest either configuration as being overall better than the other, for all operating conditions.

7. CONCLUSIONS

Based on the results of the development tests on the boiler firing batch-loaded cordwood, the following conclusions are drawn:

1. The Bosch oxygen sensor was able to distinguish between fuel-rich and fuel-lean products of biomass combustion and the sensor did not fail or show any signs of deterioration of the output during the test program.
2. The G-cell oxygen sensor provides a measure of equivalence ratio which is sufficiently accurate for control purposes.
3. In batch fueled operation, the uncontrolled boiler operates in equivalence ratio cycles which begin with refueling or agitating the fuel bed, proceed to high equivalence ratio and emissions, followed by equivalence ratio and emissions gradually dropping together. Once equivalence ratio is down to about 0.7, emissions begin to rise as equivalence ratio continues falling.
4. The tube inlet secondary combustion air supply configuration may permit secondary combustion to be maintained at slightly lower temperatures than the rear inlet configuration due to the greater thermal coupling it provides between the secondary and primary combustion zones.
5. The G-cell sensor provides more information than the Bosch sensor as a control system feedback element but responds slower and requires a conditioned gas sample.

Based on the results of the performance tests on the G-cell-controlled boiler, with catalytic secondary combustion, firing batch

loaded dry cordwood (8% mc), moist cordwood (28% mc), slash (20% mc), and poultry litter (27% mc) the following conclusions are drawn:

1. The final boiler design incorporating a catalytic combustor and the secondary combustion air control system described in Section 3.5 provides increased combustion efficiency and therefore reduced carbon monoxide emissions as compared to the unmodified boiler. The average CO/CO₂ ratio for steady operation on the baseline unit was about four times the average CO/CO₂ ratio for unsteady operation on the controlled unit and at least 8 times that for steady operation on the controlled unit.
2. Catalytic conversion of CO to CO₂ is negligible under conditions of stable, optimum equivalence ratio and adequately high combustion temperatures because of the already complete combustion achieved through noncatalytic secondary combustion.
3. The catalytic combustion rate is high under conditions of poor primary and noncatalytic secondary combustion, but not high enough with the present design to reduce the CO to an acceptably low level.
4. The final boiler design has the capability of operating in a stable mode of smoldering primary combustion with a high but inadequate catalytic combustion rate when secondary combustion air is admitted with secondary tunnel inlet temperature below the threshold of about 700°C for cordwood and slash and 600°C for poultry litter. In this mode emissions are extremely high and both heat transfer and combustion efficiencies are low.

This can occur in both the tube inlet and rear inlet configurations.

5. The stable, dirty operating mode of item 4 appears to be the result of a lack of thermal coupling between the catalytic combustor and the primary combustion zone. This is primarily due to the location of the catalytic combustor in the heat exchanger.

Based on the results of the equilibrium combustion modeling and comparison with experimental data, the following conclusion is drawn:

Under operating conditions, (with cordwood fuel) which produce relatively low emissions, from 1/2 to 2/3 of the total heat transfer from the products of combustion occurs prior to their entry into the heat exchanger.

Based on the results of the stirred-reactor kinetic modeling of the gas-phase combustion of oak cordwood at 0.84 equivalence ratio and comparison with experimental data, the following conclusions are drawn:

1. For combustion zone temperatures above 700°C, the combustion process is not kinetically limited -- i.e., given adequate mixing of the combustion products, the boiler should operate with combustion efficiency in excess of 99 percent if most or all of the combustion zone is above 700°C.
2. The adiabatic modeling shows no difference in the final combustion efficiency between the tube and rear secondary air inlet configurations. The combustion results are invalid however, due to the significant heat transfer from the actual combustion zone that is entirely neglected in the model. It is expected that a model which properly accounts for the heat

transfer would show one configuration superior to the other, but that the results would be different for different operating conditions.

8. RECOMMENDATIONS

The following areas are recommended for further research and are presented in order of descending importance.

1. Develop a commercial version of a) the secondary combustion air system presented in Section 3.5 and b) the catalytic combustor.
2. Develop an improved catalytic combustor design that would provide
 - a) higher conversion efficiency during the uncontrolled low equivalence ratio phase of the equivalence ratio cycle and
 - b) thermal coupling between the catalytic combustor and the primary combustion zone. Successful development of a catalytic combustor with these characteristics would dramatically improve the boiler's performance under unsteady operating conditions.
3. Develop and evaluate a control strategy based on both the G-cell and the Bosch oxygen sensor to reduce the extremely high CO emissions which occur during the fuel-rich periods immediately following each fuel stirring and reload. Such a control strategy is discussed in section 5.2.11.
4. Develop and test a quicker responding G-cell system (which includes the gas sample conditioning system and incinerator as well as the sensor).
5. Test the operation of G-cell sensor in the control system over an extended period of time.
6. Test the final boiler configuration on other biomass fuels.

7. Conduct a program of heat transfer analysis and experimentation on the E500 boiler to develop ways of reducing the heat transfer from the firebox and thus decrease the amount of time the combustion process is kinetically limited.
8. Develop and test a means of increasing the temperature of the secondary combustion air in the tube inlet (or comparable) configuration.

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APPENDIX A

SAMPLE DATA ACQUISITION AND CONTROL COMPUTER CODE

Explanatory Notes

This code is the latest of several versions used during the experimental program and includes all of the useful features developed. The code executes seven primary tasks:

1. reads any selected input voltage during a pretest calibration,
2. switches the gas sample multiplexing solenoid valves every 15 seconds,
3. collects data every 30 seconds,
4. reduces each set of data immediately after collection,
5. stores data to disk every 30 or 60 seconds (user-selected),
6. updates data on screen display every 30 seconds, and
7. controls secondary combustion air flow rate.

In addition, the code provides secondary features including on-line parameter changes, data storage inhibit and others, all documented internally.

Usage Notes

The code is written in the IBM PC ADVANCED BASIC language and runs in

conjunction¹ with the PCTHERM version 1.00 software² which accompanies the Data Translation hardware used to interface the PC to the instrumentation. The program must be run compiled (as opposed to interpreted) to provide adequate time for the control task (i.e., to prevent missing a set of data). The code presented below will run compiled. However, the program may be run interpreted for the purpose of troubleshooting the code. To do this remove comment notation from statement number 130 and delete (or comment) statement numbers 4760 and 4780.

Three files, all on the B diskette drive, are created by the program (in the file names given below, "number" is the user-assigned test number):

1. Tnumber.DTA: is the primary data storage file,
2. Tnumber.INT: is used for storage of information on parameter changes, fuel reloads and other on-line changes, and
3. TVADPCEL.ZRO: is used to store the zero voltages of the two differential pressure transmitters so they will be available to the test routine even if program execution is halted between the calibration and test routines.

¹ i.e., for compiled operation the code must be linked with the PCTHERM.LIB object file; for interpreted operation the PCTHERM.BAS file must reside on the diskette in the default drive when the code is run.

² Data Translation Inc. part number SP-0142-GA-1

Source Code Listing

```
5 ' **** STEPTVA.BAS revised 7/6/87 ****
10 '***** STEPTVA.BAS revised 7/6/87 ****
15 '***** STEPTVA.BAS revised 7/6/87 ****
20 '
25 '***** written by Chuck Harris and Doug McCallum ****
30 '
35 '
40 '***** INITIALIZATION ****
50 '

60 KEY OFF:COLOR 7:CLS
70 DIM DAT1(8),DAT2(8),DAT3(8),STP%(20)
80 TYPE% =ASC("K"):MASK% =255:MOTOR.POSITION% =0
90 '
100 ' ***** PCTHERM subroutine entry points ****
110 XGEC=78:XSB=81:XSECW=75:XDTV=156:XVTD=153:XMCJ=144:XMT=141:XMV=138
120 XEFI=57:XIDV=63:XEFO=60:XODV=66
130 ' DEF SEG=7936:BLOAD "PCTHERM",0 'include this line for
           interpreted BASIC
140 '
150 ERROR.VALUE% =0: RECNUM=0 :STORE$="ON"
160 CALL XSECW(ERROR.VALUE%): GOSUB 830
170 '
180 ' ***** Define time input functions ****
190 DEF FNCLK(Q)=VAL(HEX$(INP(Q)))
200 DEF FNETSEC = FNCLK(708)*3600 + FNCLK(707)*60 + FNCLK(706)
210 '
220 '**** Set number of pulses for valve to open for each step ****
230 NUM.STEPS% =8:STP%(0)=0:STP%(1)=158:STP%(2)=213:STP%(3)=270:
           STP%(4)=315:STP%(5)=387:STP%(6)=472:STP%(7)=680:STP%(8)=1000
240 '
250 ' **** Initialize parameters for the Bosch - based control strategy
260 CONTROL.TEMP=850:RICH.O2SEN=.25:LEAN.O2SEN=.25:RICHDELAY=10:
           LEANDELAY=480:INIT.STEP%=6:BK.TM=6
270 '
280 '**** Initialize parameters for the G-cell - based control strategy
290 GGAIN=50:GSET=4.5:GBAND=.6:GDELAY=30:GTEMP=700:STEP.SIZE=5!
300 '
310 '***** Set orifice discharge coefficients ****
320 CDASTK=6.8 'recalibrated 4/16/87
330 CDASEC=.615 ' recalibrated 4/21/87
340 '

350 GOSUB 4900 ' energize vacuum cleaner to check proper operation
360 INPUT "VACUUM CLEANER IS NOW ON, <cr> TO DE-ENERGIZE AND CONTINUE"
           ;DUM$
370 GOSUB 4980 ' de-energize vacuum cleaner
380 GOSUB 5240 ' energize solenoids
390 CLS:PRINT "CALIBRATE OR TEST (C OR T) ?????";
400 G$=INKEY$:IF G$="" THEN 400 ELSE PRINT G$
```

```

410 IF G$="C" OR G$="c" THEN GOTO 450
420 IF G$="T" OR G$="t" THEN GOTO 940 ELSE 380
430 '
440 '
450 ***** CALIBRATE ROUTINE *****
460 '
465 *** This routine provides for pretest monitoring of input voltages
      for calibration and check out.
470 VOLT%=0:MODE$="CALIBRATE"
480 PRINT "WHICH BOARD CONTAINS THE CHANNEL TO CALIBRATE (1-3) ?";
490 B$=INKEY$:IF B$="" THEN 490 ELSE PRINT B$:BOARD%=VAL(B$)
500 IF BOARD%>3 OR BOARD%<1 THEN 480
510 PRINT "WHAT IS THE CHANNEL NUMBER ON THAT BOARD (0-7)?";
520 G$=INKEY$:IF G$="" THEN 520 ELSE PRINT G$:CHANNEL%=VAL(G$)
530 IF CHANNEL%>7 OR (CHANNEL%<=0 AND G$>>"0") THEN GOTO 510
540 CALL XSB(BOARD%):GOSUB 830
550 IF BOARD%=3 THEN VOLT%=1:GOTO 600
560 PRINT "MEASURE TEMPERATURES OR VOLTAGES? (T/V)?";
570 G$=INKEY$:IF G$="" THEN 570 ELSE PRINT G$
580 IF G$="T" OR G$="t" THEN 600
590 IF G$="V" OR G$="v" THEN VOLT%=1 ELSE 560
600 '
610 LOCATE 10,20:PRINT "BOARD#";BOARD%:IF BOARD%=3 THEN LOCATE 22,10:
      PRINT "ALT-Z TO SAVE ZERO VOLTAGE ON CH 4 AND CH 6"
620 IF VOLT%=1 THEN 740
630 '
640 DEGREES.C!=0
650 IF CHANNEL%=0 THEN 680
660 CALL XMT(TYPE%,CHANNEL%,DEGREES.C!)
670 GOTO 690
680 CALL XMCJ(DEGREES.C!)
690 GOSUB 830
700 LOCATE 10,30:PRINT USING "CH ## =##.## deg. C      ";
      CHANNEL%,DEGREES.C!
710 IF INKEY$>>"" THEN GOTO 380
720 GOTO 640
730 '
740 CALL XMV(CHANNEL%,VOLTS!):GOSUB 830
750 BOZO=0:C$=INKEY$:IF LEN(C$)=2 THEN C$=RIGHT$(C$,1) ELSE GOTO 780
760 IF C$>>"" THEN BOZO=ASC(C$)
770 IF ASC(C$)=44 THEN GOSUB 870 'alt-z to store DP transmitter zero V
780 LOCATE 10,30
790 PRINT USING "CH ## =##.#### V  ";CHANNEL%,VOLTS!
800 IF C$>>"" AND BOZO<>44 THEN GOTO 380
810 GOTO 740
820 '
830 CALL XGEC(ERROR.VALUE%)
840 IF ERROR.VALUE%<>0 THEN LOCATE 25,30:PRINT"AQUISITION ERROR "
      ;ERROR.VALUE%;
850 RETURN

```

```

860 '
870 '***** Store DP cell zero voltages for use in the test routine *****
880 IF OPEN3STATUS%<>1 THEN OPEN "B:TVADPCEL.ZRO" FOR OUTPUT AS #3:
    OPEN3STATUS%=1
890 IF BOARD%=3 AND CHANNEL%=4 AND C4%<>1 THEN ZERO34V=VOLTS!:
    LOCATE 12,22:PRINT USING "ZERO34V = #.### VOLTS";ZERO34V:
    PRINT #3,ZERO34V:C4%=1
900 IF BOARD%=3 AND CHANNEL%=6 AND C4%=1 AND C6%<>1 THEN ZERO36V=VOLTS!:
    LOCATE 12,22:PRINT USING "ZERO36V = #.### VOLTS";ZERO36V:
    PRINT #3,ZERO36V:C6%=1:CLOSE #3
910 RETURN
920 '
930 '
940 '***** TEST ROUTINE *****
950 '
960 MODE$="TEST": CLS
970 INPUT "NUMBER OF DATA FILE ",FILNUM$:GOSUB 2710 ' open data file
980 PRINT: INPUT "DO YOU WANT DATA ON 30 OR 60 SECOND INTERVALS "
    ;INTERVAL% ' interval at which data is stored to disk
990 IF INTERVAL%<>30 AND INTERVAL%<>60 THEN 980
1000 INPUT "CHECK THAT STEPPER MOTOR VALVE IS CLOSED <cr>";DUMMY$
1010 INPUT "WHICH SEC. AIR CONTROL SCHEME (G-CELL or BOSCH)"
    ;CONTROL.SCHEME$
1020 IF CONTROL.SCHEME$<>"BOSCH" AND CONTROL.SCHEME$<>"G-CELL"
    THEN 1010
1030 PRINT #2, USING "CONTROL.TEMP=###.", RICH.O2SEN=#.##
    ;CONTROL.TEMP,RICH.O2SEN;
1040 PRINT #2, USING "LEAN.O2SEN=#.##, RICHDELAY=###"
    ;LEAN.O2SEN,RICHDELAY
1050 PRINT #2, USING "LEANDELAY=###.", INIT.STEP%=##, BK.TM=###
    ;LEANDELAY, INIT.STEP%,BK.TM
1060 PRINT #2, USING "GSET=#.##, GBAND=#.##, GDELAY=###,"
    ;GSET,GBAND,GDELAY;
1070 PRINT #2, USING " GGAIN=###.###, GTEMP=###." ;GGAIN,GTEMP
1080 PRINT #2,USING " & - BASED CONTROL STRATEGY USED TO START THE"
    ;CONTROL.SCHEME$;" TEST"
1090 INPUT "BAROMETRIC PRESSURE (mm HG) ";PATM:PBAR=PATM*101.33/760!
1100 INPUT "TYPE OF FUEL ";FUEL$
1110 INPUT "MASS OF WET FUEL IN LOAD # 1 (pounds) "; FUELMASS
1120 FUELMASS=FUELMASS/2.2046 ' convert pounds to kilograms
1130 INPUT "ESTIMATED FUEL MOISTURE FOR LOAD # 1 (% WET BASIS) ";FM
1140 INPUT "INITIAL WATER CIRCULATION RATE (GPM) ";QH2O
1150 DRYFUEL=FUELMASS*(100!-FM)/100 ' kg dry fuel in load no. 1
1160 TFL = DRYFUEL ' initialize total fuel loaded this test
1170 MCD=FM/(100-FM) ' dry basis mass fraction of H2O in fuel
1180 ZNUM=1:TFC=0:EOUT=0 ' initialize variables
1190 '
1200 '***** Read & store DP transmitter zero voltages *****
1210 OPEN "B:TVADPCEL.ZRO" FOR INPUT AS #3

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1220 INPUT #3,ZERO34V,ZERO36V
1230 PRINT #2,USING "ZERO34V = #.### VOLTS,    ZERO36V = #.### VOLTS "
           ;ZERO34V;ZERO36V
1240 '
1250 PRINT #2,FUEL$
1260 PRINT #2,USING "##.## kPa BAROMETRIC PRESSURE";PBAR;
           "#.# GPM WATER CIRCULATION RATE"; QH20
1270 PRINT #2,USING "LOAD NO. 1 #.#.# KG WET WOOD AT #.#.% WB"
           ;FUELMASS;FM
1280 INPUT"TEST BEGINS WHEN YOU HIT THE ENTER KEY",DUMMY$
1290 GOSUB 5240 ' set IR702 sample to precat
1300 CLS
1310 OUT 706,0:OUT 707,0:OUT 708,0 ' *** initialize elapsed time
           clock to zero
1320 '
1330 '
1340 '***** Clock-watching loop for first 30 seconds *****
1350 '
1360 SECONDS=FNCLK(706): IF SECONDS<30 THEN GOSUB 5830: COLOR 7:
           LOCATE 25,75: PRINT FNCLK(706);: IF SECONDS<(30-BK.TM) THEN
           GOSUB 5320:IF SECONDS>14 AND IR702.GAS$="PRECAT" THEN GOSUB
           6000 ELSE DU=1 ELSE DUM=0 GOTO 1470
1370 B$=INKEY$:IF LEN(B$)=2 THEN B$=RIGHT$(B$,1) ELSE GOTO 1360
1380 IF ASC(B$)=33 THEN 3790 'alt-f to input mass of a new fuel load
1390 IF ASC(B$)=16 THEN 4020 'alt-q to change the value of QH20
1400 IF ASC(B$)=119 THEN CLEARSCR$ = "YES" ' to clear screen
1410 IF ASC(B$)=20 THEN 4520 ' alt-t to close files and end
1420 IF ASC(B$)=25 THEN 4090 ' alt-p to change sec. air
           control parameters
1430 IF ASC(B$)=31 THEN 4460 ' alt-s to change back & forth between
           Bosch and G-cell - based control strategies
1440 IF ASC(B$)=32 THEN IF STORE$="ON" THEN STORE$="OFF" ELSE
           STORE$="ON" ELSE 1460 'alt-d to toggle data storage on/off
1450 COLOR 4:LOCATE 25,2:PRINT "      -D STOP/START STORAGE";:COLOR 3:
           PRINT " DATA STORAGE: ";:COLOR 5:PRINT USING "&, ##"
           ;STORE$,INTERVAL%,:COLOR 3
1460 GOTO 1360
1470 GOSUB 1790 '*** data acquisition ***
1480 GOSUB 3360 '*** calculations ***
1490 GOSUB 5750 '***** close sec. air valve if primflow is too low
1500 FRACMIN = .5
1510 GOSUB 2210 '*** data storage ***
1520 GOSUB 2810 '*** print data to screen ***
1530 '
1540 '
1550 '***** Clock-watching loop for last 30 seconds *****
1560 '
1570 SECONDS=FNCLK(706):IF SECONDS>2 THEN GOSUB 5830:COLOR 7:LOCATE
           25,75:PRINT FNCLK(706);: IF SECONDS<(60-BK.TM) THEN GOSUB 5320
           :IF SECONDS>44 AND IR702.GAS$="PRECAT" THEN GOSUB 6000 ELSE

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        DU=2 ELSE DUM=3 ELSE GOTO 1680
1580 B$=INKEY$: IF LEN(B$)=2 THEN B$=RIGHT$(B$,1) ELSE GOTO 1570
1590 IF ASC(B$)=33 THEN 3790 'alt-f to input mass of a new fuel load
1600 IF ASC(B$)=16 THEN 4020 'alt-q to change the value of QH20
1610 IF ASC(B$)=119 THEN CLEARSCR$ = "YES"
1620 IF ASC(B$)=20 THEN 4520 ' alt-t to close files and end
1630 IF ASC(B$)=25 THEN 4090 ' alt-p to change sec. air
    control parameters
1640 IF ASC(B$)=31 THEN 4460 ' alt-s to change control scheme
1650 IF ASC(B$)=32 THEN IF STORE$="ON" THEN STORE$="OFF" ELSE STORE$=
    "ON" ELSE 1670 'alt-d to toggle data storage on/off
1660 COLOR 4:LOCATE 25,2:PRINT "      -D STOP/START STORAGE";:COLOR 3:
    PRINT "          DATA STORAGE: ";:COLOR 5:
    PRINT USING "&, #";STORE$,INTERVAL%;:COLOR 3
1670 GOTO 1570
1680 GOSUB 1790 '*** data acquisition ***
1690 GOSUB 3360 '*** calculations ***
1700 GOSUB 5750 '***** close sec. air valve if primflow is too low
1710 FRACMIN = 0!
1720 GOSUB 2210 '*** data storage ***
1730 GOSUB 2810 '*** print data to screen ***
1740 GOTO 1360
1750 '
1760 '
1770 '***** DATA ACQUISITION *****
1780 '
1790 ETIME = FNETSEC/60!:GOSUB 2040 'do board #3 first
1800 GOSUB 5240 ' switch IR-702 to PRECAT sample gas
1810 '
1820 '**** Board #1 acquisition ****
1830 BOARD%=1:CALL XSB(BOARD%):GOSUB 830
1840 CALL XMCJ(CJTEMP!):GOSUB 830
1850 DAT1(0) = CJTEMP!
1860 CALL XDTV(TYPE%,CJTEMP!,CJVOLTS!):GOSUB 830
1870 FOR CHANNEL%=1 TO 7
1880 HIGHTEMP$="NO":GOSUB 2120 ' check for temperature > 1191 deg C
1890 IF HIGHTEMP$="NO" THEN CALL XMT(TYPE%,CHANNEL%,DEGREES.C!):
    GOSUB 830
1900 DAT1(CHANNEL%)=DEGREES.C!
1910 NEXT
1920 '
1930 '**** Board #2 acquisition ****
1940 BOARD%=2:CALL XSB(BOARD%):GOSUB 830
1950 CALL XMCJ(CJTEMP!):GOSUB 830
1960 CALL XDTV(TYPE%,CJTEMP!,CJVOLTS!):GOSUB 830
1970 FOR CHANNEL%=1 TO 7
1980 HIGHTEMP$="NO":GOSUB 2120
1990 IF HIGHTEMP$="NO" THEN CALL XMT(TYPE%,CHANNEL%,DEGREES.C!):
    GOSUB 830
2000 DAT2(CHANNEL%)=DEGREES.C!

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2010 NEXT
2020 RETURN
2030 '
2040 '**** Board #3 acquisition ****
2050 BOARD%=3:CALL XSB(BOARD%):GOSUB 830
2060 FOR CHANNEL%=0 TO 7
2070 CALL XMV(CHANNEL%,VOLTS!):GOSUB 830
2080 DAT3(CHANNEL%)=VOLTS!
2090 NEXT
2100 RETURN
2110 '
2120 '***** Check for temp>1191 deg C & use curve fit if necessary ***
2130 '
2140 '*** NOTE: The PCTHERM subroutine XMT will crash every time it en-
    counters a type K temp > 1200 deg C. The present subroutine
    detects this condition before XMT would and provides an
    alternative to subroutine XMT for these high temperatures.
2150 '
2160 CALL XMV(CHANNEL%,VOLTS!):GOSUB 830:VOLTS!=VOLTS!+CJVOLTS!
2170 IF VOLTS!>.0485 THEN
    DEGREES.C!=282.14987#/+10.20775*VOLTS!*1000+0.175915*
    (VOLTS!*1000!)^2:HIGHTEMP$="YES" ELSE HIGHTEMP$="NO" '
    this is a quadratic curve fit for type K temp > 1191 deg C
2180 RETURN
2190 '
2200 '
2210 ***** RANDOM ACCESS DATA STORAGE *****
2220 '
2230 RECNUM%=RECNUM%+1
2240 IF (FRACMIN=.5 AND INTERVAL%=60) OR STORE$="OFF" THEN RETURN
2250 '
2260 RSET ETIME$=MKSS$(ETIME)      ' elapsed time
2270 RSET TIMECHK$=MKSS$(RECNUM%/2) ' elapsed time check
2280 RSET CO.DROP$=MKSS$(CO.DROP)   ' dry mol % CO drop across catalyst
2290 RSET TH20IN$=MKSS$(DAT2(1))   ' deg C water inlet
2300 RSET TH20OUT$=MKSS$(DAT2(2)) ' deg C water outlet
2310 RSET T30$=MKSS$(DAT1(1))     ' deg C prim. tunnel outlet, ctr.
2320 RSET T150$=MKSS$(DAT2(4))    ' deg C catalyst outlet
2330 RSET T50$=MKSS$(DAT2(5))    ' deg C sec. tunnel outlet
                                (avg of 2 sides)
2340 RSET T60$=MKSS$(DAT2(6))    ' deg C fire tube inlet
                                (avg 2 tubes)
2350 RSET T70$=MKSS$(DAT2(7))    ' deg C fire tube outlet
                                (avg 2 tubes)
2360 RSET T80$=MKSS$(DAT2(3))    ' deg C stack
2370 RSET COSTK$=MKSS$(COSTK)    ' stack CO, mol % dry basis
2380 RSET CO2STK$=MKSS$(CO2STK)  ' stack CO2, mol% dry basis
2390 RSET T100$=MKSS$(DAT1(2))   ' deg C primary tunnel top
2400 RSET T110$=MKSS$(DAT1(3))   ' deg C primary tunnel bottom
2410 RSET O2SENSOR$=MKSS$(O2SENSOR) ' Bosch O2 sensor output, volts

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2420      RSET DPSTK$=MKSS$(DPSTK)  ' stack orifice diff. press., pascals
2430      RSET CO2.INC$=MKSS$(CO2.INC) ' dry mole % CO2 increase across
                                         catalyst
2440      RSET DPSEC$=MKSS$(DPSEC)  ' sec air orifice diff. press., pascals
2450      RSET T120$=MKSS$(DAT1(4)) ' deg C left secondary tunnel
                                         inlet, top
2460      RSET O2GCELLMV$=MKSS$(O2GCELLMV) ' G-cell oxygen sensor
                                         output, mV
2470      RSET SECFLOW$=MKSS$(SECFLOW) ' sec. air flow rate, g/s
2480      RSET PRIMFLOW$=MKSS$(PRIMFLOW) ' prim. air flow rate, g/s
2490      RSET STKFLOW$=MKSS$(STKFLOW)  ' exhaust gas flow rate, g/s
2500      RSET EQUIVRATIO$=MKSS$(EQUIVRATIO)
2510      RSET T130$=MKSS$(DAT1(5)) ' deg C right secondary tunnel
                                         inlet, top
2520      RSET BURNRATE$=MKSS$(BURNRATE) ' combustion rate, dry g/s
2530      RSET COSTKIR$=MKSS$(COSTKIR) 'stack CO, dry mole % by IR 702
2540      RSET T40$=MKSS$(DAT1(7)) 'deg C right sec tunnel inlet, bottom
2550      RSET EMISRATIO$=MKSS$(EMISRATIO) 'CO/CO2 ratio of exhaust gas
2560      RSET SECAIRPCT$=MKSS$(SECAIRPCT) ' % of primary combustion air
2570      RSET CO2STKIR$=MKSS$(CO2STKIR) 'stack CO2, dry mole % by IR 702
2580      RSET POWER$=MKSS$(POWER) ' kW useful power output
2590      RSET COPRECAT$=MKSS$(COPRECAT) ' dry mole % CO before catalyst
2600      RSET CO2PRECAT$=MKSS$(CO2PRECAT) 'dry mol % CO2 before catalyst
2610      RSET TST$=MKSS$(TST) 'deg C avg of 4 secondary tunnel
                                         inlet temperatures
2620      RSET DRYFUEL$=MKSS$(DRYFUEL) ' kg dry fuel remaining
                                         in magazine
2630      RSET TPT$=MKSS$(TPT) 'deg C avg of 3 prim tunnel temps
2640      RSET PMIXINDEX$=MKSS$(PMIXINDEX) 'total deviation of 3 primary
                                         tunnel thermocouples from avg temp
2650      RSET T140$=MKSS$(DAT1(6)) 'deg C left sec tunnel inlet bottom
2660      RSET SMIXINDEX$=MKSS$(SMIXINDEX) 'avg left STI minus
                                         avg right STI temp (changed 6/4/87)
2670 PUT #1 '*** write data to disk ***
2680 RETURN
2690 '
2700 '
2710 '*****OPEN DATA FILE*****
2720 '
2730 OPEN "R",#1,"B:T"+FILNUM$+".DTA",164
2740 FIELD #1,4 AS ETIME$,4 AS TIMECHK$,4 AS CO.DROP$,4 AS TH20IN$,
        4 AS TH20OUT$,4 AS T30$,4 AS T150$,4 AS T50$,4 AS T60$,
        4 AS T70$,4 AS T80$,4 AS COSTK$,4 AS CO2STK$,4 AS T100$,
        4 AS T110$,4 AS O2SENSOR$,4 AS DPSTK$
2750 FIELD #1,68 AS D1$,4 AS CO2.INC$,4 AS DPSEC$,4 AS T120$,
        4 AS O2GCELLMV$,4 AS SECFLOW$,4 AS PRIMFLOW$,4 AS STKFLOW$,
        4 AS EQUIVRATIO$,4 AS T130$,4 AS BURNRATE$,4 AS COSTKIR$,
        4 AS T40$
2760 FIELD #1,116 AS D2$,4 AS EMISRATIO$,4 AS SECAIRPCT$,4 AS CO2STKIR$,
        ,4 AS POWER$,4 AS COPRECAT$,4 AS CO2PRECAT$,4 AS TST$,

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        4 AS DRYFUEL$, 4 AS TPT$, 4 AS PMIXINDEX$, 4 AS T140$,
        4 AS SMIXINDEX$
2770 OPEN "B:T"+FILNUM$+".INT" FOR OUTPUT AS #2
2780 RETURN
2790 '
2800 '
2810 '*****SCREEN DISPLAY*****
2820 '
2830 IF CLEARSCR$="YES" THEN CLS
2840 CLEARSCR$ = "NO"
2850 COLOR 7
2860 LOCATE 1,19:PRINT "TVA / ESHLAND DATA ACQUISITION ";
        PRINT DATE$:COLOR 2
2870 LOCATE 2,8: PRINT USING "PRIM TUN AVG      #####"; TPT
2880 LOCATE 3,8: PRINT USING "SEC TUN IN (4AVG) #####"; TST
2890 LOCATE 4,8: PRINT USING "SEC TUN OUT (2AVG) #####"; DAT2(5)
2900 LOCATE 5,8: PRINT USING "FIRE TUBE INLET #####"; DAT2(6)
2910 LOCATE 6,8: PRINT USING "FIRE TUBE OUTLET #####"; DAT2(7)
2920 LOCATE 7,8: PRINT USING "CATALYST OUTLET #####"; DAT2(4)
2930 LOCATE 8,8: PRINT USING "STACK          #####.#"; DAT2(3)
2940 LOCATE 9,8: PRINT USING "WATER INLET     #####.#"; DAT2(1)
2950 LOCATE 10,8: PRINT USING "WATER OUTLET    #####.#"; DAT2(2)
2960 LOCATE 11,6: PRINT USING "SEC TUN IN LEFT TOP #####"; DAT1(4)
2970 LOCATE 12,6: PRINT USING "SEC TUN IN LEFT BOT #####"; DAT1(6)
2980 LOCATE 14,5: PRINT USING "PRIM AIR FLOW   #####.# G/S"; PRIMFLOW
2990 LOCATE 15,5: PRINT USING "SEC AIR FLOW    #####.# G/S"; SECFLOW
3000 LOCATE 16,5: PRINT USING "STACK FLOW      #####.# G/S"; STKFLOW
3010 LOCATE 17,5: PRINT USING "SEC AIR % OF PRIM. #####.# %"; SECAIRPCT
3020 LOCATE 18,5: PRINT USING "WATER CIRCULATION
        WATERFLOW      #####.# GPM";
3030 LOCATE 19,5: PRINT USING "BURN RATE      #####.# DRY G/S";
        BURNRATE
3040 LOCATE 20,5: PRINT USING "USEFUL POWER    #####.# KW"; POWER
3050 LOCATE 21,5: PRINT USING "BOSCH O2 SENSOR  #####.# mV";
        O2SENSOR*1000
3060 LOCATE 22,5: PRINT USING "SEC AIR VALVE OPENING ##### pulses"
        ;MOTOR.POSITION%
3070 HOLD.TIME = FNTPSEC - POS.TIME
3080 LOCATE 23,5: PRINT USING "TIME SINCE CHANGE ##### SEC"
        ;HOLD.TIME
3090 LOCATE 2 ,40: PRINT USING "CO2 STACK (HOR) #####.%DRY "; CO2STK
3100 LOCATE 4 ,40: PRINT USING "CO STACK (HOR) #####.%DRY"; COSTK
3110 LOCATE 6 ,40: PRINT USING "CATAL CO2 RISE +#####.%DRY"; CO2.INC
3120 LOCATE 7 ,40: PRINT USING "CATAL CO DROP  +#####.%DRY"; CO.DROP
3130 LOCATE 3 ,40: PRINT USING "CO2 STACK (IR) #####.%DRY"; CO2STKIR
3140 LOCATE 5 ,40: PRINT USING "CO STACK (IR) #####.%DRY"; COSTKIR
3170 LOCATE 8,40: PRINT USING "PRIM TUN, TOP #####"; DAT1(2)
3180 LOCATE 9,40: PRINT USING "PRIM TUN, CTR   #####"; DAT1(1)
3190 LOCATE 10,40: PRINT USING "PRIM TUN, BOT   #####"; DAT1(3)
3200 LOCATE 11,39: PRINT USING "SEC TUN IN RT TOP #####"; DAT1(5)

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3210 LOCATE 12,39: PRINT USING "SEC TUN IN RT BOT #####";DAT1(7)
3220 LOCATE 13,40: PRINT USING "CO/CO2 MOLAR RATIO .###"; EMISRATIO
3230 LOCATE 14,40: PRINT USING "EQUIVALENCE RATIO #.##"; EQUIVRATIO
3240 LOCATE 15,40: PRINT USING "BOSCH O2 SENSOR #### mV "
    ;O2SENSOR*1000;:PRINT MIXTURE$
3250 LOCATE 16,40: PRINT USING "O2 G-CELL     ###.# mV CONTROL BY &" 
    ;O2GCELLMV,CONTROL.SCHEME$
3260 LOCATE 17,40: PRINT USING "PRI MIX INDEX     ###.## DEG C"
    ;PMIXINDEX
3270 LOCATE 18,40: PRINT USING "SEC MIX INDEX     ###.## DEG C"
    ;SMIXINDEX
3280 LOCATE 19,40: PRINT USING "USEFUL ENERGY OUT      #####. MJ";EOUT
3290 LOCATE 20,40: PRINT USING "TOT FUEL LOADED THIS TEST #####.#";TFL '
    dry kg
3300 LOCATE 21,40: PRINT USING "TOTAL FUEL CONSUMED      #####.#"
    ;TFC;" DRY KG"
3310 LOCATE 22,40: PRINT USING "FUEL REMAINING      #####.# DRY KG"
    ;DRYFUEL
3320 COLOR 3: LOCATE 23,40: PRINT USING "ELAPSED TIME: ###.# MIN"
    ;ETIME
3330 COLOR 4: LOCATE 24,2: PRINT "ALT -Q H2O FLOW, -F RE-LOAD, -P"
    ;" PARAM, -S STRATEGY, -T END, CNTRL HOME CLS";
3340 LOCATE 25,2:PRINT "      -D STOP/START STORAGE";:COLOR 3:
    PRINT "          DATA STORAGE: ";:COLOR 5:
    PRINT USING "&, #";STORE$,INTERVAL%;:COLOR 3
3350 RETURN
3360 '
3370 '
3380 *****CALCULATIONS*****
3390 '
3400 PCFS=DAT3(1)*20:COSTK=(.0000220628982#+.0210707036/*PCFS+
    .00021917326/*PCFS^2-.00000107298545/*PCFS^3+
    .0000000177413978/*PCFS^4):COSTK=COSTK+
    (ABS(COSTK-2.5)/2.5-1)*.025 ' CO in mole %, dry basis
3420 PCFS=DAT3(2)*20:CO2STK=.00209923625#+.0986561579/*PCFS+
    .000938160956/*PCFS^2-.00000616442064/*PCFS^3+
    .0000000691513666/*PCFS^4 'CO2
3430 CO2STK=(CO2STK+.55-.055*ABS(CO2STK-10)) ' CO2 in mole % dry basis
3440 H2OSTK=(CO2STK+2!*COSTK)*(3.3+5.56* MCD)/4.24-.75*COSTK '
    mole % dry basis
3450 IF H2OSTK<0 THEN H2OSTK=0
3460 O2STK=19.8-CO2STK-COSTK/2! 'mole % dry basis
3470 O2SENSOR = DAT3(3) ' Bosch oxygen sensor output, volts
3480 O2GCELLMV=DAT3(5)*1000!/GGAIN ' convert to get actual
    G-cell output mV
3490 IF O2SENSOR<.45 THEN MIXTURE$="LEAN" ELSE MIXTURE$="RICH"
3500 COSTKIR=DAT3(0)*3!/.1 ' IR702 dry mole %
3510 CO2STKIR=DAT3(7)*20!/.1 ' IR702 dry mole %
3520 CO.DROP=COPRECAT-COSTKIR: CO2.INC=CO2STKIR-CO2PRECAT
3530 DPSTK=(DAT3(4)-ZERO34V)*99.623 ' pascals

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3540 GOSUB 5060 ' determine water flow rate
3550 DPSEC=(DAT3(6)-ZERO36V)*498.114 ' pascals (for 0-10" transducer)
3560 STKDENSITY=PBAR*28.8/(8.3143*(DAT2(3)+273.15)) 'MW of gas = 28.8
3570 SECAIRDEN=PBAR/.287/314! ' kg/m^3, using 41 deg C sec air temp
3580 IF DPSTK>2 THEN STKFLOW=CDASTK*SQR(2*STKDENSITY*DPSTK) ELSE
      STKFLOW=0 ' g/s
3590 IF DPSEC>1.5 THEN SECFLOW=CDASEC*SQR(2!*SECAIRDEN*DPSEC) ELSE
      SECFLOW=0 ' g/s
3600 POWER=WATERFLOW*6.308E-05*977.5*4.193*(DAT2(2)-DAT2(1)) '
      kW, 977.5=H2O density @ 70 C(kg/m^3), 4.193=specific
      heat 60 TO 90 C (kJ/kg/K)
3610 EQUIVRATIO=(CO2STK+2!*COSTK)/19.8
3620 IF CO2STK>0 AND COSTK>0 THEN EMISRATIO=COSTK/CO2STK ELSE
      EMISRATIO=0!
3630 BURNRATE=2*STKFLOW/28.8*(2!*COSTK+CO2STK)*12!/(H2OSTK+100!) '
      combustion rate, dry g/s, assuming 1:1 CO:CHn by volume
      in exhaust gas
3640 IF BURNRATE<0 THEN BURNRATE=0
3650 OLDPRIM=PRIMFLOW
3660 PRIMFLOW=STKFLOW-SECFLOW-BURNRATE*(1!+MCD) ' g/s primary air
3670 IF PRIMFLOW>0 THEN SECAIRPCT=SECFLOW/PRIMFLOW*100! ELSE
      SECAIRPCT=0 % of primary combustion air
3680 DRYFUEL=DRYFUEL-BURNRATE*30!/1000! ' kg dry fuel remaining
      in magazine
3690 EOUT=EOUT+POWER*30!/1000! ' MJ, cumulative useful energy output
3700 TFC=TFC+BURNRATE*30/1000 'cumulative mass of dry wood concumed,
      dry g/s
3710 IF DAT3(3)<0! THEN DAT3(3)=0!
3720 TPT=(DAT1(3)+DAT1(1))/2! ' avg of center & bottom prim tun temps
3730 TST=(DAT1(4)+DAT1(5)+DAT1(6)+DAT1(7))/4 ' avg of 4 sec tunnel
      inlet temps
3740 PMIXINDEX=ABS(DAT1(3)-TPT)+ABS(DAT1(1)-TPT)
3750 SMIXINDEX=(DAT1(4)+DAT1(6) - (DAT1(5)+DAT1(7)))/2 ' avg left sec.
      tunnel - avg right tunnel temperature, deg C (changed 6/4/87)
3760 RETURN
3770 '
3780 '
3790 ' ***** MID-RUN PARAMETER CHANGES *****
3800 '
3810 '***** Add a batch of fuel *****
3820 '
3830 CLS
3840 ZNUM=ZNUM+1
3850 PRINT #2,USING "PRIOR TO LOAD NO. #, MCD = +#.###";ZNUM,MCD
      ;" (D.B. FUEL H2O FRAC.)"
3860 INPUT "ENTER MASS OF WET FUEL IN THE LOAD YOU ARE ADDING (lb.)",NL
3870 NL=NL/2.2046 ' convert from lb. to kg.
3880 INPUT "ENTER ESTIMATED FUEL MOISTURE FOR THIS LOAD (% WET BASIS)"
      ,FMNL
3890 MCDNL=FMNL/(100!-FMNL) ' convert from % wet basis to fraction

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    dry basis
3900 NLDRY=NL*(100!-FMNL)/100! ' calculate mass of dry fuel in the
      new load
3910 MCD=(DRYFUEL*MCD+NLDRY*MCDNL)/(DRYFUEL+NLDRY) ' calculate new
      overall moisture
3920 DRYFUEL = DRYFUEL + NLDRY ' add mass of new load to mass of fuel
      in magazine
3930 TFL=TFL+NLDRY ' add this load to total mass of fuel loaded
      this run
3940 CLS
3950 PRINT #2,USING "LOAD NO. # ##.# KG WET WOOD AT ##.# % WB, ##.#"
      ;ZNUM;NL;FMNL;ETIME;" MIN ELAPSED TIME"
3960 PRINT #2,USING " ####.# cumulative dry kg of fuel loaded";TFL
      ;" so far this test"
3970 PRINT #2,USING ". AFTER LOAD NO. #, MCD =#.###";ZNUM,MCD
3980 IF FNCLK(706)<30 GOTO 1360 ELSE GOTO 1570
3990 '
4000 ' ***** Change the value of QH20 *****
4010 '
4020 CLS
4030 PRINT USING "PRESENT COOLING WATER FLOW RATE IS ##.# GPM";QH20
4040 INPUT "ENTER NEW COOLING WATER FLOWRATE (GPM)",QH20
4050 PRINT #2, USING "AT ##.# minutes, water circulation changed"
      ;ETIME;" to ##.# GPM";QH20
4060 CLS
4070 IF FNCLK(706)<30 GOTO 1360 ELSE GOTO 1570
4080 '
4090 '***** Change secondary air control parameters *****
4100 '
4110 CLS:IF CONTROL.SCHEME$="G-CELL" THEN 4320
4120 '
4130 ' ***** Parameter change for Bosch-based control strategy *****
4140 PRINT USING " (1) CONTROL.TEMP=#/#/# (2) RICH.O2SEN=#.##"
      ;CONTROL.TEMP,RICH.O2SEN;" (3) LEAN.O2SEN=#.##";LEAN.O2SEN
4150 PRINT USING "(4) INIT.STEP%=## (5) RICHDELAY=#/#/#";INIT.STEP%
      ,RICHDELAY;" (6) LEANDELAY=#/#/# (7) BK.TM=##";LEANDELAY
      ,BK.TM
4160 INPUT "ENTER THE PARAMETER NO. TO BE CHANGED AND THE NEW VALUE"
      ;PN,NV
4170 IF PN=1 THEN OV=CONTROL.TEMP:CONTROL.TEMP=NV
4180 IF PN=2 THEN OV=RICH.O2SEN:RICH.O2SEN=NV
4190 IF PN=3 THEN OV=LEAN.O2SEN:LEAN.O2SEN=NV
4200 IF PN=4 THEN OV=INIT.STEP%:INIT.STEP%=INT(NV+.1)
4210 IF PN=5 THEN OV=RICHDELAY:RICHDELAY=NV
4220 IF PN=6 THEN OV=LEANDELAY:LEANDELAY=NV
4230 IF PN=7 THEN OV=BK.TM:BK.TM=NV
4240 PRINT USING "PARAM NO #: OLD VALUE =##/#.##, NEW VALUE =##/#.##"
      ;PN,OV,NV
4250 INPUT "ENTER P TO CHANGE ANOTHER PARAMETER OR <CR> TO RETURN";D$

```

```

4260 IF D$="P" THEN 4140
4270 PRINT #2, USING "AT ELAPSED TIME = #####.# min THE CONTROL";ETIME
      ;" PARAMETERS WERE CHANGED TO:"
4280 PRINT #2, USING "CONTROL.TEMP=#####, RICH.O2SEN=#.##,";CONTROL.TEMP
      ,RICH.O2SEN;" LEAN.O2SEN=#.##, RICHDELAY=##";LEAN.O2SEN,
      RICHDELAY
4290 PRINT #2, USING "LEANDELAY=####, INIT.STEP%#=##, BK.TM=##"
      ;LEANDELAY,INIT.STEP%,BK.TM:CLS
4300 IF FNCLK(706)<30 GOTO 1360 ELSE GOTO 1570
4310 '
4320 ***** Parameter change for G-cell control strategy *****
4330 PRINT USING "(1) GSET=#.## (2) GBAND=#.##";GSET,GBAND
      ;" (3) GDELAY=#.## (4) GTEMP=####";GDELAY,GTEMP
4340 INPUT "ENTER THE PARAMETER NO. TO BE CHANGED AND THE NEW VALUE"
      ;PN,NV
4350 IF PN=1 THEN OV=GSET:GSET=NV
4360 IF PN=2 THEN OV=GBAND:GBAND=NV
4370 IF PN=3 THEN OV=GDELAY:GDELAY=NV
4380 IF PN=4 THEN OV=GTEMP:GTEMP=NV
4390 PRINT USING "PARAM NO #: OLD VALUE =#####.###,     NEW VALUE =#####.###"
      ;PN,OV,NV
4400 INPUT "ENTER P TO CHANGE ANOTHER PARAMETER OR <CR> TO RETURN";D$
4410 IF D$="P" THEN 4330
4420 PRINT #2, USING "AT ELAPSED TIME = #####.# min THE CONTROL";ETIME
      ;" PARAMETERS WERE CHANGED TO:"
4430 PRINT #2, USING "GSET=#.##, GBAND=#.##, GDELAY=#.##, GTEMP=####"
      ;GSET,GBAND,GDELAY,GTEMP:CLS
4440 IF FNCLK(706)<30 GOTO 1360 ELSE GOTO 1570
4450 '
4460 ***** Change control scheme *****
4470 '
4480 IF CONTROL.SCHEME$="BOSCH" THEN CONTROL.SCHEME$="G-CELL" ELSE
      CONTROL.SCHEME$="BOSCH"
4490 PRINT #2,USING " AT ELAPSED TIME #####.# MIN, CONTROL";ETIME;
      SCHEME CHANGED TO & ";CONTROL.SCHEME$"
4500 IF FNCLK(706)<30 GOTO 1360 ELSE GOTO 1570
4510 '
4520 ***** Terminate test routine *****
4530 '
4540 PRINT #2,USING "END OF TEST: MCD =#.## (d.b. fuel H2O frac)";MCD
4550 PRINT #2,USING "END OF TEST: DRY FUEL REMAINING =#.## dry kg"
      ;DRYFUEL
4560 PRINT #2, USING "ACCUMULATED USEFUL ENERGY OUTPUT AT"
      ;" END OF TEST: ##### MJ";EOUT
4570 MOTOR.DIRECTION%=0:STEP.NUMBER%=MOTOR.POSITION%:GOSUB 4590 '
      close secondary combustion air valve
4580 COLOR 7:CLOSE:END
4590 '
4600 '
4610 ***** VALVE POSITIONING SUBROUTINE *****

```

```

4620 '
4630 '***** Partial list of variables *****
4640 '** MOTOR.POSITION% = the number of pulses open (closed = 0)
4650 '** MOTOR.DIRECTION% = opening = 1, closing = 0
4660 '** STEP.NUMBER% = number of pulses to move
4670 '*****
4680 '
4690 B%=3:CALL XSB(B%):GOSUB 830
4700 PORT%=1:CALL XEFO(PORT%):GOSUB 830
4710 CALL XODV(PORT%,MASK%,MOTOR.DIRECTION%):GOSUB 830 'set direction
4720 '
4730 PORT%=0:CALL XEFO(PORT%):GOSUB 830
4740 FOR I%=1 TO STEP.NUMBER%           'perform desired number of pulses
4750 DIGIT%=1:CALL XODV(PORT%,MASK%,DIGIT%)
4760 FOR A%=1 TO 210:NEXT A% 'comment this line for interpreted
                           BASIC to speed up the pulse rate
4770 DIGIT%=0:CALL XODV(PORT%,MASK%,DIGIT%)
4780 FOR A%=1 TO 210:NEXT A% 'comment this line for interpreted
                           BASIC to speed up the pulse rate
4790 NEXT I%
4800 DIGIT%=2:CALL XODV(PORT%,MASK%,DIGIT%) 'inhibit motor operation
4810 GOSUB 830 ' check for errors
4820 '
4830 '***** Update and display position *****
4840 MOTOR.POSITION%=MOTOR.POSITION%-STEP.NUMBER%*(-1)^MOTOR.DIRECTION%
4850 IF MOTOR.POSITION%<=0 THEN GOSUB 4980 ' turn off vacuum
4860 LOCATE 22,5:PRINT USING "SEC AIR VALVE OPENING #### PULSES"
      ;MOTOR.POSITION%
4870 RETURN
4880 '
4890 '
4900 '*** TURN ON SECONDARY COMBUSTION AIR FAN (VACUUM CLEANER) *****
4910 '
4920 B%=2:CALL XSB(B%):GOSUB 830
4930 PORT%=1:CALL XEFO(PORT%):GOSUB 830
4940 D%=1:CALL XODV(PORT%,MASK%,D%):GOSUB 830:VAC$="ON"
4950 RETURN
4960 '
4970 '
4980 '***** TURN OFF SECONDARY COMBUSTION AIR FAN *****
4990 '
5000 B%=2:CALL XSB(B%):GOSUB 830
5010 PORT%=1:CALL XEFO(PORT%):GOSUB 830
5020 D%=0:CALL XODV(PORT%,MASK%,D%):GOSUB 830:VAC$="OFF"
5030 RETURN
5040 '
5050 '
5060 '***** DETERMINE PUMP STATUS AND H2O FLOW *****
5070 '
5080 B%=2:CALL XSB(B%):GOSUB 830

```

```

5090 PORT%=0:CALL XEFI(PORT%):GOSUB 830
5100 CALL XIDV(PORT%,MASK%,D%):GOSUB 830
5110 IF (D% AND 1)=0 THEN PUMPSTATUS%=0:WATERFLOW=0! ELSE
      PUMPSTATUS%=1:WATERFLOW=QH20
5120 RETURN
5130 '
5140 '
5150 '***** DE-ENERGIZE GAS SAMPLE SOLENOIDS *****
5160 '
5170 B%=1:CALL XSB(B%):GOSUB 830:IR702.GAS$="STACK "
5180 PORT%=0:CALL XEFO(PORT%):GOSUB 830
5190 D%=0:CALL XODV(PORT%,MASK%,D%):GOSUB 830
5200 IF MODE$="TEST" THEN LOCATE 13,5:
      PRINT USING "NEXT IR702 SAMPLE: & ";IR702.GAS$;
5210 RETURN
5220 '
5230 '
5240 '***** ENERGIZE GAS SAMPLE SOLENOIDS *****
5250 '
5260 B%=1:CALL XSB(B%):GOSUB 830:IR702.GAS$="PRECAT"
5270 PORT%=0:CALL XEFO(PORT%):GOSUB 830
5280 D%=1:CALL XODV(PORT%,MASK%,D%):GOSUB 830
5290 IF MODE$="TEST" THEN LOCATE 13,5:
      PRINT USING "NEXT IR702 SAMPLE: & ";IR702.GAS$;
5300 RETURN
5305 '
5310 '
5320 '***** SECONDARY COMBUSTION AIR CONTROL *****
5330 '
5340 IF PRIMFLOW<10 OR OLDPREM<10 THEN RETURN
5350 IF CONTROL.SCHEM$="G-CELL" THEN 5412
5360 '
5370 '***** Control routine for Bosch-based strategy *****
5380 '
5390 IF O2SENSOR>RICH.O2SEN AND HOLD.TIME>RICHDELAY THEN GOSUB 5440:
      GOTO 5410 ' rich
5400 IF O2SENSOR<LEAN.O2SEN AND HOLD.TIME>LEANDELAY AND
      TST<CONTROL.TEMP THEN GOSUB 5620 ' lean
5410 RETURN
5411 '
5412 '***** Control routine for G-cell based strategy *****
5413 '
5414 IF TST<GTEMP AND MOTOR.POSITION%>0 THEN MOTOR.DIRECTION%=0:
      STEP.NUMBER%=MOTOR.POSITION%:GOSUB 4610:RETURN ' close valve
5415 IF TST<GTEMP THEN RETURN
5416 IF O2GCELLMV>(GSET+GBAND) AND HOLD.TIME>GDELAY THEN GOSUB 5620 ' lean
5417 IF O2GCELLMV<(GSET-GBAND) AND HOLD.TIME>GDELAY THEN GOSUB 5440 ' rich
5418 RETURN

```

```

5420 '
5440 ' ***** Rich *****
5450 '
5460 MOTOR.DIRECTION% = 1
5470 IF MOTOR.POSITION%>=STP%(NUM.STEPS%) THEN RETURN
5480 IF VAC$="OFF" THEN GOSUB 4900 ' turn on vacuum
5490 IF CONTROL.SCHEME$="BOSCH" THEN STEP.NUMBER%=900-MOTOR.POSITION%:
      GOTO 5560
5500 FOR I%=1 TO NUM.STEPS%
5510 IF MOTOR.POSITION%<STP%(I%) THEN STEP.NUMBER%=STP%(I%)-MOTOR.POSITION%:GOTO 5530
5520 NEXT I%
5530 IF O2GCELLMV>(GSET-GBAND-1) THEN 5560 ELSE A%=NUM.STEPS%-I%:
      EXT.STP%=CINT((GSET-O2GCELLMV)*2.7/STEP.SIZE)-1
5540 IF EXT.STP%>A% THEN EXT.STP%=A%
5550 STEP.NUMBER%=STP%(I%+EXT.STP%)-MOTOR.POSITION%
5560 A=SECONDS: IF STEP.NUMBER%>120 THEN IF((A>15) AND (A<30)) OR
      ((A>45) AND (A<60)) THEN RETURN ' this inhibits control
      actions that would take so long that a set of data would be
      missed
5570 GOSUB 4610 ' open the secondary comb. air control valve
5580 POS.TIME = FNETSEC: VALVE.CHG$="OPEN"
5590 RETURN
5600 '
5620 ' ***** Lean *****
5630 '
5640 MOTOR.DIRECTION% = 0
5650 IF MOTOR.POSITION%=0 THEN RETURN
5660 FOR I%=1 TO NUM.STEPS%
5670 IF MOTOR.POSITION%>STP%(NUM.STEPS%-I%) THEN
      STEP.NUMBER%=MOTOR.POSITION%-STP%(NUM.STEPS%-I%):GOTO 5690
5680 NEXT I%
5690 A=SECONDS: IF STEP.NUMBER%>120 THEN IF((A>15) AND (A<30)) OR
      ((A>45) AND (A<60)) THEN RETURN
5700 GOSUB 4610 ' close the sec comb. air valve
5710 POS.TIME = FNETSEC: VALVE.CHG$="CLOSE"
5720 RETURN
5730 '
5740 '
5750 ' ***** AUTOMATIC BOILER SHUTDOWN *****
5760 '
5770 IF PRIMFLOW>10 OR MOTOR.POSITION%<=0 THEN RETURN
5780 MOTOR.DIRECTION%=0:STEP.NUMBER%=MOTOR.POSITION%
5790 GOSUB 4610 ' close down the secondary combustion air valve
5800 RETURN
5810 '
5820 '
5830 ' ***** CONTROL SCREEN UPDATE *****
5840 '
5850 HOLD.TIME = FNETSEC - POS.TIME: COLOR 2

```

```

5860 LOCATE 23,5: PRINT USING "TIME SINCE CHANGE ##### SEC";HOLD.TIME
5870 B%=3:CALL XSB(B%):GOSUB 830:CH%=3:CALL XMV(CH%,V!):GOSUB 830:
      O2SENSOR=V!
5880 LOCATE 15,40: PRINT USING "BOSCH O2 SENSOR ##### mV      "
      ;O2SENSOR*1000;:PRINT MIXTURE$
5890 CH%=5:CALL XMV(CH%,V!):GOSUB 830:O2GCELLMV=V!*1000!/GGAIN
5900 LOCATE 16,40: PRINT USING "O2 G-CELL    ##.# mV CONTROL BY &"
      ;O2GCELLMV,CONTROL.SCHEME$
5910 CH%=6:CALL XMV(CH%,V!):GOSUB 830:DPSEC=(V!-ZERO36V)*498.114
5920 SECAIRDEN=PBAR/.287/314! ' kg/m^3 using sec air temp = 41 deg C
5930 V=DPSEC/498.114
5940 IF V<.107 THEN CDASEC=.707-.5047*V ELSE IF V<.34 THEN
      CDASEC=.6675-.1397*V ELSE IF V<.9 THEN CDASEC=.628-.0239*V
      ELSE CDASEC=.6065
5950 IF DPSEC>3 THEN SECFLOW=CDASEC*SQR(2!*SECAIRDEN*DPSEC) ELSE
      SECFLOW=0 ' g/s
5960 LOCATE 15,5: PRINT USING "SEC AIR FLOW      ##### G/S"; SECFLOW
5970 RETURN
5980 '
5990 '
6000 '***** IR702 STACK GAS MEASUREMENTS *****
6010 '
6020 B%=3:CALL XSB(B%):GOSUB 830:CH%=0:CALL XMV(CH%,COV!):GOSUB 830
6030 CH%=7: CALL XMV(CH%,CO2V!):GOSUB 830
6040 GOSUB 5150 '***** switch solenoid to sample stack gas *****
6050 COPRECAT=COV!*3!/.1: CO2PRECAT=CO2V!*20!/.1
6060 RETURN

```

APPENDIX B

STIRRED REACTOR KINETIC MODEL FORTRAN CODE

Usage Notes

The FORTRAN source code included herein must be linked with the following FORTRAN subroutines :

PSPNT, PSRTWO, PSRJAC, PSRFUN, PSPRNT, PSPRT1, PSRKEY, PSRSEN, PSRROP, SYMSTR, and XNUMER.

These subroutines are contained in the PSR source code [30]. The model code must also be linked with the double precision gas phase subroutine library of the CHEMKIN package [31].

Source Code Listing

```
C//////////  
C  
C          PSR: PERFECTLY STIRRED REACTOR  
C  
C          WRITTEN BY:  
C          PETER GLARBORG  
C          LABORATORY FOR HEATING AND AIR CONDITIONING  
C          TECHNICAL UNIVERSITY OF DENMARK  
C          2800 LYNGBY  
C          DENMARK  
C          AND  
C          ROBERT J. KEE  
C          COMPUTATIONAL MECHANICS DIVISION  
C          SANDIA NATIONAL LABORATORIES  
C          LIVERMORE, CA 94550  
C  
C  
C//////////  
C  
C          MODIFIED BY C. G. HARRIS 8/87 FOR MODELING THE GAS-PHASE  
C          COMBUSTION IN THE ESHLAND MODEL E500 BOILER  
C  
C//////////  
C  
C  
C-----  
C  
PROGRAM PSRMOD  
IMPLICIT REAL*8 (A-H, O-Z)  
IMPLICIT INTEGER (I-N)  
C NNREAC=total number of stirred reactors in the model  
C NPREAC=total number of stirred reactors in the primary tunnel  
      PARAMETER (LENLWK=200, LENIWK=2000, LENRWK=2000, NNREAC=11,  
1           NPREAC=5)  
      DIMENSION L(LENLWK), I(LENIWK), R(LENRWK)  
      COMMON /PSPSPS/ NCKW, NWT, NFU, NOX, NADD, NSTO, NXIN, NYIN,  
1           NHIN, NXST, NSCR, NABV, NBLW, NBUF, NWNT,  
2           NS, NSN, NF, NFN, NA, NEQ, ICKW, IIS, IKS,  
3           INCF, IIP, IKPR, IKSP, IEQ, LACT, LIS, LIR  
C  
C  
DATA LINP/5/, LOUT/7/, LSHORT/8/, LINKCK/25/, LSMOUT/9/  
C  
C          OPEN INPUT & OUTPUT FILES.  
C  
CALL OPEN (NNREAC, LINP, LSHORT, LOUT, LINKCK, LSMOUT)  
C
```

```

C          WRITE VERSION NUMBER
C
    WRITE (LOUT,*) '
    WRITE (LOUT,*) '
1'      PSR : Perfectly Stirred Reactor Code'
    WRITE (LOUT,*) '
1'      Modified 8/87 to model the Eshland E500 boiler'
    WRITE (LOUT,*) '
1'      DOUBLE PRECISION'
C
    WRITE (LOUT,*) '
    WRITE (LOUT,*) '
C          SET UP INTERNAL WORK POINTERS
C
    CALL PSPNT (LINKCK, NMAX, LOUT, MM, KK, II, NIK, LENSYM, NATJ,
1           LENICK, LENCK, LENITP, LENTP, LENIEQ, LENEQ,
2           LTOT, ITOT, NTOT,
3           NT, NYS, NY)
C
C          CHECK FOR ENOUGH SPACE
C
    WRITE (LOUT,*) '
    WRITE (LOUT, *) '                                WORKING SPACE REQUIREMENTS'
    WRITE (LOUT, *) '                                PROVIDED        REQUIRED'
    WRITE (LOUT, 7000) LENLWK, LTOT
    WRITE (LOUT, 7010) LENIWK, ITOT
    WRITE (LOUT, 7020) LENRWK, NTOT
    WRITE (LOUT,*) '
7000  FORMAT (' LOGICAL ', 2I15)
7010  FORMAT (' INTEGER ', 2I15)
7020  FORMAT (' REAL ', 2I15)
C
    IF (LTOT.GT.LENLWK .OR. ITOT.GT.LENIWK .OR. NTOT.GT.LENRWK) THEN
        WRITE (LOUT, *) ' FATAL ERROR, NOT ENOUGH WORK SPACE PROVIDED'
        STOP
    ENDIF
C
    CALL PSRDRV (LOUT, LINKCK, LSHORT, LINP, LSMOUT,
1           MM, KK, II, NIK, NATJ,
2           LENICK, LENCK, I(ICKW), R(NCKW), R(NWT),
3           LENSYM, I(IKS), I(IIS), I(INCF),
4           LENIEQ, LENEQ, I(IEQ), R(NEQ),
5           R(NFU), R(NOX), R(NADD), R(NSTO), I(IKPR), I(IKSP),
6           L(LIS), L(LIR), I(IIP),
7           R(NXIN), R(NYIN), R(NHIN), R(NXST), R(NSCR),
8           R(NS), R(NSN), R(NF), R(NFN), R(NA),
9           L(LACT), R(NABV), R(NBLW), R(NBUF), R(NWNT),
*           NT, NYS, NY)

```

```

DO 100 N=1,NNREAC
      LKEY = N + 50
100   CLOSE (LKEY)
      CLOSE (LOUT)
      CLOSE (LINP)
      CLOSE (LINKCK)
      CLOSE (LSHORT)
      CLOSE (LSMOUT)

C
C
      STOP
      END

C
C-----C
C
      SUBROUTINE OPEN (NNREAC, LINP, LSHORT, LOUT, LINKCK, LSMOUT)
C
      IMPLICIT REAL*8 (A-H, O-Z)
      IMPLICIT INTEGER (I-N)
      CHARACTER*23 KEYNAM, SAVNAM

C
C      OPEN A KEYWORD FILE FOR EACH REACTOR
C
      DO 10 L=1,NNREAC
C
      LKEY = L + 50
C
      IF (L .LE. 9) THEN
          KEYNAM = '[HARRISCG.OUT]KEY0'//CHAR(L+48)//'.DAT'
      ELSE
          NUMB1 = AINT(REAL(L)/10.)+48
          NUMB2 = L - (NUMB1-48)*10 + 48
          KEYNAM = '[HARRISCG.OUT]KEY'//CHAR(NUMB1)//CHAR(NUMB2)//'.DAT'
      END IF
C
      OPEN(UNIT=LKEY, STATUS='NEW', FORM='FORMATTED', FILE=KEYNAM,
1           CARRIAGECONTROL='LIST')
C
      10 CONTINUE
C
      OPEN(UNIT=LINP, STATUS='OLD', FORM='FORMATTED',
1           FILE='[HARRISCG.IN]PSRMOD.DAT')
      OPEN(UNIT=LOUT, STATUS='NEW', FORM='FORMATTED',
1           FILE='[HARRISCG.OUT]PSRMOD.OUT', CARRIAGECONTROL='LIST')
      OPEN(UNIT=LSHORT, STATUS='NEW', FORM='FORMATTED',
1           FILE='[HARRISCG.OUT]PSHORT.OUT', CARRIAGECONTROL='LIST')
      OPEN(UNIT=LINKCK, STATUS='OLD', FORM='UNFORMATTED',
1           FILE='[HARRISCG]LINK.BIN')
      OPEN(UNIT=LSMOUT, STATUS='NEW', FORM='FORMATTED',
1           FILE='[HARRISCG.OUT]PSUM.OUT', CARRIAGECONTROL='LIST')

```

```

RETURN
END

C
C-----
C
C      SUBROUTINE WRTKEY (LKEY,NKK,ETYPE,TEMP,FLRT,VOL,QLOS,TINL,XINLET)
C
C      IMPLICIT REAL*8 (A-H, 0-Z)
C      IMPLICIT INTEGER (I-N)
C      CHARACTER*4 ETYPE
C      DIMENSION XINLET(NKK)

C
      WRITE (LKEY,FMT='(A4)') ETYPE
      WRITE (LKEY,20) TEMP
 20 FORMAT ('TEMP',3X,F7.2)
      WRITE (LKEY,30) 0.93
 30 FORMAT ('PRES',3X,F4.2)
      WRITE (LKEY,40) FLRT
 40 FORMAT ('FLRT',3X,F5.2)
      WRITE (LKEY,50) VOL
 50 FORMAT ('VOL',3X,F6.0)
      IF (ETYPE .EQ. 'ENRG') WRITE (LKEY,15) QLOS
 15 FORMAT ('QLOS',3X,F8.2)
      IF (ETYPE .EQ. 'ENRG') WRITE (LKEY,55) TINL
 55 FORMAT ('TINL',3X,F7.2)
      WRITE (LKEY,60) XINLET(1)
 60 FORMAT ('REAC CO',2X,F16.14)
      WRITE (LKEY,70) XINLET(2)
 70 FORMAT ('REAC CO2',2X,F16.14)
      WRITE (LKEY,80) XINLET(3)
 80 FORMAT ('REAC O',2X,E13.7)
      WRITE (LKEY,90) XINLET(4)
 90 FORMAT ('REAC O2',2X,F16.14)
      WRITE (LKEY,100) XINLET(5)
100 FORMAT ('REAC H',2X,E13.7)
      WRITE (LKEY,110) XINLET(6)
110 FORMAT ('REAC H2',2X,E13.7)
      WRITE (LKEY,120) XINLET(7)
120 FORMAT ('REAC OH',2X,E13.7)
      WRITE (LKEY,130) XINLET(8)
130 FORMAT ('REAC H2O',2X,F16.14)
      WRITE (LKEY,140) XINLET(9)
140 FORMAT ('REAC HO2',2X,E13.7)
      WRITE (LKEY,150) XINLET(10)
150 FORMAT ('REAC H2O2',2X,E13.7)
      WRITE (LKEY,160) XINLET(11)
160 FORMAT ('REAC N2',2X,F9.7)
      WRITE (LKEY,170) 0
170 FORMAT ('PRNT',3X,I1)
      WRITE (LKEY,180)

```

```

180 FORMAT ('END')
      REWIND LKEY
      RETURN
      END
C
C
C-----  

C
      SUBROUTINE MIX (LOUT,LENICK,LENCK,ETYPE,KK,TF,XF,FFLO,TO,XO,OXFLO,
1           ICKWRK,CKWRK,TMX,XMX,OUTFLO)
C
C finds temp of mixture of 2 streams, each of arbitrary temp & composition
C
      IMPLICIT REAL*8 (A-H,O-Z)
      IMPLICIT INTEGER (I-N)
      CHARACTER*4 ETYPE
      DIMENSION XF(KK),XO(KK),XMX(KK),ICKWRK(LENICK),CKWRK(LENCK)
C
      DATA RELTOL/0.0001/
      OUTFLO = FFLO + OXFLO
C
C DETERMINE MEAN MOLECULAR WEIGHTS
      CALL CKMMWX (XF,ICKWRK,CKWRK,WTMF)
      CALL CKMMWX (XO,ICKWRK,CKWRK,WTMO)
C
C calculate total molar flow rate (mol/s)
      OXFLON = OXFLO / WTMO
      FFLON = FFLO / WTMF
      OUTFLN = OXFLON + FFLON
C
C calculate mixture mole fractions
      DO 10 K=1,KK
      XMX(K) = 0.0
      XMX(K) = (OXFLON*XO(K) + FFLON*XF(K)) / OUTFLN
      10 CONTINUE
C
C
      IF (ETYPE .EQ. 'TGIV') RETURN
C
C      CALCULATE MIXTURE TEMPERATURE FOR ENRG PROBLEMS
C
      IF (TO.LT.TF) THEN
      TLO = TO
      THI = TF
      ELSE IF (TO .GT. TF) THEN
      TLO = TF
      THI = TO
      ELSE IF (TO.EQ.TF) THEN
      TMX=TO

```

```

RETURN
END IF
C
C           calculate mean molar enthalpy (ergs/mol)
C
CALL CKHBML (TF,XF,ICKWRK,CKWRK,HBMLF)
CALL CKHBML (TO,XO,ICKWRK,CKWRK,HBMLO)
HBMLMX = (HBMLF*FFLON + HBMLO*OXFLON) / OUTFLN
C
WRITE(6,211) TO, TF, HBMLO, HBMLF, HBMLMX
211 FORMAT(2X,'Tox=',F7.2,2X,'Tf=',F7.2,2X,'Hox=',E12.6,/,2X,'Hf=',
1           E12.6,2X,'Hmx=',E12.6)
C
CALL CKHBML (TLO,XMX,ICKWRK,CKWRK,HLO)
IF (ABS((HBMLMX-HLO)/HBMLMX) .LT. RELTOL) THEN
TMX = TLO
GO TO 100
END IF
CALL CKHBML (THI,XMX,ICKWRK,CKWRK,HUPPER)
IF (ABS((HBMLMX-HUPPER)/HBMLMX) .LT. RELTOL) THEN
TMX = THI
GO TO 100
END IF
TMID = (TLO + THI) / 2.0
ITER = 0
C
C begin loop to iterate to convergence of TMX
C
20 ITER = ITER + 1
CALL CKHBML (TMID,XMX,ICKWRK,CKWRK,HMID)
C
WRITE(6,212) ITER, HMID, TMID
212 FORMAT(3X,'ITERATION ',I3,2X,'HMID=',E12.6,2X,'TMID=',F7.2)
C
IF (ABS((HBMLMX-HMID)/HBMLMX) .LT. RELTOL) THEN
TMX = TMID
GO TO 100
ELSE
IF (HBMLMX .LT. HMID) THEN
THI = TMID
TMID = (TMID + TLO) / 2.0
ELSE
TLO = TMID
TMID = (TMID + THI) / 2.0
END IF
GO TO 20
END IF
100 CONTINUE
WRITE (LOUT,*) ' '
WRITE (LOUT,*) '      ITERATIONS TO SUCCESSFUL MIXED TEMP:',ITER,TMX

```

```

      WRITE (LOUT,*) '
      RETURN
      END

C
C-----
C
      SUBROUTINE PSRDRV (LOUT, LINKCK, LSHORT, LINP, LSMOUT,
1                      NMM, NKK, NII, NIK, NATJ,
2                      LENICK, LENCK, ICKWRK, CKWRK, WT,
3                      LENSYM, KSYM, ISYM, NCF,
4                      LENIEQ, LENEQ, IEQWRK, EQWRK,
5                      FUEL, OXID, ADD, STOICH, KPROD, KSP,
6                      ISEN, IROP, IPVT,
7                      XIN, YIN, HIN, X, SCRTCH,
8                      S, SN, F, FN, A,
9                      ACTIVE, ABOVE, BELOW, BUFFER, WNEWTN,
*                      NT, NYS, NY)

C
      IMPLICIT REAL*8 (A-H, O-Z)
      IMPLICIT INTEGER (I-N)

C
      VOLUMES OF BOILER COMPONENTS (cubic cm)

C
      PTUNVL=prim tun volume; STUNVL=combined vol of both sec tunnels;
C      TUBEVL=vol occupied by the OD of the mullite sec air tube where
C      it lies inside the primary tunnel; PLENVL=volume of the rear plenum
C      chamber(actual clean vol=17700, allowance is made for ash);
C      BRIKVL=vol occupied by the brick which supports the mullite tube
C      (actual clean vol=1660, allowance is made for ash).

C
      PARAMETER (PTUNVL=41500.D0, STUNVL=43600.D0, TUBEVL=1900.D0,
1                 PLENVL=16500.D0, BRIKVL=2500.D0)

C
      NNREAC=total number of stirred reactors in the model
C      NPREAC=total number of stirred reactors in the primary tunnel
C      NUMSPC=total number of species in the mechanism

C
      PARAMETER (NNREAC=11, NPREAC=5, NUMSPC=11)

C
      DIMENSION ICKWRK(LENICK), CKWRK(LENCK), WT(NKK),
1                 KSYM(LENSYM,NKK), ISYM(NKK), NCF(NMM, NKK)
      DIMENSION IEQWRK(LENIEQ), EQWRK(LENEQ)
      DIMENSION FUEL(NKK), OXID(NKK), ADD(NKK), STOICH(NKK), KPROD(NKK),
1                 KSP(NKK), XSEC(NUMSPC), XFUEL(NUMSPC), YSEC(NUMSPC)
      DIMENSION TREAC(NNREAC), VOLUME(NNREAC), HEATLS(NNREAC)
      DIMENSION IPVT(NATJ)
      DIMENSION XIN(NKK), YIN(NKK), HIN(NKK), X(NKK), SCRTCH(NIK, 5)
      DIMENSION S(NATJ), SN(NATJ), F(NATJ), FN(NATJ), A(NATJ,NATJ)
      DIMENSION ABOVE(NATJ), BELOW(NATJ), BUFFER(NATJ), WNEWTN(NATJ,7)

C

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DIMENSION LEVEL(2)
C
LOGICAL ISEN(NKK), IROP(NKK)
LOGICAL ACTIVE(NATJ)
C
LOGICAL LENRGY, LFLRT, LEQUIV
LOGICAL LRSTRT, LCNTUE, RSTCNT
LOGICAL LSEN, LSENT, LROP
LOGICAL LPRTIC
C
CHARACTER*18 ISOLUT, ICHR
CHARACTER*4 ETYPE
CHARACTER*7 CONFIG
DATA ISOLUT/'SOLUTION'/
C
DATA LCNTUE/.FALSE./
C
C          COMPUTE THE UNIT ROUNDOFF, AND THE RELATIVE AND ABSOLUTE
C          PERTURBATIONS FOR THE JACOBIAN EVALUATION.
C
U = 1.0
30 CONTINUE
U = U*0.5
COMP = 1.0 + U
IF (COMP .NE. 1.0) GO TO 30
ABSOL = SQRT(2.0*U)
RELAT = SQRT(2.0*U)
C
RSTCNT = .FALSE.
C
C          INITIALIZE CHEMKIN
C
CALL CKINIT (LENICK, LENCK, LINKCK, LOUT, ICKWRK, CKWRK)
CALL CKINDX (ICKWRK, CKWRK, MM, KK, II, LENEL, LENSYM, NFIT)
CALL CKSYMS (LENSYM, ICKWRK, CKWRK, KSYM)
CALL CKWT (ICKWRK, CKWRK, WT)
CALL CKNCF (NMM, ICKWRK, CKWRK, NCF)
CALL CKRP (ICKWRK, CKWRK, RU, RUC, PATM)
C
C          SET THE SOLUTION BOUNDS
C
BELOW(NT) = 200.
ABOVE(NT) = 6000.0E0
DO 40 K=1,KK
    BELOW (NYS+K) = -1.0E-12
    ABOVE (NYS+K) = 1.01
40 CONTINUE
C
C          READ THE INPUT FILE

```



```

90 FORMAT ('REAC O2',2X,F16.14)
      WRITE (LOUT,100) XFUEL(5)
100 FORMAT ('REAC H',2X,E13.7)
      WRITE (LOUT,110) XFUEL(6)
110 FORMAT ('REAC H2',2X,E13.7)
      WRITE (LOUT,120) XFUEL(7)
120 FORMAT ('REAC OH',2X,E13.7)
      WRITE (LOUT,130) XFUEL(8)
130 FORMAT ('REAC H2O',2X,F16.14)
      WRITE (LOUT,140) XFUEL(9)
140 FORMAT ('REAC HO2',2X,E13.7)
      WRITE (LOUT,150) XFUEL(10)
150 FORMAT ('REAC H2O2',2X,E13.7)
      WRITE (LOUT,160) XFUEL(11)
160 FORMAT ('REAC N2',2X,F9.7)

C
C ALL TEMPERARURES ARE OUTPUT IN DEG C
C
      WRITE (LOUT,'(A,2X,F7.2)') 'TFUEL', (TFUEL - 273.15D0)
      WRITE (LOUT,'(A,2X,F5.2)') 'STACK FLOW', STKFLO
      WRITE (LOUT,'(A,2X,F5.2)') 'SEC FLOW', SECFL0
      WRITE (LOUT,'(A,2X,F7.2)') 'TSEC', (TSEC - 273.15D0)
      WRITE (LOUT,*) 'ETYPE: ', ETYPE
      WRITE (LOUT,*) 'CONFIG: ', CONFIG
      WRITE (LOUT,'(A,2X,F5.3)') 'PHI', PHI
      IF (ETYPE .EQ. 'TGIV') THEN
        DO 162 NREAC=1,NNREAC
162     WRITE (LOUT,*) (TREAC(NREAC) - 273.15D0), NREAC
      END IF

C
C SET SECONDARY AIR MOLE FRACTIONS
C
      DO 200 N=1,NKK
200     XSEC(N) = 0.0D0
      XSEC(4) = 0.21D0
      XSEC(11) = 0.79D0

C
C SET REACTOR VOLUMES
C
      IF (CONFIG .EQ. 'SECREAR') THEN
        DO 220 N=1, NNREAC
          IF (N .LE. NPREEAC) VOLUME(N) = PTUNVL/DBLE(NPREEAC)
          IF (N .EQ. (NPREEAC+1)) VOLUME(N) = PLENVL
          IF (N .GE. (NPREEAC+2)) VOLUME(N)=STUNVL/DBLE(NNREAC-NPREEAC-1)
220     CONTINUE
      END IF
      IF (CONFIG .EQ. 'SECTUBE') THEN
        VOLUME(1) = ((PTUNVL-TUBEVL)/DBLE(NPREEAC)) - BRIKVL
        DO 250 N = 2,NNREAC
          IF (N .LE. NPREEAC) VOLUME(N) = (PTUNVL - TUBEVL)/DBLE(NPREEAC)

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      IF (N .GE. (NPREAC+2)) VOLUME(N)=STUNVL/DBLE(NNREAC-NPREAC-1)
250  CONTINUE
      VOLUME(NPREAC+1) = PLENVL
END IF

C
C      SET REACTOR HEAT LOSSES FOR THE ENRG PROBLEM
C
IF (ETYPE .EQ. 'ENRG') THEN
  IF (CONFIG .EQ. 'SECREAR') THEN
    DO 260 N=1,NNREAC
260  HEATLS(N) = 0.0D0
  ELSE IF (CONFIG .EQ. 'SECTUBE') THEN

C
C      calculate heat input to secondary combustion air
C
  CALL CKXTY (XSEC,ICKWRK,CKWRK,YSEC)
  CALL CKHBMS (TSEC,YSEC,ICKWRK,CKWRK,HSCOUT)
  TSECIN = 40.0D0 + 273.0D0
  CALL CKHBMS (TSECIN,YSEC,ICKWRK,CKWRK,HSECIN)
  HTSEC = HSCOUT - HSECIN
  HEAT = HTSEC * SECFL0
C
C      convert from erg/s to cal/s
  HEAT = HEAT * 2.389D-8
C
  DO 270 N=1,NPREAC
270  HEATLS(N) = HEAT / DBLE(NPREAC+1)
  HEATLS(NPREAC+1) = HEAT / DBLE(NPREAC+1)
  DO 280 N=(NPREAC+2),NNREAC
280  HEATLS(N) = 0.0D0
  ELSE
    WRITE (LOUT,*) ' '
    WRITE (LOUT,*) ' '
    WRITE (LOUT,*) '
1     ' FATAL ERROR...CONFIG KEYWORD IMPROPERLY DEFINED'
    WRITE (LOUT,*) ' '
    RETURN
  END IF
END IF

C
FUELFL=(STKFLO-SECFL0)/DBLE(NPREAC)
TAUSUM = 0.0D0

C
C      WRITE HEADINGS TO SUMMARY OUTPUT FILES
C
  WRITE(LSMOUT,*) ' '
  WRITE(LSMOUT,*) ' '
  WRITE(LSMOUT,2) IRUN
2 FORMAT(34X,'REACTOR SUMMARY FOR MODEL RUN NO.',I3)
  WRITE(LSMOUT,*) ' '
  WRITE(LSMOUT,*) ' '

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    IF(ETYPE.EQ.'ENRG') WRITE(LSMOUT,4)
4 FORMAT(40X,'ENERGY EQUATION SOLVED')
    IF(ETYPE.EQ.'TGIV') WRITE(LSMOUT,6)
6 FORMAT(38X,'TEMPERATURE PROFILE GIVEN')
    WRITE(LSMOUT,*) '
    IF(CONFIG.EQ.'SECTUBE') WRITE(LSMOUT,8)
8 FORMAT(29X,'SECONDARY AIR INLET CONFIGURATION : tube inlet')
    IF(CONFIG.EQ.'SECLEAR') WRITE(LSMOUT,10)
10 FORMAT(29X,'SECONDARY AIR INLET CONFIGURATION : rear inlet')
    WRITE(LSMOUT,*) '
    WRITE(LSMOUT,12)
12 FORMAT(T38,'C',T46,'C',T65,'Xinlet',T81,'Xoutlet')
    WRITE(LSMOUT,14)
14 FORMAT(13X,'rctr',T21,'vol',T29,'Qlos',T37,'Tinl',T45'Tout',T53,
1      'Mdot',T63'CO',T71,'CO2',T79,'CO',T88,'CO2',T95,'tau')
    WRITE(LSMOUT,*) '
    WRITE(LSMOUT,16) (TFUEL-273.15D0),FUELFL,XFUEL(1),XFUEL(2)
16 FORMAT(13X,'fuel',T44,F6.1,T52,F5.2,T75,F9.8,T86,F6.5)
    WRITE(LSMOUT,18) (HEAT*-1.),40.D0,(TSEC-273.15D0),SECFLO
18 FORMAT(12X,'sec air',T26,F8.2,T36,F6.1,T44,F6.1,T52,F5.2)

C
C WRITE HEADINGS FOR SHORT OUTPUT FILE
C
        WRITE(LSHORT,22) IRUN
22 FORMAT(///,36X,'TABLE OF COMPOSITION RESULTS FOR MODEL RUN NO.',,
1      I3,/)
        WRITE(LSHORT,23)
23 FORMAT(40X,'mass fractions in and out of each reactor',/)
        WRITE(LSHORT,24)
24 FORMAT(1X,'rctr',T8,'CO',T17,'CO2',T27,'O',T37,'O2',T47,'H',T57,
1      'H2',T67,'OH',T77,'H2O',T87,'HO2',T97,'H2O2',T107,'N2',/)
C
        DO 500 NREAC=1,NNREAC
C
        LKEY = NREAC + 50
        WRITE (LOUT,*) '
        WRITE (LOUT,*) '
        WRITE (LOUT,*) '
        WRITE (LOUT,310) NREAC
        WRITE (6,310) NREAC
310 FORMAT (10X,'REACTOR NUMBER',I4)
        WRITE (LOUT,*) '
        WRITE (LOUT,*) '
        WRITE (LOUT,*) '

C
C SET REACTOR INLET MOLE FRACTIONS AND TEMP FOR REACTORS WITH MIXED INLETS
C
        IF (ETYPE .EQ. 'TGIV') THEN
            IF (CONFIG .EQ. 'SECTUBE') THEN
                IF (NREAC .EQ. 1) THEN
                    CALL MIX (LOUT,LENICK,LENCK,ETYPE,NKK,TFUEL,XFUEL,FUELFL,

```

```

1           TSEC,XSEC,SECFLO,ICKWRK,CKWRK,TIN,XIN,FLRTIN)
1      ELSE IF (NREAC .LE. NPREAC) THEN
1          CALL MIX (LOUT,LENICK,LENCK,ETYPE,NKK,TFUEL,
1                         XFUEL,FUELFL,T,X,FLRT,ICKWRK,CKWRK,TIN,XIN,FLRTIN)
1      ELSE
1          DO 315 N=1,NKK
315      XIN(N) = X(N)
1          TIN = T
1          FLRTIN = FLRT
1      END IF
1      ELSE IF (CONFIG .EQ. 'SECLEAR') THEN
1          IF (NREAC .EQ. 1) THEN
1              DO 317 K=1, NKK
317      XIN(K) = XFUEL(K)
1              TIN = TFUEL
1              FLRTIN = FUELFL
1          ELSE IF (NREAC .LE. NPREAC) THEN
1              CALL MIX (LOUT,LENICK,LENCK,ETYPE,NKK,TFUEL,
1                         XFUEL,FUELFL,T,X,FLRT,ICKWRK,CKWRK,TIN,XIN,FLRTIN)
1          ELSE IF (NREAC .EQ. (NPREAC+1)) THEN
1              CALL MIX (LOUT,LENICK,LENCK,ETYPE,NKK,313.,XSEC,SECFLO,T,X,
1                         FLRT,ICKWRK,CKWRK,TIN,XIN,FLRTIN)
1          ELSE
1              DO 320 N=1,NKK
320      XIN(N) = X(N)
1              TIN = T
1              FLRTIN = FLRT
1          END IF
1      END IF
C
1      ELSE IF(ETYPE .EQ. 'ENRG') THEN
1          IF (CONFIG .EQ. 'SECTUBE') THEN
1              IF (NREAC .EQ. 1) THEN
1                  CALL MIX (LOUT,LENICK,LENCK,ETYPE,NKK,TFUEL,XFUEL,FUELFL,
1                             TSEC,XSEC,SECFLO,ICKWRK,CKWRK,TIN,XIN,FLRTIN)
1              ELSE IF (NREAC .LE. NPREAC) THEN
1                  CALL MIX (LOUT,LENICK,LENCK,ETYPE,NKK,TFUEL,
1                             XFUEL,FUELFL,S(1),X,FLRT,ICKWRK,CKWRK,TIN,XIN,FLRTIN)
1              ELSE
1                  DO 316 N=1,NKK
316      XIN(N) = X(N)
1                  TIN = S(1)
1                  FLRTIN = FLRT
1              END IF
1          ELSE IF (CONFIG .EQ. 'SECLEAR') THEN
1              IF (NREAC .EQ. 1) THEN
1                  DO 318 K=1, NKK
318      XIN(K) = XFUEL(K)
1                  TIN = TFUEL
1                  FLRTIN = FUELFL

```

```

        ELSE IF (NREAC .LE. NPREAC) THEN
          CALL MIX (LOUT,LENICK,LENCK,ETYPE,NKK,TFUEL,
1           XFUEL,FUELFL,S(1),X,FLRT,ICKWRK,CKWRK,TIN,XIN,FLRTIN)
        ELSE IF (NREAC .EQ. (NPREAC+1)) THEN
          CALL MIX (LOUT,LENICK,LENCK,ETYPE,NKK,313.,XSEC,SECFLO,
1           S(1),X,FLRT,ICKWRK,CKWRK,TIN,XIN,FLRTIN)
        ELSE
          DO 321 N=1,NKK
321       XIN(N) = X(N)
          TIN = S(1)
          FLRTIN = FLRT
        END IF
      END IF

C
      ELSE
        WRITE(6,*) ' FATAL ERROR ... ETYPE KEYWORD NOT DEFINED'
C
      END IF

C
C
C  WRITE THE KEYWORD INPUT FILE FOR THIS REACTOR
C
      IF (ETYPE .EQ. 'TGIV') CALL WRTKEY (LKEY,NKK,ETYPE,TREAC(NREAC),
1       FLRTIN,VOLUME(NREAC),0.D0,0.D0,XIN)
C
      IF (ETYPE .EQ. 'ENRG') CALL WRTKEY (LKEY,NKK,ETYPE,TIN,FLRTIN,
1       VOLUME(NREAC),HEATLS(NREAC),TIN,XIN)
C
C
      CALL      PSRKEY (LKEY, LOUT, MM, KK, NATJ, ICKWRK, CKWRK,
1                   LENSYM, KSYM, ISYM, NCF,
2                   LENRGY, LFLRT, LEQUIV, LRSTRT, LCNTRUE, IPRNT,
3                   LSEN, LSENT, ISEN, EPSS, EPST, LROP, IROP, EPSR,
4                   TIN, XIN, T, X,
4                   EQUIV, PATM, PA, P, TAU, FLRT, V, Q,
5                   FUEL, OXID, ADD, STOICH, KPROD, KSP,
6                   ATOL, RTOL, ATIM, RTIM,
7                   NUMDT, DT, NUMDT2, DT2,
8                   LENIEQ, LENEQ, IEQWRK, EQWRK,
9                   SCRTCH, IPVT, SCRTCH(1,1), A,
*                   NT, NYS, NY)

C
      IF (LENRGY) CALL CKHMS( TIN, ICKWRK, CKWRK, HIN)
      CALL CKXTY( XIN, ICKWRK, CKWRK, YIN)
C
      IF (.NOT. LRSTRT) THEN
        CALL CKXTY( X, ICKWRK, CKWRK, S(NY))
        S(NT) = T
      ENDIF

C

```

```

DO 300 N=1,NATJ
  SN(N) = S(N)
300 CONTINUE
C
IF (IPRNT .LT. 10) THEN
  LEVEL(1) = MIN (2, IPRNT)
  LEVEL(2) = LEVEL(1)
ELSE
  LEVEL(1) = IPRNT/10
  LEVEL(2) = IPRNT - 10*LEVEL(1)
  LEVEL(1) = MAX( LEVEL(1), LEVEL(2) )
ENDIF
C
C
C      CALL THE DRIVER TO TWOPNT
C
CALL      PSRTWO (LOUT, KK, NATJ, LENSYM,
1           LENRGY, LFLRT, LEQUIV,
2           LEVEL, ACTIVE,
3           ICKWRK, CKWRK, WT, KSYM,
4           ATIM, RTIM, ATOL, RTOL,
5           TIN, XIN, YIN, HIN,
6           ABSOL, RELAT, ABOVE, BELOW, BUFFER, WNEWTN,
7           IPVT, SCRTCH,
8           T, X, S, SN, F, FN, A,
9           NUMDT, NUMDT2, DT, DT2,
*           P, PA, TAU, FLRT, V, Q, EQUIV,
1           NT, NYS, NY)
C
C      PRINT FINAL SOLUTION, IF NO PRINTING THROUGHOUT ITERATION
C
IF (IPRNT.EQ.0) THEN
  LPRTIC = .TRUE.
  CALL      PSPRNT (KK, NATJ, LOUT, LENSYM, KSYM,
1           LENRGY, LFLRT, LEQUIV, LPRTIC,
2           EQUIV, PA, P, TAU, FLRT, V, Q,
3           TIN, XIN, T, X, S, ICKWRK, CKWRK,
1           NT, NYS, NY)
ENDIF
C
C      WRITE TO THE SUMMARY OUTPUT FILE
C
IF(ETYPE .EQ. 'ENRG') THEN
  WRITE(LSMOUT,410) NREAC,V,Q*2.389E-8,(TIN-273.15D0),
1  (S(NT)-273.15D0),FLRT,XIN(1),XIN(2),X(1),X(2),TAU*1000.0D0
410 FORMAT(13X,I3,T19,F6.0,T26,F8.2,T36,F6.1,T44,F6.1,T52,F5.2,T58,
1        F9.8,T69,F5.4,T75,F9.8,T86,F6.5,T94,F6.2)
  ELSE
    WRITE(LSMOUT,410) NREAC,V,Q*2.389D-8,0.0D0,
1  (T-273.15D0),FLRT,XIN(1),XIN(2),X(1),X(2),TAU*1000.0D0

```

```

END IF
C
C WRITE TO THE SHORT OUTPUT FILE
C
        WRITE(LSHORT,417) NREAC, (YIN(K), K=1,NKK)
        WRITE(LSHORT,419) (S(K+1), K=1,NKK)
 417 FORMAT(1X,I2,11(1X,E9.4))
 419 FORMAT(3X,11(1X,E9.4),/)

C
        TAUSUM = TAUSUM + TAU
C
        IF (LSEN .OR. LSENT) THEN
C
            CALL    PSRSEN (LOUT, KK, II, NATJ,
1                  LENSYM, KSYM, LENRGY, LFLRT,
2                  ABSOL, RELAT, DT, WT, HIN, YIN, TIN,
3                  P, TAU, FLRT, V, Q, T,
4                  S, SN, F, FN, A,
5                  LSEN, LSENT, ISEN, EPSS, EPST,
6                  ICKWRK, CKWRK,
7                  IPVT, SCRTCH,
8                  NT, NYS, NY)
C
            IF (LEVEL(2) .GT. 0) THEN
                WRITE (LOUT,*) '
                WRITE (LOUT,*) ' SENSITIVITY CALCULATION COMPLETE'
                WRITE (LOUT,*) '
            ENDIF
C
            ENDIF
C
            IF (LROP) THEN
C
                CALL    PSRROP (LOUT, KK, II, NATJ,
1                  LENSYM, KSYM, P, S,
2                  ICKWRK, CKWRK,
3                  LROP, IROP, EPSR,
4                  SCRTCH(1,1), SCRTCH(1,2), SCRTCH(1,3),
5                  NT, NYS, NY)
C
                IF (LEVEL(2) .GT. 0) THEN
                    WRITE (LOUT,*) '
                    WRITE (LOUT,*) ' RATE-OF-PRODUCTION CALCULATION COMPLETE'
                    WRITE (LOUT,*) '
                ENDIF
C
                ENDIF
C
                500 CONTINUE
C

```

```
      WRITE(LSMOUT,*) ' '
C      WRITE(LSMOUT,510) TAUSUM*1000.0D0
 510 FORMAT(25X,'Total residence time :',F7.2,' ms')
C
C      RETURN
      END
```

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the scanned document**