# STUDY OF BIOMASS COMBUSTION CHARACTERISTICS FOR THE DEVELOPMENT OF A CATALYTIC COMBUSTOR/GASIFIER

by

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Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Mechanical Engineering

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October, 1985
Blacksburg, Virginia

# ACKNOWLEDGEMENTS

# TABLE OF CONTENTS

Appendix

# LIST OF FIGURES

vi

# LIST OF FIGURES
## (Continued)

## LIST OF FIGURES
### (Continued)

# LIST OF FIGURES
## (Continued)

# LIST OF FIGURES
## (Continued)

LIST OF FIGURES
(Continued)

xi

xii

LIST OF FIGURES ·
(Continued)

xiii

# LIST OF FIGURES
## (Continued)

# LIST OF TABLES

# Chapter I

## INTRODUCTION

Biomass is becoming an increasingly attractive alternative to traditional fossil fuels. In order to be economical though, biomass fuels must be used locally. This implies that biomass fuels are most appropriate for rural wooded and agricultural regions. This is not a serious limitation, however, since often there are many applications for process heat in or near such areas. Some examples are dyeing and drying textiles, crop drying, and heating of chicken houses.

The most serious limitation to the use of biomass fuels for small-scale[1] process heat applications is a lack of economical, clean-burning conversion processes. If not completely burned, biomass combustion products can foul heat exchangers and other equipment and are polluting.

The conversion processes most frequently used today are direct combustion and gasification. In direct combustion processes the fuel must be burned at elevated temperatures in order to achieve relatively clean combustion products. This approach works well when it is not necessary to control the power output. Unfortunately, there are many applications which require control (e.g., the chicken house).

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[1] Small-scale in this report refers to combustors and gasifiers capable of delivering maximum output power in the range between 100 and 500 kW.

1

Gasification is the heating of solid fuels in the absence of oxygen in order to drive off higher grade, clean-burning gaseous fuels. The "producer" gases can then be used in applications such as those already mentioned. Gasification processes were commonly used at the turn of the century but became uneconomical with the availability of inexpensive fossil fuels. With the rising cost of fuel in recent years though, gasification processes are once again becoming economical. However, since gasification requires more sophisticated equipment than direct combustion its use has been limited to the larger-scale operations. Note also that most gasifiers are not omnivorous (i.e., capable of operating effectively for a wide variety of biomass fuels).

The research reported here explores a "new" approach to biomass energy conversion for small-scale process heat applications. The conversion process uses close-coupled, catalytic combustion to burn combustibles in effluent generated by primary combustion or gasification of biomass fuels. Although catalysis is not a new concept, its widespread use in small-scale combustion processes is new. In the past 15 years catalysts have been developed to control automobile exhaust emissions; and even more recently, within the past 5 years, catalysts have been developed for woodstoves. This research is the first step in an attempt to develop a catalytic combustor/gasifier [2] for biomass fuels.

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[2] The distinction between direct combustion and gasification is not always clear. Depending on fuel-type and on operating conditions the primary combustor/gasifier at times behaves like a combustor and at other times, more like a gasifier--hence the name, combustor/gasifier.

The proposed catalytic combustor/gasifier is shown schematically in Figure 1. Major components of the system are: a fuel magazine, a primary combustion/gasification zone, and a secondary, catalytic combustion zone. The combustion rate (i.e., the output power) is controlled by intelligent (microprocessor) control of the primary air flow without concern for the completeness of combustion. The role of the secondary catalytic combustor is then to "clean-up" the products of primary combustion/gasification utilizing catalyst technology developed recently for the woodstove industry. Secondary air, also microprocessor controlled, is added as necessary to provide enough oxygen to achieve complete combustion. The amount of secondary air required is dependent on the extent to which the combustor/gasifier behaves as a gasifier. Control of the secondary air is based on feedback signals from automobile exhaust gas oxygen sensors.

The catalytic combustor/gasifier, as described above, appears to be both feasible and economical with the development of microprocessor, woodstove catalyst, and automobile exhaust gas oxygen sensor technologies. It promises to not only be clean burning, but to also be energy efficient, omnivorous, and able to operate unattended for long periods of time. These features, coupled with the widespread availability of biomass, make the catalytic combustor/gasifier a device with great potential value.
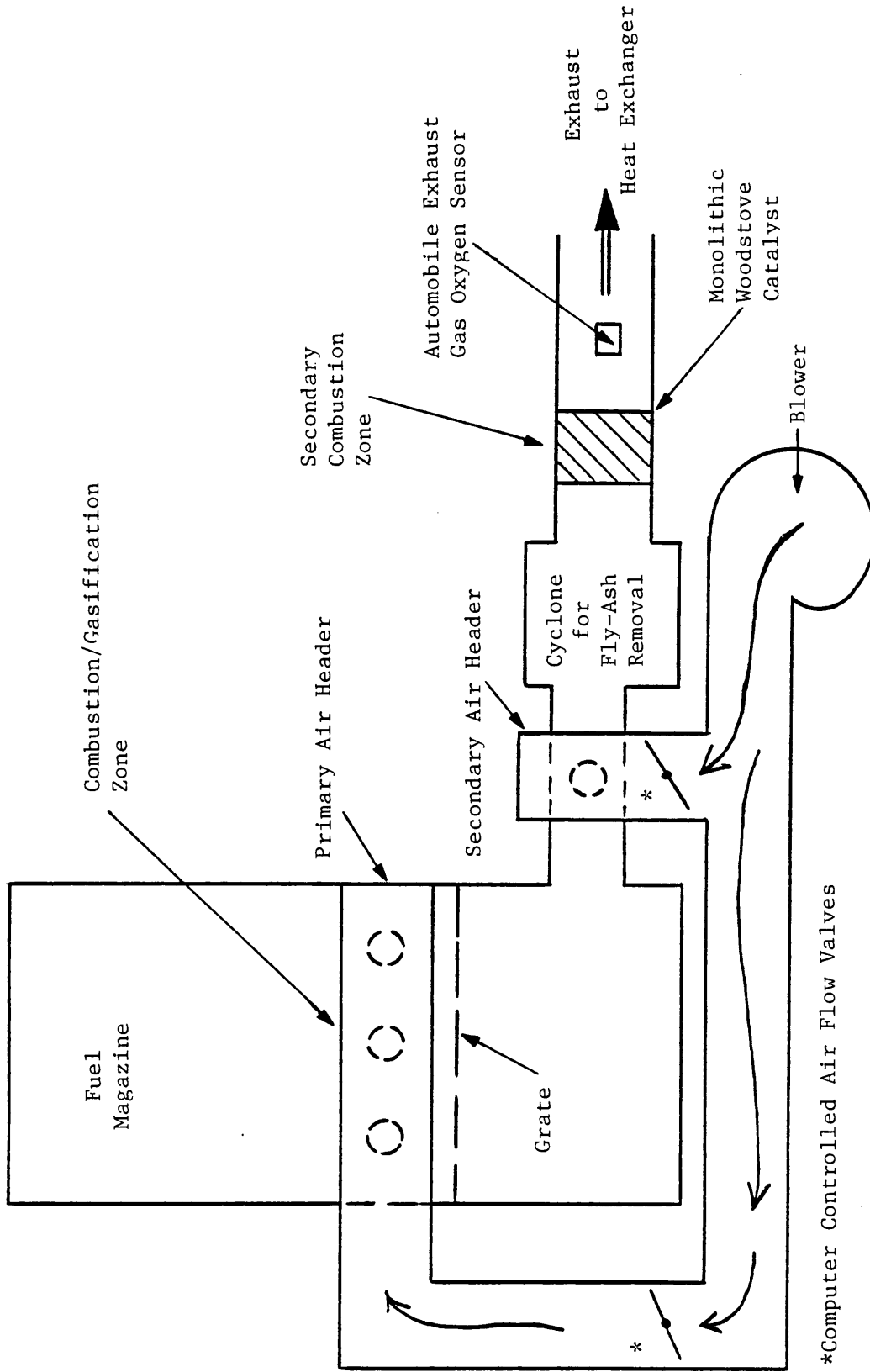
Figure 1  Schematic of Catalytic Combustor/Gasifier

*Computer Controlled Air Flow Valves

The objective of the research reported in this thesis was to develop and evaluate the performance of a small-scale prototype of the catalytic combustor/gasifier. The following steps were taken:

1.  a prototype (small-scale--approximately 50 kW maximum output power) combustor/gasifier was built and instrumented,

2.  the combustion characteristics of three biomass fuels--cordwood, baled slash (refuse remaining after a logging operation), and corn fodder--were studied so that primary and secondary air flow control strategies could be devised,

3.  several automobile exhaust gas oxygen sensors were tested to determine their ability to adapt to the combustion environment of biomass fuels,

4.  primary and secondary air flow control strategies were devised and implemented,

5.  woodstove catalysts were installed in the prototype to facilitate secondary combustion, and finally,

6.  the performance of the prototype was evaluated using each of the test fuels.

# Chapter II

# LITERATURE REVIEW

This literature review is divided into three sections. Section 2.1 reviews two approaches currently used to harness the energy available in biomass fuels: direct combustion and gasification. Sections 2.2 and 2.3 review woodstove catalyst and automobile exhaust gas oxygen sensor technologies respectively. The recent development of these technologies and microprocessor technology have made the catalytic combustor/gasifier feasible. Microprocessor technology is not reviewed since its use is so common.

## 2.1    CONVERTING BIOMASS FUELS INTO USABLE ENERGY

### 2.1.1    Direct Combustion Processes

Direct combustion is the simplest approach to harnessing bio-energy. Therefore, it is no surprise that direct combustion processes make the most significant contribution to the total U.S. bio-energy balance (1). Applications range from residential woodstoves to 50 MW cogeneration plants.

The combustion process, a series of time and temperature dependent chemical reactions, is very complex. Biomass does not actually burn directly; rather, a two-stage process occurs. In the first stage the fuel must be heated in order to form and drive off combustible gases. This process is known as pyrolysis. In the second stage the gases

generated by pyrolysis oxidize (i.e., burn) and release energy. Heat from the burning gases causes more gases to be pyrolyzed and the cycle continues.

More precisely, pyrolysis is chemical decomposition by the action of heat in the absence of oxygen. As biomass fuels are heated they undergo the following changes (2):

The first effect of the addition of heat is that moisture is driven off. During this period the fuel may reach $100^{\circ}C$. Once most of the moisture is evaporated the fuel temperature begins to rise above $100^{\circ}C$ and a variety of compounds begin to be driven off: carbon dioxide, carbon monoxide, small amounts of water and many other compounds. Although the first gases given off contain combustibles, the gases are not flammable (ignitable) because they are so heavily diluted with non-combustible gases. As the fuel temperatures continue to rise (to above $280^{\circ}C$ for wood) exothermic reactions begin to occur and large quantities of gases are generated: carbon monoxide, methane, methanol, formaldehyde, hydrogen and others. Tiny liquid tar droplets are carried off with the gases as well. The final product after pyrolysis is complete (at about $500^{\circ}C$ for wood) is charcoal. Charcoal is stable to very high temperatures and thus oxygen must come in contact with its surface in order for it to burn.

The preceding description of pyrolysis is actually oversimplified. The types of products driven off are dependent on the rate at which pyrolysis is made to occur. Also, since many biomass fuels are burned as large pieces (e.g., cordwood) heating is not uniform and "secondary" pyrolysis reactions occur (e.g., water vapor being released from the cooler interior of a piece of fuel may react with char at the surface to form carbon monoxide and hydrogen gases).

The gases generated by pyrolysis (once most of the non-combustibles have been driven off) typically ignite at temperatures around $600^{o}C$ and burn at temperatures around $1100^{o}C$.

In summary, direct combustion of biomass is complex. Characteristics of combustion depend on fuel parameters and the rate at which combustion occurs. Important fuel parameters are chemical composition, moisture content, and surface to volume ratio.

The most significant drawback to direct combustion processes is that often incomplete combustion occurs resulting in air pollution and fouling of heat exchangers and other equipment. Typical pollutants are carbon monoxide, unburned hydrocarbons, and particulates. Beyond the obvious visual effects of such pollutants, investigations have shown that some of the hydrocarbons formed are carcinogenic.

Note though, that when complete combustion is achieved biomass fuels have very little negative impact on the environment. Since the combustion of biomass essentially only speeds up and harnesses the

chemical processes which occur naturally during decomposition there is no net influx of carbon dioxide or energy into the environment and no net reduction of oxygen. Also, unlike fossil fuels, biomass fuels contribute very little to sulfur and nitrogen oxide emissions.

Two approaches are typically taken to control emissions. The first approach uses elevated combustion temperatures to encourage complete combustion while the second uses one or more of a variety of pollution control devices such as thermal incinerators, catalytic combustors, cyclones, etc.

For small-scale process heat applications elaborate pollution control equipment is not economically feasible. Thus, most current small-scale direct combustion units either rely on elevated combustion temperatures or ignore the problem. Farmers, the agricultural processing industry, and the forest products industry have recently begun to aggressively utilize their "waste" biomass by-products in such small-scale direct combustion units.

A typical example is Rosendahl Farms, Inc. of Fresno, California (1). Rosendahl Farms grows grapes and processes them into raisins with a dehydration process. Recently, Rosendahl installed a 4 MW moving grate, biomass combustor to decrease their consumption of natural gas. Other advantages are: 1) the combustion system, which includes some air pollution control equipment, decreases air pollution since it reduces open-field burning of prunings, and 2) removal of prunings from the fields reduces the potential for plant diseases. Since

there are two million tons of orchard and vineyard prunings generated yearly in California alone such a combustor has great potential.

Combustion systems similar to the Rosendahl system are being developed to burn cotton gin trash, peach pits, soybean residue, corn fodder, and other biomass fuels (1). The drawback to such systems is that since they must maintain elevated combustion temperatures it is very difficult to control the rate at which power is delivered. For applications requiring constant power output this is not a significant drawback. However, there are many process heat applications that require control of the output power.

Richard Hill, from the University of Maine, developed a non-catalytic, clean burning small-scale combustor to be used in conjunction with a water heat storage system in 1979 (3). Today, versions of the combustion/heat storage system are being manufactured and sold in the U.S. and Canada. The key to the system is that the wood combustion process is separated from the thermal energy distribution process by using a water filled energy storage tank. The water in the tank is heated with short "bursts" of energy delivered by burning batch loads of fuel in a highly efficient combustor. The forced draft system uses high temperatures and turbulence to achieve complete combustion. Clean combustion products are particularly important for this application in order to avoid fouling of the exhaust-to-water heat exchanger. The energy is later distributed as needed with a water-to-air heat exchanger or a hot water baseboard or radiator system.

In recent years the woodstove industry has revived. Concern about pollutants and creosote formation have motivated the development of cleaner burning residential woodburning appliances. The most promising development has been the development of a woodstove catalyst by Corning (reviewed in Section 2.2). This development was the primary motivation for the initation of this research--the development of a catalytic combustor/gasifier for small-scale process heat applications. Woodstove catalysts were used on the prototype.

### 2.1.2    Gasification Processes

Gasification processes convert solid fuels into higher grade, clean burning gaseous fuels. The "producer gas" is in turn used in internal combustion engines, furnaces and boilers, direct fired heaters and dryers, and gas turbines.

Gasification is the heating of the solid fuel in the absence of oxygen to drive off a mixture of non-condensible gases (carbon monoxide, carbon dioxide, hydrogen, and hydrocarbons), liquids, tars, and charcoal. The energy required to drive the gasification can either be provided by an outside source or by partial combustion of the biomass feedstock. The former produces a high grade gas while partial combustion produces either medium or low grade products depending on whether pure oxygen or air is used to stimulate combustion.

There are many variations to the gasification theme: different combustor designs, steam injection, differing air and steam inlet flow rates, pressurization, etc.. By controlling these parameters one is able to control the types of products produced and is able to optimize the processes. Much research has been and continues to be conducted on gasification at both applied and theoretical levels (1 and 4). Some gasifiers produce gas to be stored and transported while others are "close-coupled" to combustors which burn the gas as it is generated. Since the catalytic combustor/gasifier most closely resembles smaller-scale versions of the latter the remainder of this review will focus on gasifiers of that type.

In recent years researchers at Georgia Tech have been heavily involved in applied gasifier research (5). In 1980 they completed construction of a pilot plant, updraft wood gasifier (6). Some of the first tests conducted with the gasifier evaluated its potential for providing gas that would burn cleanly enough to be used for direct drying[3] of textiles (7). A furnace and hot gas takeoff system were designed, built, and connected to a modified textile drying oven. Textiles were dried in the modified oven and compared to textiles which had been dried with electrically heated air. It was found that the textiles could be dried by the direct firing of wood gas without significantly affecting quality.

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[3] Direct drying refers to the use of exhaust gases in direct contact with the product needing drying (textiles, crops, etc.), thereby eliminating the need for heat exchangers.

In future tests Georgia Tech intends to produce baseline data for air and steam addition and to quantify the effect these parameters have on the chemical composition of the gasifier output, the fuel consumption rate, and bed temperatures. Following this effort they intend to develop application programs where the off-gas will be used in internal combustion engines, gas turbines, boilers, dryers, and kilns.

Researchers at the University of Kentucky have also recently developed a two-stage gasification/combustion process (8). Their process converts corncobs into thermal energy for drying grain. Fuel is gasified in the first stage; then the gases are transfered to a secondary combustion chamber where additional air is added to complete the combustion of the gas. The exhaust is then mixed with outside air at a ratio of approximately 1:20 (mass basis) and forced through the grain for drying. Thermal efficiencies of 70-80 percent were reported for the system and the exhaust gases were sufficiently clean for direct drying. This gasifier/combustor accomplishes many of the objectives of the catalytic combustor/gasifier except that it is not omnivorous.

The distinction between direct combustion and gasification is not always clear. Depending on fuel-type and on operating conditions, the catalytic combustor/gasifier at times behaves like a combustor and at other times more like a gasifier. When the combustor/gasifier behaves as a combustor the effluent entering the secondary, catalytic combustor is fuel-lean and the catalyst functions primarily as a pollution control

device. On the other hand, when the combustor/gasifier behaves as a gasifier the effluent is fuel-rich and the secondary combustion system (catalyst and secondary air) serves to convert the gasification off-gas into usable thermal energy.

To the author's knowledge no one has yet explored the use of close-coupled, catalytic combustion to burn combustibles in effluent generated by primary combustion or gasification of biomass fuels for small-scale process heat applications.

## 2.2    WOODSTOVE CATALYSTS

### 2.2.1    Development of Woodstove Catalysts

With the rising cost of traditional fuels over the past decade woodstove usage has increased markedly (9). Air pollution has become a significant concern in many areas of the country (10). The problem has been exacerbated by the resurgence of air-tight stoves which control the burning rate by controlling the air flow into the stove. Although thermal efficiencies are increased, a typical stove often burns (smolders) at low firing rates with high emissions. Not only is air quality degraded (reduced visibility, odor, soiling), but long-range health effects may also result. Particulate and POM (polycyclic organic matter) emissions are of particular concern since many of the chemicals classified as POM are known to be carcinogenic (11). Creosote-forming volatiles are another concern since they tend to accumulate on stove pipe walls and can then pose fire hazards.

Woodstove catalysts were developed by Corning in the late 1970's (12). A typical woodstove catalyst is shown in Figure 2. The effectiveness of woodstoves equipped with Corning catalytic combustors have been tested in their laboratories and in independent laboratories (13, 14). Corning claims to be able to achieve 70 to 90 percent reductions in condensable volatiles at burn rates of 10 pounds of wood an hour and below, 76 percent reductions of POMs and 90 percent reductions of non-POM organic material, and increases in overall stove efficiencies of up to 20 percentage points (15).

## 2.2.2 Operating Principles of Woodstove Catalysts

Oxidation catalysis is "basically the chemical union of hydrocarbons and oxygen and their conversion to carbon dioxide and water. The reaction involves the absorption of oxygen in a highly activated state and the absorption of combustible vapor onto a catalyst surface where oxidation takes place. The catalytic agent increases the speed of the oxidation reaction and remains unaltered in the process."(16) The catalyst also decreases the temperature at which the combustible gases burn. Typical woodstove catalytic combustors reduce the temperature required for wood smoke to burn by approximately $260^{o}C$. As the combustible gases burn, the heat released raises the catalyst temperature and increases the catalytic activity.

Several factors strongly influence catalytic action: flue gas temperatures, oxygen availability, residence time at the catalyst, and

14.5 cm

5 mm

1 mm

Depth = 5.0 cm

Note: Not to Scale
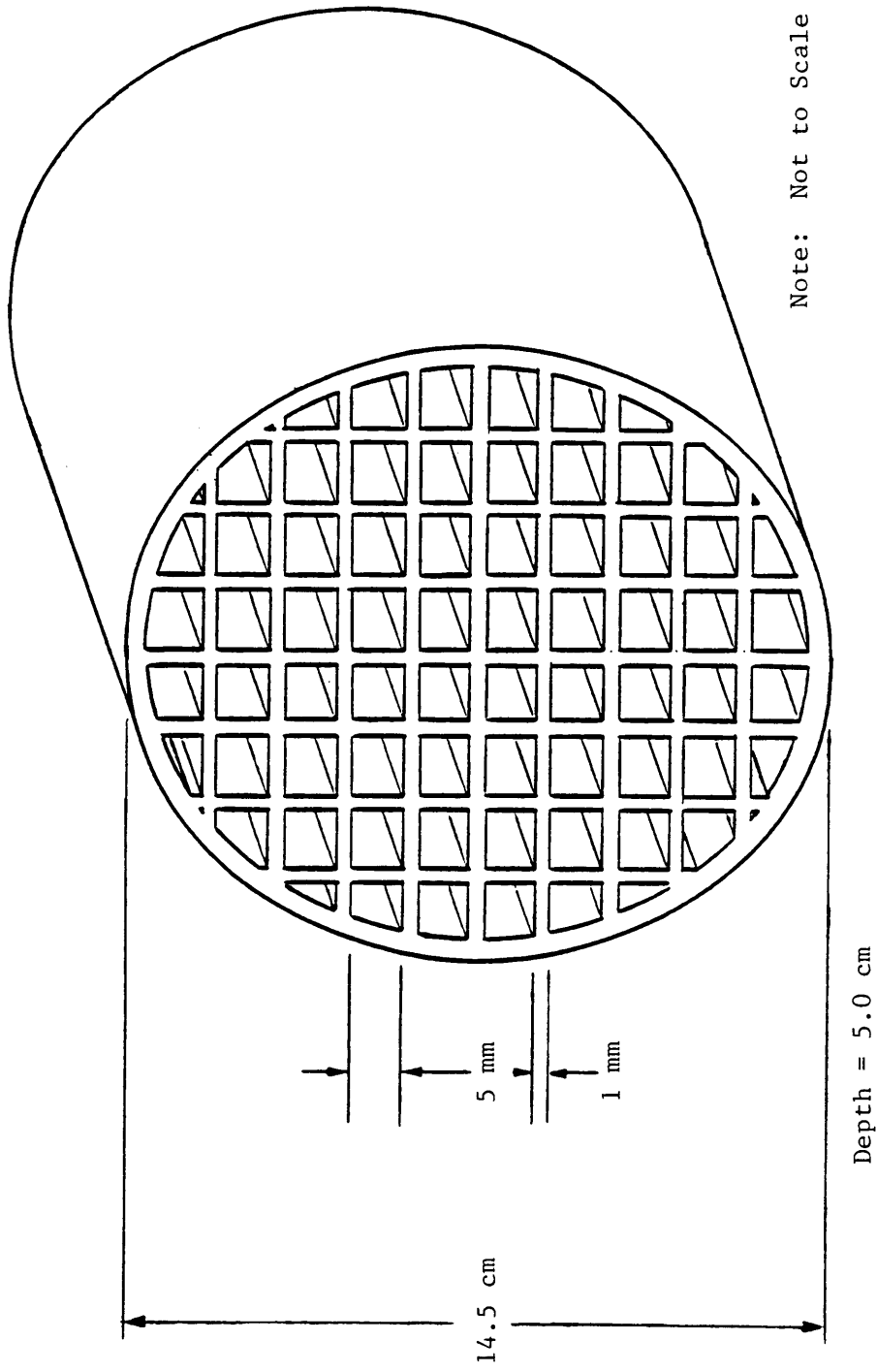
Figure 2  Monolithic Woodstove Catalyst

proper mixing of the combustible gases with combustion air (17). These factors are so significant that many attempts to utilize woodstove catalytic combustors have failed due to inappropriate stove designs (16).

Very little is known about the conditions within the passages of typical woodstove catalysts. Jaasma and Hall have begun to develop a fundamental understanding of the processes which occur within the passages (18,19). They developed a very simple, two-dimensional, single-phase flow, low chemical energy content model and conducted experiments to validate their model. They see their work as a first step toward the eventual development of a three-dimensional, multi-phase flow, high chemical energy content model. They claim, based on literature values for soot and carbon oxidation rates, that significant catalytic oxidation of particulates is unlikely; and suggest that the large reported reductions of particulate emissions is due to catalytic oxidation of vapor-phase condensable organics rather than direct combustion of particles.

## 2.2.3    Description of Woodstove Catalysts

Catalysts consist of three components:  a support structure, a carrier, and the precious metal. This is illustrated in Figure 3. The support structure, or substrate, is typically a ceramic material. Ceramics are used because they are stable at high temperatures. In recent years honeycomb support structures have been preferred over

Carrier

Precious Metal (catalyst)

Support Structure
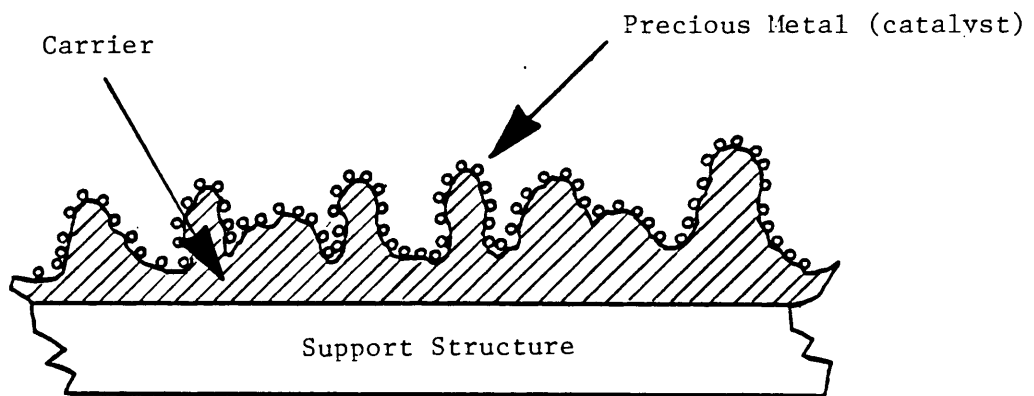
Figure 3   Schematic of Catalyst Components

conventional pellet support (20). The major advantages for honeycombs are: fast warm-up, lower pressure drops, good shock and vibration properties, and no attrition losses (loss of precious metal as pellets rub against each other). Since ceramics can be extruded the honeycomb structures can be manufactured in a variety of shapes, sizes, and cell densities. The Corning woodstove catalytic combustor, shown in Figure 2, is based on a honeycomb ceramic structure.

The carrier, or wash coat, is an inert substance deposited on the support structure. Its role is to increase the surface area exposed to the exhaust gases and maintain a dispersion of the precious metal. Alumina is often used because of its unique phase transformation properties. Its melting temperature is $1410^{o}C$. Although many chemical elements have catalytic activity, the precious metals have proven to be the most active and durable catalysts for pollution control applications (20). The most commonly used precious metals are platinum, palladium, and rhodium.

## 2.2.4    Potential Problems/Concerns

There are several concerns and limitations associated with the use of catalysts: poisoning, masking, plugging, substrate failure, thermal ageing and extreme temperatures.

A catalyst becomes "poisoned" when non-catalytic alloys are formed from the precious metals. Lead, zinc, phosphorus, and sulfur are typical "poisons". Although wood (or any biomass fuel) is essentially

free from "poisons", care must be taken to ensure that other materials such as manures, garbage, trash, treated or painted wood, coal, inked paper, and chemical fire starters are not allowed to "poison" the catalyst.

Masking is the accumulation of organic char, dust, ash, and/or metal oxides on the catalyst surface, reducing its activity. Combustible masking materials can be removed by raising the catalyst temperature for a short period. Other "masks" can be removed with high velocity air or by leaching.

Factors which influence plugging are catalyst cell density and burning conditions. Corning has determined that optimal cell densities for their 5 and 7.5 cm deep catalysts respectively are 4 and 7.5 cells per square cm. Shelton (21) has studied the effect of different catalytic combustion geometries on catalytic combustion efficiency and plugging. He constructed three constant-area but different density combustors each from 26 catalyzed metal plates and tested them in a modified Riteway Model 37 stove. The first combustor consisted of one 26-plate layer; the second of two 13-plate layers; and the third of two 9-plate layers and one 8-plate layer. He found that the more dense, single layer configuraiton was more efficient but also more susceptible to plugging. He also investigated and recommends the use of bypass systems in the design of appliances using catalytic combustors.

The ceramic substrate of a catalyst may fail (i.e., crack) due to thermal cycling. Catalysts are often "canned" (a thin stainless steel

band, equal in width to the catalyst width is wrapped tightly around the catalyst and welded in place) to provide extra support. Then, even if the catalyst cracks it will hold together and continue functioning as normal.

Thermal aging is a sintering process. The precious metal is deposited originally on its carrier as very fine particles. With time and temperature though, the particles agglomerate, reducing the activity of the catalyst (activity is reduced due to the reduction in catalyst surface area exposed to the exhaust stream). The rate of aging corresponds directly to the average temperature of the catalyst. Catalysts consistently run at higher temperatures age more quickly than those run at lower temperatures. Temperatures consistantly in excess of $1000^{o}C$ will accelerate the sintering process. Catalyst life is also a function of the amount of precious metal initially deposited. Average woodstove catalysts are claimed to last 6000 hours. Ageing is most pronounced during the first 100 hours of operation.

### 2.2.5    Achieving and Maintaining Catalytic Combustion

As described previously, there are minimum temperature requirements (reduced when using catalysts) for the combustion of wood smoke. In order to "light-off" a catalytic combustor it is necessary to achieve exhaust gas inlet temperatures of at least $260^{o}$ to $320^{o}C$. As the catalyst ages the "light-off" temperature increases.

Catalytic combustion can be maintained with exhaust gas inlet temperatures less than 260°C since catalytic combustion of the gases generates heat. Extremely low fires, or poor placement of the catalytic combustor may cause catalytic combustion to cease however. Whenever fuel charges are changed it is important to ensure the continuation of both firebox combustion and catalytic combustion by firing the new load at a moderate to high rate for a short period of time (10-15 minutes).

In order to achieve complete combustion, provision must be made to supply adequate oxygen to the exhaust entering the catalyst if it has become fuel-rich. Secondary air should be supplied in a way that encourages mixing.

Although not used in this investigation, catalyst technology developed for other emission control applications may be applicable to biomass applications. The recent development of automobile exhaust catalysts in particular has provided a wealth of valuable information (22-29).

## 2.3  AUTOMOBILE EXHAUST GAS OXYGEN SENSORS

In the past 20 years considerable effort has been expended by the automobile industry to develop engine control systems to meet emission standards. Most manufacturers today use closed-loop control of fuel-air ratios in conjunction with three-way catalysts to control emissions. In most cases the feedback signal for control of the fuel-air mixture is provided by zirconia exhaust gas oxygen sensors.

## 2.3.1  Development of the Zirconia Exhaust Gas Oxygen Sensor

Fuel-air ratio affects engine power output, fuel economy, and vehicle driveability as well the efficiency of catalytic emission control devices. Three-way catalytic conversion is most effective for fuel-air ratios near stochiometric. Fortunately, the stoichiometric fuel-air ratio is also appropriate for other engine operation considerations.

Closed-loop control systems have been developed to maintain fuel-air ratios within a narrow band about the stochiometric point. Electronic control using feedback signals from an exhaust gas oxygen sensor meters stoichiometric fuel-air mixtures to the engine.[4] Although other emission control schemes have been proposed, the closed-loop feedback control system has been adopted because it requires no calibrations (as open-loop control systems would) and can accurately provide appropriate fuel-air mixtures for a wide range of operating and environmental conditions.

Figure 4 shows the characteristic output curve of the zirconia type sensor. It is particularly well suited for fuel-air ratio control about the stoichiometric point since there is a clear voltage output distinction between fuel-rich and fuel-lean mixtures. In the overall control strategy the sensor acts as a switch indicating either fuel-rich or fuel-lean.

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[4] It is possible to use exhaust gas analysis for fuel-air ratio control since the exhaust gas composition is dependent on the pre-combustion fuel-air ratio.
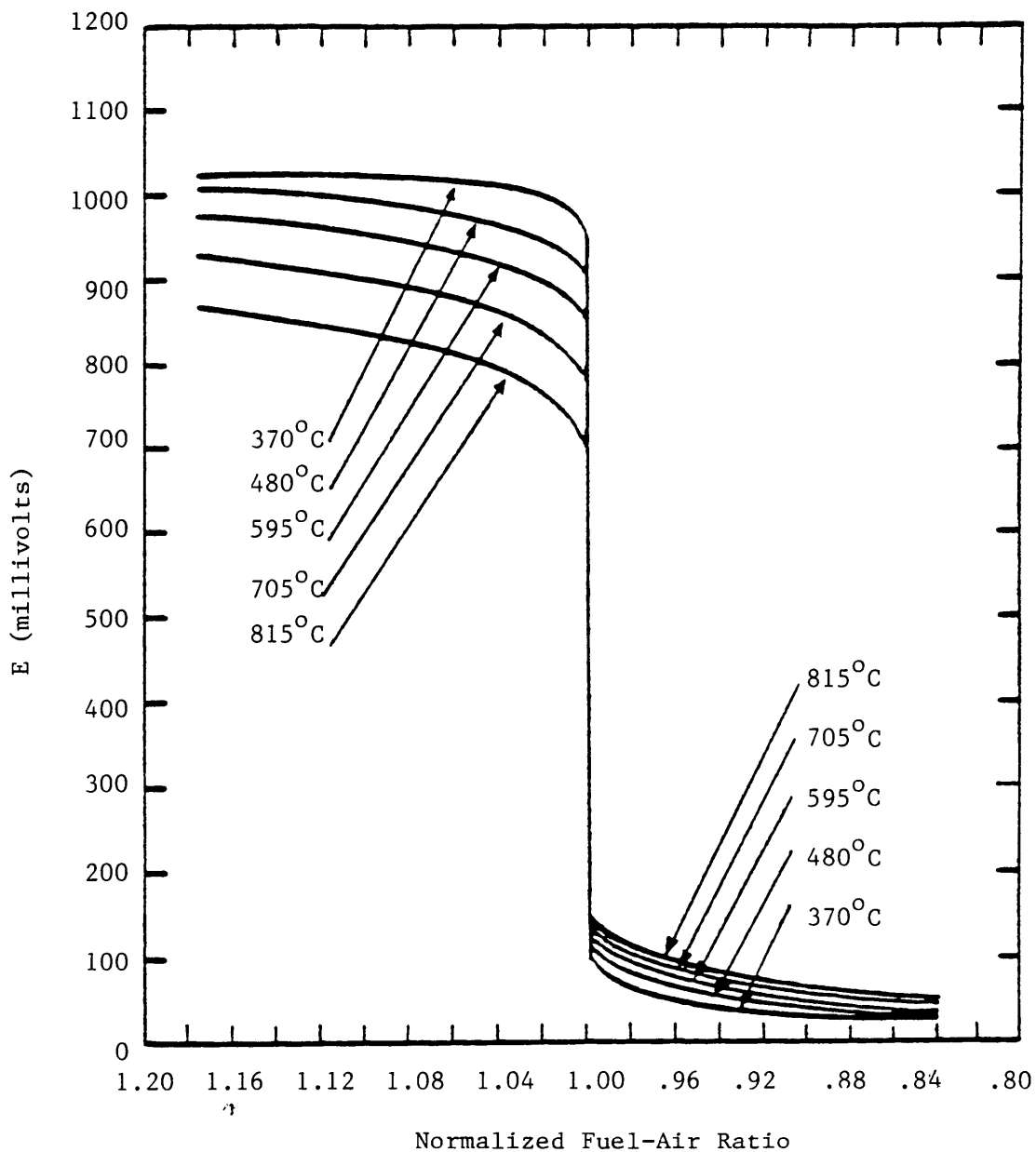
Figure 4  Theoretical Galvanic Potential of the Zirconia Exhaust Gas
Oxygen Sensor vs Normalized Fuel-Air Ratio (adapted from
ref. 30)

## 2.3.2 Operating Principles of the Zirconia Exhaust Gas Oxygen Sensor

Zirconia exhaust gas oxygen sensors are galvanic devices. Ceramic zirconia dioxide tubes, closed at one end, function as the electrolyte (see Figure 5). The electrodes of the galvanic cell are formed by coating both the inside and outside of the ceramic tube with fine layers of porous platinum. The closed end of the sensor is exposed to exhaust gas while the inside of the probe is exposed to ambient air.

Operation of the zirconia sensor is based on electrochemical principles (30). A galvanic potential is established between the inner and outer electrodes corresponding to the difference between the partial pressures of oxygen at the two electrodes. Since the partial pressure of oxygen in air is constant and the partial pressure of oxygen in the exhaust is a function of the exhaust composition the galvanic potential changes as the fuel-air ratio is varied.

The theoretical galvanic potential is given by the Nernst equation:

$$E = [RT/(4F)] * \ln(P1/P)$$

where:      E = the sensor signal in millivolts,

R = the gas constant,

T = absolute temperature,

F = the Faraday constant,

P1 = the partial pressure of oxygen in ambient air, and

P = the partial pressure of exhaust gas oxygen.

Notice that the output voltage is a function of temperature as well as fuel-air ratio (see also Figure 4).

Exhaust Pipe Wall

Platinum Electrodes

+
−

Ambient Air

Zirconia Ceramic Tube
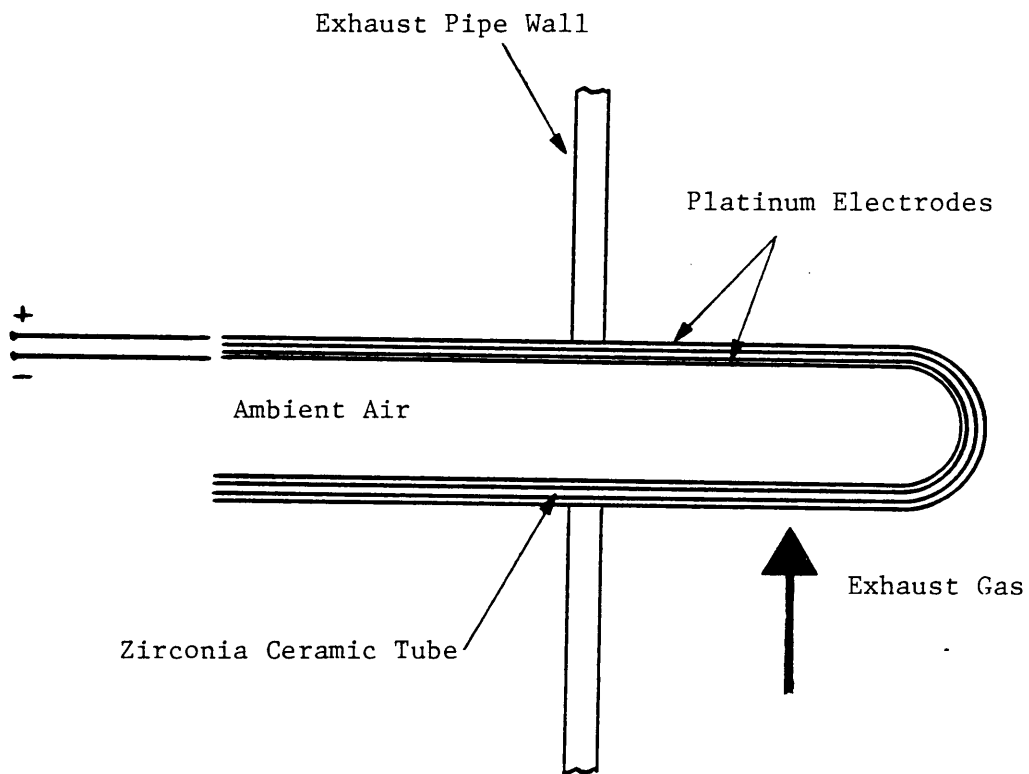
Exhaust Gas

Figure 5   Schematic of Zirconia Exhaust Gas Oxygen Sensor
            (adapted from ref. 30)

It should be noted that the platinum surface on the exhaust gas side of the sensor also functions as a catalyst, promoting complete combustion of the exhaust gases at the electrode surface. Without being able to assure a stable equilibrium amoung the exhaust gases the oxygen measurement would be insignificant.

A drawback to the use of zirconia as an oxygen ion electrolyte is that significant ionic conductivity does not occur until the zirconia material is heated to temperatures exceeding approximately $400^{\circ}C$ (30). As zirconia is heated its crystalline structure changes from monoclinic to cubic. It is these cubic structures which have the ability to conduct oxygen ions. The temperature limitation for the automobile fuel-air ratio control application is not severe since exhaust gas temperatures typically range between $400^{\circ}C$ and $900^{\circ}C$. It does however influence where the oxygen sensor is located in the exhaust stream. In order to achieve early light-offs for cold starts the exhaust gas sensor is placed as far upstream as possible. This placement also improves the overall time response of the control system. In some automobiles light-off time has been reduced by the use of heated sensors.

Most exhaust gas oxygen sensors available today are made by spark-plug manufacturers and have many design characteristics in common with spark-plugs (see Figure 6). The zirconia ceramic is typically stabilized with calcium dioxide and yttrium dioxide to provide thermal and mechanical strength respectively. The outer surface of the ceramic
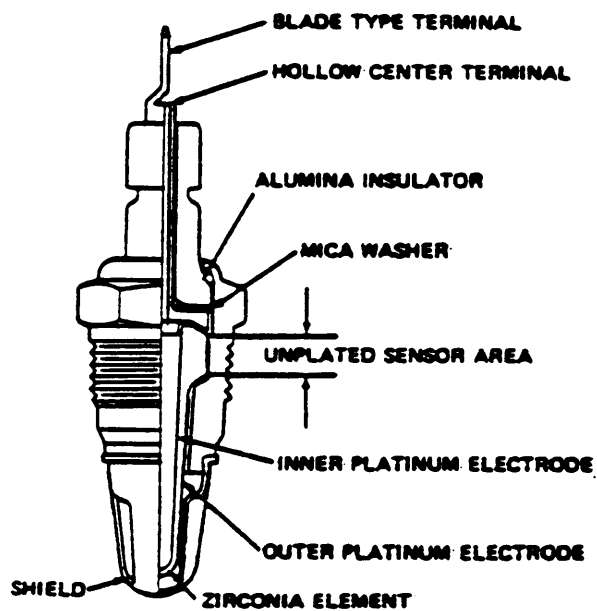
Figure 6   Zirconia Exhaust Gas Oxygen Sensor (31)

is usually coated with a layer of spinel to protect it from the abrasiveness of the exhaust gases. Often, additional protection is provided by covering the portion of the sensor exposed to the exhaust with a metal slotted shield.

### 2.3.3    New Developments in Exhaust Gas Oxygen Sensing

An alternative control scheme for reducing exhaust emissions has been devised which also utilizes the zirconia exhaust gas oxygen sensor (32). Rather than controlling the fuel-air ratio, of the gas mixture fed to the engine, this scheme proposes to add additional air (secondary air) to the exhaust stream until a stoichiometric mixture is achieved. The mixture is fed into the catalyst. This is the emission control approach used in the catalytic combustor/gasifier research.

Some laboratory exhaust gas analyzers are now using zirconia type sensors to measure oxygen concentrations over a full range from lean to rich. They either control or compensate for temperature changes and use the sensor's full output range; or else, they add oxygen to the sample gas until the stoichiometric point is recognized with the sensor and then "back out" the original gas composition.

Ford Motor Company has been working on the development of an alternative exhaust gas sensor, using titania ceramic, for the past decade (34,35,36). Recently they were able to prove the durability and effectiveness of two types of titania thick film sensors for over 80,000 km. Titania sensors are resistive devices which respond primarily to

changes in oxygen concentrations. Temperature changes affect the resistance only slightly over most of the exhaust gas temperature range. Therefore, titania sensors do not require electrical heating or temperature compensation.

Ford Motor Company has also been developing an oxygen sensor based on electrochemical pumping between two zirconia galvanic cells (37,38). The two cells are separated by a hollow ceramic spacer forming an enclosed volume. One electrode from each cell is exposed to the enclosed volume. One cell is used to pump oxygen into and out of the volume. Oxygen is pumped by applying a voltage across the cell through a load resistor. The second cell then responds as normal to the difference between the oxygen partial pressure at its two electrodes; one exposed to the exhaust, the other exposed to the enclosed volume. It is hoped that this sensor will be capable of accurately measuring fuel-air ratios over a full range from lean to rich. The sensor's output is approximately proportional to the fuel-air ratio and is only weakly dependent on temperature and gas pressures. Laboratory versions of the sensor have been developed.


To the author's knowledge, no one has studied the performance of zirconia exhaust oxygen sensors applied to the combustion of biomass fuels. There is some concern that the ash and or organics present in biomass exhaust might foul the sensors.

# Chapter III

## EXPERIMENTAL PROGRAM

### 3.1    INTRODUCTION

The objective of this research project was to develop and test a prototype (small-scale) catalytic combustor/gasifier.  The following steps were taken to accomplish this objective:

1.  a small-scale, down-draft combustor/gasifier was built and instrumented,

2.  the combustion characteristics of three biomass fuels--cordwood, bailed slash (refuse remaining after a logging operation), and corn fodder--were studied so that primary and secondary air flow strategies could be devised,

3.  several automobile exhaust gas oxygen sensors were tested to determine their ability to adapt to the combustion environment of biomass fuels,

4.  primary and secondary air flow control strategies were devised and implemented on the prototype combustor/gasifier,

5.  woodstove catalysts were installed to facilitate secondary combustion, and finally,

6.  the performance of the prototype catalytic combustor/gasifier was evaluated for each test fuel.

This chapter describes the experimental set-up, the experiments, and the experimental procedures used to develop and test the prototype catalytic combustor/gasifier.

31

## 3.2    EXPERIMENTAL SET-UP

### 3.2.1    Test Combustor

The prototype combustor used for this research, shown in Figure 7, had previously been used to investigate the effect of various burning conditions on the emissions of Wyoming bituminous coal (39). It was constructed from type 304 stainless steel pipe and is 137 cm long, with an outside diameter of 32.4 cm and a wall thickness of 4.6 mm. The cylinder is supported vertically by four legs.

Fuel is batch-loaded through the top onto a grate which is supported by three rods that hang from brackets bolted near the top of the combustor. The level of the grate is adjustable. The grate itself consists of a tubular stainless steel frame which supports a type 330 stainless steel mesh. The mesh, a square gridwork, is constructed from 0.9 mm diameter wire on 4.2 mm centers. An inducer draws the exhaust down through the combustor and through 6 meters of stovepipe (15 cm in diameter) and then delivers the exhaust to the stack. The 6 meter length of stovepipe allows the exhaust to cool before passing through the inducer. A barometric damper, located 30 cm upstream from the inducer provides additional protection by allowing cool room air to be drawn in with the hot exhaust, providing a dilution effect.

The prototype has three sets of four air inlet ports and thirteen probe ports. The positions of the ports are shown in Figure 8, where the vertical distance measurements have been made with respect to the grate level used during this research. The lid of the combustor
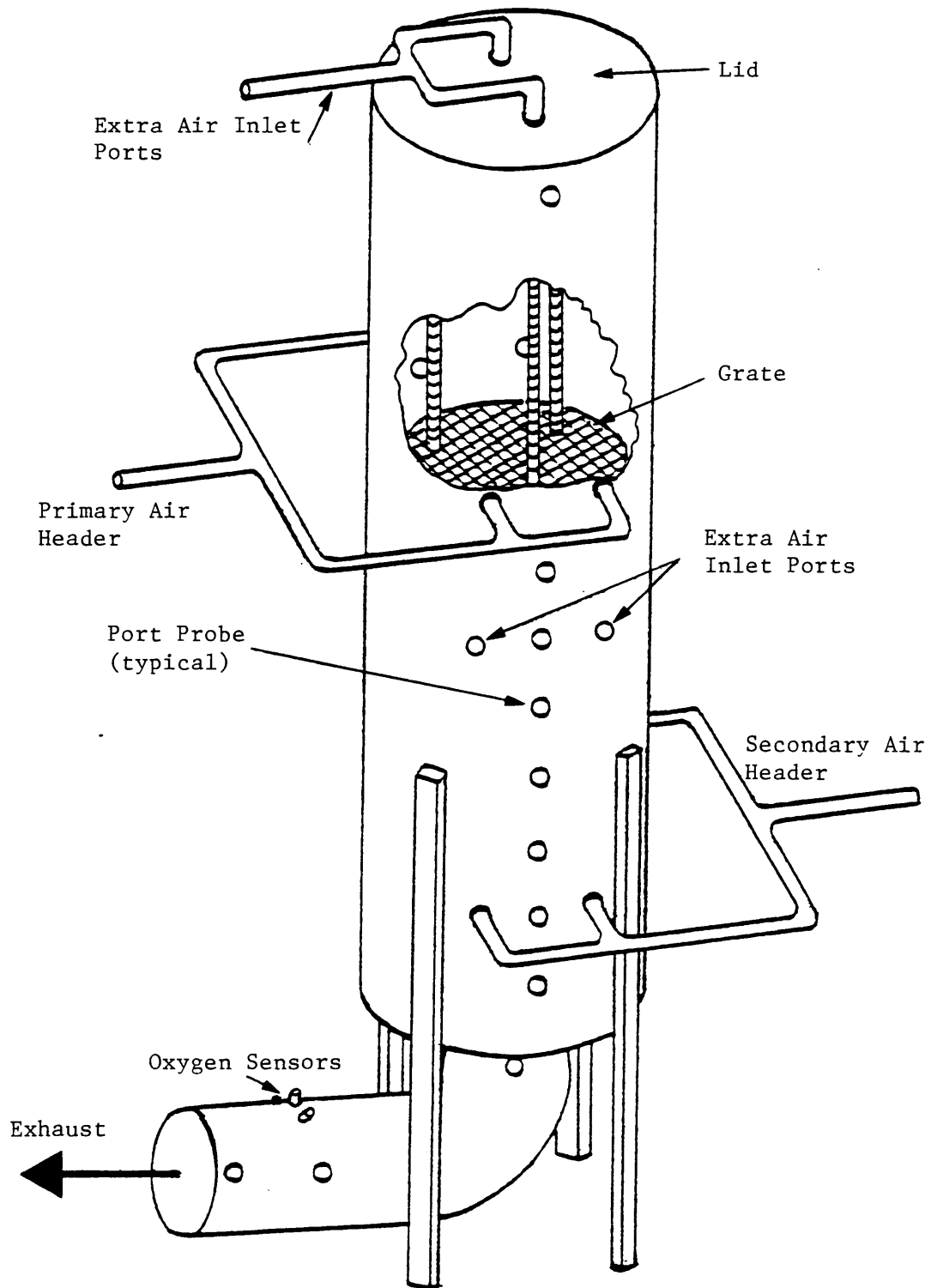
Figure 7   Prototype Catalytic Combustor/Gasifier--Isometric View
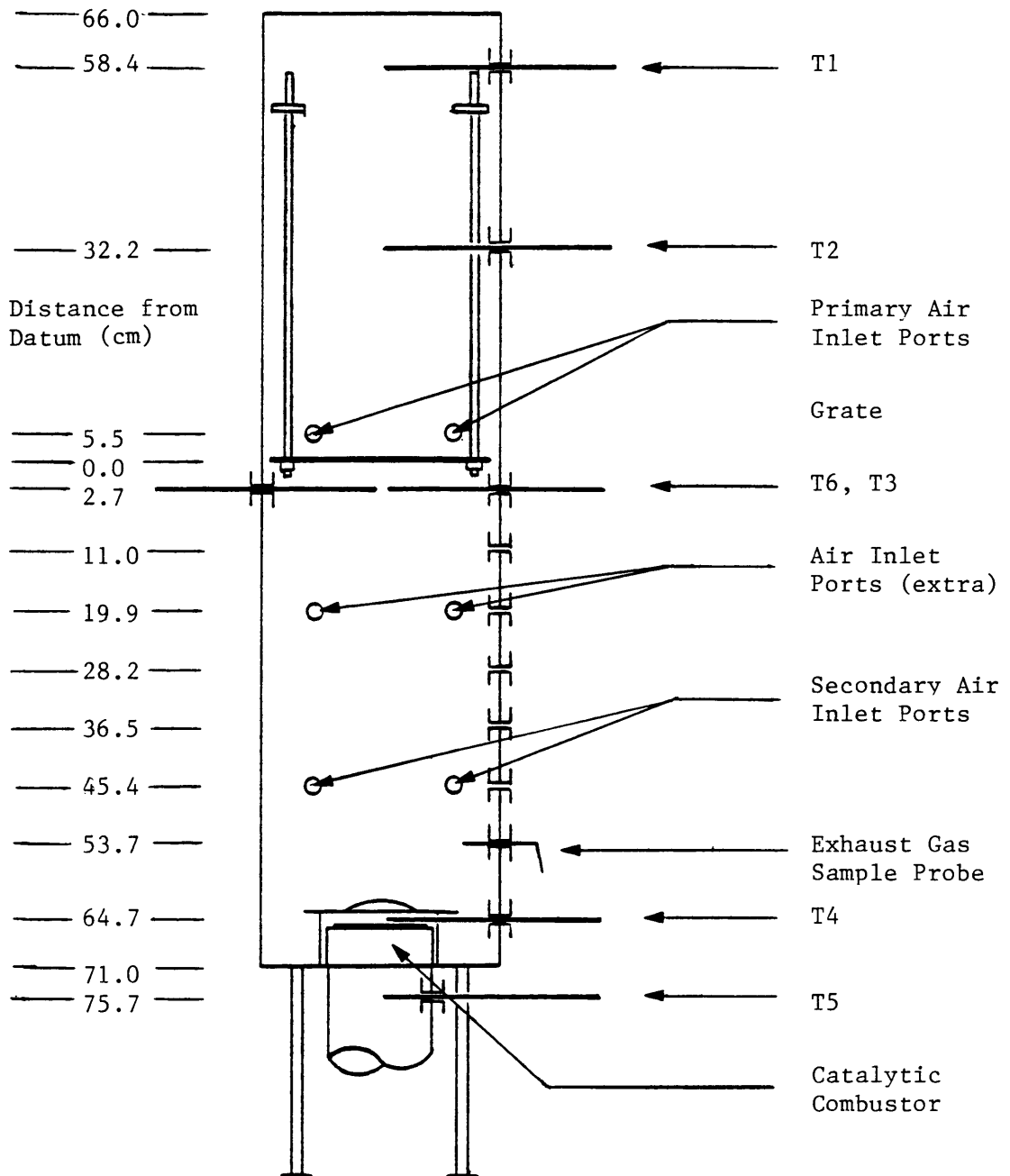
Notes: - T1 - T6 are Thermocouple Probes
- Stovepipe Exhaust Sample Probe Not Shown

Figure 8  Prototype Catalytic Combustor/Gasifier--
Orthographic View

contains two additional air inlet ports (see Figure 7) which were not used.

Fiberfrax Durablanket gasket material was used to seal the removeable lid and base plate on either end of the steel cylinder.

### 3.2.2    Air Supplies

Compressed air for the primary and secondary air flows was supplied by the university power plant.    The primary air flow was injected into the combustor, through four nozzles, 5.5 cm above the grate as shown in Figure 8.    The nozzles were 7 mm in diameter at their exits and were directed so as to produce a counter-clockwise flow (viewing the combustor from above).    Exit velocities, corresponding to typical flow rates ranging between 5 and 16 l/s, ranged between 30 and 100 m/s.

Secondary air was injected straight into the combustor 45.5 cm below the grate (see Figure 8) through four 9 mm (exit) diameter nozzles.    Exit velocities, corresponding to typical flow rates ranging between 3 and 7 l/s, ranged between 10 and 30 m/s.

Each flow rate[5] was measured and controlled by regulating the pressure upstream of a sonic orifice as is shown in Figure 9.    Orifice calibration curves are presented in Appendix A along with a description of the calibration technique.    The pressure regulator in each system was driven by a DC motor which could be controlled either manually or

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[5] The flow rates presented in this thesis are based on local atmospheric conditions (T = $27^{\circ}$C,  P = 94 kPa).
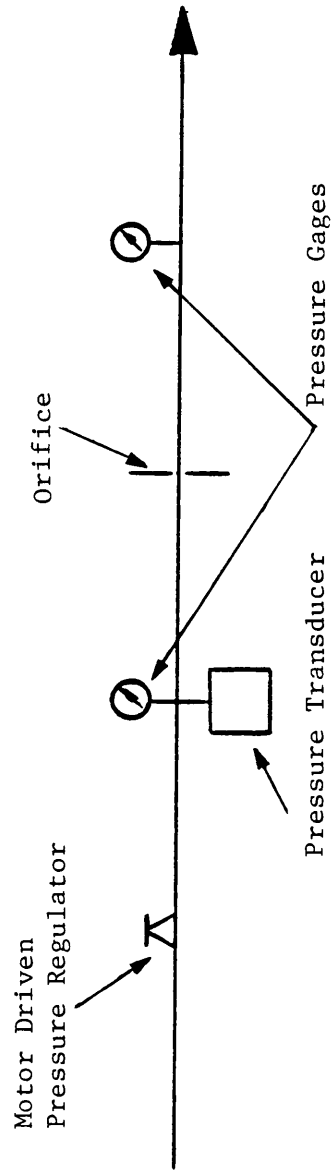
Figure 9  Sonic Orifice Arrangement for Primary or Secondary Air Flow Rate Measurement

by a computer. Schematics of the control circuits are shown in Appendix B.

Note that practical systems would probably use blowers rather than air compressors to supply primary and secondary air (see Figure 1). Compressed air was more convenient for the small-scale prototype testing since compressed air is readily available in the laboratory and since the air flow rates could be measured and controlled easily using the system described above.

### 3.2.3 Catalytic Combustor Assembly

The catalytic combustor is shown in Figure 10. The catalysts used were woodstove catalysts manufactured by Corning (see Figure 2 for dimensions). They had been "canned" prior to obtaining them, meaning that a thin (0.8 mm) stainless steel band, equal in width to the catalyst width (5 cm) had been wrapped tightly around the catalyst and welded in place. An insulation mat, approximately 1 mm thick, separated the band from the catalyst. The purpose of a "can" is to increase catalyst durability. Even if the ceramic cracks with age, as long as the catalyst holds together it will continue to function normally.

The catalyst rests on a lip on the inside of the mount near the bottom. Fiberfrax Durablanket gasket material was wrapped around the catalyst to prevent exhaust from flowing between the catalyst and the mount. The outside diameter of the mount has been cut back at the bottom so that the mount fits snuggly into the base plate. Exhaust
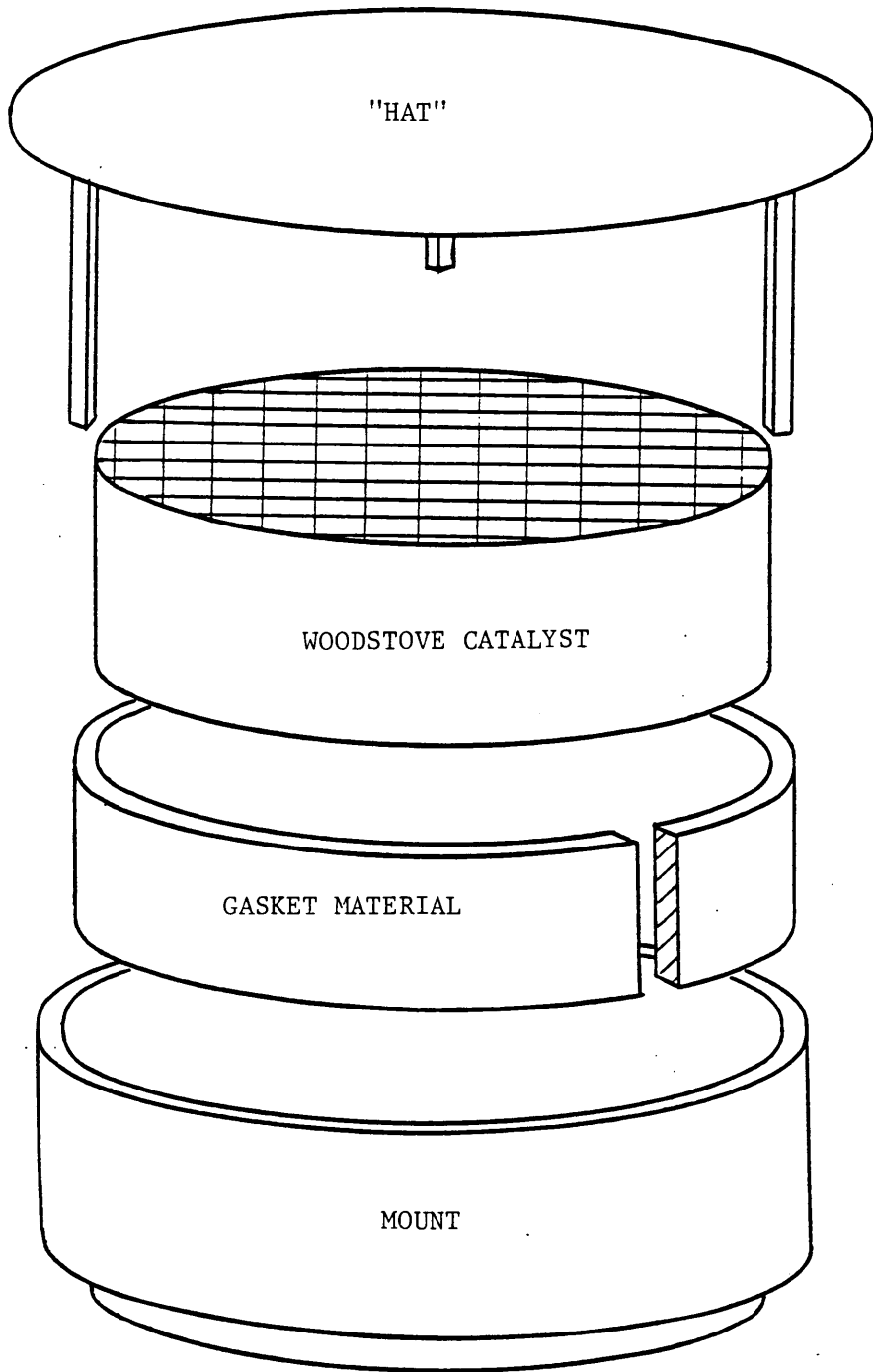
Figure 10   Catalytic Combustor

passes through the catalyst and into the 15 cm diameter stovepipe mounted to the other side of the plate.

Three legs hold the "hat", shown in Figure 10, 3.5 cm above the catalyst entrance to keep ash from falling in.

### 3.2.4    Exhaust Gas Oxygen Sensors

Zirconia type automobile exhaust gas oxygen sensors were obtained from Bendix Autolite Corporation (part no. X741-858), the AC Spark Plug Division of General Motors (part no. 4833A), and Robert Bosch Corporation (part no. 0 258 003 002) A sensor from each manufacturer was mounted in the stovepipe, along with a thermocouple, 42 cm downstream from the catalyst exit. The thermocouple was used to monitor the exhaust temperature. Remember that zirconia type oxygen sensors do not operate properly until they have been "lit-off" (i.e., heated to approximately $250^{o}C$). The Bosch sensor was a heated sensor, designed to reduce the light-off time. The heating element was supplied with 12 volts DC continuously whenever the sensor was used, providing approximately 11 W of heating power.

Note that neither the catalytic combustor nor the oxygen sensors were installed until after the completion of the biomass combustion characterization study.

### 3.2.5     Instrumentation and Data Acquisition

A Radio Shack TRS-80 model III microcomputer interfaced (through an STD bus) to two 16-channel analog-to-digital cards and to a parallel input/output card was used for data acquisition and to control the primary and secondary air flows.   Initially the computer system was used only for data acquisition; collecting and storing various temperatures, air flow rates, and the concentrations of carbon monoxide, carbon dioxide and oxygen in the exhaust.   From the data, heat release rates[6] and fuel-air equivalence ratios were calculated and stored as well.   With the implementation of the air flow control stategies the computer system was used in addition, to read the status of a thermostat switch, to read three oxygen sensor output voltages, and to automatically adjust the pressure regulators in the primary and secondary air flow systems as dictated by their control algorithms. Information flow to and from the computer system is summarized schematically in Figure 11 and a copy of the program used for data acquisition and control can be found in Appendix C.

### 3.2.5.1   Flow Rates

As described previously, sonic orifices were used to measure the primary and secondary air flow rates.   Solid state piezo-resistive pressure transducers were installed in each line to measure the

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[6] Heat Releast Rate is herein defined as the molar rate of carbon evolution from the fuel multiplied by the fuel's higher heating value per mole of carbon.
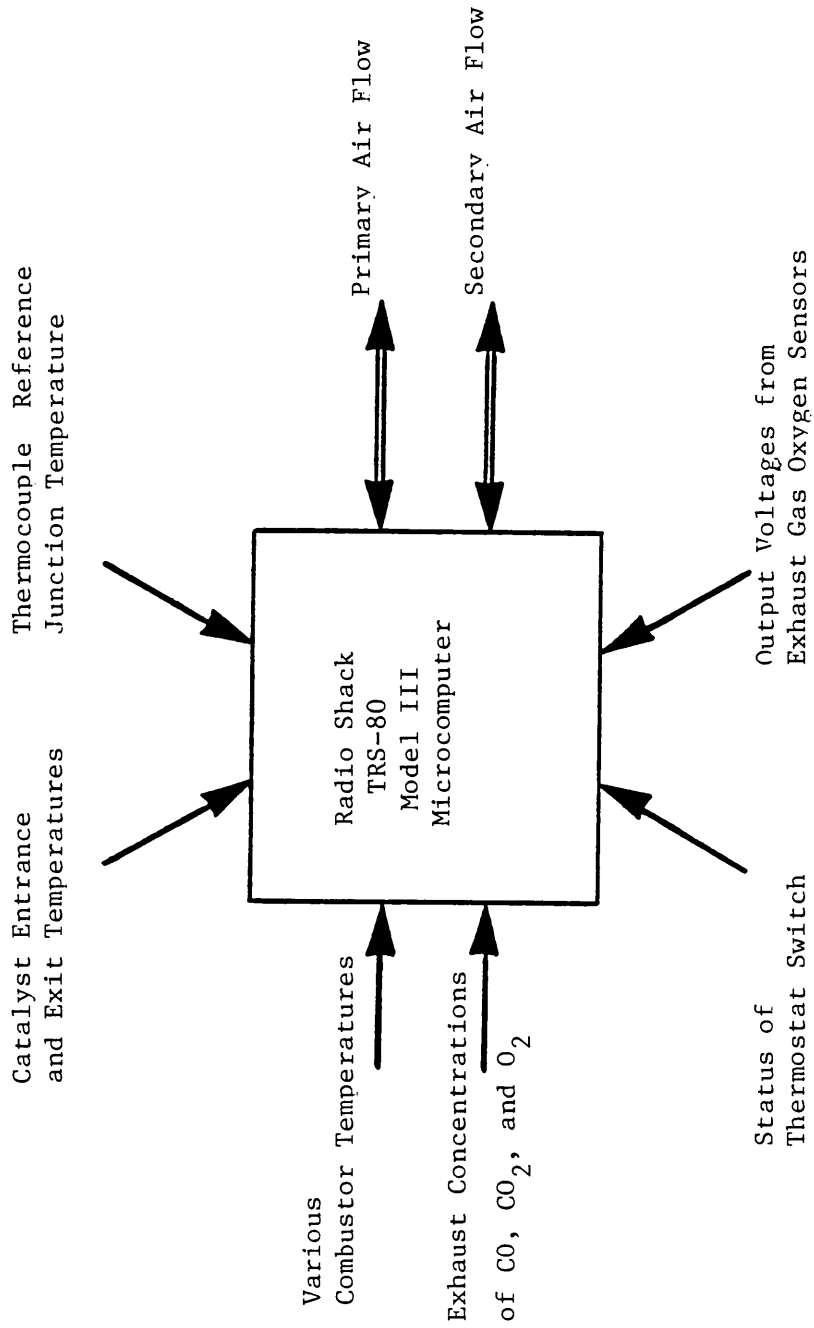
Figure 11  Information Flow To/From Computer System

pressures just upstream of the orifices. The pressures were converted into flow rates using the calibration curves of Appendix A.

### 3.2.5.2 Temperatures

Temperatures were measured using Chromel-Alumel (type K) thermocouple probes. The inconel-sheathed probes were 1 mm in diameter and had ungrounded junctions. All temperatures were measured near the centerlines of either the combustor or the stovepipe. The various locations at which temperatures were monitored with the computer system are shown in Figure 8. T1, T2, T3, and T6 are primary combustion/gasification zone temperatures. T4 and T5 give the entrance and exit temperatures of the catalyst when one is used. T7 is the temperature of the exhaust near the oxygen sensors.

Duplex, glass insulated, Chromel-Alumel (type K) thermocouple wire (0.51 mm in diameter) was used to extend the probe leads several meters. Reference junctions existed between the thermocouples and a ribbon cable to the data acquisition system at a connector strip. The junctions were at room temperature, requiring the voltage corresponding to the junction temperature to be added to the thermocouple voltages so that standard thermocouple tables and calibration curves (referenced at $0^{\circ}C$) could be used (41). The reference junction temperature was obtained by reading an electronically compensated, type K thermocouple, digital thermometer with a linearized analog output. Thermocouple voltages were converted to temperatures using two

third-order polynomial curve fits (42); one for the range $0^o$ to $600^oC$ and the other for the range $601^o$ to $1000^oC$.

T3 and T6 each measure the temperature of the exhaust 0.7 cm below the grate. The thermocouple probes used were identical and were separated by 3.0 cm (see Figure 8). While T6 was measured as described above, T3 was measured and displayed using a commercially available, type K digital thermometer with a lineraized analog output. Initially the purpose of having both probes was to verify the measuring technique described above. Later it was discovered that, at times, large temperature gradients existed near the grate (perhaps due to air flow patterns). Thus, the exhaust temperature at the grate was considered to be the average of T3 and T6.

### 3.2.5.3   Exhaust Gas Analysis

A schematic of the exhaust gas sampling train is shown in Figure 12. The system continuously conditioned an exhaust gas sample and measured the dry mole percent concentrations of carbon monoxide, carbon dioxide, and oxygen. The gas concentrations were used in the heat release rate, the equivalence ratio calculations, and to document the quality of the exhaust (i.e., completeness of combustion) throughout each run.

During the combustion characterization studies samples were drawn into the sampling train through either of two probes near the bottom of the combustor (see Figure 8). Occasionally one probe would clog
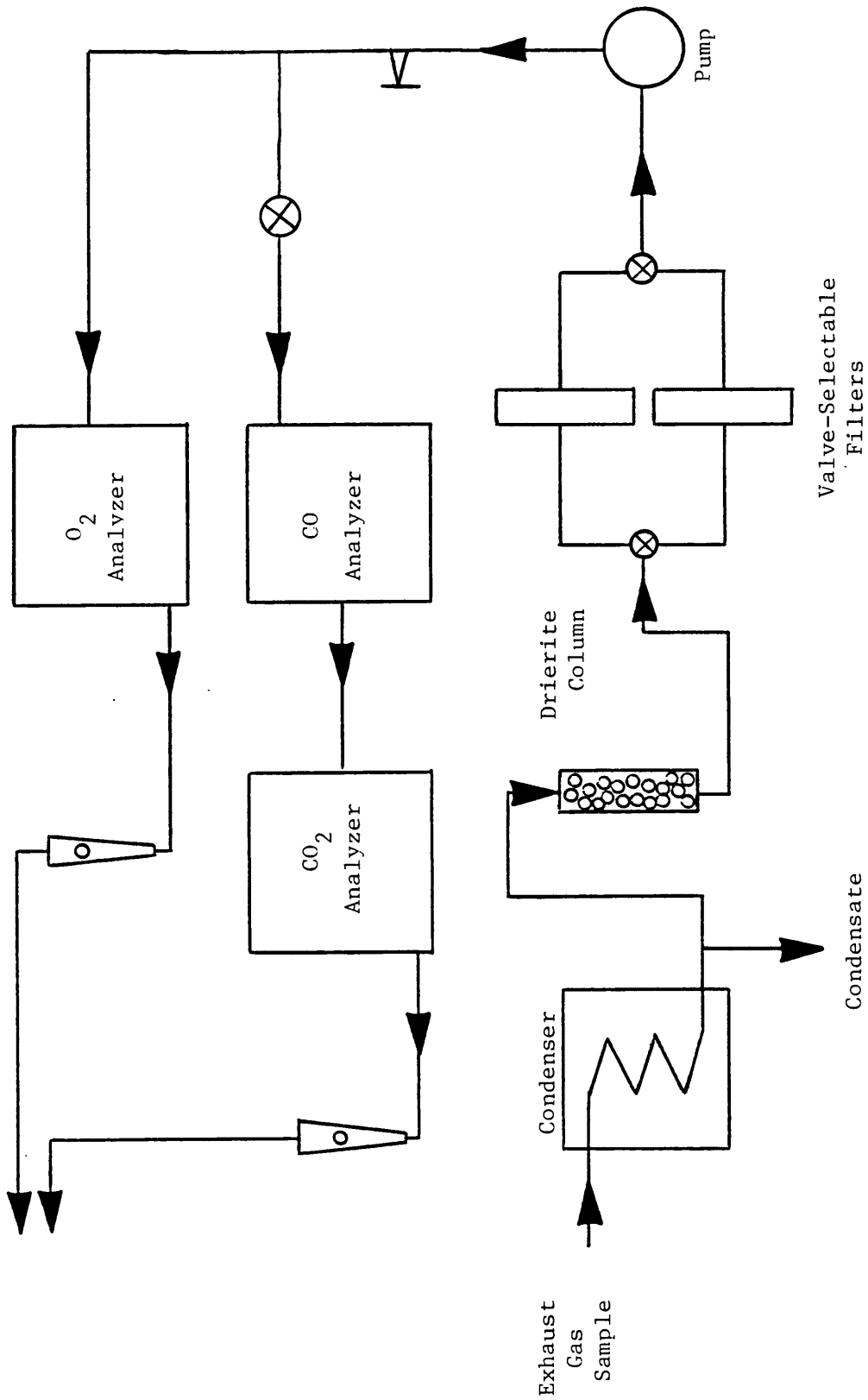
Figure 12   Schematic of Exhaust Gas Sampling System

during a run and the sample line would be switched to the second probe. Later, once the catalyst was employed, samples were drawn through a third probe in the stovepipe, 50 cm downstream of the catalyst exit. All sample probes protruded into the combustor or stovepipe several centimeters.

Samples were conditioned by passing them through a condenser, a drierite column, and a filter. All of the tubes and fittings used in the sampling system were either Teflon or stainless steel. The condenser was a stainless steel coiled tube packed in an ice bed. The condensed moisture collected in a jar at the exit of the condenser while the gas continued on through the drierite column where any remaining moisture was absorbed. Finally, the sample was drawn through one of two filters. The parallel filter system allowed selection of one filter at a time so that filters could be changed while running tests.

The samples then passed through a pump and a pressure regulator so that the pressure upstream of the analyzers was maintained at 21 kPa. The flow was split, with one flow passing successively through CO and $CO_2$ analyzers and the other passing through an oxygen analyzer. The rotometers shown were used to provide the proper flow rates and pressures to the analyzers. The CO and $CO_2$ analyzers were Horiba PIR-2000 general purpose nondispersive infrared gas analyzers and the $O_2$ analyzer was a Horiba MPA-21 paramagnetic analyzer.

### 3.2.5.4   Heat Release Rate Calculation

The heat release rate, HRR, is calculated by assuming a higher heating value for the fuel on a per mole of carbon basis and multiplying by the carbon release rate:

$$HRR = HHV * CRR$$

where:   HHR   = heat release rate (kW),

HHV   = energy per mole of carbon (kJ/mol C), and

CRR   = carbon release rate (mol C/s).

The carbon release rate, CRR, was approximated from the known primary and secondary air flow rates and concentrations of carbon monoxide and carbon dioxide in the exhaust, using the following formula:

$$CRR = (2 * [CO] + [CO_2])/100 * (molar\ air\ flow\ rate).$$

The first term represents the mole fraction of carbon in the exhaust flow.[7] The concentration of carbon monoxide and carbon dioxide are actually slightly high since moisture was removed from the sampled exhaust gases prior to passing them through the analyzers.   The carbon monoxide concentration was doubled to approximate the amount of carbon present in the exhaust in the form of unburned hydrocarbons.   The molar air flow rate approximates the exhaust flow rate.   Obviously this approximation is low since the fuel also contributes to the exhaust flow; however, since typical fuel-air ratios for biomass fuels are on the order of 1 to 10 this is a fair

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[7] The bracket notation, [XX], represents the concentration of XX as dry mole percentage.

approximation.

Higher heating values were assumed for each fuel based on values cited in the literature. The assumed higher heating values and other fuel properties are presented in Table 1. An average higher heating value of 465 kJ/mol C was used in the data acquisition program for all three fuels.

The uncertainty in the heat release rate calculation may be as high as 30 percent, due to the various approximations used in the calculation. Although only a "ball park" estimate, the calculation was adequate since the heat release rate was used primarily for relative comparisons.

### 3.2.5.5 Fuel-Air Equivalence Ratio Calculation

The fuel-air equivalence ratio, E, is defined as the ratio of the amount of fuel present in the effluent to the amount of fuel which could be oxidized by the oxygen which is concurrently present. When the equivalance ratio is one the mixture is stoichiometric, while values greater than one indicate fuel-rich (insufficient oxygen) mixtures and values less than one indicate fuel-lean mixtures.

Consistent with the definition above, a fuel-air equivalence ratio was calculated by subtracting the excess oxygen concentration (dry basis) from the concentration of oxygen present in atmospheric air and then dividing by the atmospheric air concentration:

$$E = (21 - EOC)/21$$

where:   EOC = percentage of excess oxygen in the exhaust.

Table 1.   Fuel Properties of the Three Test Fuels

| Test fuel<br>Item | Cordwood or<br>Baled slash | Corn Fodder |
|---|---|---|
| Molecular Formula (6,11) | $C_{4.24}H_{6.6}O_{2.66}$ | $C_6H_{9.14}O_{4.18}$ |
| Percent C by weight | 50.9 | 48.6 |
| Percent H by weight | 6.6 | 6.2 |
| Percent O by weight | 42.5 | 45.2 |
| HHV (MJ/kg) (6,11) | 20 | 18.5 |
| HHV (kJ/mol C) | 472. | 457. |
| Percent Moisture (wet basis) | 25.(C)<br>12.(S) | 8. |

C = Cordwood
S = Slash

The excess oxygen concentration represents the amount of oxygen that would have been present in the exhaust had complete combustion occurred. Note that if the mixture is rich the excess oxygen concentration will have a negative value. The excess oxygen concentration was approximated from the measured exhaust gas concentration as follows:

$$EOC = [O_2] - (1.5 * [CO]).$$

The exhaust stream carbon monoxide concentration was modified by a factor of 1.5 in order to account for the presence of unburned hydrocarbons in the exhaust which could have been oxidized.

### 3.2.6    Fuels

The combustion characteristics of biomass depend strongly on the type of biomass fuel used. Significant parameters are:  moisture content, surface to volume ratio, and chemical composition.  Three biomass fuels were studied in this research:  cordwood, corn fodder, and baled slash.

The cordwood used was split oak cordwood which had been kept in a humidified room.  A typical log weighed 3 kg and had a moisture content of 25 percent (wet basis).

The corn fodder used was baled in the late fall several weeks after it was cut, allowing it time to dry.  It had a moisture content of 8 percent (wet basis).

Slash refers to branches and tree tops which are left over after a logging operation. The slash used consisted primarily of oak and maple branches ranging between 2 and 10 cm in diameter, cut to 50 cm lengths. The moisture content averaged 12 percent (wet basis).

Fuel properties for the three test fuels are presented in Table 1.

## 3.3    DESCRIPTION OF EXPERIMENTS

Three groups of tests were conducted. Basic research was first conducted to study the combustion characteristics of the three biomass test fuels so that primary and secondary air flow control strategies, capable of controlling output power while maintaining a "clean" exhaust could be devised. Several automobile exhaust gas oxygen sensors were then tested to determine their ability to adapt to the combustion environment of biomass fuels. Finally, the control strategies and the catalytic combustor were incorporated and the prototype catalytic combustor/gasifier's performance was tested using each of the test fuels.

### 3.3.1    Biomass Combustion Characterization Study

The objective of the biomass combustion characterization study was to determine for each of the test fuels:

1.    the relationship between primary air flow and fuel-air equivalence ratio,

2.    the relationship between primary air flow and power output,

3.  the minimum primary air flow required to maintain combustion,

4.  the amount of secondary air required to maintain fuel-lean conditions, and

5.  the response of the combustion process to large step changes in primary air flow rate.

Four types of tests were run with each of the test fuels: a high fire test where the primary air flow rate was set near the maximum that the air compressor system could deliver, a low fire test where the primary air flow rate was limited so as to just maintain combustion, a variable firing rate test where the prototype combustor was run at various primary air flow rates between the high and low fire settings and finally, a bang-bang type test where the primary air flow rate was switched several times between high and low settings. Data was collected at 15 second intervals throughout each test.

Corn fodder, because of its low density and high surface to volume ratio, was consumed much more quickly than cordwood or slash. In order to accumulate a comparable amount of data the schedule of tests described above was modified for corn fodder. In addition to high fire and low fire tests two other tests were run at intermediate primary air flow rates on the corn fodder, and, a fifth test was conducted where the primary air flow rate was varied, alternating between high settings and low settings.

### 3.3.2    Exhaust Gas Oxygen Sensor Test

In order to determine the ability of automobile exhaust gas oxygen sensors to detect fuel-rich conditions in biomass exhaust gases, a test was run with the prototype combustor using baled slash for fuel. Slash was selected since it had been found to be more prone to burn rich than the other fuels. One of each type oxygen sensor was mounted in the stovepipe near the exit of the combustor. A woodstove catalyst was installed at the exit of the combustor to provide secondary combustion and thus minimize the quantity of unburned hydrocarbons and creosote which could potentially "gunk-up" the sensors.

### 3.3.3    Prototype Performance Tests

Having characterized the combustion of the three biomass test fuels and having evaluated the performance of the exhaust gas oxygen sensors, air flow control strategies were devised. A "bang-bang" control scheme was chosen for primary air control where the combustion rate would alternate between high fire and low fire based on the status of a thermostat switch. Secondary air was controlled based on feedback information provided by the Bosch heated oxygen sensor. In order to keep the catalyst from getting too hot, the catalyst entrance and exit temperatures were monitored and the air flows adjusted accordingly.

The control strategies and the secondary catalytic combustor were then implemented on the prototype combustor/gasifier. The Radio Shack TRS-80 microcomputer was now being used to control the primary

and secondary air flows as well as to collect and store data. This dual use of the microcomputor limited the way the control strategies could be implemented, however, the combustor responds slowly relative to the amount of time it takes to collect and store data (approximately 10 seconds) and this limitation is not as severe as it might at first seem. The "slowness" of the computer system was due primarily to the fact that it was programmed in interpreted basic. In a practical system speed would not be a problem since a microprocessor, programmed in machine language, could be dedicated solely to the task of controlling the air flows.

The performance of the prototype was evaluated for each of the three test fuels. The tests were conducted using a high fire primary air flow set point of 16 l/s and a low fire set point of 5 l/s. These set points were selected based on the results of the biomass combustion characterization study. Two runs were conducted using corn fodder since it is consumed so rapidly while only one run was conducted with each of the other fuels.

During the baled slash test it was noticed that the performance of the prototype could possibly be improved by reducing the high fire primary air flow set point (discussed in more detail later). Thus an extra run was conducted using slash with the high fire primary air flow set point reduced to 13.5 l/s from 16 l/s.

The tests conducted are summarized in Table 2.

Table 2.   Summary of Tests

| Test Description | Test Label | Fuel Type | Fuel Weight (kg) |
|---|---|---|---|
| **1.   Biomass Combustion** | | | |
| **Characterization Tests:** | | | |
| Low Fire | JUN28CDE | W | 8.7 |
| High Fire | JUN17A | W | 8.1 |
| Variable Fire Rate | JUN26AB | W | 9.6 |
| Bang-Bang | JUN30A | W | 12.0 |
| | | | |
| Low Fire | JUL1ABC | S | 9.8 |
| High Fire | JUN27A | S | 8.8 |
| Variable Fire Rate | JUN28AB | S | 9.4 |
| Bang-Bang | JUL3A | S | 9.7 |
| | | | |
| Low Fire | JUL20E | C | NW |
| High Fire | JUL2B | C | NW |
| Medium-Low Fire Rate | JUL2A | C | NW |
| Medium-High Fire Rate | JUL2C | C | NW |
| Bang-Bang | JUL2F | C | NW |
| | | | |
| **2.   Oxygen Sensor Test:** | JUL13A | S | 6.9 |
| | | | |
| **3.   Prototype Performance Tests:** | | | |
| Wood | JUL25B | W | 10.4 |
| Baled Slash     (Test I) | JUL24A | S | 9.2 |
| Baled Slash     (Test II) | JUL25A | S | 10.0 |
| Corn Fodder    (Test I) | JUL24C | C | NW |
| Corn Fodder    (Test II) | JUL24D | C | NW |

NW  = Not weighed
 S   = Slash
 C   = Corn
 W   = Wood

## 3.4 EXPERIMENTAL PROCEDURES

The following preparations were made prior to each test:

1.  The combustor was "cleaned-up" from the previous run. Any ash or charcoal remaining on the grate was removed. During the biomass characterization studies the stovepipe tended to fill with ashes after several runs. Thus, every three to four runs the stovepipe was also cleaned. At the same time, the base plate was removed so that the ash which had collected on it could be cleared. The stovepipe and base plate would then be reassembled. Stovepipe cement was used to ensure that the stovepipe was sealed up until the section containing the sample probes. Gaskets for the base plate and the lid were replaced when necessary.

2.  Whenever a catalyst was required, either a new one was installed or the existing one was cleaned (blown with pressurized air), inspected, and reinstalled.

3.  The sample system was leak tested.

4.  The fuel was weighed.

5.  The power supplies providing the excitation voltages for the pressure transducers were set at 10.0 volts.

6.  Each analyzer was calibrated (i.e., zeroed and spanned). When more than one test was conducted on the same day, the analyzers were not necessarily recalibrated after the first run.

Two procedures were used to initiate combustion; one for cordwood and baled slash and the other for corn fodder. The cordwood and slash runs were started by building a small kindling fire on the grate. The induced draft fan was used to draw air in through the top of the combustor. Once some coals were created, the wood or slash was loaded endwise onto the grate, the lid was bolted on, and the primary air flow was adjusted to deliver a high flow rate. The high flow rate was typically maintained at least ten minutes to ensure that the primary combustion/gasification process had been established.

For the runs with corn fodder, as much fuel as possible was loaded into the fuel magazine. The inducer was turned on and a small primary air flow was initiated. The fuel was lit near the grate by reaching through the fuel, and then the combustor lid was put on. Since corn fodder combustion/gasification was established very quickly it was not necessary to maintain high primary air flows.

During each run, the exhaust gas oxygen concentration was monitored on a strip chart recorder. Observations were noted on the strip chart as well. During the variable firing rate test the oxygen concentration was used to determine when combustion/gasification reached steady state conditions. The primary air flow was adjusted to a new setting only after having been at steady state for several minutes.

Throughout the run ice was added to the ice bath and filters were changed in the exhaust sampling system as necessary. The filters

loaded more quickly at the beginning of runs, and therefore the first filter change was typically made after only 30 minutes; subsequent changes were made less frequently. It is noted that switching between filters interrupted the steady inlet pressures to the analyzers, momentarily affecting their output signals.

At the end of a run, the data collected was transfered to an IBM PC with which plots were later generated. When a catalyst had been used during the run it was removed and examined.

# Chapter IV

## RESULTS AND DISCUSSION OF THE BIOMASS COMBUSTION CHARACTERIZATION STUDY

The objectives of the biomass combustion characterization study were to determine for each fuel:

1.  the relationship between primary air flow and fuel-air equivalence ratio,

2.  the relationship between primary air flow and power output,

3.  the minimum primary air flow required to maintain combustion,

4.  the amount of secondary air required to maintain fuel-lean conditions, and

5.  the response of the combustion process to large step changes in primary air flow.

Data collected during the study are presented graphically in Appendix D. The format used for presenting the data is described below followed by discussions of the tests conducted with each fuel.

## 4.1    PRESENTATION OF DATA

Data from each run are presented with five plots. The sets of plots are found in Appendix D and are organized first by fuel type, then by type of run (high fire test, low fire test, etc.), and finally, by plot type. The five types of plots are described below. An example set of plots (Example Figures 1-5) have been included with the text for this discussion.

58
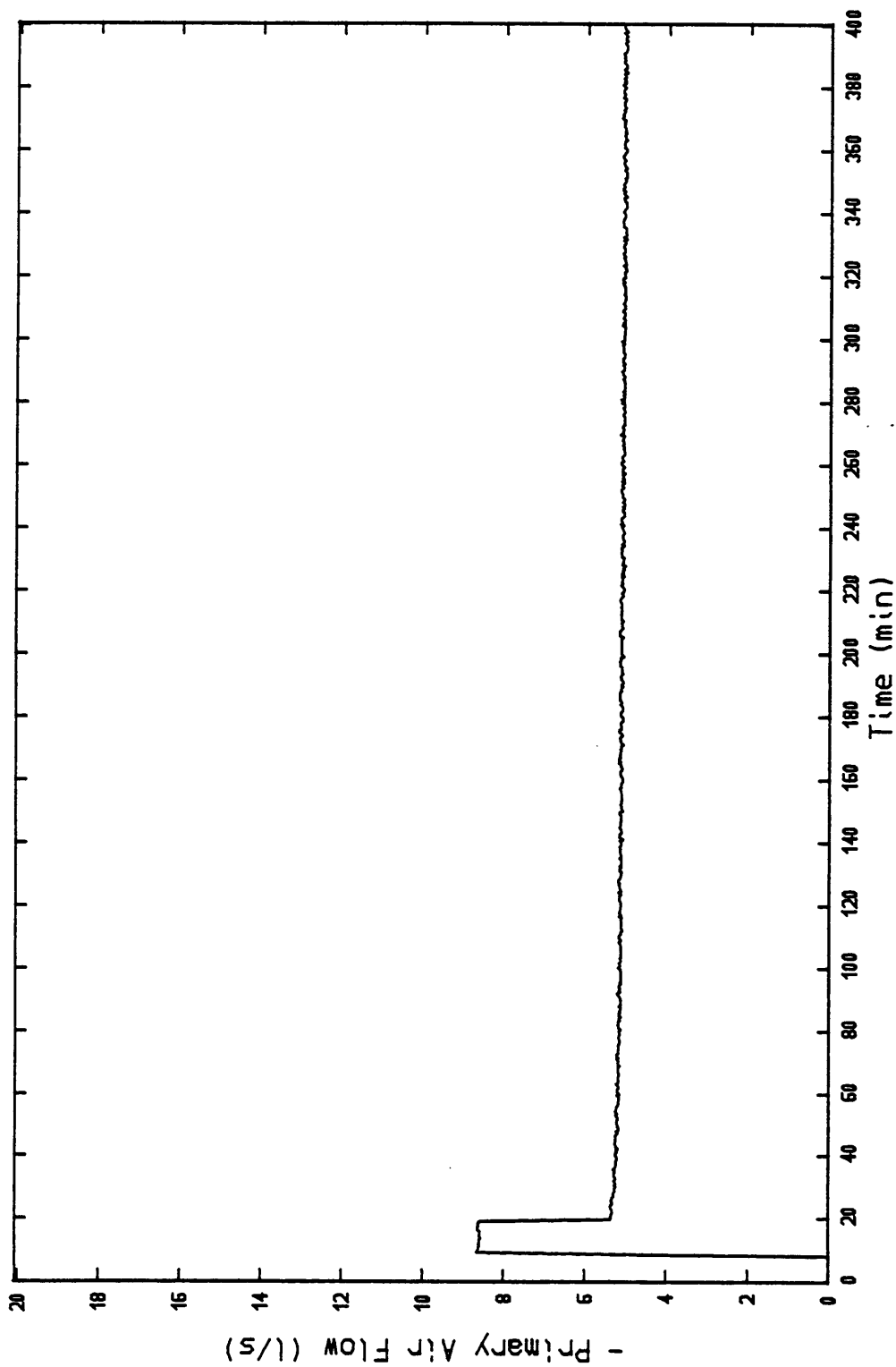
Example Figure 1  Primary Air Flow vs. Time
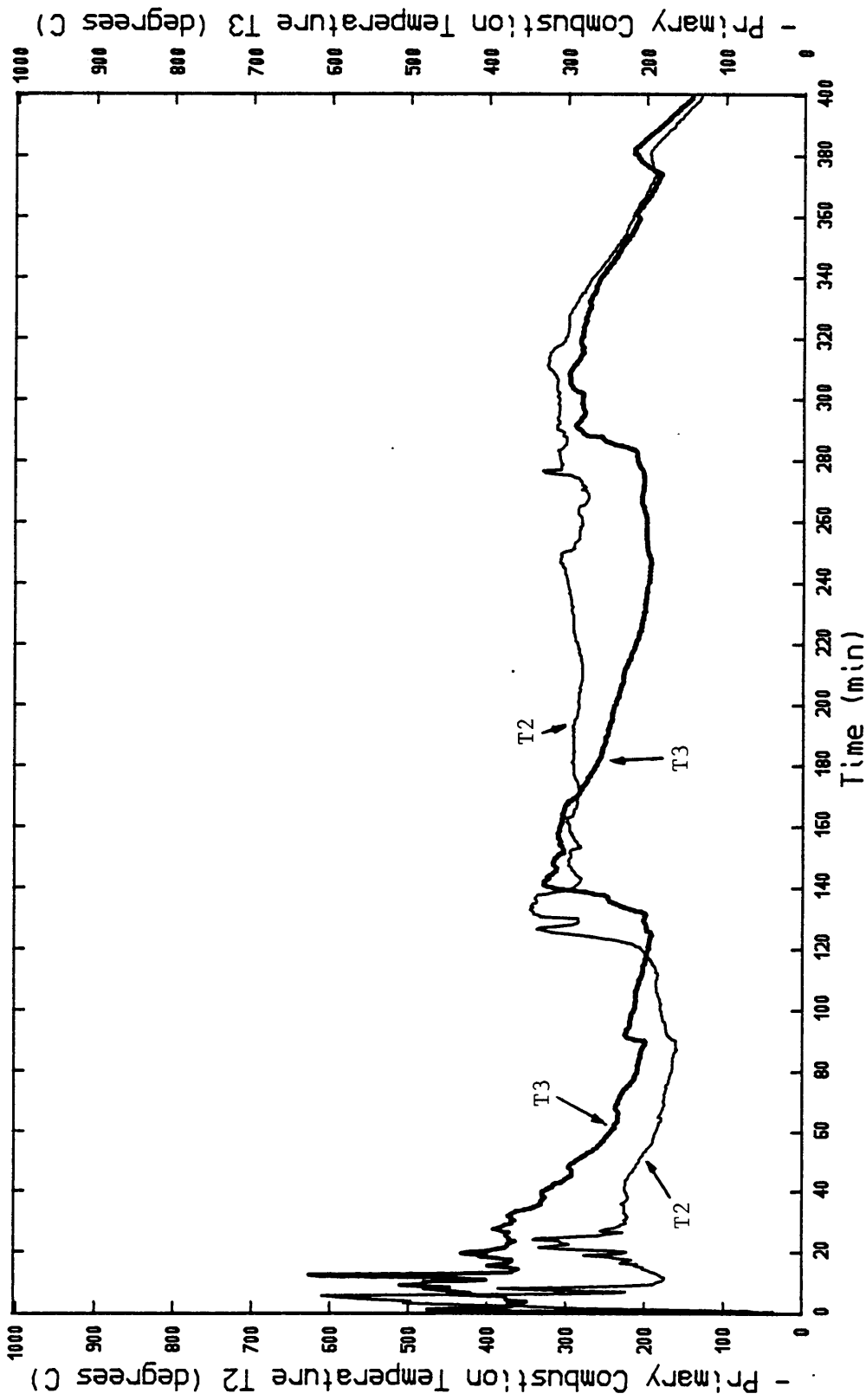
Example Figure 2  Primary Combustion Temperatures, T2 and T3, vs. Time
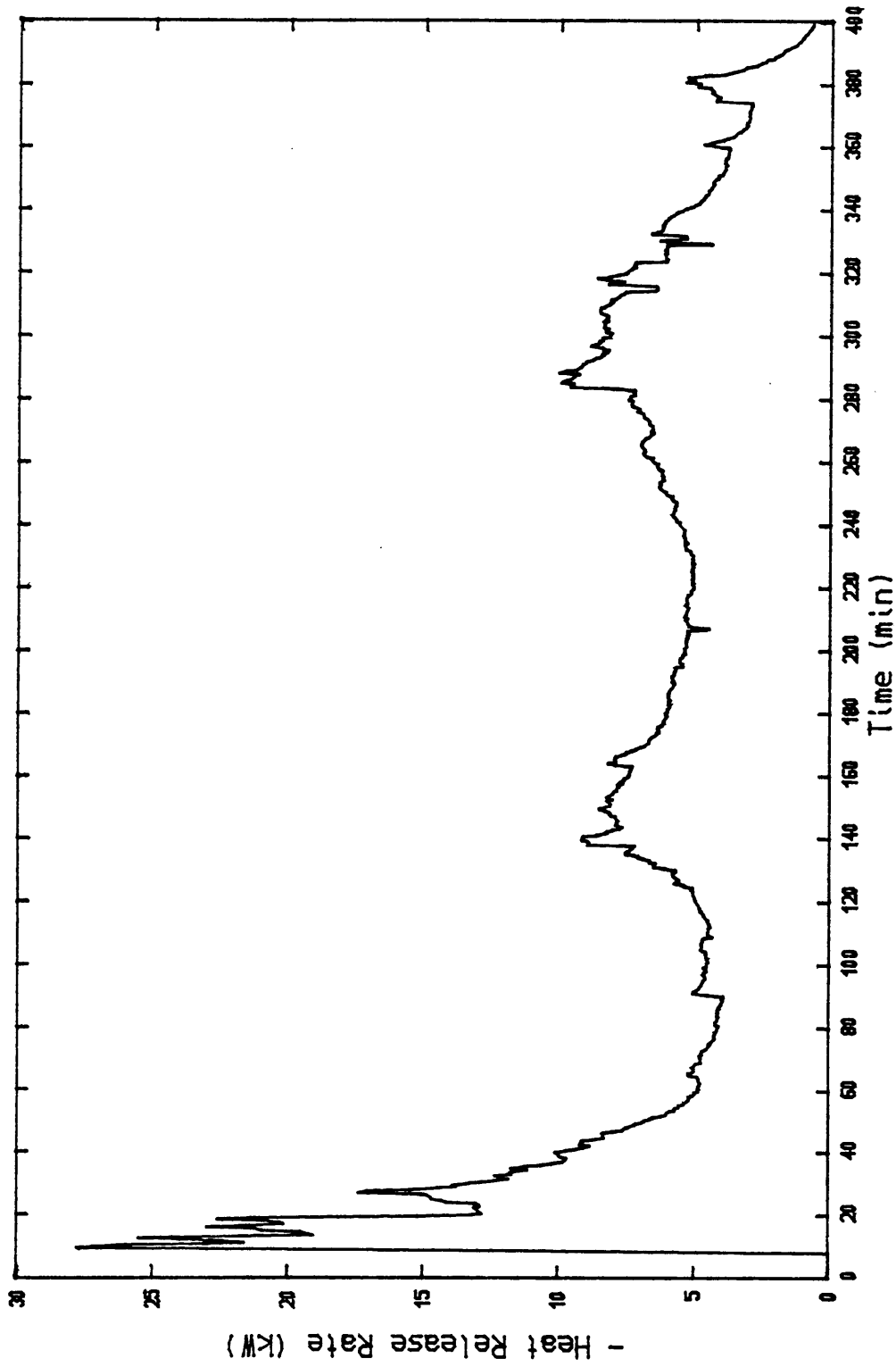
Example Figure 3  Heat Release Rate vs. Time
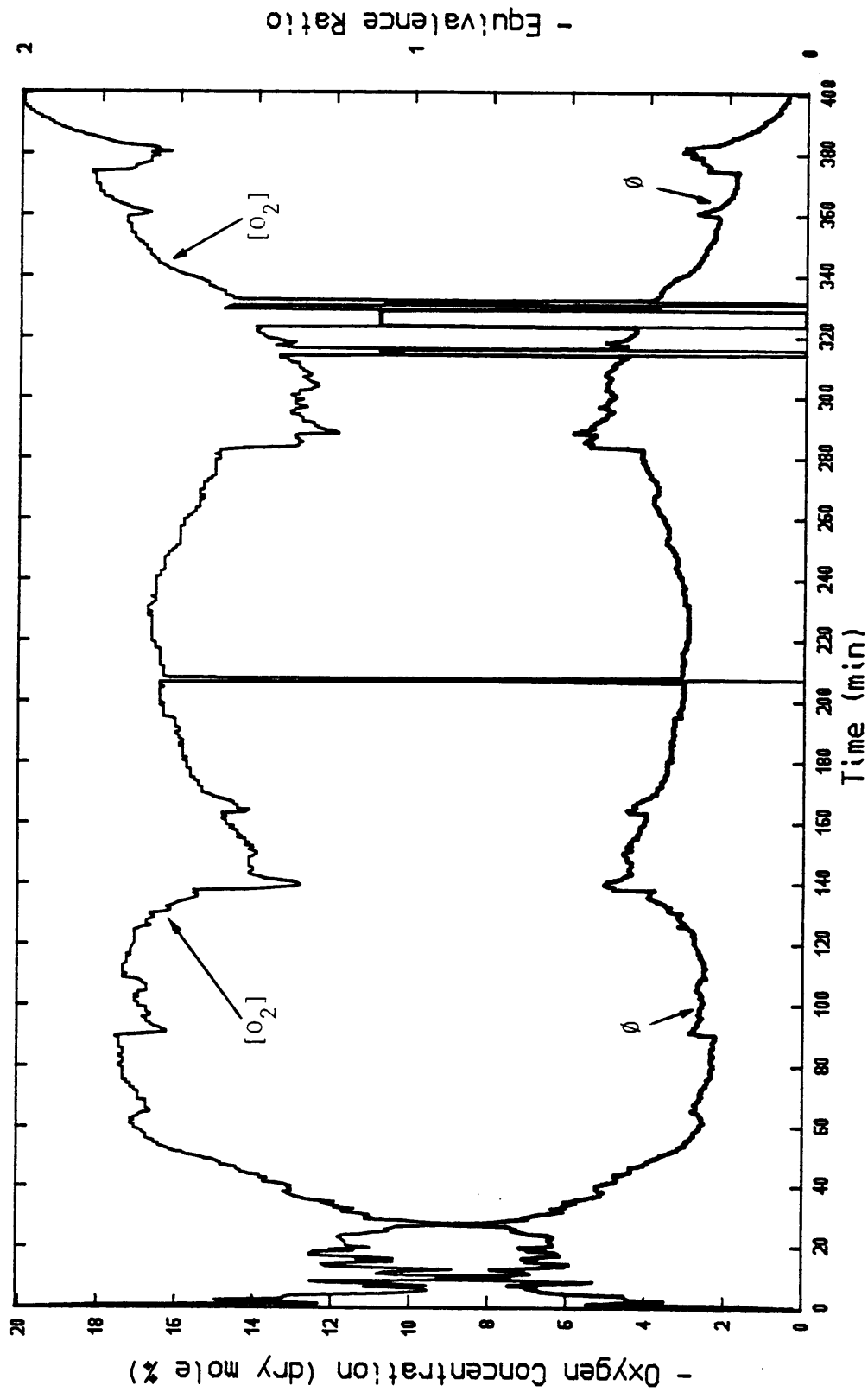
Example Figure 4  Oxygen Concentration and Equivalence Ratio vs. Time
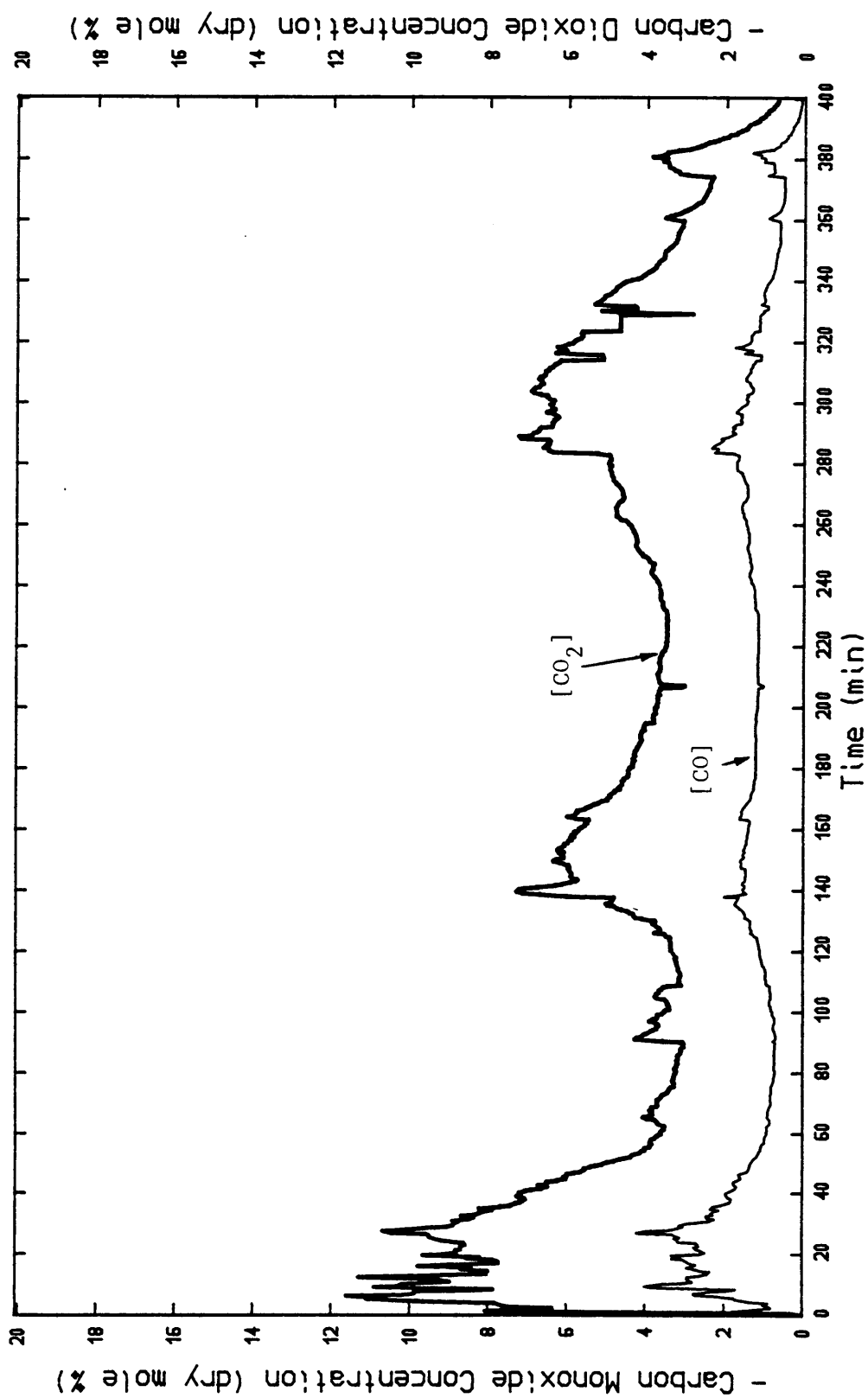
Example Figure 5  Carbon Monoxide and Carbon Dioxide Concentrations vs. Time

The first plot in each set of five shows the primary air flow rate as a function of time. Remember that air flow was the only input to the system during the combustion characterization study.

Many of the "primary air" plots show a brief period at the beginning of the run (up to 10 minutes) where there was no primary air flow, however other plots indicate that combustion had already started. In a sense it had; during those periods the kindling fires needed to start the cordwood and baled slash runs had been lit and were burning down to coals. Air for combustion was drawn through the top of the combustor by the inducer. Primary air was first introduced in each run only after the fuel had been loaded onto the grate and the lid bolted in place. Thus, the initiation of the primary air flow essentially "marked" the beginning of each run. During the run the measured primary air flow is the true air flow to the combustion/gasification zone.

In some plots the primary air flow rate is shown to fluctuate sinusoidally about a set point. The amplitude of the fluctuations seems to increase with flow rate (see Figure 36). The fluctuations may have been due to fluctuations in the supply pressure to the air regulator or to the regulator itself. In any case, the regulator maintained the desired flow rates to within $\pm 4$ percent, which was more than adequate.

The second plot in each set shows the primary combustion temperatures T2 and T3 as functions of time. Although these temperatures turned out to be fairly insignificant parameters for the

development of the control strategies, they help characterize the combustion process and thus, have been included in this report.

The third plot in each set shows the calculated heat release rate (i.e., output power) as a function of time. Note that the heat release rate is zero until the primary air is turned on since the HRR calculation uses the primary air flow rate to approximate the exhaust flow rate.

The fourth plot in each set shows the measured exhaust gas oxygen concentration (dry basis) and the calculated equivalence ratio as functions of time. Given complete combustion, the curves should be mirror images of each other except for a scale factor (see Equivalence Ratio Calculation, Section 3.2.5.5).

The occasional "spikes" in the oxygen concentration and equivalence ratio data were caused by interruptions of the sample flow to the analyzers. The most common interruptions occurred very briefly during switches between filters. However, on some of the longer runs the sample flow rate was interruped for several minutes in order to work on the sampling system (replace drierite, etc.). These "down" periods are marked clearly by their effect on the oxygen concentration curve (see Example Figure 4 at t = 208 minutes and around t = 320 minutes).

Finally, the fifth plot in each set shows the exhaust gas concentrations (dry basis) of carbon monoxide and carbon dioxide as functions of time. Due to differences in instrument design, the interruptions in exhaust gas sample flow affected the carbon monoxide and carbon dioxide data much less significantly than it did the oxygen

data. The oxygen analyzer gives an output corresponding to zero percent if no sample is flowing, whereas the carbon monoxide and carbon dioxide analyzers maintain a reading near that which existed when the flow was stopped (compare Example Figure 50 to Example Figure 4). Note that the heat release rate calculation was also affected since it is a function of the carbon monoxide and carbon dioxide concentrations (see Example Figure 3).

## 4.2   DISCUSSION OF DATA

The four types of tests run on each fuel (described in Section 3.3) were a low fire test, a high fire test, a variable firing rate test, and a bang-bang (primary air flow rate switch between the high and low fire settings) test. Following a general discussion, each test is discussed briefly in the order in which they appear in Appendix D.

### 4.2.1   General Discussion

Although primary air was the only input to the combustion system during the combustion characterization study the test results were complicated by the changing chemical characteristics of the fuel throughout the run. However, there appeared to be three relatively distinct phases during each run: a "start-up" phase, an "established combustion" phase, and a "burn-out" phase.

During start-up, moisture is driven from the fuel, the feedstock heats up, and combustion is established (i.e., achieves quasi-steady

conditions). The time required to establish combustion at a desired operating point (e.g., low fire or high fire) depended on the type of fuel used and the type of test being conducted.

During the "established combustion" phase the fuel characteristics seemed to remain constant. Since the primary air was introduced at the grate "new" fuel was "added" throughout this phase as the batch of fuel burned down onto the grate. Thus, the proportion of charcoal to "new" fuel was probably fairly constant. This theory was tested by stopping tests with cordwood and baled slash after the combustion process had been established. When the fuel feedstock was examined coals were found on the grate, the lower portion of the feedstock was charred, and the top of the feedstock appeared to be "untouched" by the combustion process. Again, the duration of the phase depended on fuel type and run type, ranging from 10 minutes for corn at high fire, to 5 hours for wood at low fire.

During the "burn-out" phase the fuel was characterized mostly of charcoal. As with the "start-up" and "established combustion" phases, the length of the "burn-out" phase also varied.

Data analysis was limited to the "established combustion" phase since it is expected that larger-scale combustor/gasifiers would normally operate in this mode. Large-scale systems would have either very large fuel-magazines or automatic fuel feeding systems which would allow them to maintain "established combustion" for long periods of time.

The assignment of a time window corresponding to the "established combustion" phase for each test is somewhat arbitrary. Several of the combustion parameters monitored could have been used to determine the period for which combustion can be considered to have been "established."[8] In this analysis heat release rate was used.

The first two types of tests discussed for each fuel are the high and low fire tests. They were designed to characterize the combustion process at extreme primary air flow rates. Characteristics of interest at the extreme firing rates were:

1. output power (i.e., the Heat Release Rate),

2. equivalence ratio, and

3. the concentrations of carbon monoxide, carbon dioxide, and oxygen in the exhaust.

A second objective of the low fire test was to determine the minimum air flow required to maintain combustion.

The variable firing rate test was designed to determine:

1. the response of the output power to increases in the primary air flow,

2. the power turn down ratio, and

3. the potential for running rich at intermediate firing rates.

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[8] Note that "established combustion" only refers to the establishment of a fairly constant fuel chemistry. Within the "established combustion" time-window combustion characteristics varied in response to changes in the primary air flow rate.

The results from the variable firing rate test were particularly difficult to analyze because of the changing fuel characteristics. It was hard to determine when the combustion process was "established" and when it was beginning to die out. Also, the duration of the "established combustion" phase was often too short to evaluate combustion characteristics at more than 1 or 2 intermediate air flow rates.

The final type of test discussed for each fuel is the "bang-bang" test. It was designed to evaluate the response of the combustion process to large step changes in primary air flow rate. It is noted that this test was motivated, in part, by a desire to "try out" an idea for primary air control. The idea was that the output power from the combustor could be regulated with what is known as a "bang-bang" control scheme in control theory; hence the name for the fourth type of test. "Bang-bang" controllers control their systems by alternating them between two predefined set points, forward--reverse, on--off, or in this case high fire--low fire.

Specifically, the objectives of the bang-bang type test were to:

1. observe how large step changes in the primary air flow rate affect the combustion process,

2. determine and compare the output power turn down ratio with the ratio determined from the high and low fire tests, and

3. determine the rate of response of the output power to the step changes in the air flow.

### 4.2.2    Combustion Characteristics of Cordwood

#### 4.2.2.1    Low Fire Test

Data from the low fire test are presented in figures 26-30. Notice that the run lasted for over six and a half hours and notice that the sample system was worked on for several minutes around t = 320 minutes (see Figure 29). Also, more data was collected than could be held in the RAM of the IBM-PC used to generate the plots. Thus, only every other data point was plotted (i.e., 30 second intervals between data points).

Low fire conditions are considered to have been "established" during the period between 60 and 320 minutes (see Figure 28). Remember that during the first 60 minutes the combustion process was still being established (higher primary air flow rates were used); and during the final 40 minutes the fire was going out due to lack of fuel.

Combustion at low fire was characterized by:

1.    the output power ranging between 4 and 10 kW, averaging about 6 kW (Figure 28),

2.    the equivalence ratio ranging between 0.22 and 0.60, averaging about 0.35 (Figure 29),

3.    the carbon monoxide concentration ranging between 0.7 and 2.5 percent, averaging about 1.3 percent (Figure 30),

4.    the carbon dioxide concentration ranging between 3.0 and 7.5 percent, averaging about 4.5 percent (Figure 30), and

5.  the oxygen concentration ranging between 12.0 and 17.5 percent, averaging about 15.7 percent (Figure 29).

Note that the products from the combustion/gasification zone never ran fuel-rich.

The low fire test showed that combustion could be maintained over extended periods of low firing when primary air flow rates of 6 l/s or greater are used. During a previous low fire test (graphs of which are not included in this report) where the primary air flow rate was varied between 3 and 6 l/s throughout the five-hour run, the fire went out while there was still plenty of fuel (4.5 kg out of the original 7.1 kg). However, in that test not as much care was taken to ensure that the combustion process was initially established. Thus, it may be possible to sustain combustion with primary air flow rates less than 6 l/s.

## 4.2.2.2   High Fire Test

Figures 31-35 present the data from the high fire test. High fire conditions are considered to have been established during the period between 35 and 72 minutes (see Figure 33). Combustion at high fire was characterized by:

1.  the output power ranging between 23 and 44 kW, averaging about 36 kW (Figure 33),

2.  the equivalence ratio ranging between 0.40 and 0.70 averaging about 0.62 (Figure 34),

3. the carbon monoxide concentration ranging between 1.4 and 3.4 percent, averaging about 2.8 percent (Figure 35),

4. the carbon dioxide concentration ranging between 4.7 and 8.0 percent, averaging about 7.1 percent (Figure 35), and

5. the oxygen concentration ranging between 11.4 and 15.5 percent, averaging about 12.5 percent (Figure 34).

Note again that, although the equivalence ratio was higher than it was during the low fire test, the effluent from the combustion/gasification zone never ran fuel-rich.


4.2.2.3   Variable Firing Rate Test

The variable firing rate test data are shown in Figures 36-40. Figure 36 shows the various primary air flow rates used during the test. The time window for which the combustion process was "established" is considered to be from 25 to 95 minutes.

Based on the heat release rate plot (Figure 38), and data from previous runs, the output power appears to increase monotonically with increases in the primary air flow rate. Using the average values for output power from the high and low fire tests gives a turn down ratio of 6 to 1. Although the average high and low fire output powers were slightly greater (45 and 7 kW) during the variable firing rate test than during the individual high and low fire tests (36 and 6 kW) the turn down ratio was still approximately 6 to 1. None of the air flow rates used during the test produced fuel-rich effluents. The highest fuel-air

equivalence ratio achieved was 0.8 (Figure 39). Values for high and low fire equivalence ratios are consistent with those determined in the high and low fire tests discussed previously.

### 4.2.2.4 Bang-Bang Test

Figures 41-45 present the bang-bang test data. Combustion is considered to have been "established" during the period between 10 and 135 minutes. Figure 44 shows that from t = 114 to 118 minutes the sample system was down.

Figure 41 shows how the primary air flow was manipulated during the run. Early in the run (t = 10 to 50 minutes) the air flow was alternated between high and low fire set points on 10 minute intervals. During the next 35 minutes (t = 50 to 85 minutes) 5 minute intervals were used. Random time intervals were used for the remainder of the run. The high flow rate set point was 16 l/s while the low flow rate set point ranged between 8 and 5.5 l/s.

The effect of the large step changes in the primary air flow rate on the composition of the effluent leaving the combustion/gasification zone is shown in Figures 44 and 45. When the flow is switched from low to high carbon monoxide and carbon dioxide concentrations drop momentarily and then start climbing, while the oxygen concentration momentarily rises and then starts falling.

The effect is reversed and is more pronounced when the flow is switched from high to low. It was not unusual for the flow to even run

slightly rich for about a minute after a switch was made. The amount of secondary air that would have been required to "lean-out" the flow was always less than 1 l/s (calculated from equivalence ratio and exhaust flow rate).

Average low and high fire output powers were determined for the run using the heat release rate plot, Figure 43. The average high fire power was determined to be approximately 45 kW and the average low fire power to be approximately 9 kW (based on output power at the 5.5 l/s low fire setting). Both powers were larger than those calculated during the individual high and low fire tests. The turn down ratio of 5 to 1 was less, however.

The power at low fire would most likely have been lower had the combustion process been given more time to settle each time a switch was made from high to low. The heat release rate plot, Figure 43, shows the power typically still falling when switches to high fire were made, particularly when the time interval between switches was only 5 minutes long. It is not clear what effect longer time intervals would have had on the output power at high fire.

The response of the output power to the air flow switches was characterized by rise times ranging between 15 and 160 seconds, averaging about 70 seconds, and fall times ranging between 15 and 135 seconds, averaging about 70 seconds also.

### 4.2.3    Combustion Characteristics of Baled Slash

### 4.2.3.1    Low Fire Test

Data from the low fire test of baled slash are presented in Figures 46-50. Since the run lasted approximately 5 hours (see Figure 46) and the amount of data collected exceeded the amount that could be held in the RAM of the IBM-PC used to generate the plots only every other data point was plotted (i.e., 30 second intervals between data points instead of 15 seconds). Low fire conditions are considered to have been "established" during the period between 60 and 280 minutes. Combustion at low fire was characterized by:

1.  the output power ranging between 3 and 9 kW, averaging about 6 kW (Figure 48),

2.  the equivalence ratio ranging between 0.40 and 0.87, averaging about 0.60 (Figure 49),

3.  the carbon monoxide concentration ranging between 0.8 and 3.8 percent, averaging about 1.6 percent (Figure 50),

4.  the carbon dioxide concentration ranging between 6.5 and 12.2 percent averaging about 9.1 percent (Figure 50), and

5.  the oxygen concentration ranging between 8.9 and 14.0 percent, averaging about 11.3 percent (Figure 49).

Note that although the products from the combustion/gasification zone approached fuel-rich conditions early in the run they never ran fuel-rich.

The low fire test showed that combustion could be maintained for long periods at low firing rates with primary air flows as low as 3 l/s (Figure 46). Note that it is possible that even lower flow rates would be able to sustain combustion.

### 4.2.3.2   High Fire Test

Data from the high fire test are presented in Figures 51-55. The primary air flow rates used throughout the run are shown in Figure 51. Combustion is considered to have been established during the period from t = 10 to 62 minutes. The quickness with with which combustion was established is due to having used an ususually hot kindling fire. The fact that the combustor/gasifier was initially run for about 6 minutes using a low air flow rate should not be a concern since the high fire combustion characteristics of baled slash were not evaluated over that period. The primary air flow rate was also reduced from the high fire set point for five minutes during the middle of the run (t = 39 to 45 minutes) to keep the combustor from overheating. High fire characteristics were not evaluated for this period either.

This run was probably the most interesting of all the runs conducted during the biomass combustion characterization study. Many "explosions" occurred within the combustor during the run and on two occasions the combustion/gasification process went into a "runaway" situation (at t = 38 minutes and t = 54 minutes).

Each runaway situation was initiated by an "explosion" within the combustor. In the first case the explosion blew the cover off of the barometric damper. Note that smaller "explosions" had occurred earlier in the run without a runaway situation developing.

During the first runaway situation the combustor got so hot that a 25 cm diameter brightly glowing spot appeared on one side of the combustor (above the grate level). In order to protect the combustor the primary air flow rate was reduced for approximately 6 minutes, arresting the runaway situation.

Each "explosion" was accompanied by step increases in the equivalence ratio and in the concentration of carbon dioxide in the exhaust and step decreases in the exhaust concentrations of carbon monoxide and oxygen, see Figures 54 and 55. Note the high chemical energy content of the effluent just prior to the "explosions" (i.e., large concentrations of carbon monoxide).

The data strongly suggest that secondary combustion, unassisted by catalysis, was initiated with each explosion. Step increases in the exhaust temperatures entering the stovepipe, T4, support this theory, see Figure 56 (this is an additional plot to the standard set of five). The step increases in equivalence ratio with the initiation of secondary combustion is probably due to the fact that the increased combustor/gasifier temperatures increased the pyrolysis rate.

The data suggest that secondary combustion also occured at the beginning of the run from t = 10 to 17 minutes, but ceased at t = 17

minutes. Notice again the large step changes in the exhaust gas concentrations.

It is not clear what caused the secondary combustion to start and stop. The variable firing rate test and the Bang-Bang test, along with this test suggest, however, that it is difficult to maintain secondary combustion.

During the second runaway condition the additional heat release again caused the combustor to glow, but this time the glowing portion was a narrow band around the combustor at the grate level. It is surmised that, since the run was nearly over, most of the fuel had been spent and that only a few small pieces of charred slash and charcoal remained on the grate. This would explain the difference in the glowing patterns and the fact that it was not necessary to turn the air flow down to control the condition.

The combustion characteristics were determined for high fire over the time intervals t = 15 to 38 minutes and t = 45 to 62 minutes. Combustion was characterized by:

1. the output power ranging between 43 and 75 kW, averaging about 58 kW (Figure 53),

2. the equivalence ratio ranging between 0.77 and 1.30, averaging about 0.98 (Figure 54),

3. the carbon monoxide concentration ranging between 0.1 and over 5 percent (the analyzer was calibrated only up to 5 percent), averaging about 3.8 percent (Figure 55),

4.  the carbon dioxide concentration ranging between 6.3 and 19.5 percent, averaging about 12.2 percent (Figure 55), and

5.  the oxygen concentration ranging between 0.5 and 11.0 percent, averaging about 6.5 percent (Figure 54).

The combustor ran rich for several minutes during two periods, (t = 32 to 43 minutes and t = 54 to 60 minutes--see Figure 54). The maximum secondary air flow rate which would have been required in order to "lean-out" the flow was calculated to be 5 l/s. The calculation is based on the known equivalence ratio and exhaust flow rate where the exhaust flow rate is approximated by the primary air flow rate. The worst case occurred at t = 39 minutes, just after the first runaway condition was initiated but before the primary air flow was reduced.

### 4.2.3.3   Variable Firing Rate

Figures 57-61 present the data from the variable firing rate test. Combustion is considered to have been "established" during the period between 45 and 110 minutes. In this time window only 1 primary air flow rate, 8 l/s, was used. Again, as in the high fire test, many explosions occurred during the run, having the same effect on the equivalence ratio and the concentrations of carbon monoxide, carbon dioxide, and oxygen in the effluent from the combustion/gasification zone. Note however that secondary combustion was not sustained.

Combustion was characterized at the intermediate flow rate by:

1.  the output power ranging between 20 and 38 kW, averaging about 29 kW (Figure 59),

2.  the equivalence ratio ranging between 0.74 and 1.35, averaging about 0.96 (Figure 60),

3.  the carbon monoxide concentration ranging between 0.3 and over 5 percent, averaging about 4.2 percent (Figure 61),

4.  the carbon dioxide concentration ranging between 9.7 and 18.1 percent, averaging about 12.0 percent (Figure 61), and

5.  the oxygen concentration ranging between 1.0 and 9.6 percent, averaging about 7.5 percent (Figure 60).

The combustor ran rich for 22 minutes at the intermediate firing rate from, t = 70 to 92 minutes. The highest equivalence ratio achieved occurred at t = 81 minutes. A secondary air flow rate of 2.9 l/s would have been required to "lean-out" the effluent.

## 4.2.3.4 Bang-Bang Test

Data from the bang-bang test are presented in Figures 62-66. Combustion is considered to have been "established" during the period between 20 and 95 minutes. Again, on several occasions, the off-gas produced by the combustion/gasification process ignited and affected the equivalence ratio and gas concentration (Figures 65 and 66). The most significant "explosion" occurred at 39 minutes.

The large "spikes" on the equivalence ratio and gas concentration plots at 43 and 55 minutes are due to step changes in the air flow from

high to low rather than to "explosions" however. On both occasions the effluent leaving the combustion/gasification zone became and ran fuel-rich for several minutes. Each time, the maximum "richness" for the period occurred within 15 seconds. The effluent then slowly became lean again over periods of 5 and 4 minutes, respectively. Secondary air flows of 2.1 and 1.1 l/s respectively would have been required to "lean-out" the flow.

Comparisons of the output powers at high and low firing rates to those determined in the high and low fire tests cannot be made accurately for a couple of reasons: (1) the air flows used for low fire were not the same for the two tests and (2) the short amount of time at each set point did not allow the output power to reach steady-state values in many cases.
Qualitatively, the turn down ratio appears to be approximately 5:1.

The rate of response of the output power to the step changes in the primary air flow averaged about 130 seconds for rise times and about 140 seconds for fall times.


4.2.4    Combustion Characteristics of Corn Fodder

4.2.4.1    Low Fire Test

Figures 67-71 present the data from the low fire test. Low fire conditions are considered to have been established during the period between 15 and 80 minutes. Combustion at low fire was characterized by:

1. the output power ranging between 3 and 7 kW, averaging about 4 kW (Figure 69),

2. the equivalence ratio ranging between 0.30 and 0.70, averaging about 0.47 (Figure 70),

3. the carbon monoxide concentration ranging between 0.5 and 2.5 percent, averaging about 1.3 percent (Figure 71),

4. the carbon dioxide concentration ranging between 4.7 and 9.3 percent averaging about 7.3 percent (Figure 71), and

5. the oxygen concentration ranging between 9.8 and 15.7 percent, averaging about 13.0 percent (Figure 70).

Notice that at low fire the products produced by the combustion/gasification process never ran fuel-rich.

The low fire test showed that combustion of corn fodder could be sustained at low firing rates with primary air flows as low as 3 l/s (Figure 67). It is probable that even lower flow rates (1 to 2 l/s) would be able to sustain combustion.

### 4.2.4.2   High Fire Test

The high fire test data are presented in Figures 72-76. High fire conditions are considered to have been established for only 10 minutes, during the period between 9 and 19 minutes. The combustion was characterized by:

1. the output power ranging between 42 and 66 kW, averaging about 51 kW (Figure 74),

2.  the equivalence ratio ranging between 0.74 and 1.00, averaging about 0.85 (Figure 75),

3.  the carbon monoxide concentration ranging between 2.8 and 5.6 percent, averaging about 4.2 percent (Figure 76),

4.  the carbon dioxide concentration ranging between 7.5 and 12.5 percent, averaging about 10.5 percent (Figure 76), and

5.  the oxygen concentration ranging between 8.1 and 11.0 percent, averaging about 9.2 percent (Figure 75).

Again, the products of the combustion/gasification process never ran fuel-rich.

4.2.4.3  Intermediate Firing Rate Tests

Since corn fodder was consumed much more rapidly than the other fuels, two tests were run using intermediate primary air flow rates rather than one test with variable firing rates. The intermediate tests were run using primary air flow rates of 5.5 (Medium-Low Fire Test) and 11.0 l/s (Medium-High Fire Test). Data from the tests are presented in Figures 77-81 and Figures 82-86, respectively.

Combustion at the 5.5 l/s air flow rate is considered to have been "established" during the period from 5 to 90 minutes and was characterized by:

1.  the output power ranging between 9 and 23 kW, averaging about 13 kW (Figure 79),

2. the equivalence ratio ranging between 0.50 and 1.00, averaging about 0.65 (Figure 80),

3. the carbon monoxide concentration ranging between 0.8 and 5.6 percent, averaging about 2.2 percent (Figure 81),

4. the carbon dioxide concentration ranging between 7.6 and 13.2 percent, averaging about 9.9 percent (Figure 81), and

5. the oxygen concentration ranging between 8.2 and 12.2 percent, averaging about 10.3 percent (Figure 80).

Combustion at the 11.0 l/s air flow rate is considered to have been "established" during the period from 7 to 19 minutes and was characterized by:

1. the output power ranging between 24 and 44 kW, averaging about 30 kW (Figure 84),

2. the equivalence ratio ranging between 0.63 and 1.00, averaging about 0.77 (Figure 85),

3. the carbon monoxide concentration ranging between 1.7 and 5.7 percent, averaging about 3.0 percent (Figure 86),

4. the carbon dioxide concentration ranging between 7.8 and 12.0 percent, averaging about 9.9 percent (Figure 86), and

5. the oxygen concentration ranging between 8.6 and 11.2 percent, averaging about 9.8 percent (Figure 85).

The output power, the equivalence ratio, and the carbon monoxide and carbon dioxide concentrations each appear to increase monotonically with increases in the primary air flow rate based on the results of the

high and low fire tests and the two intermediate air flow rate tests. Thus, the turn down ratio, based on the average power output values determined from the high and low fire tests, was 8.5 to 1. Fuel-rich effluent was not achieved for any flow rate.

4.2.4.4   Bang-Bang Test

Figures 87-91 present the data from the bang-bang test. Combustion is considered to have been "established" during the period between 5 and 24 minutes. The short duration of the test, limits the conclusions that can be drawn.

Figure 87 shows how the primary air flow was manipulated throughout the run. The effect of step changes in the primary air flow on the effluent leaving the combustion/gasification zone is shown in Figures 90 and 91. Notice the absence of "spikes" in the gas concentrations, which occurred during both the cordwood and baled slash tests. Also notice that the effluent never became fuel-rich even during changes from high to low fire as it did with cordwood. These observations indicate the combustion process with corn fodder responds more quickly to step changes in air flow. This is probably due to the fact that less thermal energy can be stored in the less dense fuel. The overshoots in the gas concentrations and the equivalence ratios for the other fuels can be thought of as a "capacitor" effect.

The response of the output power to the air flow switches was characterized by typical rise times of 45 seconds and fall times of 30 seconds.

The results of the biomass characterization study are summarized in Table 3.

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Table 3.    Summary of Results of Biomass Combustion Characterization
Study

| Item / Fuel Type | Cord-wood | Baled Slash | Corn Fodder |
|---|---|---|---|
| Air Flow During High Fire Test (l/s) | 16 | 16 | 16 |
| Air Flow During Low Fire Test (l/s) | 6 | 3 | 3 |
| Avg. High Fire Equivalence Ratio | 0.62 | 0.98 | 0.85 |
| Avg. Low Fire Equivalence Ratio | 0.35 | 0.60 | 0.60 |
| Avg. Power at High Fire (kW) | 36 | 58 | 51 |
| Avg. Power at Low Fire (kW) | 6 | 6 | 6 |
| Response of Output Power to Increase in Primary Air Flow Rate | IM | IM | IM |
| Avg. Percent Carbon Monoxide at Low Fire | 1.3 | 1.6 | 1.6 |
| Avg. Percent Carbon Dioxide at Low Fire | 4.5 | 9.1 | 9.1 |
| Avg. Percent Oxygen at Low Fire | 15.7 | 11.3 | 13.0 |
| Avg. Percent Carbon Monoxide at High Fire | 2.8 | 3.8 | 4.2 |
| Avg. Percent Carbon Dioxide at High Fire | 7.1 | 12.2 | 10.5 |
| Avg. Percent Oxygen at High Fire | 12.5 | 6.5 | 9.2 |
| Conditions under which Fuel-Rich Effluent was Produced | H-L | HF,MF H-L | None |
| Maximum Secondary Air Flow Needed when Rich (l/s) | 1 | 5 | NA |

Notes:

   IM = increases monotonically        HF = High Fire
  H-L = High to Low Fire              MF = Medium Fire

# Chapter V

## EVALUATION OF EXHAUST GAS OXYGEN SENSORS

The objective of the exhaust gas oxygen sensor test was to evaluate the ability of three automobile exhaust gas oxygen sensors to detect fuel-rich conditions in the exhaust of biomass fuels. The three sensors were made by different manufacturers, and one sensor was heated.

The ability of the exhaust gas oxygen sensors to detect fuel-rich effluent was evaluated by comparing the voltage output signals from the oxygen sensors to the fuel-air equivalence ratio calculated from the measured concentrations of carbon monoxide and oxygen in the exhaust. Figures 13, 14, and 15 compare the output voltage from the Autolite, the AC Spark and the heated Bosch oxygen sensors respectively to the equivalence ratio throughout the run. Remember, fuel-rich conditions existed whenever the fuel-air equivalence ratio was greater than one.

Properly operating oxygen sensors respond to fuel-rich conditions by producing voltages between 700 and 1000 mV. Voltage levels associated with fuel-lean conditions should be less than 200 mV (see Figure 4). It should be remembered that in order for zirconia-type oxygen sensors to operate properly the zirconia material must be heated to at least $400^{\circ}$C. Figure 16 shows the temperature of the exhaust at the sensors throughout the run.

The plots show that each of the sensors, once lit-off, was able to clearly distinguish between fuel-lean and fuel-rich effluent. The heated
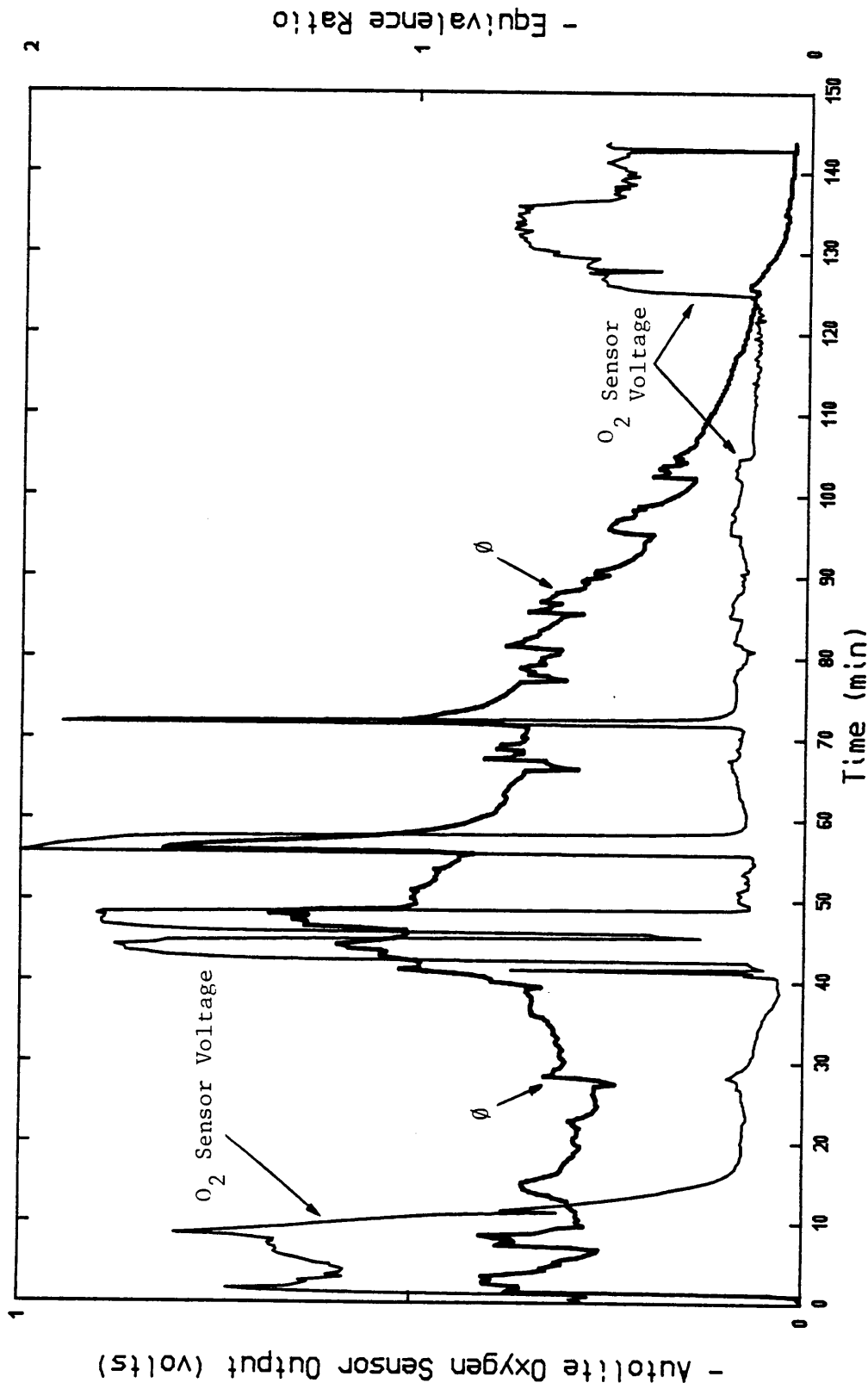
Figure 13  Equivalence Ratio and Autolite Oxygen Sensor Output During Exhaust Gas
Oxygen Sensor Test
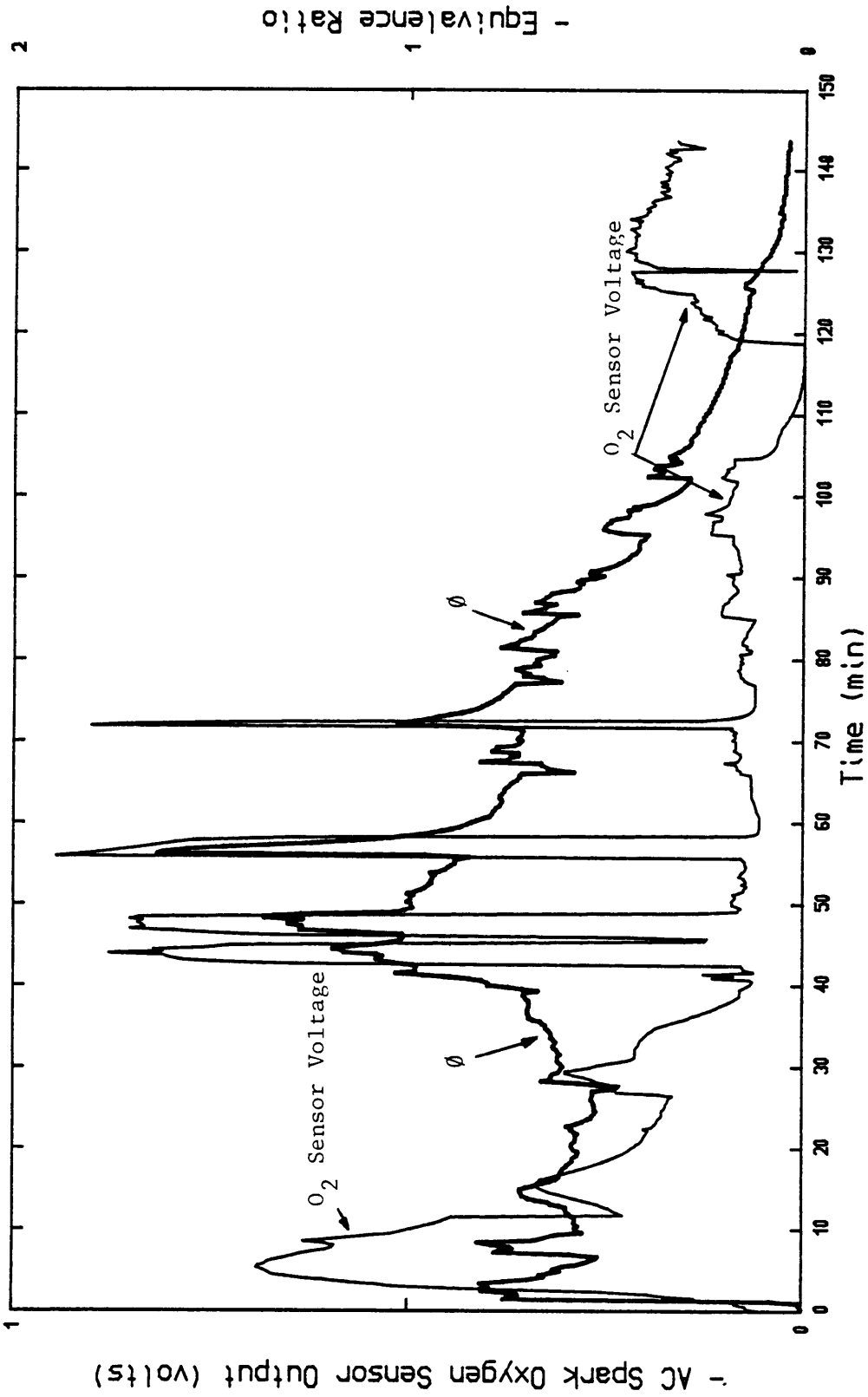
Figure 14  Equivalence Ratio and AC Spark Oxygen Sensor Output During Exhaust Gas
Oxygen Sensor Test
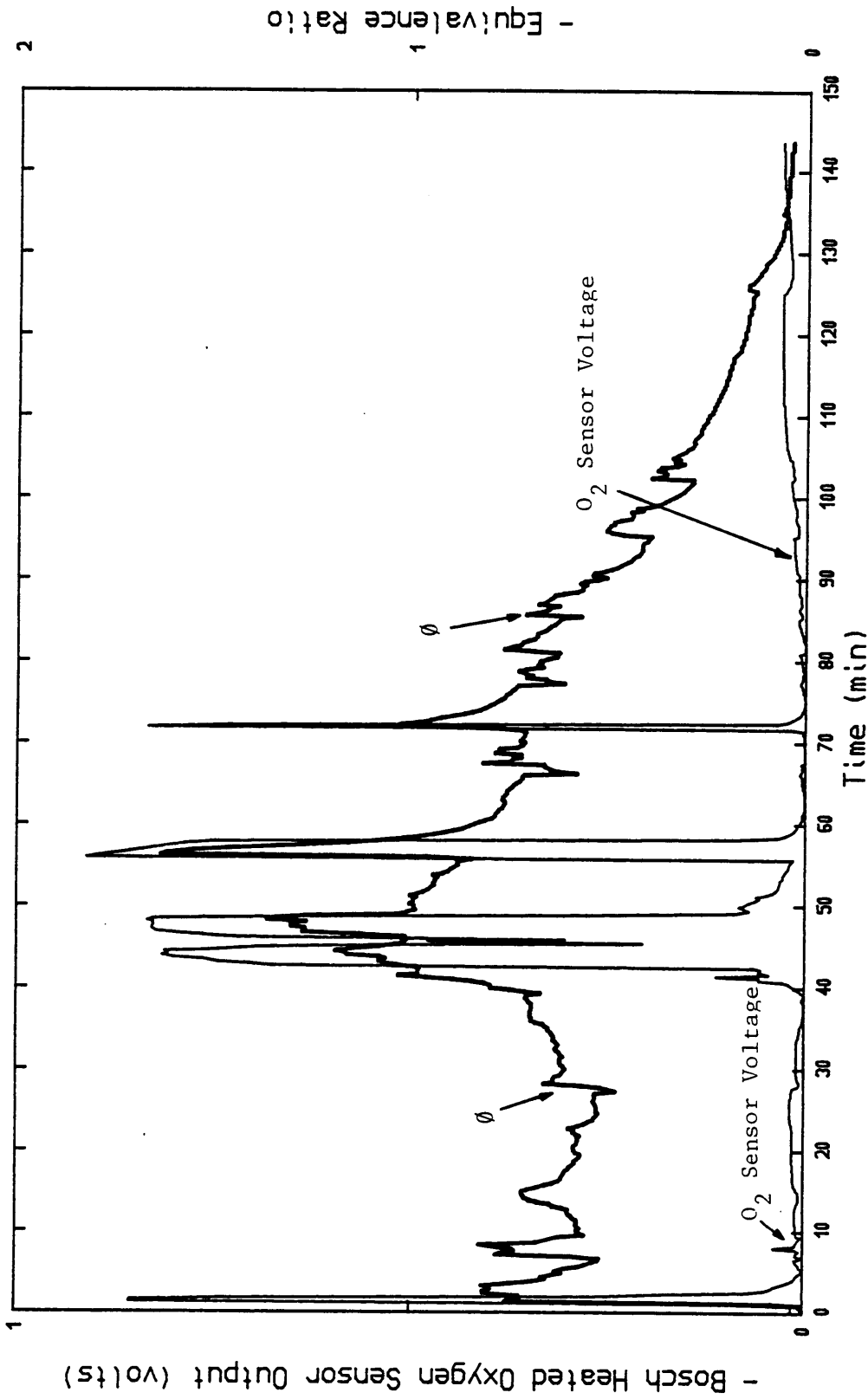
Figure 15  Equivalence Ratio and Bosch Heat Oxygen Sensor Output During Exhaust Gas Oxygen Sensor Test
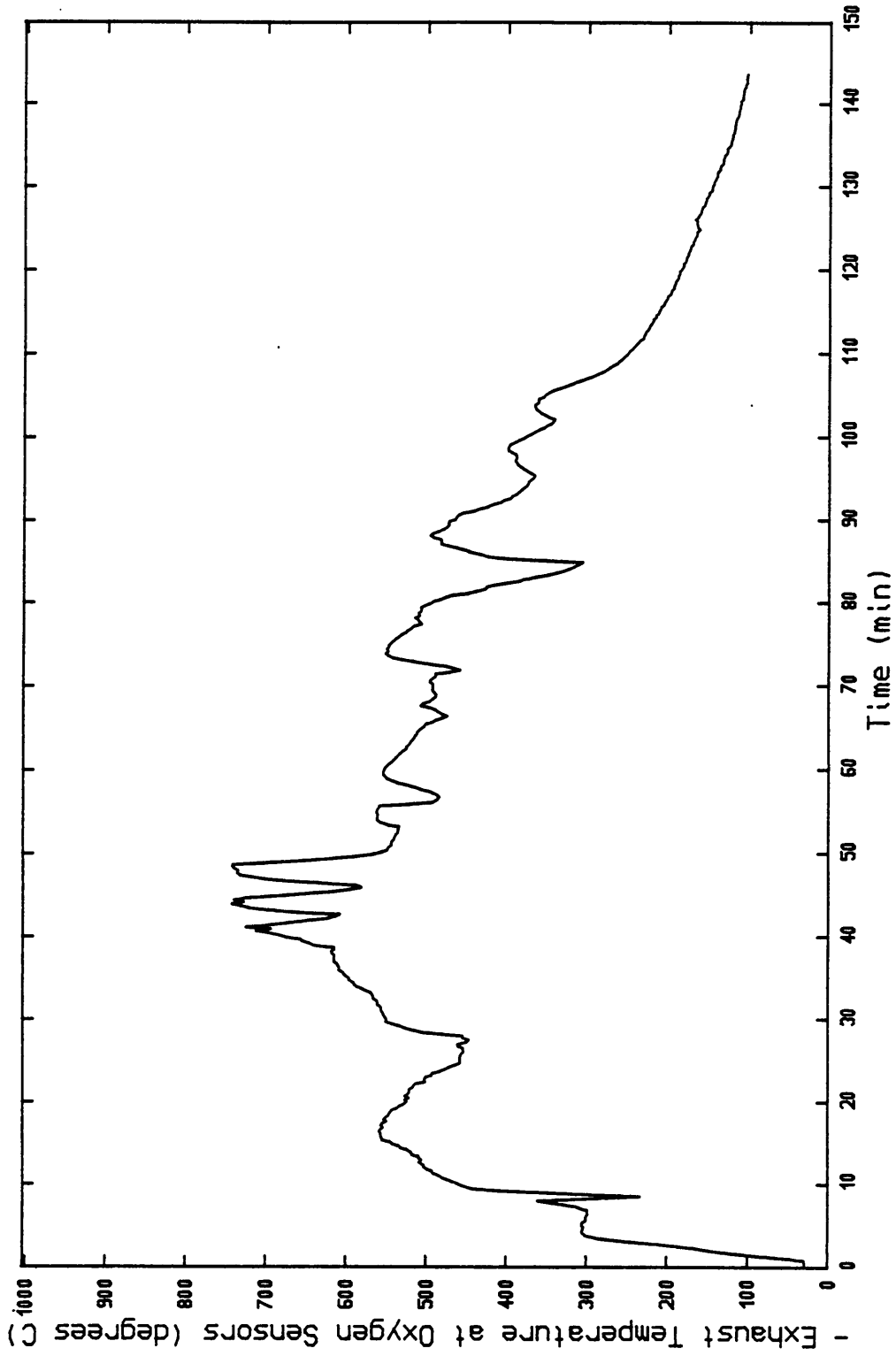
Figure 16  Exhaust Temperature, T7, During Exhaust Gas Oxygen Sensor Test

sensor, Figure 15, was able to make the most clear distinction; its output voltage was typically less than 50 mV for fuel-lean conditions and greater than 800 mV for fuel-rich conditions. Note that the first rich signal from the heated oxygen sensor, at 2 minutes, should be ignored since at that time only the kindling fire was burning. The fuel was not added until after six minutes.

Since the Autolite and AC Spark sensors were not heated they required some time to light-off at the beginning of the run (see Figures 13 and 14). The Autolite sensor appears to be fully lit-off at 15 minutes and the AC Spark sensor at 38 minutes. Although not fully lit-off, the AC Spark sensor could possibly have been used to detect the condition of the flow any time after 15 minutes if it was assumed that voltages less than 450 mV were indicative of fuel-lean conditions and that voltages greater than 450 mV were indicative of fuel-rich conditions. This assumption is made when zirconia exhaust gas oxygen sensors are used in automobile applications. In such applications a comparitor determines whether the sensor's output voltage is greater than or less than 450 mV and sets a flag in the digital control system.

The reason the unheated sensors did not light-off earlier is explained by the exhaust temperature plot, Figure 16. Note that the exhaust temperature at the sensors did not exceed $400^{\circ}C$, until after 10 minutes. Once the exhaust temperature did exceed $400^{\circ}C$ additional time was required to fully heat the thermal mass of the sensors. Notice also, that as the exhaust temperature at the sensors

dropped below 400$^\circ$ toward the end of the run, the voltage signals from the unheated sensors slowly degraded.

# Chapter VI

## DEVELOPMENT OF PRIMARY AND SECONDARY AIR FLOW
## CONTROL STRATEGIES

Previous chapters have presented the results of tests designed to lay the groundwork for the development of primary and secondary air flow control strategies. The objective of primary air flow control is to be able to control the power output from the combustor while the objective of secondary air flow control is to provide stoichiometric or lean gas mixtures to the secondary "catalytic" combustion region. This chapter describes the development of primary and secondary air flow control strategies and their integration into a control/data acquisition program for use on the prototype combustor.

## 6.1     PRIMARY AIR FLOW CONTROL STRATEGY

### 6.1.1     Introduction

Two control schemes which seem to make sense for primary air control, based on the biomass combustion characterization study, are proportional control and bang-bang control.

Proportional control of output power is feasible (at least for the range of air flows and fuels tested) because of the monotonic relationship between output power and primary air flow. However, to use proportional control effectively requires being able to measure the difference between the power needed at a particular time and the power being generated. For most heating operations this is hard to achieve.

Bang-bang control, on the other hand, is widely used for control in many heating operations. Results from the biomass combustion characterization study were quite favorable for bang-bang control, suggesting that turn down ratios of 5 to 1 and response times on the order of 2-3 minutes could be reasonably expected (at least for the fuels tested). Thus, a bang-bang control algorithm was developed to control primary air flow.

6.1.2    Strategy for Primary Air Control

A flow chart of the control algorithm developed for control of primary air is shown in Figure 17. The air flow is switched between high and low fire set points according to the status of a thermostat input switch. Catalyst entrance and exit temperatures are also monitored. Whenever the catalyst is in danger of becoming too hot the air flow is maintained at low fire regardless of thermostat status.

The algorithm begins by determining the current firing rate. If at high fire, it proceeds to check if the flow needs to be switched from high to low and if at low fire it checks to see if the flow needs to be switched from low to high.

In order to determine if a low to high switch needs to be made the algorithm first polls the thermostat switch. If the thermostat is calling for low fire then nothing is done. Otherwise, the algorithm checks the catalyst entrance and exit temperatures to determine if it would be "safe" to switch to high fire. The catalyst temperatures must be less
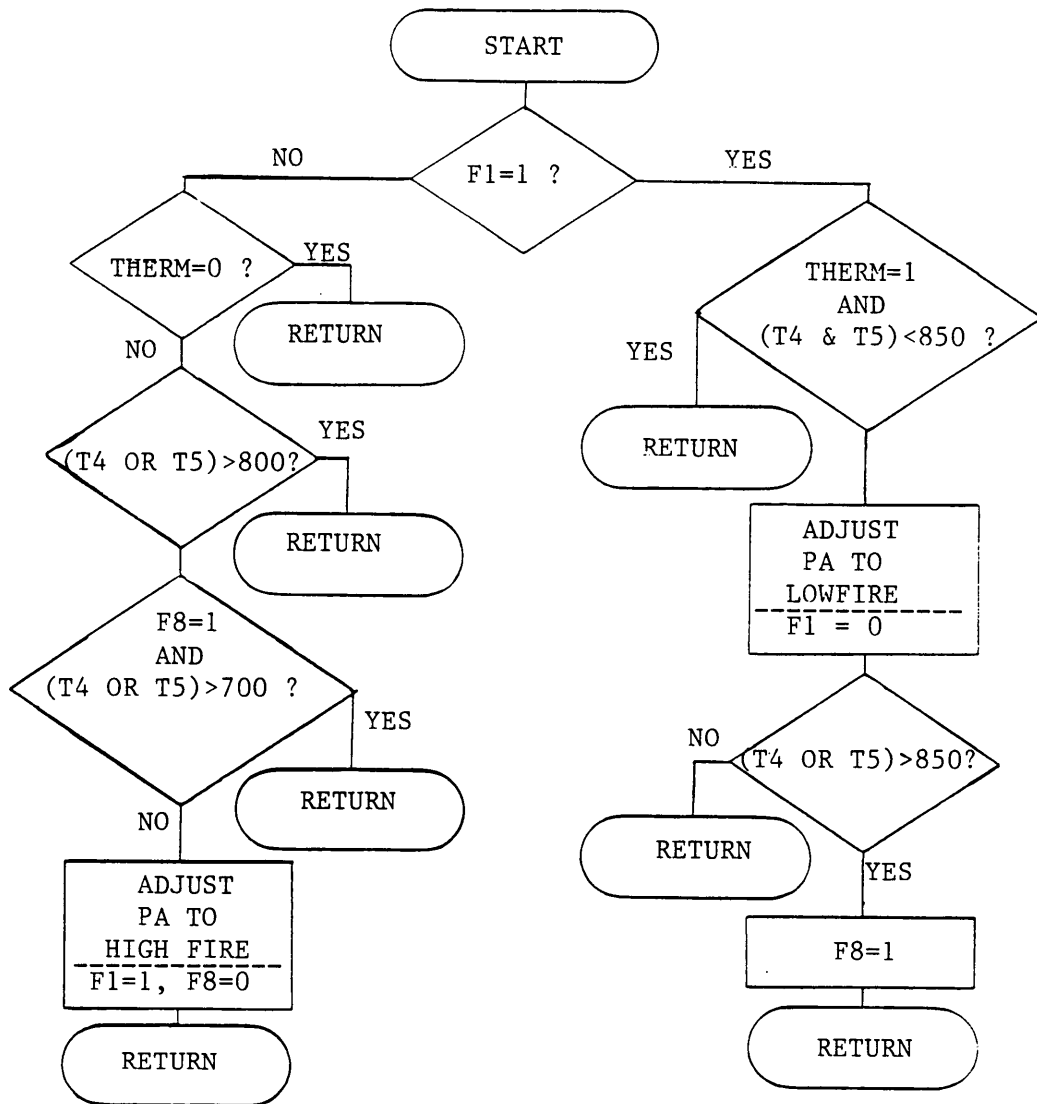
F1 = Primary Air Flow Status Flag (1=High Fire, 0=Low Fire)

THERM = Status of Thermostat (1=High Fire, 0 = Low Fire)

T4 and T5 = Catalyst Entrance and Exit Temperatures, Respectively

PA = Primary Air Flow Rate

F8 = High-Low Flag (1=flow "forced" to low fire")

Figure 17   Flow Chart of Primary Air Control Subroutine

than 800°C for the switch to be made and less than 700°C if the air flow had been "forced" to the low fire set point because of excessive catalyst temperatures while firing at high fire. The purpose of this lower temperature criteria is to prevent rapid cycling of the primary air flow which might thermally stress the catalyst. If the catalyst temperatures meet the criteria above then the flow is adjusted to high fire. Otherwise, the subroutine is exited.

In order to determine if a high to low switch needs to be made the algorithm polls the thermostat switch and the catalyst entrance and exit temperature probes. If the thermostat is calling for high fire and the catalyst temperatures are not in excess of 850°C, then the firing rate is left at high fire. Otherwise it is switched to the low fire set point.

## 6.2    SECONDARY AIR FLOW CONTROL STRATEGY

### 6.2.1    Introduction

Secondary air is only needed when the effluent from the combustion/gasification zone is fuel-rich. The biomass combustion characterization study showed that rich conditions frequently existed for several minutes after changing from high fire to low fire when the combustor/gasifier was fueled with cordwood or baled slash. But, of the three fuels tested only slash was able to sustain rich conditions. It was noted that often the effluent achieved maximum richness early, within the first 15 to 30 seconds, during a period of richness. This was always the case for rich periods caused by switches in the primary

air flow rate, but also occurred frequently when the off-gas from medium and high fire runs with slash ignited, causing a step change in the pyrolysis rate.

Neither bang-bang nor proportional control schemes are suitable for optimum control of secondary air. Bang-bang (on-off) control of secondary air, if designed to provide enough secondary air to meet peak rich conditions, would on the average add much more air than required, thereby reducing the thermal efficiency of the combustor. True proportional control, on the other hand, requires knowledge about how rich the effluent is. As has been discussed previously, inexpensive exhaust gas oxygen sensors capable of measuring equivalence ratios are not currently available. Current sensors are only able to differentiate between lean and rich conditions.

A psuedo-proportional control scheme was thus developed for control of secondary air. In the scheme secondary air is increased or decreased by steps. After each step the exhaust is analyzed, using a heated exhaust gas oxygen sensor, to determine whether the effluent is rich or lean. Based on the results and on previous conditions a decision is made to either step up, step down, or maintain the current flow rate.

## 6.2.2    Strategy for Secondary Air Control

The orifice used to meter the secondary air flow was capable or providing flowrates between 0 and 7 l/s. Set points were established at 0, 3, 4, 5, 6, and 7 l/s. Set points were not established between 0 and 3 l/s since the orifice had not been calibrated for this non-linear range. Note that the maximum secondary airflow needed according to the combustion characterization study was 5 l/s.

A flow chart of the control algorithm developed for control of secondary air is shown in Figure 18. The subroutine calls two other subroutines, "Rich" and "Lean." The subroutines are flow charted as well and are presented in Figures 19 and 20.

Prior to branching into either of the subroutines catalyst temperatures are polled. If the catalyst is too hot (catalyst entrance or exit temperature greater than $850^{\circ}C$), and the secondary air is on, then the secondary air is turned off, limiting the amount of oxygen available for combustion within the catalyst. Alternatively, the catalyst could be "flooded" with secondary air. The excess air would cool the catalyst. "Flooding" is preferred when adequately large secondary air flow rates are available because the tars and creosotes, continue to be burned, thereby minimizing potential fouling of the oxygen sensor.

If the catalyst is not too hot, the heated oxygen sensor is then polled to determine whether the flow is fuel-rich or fuel-lean. The heated sensor was selected for use from the three sensors tested since the heated sensor's output is not dependent on exhaust temperatures.

START

(T4 OR T5)>850?

YES — "TOO HOT"

F3=1?

NO — RETURN

TURN SAIR
OFF
--------------
F3=0

RETURN

NO — RICH?

GOSUB "LEAN"

YES — GOSUB "RICH"
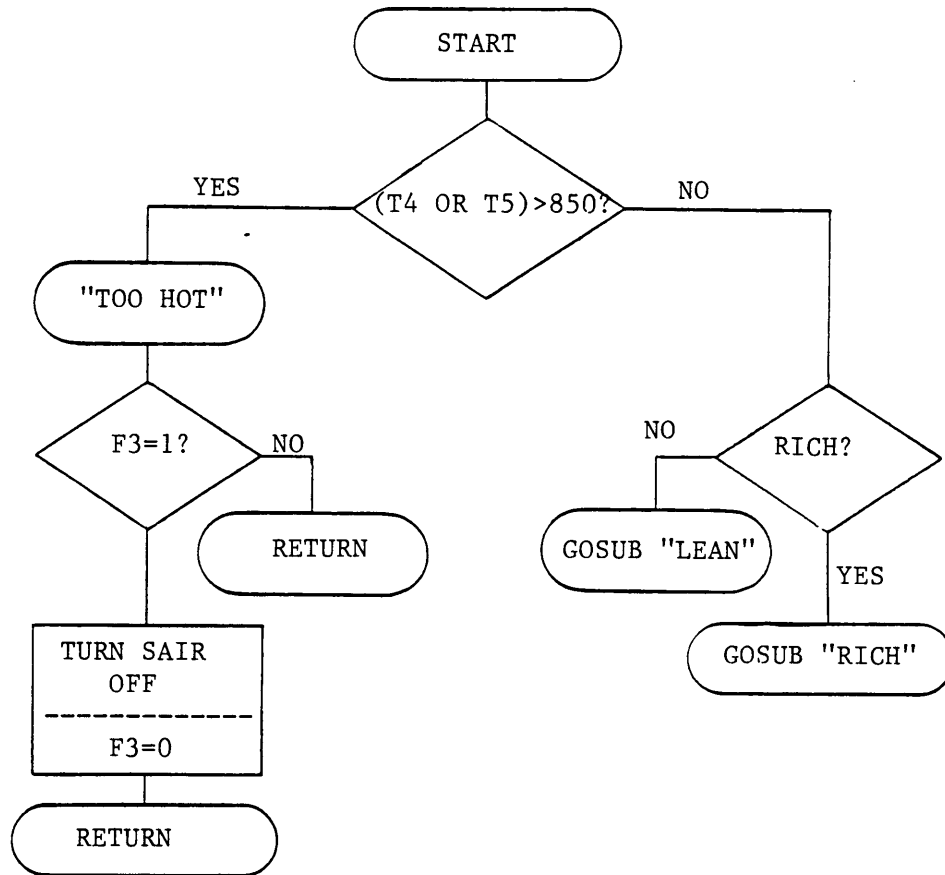
T4 AND T5 = Catalyst  Entrance and Exit Temperatures,
           Respectively

F3 = Secondary Air Flow Flag (1=ON, 0=OFF)

SAIR = Secondary Air Flow Rate

F5 = Toggle Flag (1=ON, 0=OFF)

F7 = Maximum Secondary Air Flow Flag (1=Max Flow)

Figure 18   Flow Chart of Secondary Air Control Subroutine
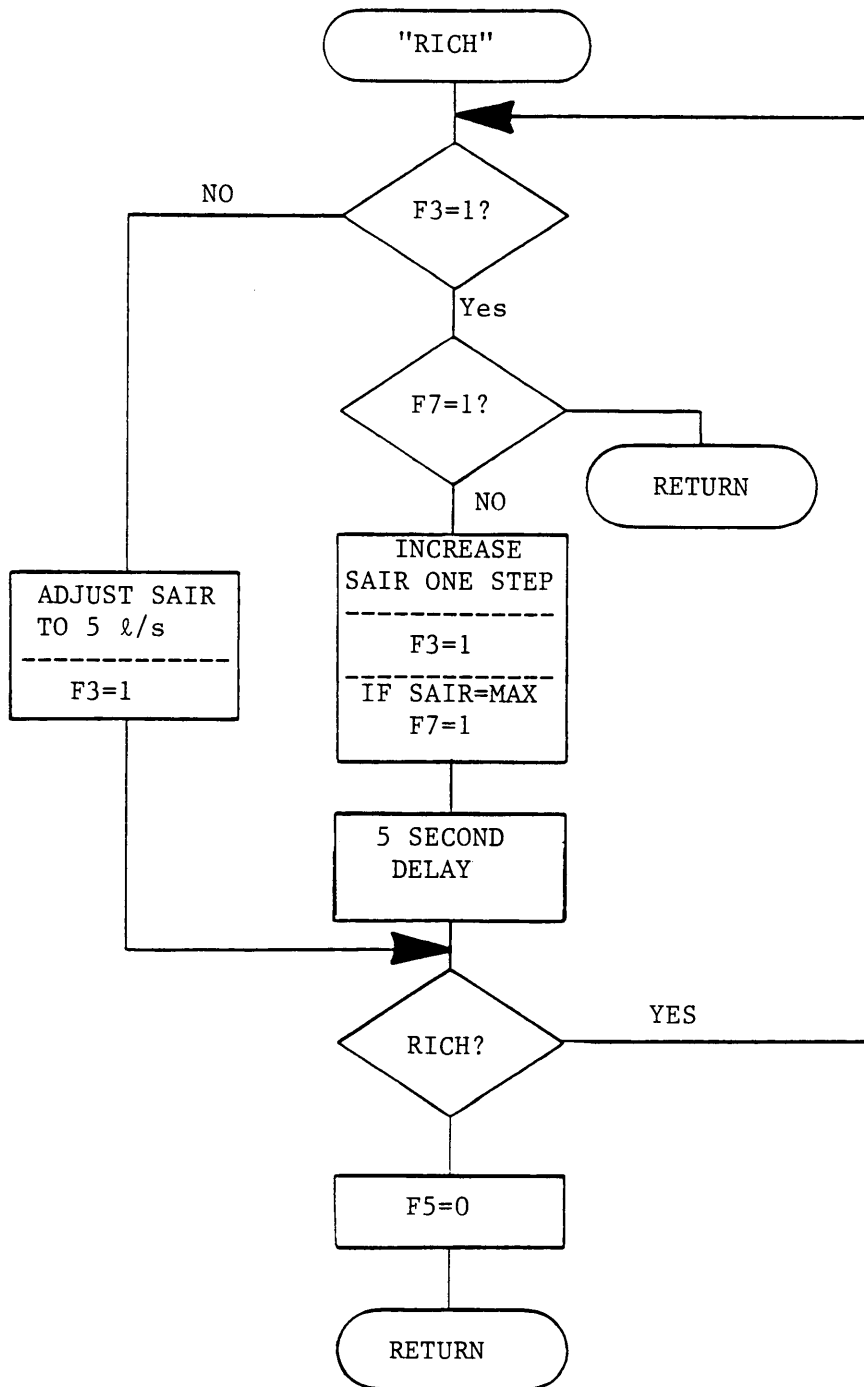
Figure 19   Flow Chart of Subroutine "RICH"
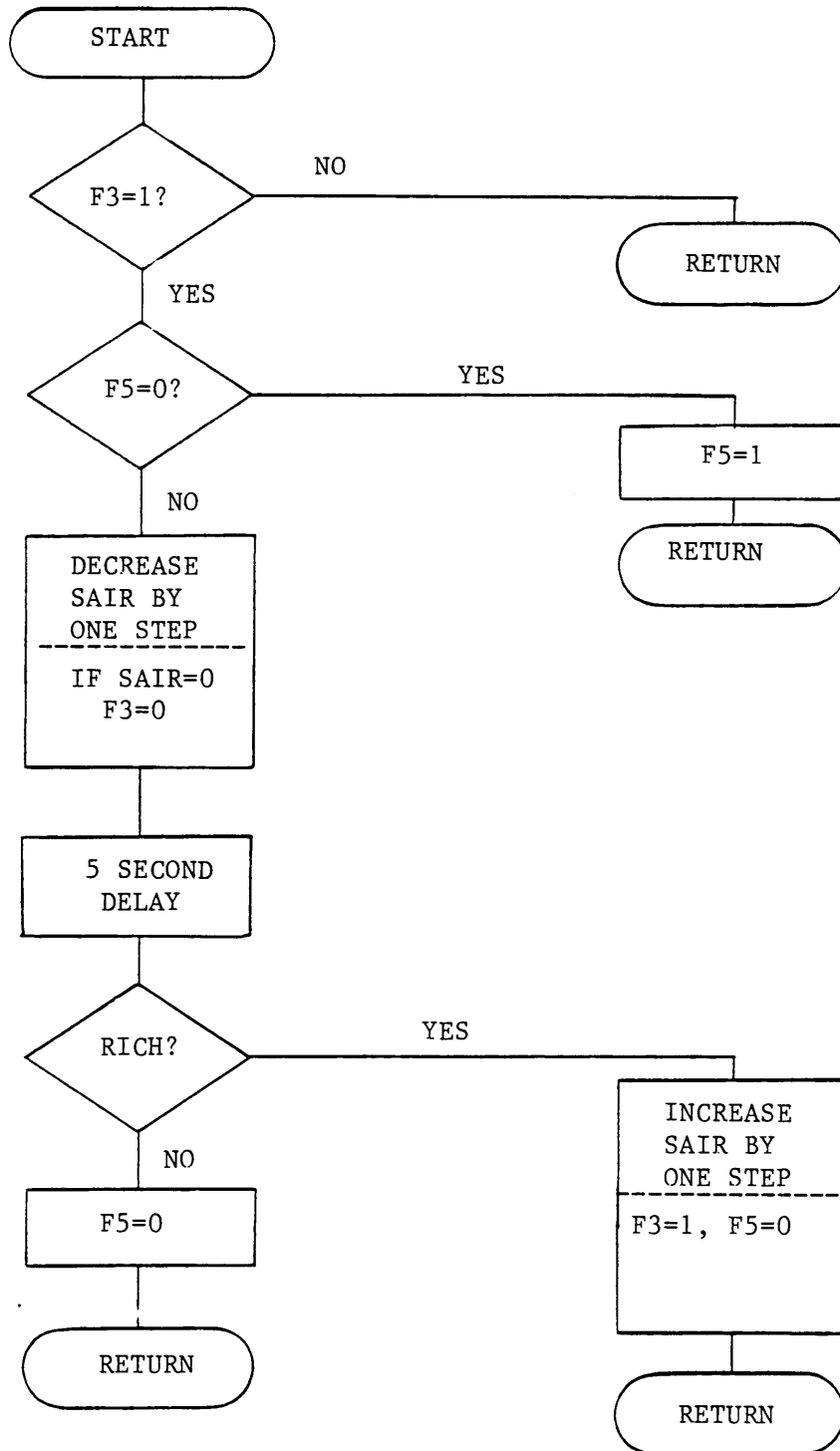
Figure 20  Flow Chart of Subroutine "LEAN"

Voltage levels greater than 0.45 volts were considered to indicate rich flows and those less than 0.45 volts, lean flows. Rich flows were handled by subroutine "Rich" while lean flows were handled by subroutine "Lean."

## 6.2.2.1 Subroutine "Rich"

Given that the flow is rich, the secondary air control algorithm turns the secondary air flow to 5 l/s if it is not currently on and increases it by 1 l/s if it is currently on, unless the maximum secondary air flow (7 l/s) is already being used.

The extra large step to 5 l/s when the secondary air has not been on is designed to provide an adequate air flow during those peaks of richness which were observed to frequently occur within the first 15 to 30 seconds of fuel-rich periods. The large initial step gets to the mid-range set point much more quickly than would a series of 3 shorter steps; 0 to 3 l/s, 3 to 4 l/s, and finally 4 to 5 l/s. The length of time required to complete a step is approximately 7 seconds: 4 seconds to turn the valve, and 3 seconds system response time. Once at the mid-range set point the flow can be adjusted either up or down.

Once the first step is taken the algorithm delays for 5 seconds to give the new exhaust/air mixture time to get through the secondary, catalytic, combustor and arrive at the oxygen sensor. The oxygen sensor is then polled. If the flow is still rich the process is repeated and another step is taken if possible. If the flow is lean then the flow

is left at that set point for approximately 30 seconds unless it gets rich again, in which case the flow is increased as before. The intent of the 30 second delay is to minimize oscillation between rich and lean flows. Such a scheme provides a small amount of excess air, but this is not a disadvantage because some excess air is appropriate. The flag, F5, shown in the flow charts is used by the data acquisition and control program to keep track of how long the secondary air flow has been kept at a particular set point. Basically, two cycles of data acquisition, primary air control, and secondary air control take approximately 30 seconds. Thus F5 is "toggled" from low to high the next time through the secondary air control subroutine without the flow being changed, unless of course, the flow becomes rich.

### 6.2.2.2    Subroutine "Lean"

Given that the flow is lean, the secondary air control algorithm reduces the secondary air flow by one step if the secondary air is currently on and has been at the current set point for 30 seconds (as indicated by the toggle flag, F5).

Once the new flowrate has been established, the algorithm delays for 5 seconds again providing time for the new exhaust/air mixture to arrive at the oxygen sensor. The oxygen sensor is then polled. If the flow is lean the toggle flag is set low and the flow is left at the new set point for approximately 30 seconds. If the flow is rich the flowrate is increased by a step and left for an additional 30 seconds.

## 6.3 INTEGRATION OF CONTROL STRATEGIES INTO DATA ACQUISITION AND CONTROL PROGRAM

The data acquisition and control program has been included in this report as Appendix C. The main program, lines 50 to 230, shows how the data acquisition, the primary air control, and the secondary air control tasks are integrated.

Basically, once the program and both air flows have been initialized (lines 50 to 140) the program sequences from data acquisition, to primary air control, to secondary air control. However, whenever the primary air controller switches the primary air flow, the sequence is broken and starts over with data acquisition. This insures that the switch in primary air flow is recorded immediately.

Since the computer was required to control the air flows as well as take data, the time intervals between sampling were not constant but were a function of what happened during the periods of primary and secondary air control.

Note that although the control algorithms in the program are identical to those presented in this chapter, there are some differences in the coding (i.e., the algorithms have been simplified for presentation).

# Chapter VII

## RESULTS AND DISCUSSION OF CATALYTIC
## COMBUSTOR/GASIFIER PERFORMANCE TESTS

Performance tests were conducted on the prototype combustor/gasifier implemented with automatic primary and secondary air flow control and secondary catalytic combustion. The objectives of the tests were to determine for each of the test fuels:

1. output power turn down ratio achievable with air flow control and catalytic combustion in place.

2. the ability of the secondary air flow control strategy to maintain stoichiometric or fuel-lean flows through the catalytic combustor, and

3. the combined effectiveness of the secondary air flow control strategy and the catalytic combustor to convert chemical energy in the effluent into thermal energy, thereby increasing efficiency and reducing emissions.

Data collected during the tests are presented graphically in Appendix E. Section 7.1 describes the types of plots used to present the data. Each test is then discussed in sections which follow. Finally, based on the results of the performance tests, the prototype combustor/gasifier is evaluated.

## 7.1  PRESENTATION OF DATA

Sets of 6 plots are used to present the data from each test. The sets of plots can be found in Appendix E where they are organized by fuel type. Five of the six plot types are very similiar to those used to present the biomass combustion characterization study data (see Section 6.2 for reference).

The first plot in each set of six shows the primary and secondary air flow rates and the status of the thermostat switch throughout the run. Note that the thermostat switch was the only input to the system during the prototype performance tests. Since the thermostat switch is used to control the primary air flow, the primary air flow rate ("high" or "low") should correspond to the status of the thermostat switch ("high" or "low") unless the catalyst becomes too hot, in which case the primary air flow should remain at the "low" setting reguardless of the thermostat status.

The second plot in each set presents the primary combustion zone temperatures, T2 and T3, and the third plot presents the calculated heat release rate (i.e., output power). These plots are identical to those used to present the biomass combustion characterization results.

Large fluctuations typically occur in the calculated heat release rate immediately after changes in the primary and/or secondary air flow rates. The fluctuations however, do not represent a true phenomena, but rather are due to differences in instrument/system response times, i.e., a 5-10 second delay in the exhaust sampling system. Since the

heat release rate is a strong function of the amount of carbon present in the exhaust and the exhaust flow rate (see Heat Release Rate Calculation, Section 3.2.5.4.), and since changes in the exhaust flow rate are recognized 5 to 10 seconds before accompanying changes the exhaust composition the calculated heat release rate may be grossly in error whenever the exhaust flow rate is changing rapidly, as is the case during transitions between air flow settings.

The fourth plot in each set, as in the biomass combustion characterization study, presents the exhaust gas oxygen concentration (dry basis) and the calculated equivalence ratio as functions of time. It also shows the output voltage from the Bosch heated oxygen sensor. Due to the 5 to 10 second sampling system delay an exact correlation does not exist between the status of the oxygen sensor and the calculated equivalence ratio. Thus, momentary periods of richness (5 to 10 seconds) were sometimes recorded in the equivalence ratio data but not in the oxygen sensor data. The output of the oxygen sensor correlates well with the equivalence ratio data for sustained periods of richness or leanness though. Since the secondary air control algorithm trys to maintain fuel-lean flows, the oxygen sensor voltage should be approximately zero (i.e., lean) throughout each run unless the catalyst becomes too hot and the secondary air is turned off. Thus, the absence of sustained rich signals from the oxygen sensor is evidence that the secondary air flow control system is, for the most part, maintaining lean flows.

The fifth plot in each set presents the gas concentrations (dry basis) of carbon monoxide and carbon dioxide as functions of time and is identical to plots used to present the earlier data.

Finally, the sixth plot in each set shows the catalyst entrance and exit temperatures during the run. The increase in temperature through the catalyst is a good measure of the catalytic activity.

## 7.2 DISCUSSION OF DATA

The performance of the prototype catalytic combustor/gasifier when fueled with each of the three test fuels is discussed in the following subsections. As in discussion of the biomass combustion characterization study data, discussion is limited to those periods for which combustion is considered to have been "established" (see Section 4.2.1).

### 7.2.1 Performance of Prototype When Fueled with Cordwood

Data from the prototype cordwood performance test are presented in Figures 92-97. Combustion is considered to have been "established" during the period between 40 and 120 minutes.

Figure 92 shows the primary and secondary air flow rates and the status of the thermostat switch throughout the run. The one-to-one correspondence between the primary air flow rate and the status of the thermostat indicates that at no point during the run was it necessary to "force" the primary air flow rate from "high" to "low" in order to protect the catalyst.

Secondary air, as predicted by the biomass combustion characterization study, was only required when the primary air flow rate was switched from "high" to "low". Such switches occurred at 49, 69, and 101 minutes, as shown in Figure 92. The response of the equivalence ratio to the changing air flows is shown in Figure 95. Notice that the initial midrange secondary air flow rate of 5 l/s, was more than adequate to "lean-out" the flows in each case and that the flow rate was reduced by steps until it was off, as quickly as the algorithm allowed (90 seconds). Remember that the algorithm requires the air flow to be reduced by one step at a time and that each step must be maintained for at least 30 seconds.

The effect of the additions of secondary air on the exhaust gas concentrations of oxygen, carbon monoxide, and carbon dioxide are shown in Figures 95 and 96. Notice that the effluent only became rich momentarily after the primary air flow switched from "high" to "low" and prior to the initiation of the secondary air flows.

Combustion during the "established" period was characterized by:

1.  average low and high fire output powers of approximately 9 and 38 kW respectively, exhibiting a turn down ratio of approximately 4 to 1 (Figure 94),

2.  average carbon monoxide concentrations of about 0.5 percent (Figure 96),

3.  average carbon dioxide concentrations of about 11.5 percent (Figure 96), and

4.   average oxygen concentrations of about 9.5 percent (Figure 95).

Notice that the concentration of carbon monoxide was lower during periods of low fire (compare Figures 92 and 96) although the temperature rise through the catalyst indicates the catalyst was more active during high fire periods (compare Figures 92 and 97). This seems to suggests that better conversion is achieveable at lower exhaust flow rates where the effluent has more residence time within the catalyst.

7.2.2    Performance of Prototype when Fueled with Slash

Data from the first slash performance test are presented in Figures 98-103.  Combustion is considered to have been "established" during the period between 20 and 100 minutes.

Figure 98 shows the primary and secondary air flow rates and the status of the thermostat switch throughout the run.  Notice that although the thermostat called for "high" fire during the period between 8 and 45 minutes the primary air controller "forced" the primary air flow to its low fire setting 4 times, at approximately t = 23, 27, 32, and 37 minutes.  Notice also, that twice the secondary air was very briefly "forced" off as well, at approximately t = 33 and 37 minutes.  The effects of the air flow switches on the equivalence ratio (Figure 101) and the exhaust gas concentrations (Figures 101 and 102) are similiar to those discussed previously for the cordwood performance test.

The overall effectiveness of the catalytic combustor/gasifier was affected by the cycling. The response of the combustor/gasifier to energy needs, as signaled for by the thermostat, was slowed considerably by the "forced" periods of low fire. Also, although the cycling had no apparent immediate effect on the catalyst, it is not known what effect such cycling would have over the long term.

Some of the cycling can be eliminated if a lower flow rate is used for the high fire primary air flow set point. This was shown by running a second test with slash with the high fire primary air flow set point reduced from 16 to 13.5 l/s. This test is discussed later. An alternative approach to eliminating the cycling would be to design a catalytic combustor that could dissipate heat more rapidly and thus not overheat as often.

Figure 98 shows that the effluent from the primary combustion/gasification zone was rich for 17 minutes during the period between 45 and 62 minutes, requiring the addition of secondary air. Notice that during most of that period, t = 47 to 58 minutes, the secondary air controller maintained a secondary air flow of 3 l/s.

The equivalence ratio (Figure 101), averaged about 0.9 (nearly stoichiometric) while the carbon monoxide and carbon dioxide concentrations (Figure 102) averaged approximately 0.5 and 17.0 percent respectively during the period. The fluctuations in the equivalence ratio and gas concentration plots over the period were caused by the secondary air controller's attempts to reduce the

secondary air flow rate. Each time the flow was reduced the effluent became rich during the 5 second delay at the reduced flow rate and consequently the flow rate was returned to its original setting (see Secondary Air Flow Control Strategy, Section 6.2). Remember though that data was not collected while the computer was running the air flow control algorithms. Therefore, the changing status of the oxygen sensor (lean to rich to lean) is not observed in the data. The fluctuations in the equivalence ratio and the gas concentrations can only be observed in the data because of the sampling system delay.

The heat release rate during the 17 minute period when the combustor/gasifier was running rich is shown in Figure 100. Notice that the average heat release rate for the low fire condition was approximately 10 kW greater than for other low fire conditions, during the same run, which did not use secondary air. Clearly there is some coupling in the prototype combustor/gasifier between the addition of secondary air and the primary combustion/gasification process.

Two explanations for the coupling are (1) oxygen from the secondary air flow helped support primary combustion/gasification and/or (2) increased temperatures in the lower portion of the combustor/gasifier, due to secondary combustion (catalytic and non-catalytic), heated the primary combustion/gasification zone by radiation, thereby increasing the gasification rate. Note that during several runs utilizing catalytic combustion (some documented in this report and others not) the lower portion of the combustor got hot enough to glow.

Combustion during the "established" period was characterized by:

1.  average low and high fire output powers of approximately 16 and 44 kW respectively, exhibiting a turn down ratio of less than 3 to 1 (Figure 100),

2.  average carbon monoxide concentrations of about 0.7 percent (Figure 102),

3.  average carbon dioxide concentrations of about 15.0 percent (Figure 102), and

4.  average oxygen concentrations of about 5.0 percent (Figure 101).

As in the cordwood performance test, the concentration of carbon monoxide was lower during periods of low fire (compare Figures 98 and 102) although the temperature rise through the catalyst indicates the catalyst was more active during high fire periods (compare Figures 98 and 103).

Data from the second slash performance test, with the high fire primary air flow set point reduced from 16 l/s to 13.5 l/s, are presented in Figures 104-109. Combustion is considered to have been "established" during the period between 10 and 100 minutes.

Figure 104 shows the primary and secondary air flow rates and the status of the thermostat switch throughout the run. Notice that the high fire primary air flow set point was 13.5 l/s rather than 16 l/s and

notice that the primary air flow was only "forced" to the low fire set point twice during separate high fire periods (at t = 14 and 42 minutes). The secondary air never needed to be "forced" off in order to protect the catalyst.

The catalytic combustor/gasifier ran rich during two periods, from approximately t = 20 to 51 minutes and t = 53 to 62 minutes. During the first rich period the primary air flow was switched from high fire to low fire and back to high fire. The second, briefer, rich period occured only during low fire. Notice also the need for secondary air after switches in the primary air flow from "high" to "low" as predicted by the biomass combustion characterization study.

While the combustor was running rich the secondary air controller was again able to maintain fuel-lean conditions in the effluent entering the catalyst, as shown by Figure 107. Note though, that the secondary air tended to cycle from 5 l/s to 4 l/s to 3 l/s to 0 l/s and back to 5 l/s instead of maintaining a steady 3 l/s flow. Whenever the controller tried to turn the flow off it should have detected that the effluent was still rich requiring the flow to be maintained at the previous setting (3 l/s). The five second delay between when the flow was turned off and when the oxygen sensor was polled was not long enough to detect that the flow had become rich and as a consequence, more secondary air was added during the rich periods than necessary, reducing the combustor/gasifier's thermal efficiency. A second consequence was the effluent was slightly rich during those periods when the secondary air flow was turned completely off.

Combustion during the established period was characterized by:

1. average low and high fire output powers of approximately 14 and 45 kW respectively, exhibiting a turn down ratio of approximately 3 to 1 (Figure 106),

2. average carbon monoxide concentrations of about 0.7 percent (Figure 108),

3. average carbon dioxide concentrations of about 15.0 percent (Figure 108), and

4. average oxygen concentrations of about 5.0 percent (Figure 107).

Note that very few "explosions" occurred during either of the prototype slash performance tests as compared to the biomass combustion characterization tests with slash. It is suspected that the presence of the catalytic combustor increased the temperatures in the lower portion of the prototype combustor/gasifier enough to maintain secondary non-catalytic combustion of the effluent exiting the combustion/gasification zone.

7.2.3    Performance of Prototype when Fueled with Corn Fodder

Data from the first and second corn fodder performance tests are presented in Figures 110-115 and Figures 116-121 respectively. The results of the two tests are very similar. The second test has only been included to substantiate the results of the first.

Combustion is considered to have been "established" for the first test during the period between 7 and 16 minutes and for the second during the period between 10 and 20 minutes. During these periods, as predicted by the biomass combustion characterization study, no secondary air was required nor was the primary air "forced" from "high" to "low" in order to protect the catalyst (Figures 110 and 116). Note the use of secondary air during the start up phase of each test, however. This also was predicted by the biomass combustion characterization study (i.e., it was noticed that during light-off the effluent became rich for as long as 4 minutes). Since combustion during the "established" period is of primary concern the need for secondary air during start-up will not be discussed.

Combustion during the "established" period for the first test was characterized by:

1.  average low and high fire power outputs of approximately 10 and 38 kW respectively, exhibiting a turn down ratio of approximately 4 to 1 (Figure 112),

2.  average carbon monoxide concentrations of about 0.6 percent (Figure 114),

3.  average carbon dioxide concentrations of about 12.5 percent (Figure 114), and

4.  average oxygen concentrations of about 7.8 percent (Figure 113).

Combustion during the "established" period for the second test was characterized by:

1. average low and high fire power outputs of approximately 10 and 39kW respectively, exhibiting a turn down ratio of approximately 4 to 1 (Figure 118),

2. average carbon monoxide concentrations of about 0.5 percent (Figure 120),

3. average carbon dioxide concentrations of about 12.0 percent (Figure 120), and

4. average oxygen concentrations of about 8.2 percent (Figure 119).

Note once again the strong correlation between firing rate and the carbon monoxide concentration.

The results of the prototype performance tests are summarized in Table 4.

## 7.3    EVALUATION OF PROTOTYPE CATALYTIC COMBUSTOR/GASIFIER

The ability of the prototype catalytic combustor/gasifier to provide controllable output power while maintaining a clean exhaust for a variety of fuels is evaluated in the following paragraphs, based on the results of the performance tests.

The output power turn down ratios achieved during the performance tests were approximately 4 to 1 for cordwood and corn fodder and

Table 4.   Summary of Results of Prototype Evaluation Tests

| Item | Fuel Type & Run No. Cord-Wood | Baled Slash No. 1 | Baled Slash No. 2* | Corn Fodder No. 1 | Corn Fodder No. 2 |
|---|---|---|---|---|---|
| Avg. Percent Carbon Monoxide | 0.5 | 0.7 | 0.7 | 0.6 | 0.5 |
| Avg. Percent Carbon Dioxide | 11.5 | 15.0 | 15.0 | 12.5 | 12.0 |
| Avg. Percent Oxygen | 9.5 | 5.0 | 5.0 | 7.8 | 8.2 |
| Output Power at High Fire | 38 | 44 | 45 | 38 | 39 |
| Output Power at Low Fire | 9 | 16 | 14 | 10 | 10 |

*High fire set point reduced to 13.5 l/s from 16.0 l/s.

approximately 3 to 1 for baled slash. Note that had there not been coupling between the primary and secondary combustion zones the turn down ratio for baled slash would have been higher.

The power turn down ratio for each fuel was less than predicted by the biomass combustion characterization study (see Table 3) primarily because the predictions from the biomass combustion characterization study were based on output powers that were maintained at the "high" and "low" fire set points throughout complete runs whereas during the performance tests the firing rate was alternated between the "high" and "low" fire set points. Alternating between the set points typically did not provide enough time for the output power to reach steady-state values. Consequently the effective power turn down ratio was less than that suggested by the earlier tests.

In this research the concentration of carbon monoxide was monitored and used as a measure of the "cleanliness" of the exhaust. Average carbon monoxide emissions during each performance test were substantially lower than those measured during either the high fire or low fire biomass combustion characterization tests for the same fuels (see Table 3).

Crude determinations of carbon monoxide reductions due to the secondary catalytic conversion system can be made by comparing average carbon monoxide concentrations during the performance tests to the average of the average high and low fire carbon monoxide concentrations determined during the biomass combustion

characterization study for the same fuels. Using this approach carbon monoxide emissions were calculated to have been reduced by approximately three-fourths.

It is possible that even greater reductions in carbon monoxide concentrations can be achieved by improving the catalyst design so that the effluent has more exposure to catalytic material, i.e., more residence time within the catalyst. This idea seems to be supported by the fact that during prototype performance tests the concentrations of carbon monoxide were lower during periods of low fire than during periods of high fire although the catalyst was more active at high fire.

# Chapter VIII

## CONCLUSIONS

Conclusions that can be drawn from the biomass combustion characterization study for the combustor design used and the range of primary air flows studied are:

1. The equivalence ratio increases monotonically with increases in the primary air flow rate for each of the three test fuels.

2. The output power increases monotonically with increases in the primary air flow rate for each of the three test fuels.

3. Of the three test fuels only baled slash is able to sustain fuel-rich effluent for more than 2-3 minutes at a time.

4. Effluent from combustion/gasification of baled slash and cordwood often becomes rich briefly after step changes in the primary air flow rate from high fire to low fire settings.

5. Non-catalytic secondary combustion, although difficult to sustain, may occur during runs with slash at medium to high firing rates.

Primary and secondary air flow control strategies and catalytic secondary combustion were successfully implemented on the prototype combustor/gasifier. Conclusions that can be drawn from the performance tests of the prototype catalytic combustor/gasifier are:

1. The primary air control system as developed and implemented on the prototype can achieve turn down ratios of approximately

4 to 1 for cordwood and corn fodder and approximately 3 to 1 for baled slash.

2.  Zirconia-type automobile exhaust gas oxygen sensors can be used in the combustion environment of biomass fuels at least for short periods of time (see Recommendations).

3.  The secondary air control system as developed and implemented on the prototype is able to maintain fuel-lean flows except when the catalyst becomes too hot, requiring the secondary air flow to be shut off.

4.  Substantial reductions in carbon monoxide emissions can be realized with the use of a secondary catalytic combustion system. (The prototype combustor/gasifier typically achieved reductions of approximately three-fourths.)

# Chapter IX

## RECOMMENDATIONS

The research presented in this thesis was conducted as the first step toward the development of a practical, large-scale catalytic combustion/gasification system. The following are recommended as possible directions for further research:

1.  The woodstove catalysts and the automobile exhaust gas oxygen sensors were shown by this research to work effectively in the combustion environment of biomass fuels, but need to be tested for long term effectiveness and durability. Potential concerns are masking, plugging, poisoning, and the effects of thermal cycling.

2.  Study the effect of different catalyst designs on the conversion efficiency of the catalyst and on the overall system performance. Results of the prototype performance tests suggest that conversion could perhaps be enhanced by greater exposure of the exhaust to the catalyst. The performance tests, using slash, also demonstrated a need for a catalyst design that is less susceptible to overheating.

3.  The characteristics of combustion/gasification of biomass fuels are affected by a number of parameters other than the primary air flow rate, which was studied during the biomass combustion characterization study. Study of several additional parameters

would provide valuable information. Two studies that might be particularly instructive are:

a) the effect of insulating the combustor/gasifier, and

b) the effect of introducing primary air in different ways (alternate locations, heating, different nozzle designs, etc.).

Note that study of the combustion characteristics of a wider variety of biomass fuels would be useful as well.

4.  The secondary air flow control sytem could be optimized. The cycling between set points during the second performance test using baled slash (see Section 7.2.2), when a steady 3 l/s secondary air flow was all that was needed, is particularly disconcerting.

5.  The secondary catalytic combustion system should be tested to determine its ability to reduce emissions other than carbon monoxide.

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# Appendix A

## CALIBRATION CURVES FOR AIR FLOW ORIFICES

Primary and secondary air flow orifices were calibrated using tracer gas techniques. The orifice plates are aluminum disks with holes drilled through their centers. The disks were mounted in pipe unions and were sealed with O-rings on either side.

Carbon monoxide was used as the tracer gas. A known flow rate, as measured with a bubble flow meter, was introduced into each air line downstream of the orifice. Samples were then drawn from the air lines approixmately one meter further downstream and analyzed with a Horiba PIR 2000 carbon monoxide analyzer to determine the carbon monoxide concentration in the flow. A range of air-flow rates, based on local atmospheric conditions (T = $27^{O}$C, P = 94 kPa), were calculated for each orifice in order to develop calibration curves. Two orifices were calibrated for the primary air flow and one for the secondary air flow (see Figures 21-23).

P. Air Rate = (Pressure)* 0.263 - 0.492

P. Air Rate = 12.60 - 163.4/(Pressure)

Absolute Pressure (kPa)
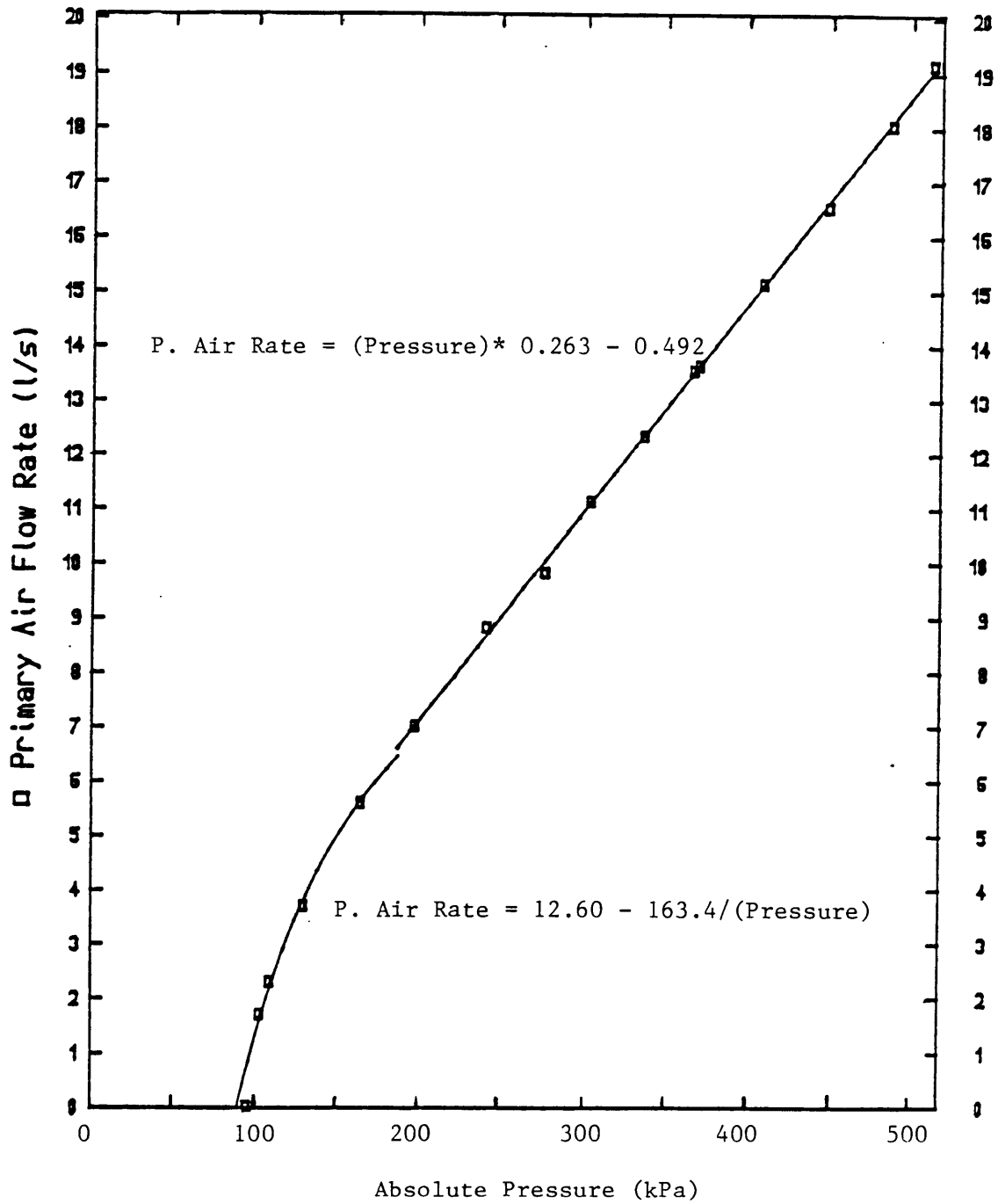
Figure 21   Calibration Curve for Orifice #1

P. Air Rate = (Pressure)* 0.113
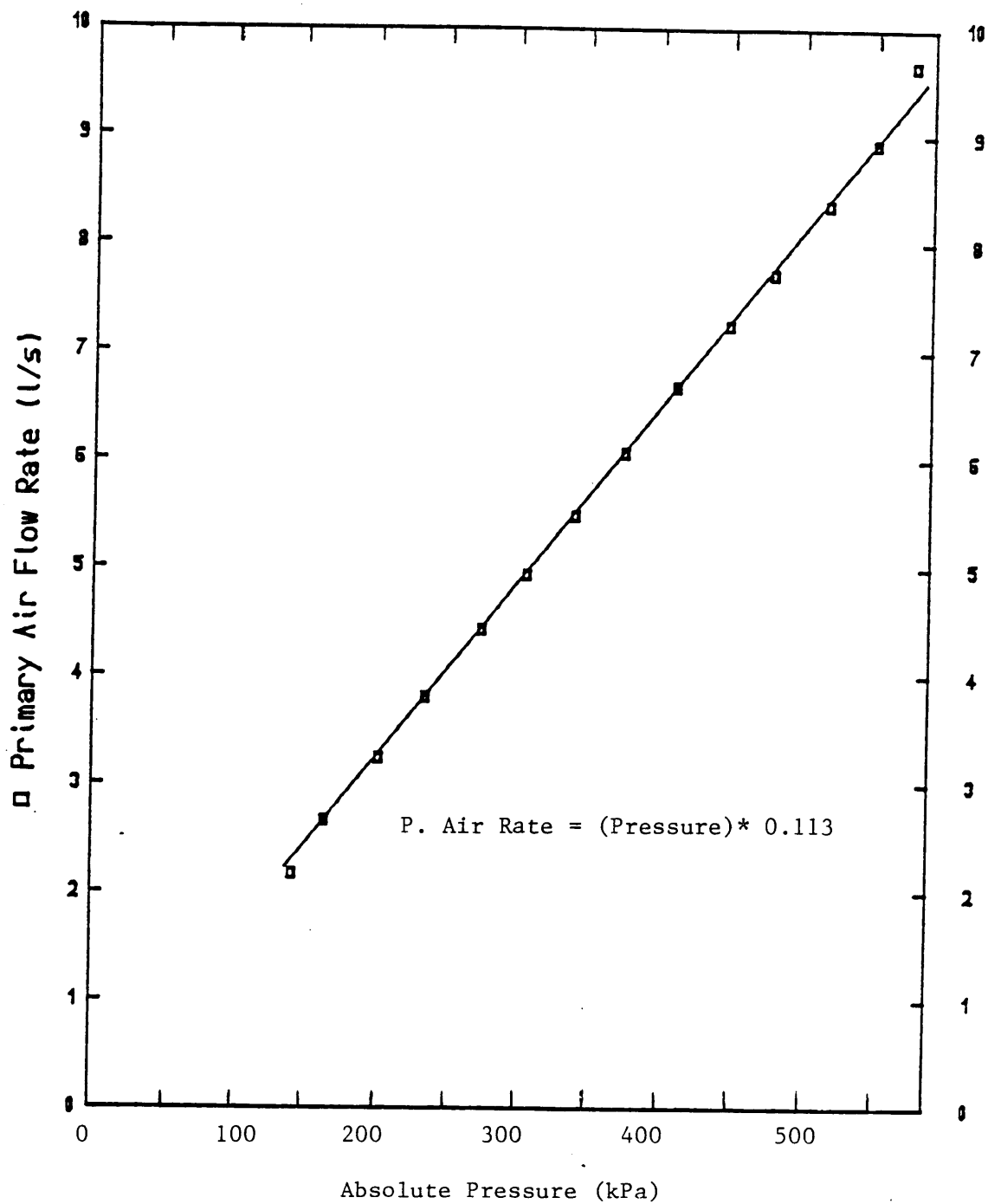
Figure 22   Calbiration Curve for Orifice #3
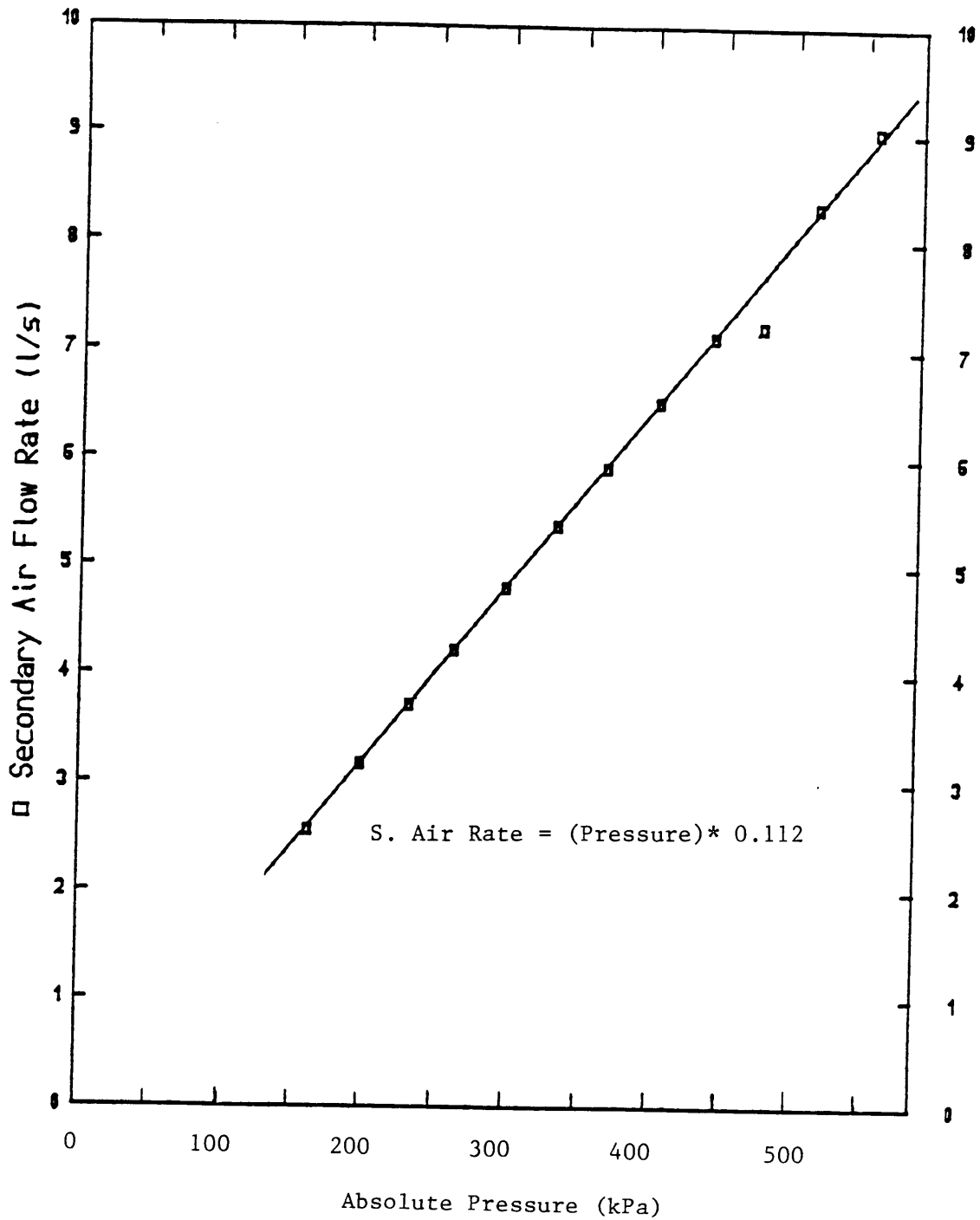
Figure 23   Calbiration Curve for Orifice #5

# Appendix B

## RELAY CIRCUITS FOR MANUAL AND AUTOMATIC
## CONTROL OF PRIMARY OR SECONDARY AIR FLOW
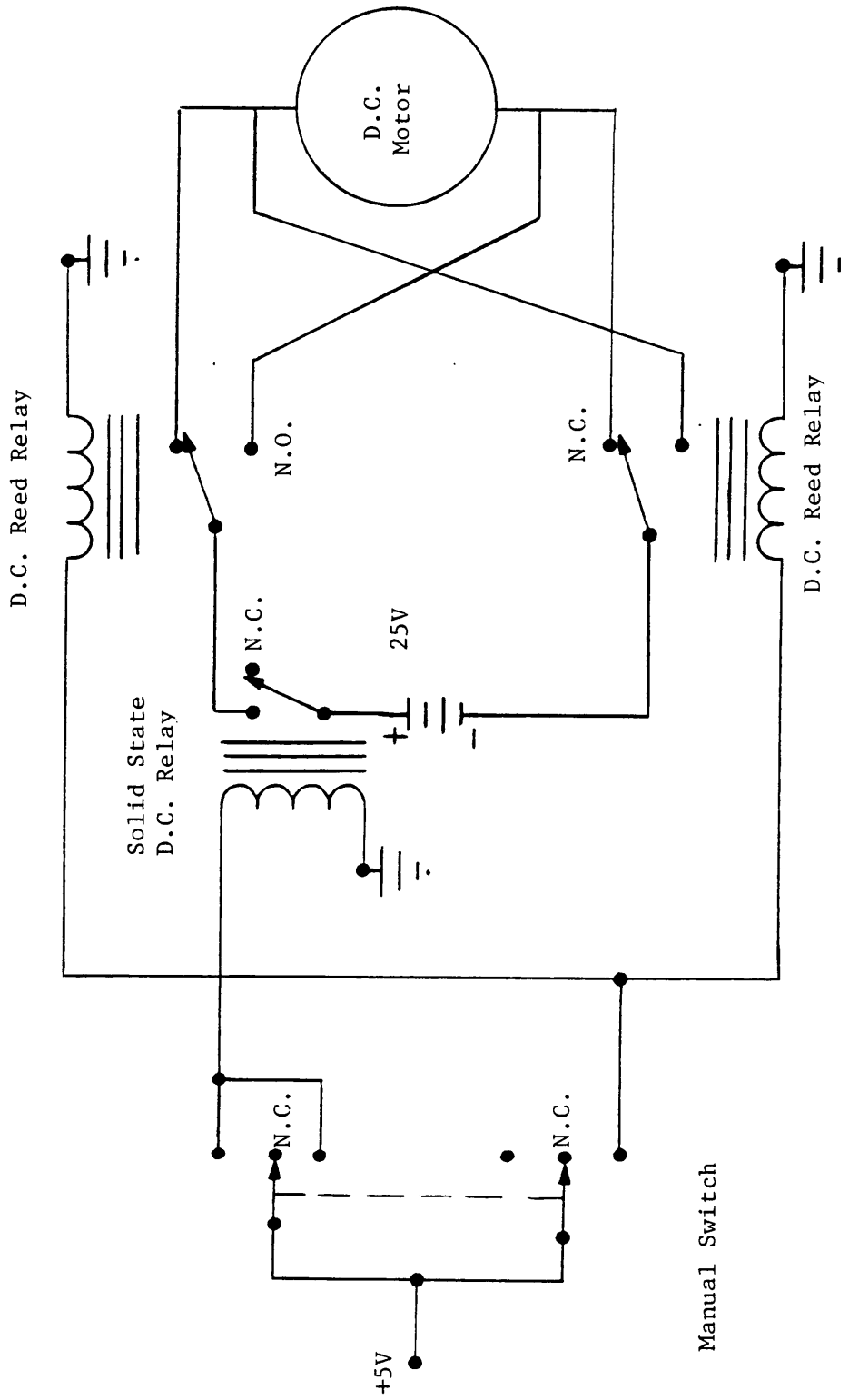
Figure 24  Relay Circuit for Manual Control of Primary or Secondary Air Flow
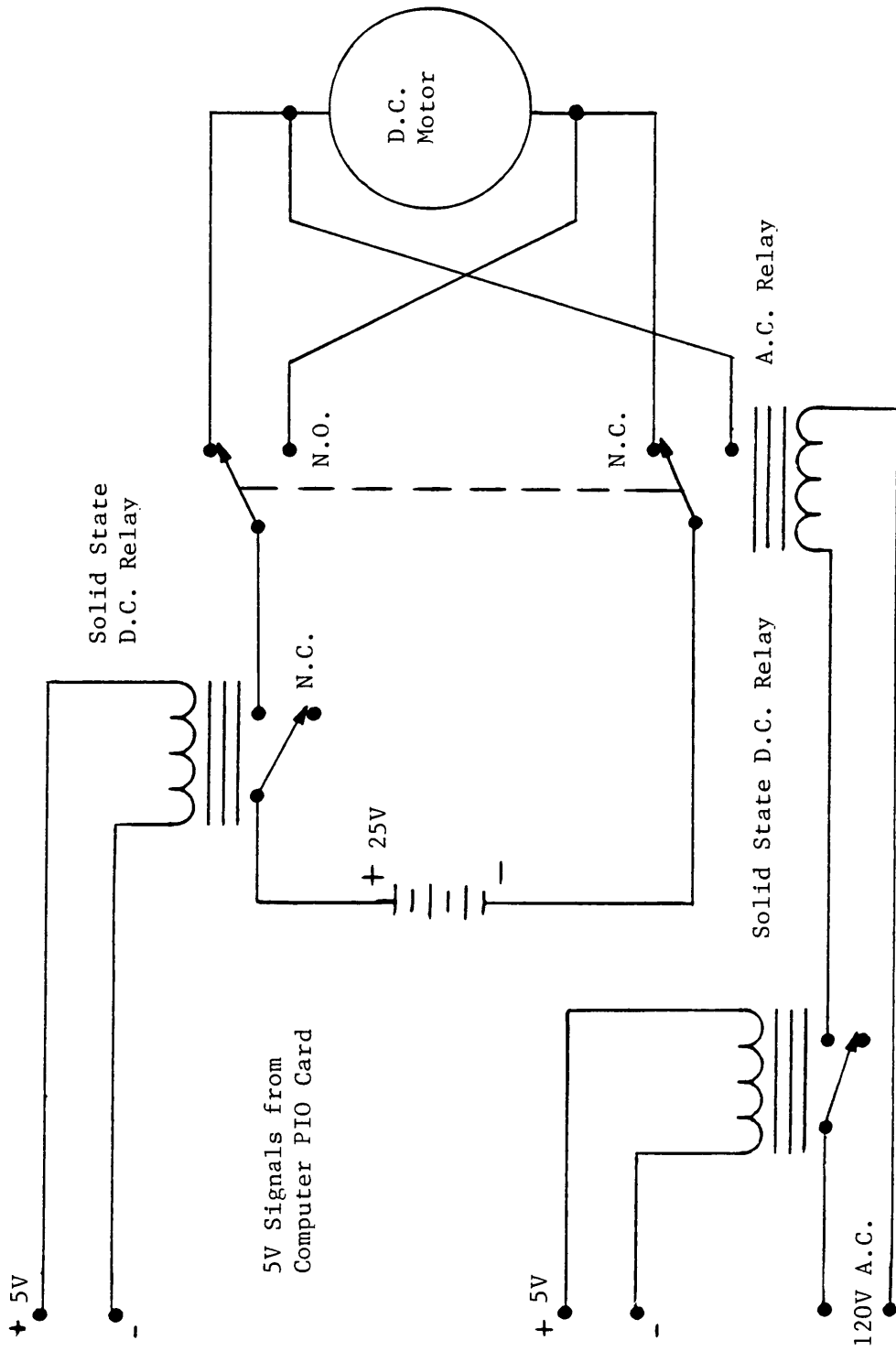
Figure 25   Relay Circuit for Computer Control of Primary or Secondary Air Flow

# Appendix C

# DATA ACQUISITION AND CONTROL PROGRAM

## DATA ACQUISITION AND CONTROL PROGRAM

The data acquisition and control program used to evaluate the effectiveness of the air flow strategies and the catalytic combustor is presented in this appendix. Note that just the data acquisition portion of the program was used during the biomass characterization studies.

Variable Listing:

| Variable Name | Variable Description |
|---|---|
| A | ----- I/O register status |
| A1P1 | ----- Voltage from primary air pressure transducer |
| A2P2 | ----- Voltage from secondary air pressure transducer |
| ANLYZ$ | ----- Type of CO and CO2 analyzers used (H=Horiba, I=Infrared) |
| B | ----- 1/2 of relay deadband (motor control algorithm) |
| B1T1 | ----- Voltage from T/C #1 |
| B2T2 | ----- Voltage from T/C #2 |
| B3T3 | ----- Voltage from T/C #3 |
| B4T4 | ----- Voltage from T/C #4 |
| B5T5 | ----- Voltage from T/C #5 |
| B6T6 | ----- Voltage from T/C #6 |
| B7T7 | ----- Voltage from T/C #7 |
| BO2 | ----- Voltage from Autolite oxygen sensor |
| C1CO | ----- Voltage from carbon monoxide analyser |
| C2CO2 | ----- Voltage from carbon dioxide analyzer |
| C3O2 | ----- Voltage from oxygen analyser |
| CURRENT | ----- Current decimal time |
| D1CO | ----- Carbon monoxide concentration in exhaust (percentage) |
| D2CO | ----- Carbon dioxide concentratio in exhaust (percentage) |
| EO2 | ----- Excess oxygen concentration in exhaust (percentage) |
| EXIT | ----- Time to initiate next reading |
| F1 | ----- Flow rate flag |
| F2 | ----- Flow switch flag |
| F3 | ----- Secondary air flag |
| F4 | ----- Change flag |
| F5 | ----- Toggle flag |
| F6 | ----- Again flag |
| F7 | ----- Max flow flag |
| F8 | ----- HI-LO flag |

| Variable Name | | Variable Description |
|---|---|---|
| FRT$ | ----- | Manual/Automatic reference temperature flag |
| FTYPE$ | ----- | Fuel Type |
| GAIR | ----- | Primary (grate) air flow rate |
| H | ----- | Loop counter (creates a 5 second delay) |
| HIGH | ----- | High fire pressure set point |
| HRR | ----- | Heat Release Rate (i.e. instantaneous output power) |
| JOE$ | ----- | Primary air flow orifice identifier |
| KEY$ | ----- | Keyboard interupt (used to quit) |
| L | ----- | Loop counter (used in timing loop) |
| LOW | ----- | Low fire pressure set point |
| M$ | ----- | Motor identifier (A=primary air, B=secondary air) |
| M1P | ----- | Primary air pressure upstream of orifice (metric units) |
| M2P | ----- | Secondary air pressure upstream of orifice (metric units) |
| NF$ | ----- | Disk storage filename |
| O2 | ----- | Oxygen concentration in exhaust (percentage) |
| OFLOW | ----- | Oxygen flowrate added to sample (not used) |
| P | ----- | Pressure set point for primary air (psig) |
| P1 | ----- | Primary Air pressure upstream of orifice (psia) |
| P2 | ----- | Secondary air pressure upstream of orifice (psia) |
| PS | ----- | Pressure set point for secondary air (psig) |
| PATM | ----- | Local atmospheric pressure |
| PG | ----- | Gage pressure (feedback signal to motor drivers) |
| S1 | ----- | Primary air pressure transducer sensitivity |
| S2 | ----- | Secondary air pressure transducer sensitivity |
| SAIR | ----- | Secondary air flow rate |
| SD$ | ----- | Disk storage flag (Y or N) |
| SP$ | ----- | Printer suppress flag (Y or N) |
| T | ----- | Temperature output from temperature subroutine |
| T1 | ----- | Temperature T1 |
| T2 | ----- | Temperature T2 |
| T3 | ----- | Temperature T3 |
| T4 | ----- | Temperature T4 |
| T5 | ----- | Temperature T5 |
| T6 | ----- | Temperature T6 |
| T7 | ----- | Temperature T7 |
| TFLOW | ----- | Sample flowrate |
| TGRAT | ----- | Temperature at grate (average of T3 and T6) |
| THERM | ----- | Status of thermostat switch (1=high fire, 0=low fire) |
| TIME$ | ----- | Time |
| TR | ----- | Reference temperature |
| V1 | ----- | Primary air pressure transducer excitation voltage |
| V2 | ----- | Secondary air pressure transducer excitation voltage |
| VR | ----- | T/C voltage corrsponding to reference temperature |
| VT | ----- | T/C voltage input to temperature subroutine |
| WAIT | ----- | Length of time delay between readings |
| WO2 | ----- | Voltage from Bosch heated oxygen sensor |
| YO2 | ----- | Voltage from AC Spark oxygen sensor |

Program Listing:

```
  10 REM **************************************************************
  20 REM **        TITLE:  DATA ACQUISITION AND CONTROL PROGRAM FOR    **
  25 REM **                PROTOTYPE BIOMASS COMBUSTOR                  **
  30 REM ** WRITTEN BY:  JOE DODY                                      **
  40 REM **************************************************************

  50 REM **************************************************************
  60 REM ** MAIN PROGRAM                                              **
  70 REM **************************************************************
  80 CLS
  90 CLEAR 1000
 100 CMD"R"                         '** TURN CLOCK ON                 **
 110 GOSUB 1000                     '** INITIALIZE PROGRAM            **
 120 GOSUB 500                      '** INITIALIZE AIR FLOW RATES     **
 140 F1=0                           '** FLOW RATE FLAG SET            **
 150 F2=0                           '** FLOW SWITCH FLAG SET          **
 160 GOSUB 2000                     '** COLLECT DATA                  **
 170 GOSUB 5000                     '** CONTROL PRIMARY AIR           **
 180 IF F2=1 GOTO 150               '** CHECK FLOW SWITCH FLAG        **
 190 GOSUB 6000                     '** CONTROL SECONDARY AIR         **
 200 KEY$=INKEY$
 210 IF KEY$<>"Q" GOTO 160
 220 CLOSE
 230 END

 500 REM **************************************************************
 510 REM ** SUBROUTINE - INITIALIZE AIR FLOW RATES .                  **
 520 REM **                                                          **
 530 REM **                                                          **
 540 REM **************************************************************
 550 P=10: GOSUB 8000              '** PRIMARY AIR MOTOR DRIVER       **
 560 P=0:  GOSUB 9000              '** SECONDARY AIR MOTOR DRIVER     **
 570 RETURN

1000 REM **************************************************************
1010 REM ** SUBROUTINE - INITIALIZE PROGRAM                          **
1020 REM **                                                          **
1030 REM **                                                          **
1040 REM **************************************************************
1050 REM ** SET UP I/O PORTS
1060 A=INP(252)OR16                 '** GET I/O REG. STATUS & SET BITS **
1070 OUT 236,A                      '** SET UP I/O PORT               **
1080 REM ** SET UP OUTPUT CONFIGURATION
1090 PRINT "STORE DATA ON DISK? (Y/N)? ";
1100 SD$=INKEY$
```

```
1110 IF SD$="" THEN 1100
1120 PRINT SD$
1130 IF SD$="N" THEN 1160
1140 INPUT "ENTER FILE NAME";NF$:NF$=NF$+":1"
1150 OPEN "O",1,NF$
1160 PRINT "SUPPRESS PRINTER? (Y/N)? ";
1170 SP$=INKEY$
1180 IF SP$="" THEN 1170
1190 PRINT SP$
1200 REM ** INPUT FUEL INFORMATION
1210 INPUT "ENTER FUEL TYPE (WOOD, SLASH, OR CORN)";FTYPE$
1240 REM ** INPUT TIME DELAY (note: force wait=0 when using control
                              version of program)
1250 INPUT "ENTER TIME DELAY BETWEEN READINGS (SEC)";WAIT
1260 IF WAIT>=10 THEN 1270
1270 PRINT "PROGRAM WILL FAIL FOR INTERVALS < 10 SECONDS"
1280 GOTO 1240
1290 REM ** INPUT ANALYZER(S) BEING USED
1300 PRINT "HORIBA OR I.R. ANALYZER(S)? (H/I)? ";
1310 ANLYZ$=INKEY$:IF ANLYZ$="" THEN 1310
1320 PRINT ANLYZ$
1330 IF ANLYZ$<>"H" AND ANLYZ$<>"I" THEN 1300
1340 REM ** SET UP T/C REFERENCE JUNCTION COMPENSATION
1350 PRINT "AUTOMATIC T/C REFERENCE JUNCTION COMPENSATION? (Y/N)?";
1360 FRT$=INKEY$
1370 IF FRT$="" THEN 1360
1380 PRINT FRT$
1390 IF FRT$="Y" THEN INPUT "ENTER LOCAL TEMP. IN DEGREES C ";TR:
     GOTO 1430
1400 IF FRT$="N" THEN 1420
1410 GOTO 1350
1420 INPUT "ENTER TEMP OF REF. JUNCTION IN DEGREES C ";TR
1430 REM ** INPUT ATMOSPHERIC PRESSURE
1440 INPUT "ENTER LOCAL ATMOSPHERIC PRESSURE IN PSI ";PATM
1450 REM ** INPUT PRIMARY AIR FLOW ORIFICE BEING USED
1460 PRINT "ENTER FLOW ORIFICE BEING USED (1 OR 3) ";
1470 JOE$=INKEY$
1480 IF JOE$="" THEN 1470
1490 PRINT JOE$
1500 IF JOE$="1" OR JOE$="3" THEN 1510 ELSE 1460
1510 REM ** INPUT PRESSURE TRANSDUCER EXCITATION VOLTAGES AND CALCULATE
             TRANSDUCER SENSITIVITIES
1520 INPUT "ENTER P1 EXCITATION VOLTAGE ";V1
1530 IF V1=0 THEN PRINT "TRY AGAIN SAM" :GOTO 1520
1540 S1=10/V1
1550 INPUT "ENTER P2 EXCITATION VOLTAGE ";V2
1560 IF V2=0 THEN PRINT "TRY AGAIN SAM" : GOTO 1550
```

```
1570 S2=10/V2
1580 REM ** INPUT SAMPLE FLOW RATE
1590 INPUT "ENTER TOTAL SAMPLE FLOWRATE (L/SEC) ";TFLOW
1630 REM ** DEFINE HIGH AND LOW FIRING RATES
1640 INPUT "ENTER HIGH FIRE PRESSURE (PSIG)";HIGH
1650 INPUT "ENTER LOW FIRE PRESSURE (PSIG)";LOW
1660 CLS
1670 REM ** PRINT HEADER PAGE TO PRINTER **
1680 LPRINT TIME$
1690 LPRINT "FUEL TYPE: ";FTYPE$
1700 LPRINT "ANALYSER: ";ANLYZ$
1710 LPRINT "FLOW ORIFICE USED:"; JOE$
1720 LPRINT "P1 PRESSURE TRANSDUCER EXCITATION VOLTAGE:";V1
1730 LPRINT "P2 PRESSURE TRANSDUCER EXCITATION VOLTAGE:";V2
1740 LPRINT "TOTAL SAMPLE FLOW RATE (L/SEC):";TFLOW
1760 LPRINT "LOCAL TEMPERATURE (DEGREES C): ";TR
1770 LPRINT "LOCAL ATMOSPHERIC PRESSURE (ATM): ";PATM
1780 LPRINT "LOCAL ATMOSPHERIC PRESSURE (KPA): ";PATM*6.89476
1790 LPRINT "HIGH FIRE PRESSURE:";HIGH
1800 LPRINT "LOW FIRE PRESSURE:";LOW
1810 LPRINT
1820 LPRINT "DATA STORED ON DISK AS ";NF$
1830 LPRINT "    FORMAT:  LINE 1 - TIME,T1,T2,TGRATE,T4,T5,T7,P2"
1840 LPRINT "             LINE 2 - %O2,%CO,%CO2,GAIR,P1,M1P,HRR,M2P"
1850 LPRINT "    FORMAT:  LINE 3 - EO2,T3,T6,BO2,WO2,YO2,THERM,SAIR"
1860 LPRINT
1870 LPRINT
1880 REM ** INITIALIZE CLOCK TO 00:00:00
1890 POKE 16919,00
1900 POKE 16920,00
1910 POKE 16921,00
1915 REM ** INITIALIZE EXIT CONDITION
1920 EXIT=WAIT
1930 RETURN


2000 REM ********************************************************************
2010 REM ** SUBROUTINE - COLLECT DATA                                    **
2020 REM **                                                              **
2030 REM **                                                              **
2040 REM ********************************************************************
2050 GOSUB 2200              '** READ DATA                               **
2060 GOSUB 3000              '** CALCULATIONS                            **
2070 GOSUB 4000              '** PRINT                                   **
2080 GOSUB 4300              '** LPRINT                                  **
2090 GOSUB 4600              '** STORE DATA                              **
2100 GOSUB 4800              '** DECIMAL TIME                            **
2110 RETURN
```

```
2200 REM ******************************************************************
2210 REM ** SUBROUTINE - READ DATA                                     **
2220 REM **                                                            **
2230 REM **                                                            **
2240 REM ******************************************************************
2250 PRINT "TAKING DATA"
2260 REM ** SET UP I/O PORTS
2270 A=INP(252)OR16                   '** GET I/O REG. STATUS & SET BITS  **
2280 OUT 236,A                        '** SET UP I/O PORT                 **
2285 REM ** INPUT PRESSURES FOR AIR FLOW RATE CALCULATIONS
2290 OUT 11,0
2300 A1P1=(((INP(13)AND15)*256+INP(12)))/41.50
2310 OUT 11,1
2320 A2P2=(((INP(13)AND15)*256 + INP(12)))/41.50 - 1.93
2330 REM  NOTE: -1.93 IS SENSOR ZERO OFFSET ADJUSTMENT
2350 REM ** INPUT T/C VOLTAGES FOR TEMPERATURE CALCULATIONS
2370 OUT 11,2
2380 B1T1=(((INP(13)AND15)*256+INP(12)))/.04150
2390 OUT 11,3
2400 B2T2=(((INP(13)AND15)*256+INP(12)))/.04150
2410 OUT 11,8
2420 B4T4=(((INP(13)AND15)*256+INP(12)))/.04150
2430 OUT 11,4
2440 B5T5=(((INP(13)AND15)*256+INP(12)))/.04150
2450 OUT 11,5
2460 B6T6=(((INP(13)AND15)*256+INP(12)))/.04150
2470 OUT 11,6
2480 B7T7=(((INP(13)AND15)*256+INP(12)))/.04150
2490 REM ** INPUT REFERENCE TEMPERATURE VOLTAGE SIGNAL FROM DISPLAY
2500 IF FRT$="N" THEN GOTO 2560
2510 OUT 11,7
2520 TR=(((INP(13)AND15)*256+INP(12)))/41.50
2540 REM ** INPUT VOLTAGE SIGNALS FROM GAS ANALYZERS
2560 OUT 16,140: OUT 16,12: FOR L = 1 TO 60: NEXT
2570 C3O2=(256*(INP(16)AND15)+INP(17))/10
2580 OUT 16,141: OUT 16,13: FOR L = 1 TO 60: NEXT
2590 C1CO=(256*(INP(16)AND15)+INP(17))/10
2600 OUT 16,142: OUT 16,14: FOR L = 1 TO 60: NEXT
2610 C2CO2=(256*(INP(16)AND15)+INP(17))/10
2615 REM ** INPUT T3 VOLTAGE SIGNAL FROM DISPLAY
2620 OUT 16,143: OUT 16,15: FOR L = 1 TO 60: NEXT
2630 B3T3=(256*(INP(16)AND15)+INP(17))
2640 REM** INPUT VOLTAGES FROM AUTOMOBILE EXHAUST GAS OXYGEN SENSORS
2650 OUT 16,138: OUT 16,10: FOR L= 1 TO 60: NEXT
2660 YO2=(256*(INP(16)AND15) + INP(17))/1000        '** AC SPARK      **
2670 OUT 16,137: OUT 16,9: FOR L = 1 TO 60: NEXT
```

```
2680 WO2=(256*(INP(16)AND15) + INP(17))/1000          '** BOSCH (HEATED) **
2690 OUT 16,136: OUT 16,8: FOR L = 1 TO 60: NEXT
2700 BO2=(256*(INP(16)AND15) + INP(17))/1000          '** AUTOLITE      **
2710 REM ** INPUT STATUS OF THERMOSTAT SWITCH
2720 THERM=INP(22) AND 1
2730 RETURN


3000 REM **********************************************************
3010 REM ** SUBROUTINE - CALCULATIONS                            **
3020 REM **                                                      **
3030 REM **                                                      **
3040 REM **********************************************************
3050 REM ** CALCULATE AIR PRESSURES
3060 P1=A1P1*S1+PATM
3070 M1P=P1*6.89476
3080 P2=A2P2*S2 + PATM
3090 M2P=P2*6.89476
3095 REM ** CALCULATE PRIMARY AIR FLOW (see calibration curves)
3100 IF JOE$="1" THEN 3120 ELSE 3160
3110 REM ** ORIFICE #1
3120 IF P1<15 THEN 3200 ELSE 3130
3130 IF P1<27 THEN GAIR=12.5932-163.37/P1:GOTO 3210
3140 GAIR=-.491985+.262746*P1
3150 GOTO 3210
3160 REM ** ORIFICE #3
3170 IF P1<20 THEN 3200 ELSE 3180
3180 GAIR=P1*.1133
3190 GOTO 3210
3200 GAIR=0                          '** CODE FOR OUT OF RANGE        **
3210 REM ** CALCULATE SECONDARY AIR FLOW (see calibration curves)
3215 REM ** ORIFICE #5
3220 SAIR=P2*.1133
3230 IF P2<16 THEN SAIR=0            '** CODE FOR OUT OF RANGE        **
3240 REM ** CALCULATE VOLTAGE ASSOCIATED WITH REFERENCE TEMPERATURE
3250 VR=0.5*(1691712.8-SQR((1691712.8[2)-4*TR*68519695))
3260 REM ** CALCULATE TEMPERATURES FROM T/C VOLTAGES
3270 VT=B1T1
3280 GOSUB 3700                      '** TEMPERATURE                 **
3290 T1=T
3300 VT=B2T2
3310 GOSUB 3700                      '** TEMPERATURE                 **
3320 T2=T
3330 VT=B4T4
3340 GOSUB 3700                      '** TEMPERATURE                 **
3350 T4=T
3360 VT=B5T5
3370 GOSUB 3700                      '** TEMPERATURE                 **
```

```
3380 T5=T
3390 VT=B6T6
3400 GOSUB 3700                        '** TEMPERATURE                    **
3410 T6=T
3420 VT=B7T7
3430 GOSUB 3700                        '** TEMPERATURE                    **
3440 T7=T
3450 REM ** CALCULATE O2 CONCENTRATION
3460 O2=C3O2*.25
3470 REM ** CALCULATE CO CONCENTRATION
3480 IF ANLYZ$="I" THEN D1CO=C1CO*.0302:GOTO 3500
3490 D1CO=2.20628982E-5+.0210707036*C1CO+2.1917326E-4*C1CO[2
          -1.07298545E-6*C1CO[3+1.77413978E-8*C1CO[4
3500 REM ** CALCULATE CO2 CONCENTRATION
3510 IF ANLYZ$="I" THEN D2CO2=C2CO2*.202:GOTO 3530
3520 D2CO2=2.09923625E-3+.0986561579*C2CO2+9.38160956E-4*C2CO
3530 REM ** CALCULATE TEMPERATURE T3
3540 T3=B3T3
3550 REM ** AVERAGE T3 AND T6 TO FORM TGRATE
3560 TGRATE=(T3+T6)/2
3570 REM ** CALCULATE EXCESS O2 (used for calculation of
          equivalence ratio, see text)
3580 EO2 = O2-D1CO*1.5
3590 REM ** CALCULATE HEAT RELEASE RATE (ie. output power, see text)
3600 HRR=((2*D1CO+D2CO2)/100)*CPM*17.46*(GAIR + SAIR)
3620 RETURN

3700 REM *****************************************************************
3710 REM ** SUBROUTINE - TEMPERATURE                                    **
3720 REM **                                                             **
3730 REM **                                                             **
3740 REM *****************************************************************
3750 VT=VT+VR
3760 IF VT<16395 THEN 3770 ELSE 3790
3770 T=.024153681*VT+(9.0047640E-8)*(VT[2)-(4.6004855E-12)*(VT[3)
3780 GOTO 3800
3790 T=4.4041973+.02519868*VT-(9.0154824E-8)*(VT[2)+
       (1.5496930E-12)*(VT[3)
3800 RETURN

4000 REM *****************************************************************
4010 REM ** SUBROUTINE - PRINT                                          **
4020 REM **                                                             **
4030 REM **                                                             **
4040 REM *****************************************************************
4050 PRINT "DATE/TIME",,LEFT$(TIME$,9);
4060 PRINT USING"####.##";EMIT
```

```
4070 PRINT "GAIR/PRES/MPRES",GAIR,P1,M1P
4080 PRINT "SAIR/PRES/MPRES",SAIR,P2,M2P
4090 PRINT "TREF/HRR(KW)",TR,,HRR
4100 PRINT "T1",,T1
4110 PRINT "T2",,T2
4120 PRINT "T3/TAVE/T6",T3,TGRATE,T6
4130 PRINT "T4",,T4
4140 PRINT "T5",,T5
4150 PRINT "T7",,T7
4160 PRINT "% O2/CO/CO2",O2,D1CO,D2CO2
4170 PRINT "% EO2/THRM 1=ON",EO2,,THERM
4180 PRINT "BO2/WO2/YO2",BO2,WO2,YO2
4190 IF GAIR=0 THEN PRINT "WARNING: ORIFICE PRESSURE OUT OF RANGE."
4200 RETURN

4300 REM ****************************************************************
4310 REM ** SUBROUTINE - LPRINT                                       **
4320 REM **                                                          **
4330 REM **                                                          **
4340 REM ****************************************************************
4350 IF SP$="Y" THEN RETURN
4360 LPRINT "DATE/TIME",,LEFT$(TIME$,9);
4370 LPRINT USING"####.##";EMIT
4380 LPRINT "GAIR/PRES/MPRES",GAIR,P1,M1P
4390 LPRINT "SAIR/PRES/MPRES",SAIR,P2,M2P
4400 LPRINT "TREF/HRR(KW)",TR,,HRR
4410 LPRINT "T1",,T1
4420 LPRINT "T2",,T2
4430 LPRINT "T3/TAVE/T6",T3,TGRATE,T6
4440 LPRINT "T4",,T4
4450 LPRINT "T5",,T5
4460 LPRINT "T7",,T7
4470 LPRINT "% O2/CO/CO2",O2,D1CO,D2CO2
4480 LPRINT "% EO2/THRM 1=ON",EO2,,THERM
4490 LPRINT "BO2/WO2/YO2",BO2,WO2,YO2
4500 IF GAIR=0 THEN LPRINT "WARNING: ORIFICE PRESSURE OUT OF RANGE."
4510 LPRINT
4520 RETURN

4600 REM ****************************************************************
4610 REM ** SUBROUTINE - STORE DATA                                  **
4620 REM **                                                          **
4630 REM **                                                          **
4640 REM ****************************************************************
4650 IF NF$="" THEN RETURN
4660 PRINT #1,USING "**####.## ";EMIT;
4670 PRINT #1,USING "+#.##[[[[ ";T1;T2;TGRATE;T4;T5;T7;P2
```

```
4680 PRINT #1,USING "+#.##[[[[ ";O2;D1CO;D2CO2;GAIR;P1;M1P;HRR;M2P
4690 PRINT #1,USING "+#.##[[[[ ";EO2;T3;T6;BO2;WO2;YO2;THERM;SAIR
4700 CMD"R"
4710 RETURN


4800 REM **************************************************************
4810 REM ** SUBROUTINE DECIMAL TIME  (DELAY OPTIONAL:  see line 1240) **
4820 REM **                                                          **
4830 REM **                                                          **
4840 REM **************************************************************
4860 CURRENT=VAL(MID$(TIME$,10,2))*3600+VAL(MID$(TIME$,13,2))*60+
          VAL(RIGHT$(TIME$,2))
4870 REM IF CURRENT<EXIT GOTO 4860
4880 EXIT=EXIT+WAIT
4890 RETURN


5000 REM **************************************************************
5010 REM ** SUBROUTINE - CONTROL PRIMARY AIR                         **
5020 REM **                                                          **
5030 REM **                                                          **
5040 REM **************************************************************
5050 PRINT "CONTROLLING PRIMARY AIR"
5060 IF F1=1 GOSUB 5090            '** CHECK IF HIGH->LOW NECESSARY   **
5070 IF F1=0 GOSUB 5170            '** CHECK IF LOW->HIGH NECESSARY   **
5080 RETURN


5085 REM **************************************************************
5090 REM ** SUBROUTINE - CHECK IF HIGH->LOW NECESSARY                **
5095 REM **                                                          **
5096 REM **                                                          **
5097 REM **************************************************************
5100 IF T4<850 AND T5<850 AND THERM=1 THEN RETURN
5110 F1=0                          '** FLOW RATE FLAG SET            **
5120 F2=1                          '** FLOW SWITCH FLAG SET          **
5130 IF T4>850 OR T5>850 THEN F8=1    '** HI-LO FLAG SET             **
5140 P=LOW
5150 GOSUB 8000                    '** PRIMARY AIR MOTOR DRIVER      **
5160 RETURN


5165 REM **************************************************************
5170 REM ** SUBROUTINE - CHECK IF LOW->HIGH NECESSARY                **
5175 REM **                                                          **
5176 REM **                                                          **
5177 REM **************************************************************
5180 IF THERM=0 OR T4>800 OR T5>800 THEN RETURN
5190 IF F8=1 AND (T4>700 OR T5>700) THEN RETURN
5200 F1=1                          '** FLOW RATE FLAG SET            **
```

```
5210 F2=1                            '** FLOW SWITCH FLAG SET        **
5220 F8=0                            '** HI-LO FLAG SET              **
5230 P=HIGH
5240 GOSUB 8000                      '** PRIMARY AIR MOTOR DRIVER    **
5250 RETURN


6000 REM ***********************************************************
6010 REM ** SUBROUTINE - CONTROL SECONDARY AIR                     **
6020 REM **                                                        **
6030 REM **                                                        **
6040 REM ***********************************************************
6050 PRINT "CONTROLLING SECONDARY AIR"
6060 REM ** RESET FLAGS MAXFLOW (F7), AGAIN (F6), AND CHANGE (F4)
6070 F7=0                            '** MAX FLOW FLAG SET           **
6080 F6=0                            '** AGAIN FLAG SET              **
6090 F4=0                            '** CHANGE FLAG SET             **
6100 REM** CHECK IF CATALYST IS TOO HOT
6110 IF T4<850 AND T5<850 GOTO 6140
6120 GOSUB 6400                      '** TOO HOT                     **
6130 RETURN
6140 REM ** INPUT VOLTAGE FROM HEATED EXHAUST GAS OXYGEN SENSOR
6150 OUT16,137: OUT 16,9: FOR L=1 TO 60: NEXT
6160 WO2=(256*(INP(16)AND15) + INP(17))/1000
6170 REM ** CHECK IF EXHAUST IS FUEL RICH
6180 IF WO2>.45 GOSUB 6600          '** RICH                        **
6190 REM ** 5 SECOND DELAY
6200 PRINT "5 SECOND DELAY"
6210 FOR H=1 TO 2200: NEXT
6220 REM ** CHECK STATUS OF MAX FLOW FLAG
6230 IF F7=1 RETURN
6240 REM ** INPUT VOLTAGE FROM HEATED EXHAUST GAS OXYGEN SENSOR
6250 OUT 16,137: OUT 16,9: FOR L=1 TO 60: NEXT
6260 WO2=(256*(INP(16)AND15) + INP (17))/1000
6270 REM ** CHECK IF EXHAUST IS FUEL RICH
6280 IF WO2>.45 GOSUB 6600 : GOTO 6190  '** RICH
6290 GOSUB 6800                      '** LEAN                        **
6300 REM ** CHECK STATUS OF AGAIN FLAG
6310 IF F6=1 GOTO 6190
6320 RETURN


6400 REM ***********************************************************
6410 REM ** SUBROUTINE - TOO HOT                                   **
6420 REM **                                                        **
6430 REM **                                                        **
6440 REM ***********************************************************
6450 REM** CHECK STATUS OF SECONDARY AIR FLAG
6460 IF F3=0 RETURN
```

```
6470 PS=0
6480 P=PS
6490 GOSUB 9000                    '** SECONDARY AIR MOTOR DRIVER      **
6500 REM ** SET SECONDARY AIR FLAG LOW, SET TOGGLE FLAG LOW
6510 F3=0                          '** SAIR FLAG SET                   **
6520 F5=0                          '** TOGGLE FLAG SET                 **
6530 RETURN


6600 REM ********************************************************************
6610 REM ** SUBROUTINE - RICH                                         **
6620 REM **                                                           **
6630 REM **                                                           **
6640 REM ********************************************************************
6650 REM ** ADD SECONDARY AIR IF POSSIBLE
6660 IF F3=0 THEN PS=30: F3=1: GOTO 6690   '** SECONDARY AIR FLAG SET **
6670 IF PS=50 THEN F7=1: GOTO 6710         '** MAX FLOW FLAG SET      **
6680 PS=PS + 10
6690 P=PS
6700 GOSUB 9000                    '** SECONDARY AIR MOTOR DRIVER      **
6710 REM ** SET CHANGE FLAG HIGH, SET TOGGLE FLAG LOW
6720 F4=1                          '** CHANGE FLAG SET                 **
6730 F5=1                          '** TOGGLE FLAG SET                 **
6740 RETURN


6800 REM ********************************************************************
6810 REM ** SUBROUTINE - LEAN                                         **
6820 REM **                                                           **
6830 REM **                                                           **
6840 REM ********************************************************************
6850 REM ** CHECK STATUS OF SECONDARY AIR FLAG
6860 IF F3=0 RETURN
6870 REM ** CHECK STATUS OF TOGGLE FLAG
6880 IF F5=1 GOTO 6930
6890 REM ** SET TOGGLE FLAG HIGH, SET AGAIN FLAG LOW
6900 F5=1                          '** TOGGLE FLAG SET                 **
6910 F6=0                          '** AGAIN FLAG SET                  **
6920 RETURN
6930 REM ** CHECK STATUS OF CHANGE FLAG
6940 IF F4=0 THEN GOSUB 7050 : RETURN   '** CHANGE FLAG SET           **
6950 GOSUB 6970                         '** CHANGE ON                 **
6960 RETURN


6965 REM ********************************************************************
6970 REM ** SUBROUTINE - CHANGE ON                                    **
6975 REM **                                                           **
6976 REM **                                                           **
6977 REM ********************************************************************
```

```
6980 REM ** SET CHANGE LOW, SET TOGGLE LOW, SET AGAIN LOW
6990 F4=0                              '** CHANGE FLAG SET              **
7000 F5=0                              '** TOGGLE FLAG SET              **
7010 F6=0                              '** AGAIN FLAG SET               **
7020 REM ** SET SECONDARY AIR FLAG
7030 IF PS=0 THEN F3=0                 '** SECONDARY AIR FLAG SET       **
7040 RETURN


7045 REM ************************************************************
7050 REM ** SUBROUTINE CHANGE OFF                                    **
7055 REM **                                                          **
7056 REM **                                                          **
7057 REM ************************************************************
7059 REM ** REDUCE SECONDARY AIR FLOW RATE
7060 PS=PS - 10
7070 P=PS
7080 GOSUB 9000                        '** SECONDARY AIR MOTOR DRIVER   **
7090 REM ** SET CHANGE FLAG, SET AGAIN FLAG
7100 F4=1                              '** CHANGE FLAG SET              **
7110 F6=1                              '** AGAIN FLAG SET               **
7120 RETURN


8000 REM ************************************************************
8010 REM ** SUBROUTINE - PRIMARY AIR MOTOR DRIVER                    **
8020 REM **                                                          **
8030 REM **                                                          **
8040 REM ************************************************************
8050 A=INP(252)OR16: OUT 236,A     '** SET UP I/O PORTS              **
8060 PRINT "TURNING P1 TO ",P
8070 B=5    '** NOTE:   DELAY NECESSARY IF B < 5 TO ALLOW MOTOR TIME TO **
                        COAST TO A STOP--PRESSURE SHOULD NOT BE CHECKED **
                        FOR BEING WITHIN THE DEADBAND UNTIL MOTOR HAS   **
                        COME TO REST-- SET-POINT CAN BE OVERSHOT.  IF B **
                        IS SET TOO SMALL THE SYSTEM BECOMES UNSTABLE.   **
8080 OUT 11,0
8090 PG=(((INP(13)AND15)*256+INP(12)))/41.5
8100 IF PG<P-B THEN GOSUB 8140     '** FORWARD DIRECTION            **
8110 IF PG>P+B THEN GOSUB 8200     '** REVERSE DIRCETION            **
8120 IF PG<P-B OR PG>P+B GOTO 8100
8130 RETURN
8140 REM ***** SUBROUTINE - FORWARD DIRECTION *****
8150 OUT 11,0
8160 PG=(((INP(13)AND15)*256+INP(12)))/41.5
8170 IF PG<P-B THEN OUT 20,1: GOTO 8150
8180 OUT 20,0: FOR L=1 TO 10: NEXT
8190 RETURN
8200 REM ***** SUBROUTINE - REVERSE DIRECTION *****
```

```
8210 OUT 11,0
8220 PG=(((INP(13)AND15)*256+INP(12)))/41.5
8230 IF PG>P+B THEN OUT 20,5: GOTO 8210
8240 OUT 20,0: FOR L=1 TO 10: NEXT
8250 RETURN

9000 REM ************************************************************
9010 REM ** SUBROUTINE - SECONDARY AIR MOTOR DRIVER              **
9020 REM **                                                      **
9030 REM **                                                      **
9040 REM************************************************************
9050 A=INP(252)OR16: OUT 236,A9    '** SET UP I/O PORTS           **
9060 PRINT "TURNING P2 TO ",P
9070 B=6                           '** SEE NOTE ABOVE             **
9080 OUT 11,1
9090 PG=(((INP(13)AND15)*256+INP(12)))/41.5 - 1.93
9100 IF PG<P-B THEN GOSUB 9150     '** FORWARD DIRECTION          **
9110 IF PG>P+B THEN GOSUB 9210     '** REVERSE DIRECTION          **
9120 IF PG<P-B OR PG>P+B GOTO 9100
9130 IF P=0 AND PG>1 THEN B=1: GOTO 9100
9140 RETURN
9150 REM ***** SUBROUTINE - FORWARD DIRECTION *****
9160 OUT 11,1
9170 PG=(((INP(13)AND15)*256+INP(12)))/41.5 - 1.93
9180 IF PG<P-B THEN OUT 20,2: GOTO 9160
9190 OUT 20,0: FOR L=1 TO 10: NEXT
9200 RETURN
9210 REM ***** SUBROUTINE - REVERSE DIRECTION *****
9220 OUT 11,1
9230 PG=(((INP(13)AND15)*256+INP(12)))/41.5 - 1.93
9240 IF PG>P+B THEN OUT 20,10: GOTO 9220
9250 OUT 20,0: FOR L=1 TO 10: NEXT
9260 RETURN

10000 REM ************************************************************
10010 REM ** ROUTINE TO CHECK MOTORS   (TYPE "RUN 10000)         **
10015 REM **                                                     **
10016 REM **                                                     **
10020 REM ************************************************************
10030 INPUT"MOTOR A OR B";M$
10040 INPUT"DESIRED PRESSURE";P
10050 A=INP(252)OR16: OUT236,A
10060 IF M$="A" GOSUB 8000
10070 IF M$="B" GOSUB 9000
10080 GOTO 10000
```

# Appendix D

## PRESENTATION OF DATA FROM BIOMASS COMBUSTION CHARACTERIZATION STUDY

Cordwood Low Fire Combustion Characterization Test
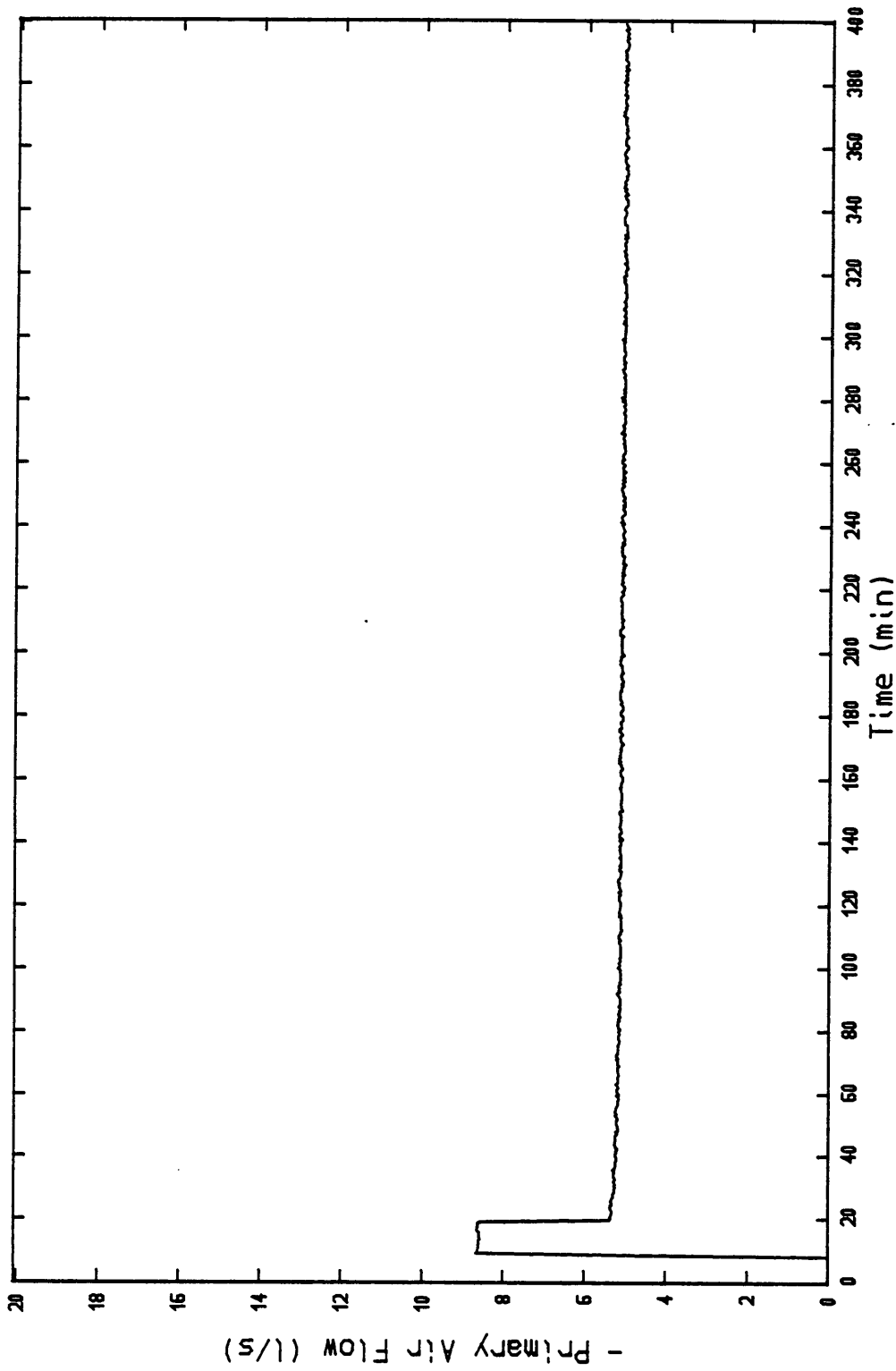
Figure 26  Primary Air Flow During Cordwood Low Fire Test
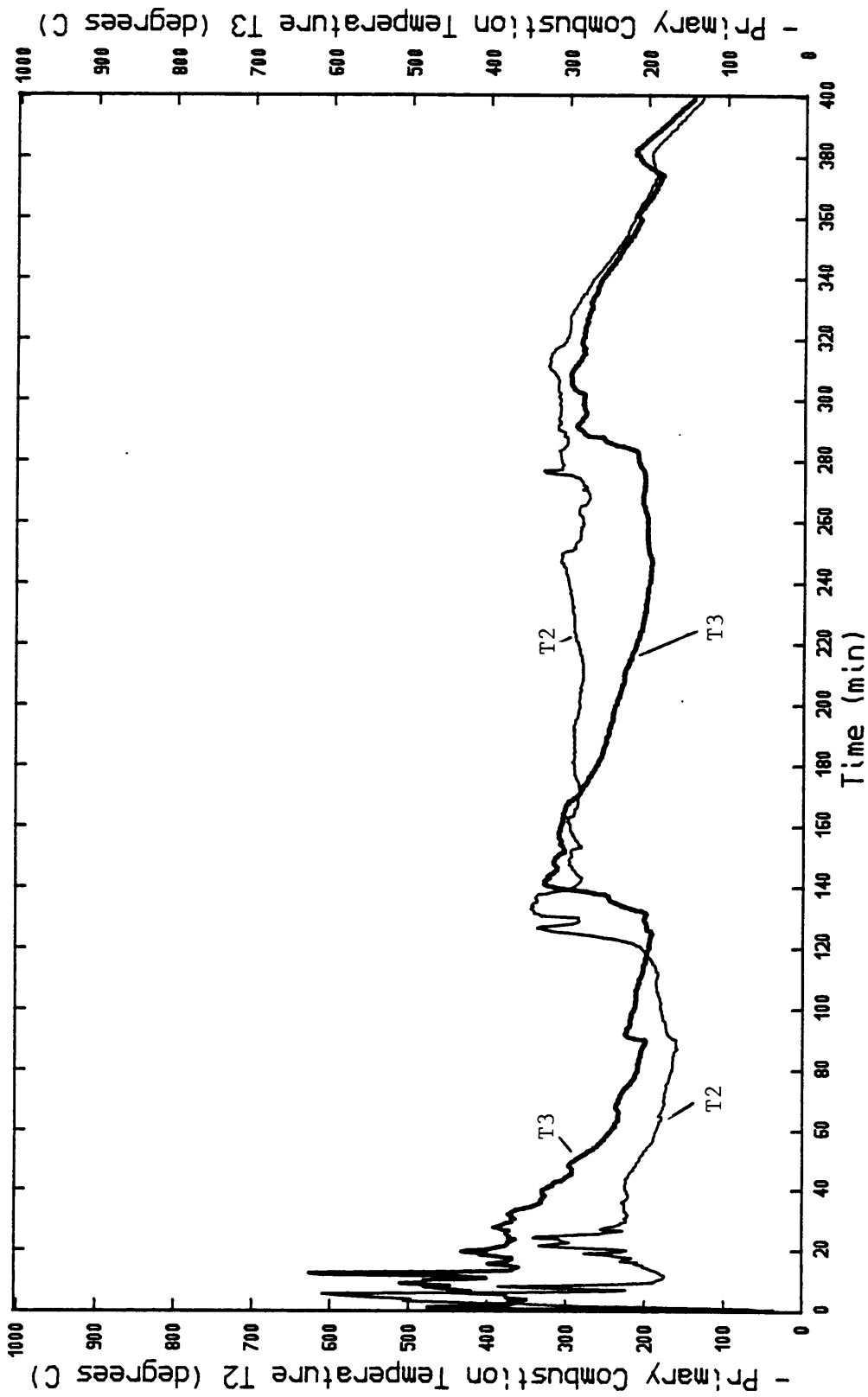
Figure 27  Primary Combustion/Gasification Temperatures, T2 and T3, During Cordwood Low Fire Test
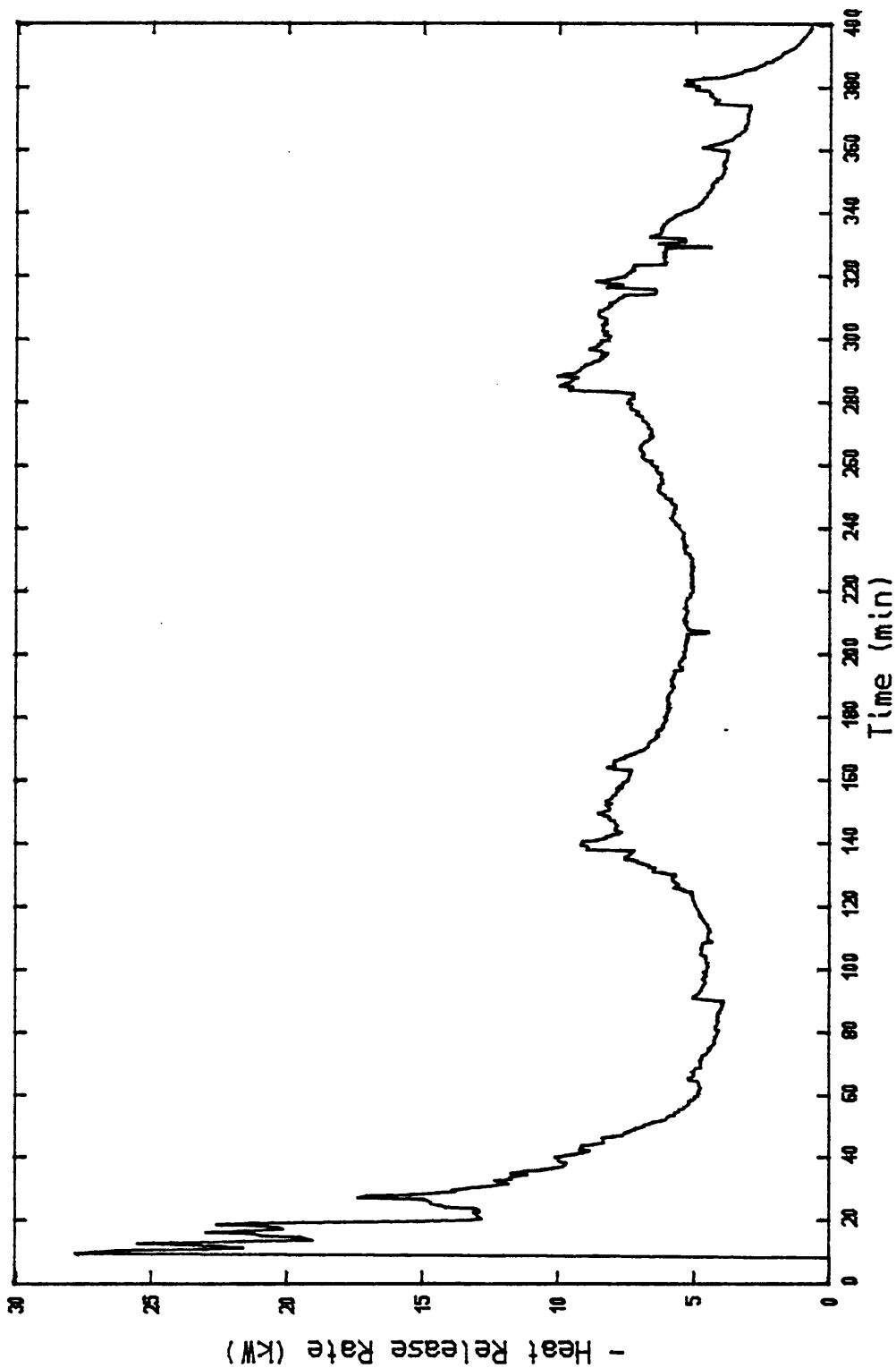
Figure 28  Heat Release Rate During Cordwood Low Fire Test
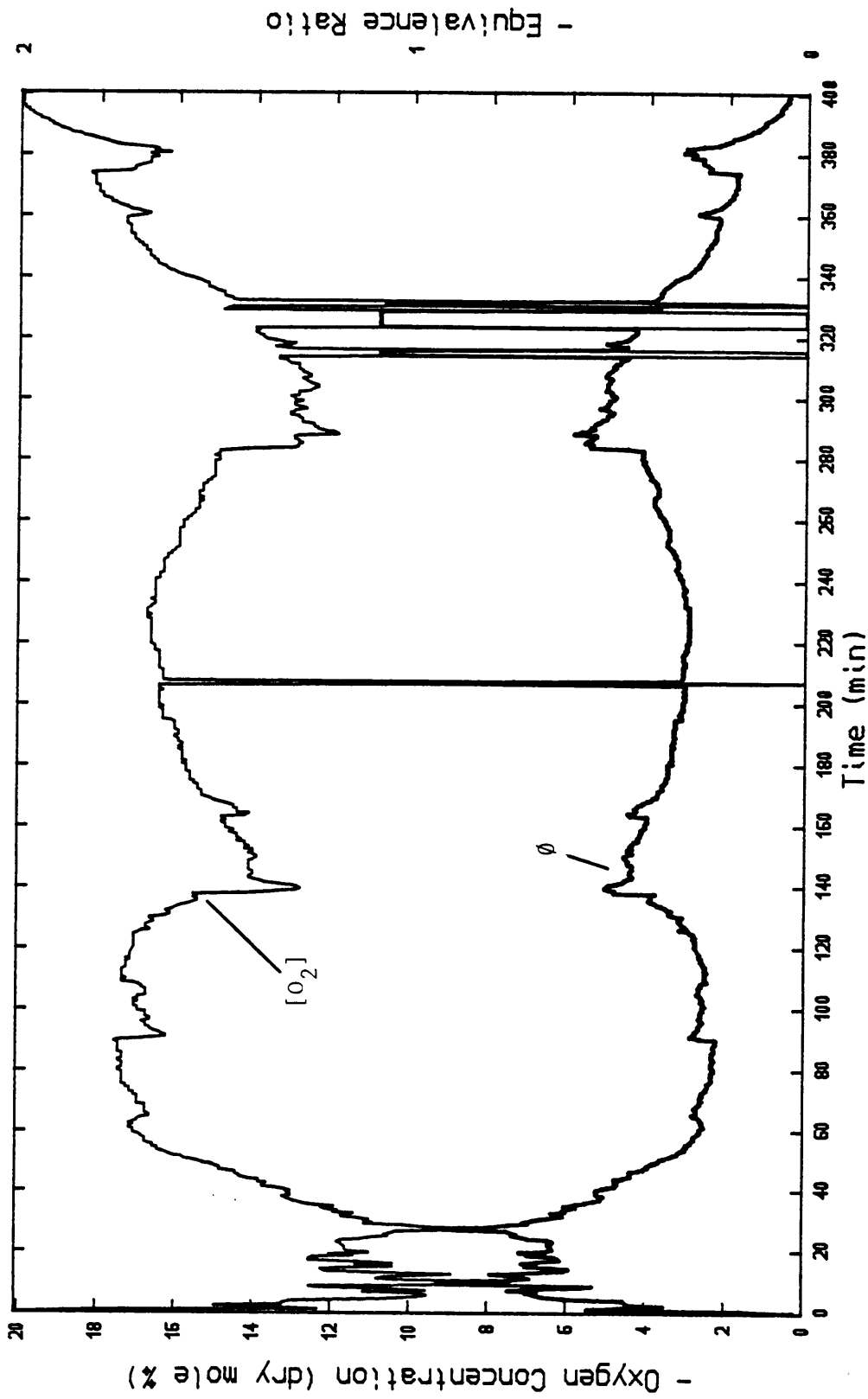
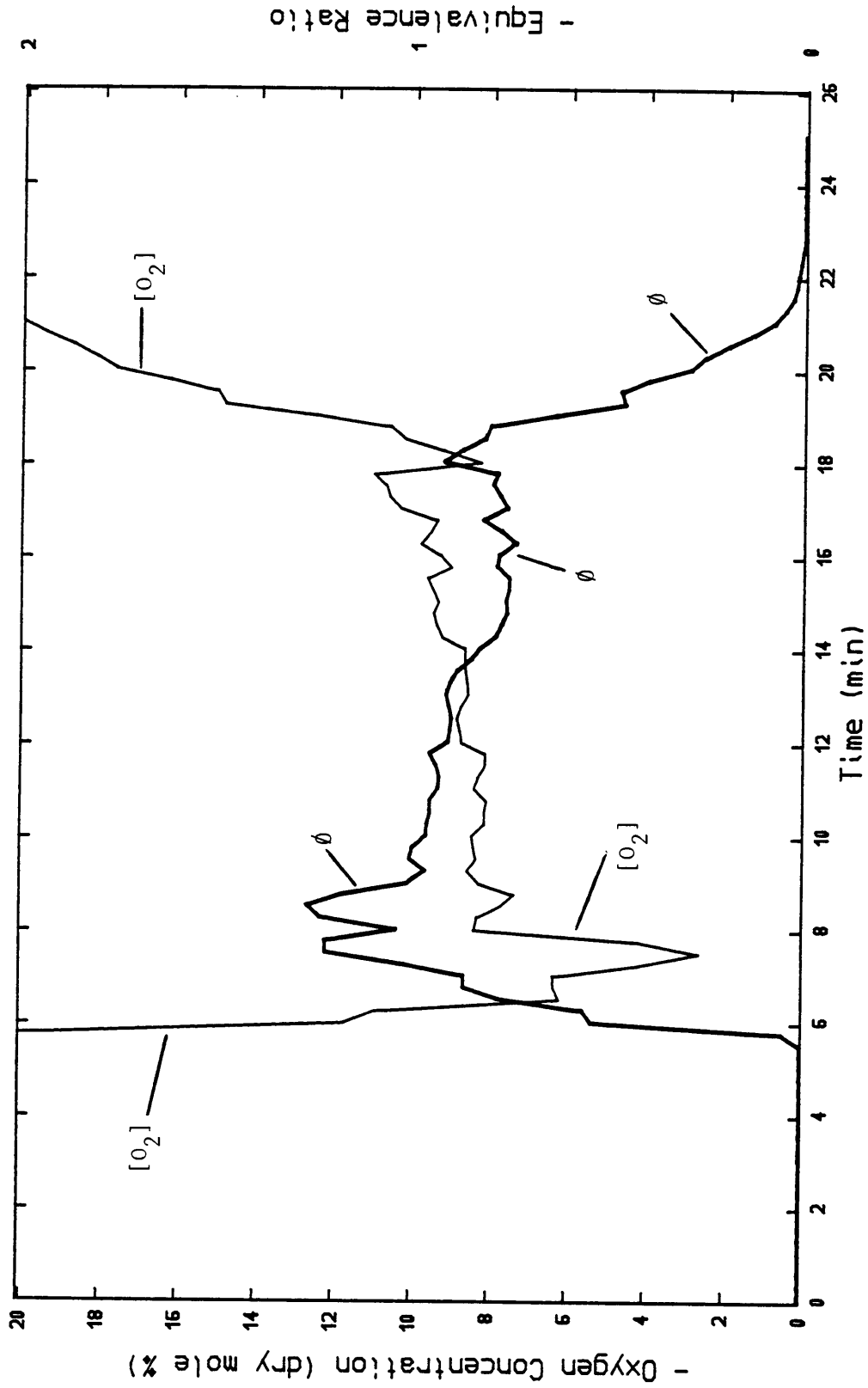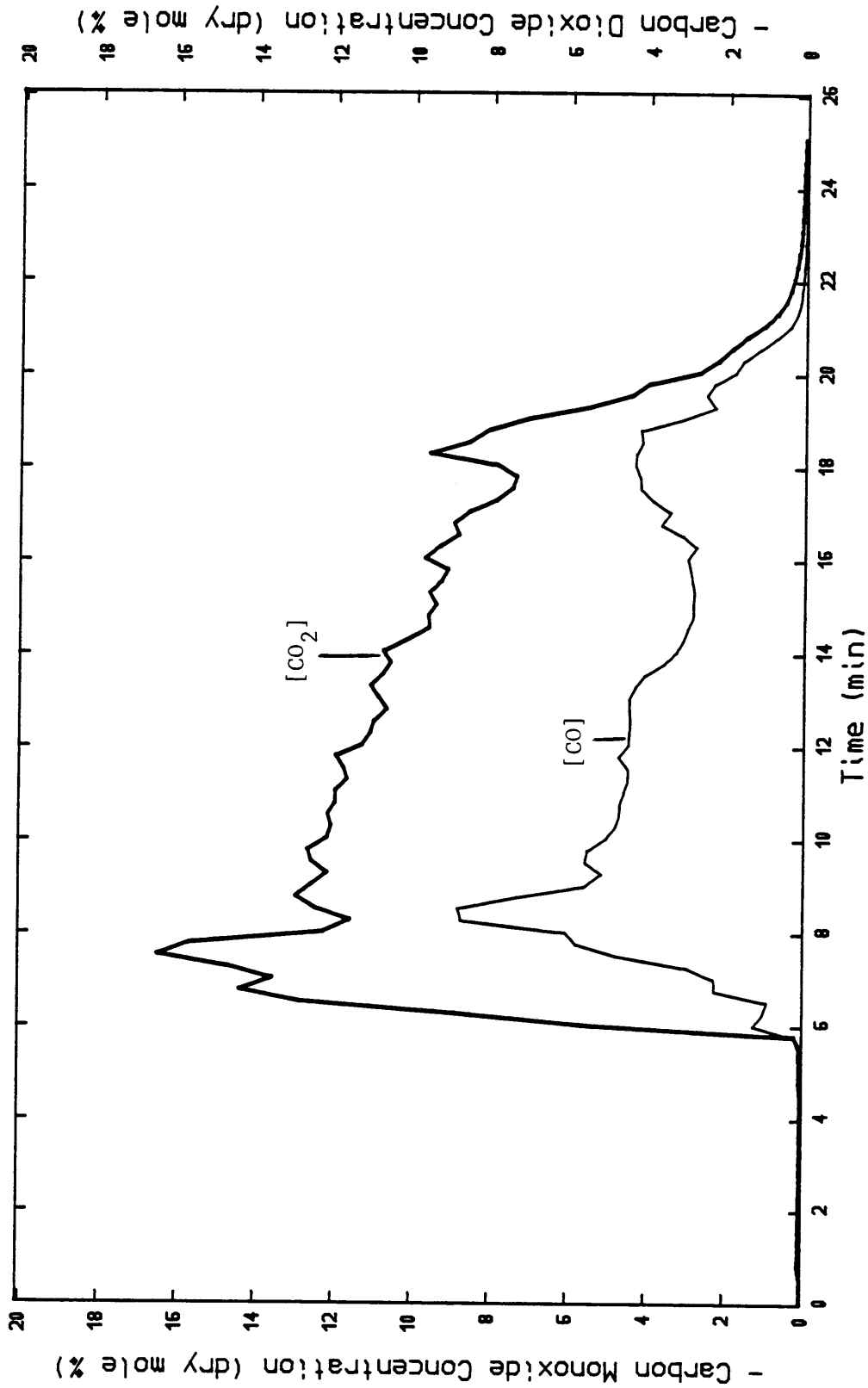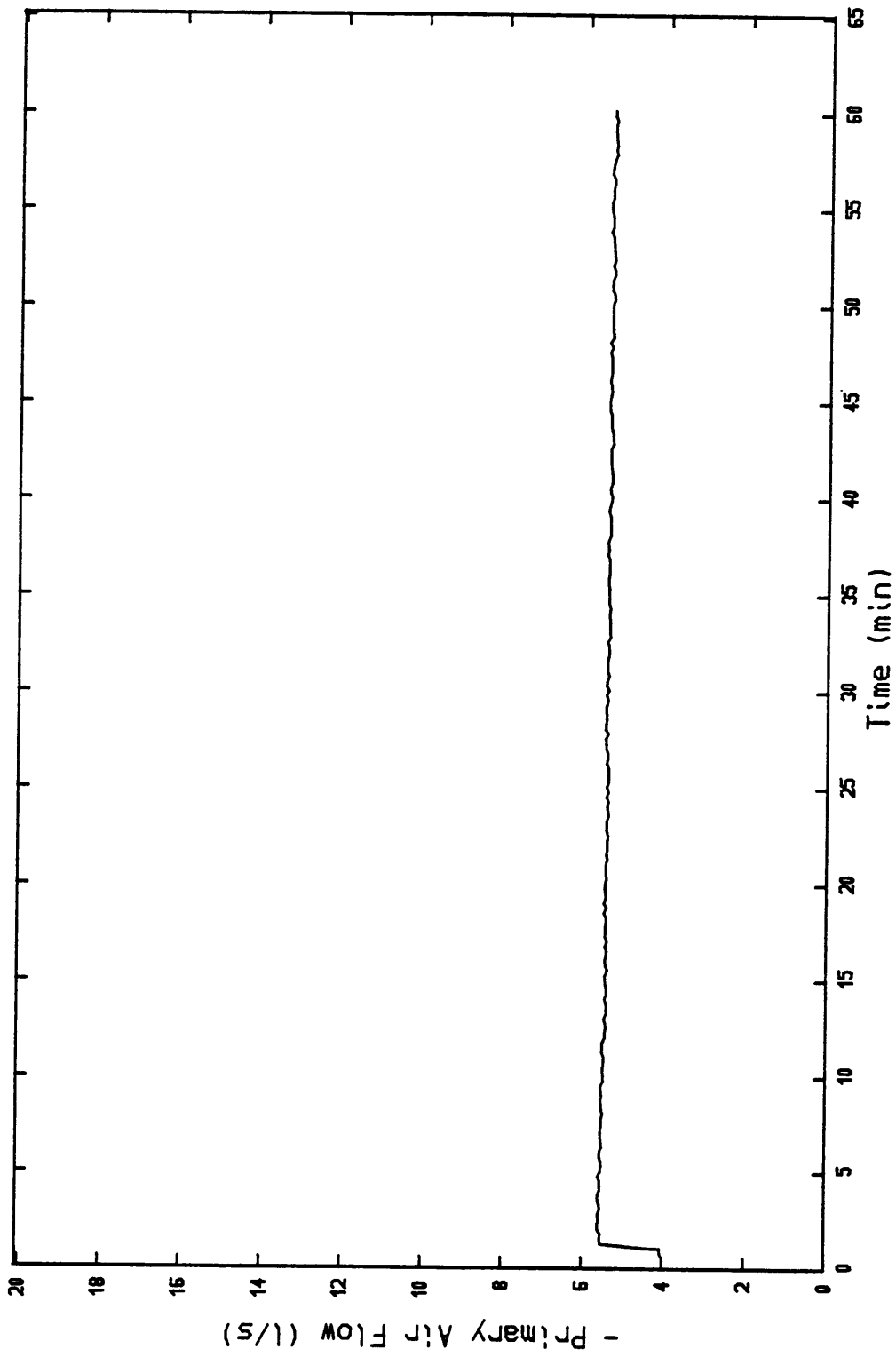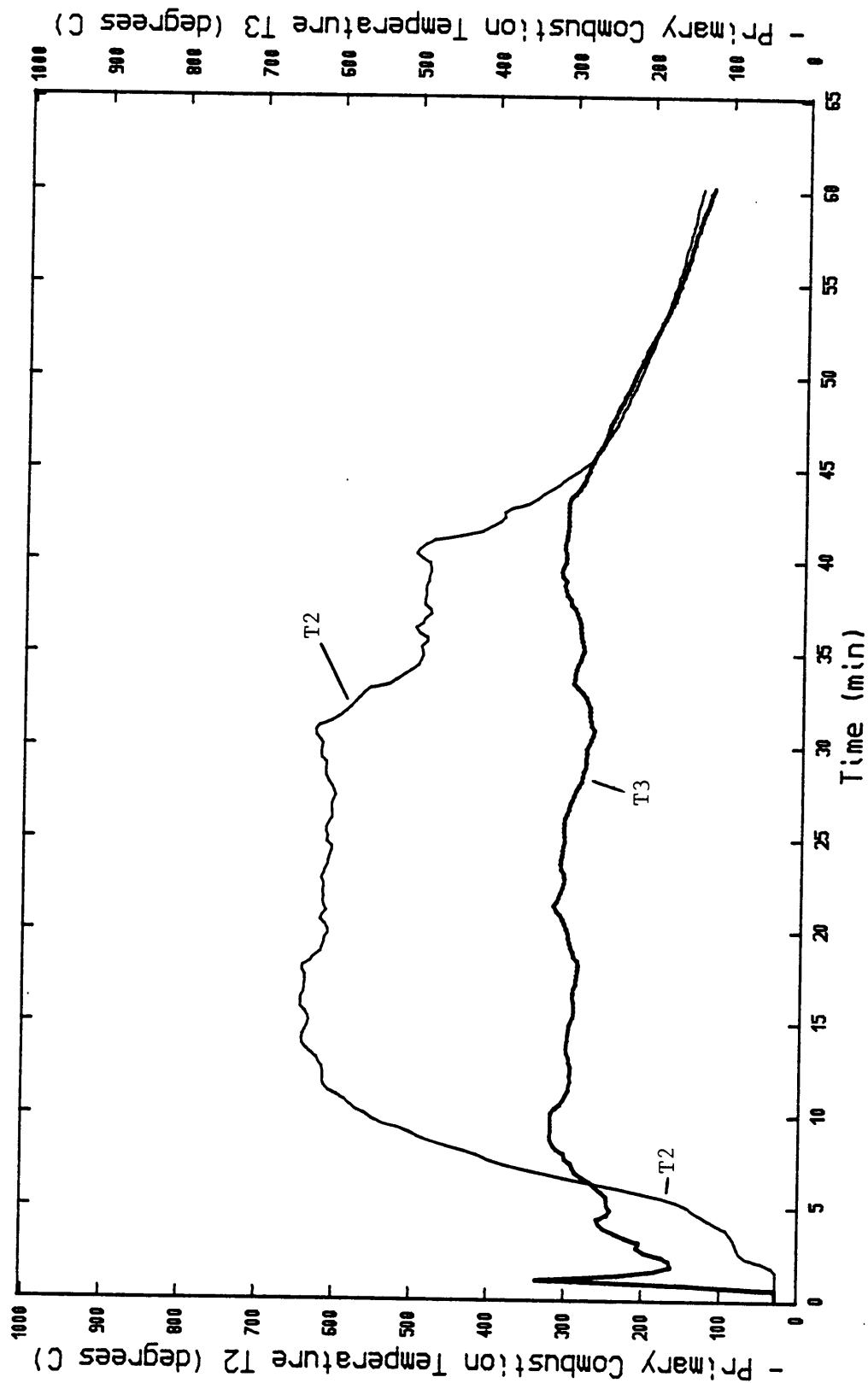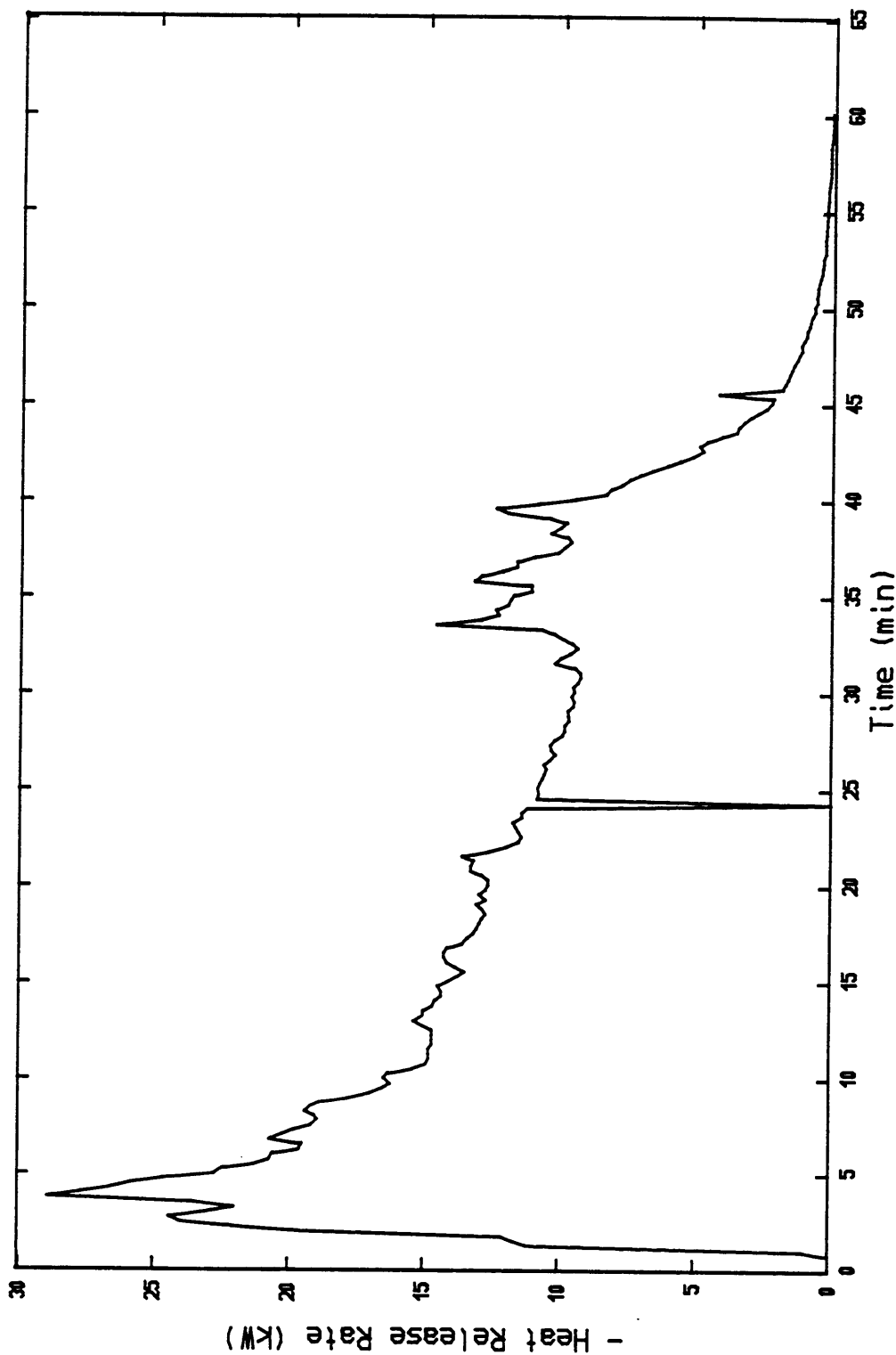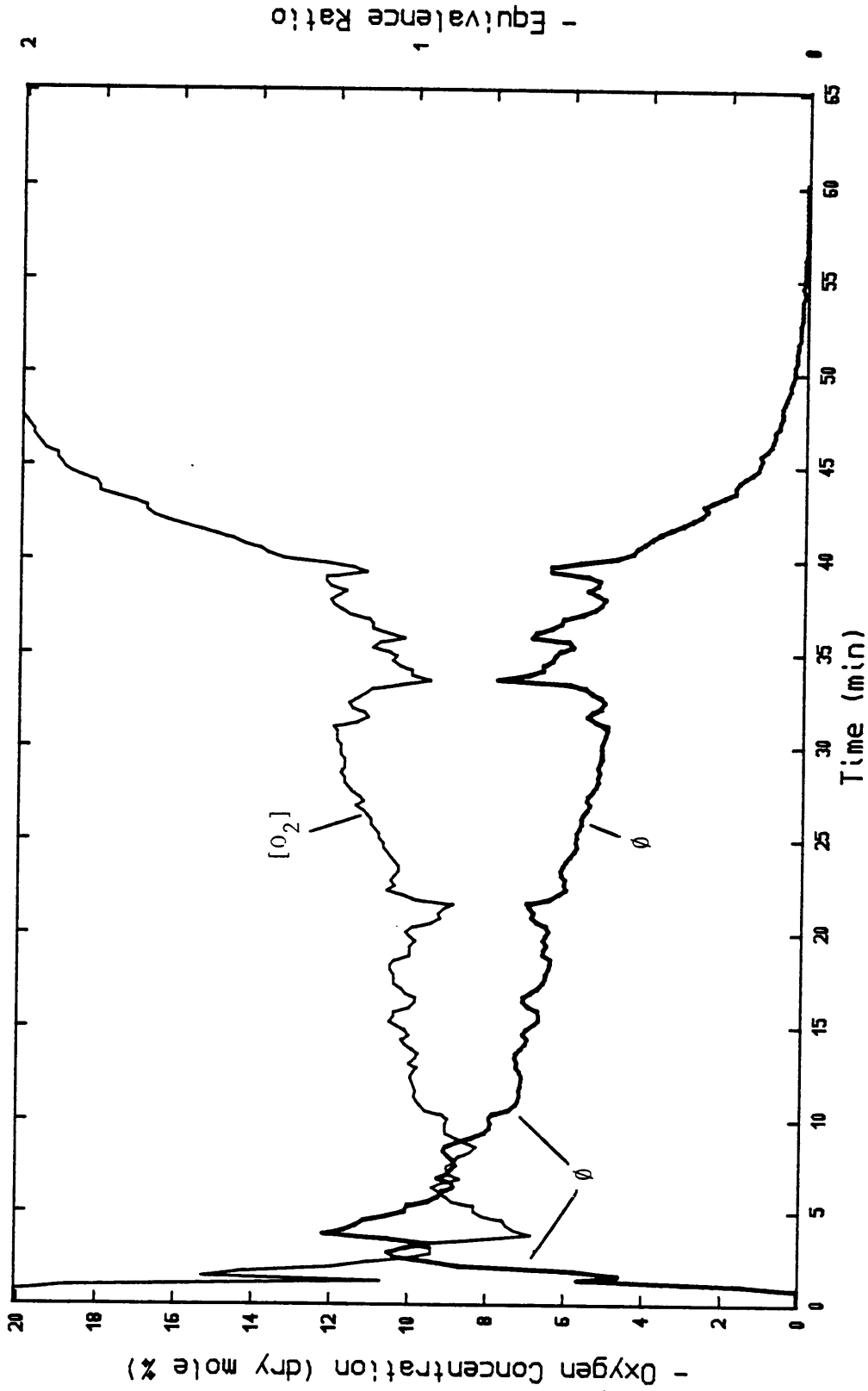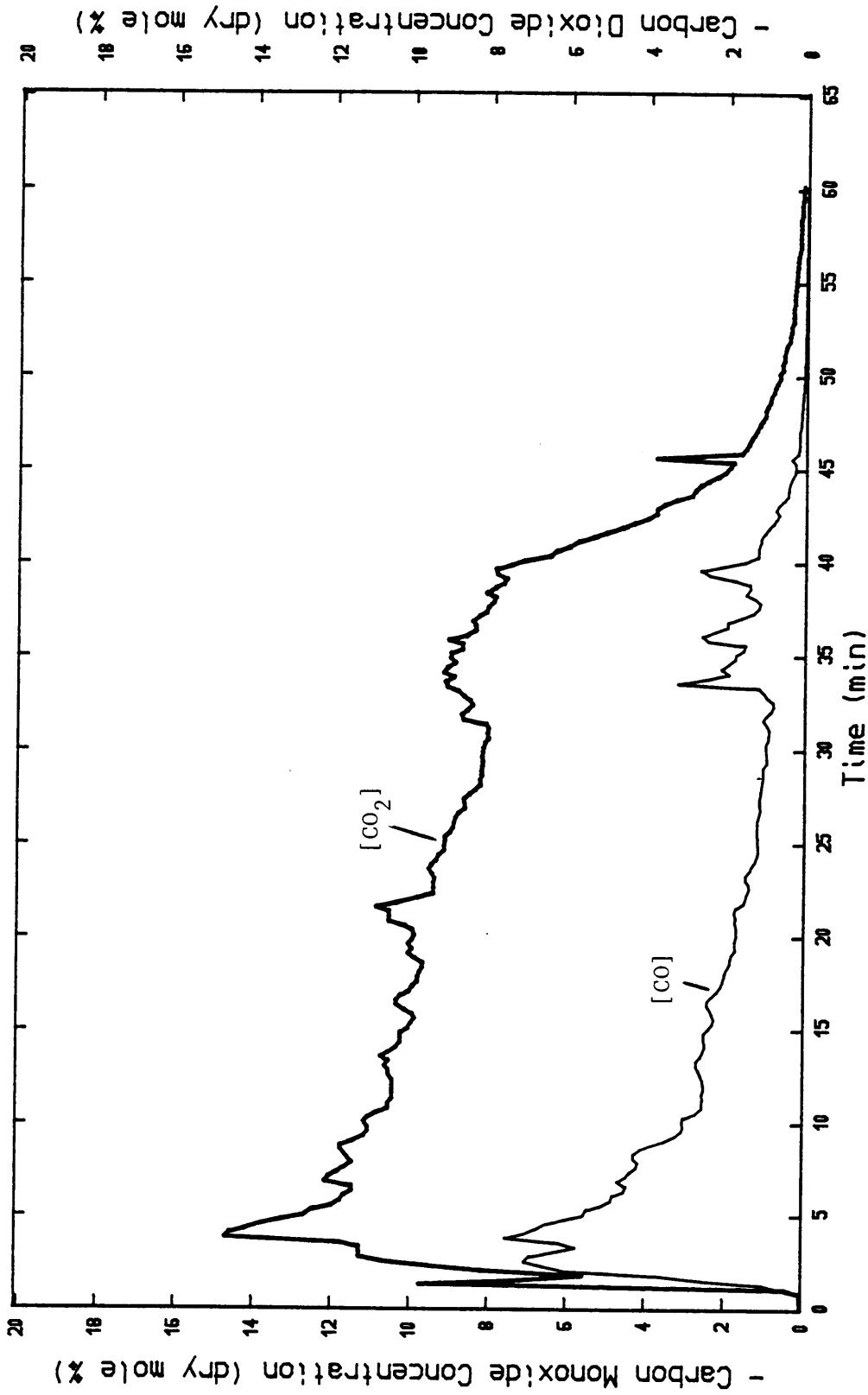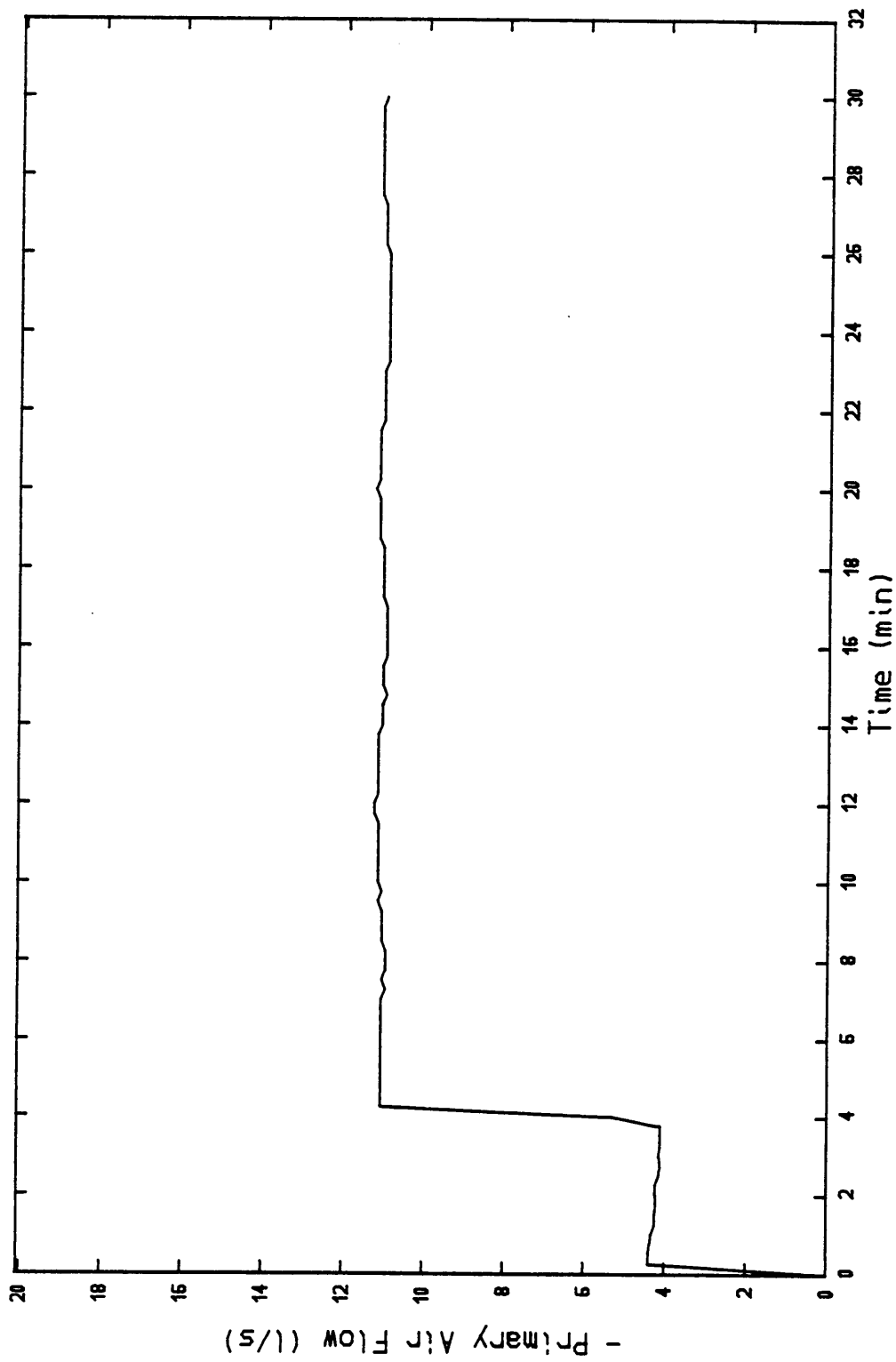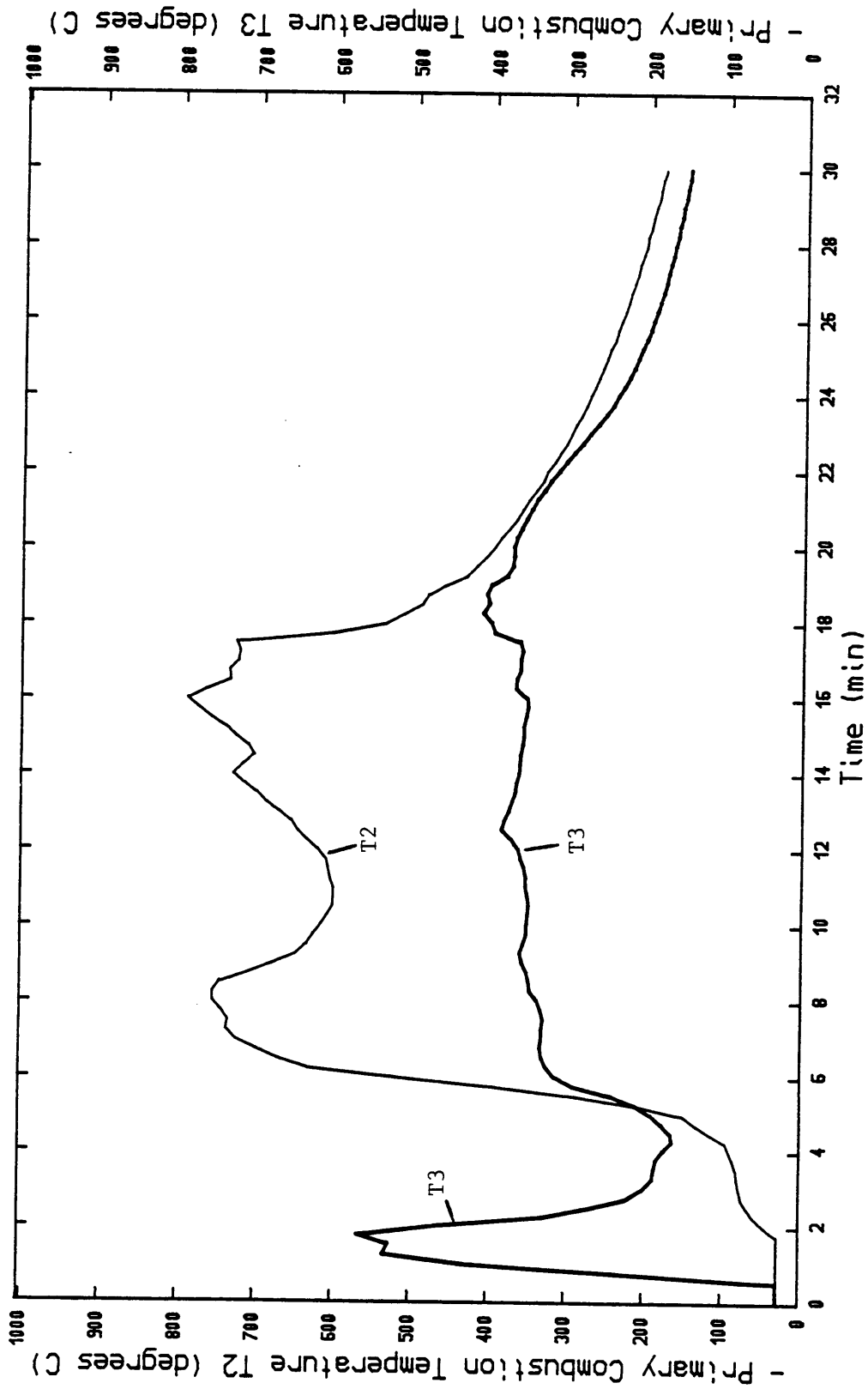Figure 29   Oxygen Concentration and Fuel-Air Equivalence Ratio During Cordwood Low Fire
Test
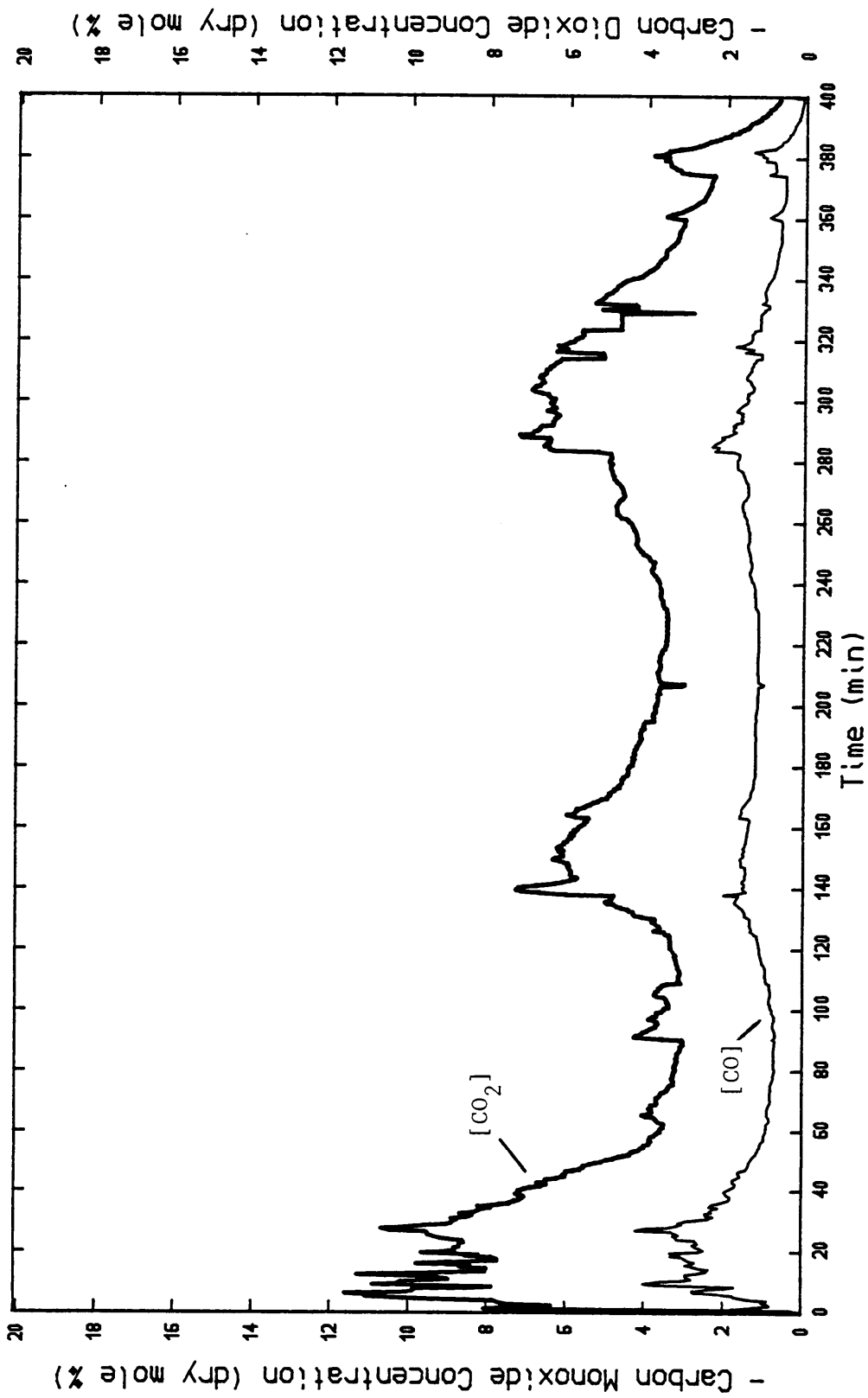
Figure 30   Carbon Monoxide and Carbon Dioxide Concentrations During Cordwood Low Fire Test

Cordwood High Fire Combustion Characterization Test
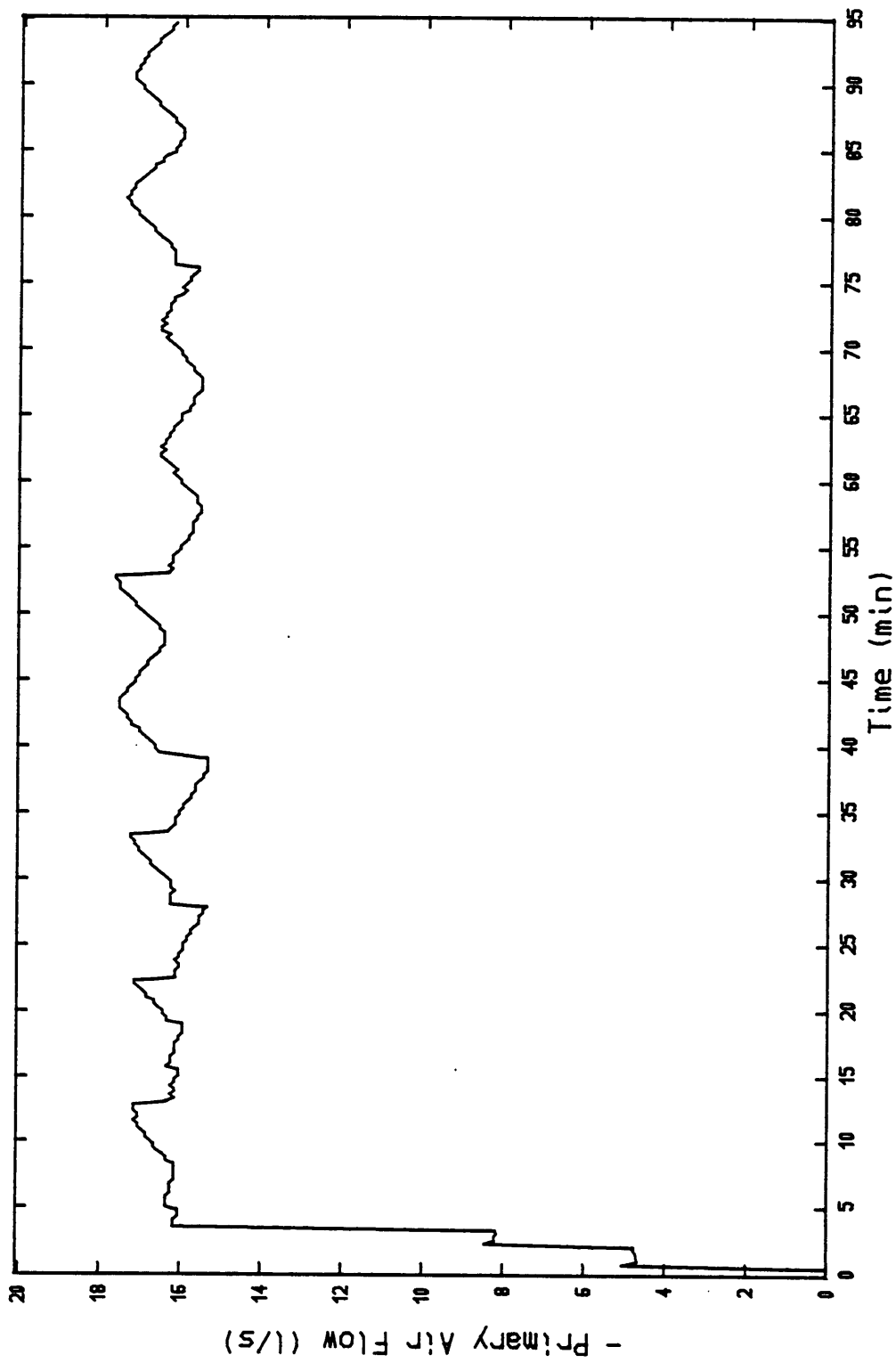
Figure 31  Primary Air Flow During Cordwood High Fire Test
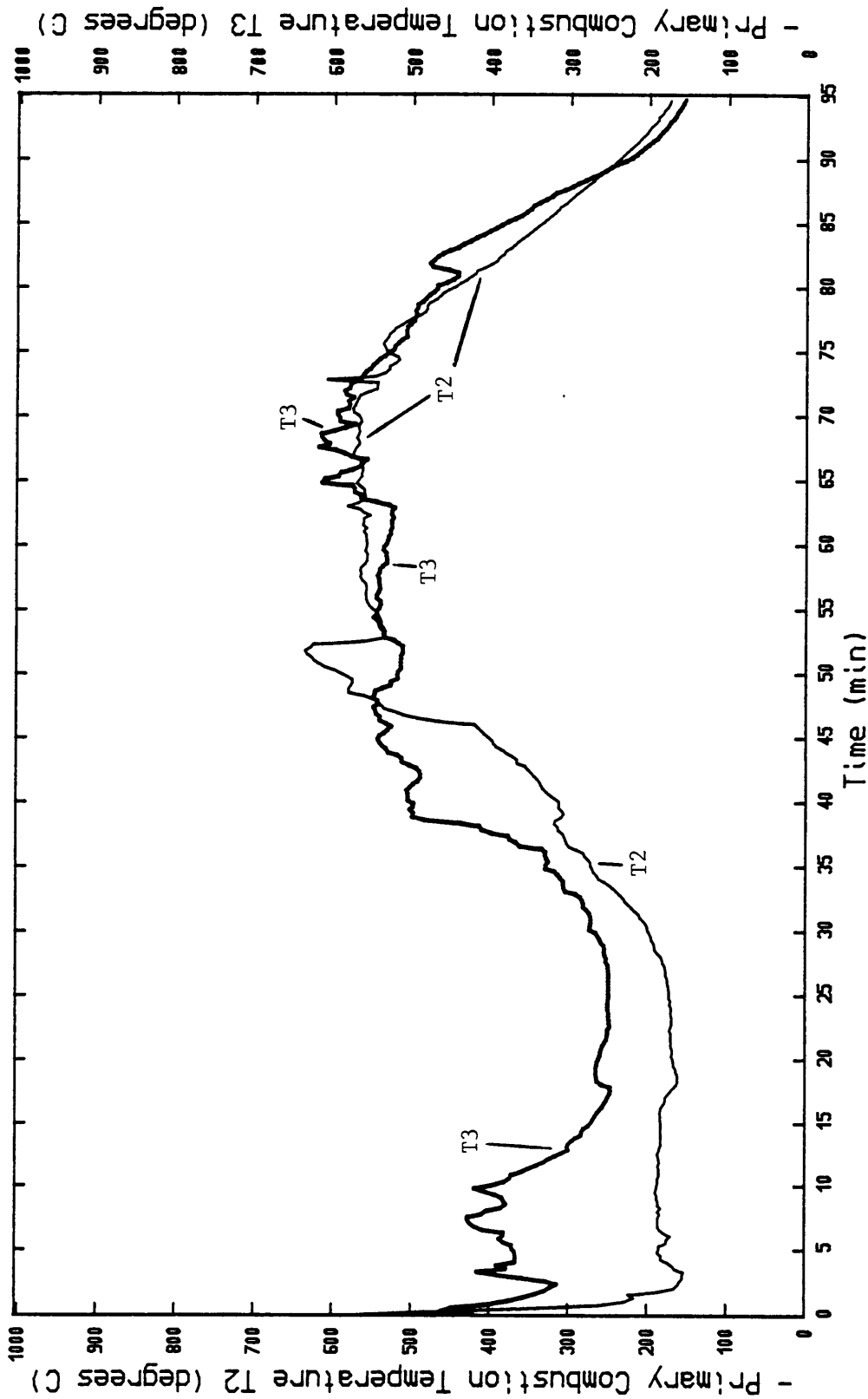
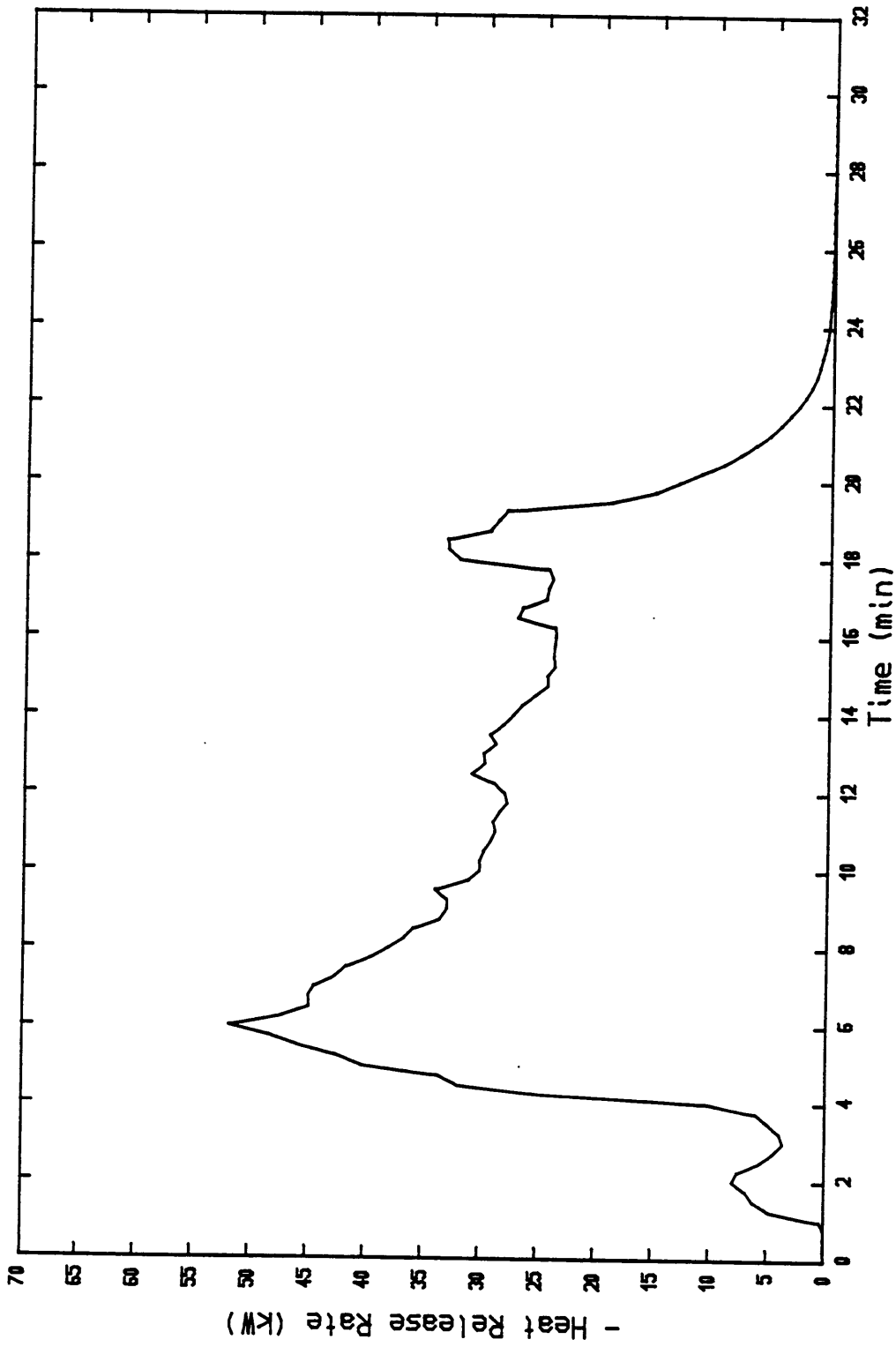Figure 32  Primary Combustion/Gasification Temperatures, T2 and T3, During Cordwood High Fire Test
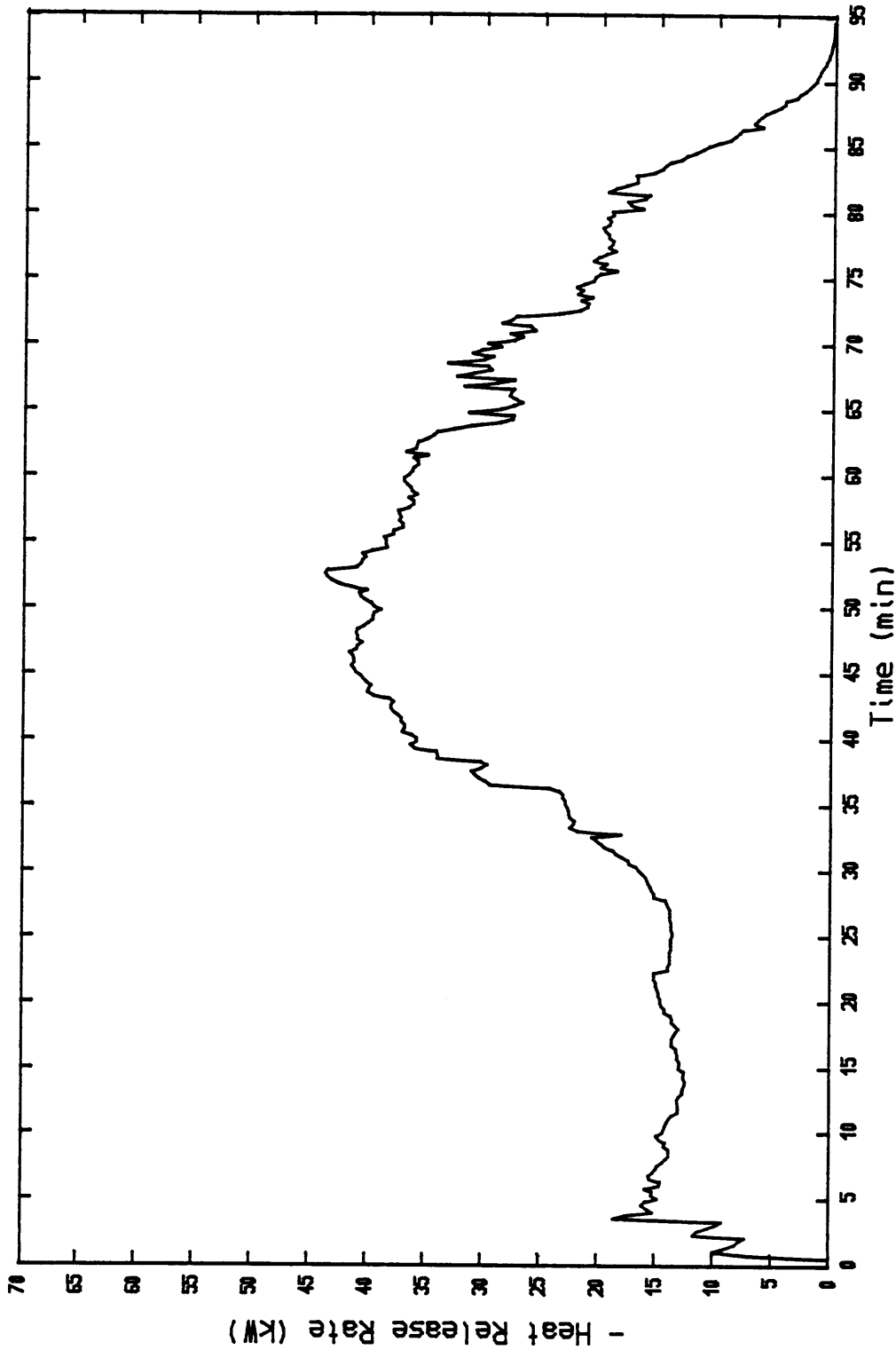
Figure 33   Heat Release Rate During Cordwood High Fire Test
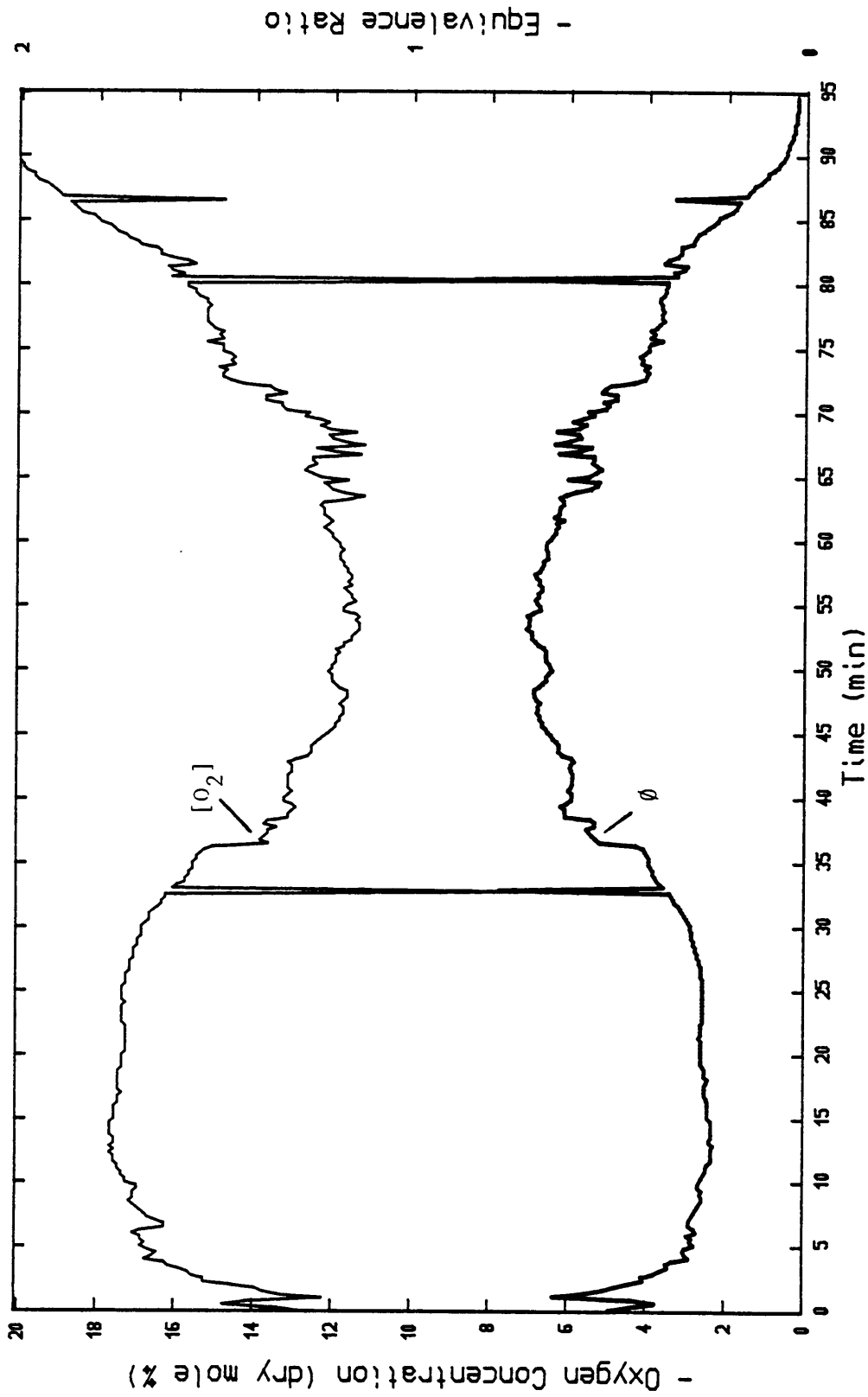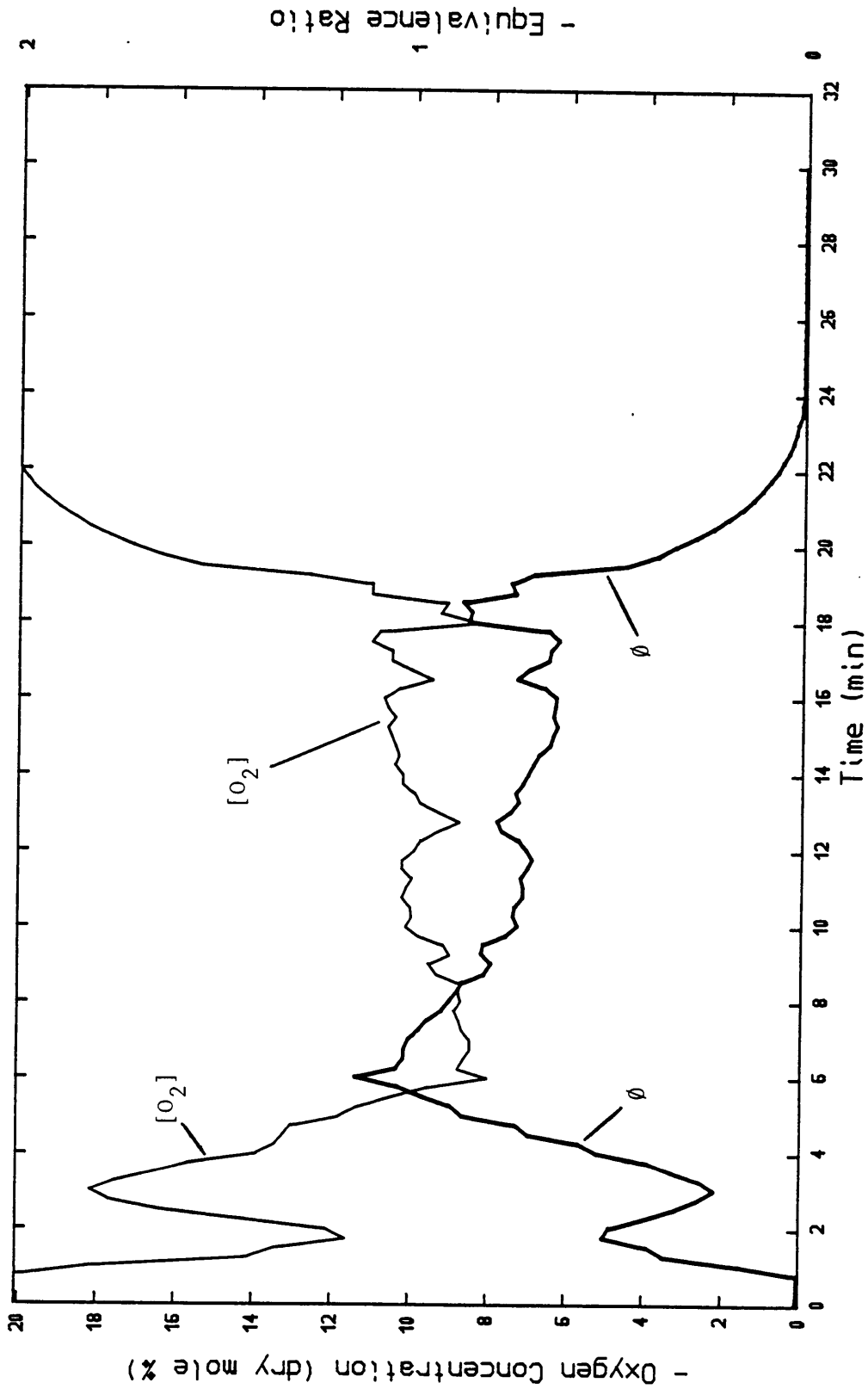
Figure 34  Oxygen Concentration and Fuel-Air Equivalence Ratio During Cordwood High
Fire Test
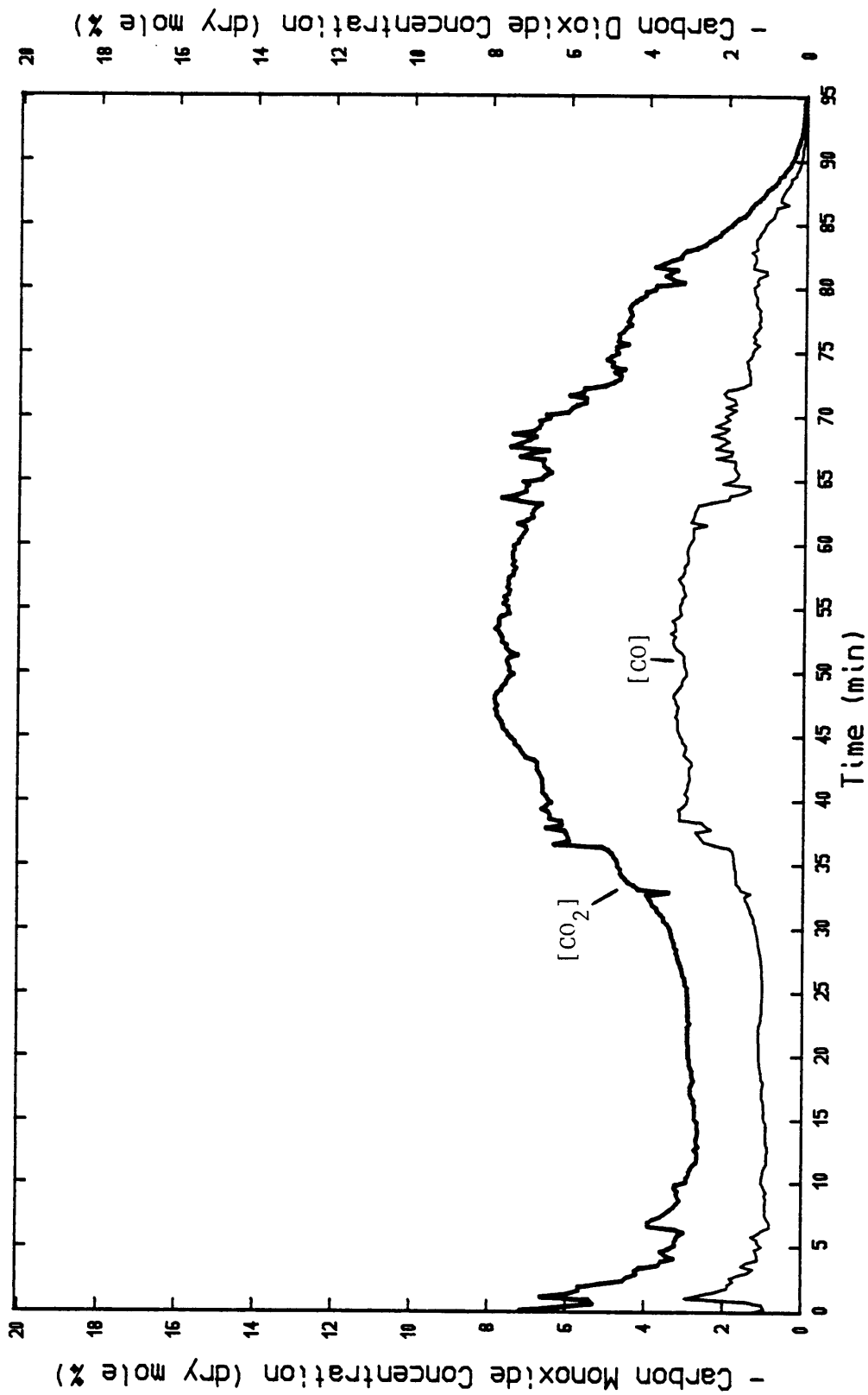
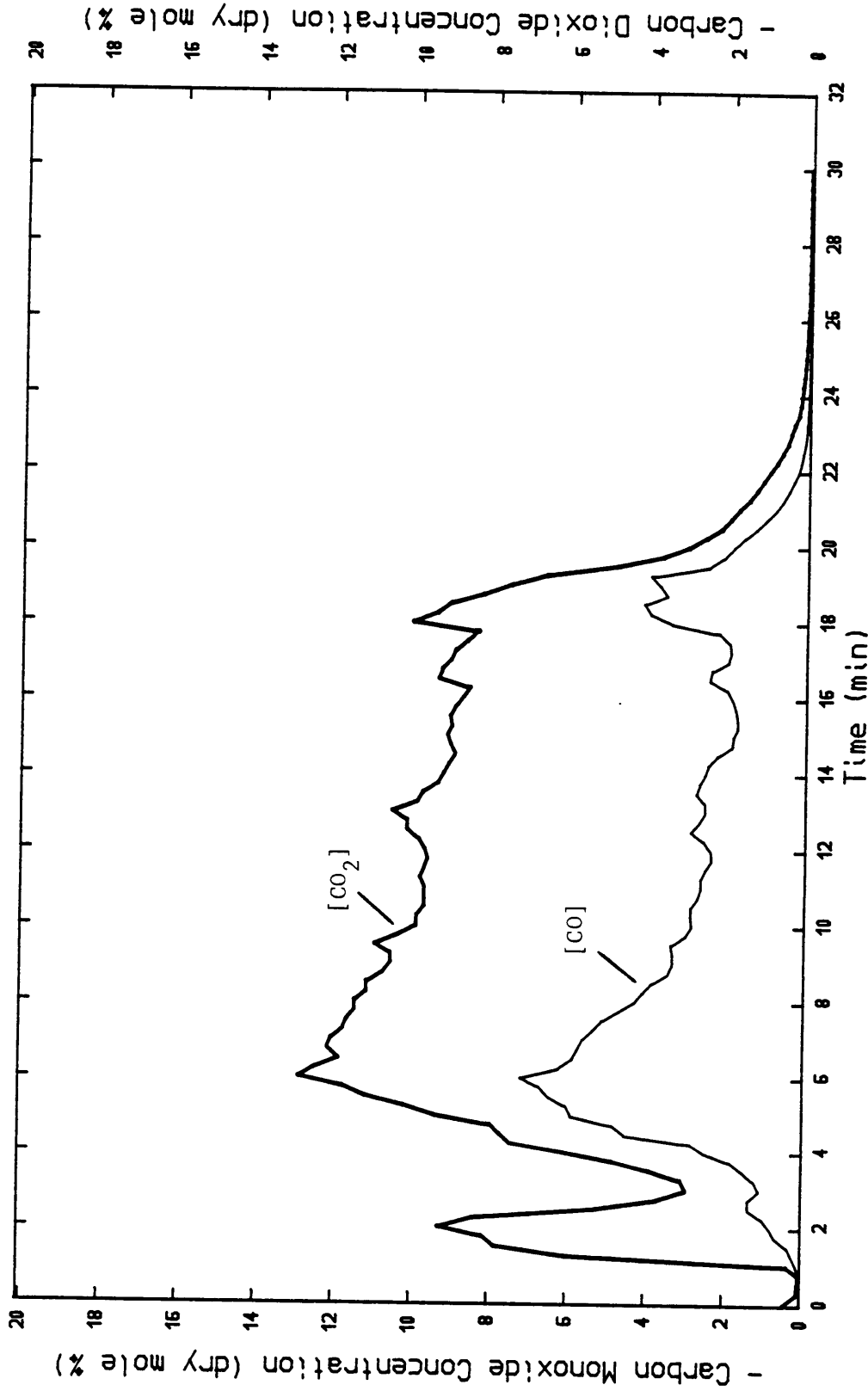Figure 35   Carbon Monoxide and Carbon Dioxide Concentrations During Cordwood High Fire Test

Cordwood Variable Firing Rate Characterization Test
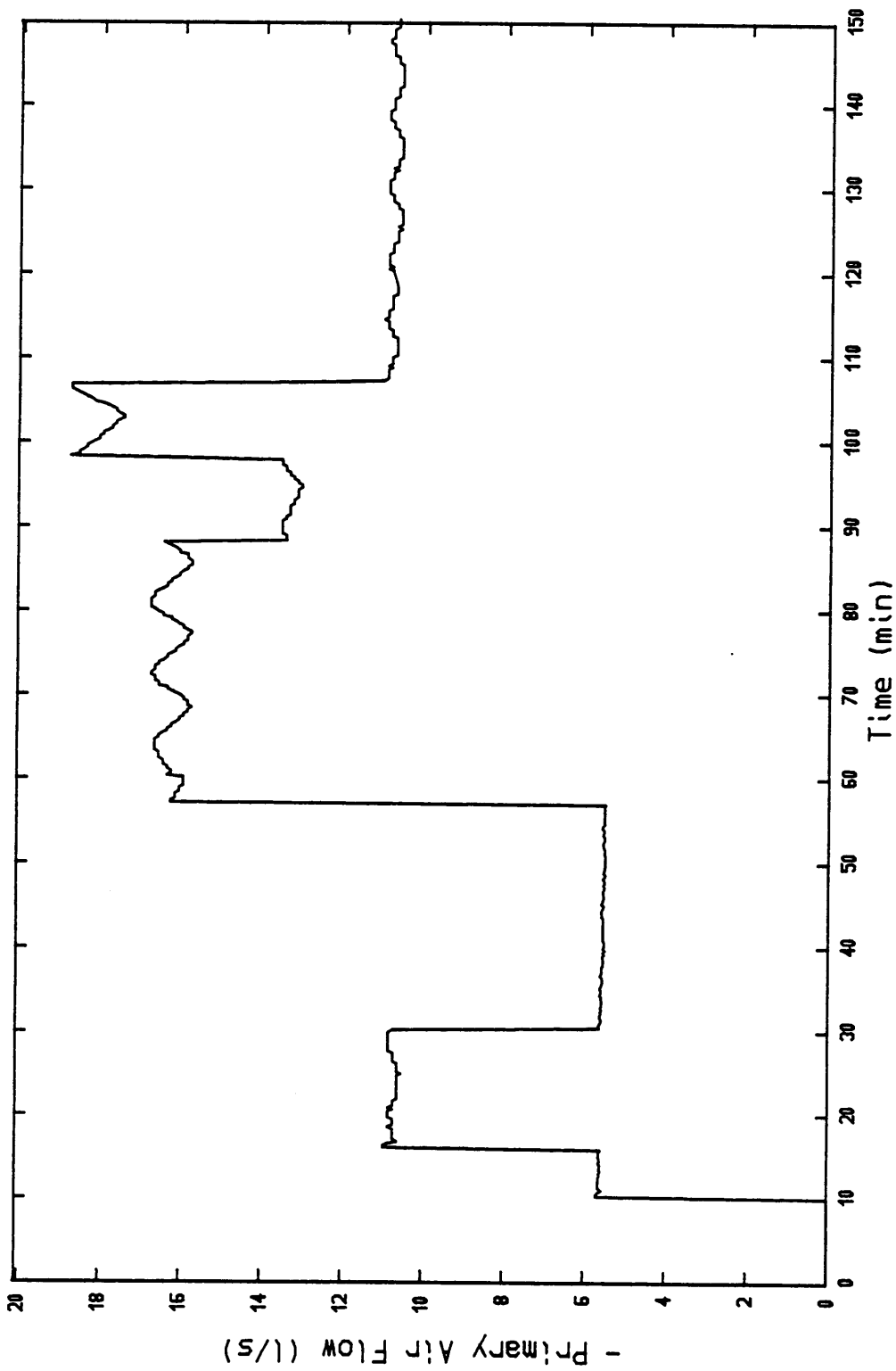
Figure 36  Primary Air Flow During Cordwood Variable Firing  Rate Test
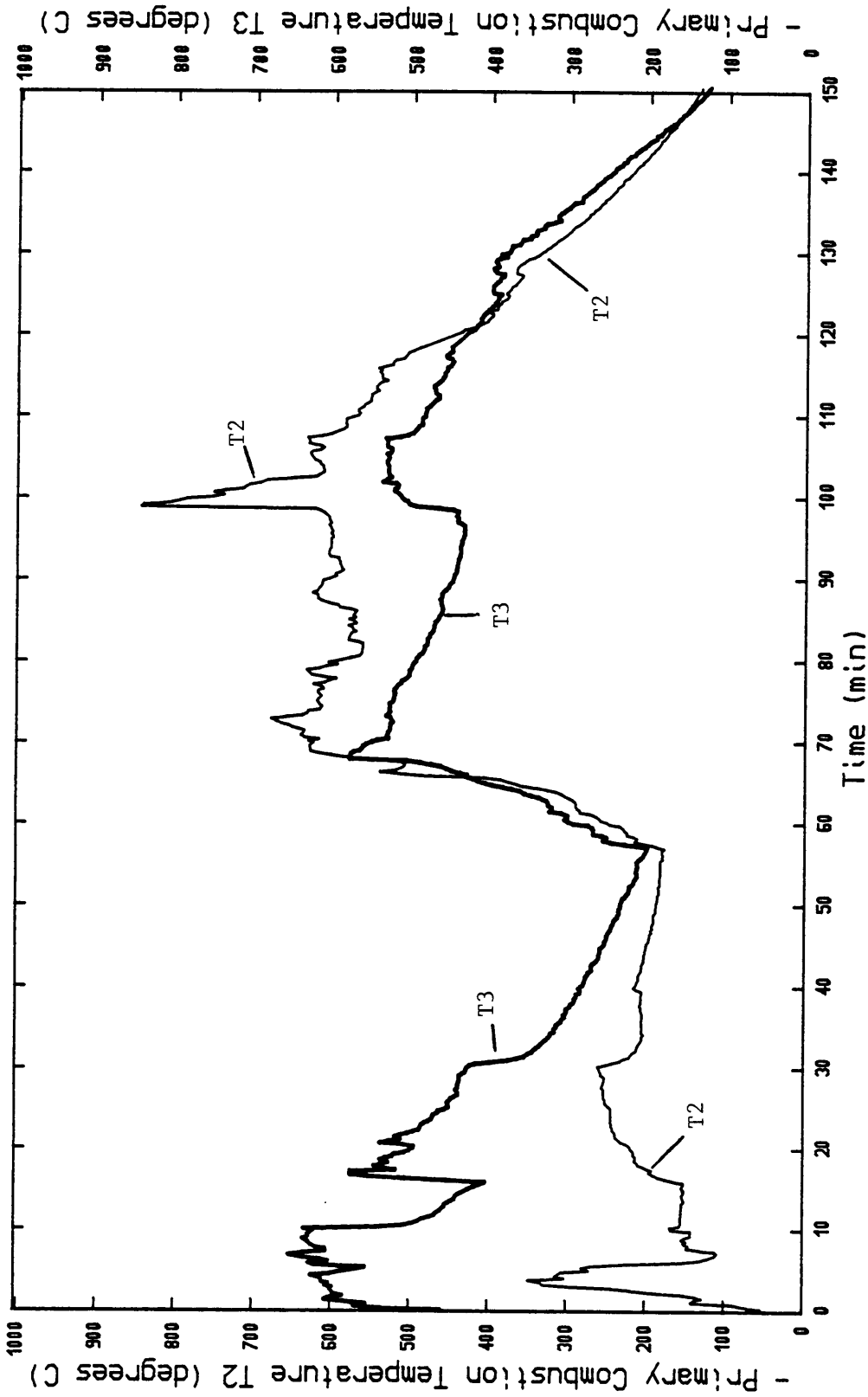
Figure 37  Primary Combustion/Gasification Temperatures, T2 and T3, During Cordwood Variable Firing Rate Test
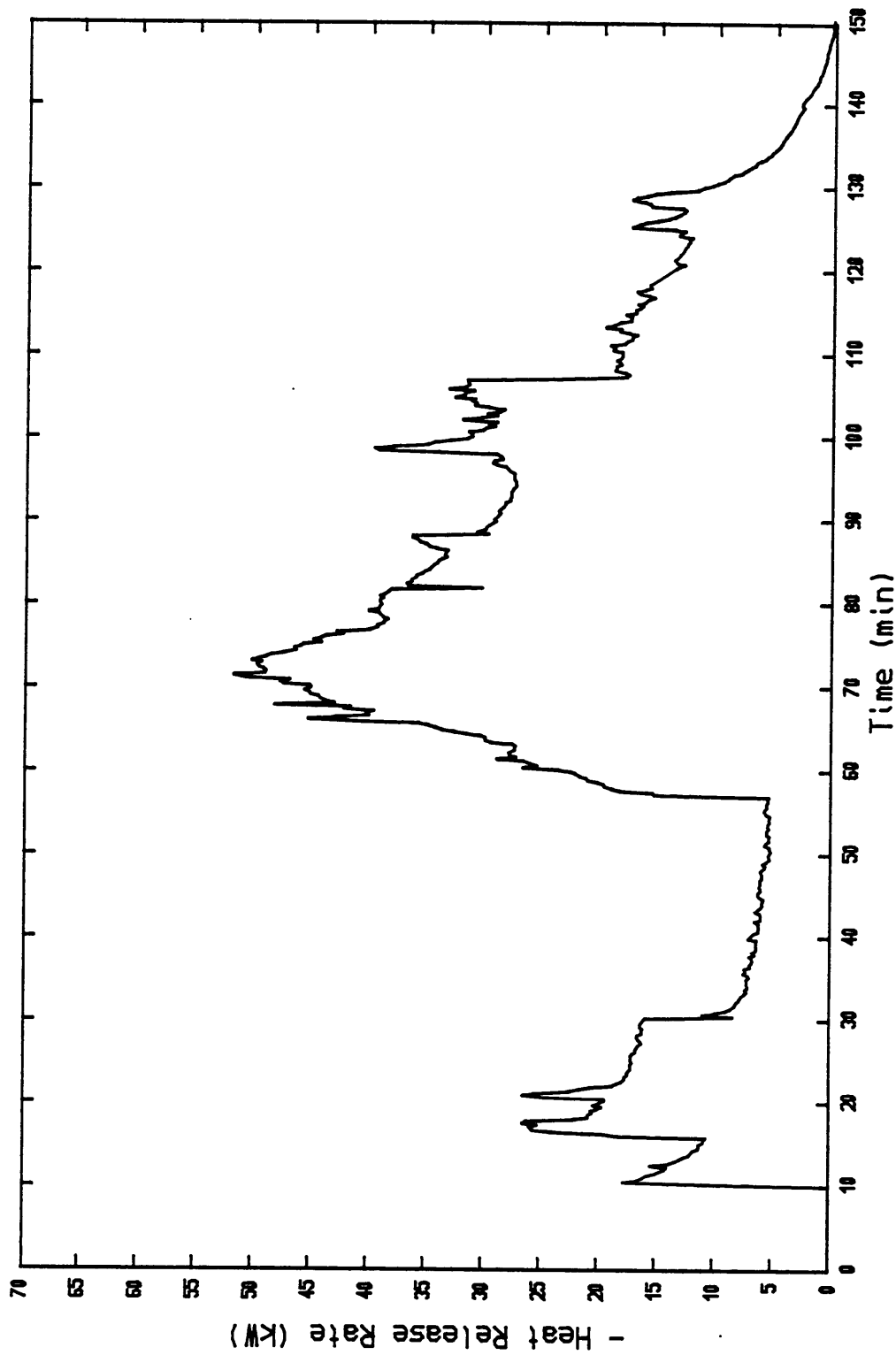
Figure 38  Heat Release Rate During Cordwood Variable Firing Rate Test
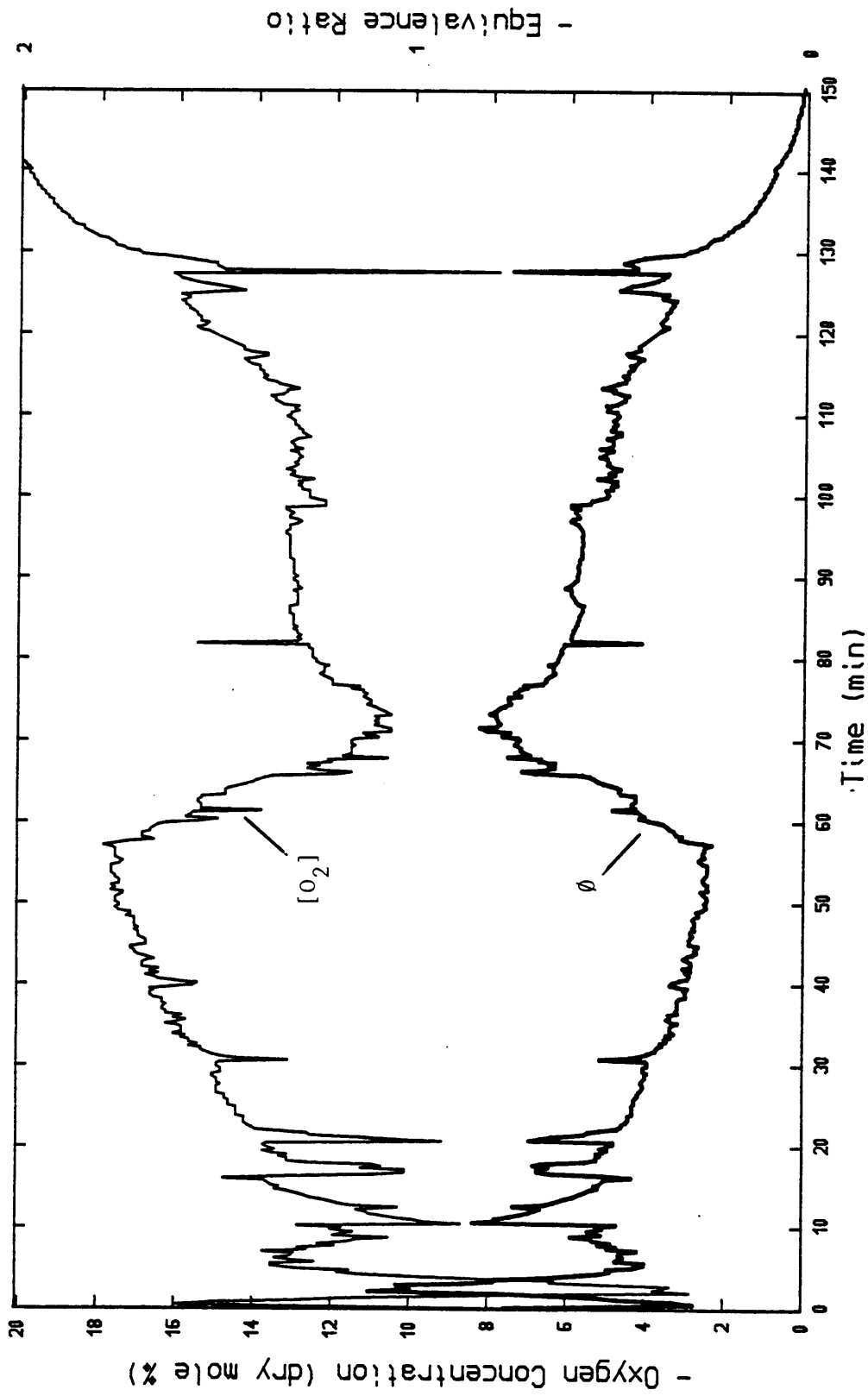
Figure 39 Oxygen Concentration and Fuel-Air Equivalence Ratio During Cordwood Variable Firing Rate Test
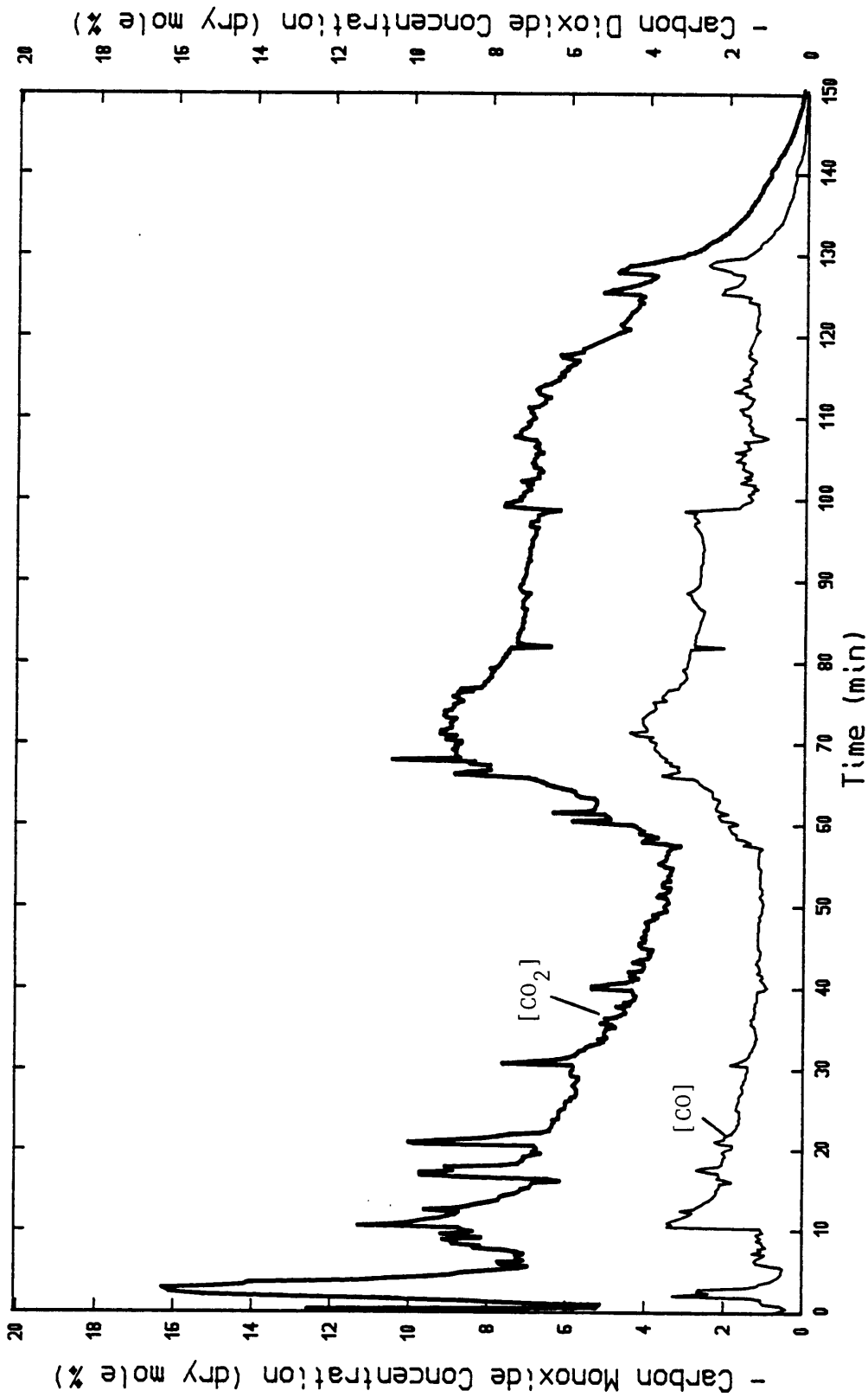
Figure 40  Carbon Monoxide and Carbon Dioxide Concentrations  During Cordwood Variable
Firing Rate Test
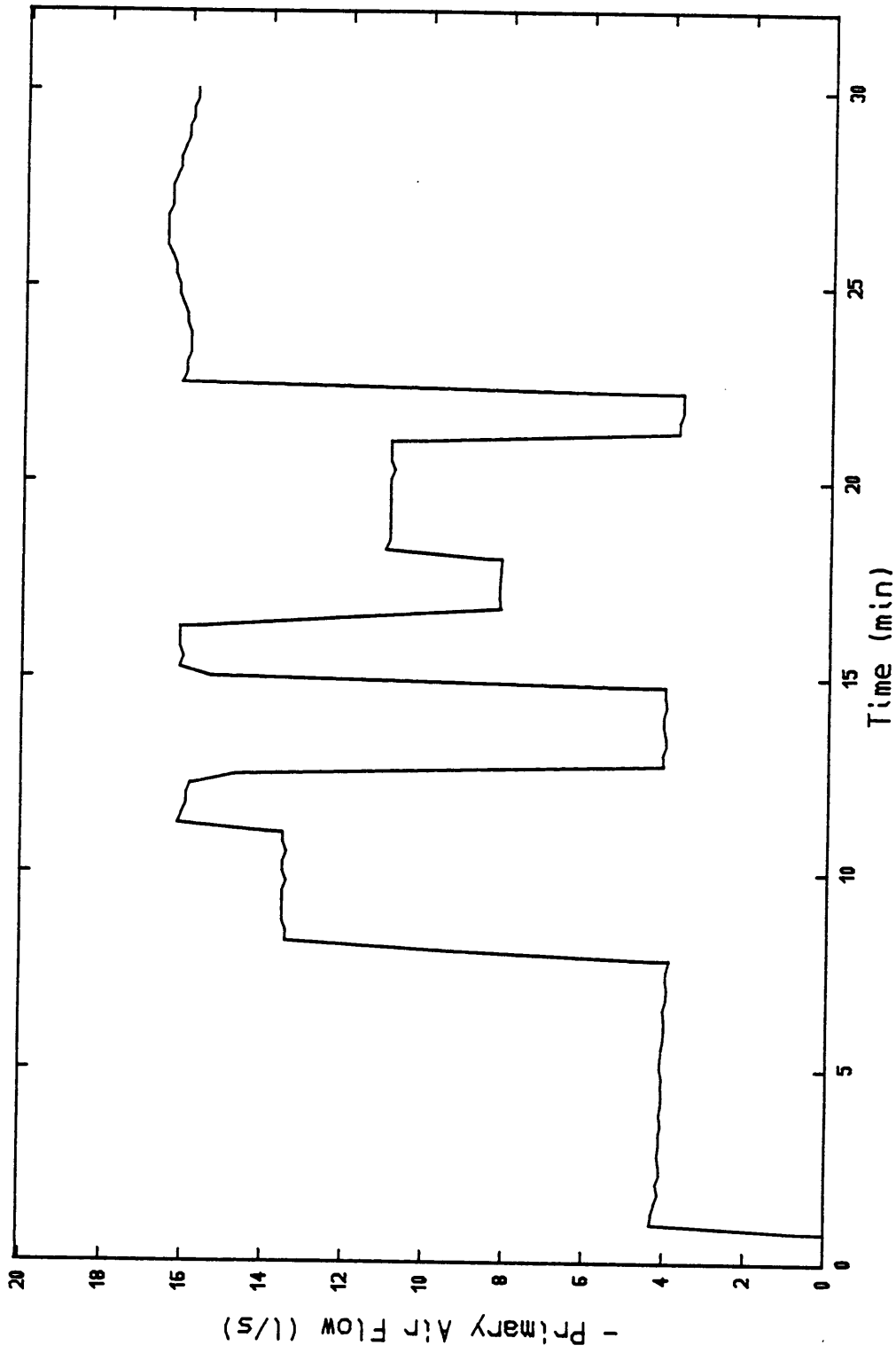
Cordwood Bang-Bang Combustion Characterization Test
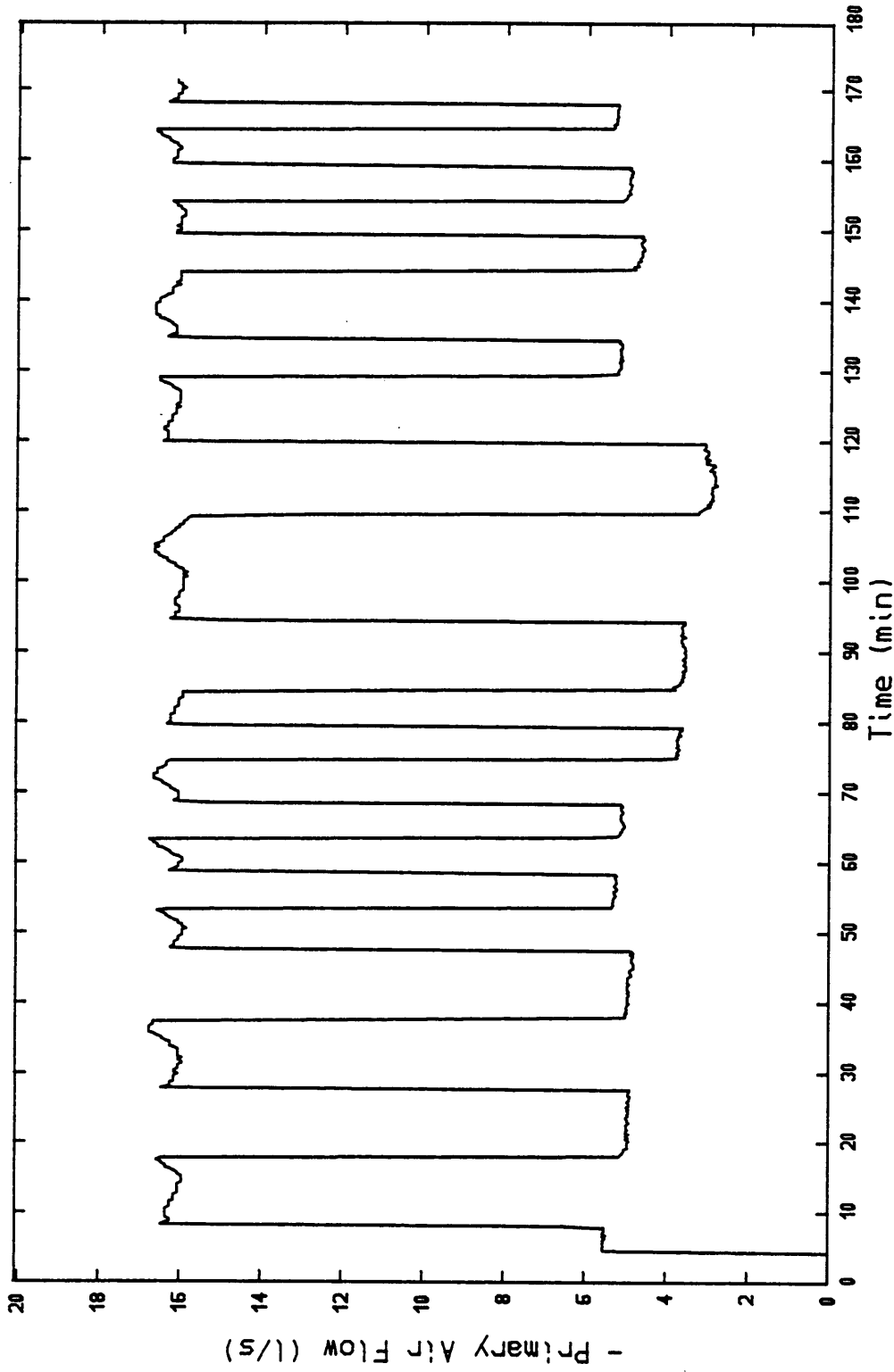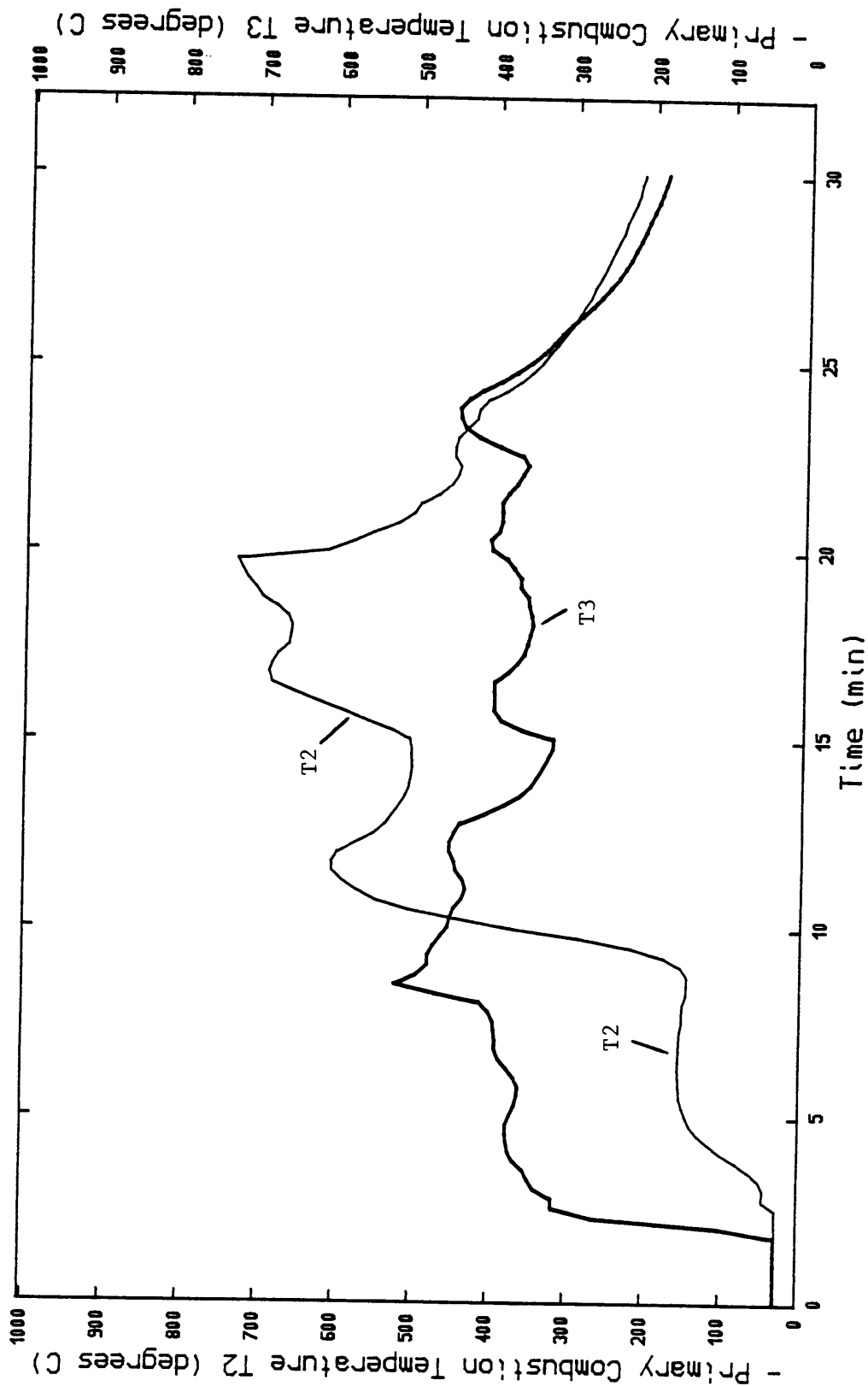
Figure 41   Primary Air Flow During Cordwood Bang-Bang Test
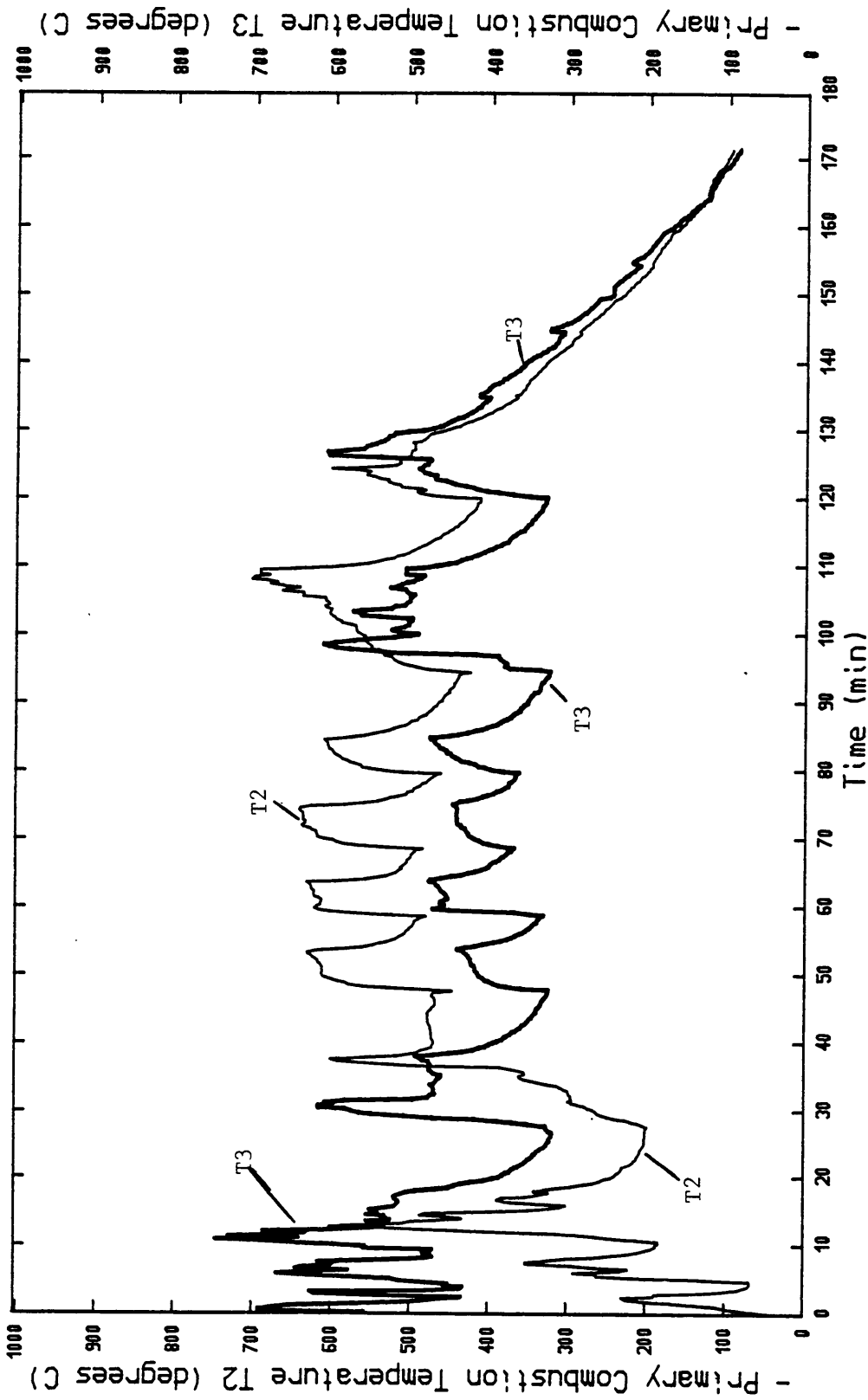
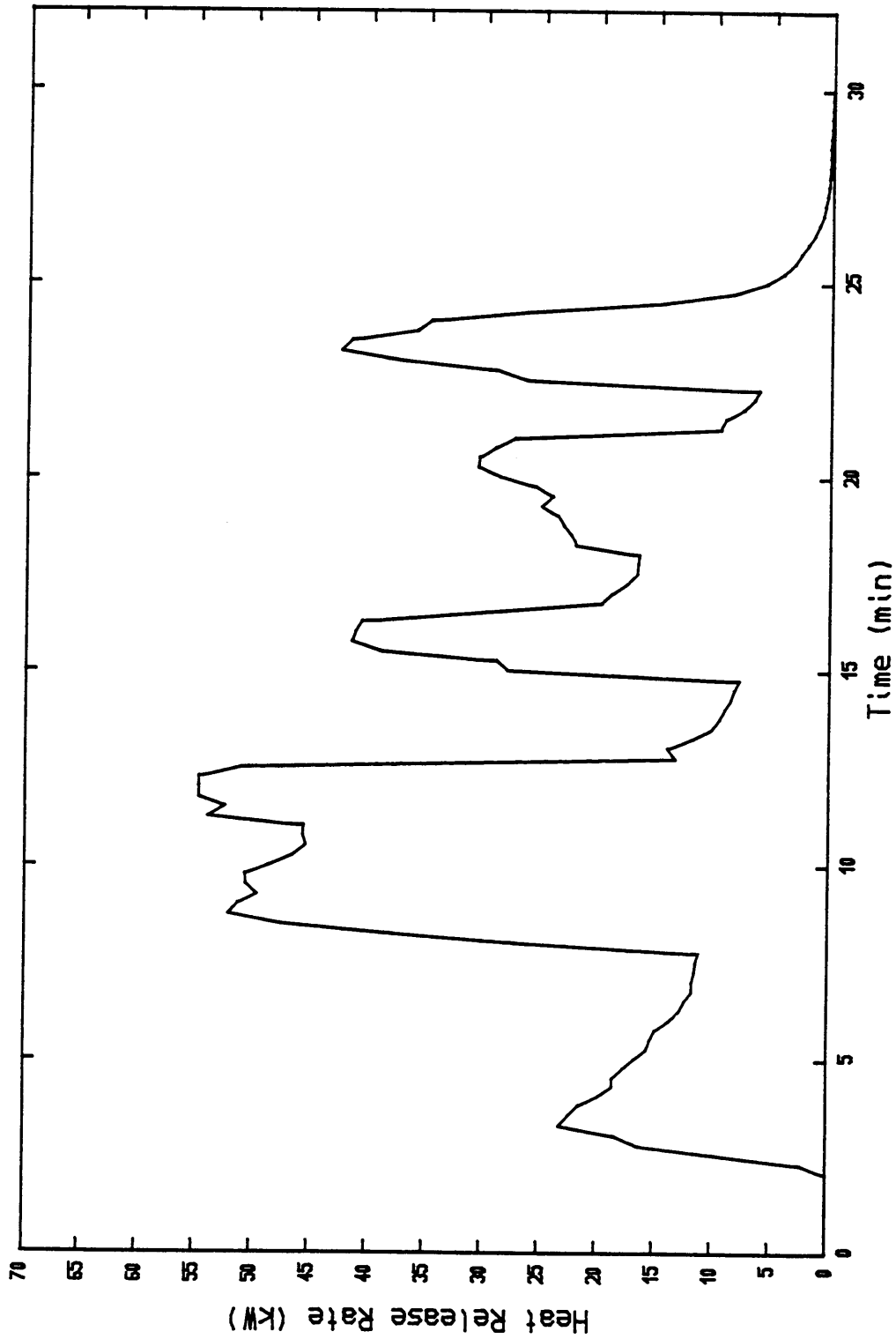Figure 42  Primary Combustion/Gasification Temperatures, T2 and T3, During Cordwood Bang-Bang Test
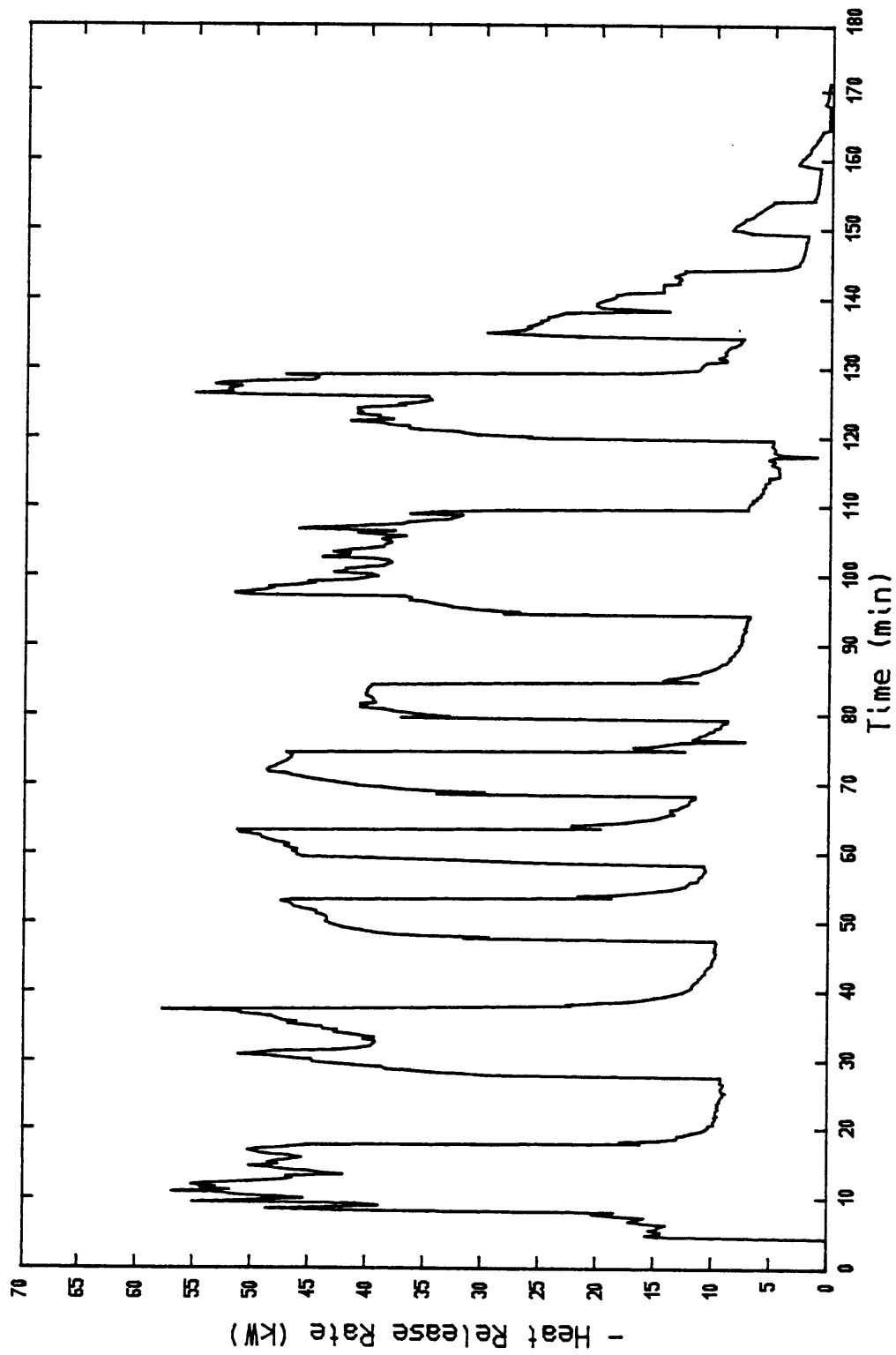
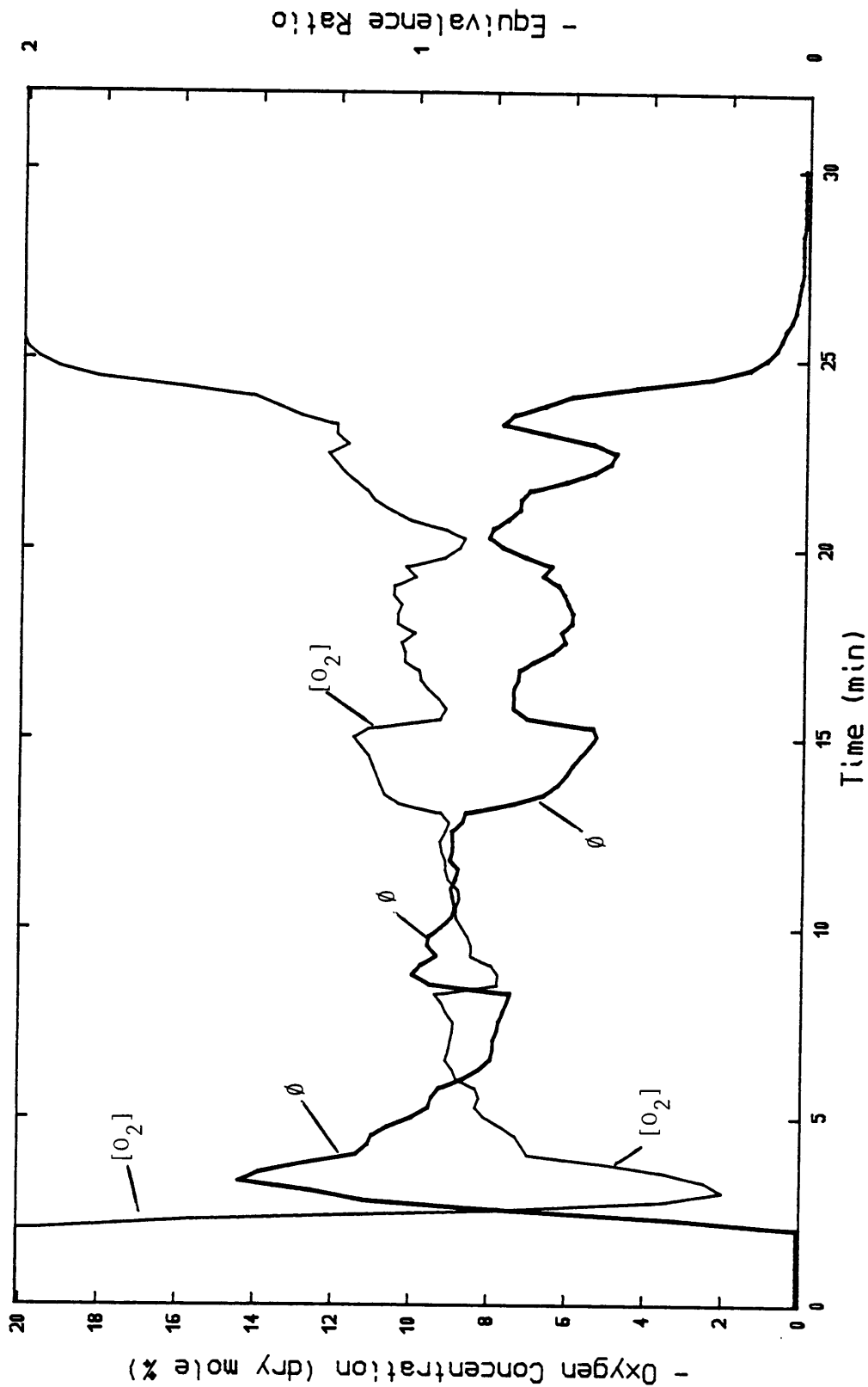Figure 43  Heat Release Rate During Cordwood Bang–Bang Test
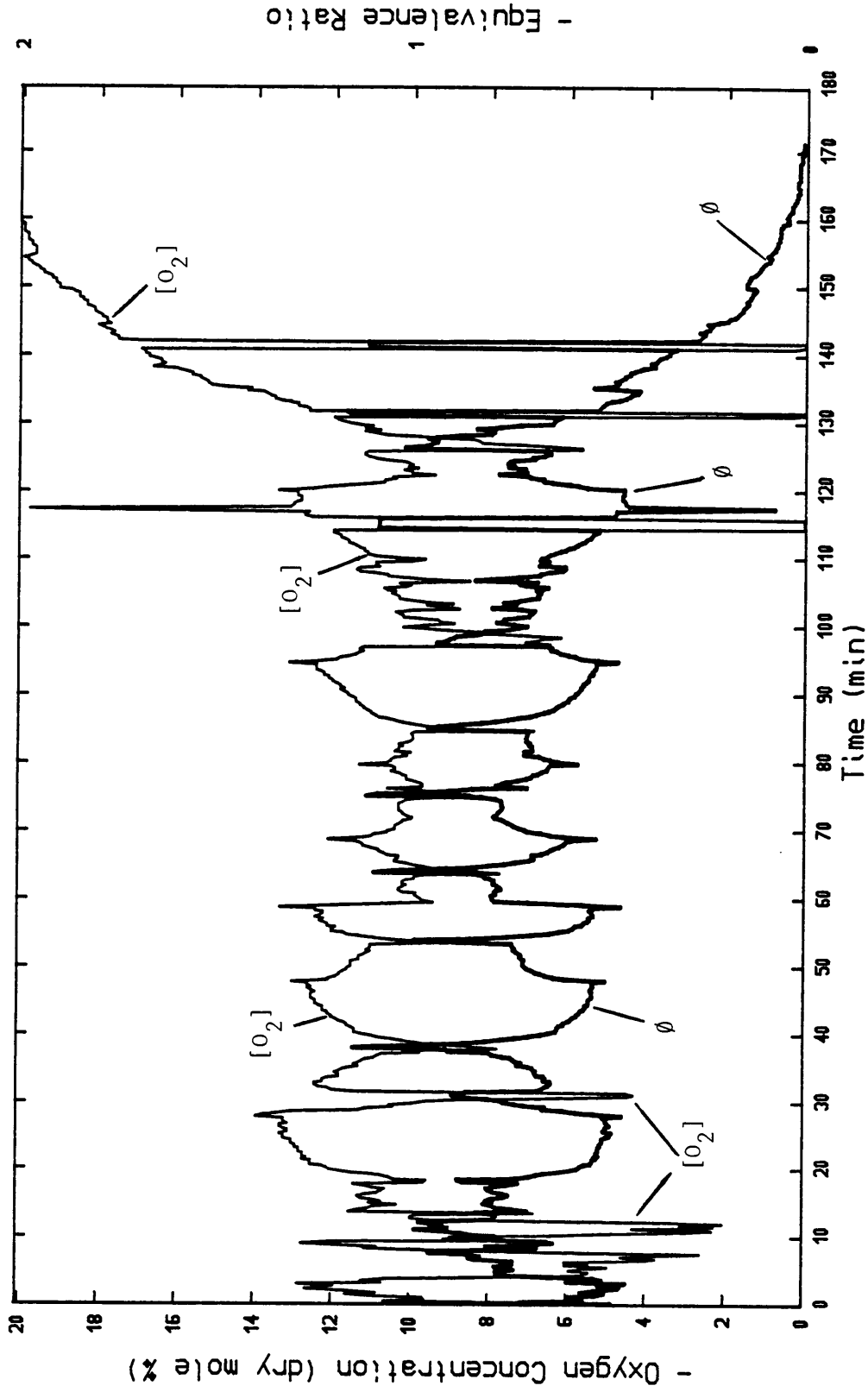
Figure 44  Oxygen Concentration and Fuel-Air Equivalence Ratio During Cordwood Bang-Bang Test
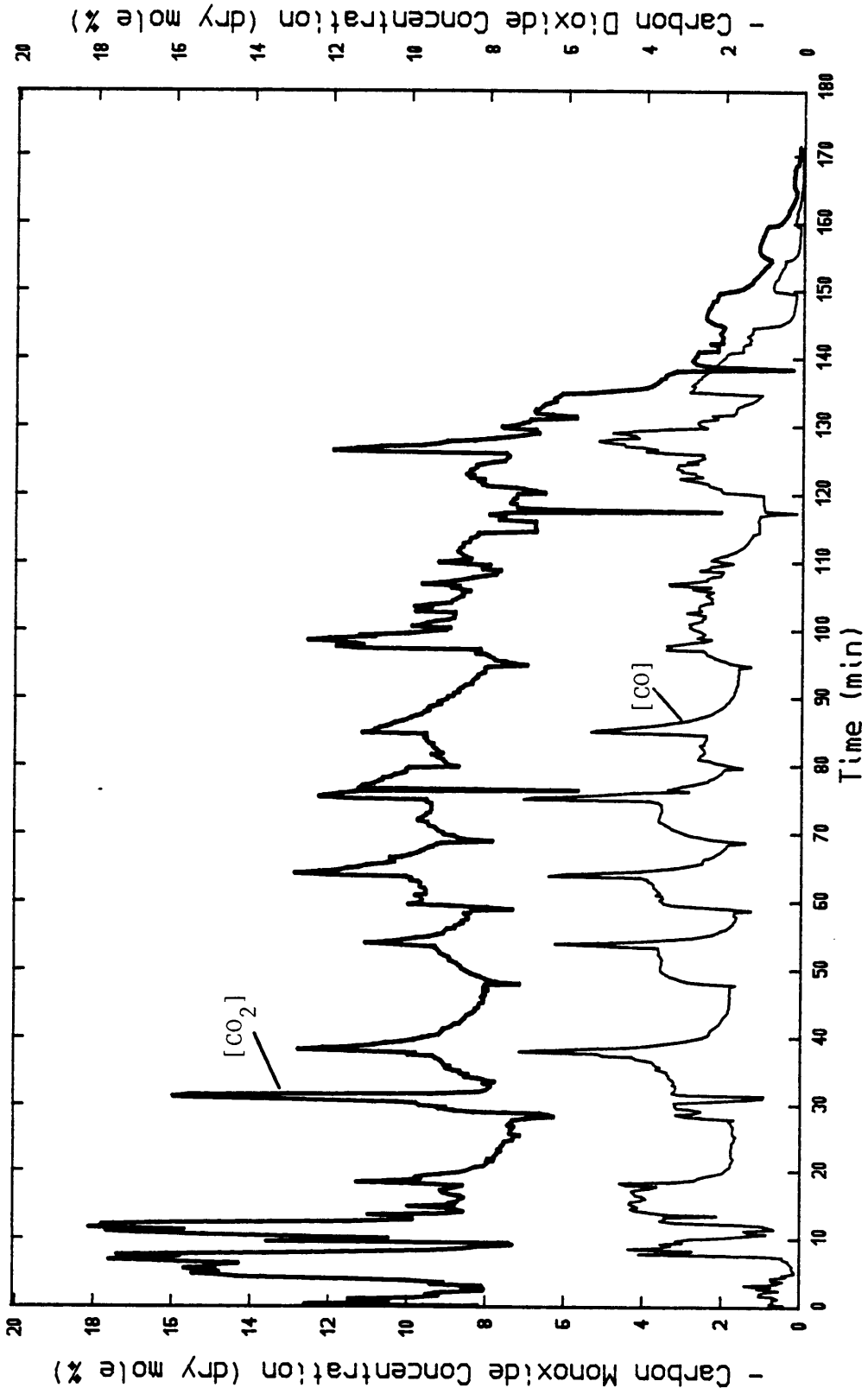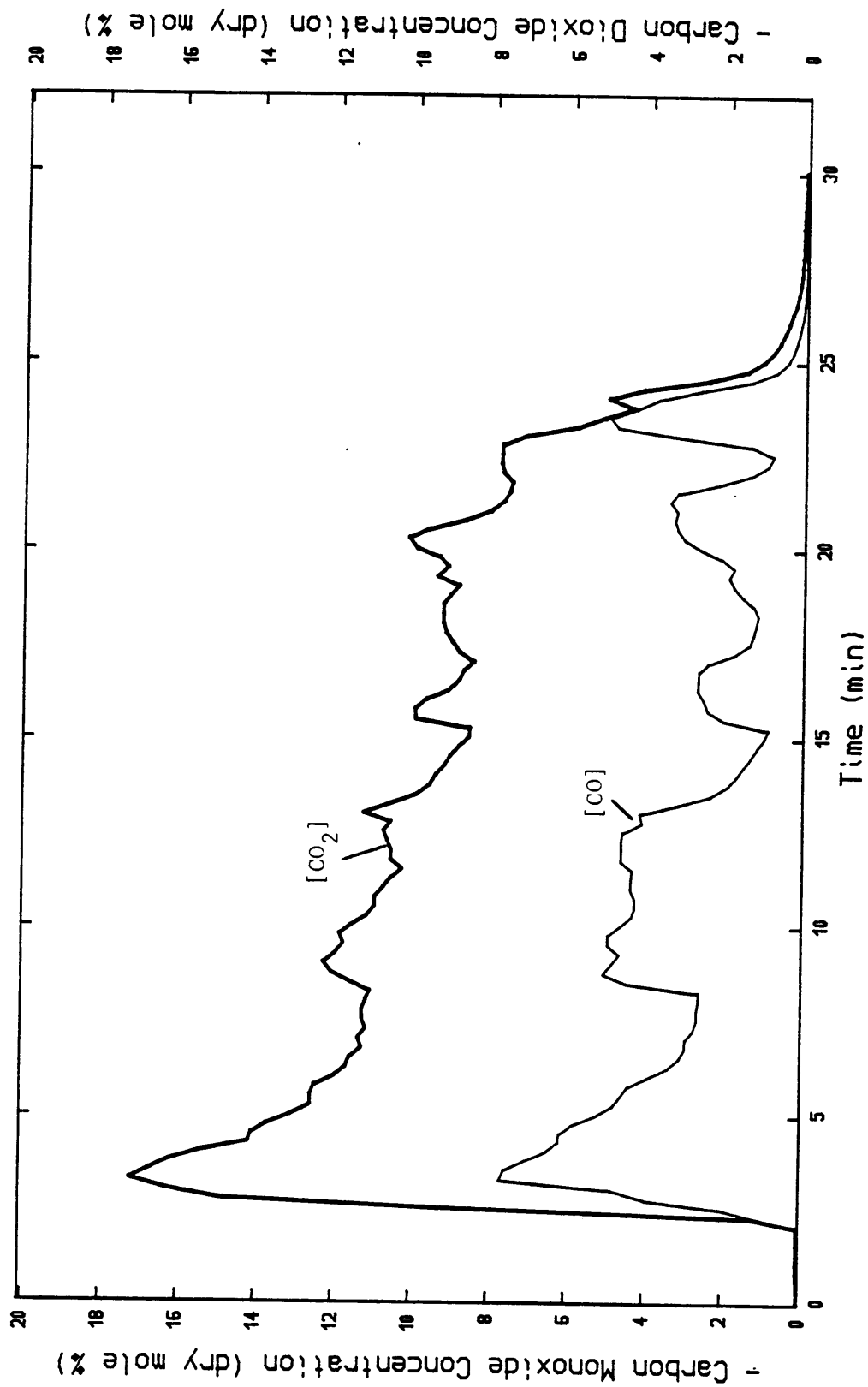
Figure 45  Carbon Monoxide and Carbon Dioxide Concentrations During Cordwood Bang–Bang Test

Baled Slash Low Fire Combustion Characterization Test
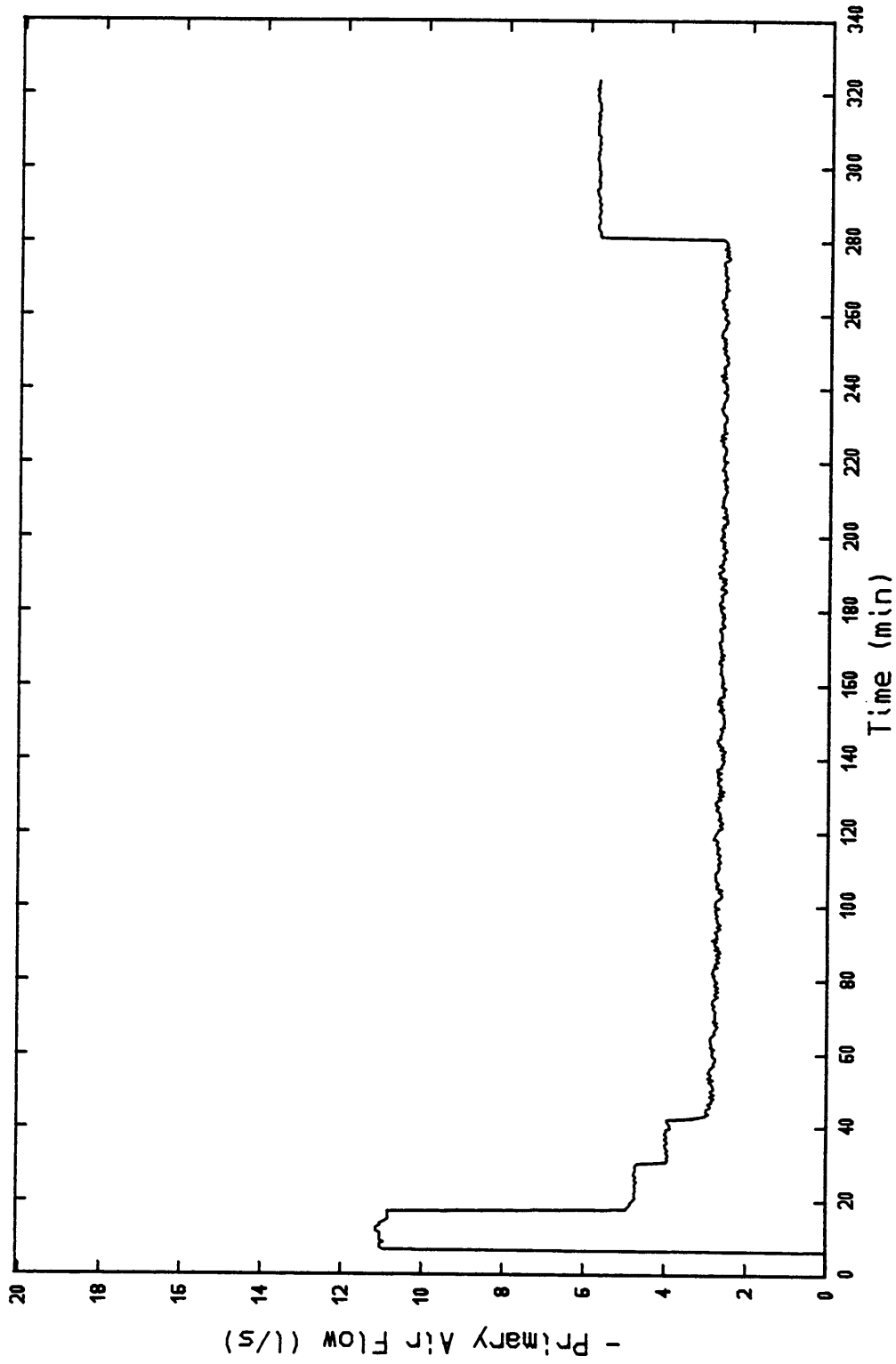
Figure 46  Primary Air Flow During Baled Slash Low Fire Test
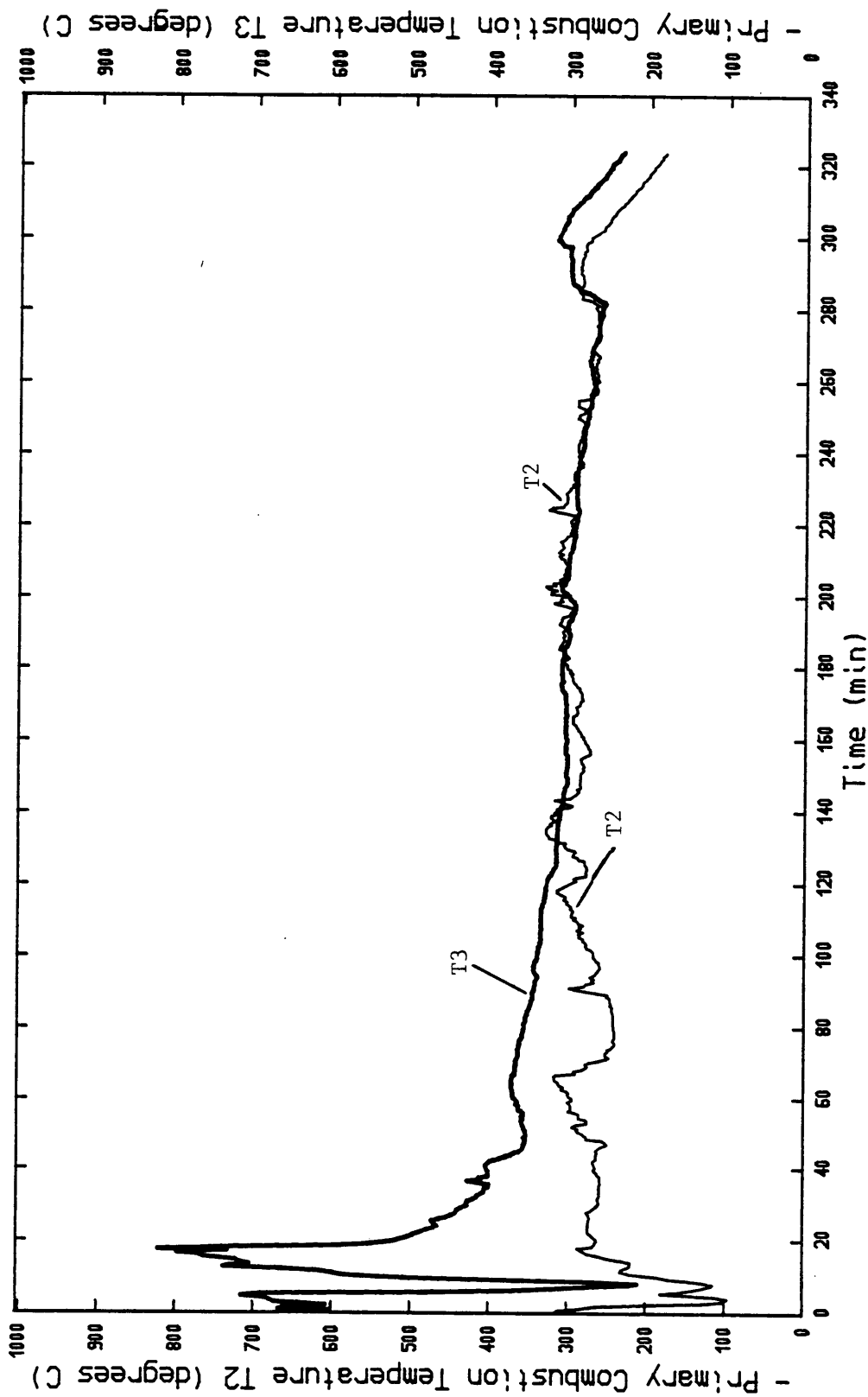
Figure 47  Primary Combustion/Gasification Temperatures, T2 and T3, During Baled Slash
Low Fire Test
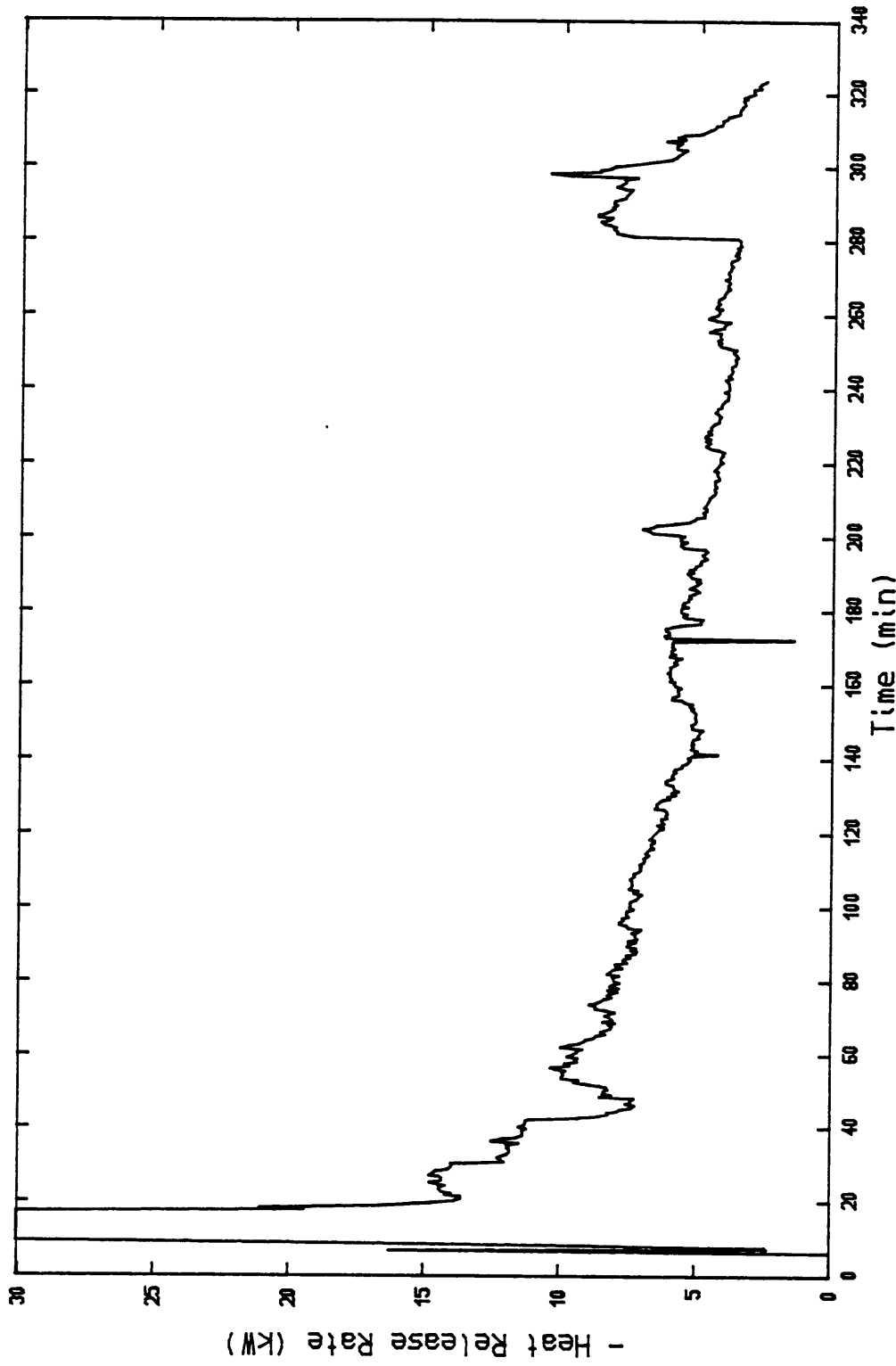
Figure 48  Heat Release Rate During Baled Slash Low Fire Test
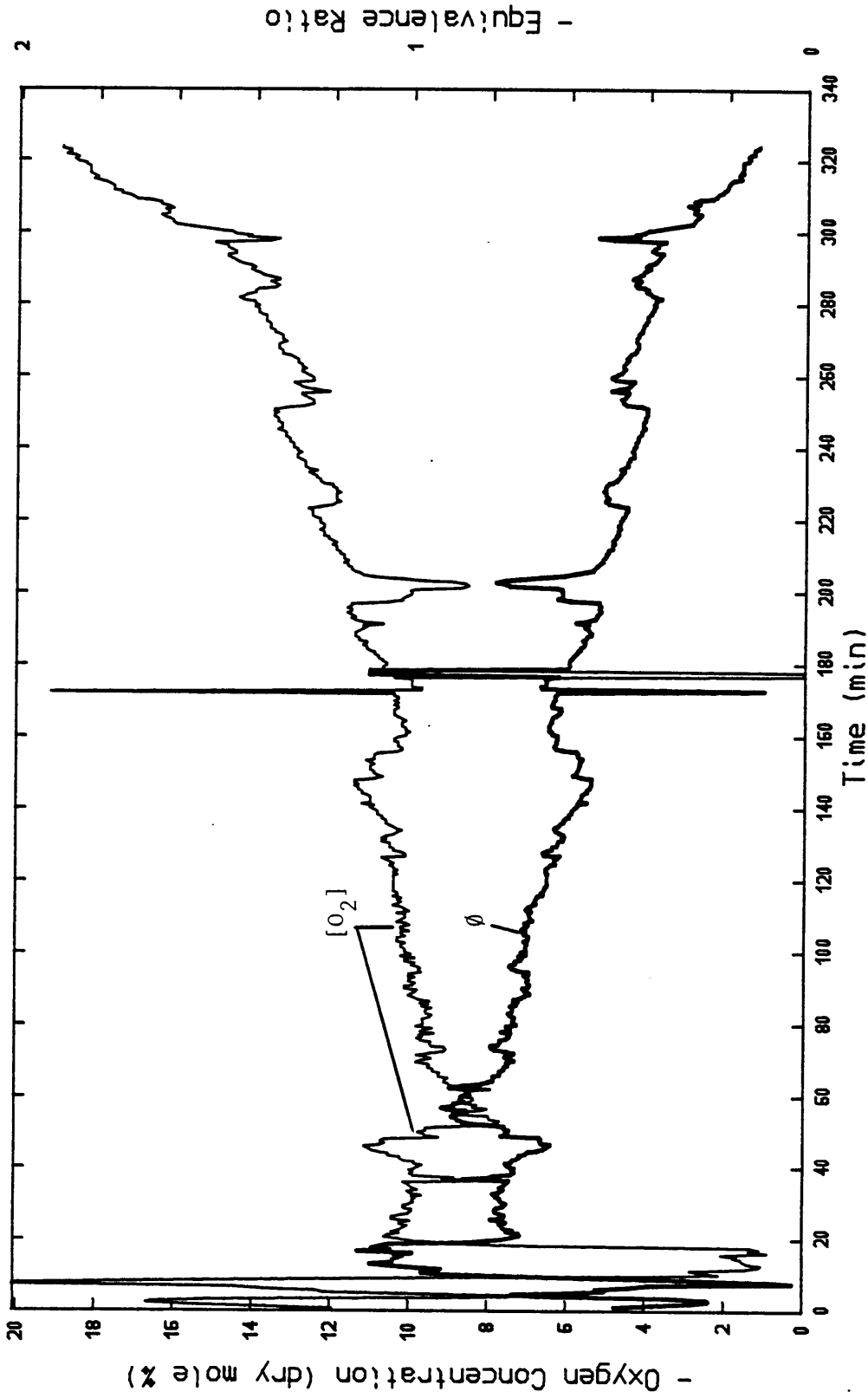
Figure 49  Oxygen Concentration and Fuel-Air Equivalence Ratio During Baled Slash Low Fire Test
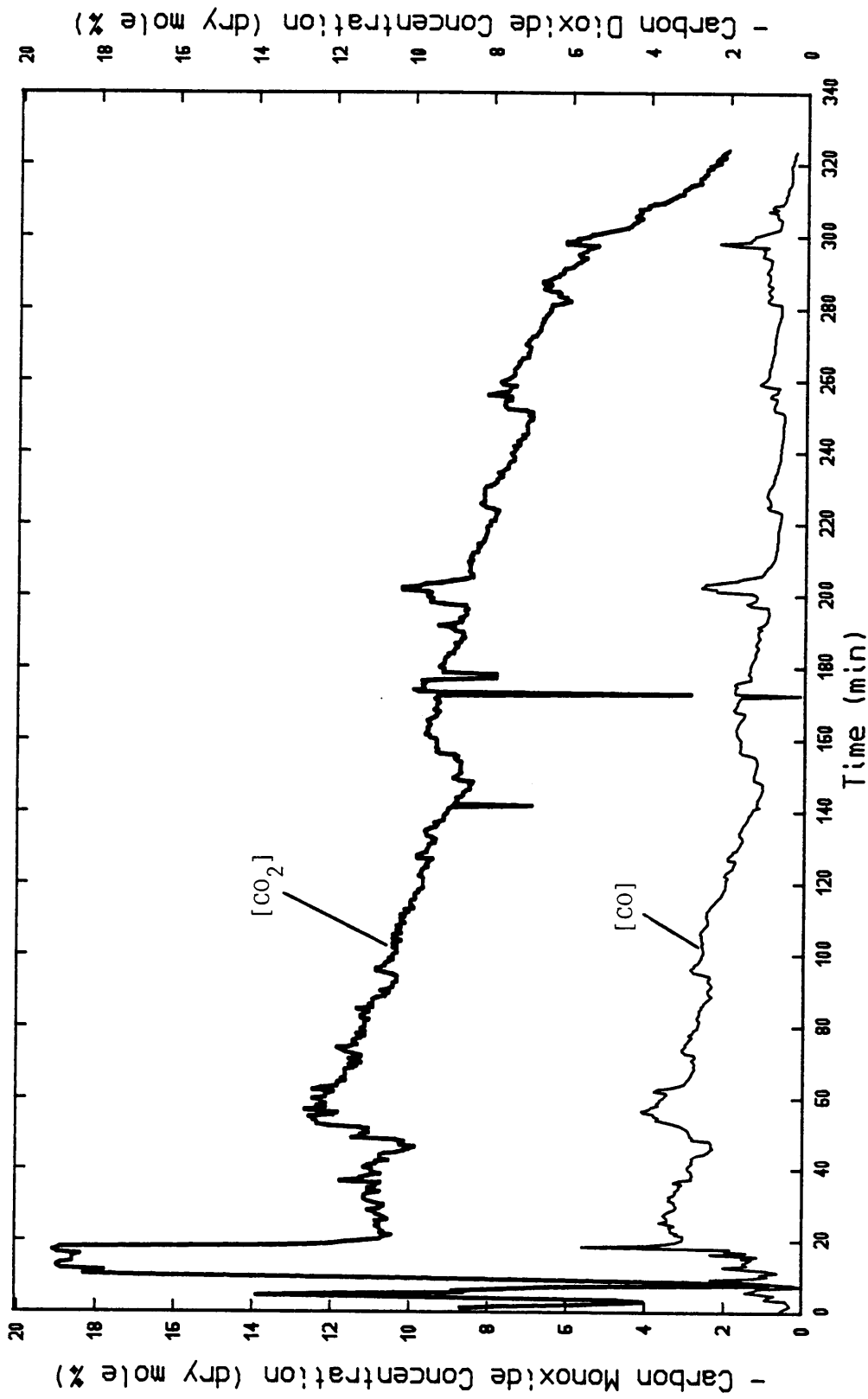
Figure 50  Carbon Monoxide and Carbon Dioxide Concentrations During Baled Slash Low Fire Test

Baled Slash High Fire Combustion Characterization Test
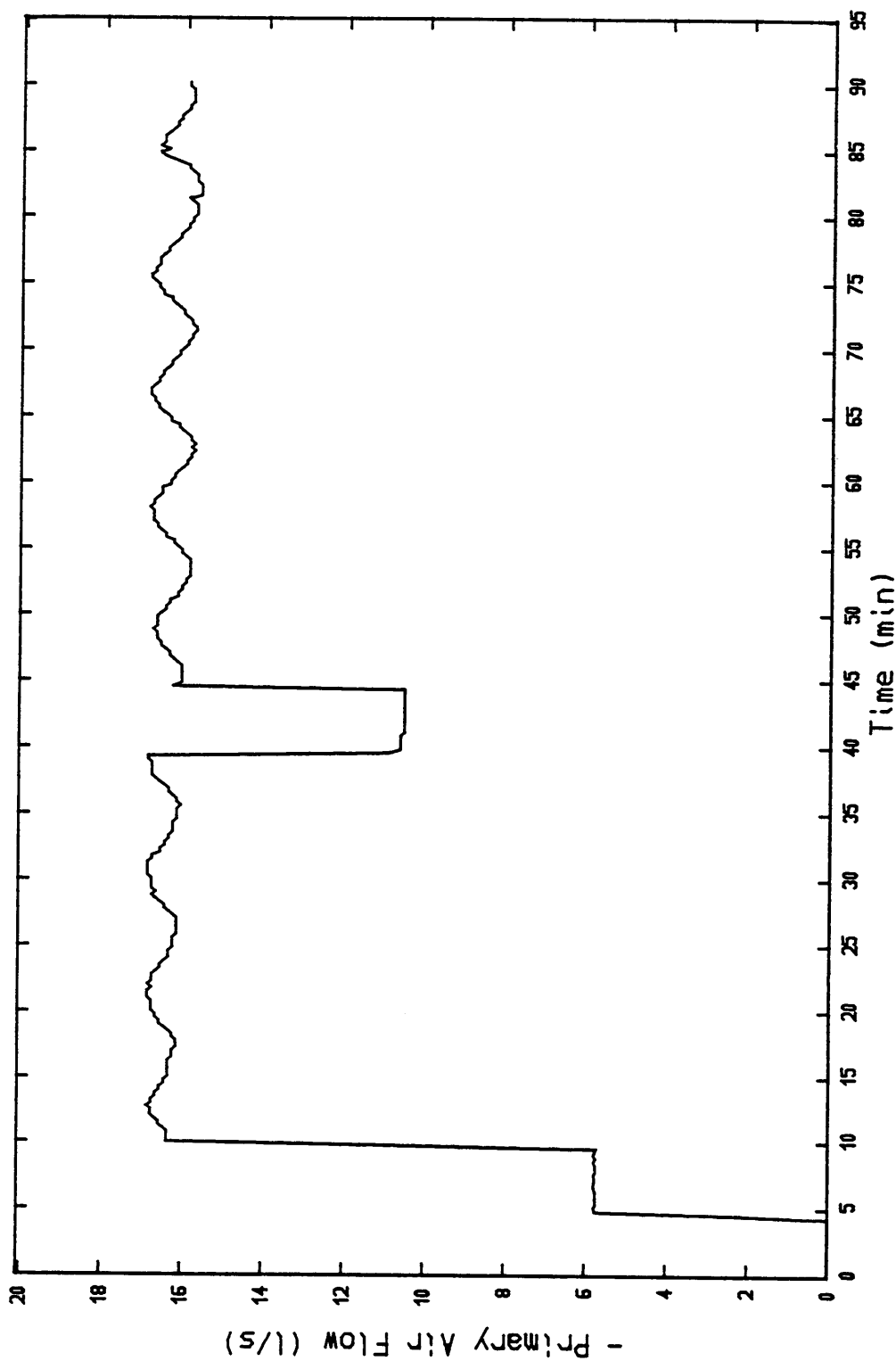
Figure 51   Primary Air Flow During Baled Slash High Fire Test
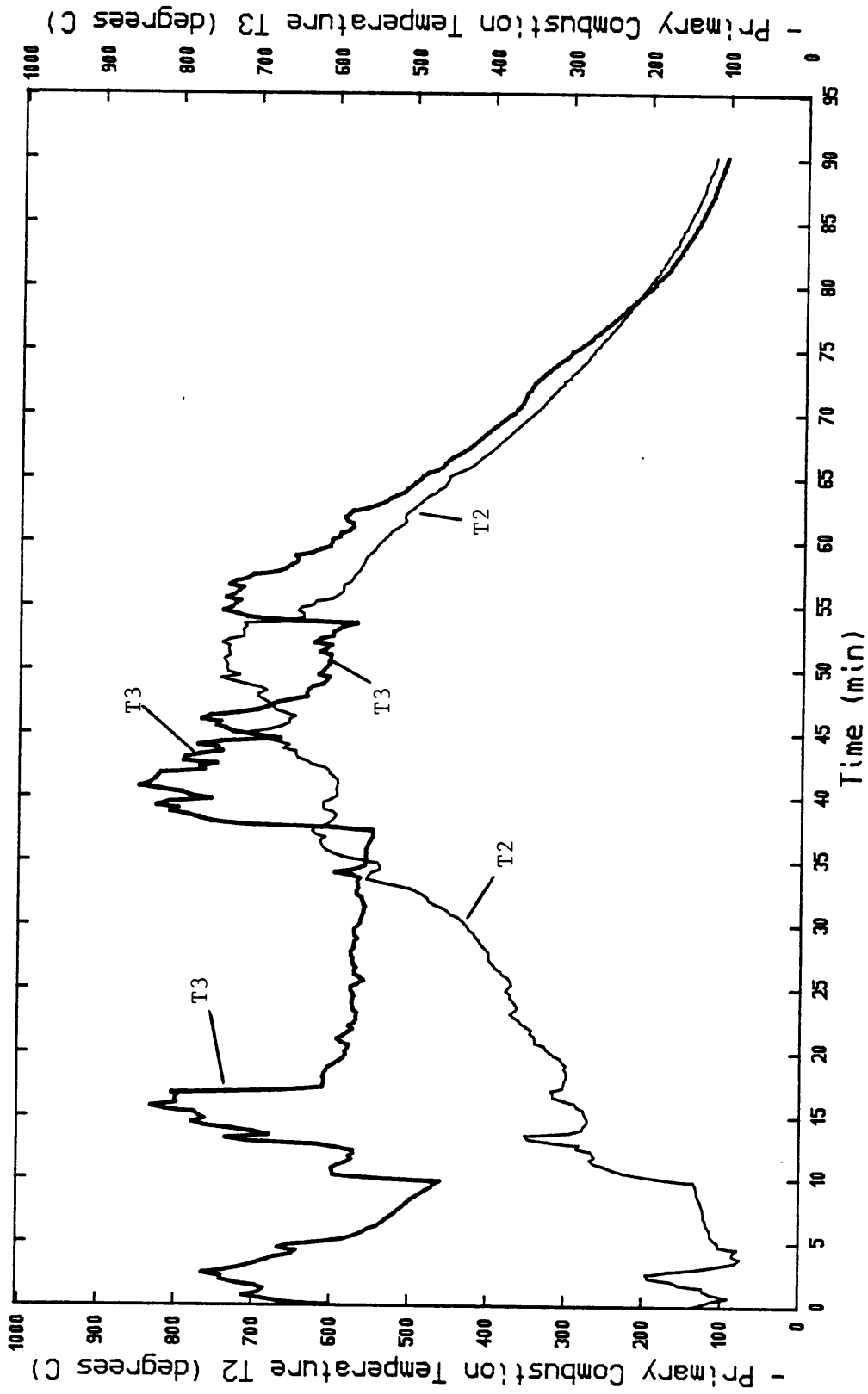
Figure 52  Primary Combustion/Gasification Temperatures, T2 and T3, During Baled Slash High Fire Test
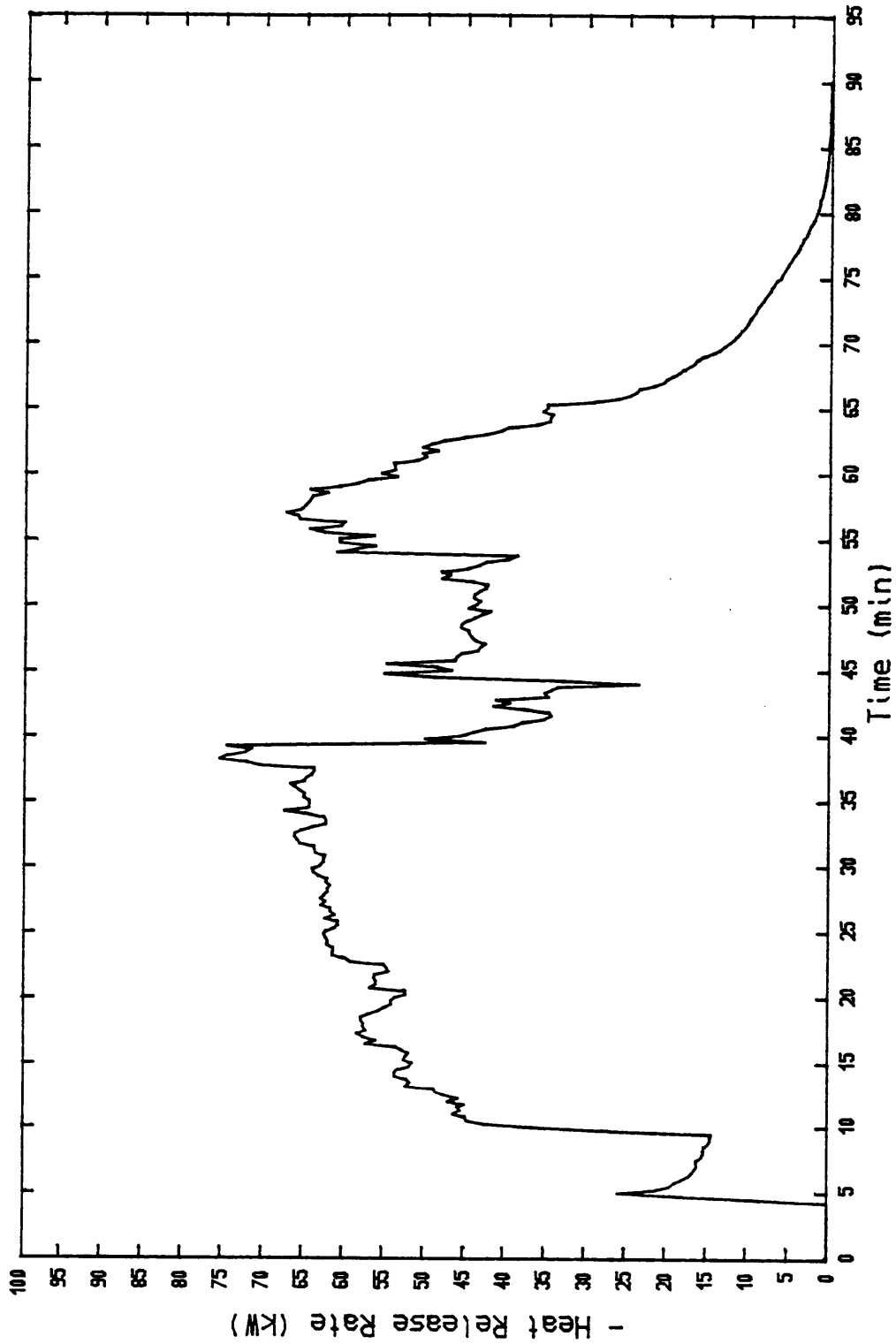
Figure 53  Heat Release Rate During Baled Slash High Fire Test
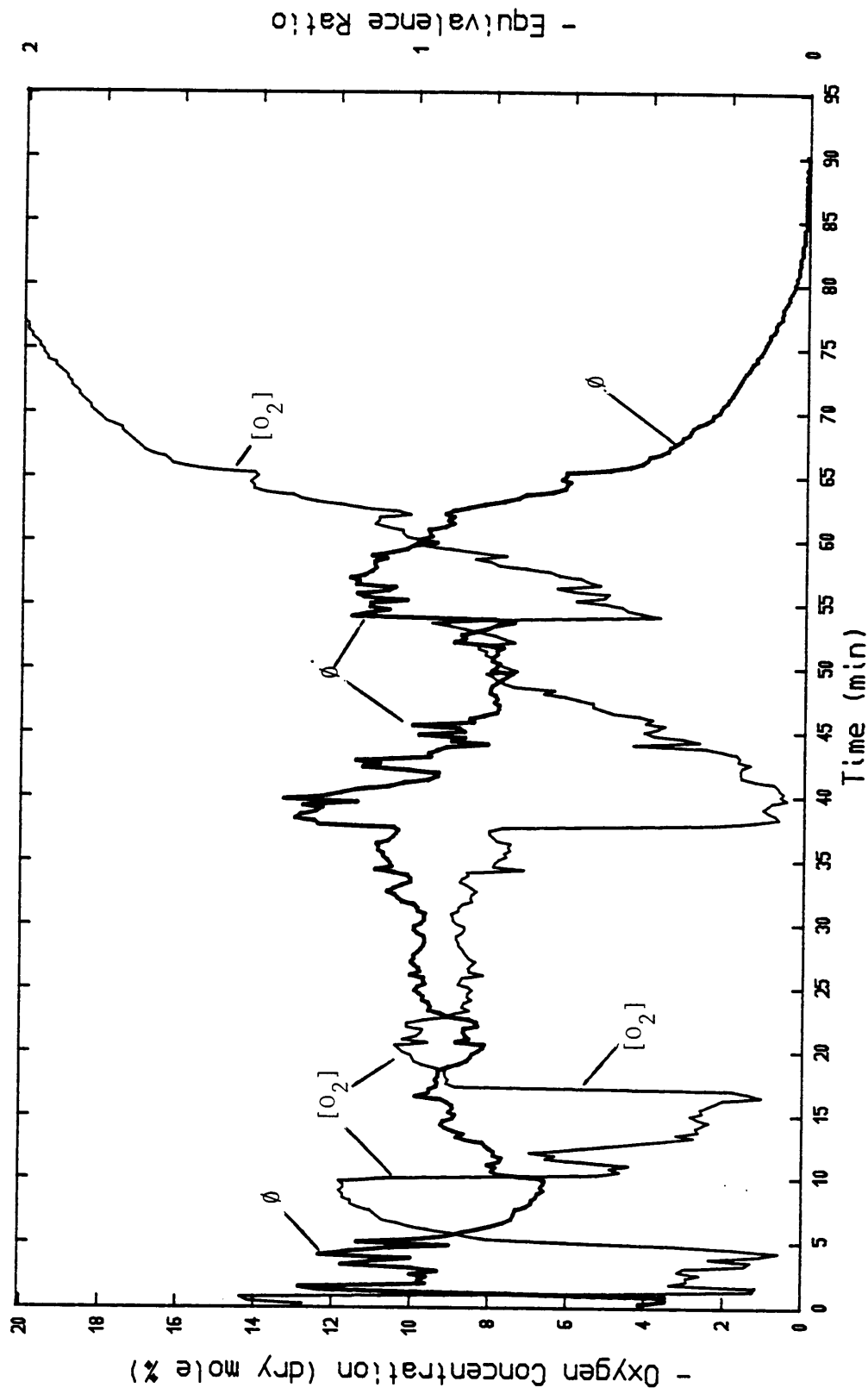
Figure 54  Oxygen Concentration and Fuel-Air Equivalence Ratio During Baled Slash High Fire Test
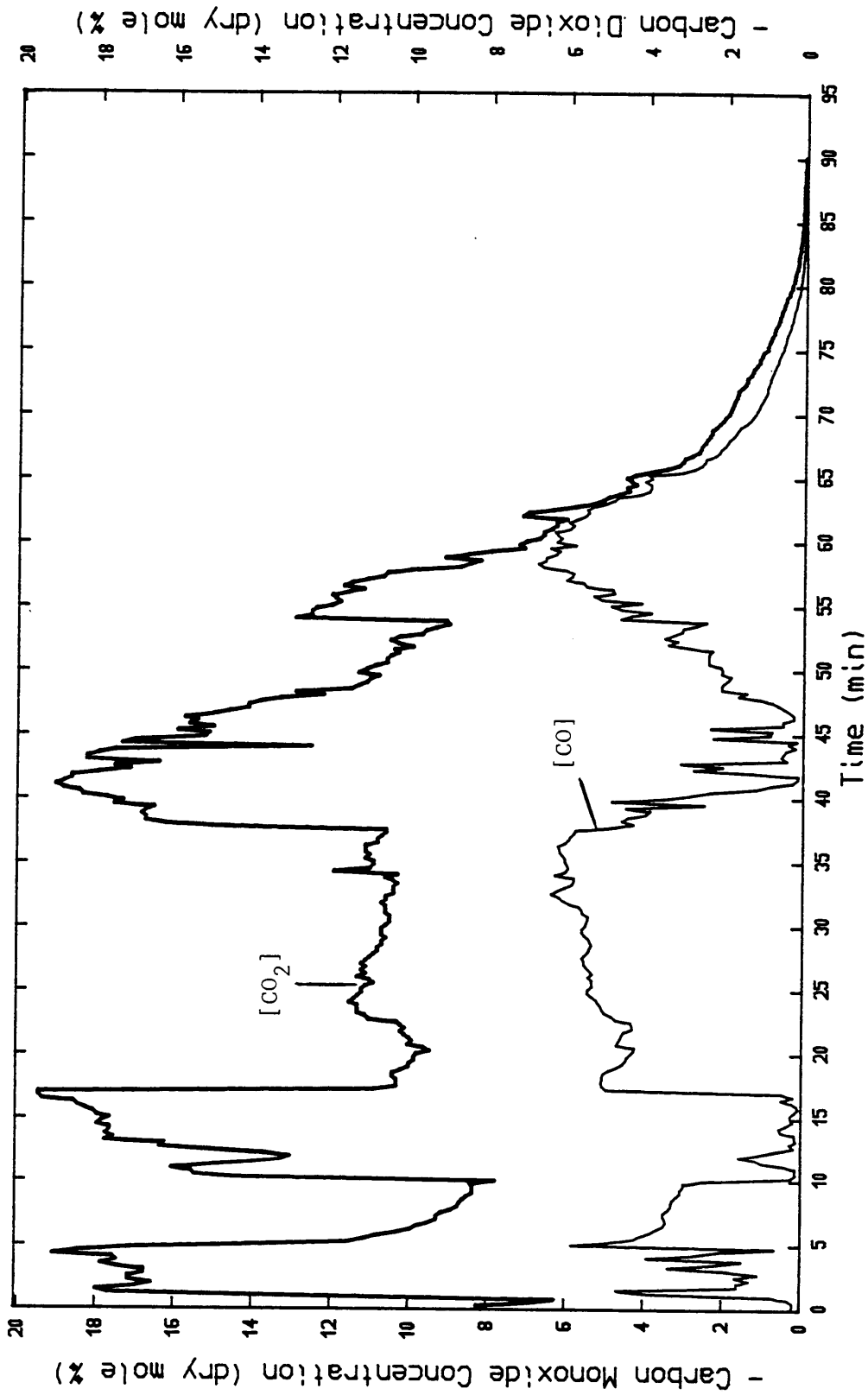
Figure 55  Carbon Monoxide and Carbon Dioxide Concentrations During Baled Slash High
Fire Test
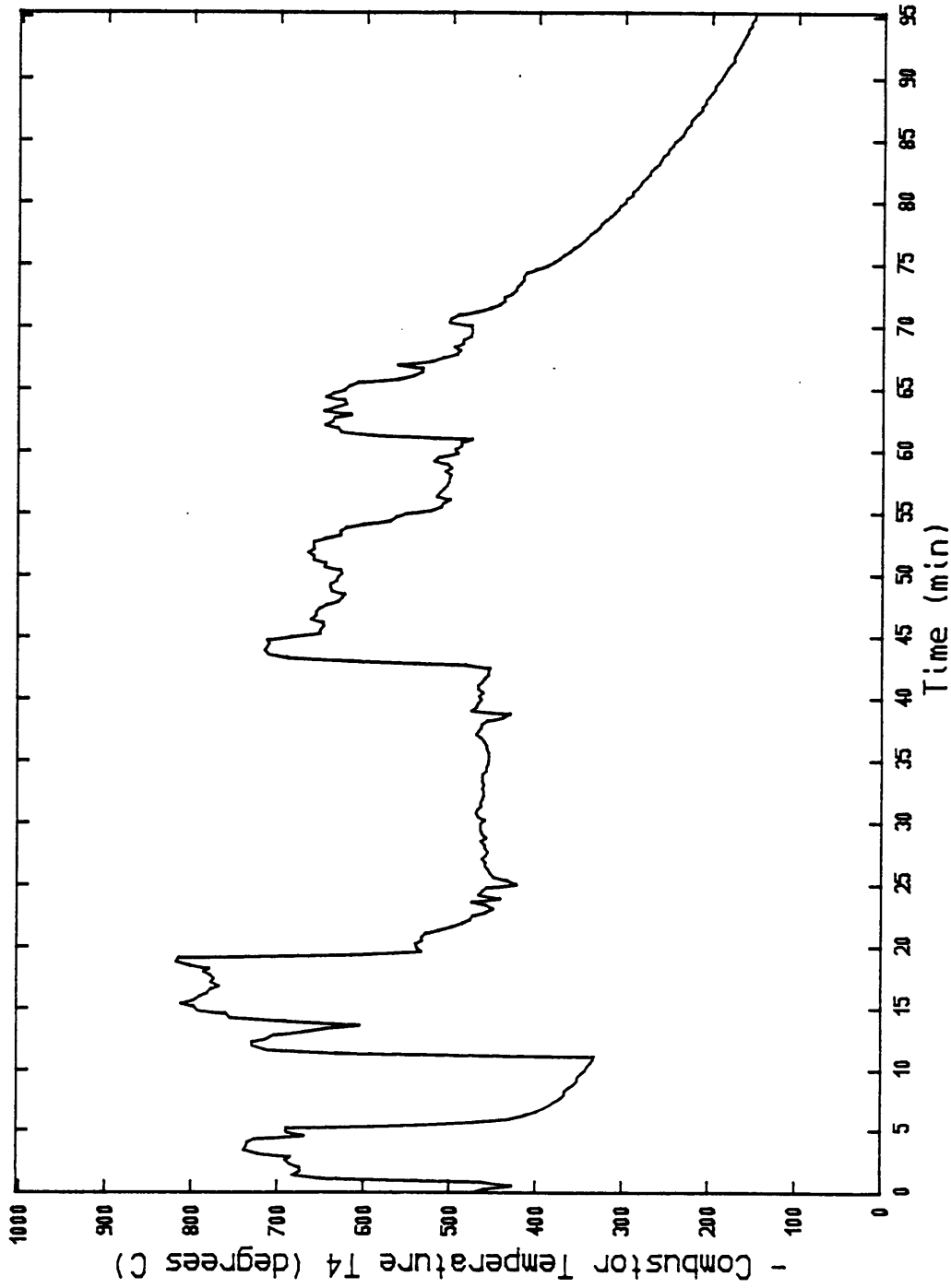
Figure 56  Combustor Temperature, T4, During Baled Slash High Fire Test

Baled Slash Variable Firing Rate Characterization Test
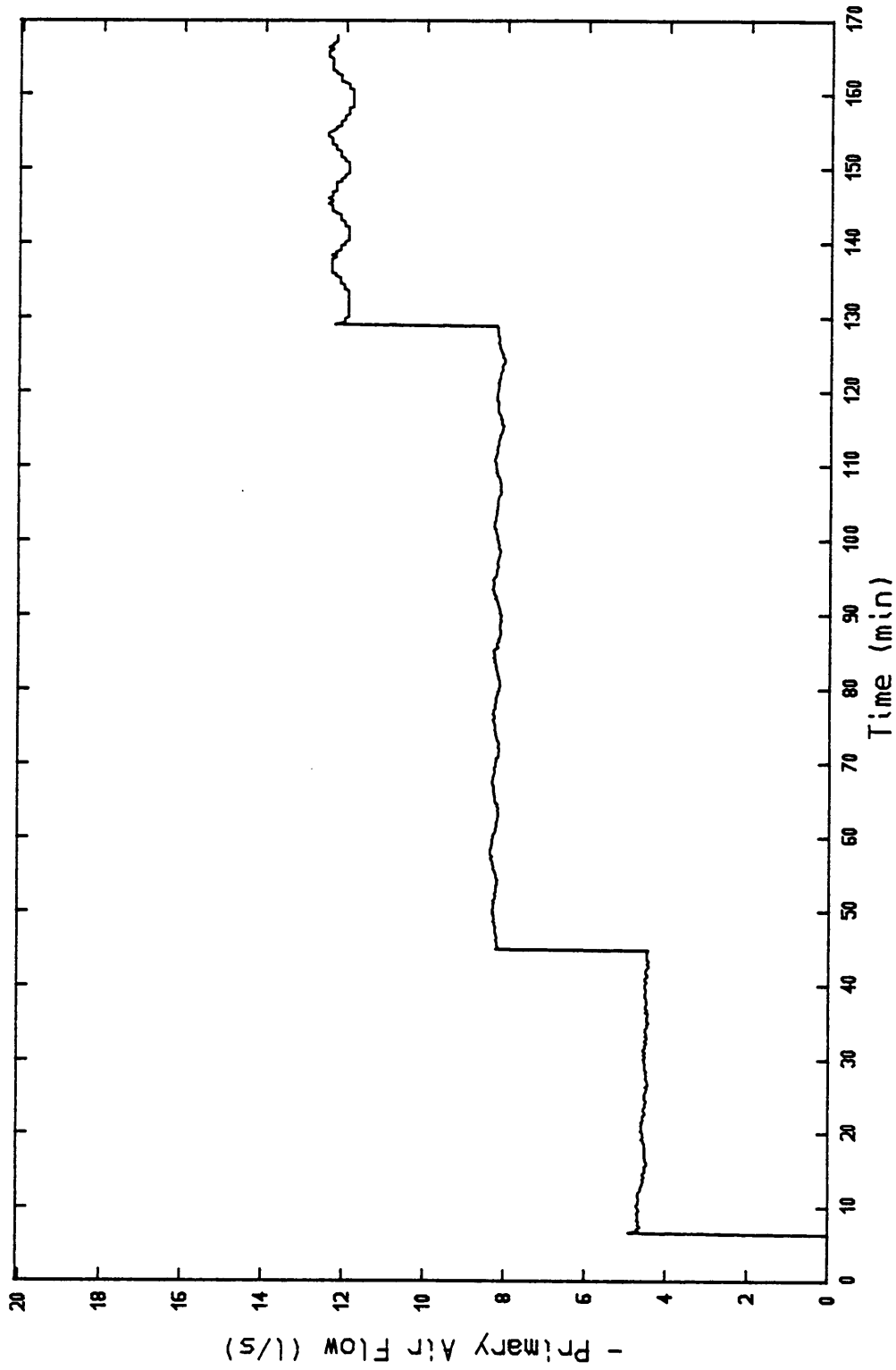
Figure 57  Primary Air Flow During Baled Slash Variable Firing Rate Test
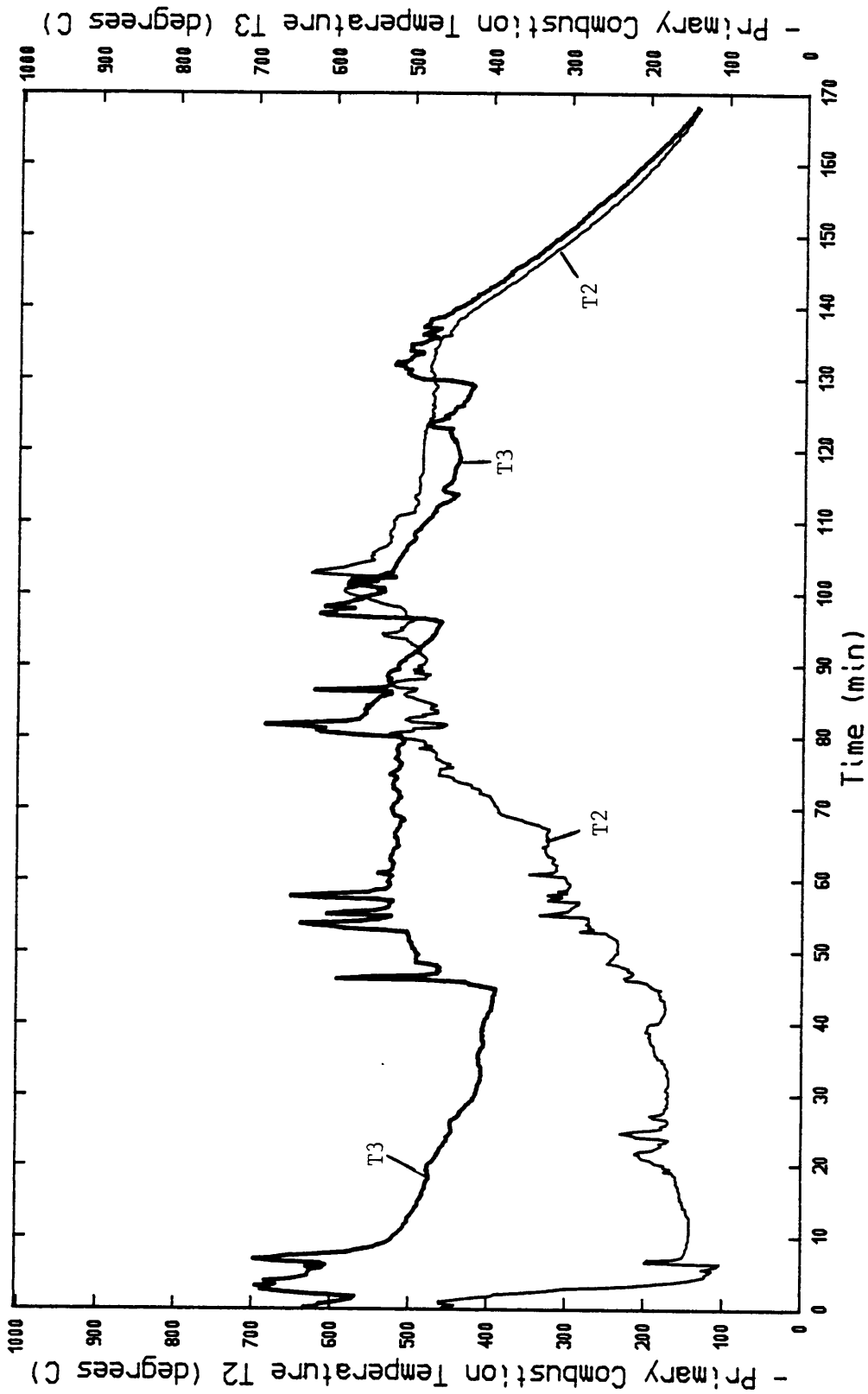
Figure 58  Primary Combustion/Gasification Temperatures, T2 and T3, During Baled Slash
Variable Firing Rate Test
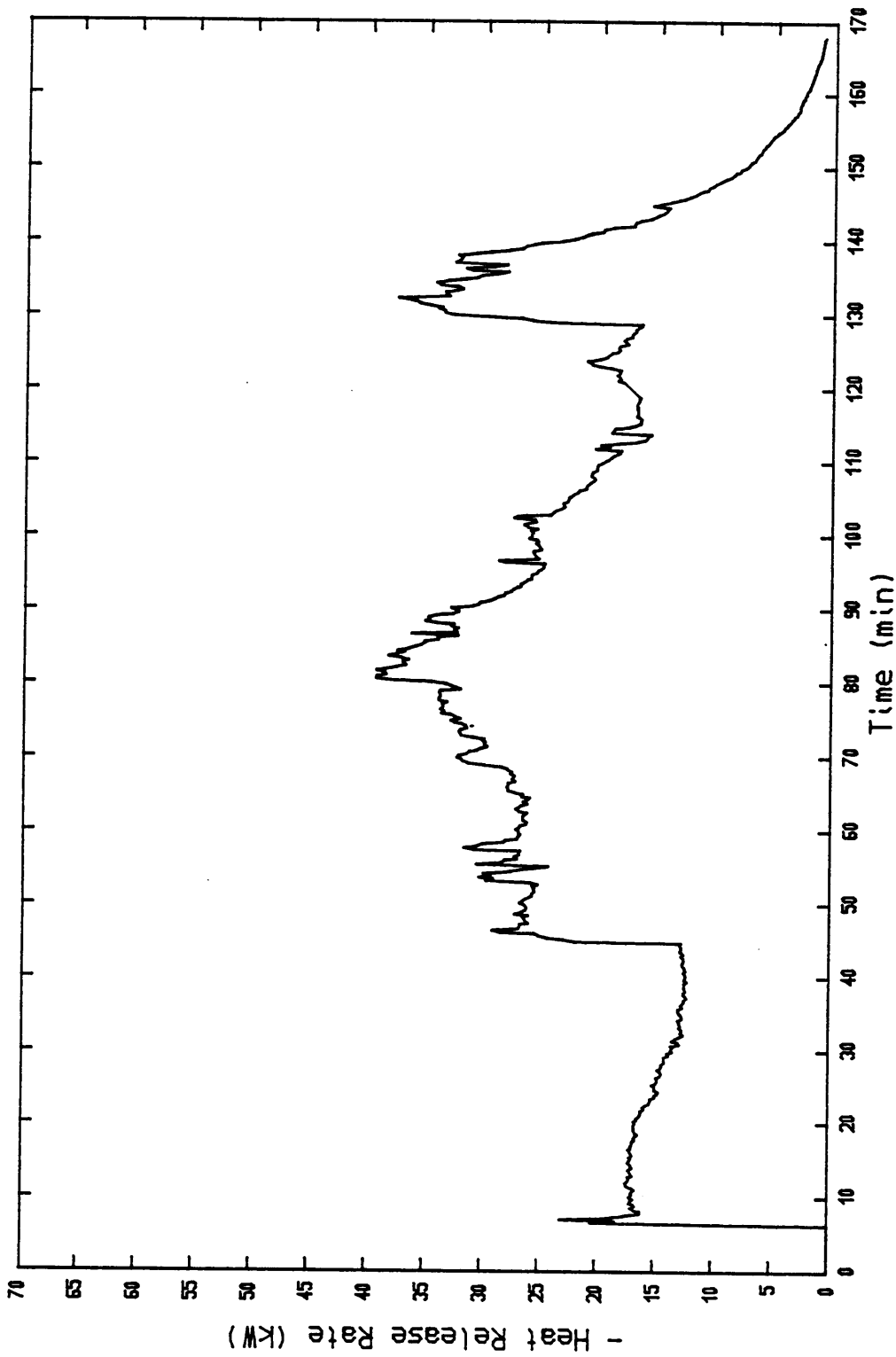
Figure 59  Heat Release Rate During Baled Slash Variable Firing Rate Test
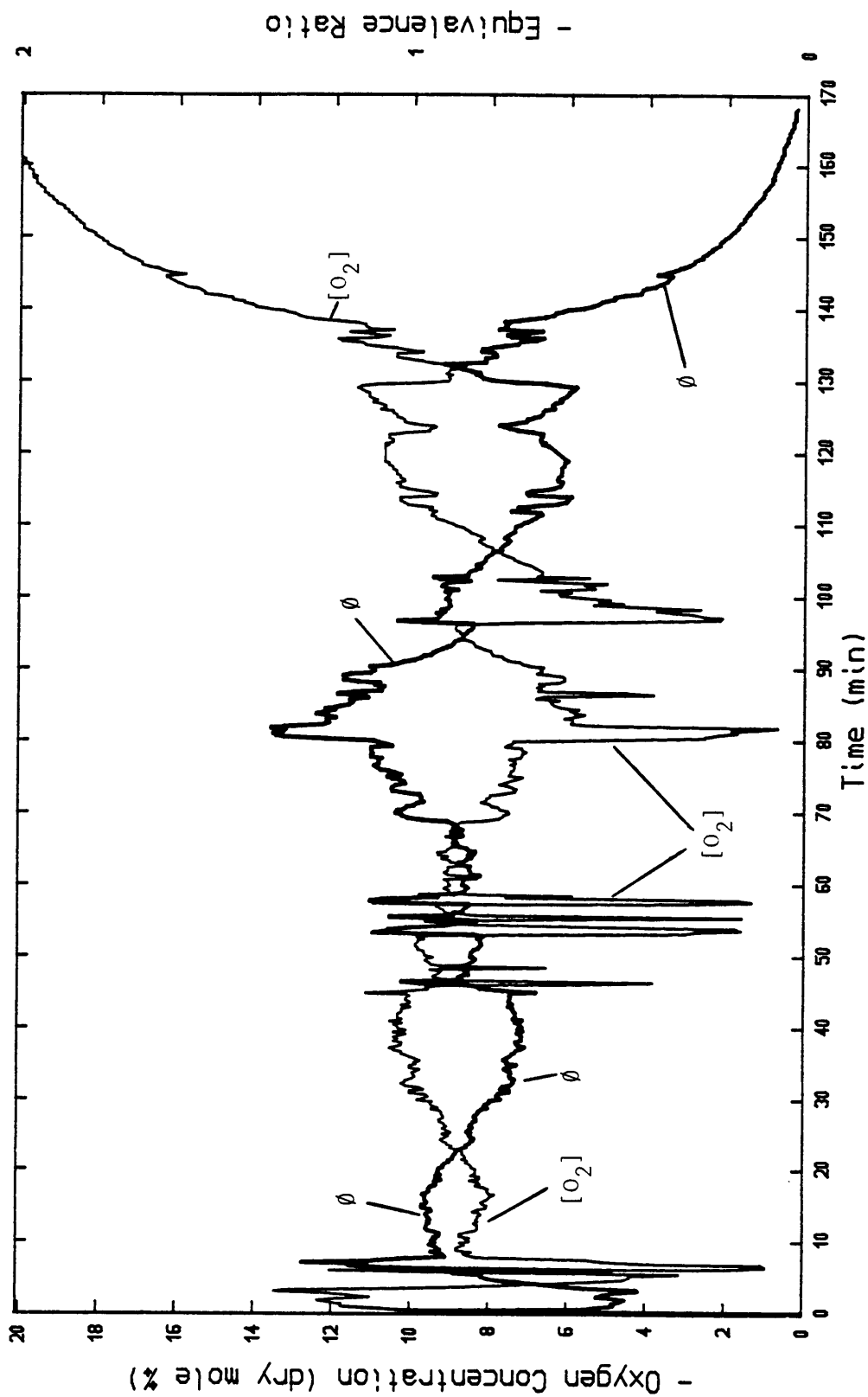
Figure 60  Oxygen Concentration and Fuel-Air Equivalence Ratio During Baled Slash
Variable Firing Rate Test
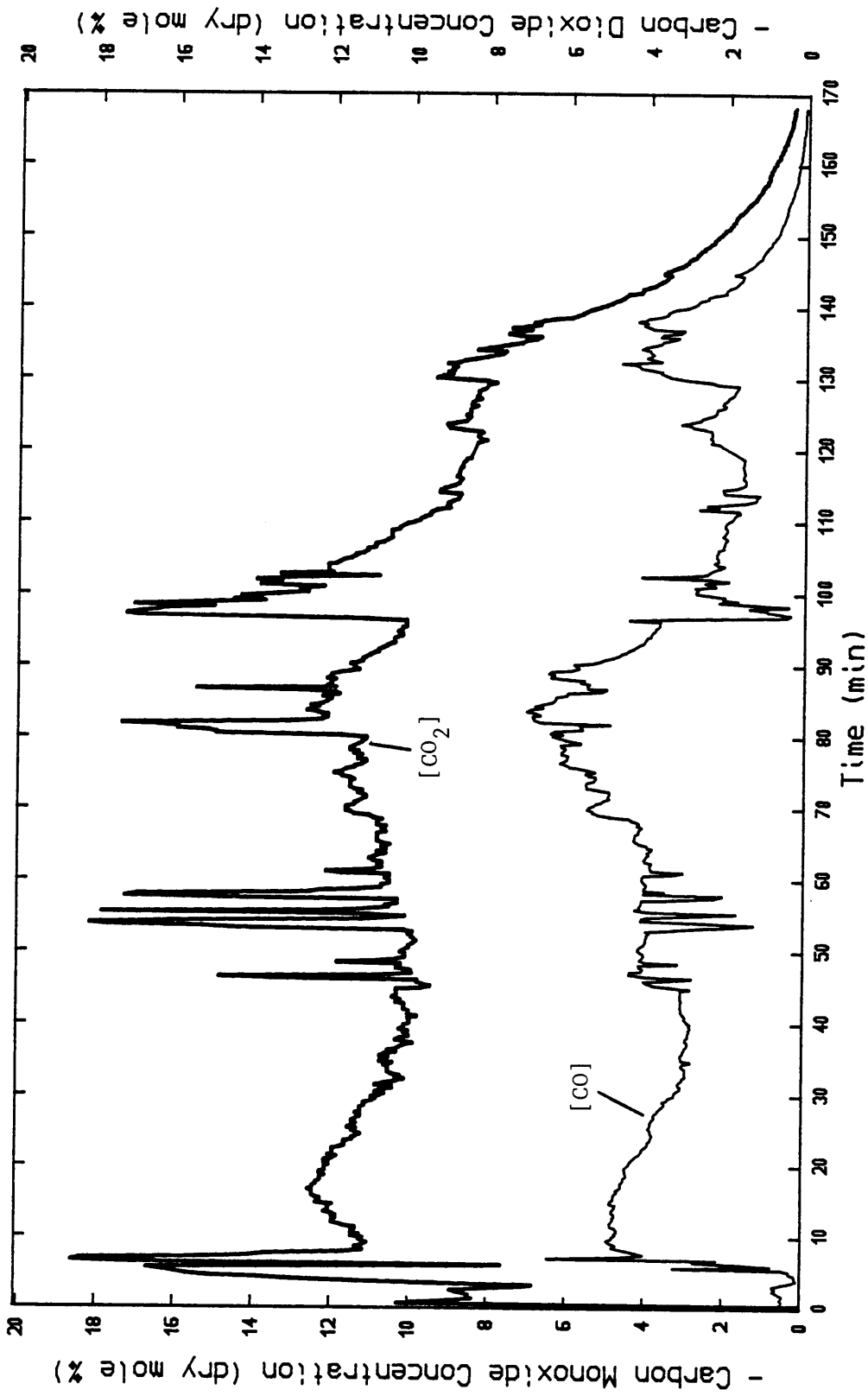
Figure 61  Carbon Monoxide and Carbon Dioxide Concentrations During Baled Slash Variable Rate Test

Baled Slash Bang-Bang Combustion Characterization Test
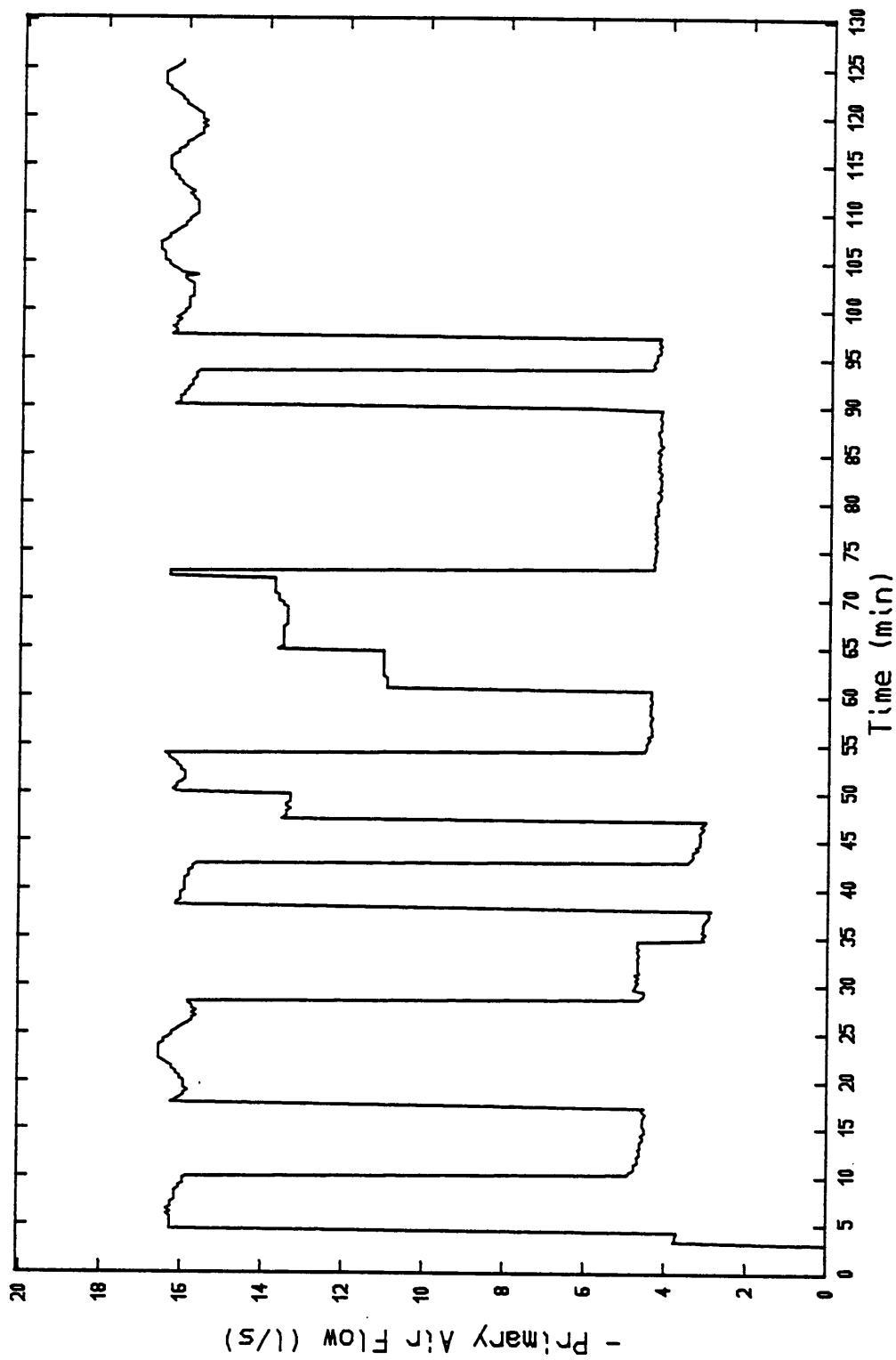
Figure 62   Primary Air Flow During Baled Slash Bang-Bang Test
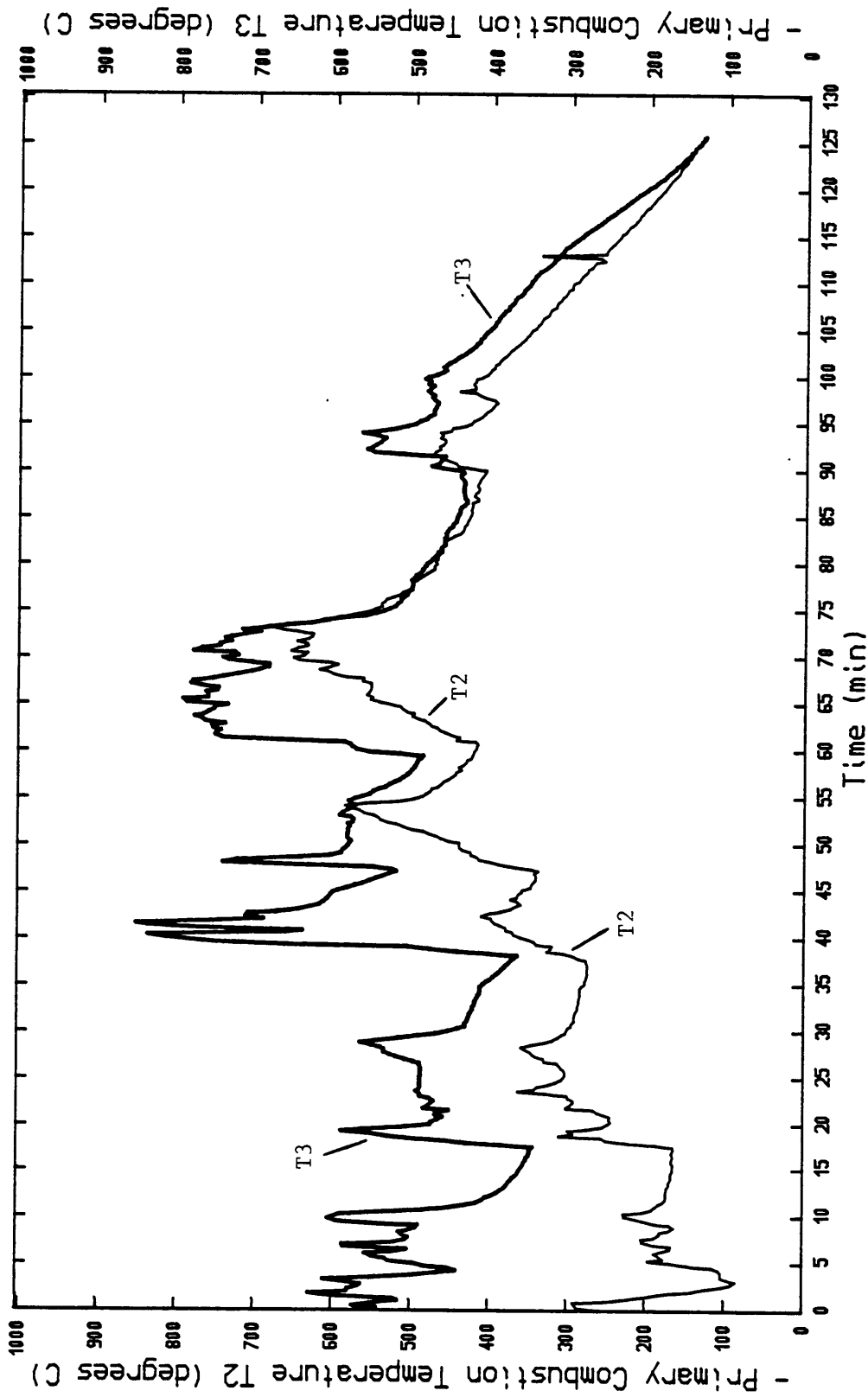
Figure 63  Primary Combustion/Gasification Temperatures, T2 and T3, During Baled Slash Bang-Bang Test
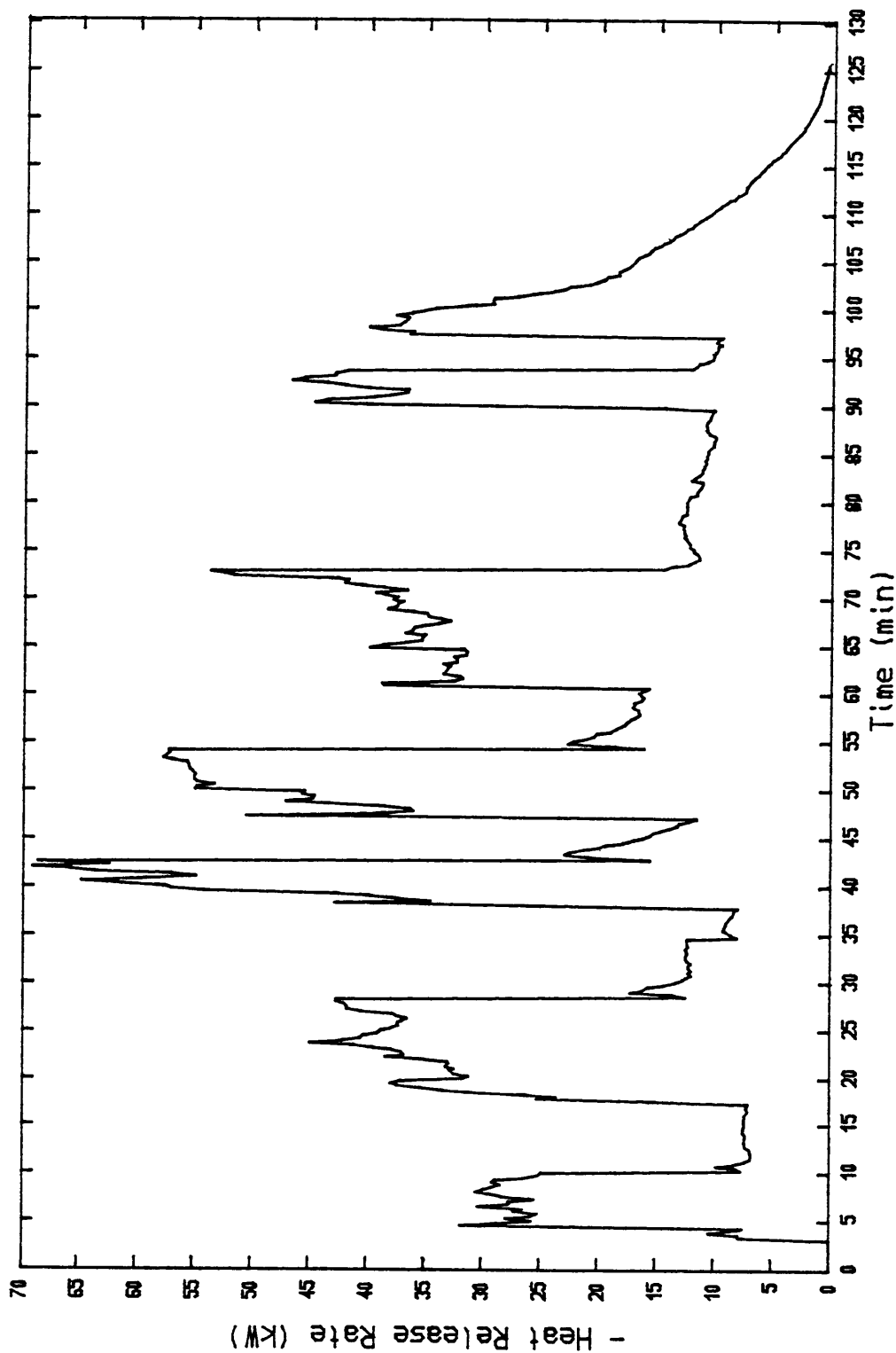
Figure 64  Heat Release Rate During Baled Slash Bang-Bang Test
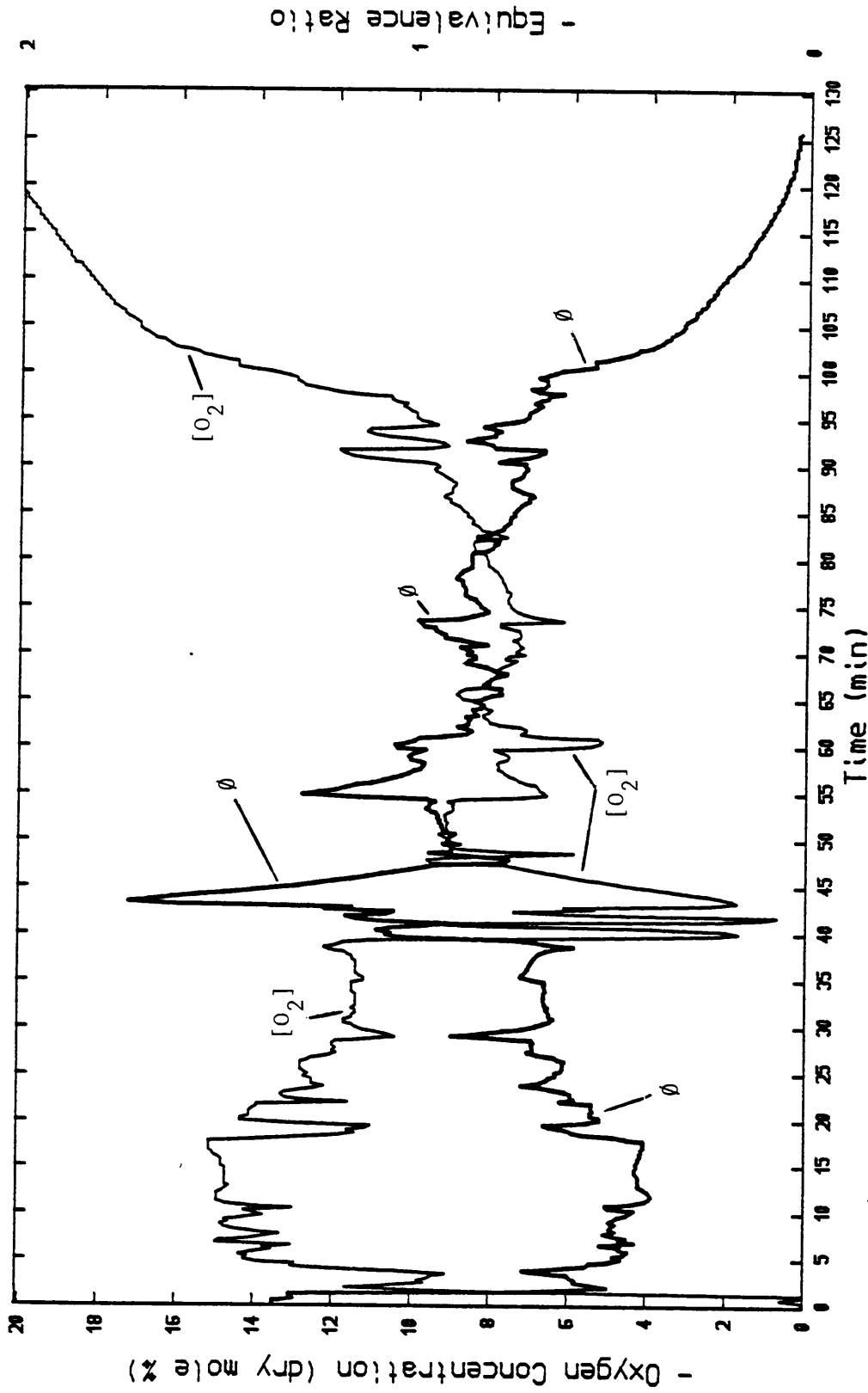
Figure 65   Oxygen Concentration and Fuel-Air Equivalence Ratio  During Baled Slash
Bang-Bang Test
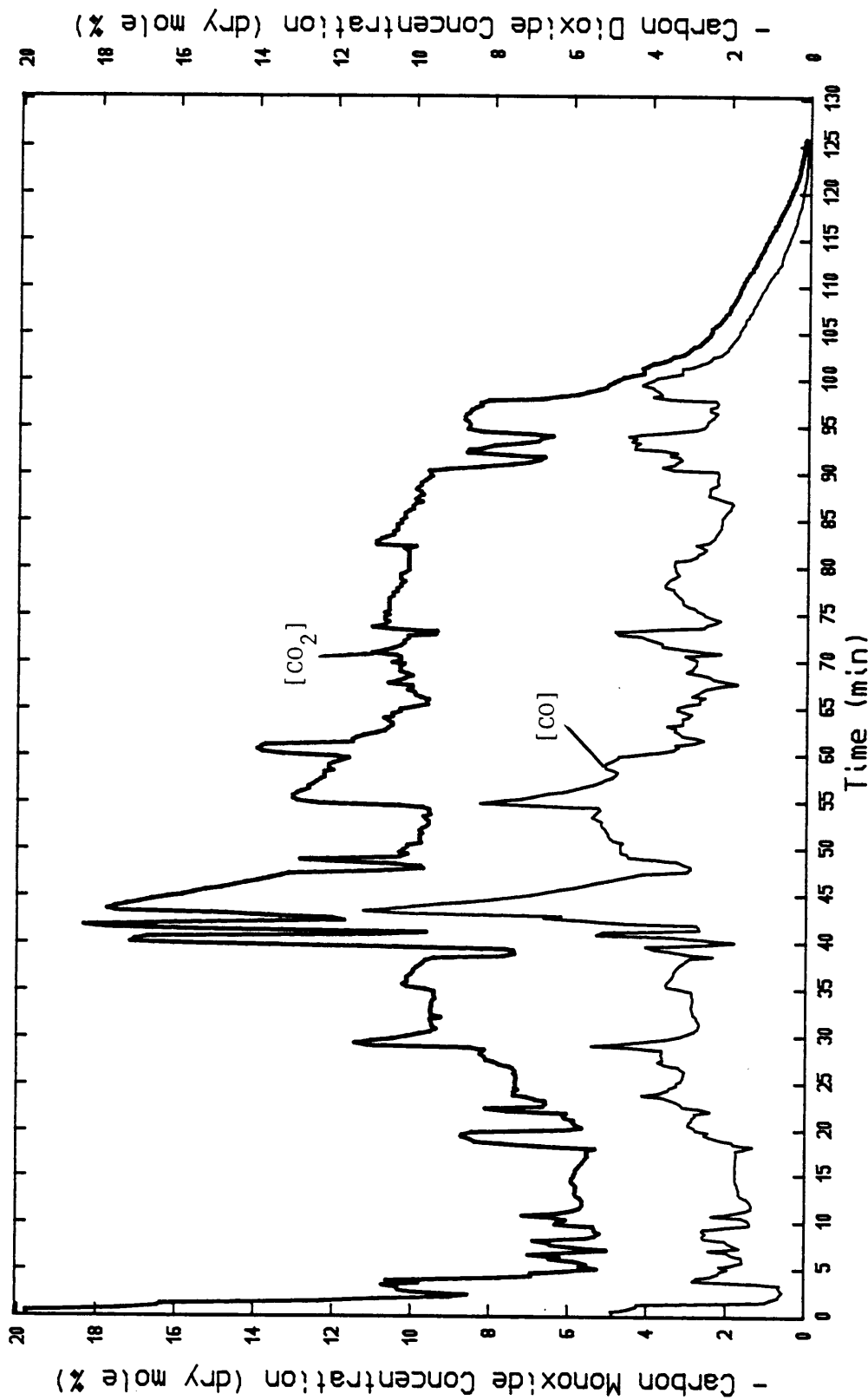
Figure 66   Carbon Monoxide and Carbon Dioxide Concentrations During Baled Slash Bang-Bang Test

Corn Fodder Low Fire Combustion Characterization Test
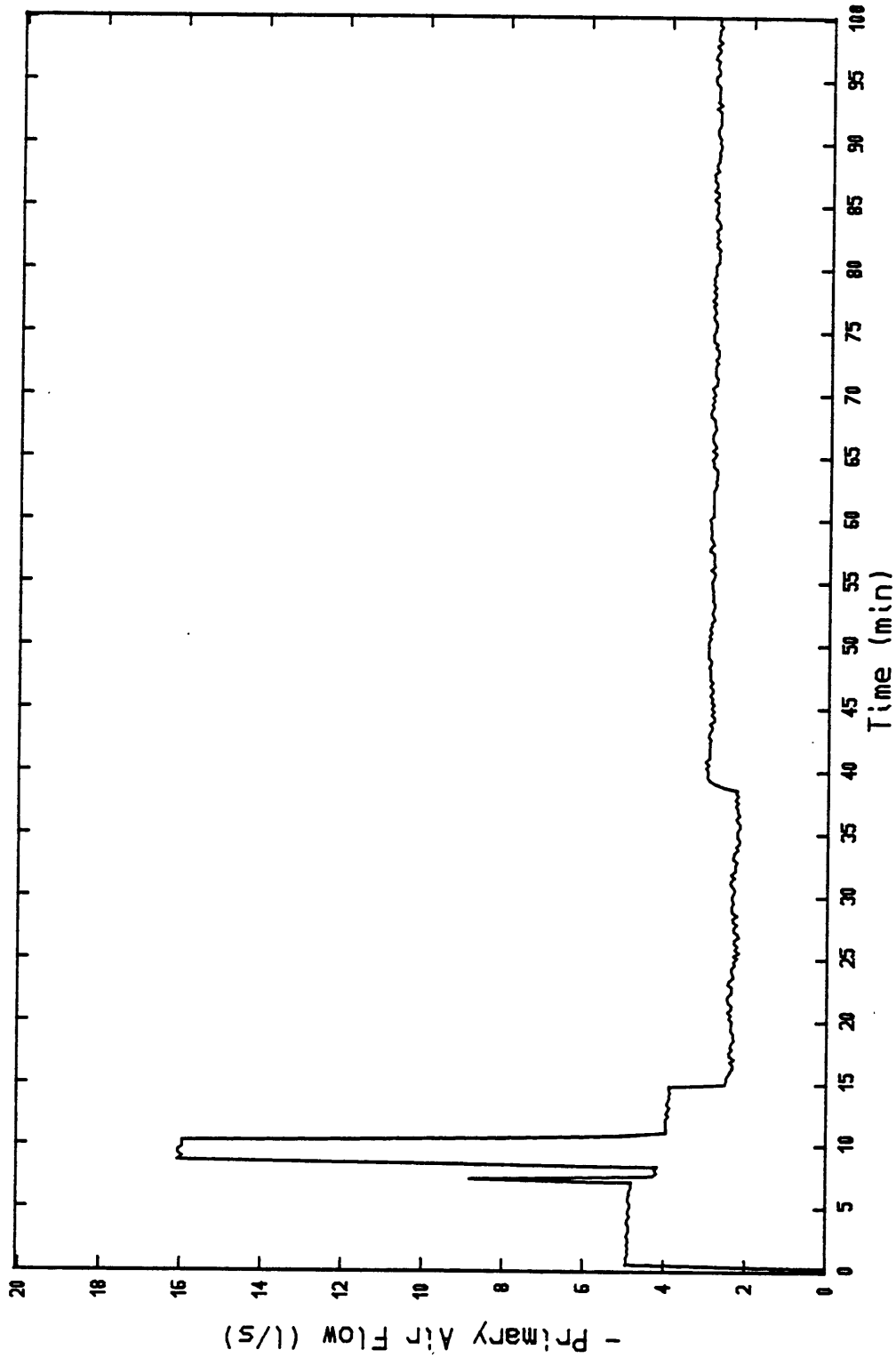
Figure 67  Primary Air Flow During Corn Fodder Low Fire Test.
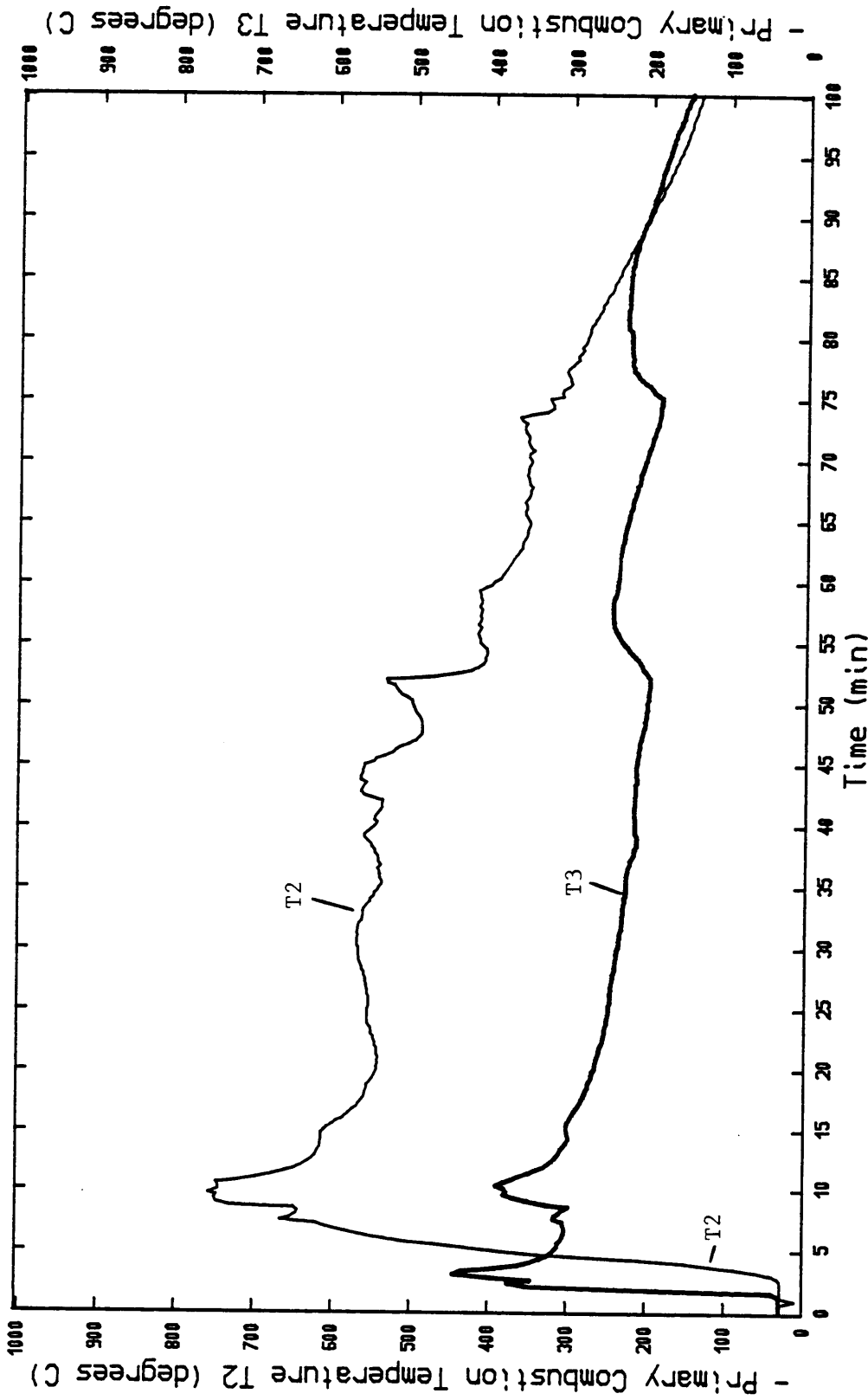
Figure 68  Primary Combustion/Gasification Temperatures, T2 and T3, During Corn Fodder Low Fire Test
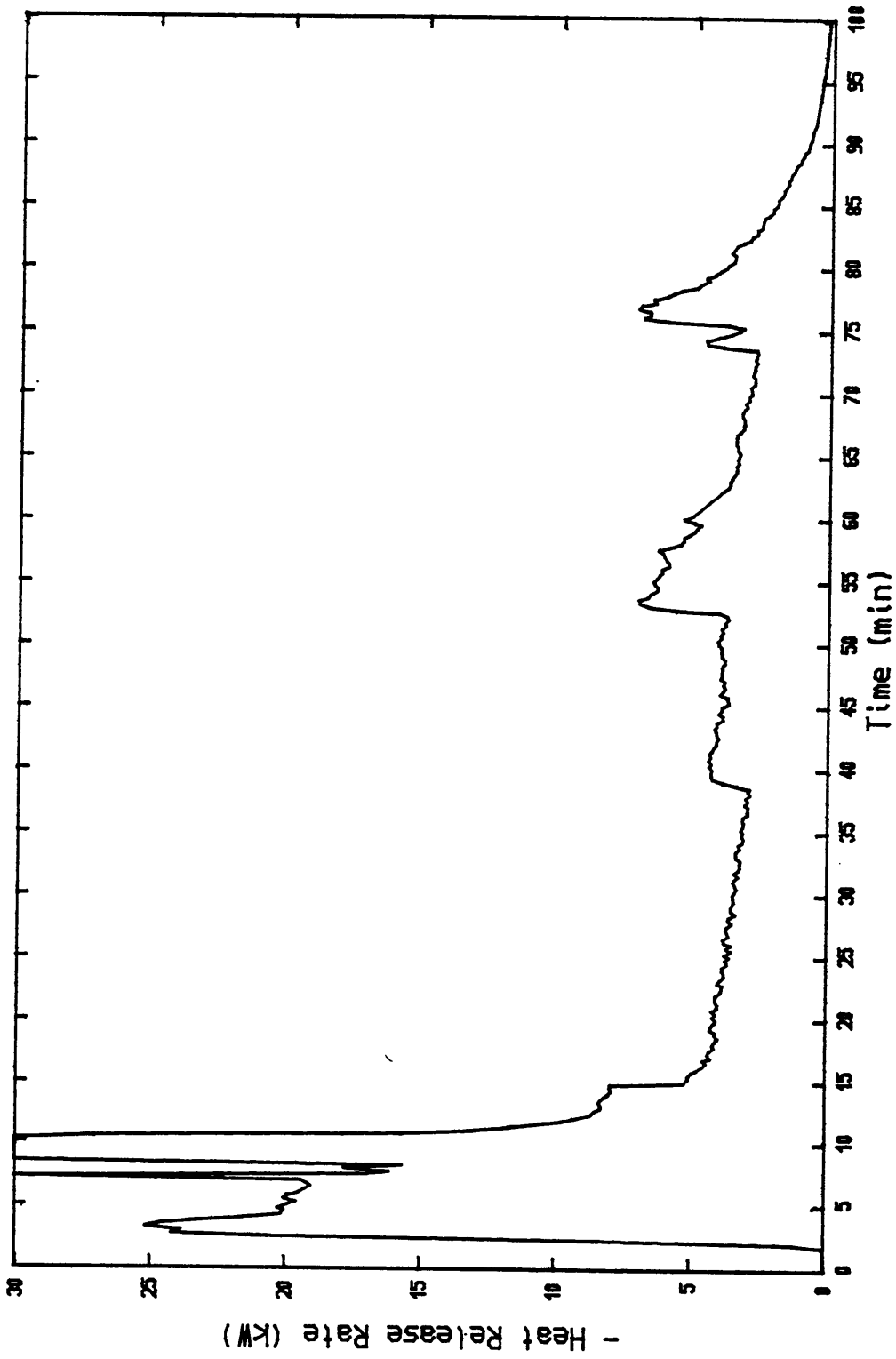
Figure 69  Heat Release Rate During Corn Fodder Low Fire Test
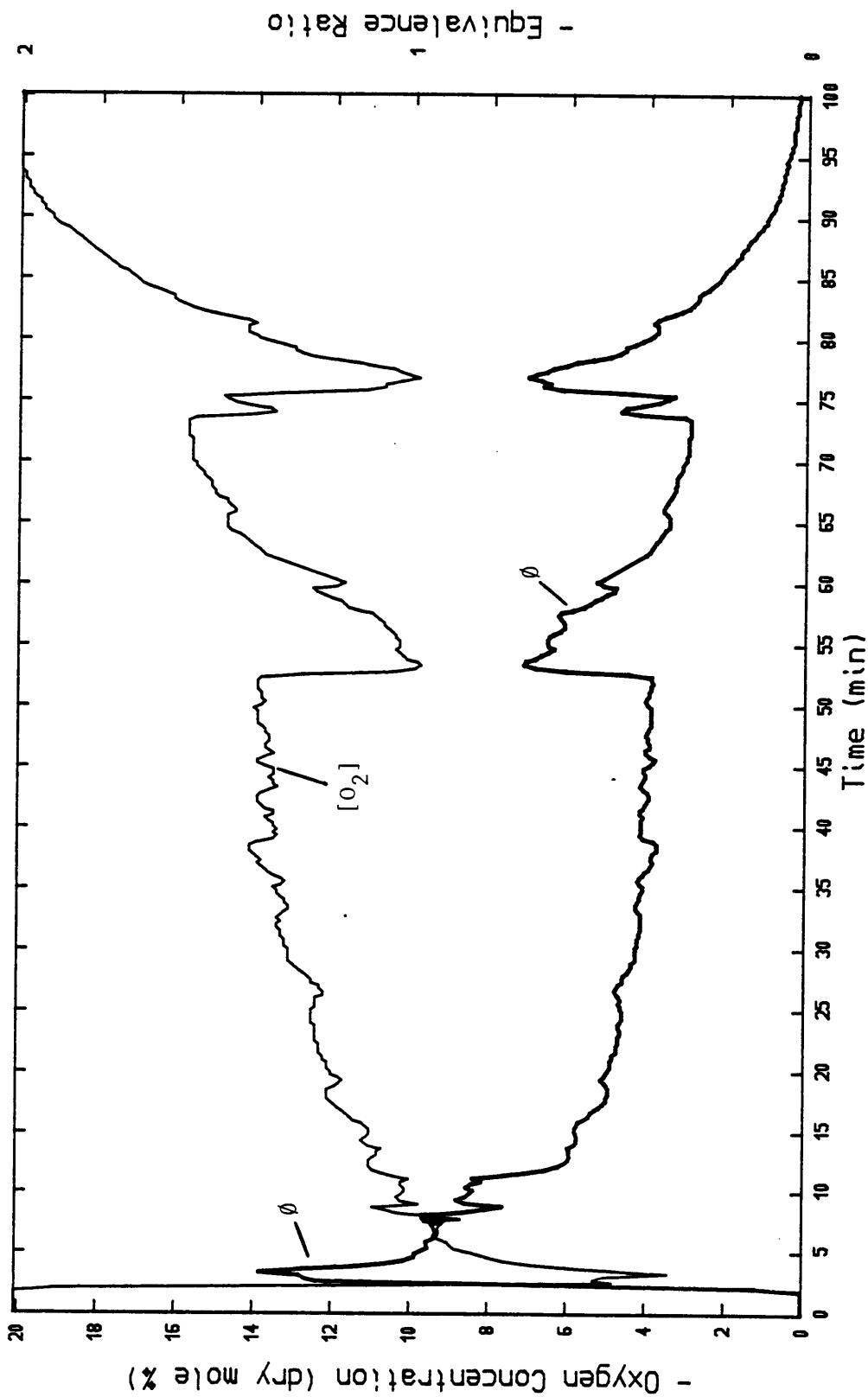
Figure 70  Oxygen Concentration and Fuel-Air Equivalence Ratio During Corn Fodder Low Fire Test
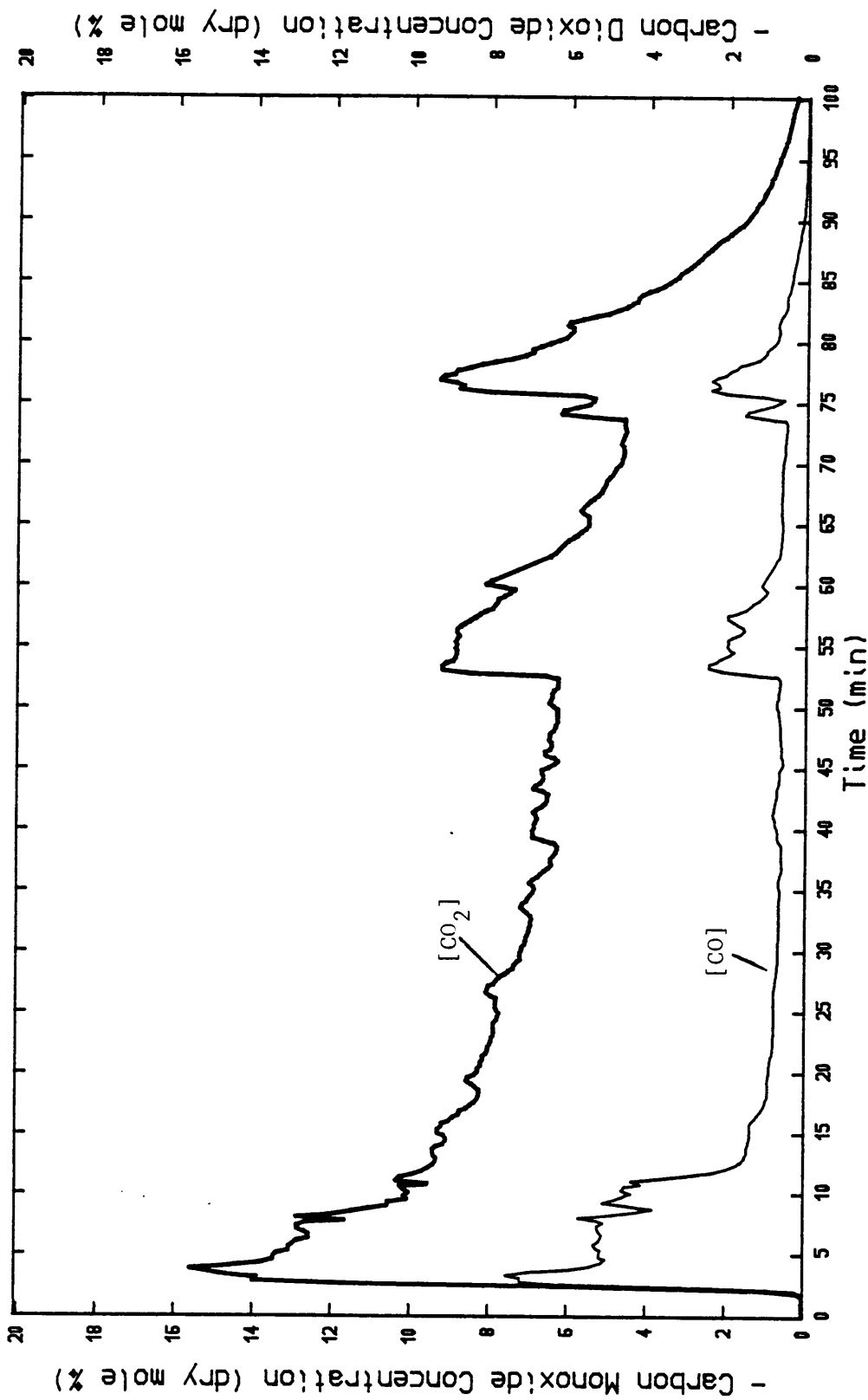
Figure 71  Carbon Monoxide and Carbon Dioxide Concentrations During Corn Fodder Low Fire Test

Corn Fodder High Fire Combustion Characterization Test
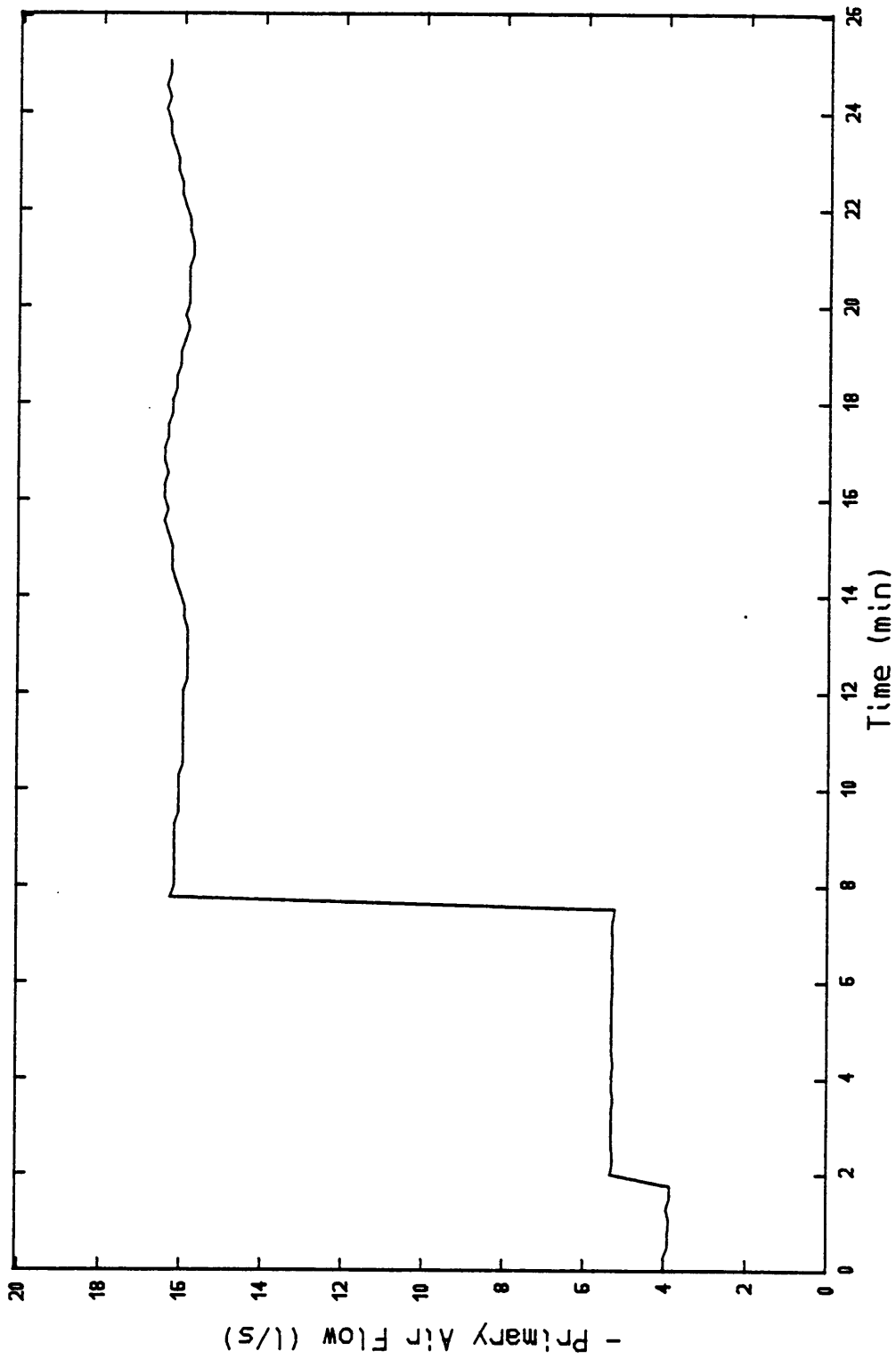
Figure 72  Primary Air Flow During Corn Fodder High Fire Test
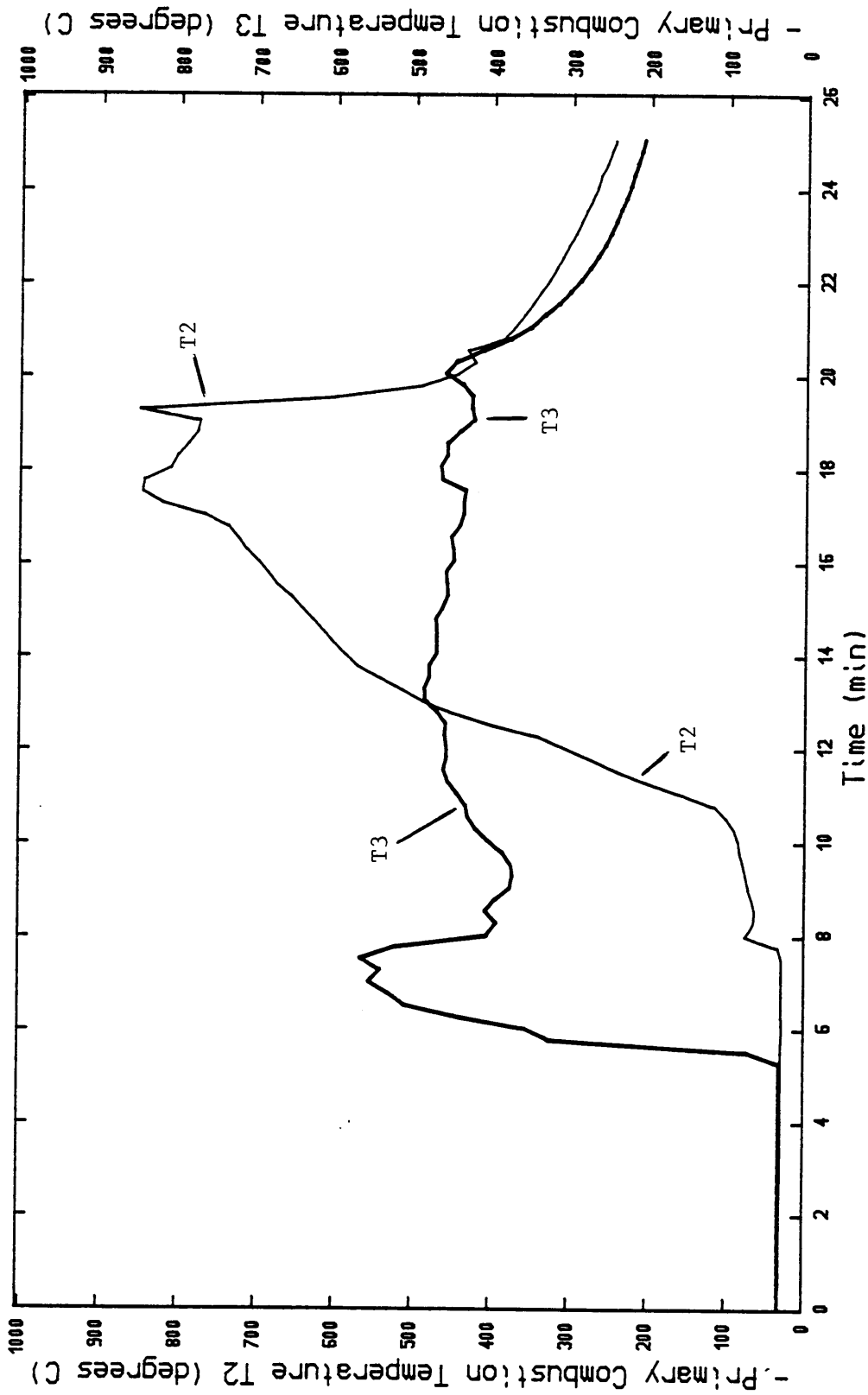
Figure 73  Primary Combustion/Gasification Temperatures, T2 and T3, During Corn Fodder High Fire Test
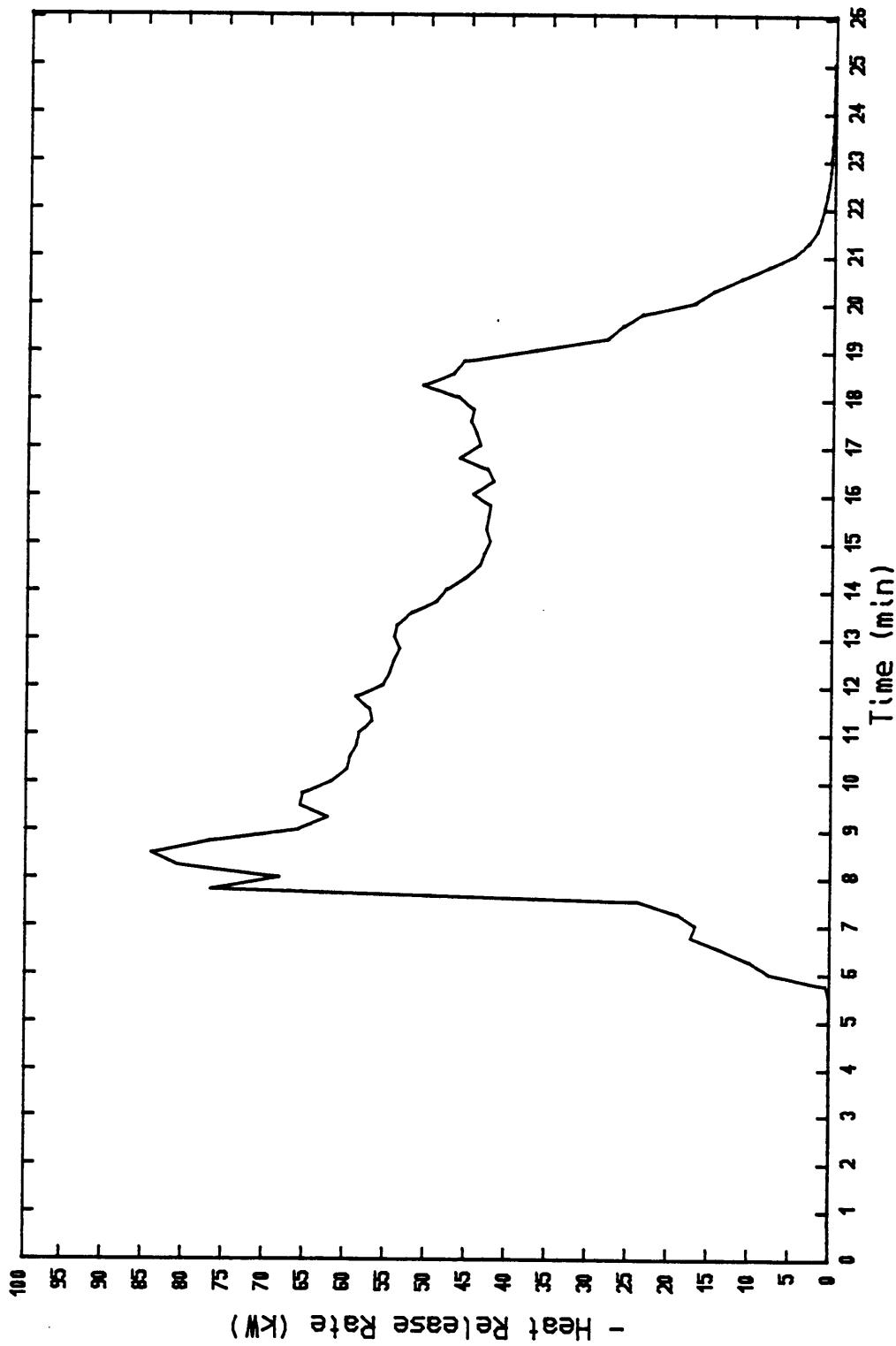
Figure 74   Heat Release Rate During Corn Fodder High Fire Test

Figure 75   Oxygen Concentration and Fuel-Air Equivalence Ratio During  Corn  Fodder
High Fire Test

Figure 76  Carbon Monoxide and Carbon Dioxide Concentrations During Corn Fodder High Fire Test

Corn Fodder Medium-Low Fire Combustion Characterization Test

Figure 77  Primary Air Flow During Corn Fodder Medium-Low Fire Test

Figure 78  Primary Combustion/Gasification Temperatrues, T2 and T3, During Corn Fodder Medium-Low Fire Test

Figure 79  Heat Release Rate During Corn Fodder Medium-Low Fire Test

Figure 80  Oxygen Concentration and Fuel-Air Equivalence Ratio During Corn Fodder
Medium-Low Fire Test

Figure 81 Carbon Monoxide and Carbon Dioxide Concentrations During Corn Fodder
Medium-Low Fire Test

Corn Fodder Medium-High Fire Combustion Characterization Test

Figure 82 Primary Air Flow During Corn Fodder Medium-High Fire Test

Figure 83  Primary Combustion/Gasification Temperatures, T2 and T3, During Corn Fodder Medium-High Fire Test

Figure 84   Heat Release Rate During Corn Fodder Medium-High Fire Test

Figure 85  Oxygen Concentration and Fuel-Air Equivalence Ratio During Corn Fodder
Medium-High Fire Test

Fgiure 86  Carbon Monoxide and Carbon Dioxide Concentrations During Corn Fodder Medium-High Fire Test

Corn Fodder Bang-Bang Combustion Characterization Test

Figure 87  Primary Air Flow During Corn Fodder Bang-Bang Test

Figure 88  Primary Combustion/Gasification Temperatures, T2 and T3, During Corn Fodder Bang-Bang Test

Figure 89  Heat Release Rate During Corn Fodder Bang-Bang Test

Figure 90  Oxygen Concentration and Fuel-Air Equivalence Ratio During Corn Fodder Bang-Bang Test

Figure 91  Carbon Monoxide and Carbon Dioxide Concentrations During Corn Fodder Bang-Bang Test

# Appendix E

## PRESENTATION OF DATA FROM PROTOTYPE CATALYTIC COMBUSTOR/GASIFIER PERFORMANCE TESTS

Prototype Catalytic Combustor/Gasifier Performance Test
Using Cordwood for fuel

235
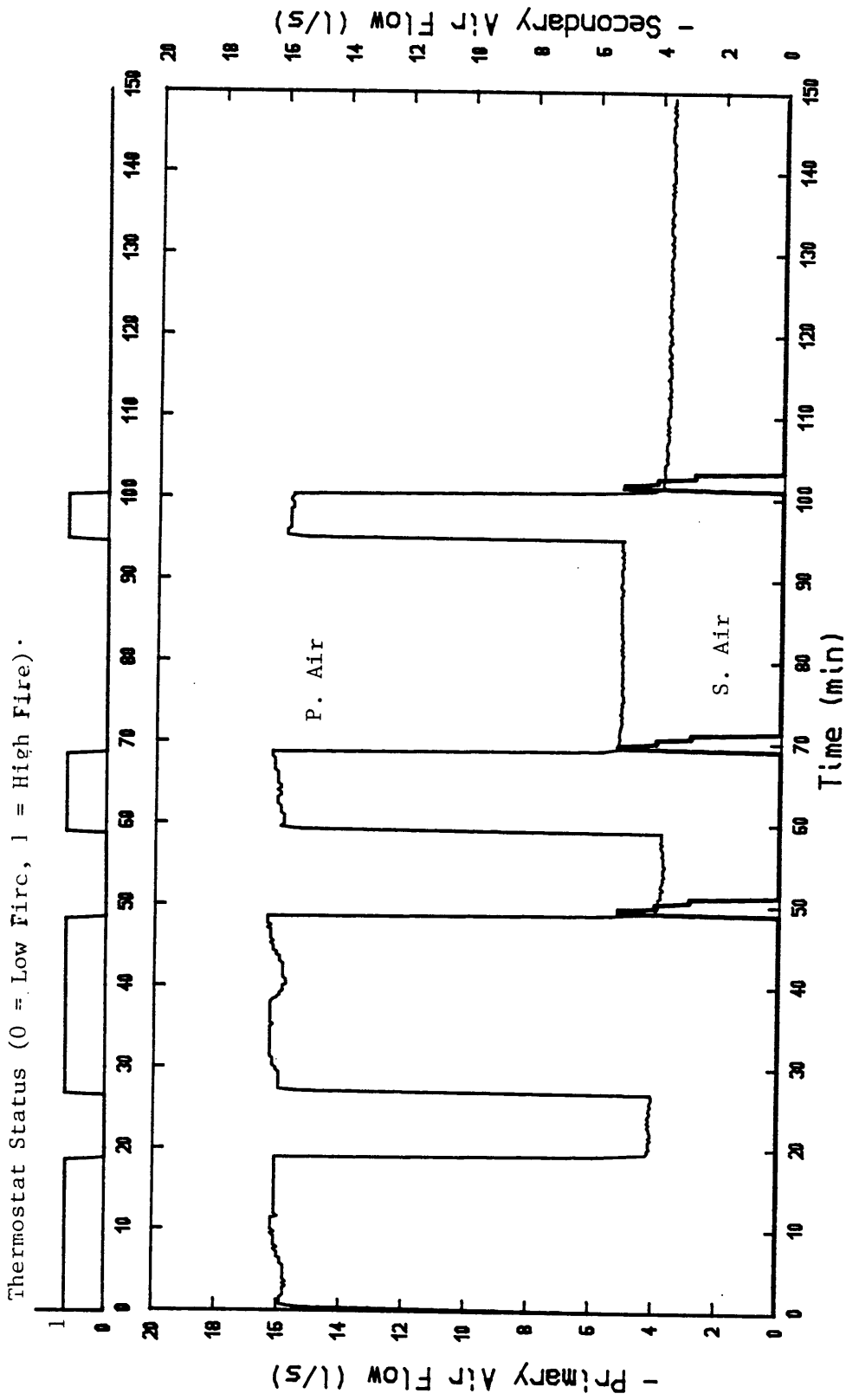


Figure 92  Primary and Secondary Air Flows During Performance Test
Using Cordwood for Fuel
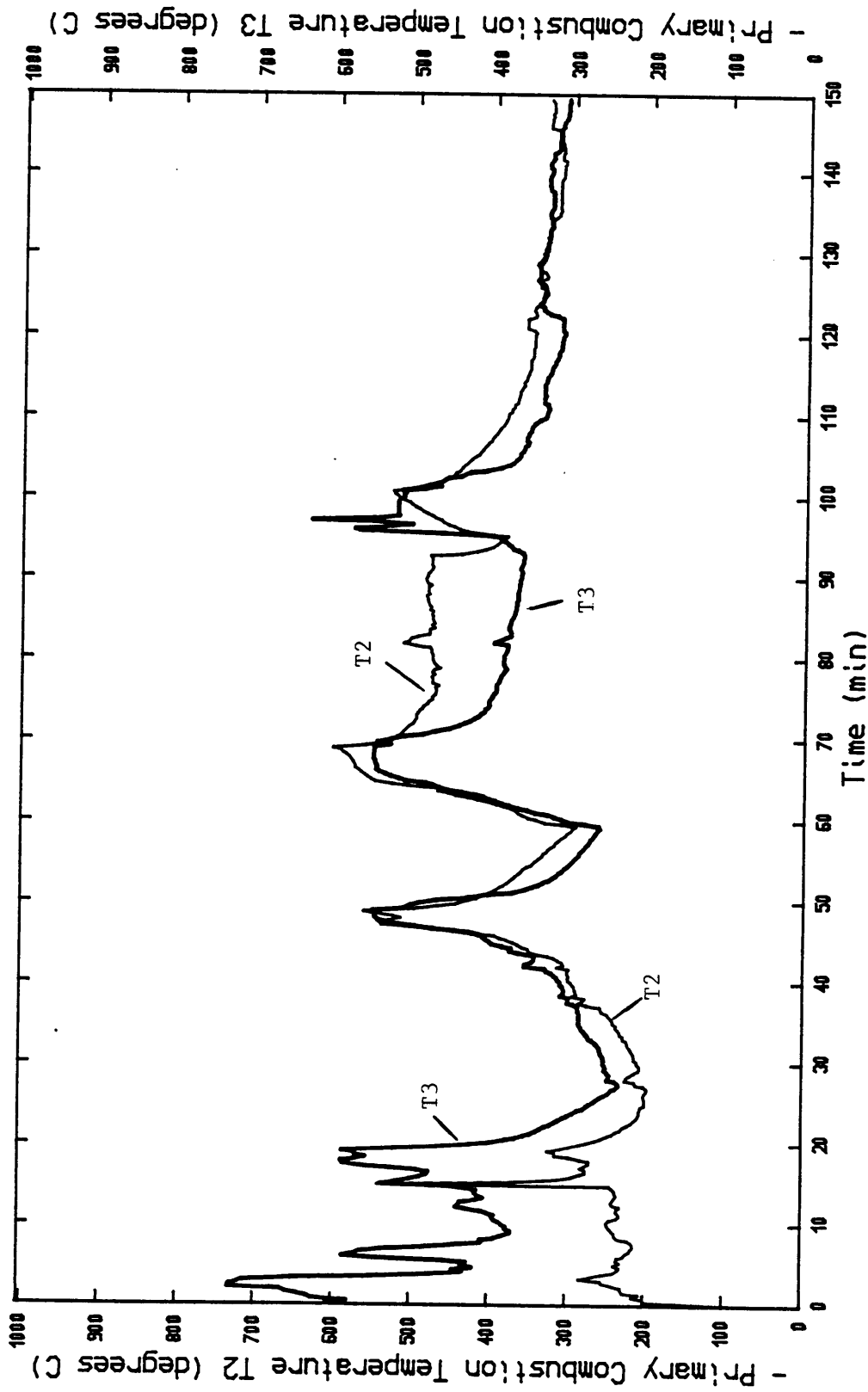
Figure 93   Primary Combustion/Gasification Temperatures, T2 and T3, During Performance
Test Using Cordwood for Fuel
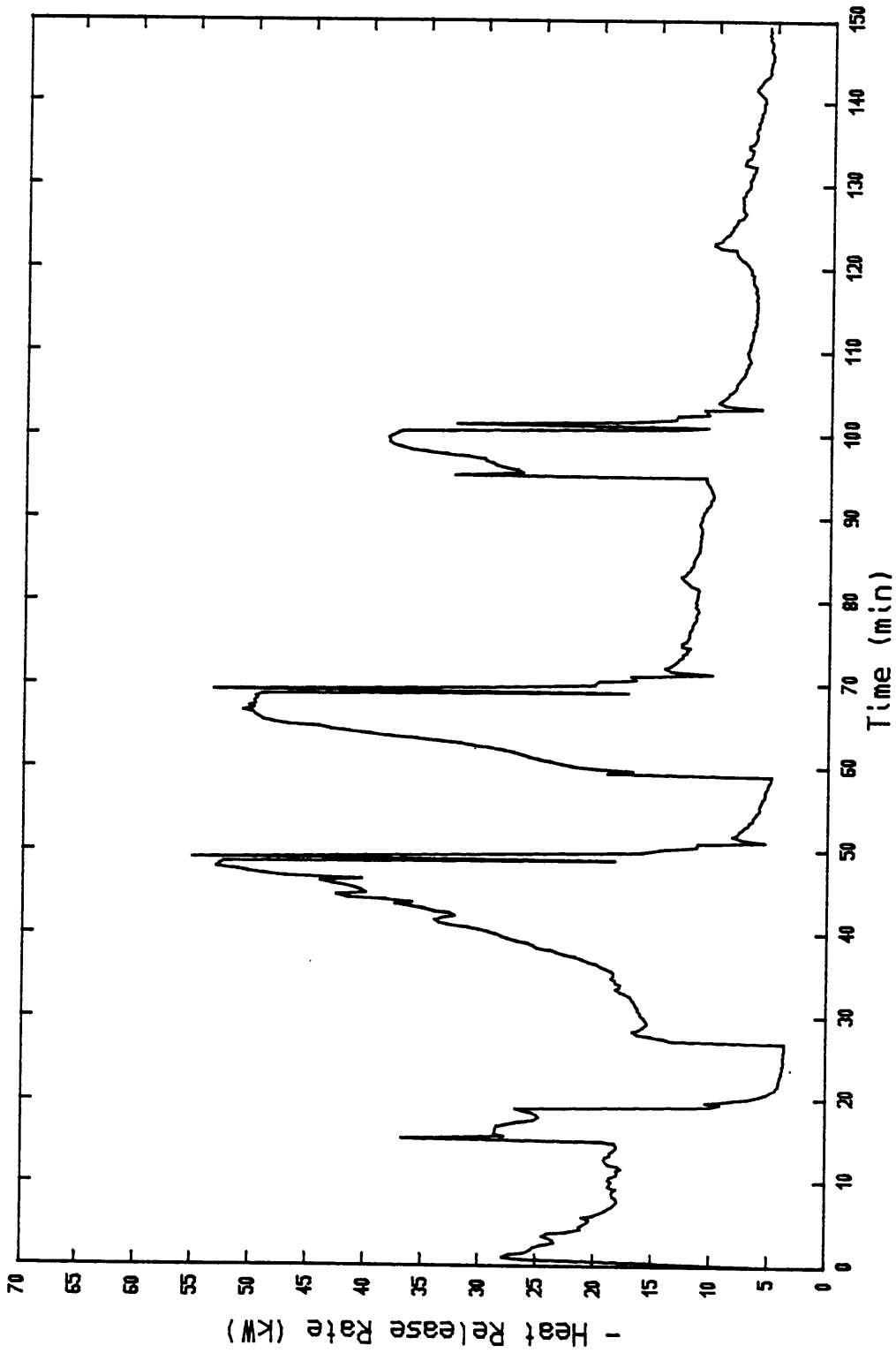
Figure 94   Heat Release Rate During Performance Test Using Cordwood for Fuel

238
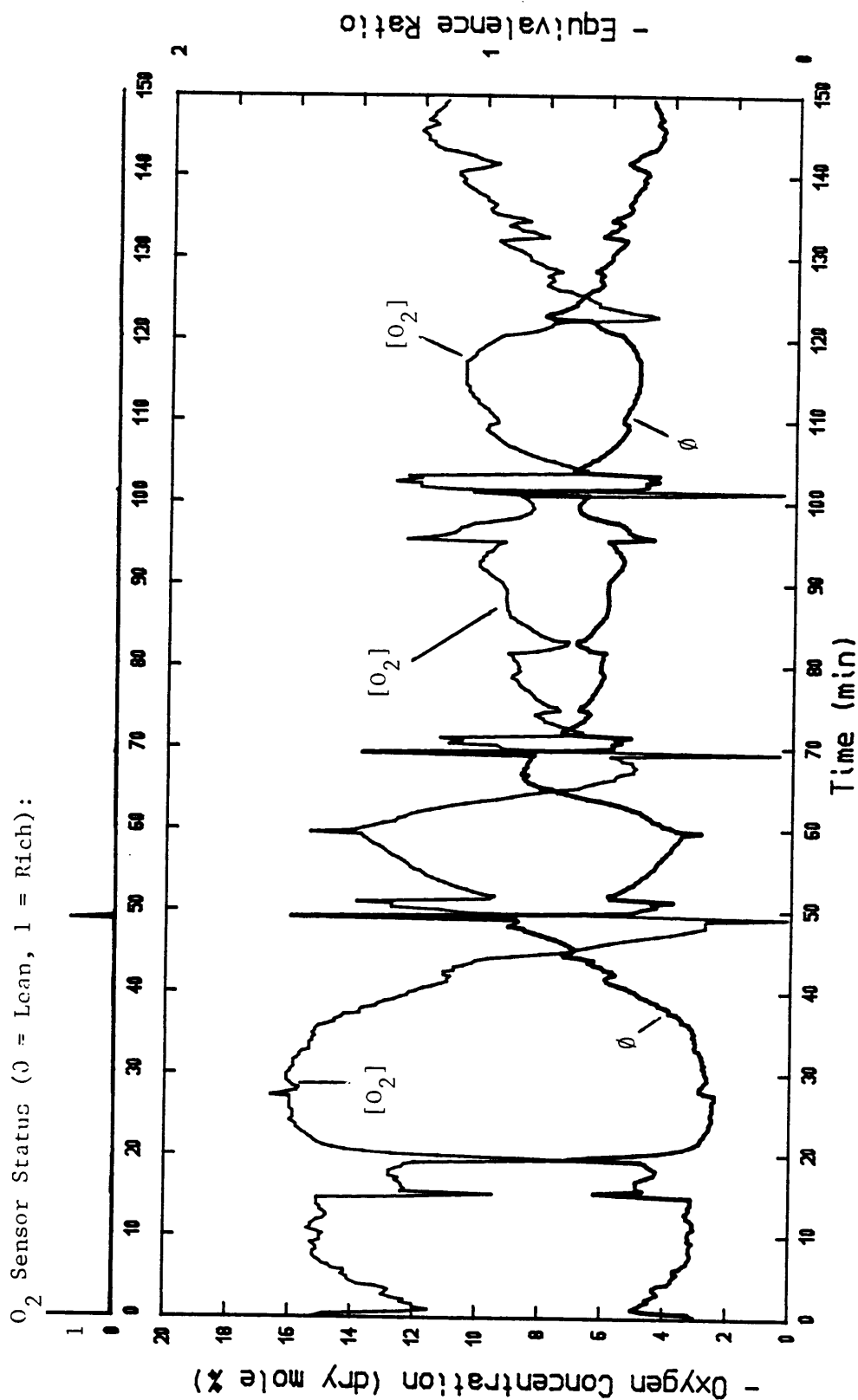


Figure 95   Oxygen Concentration and Equivalence Ratio During Performance Test Using Cordwood for Fuel
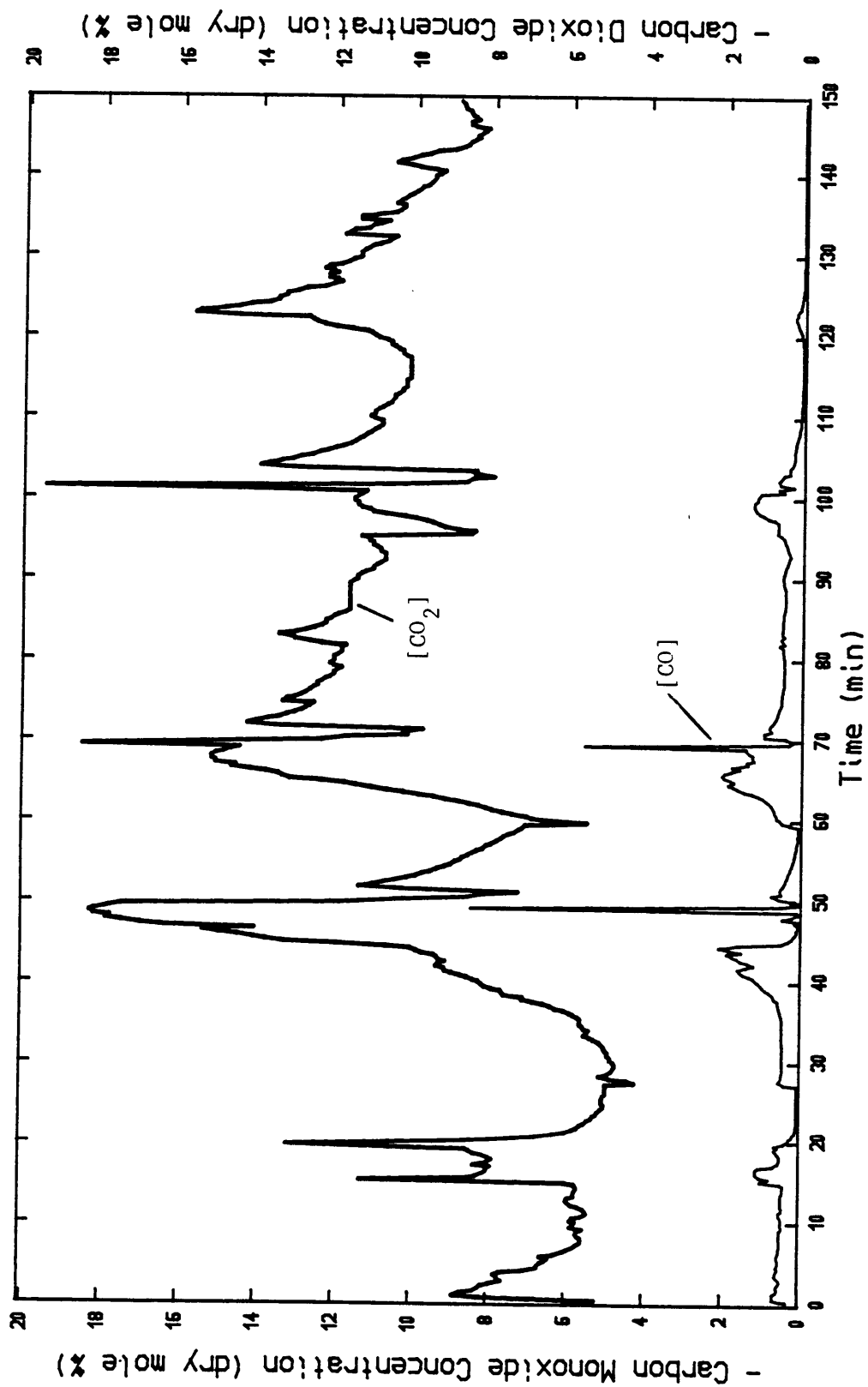
Figure 96   Carbon Monoxide and Carbon Dioxide Concentrations During Performance Test
Using Cordwood for Fuel
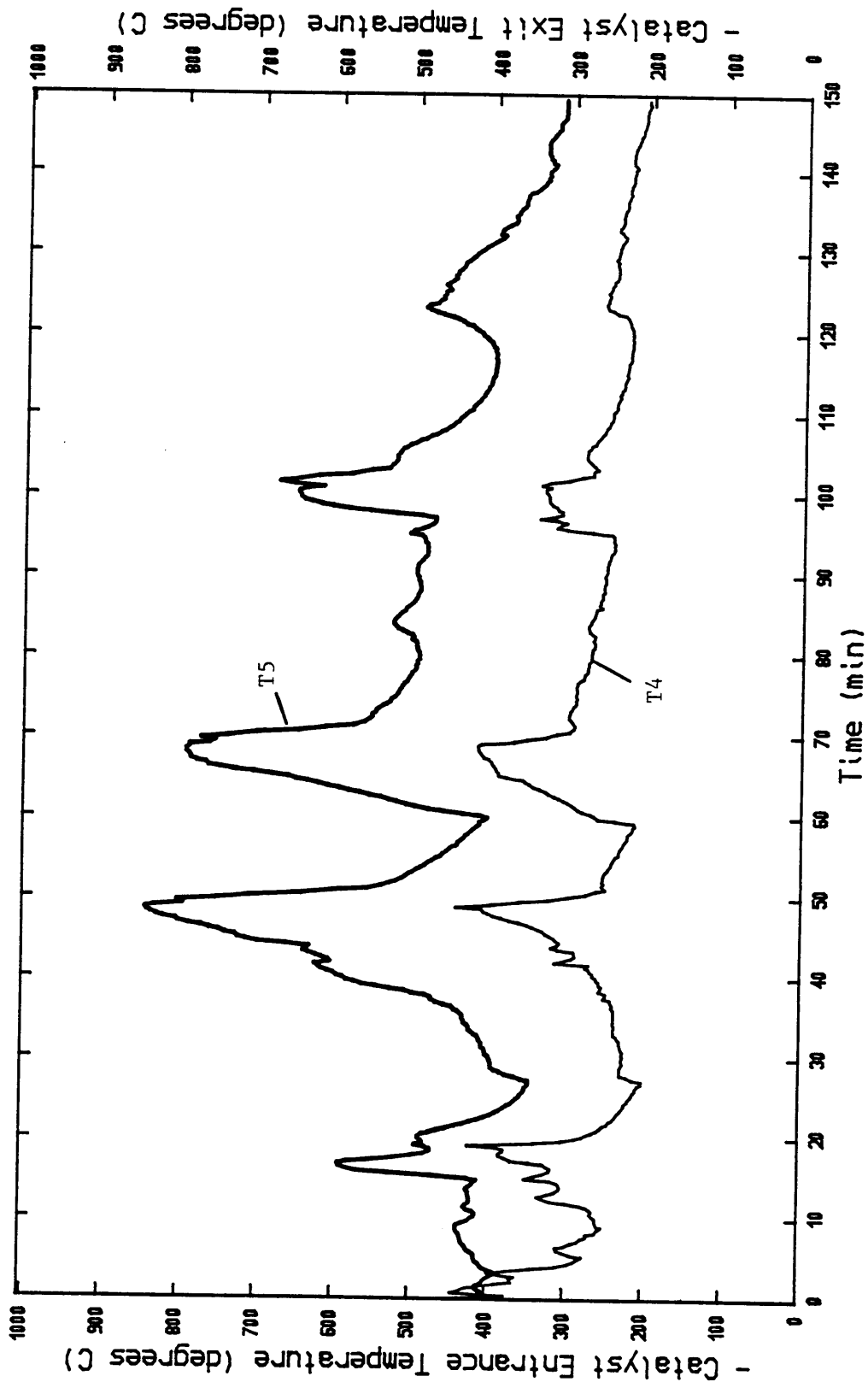
Figure 97  Catalyst Entrance and Exit Temperatures, T4 and T5, During Performance Test Using Cordwood for Fuel

Prototype Catalytic Combustor/Gasifier Performance Test
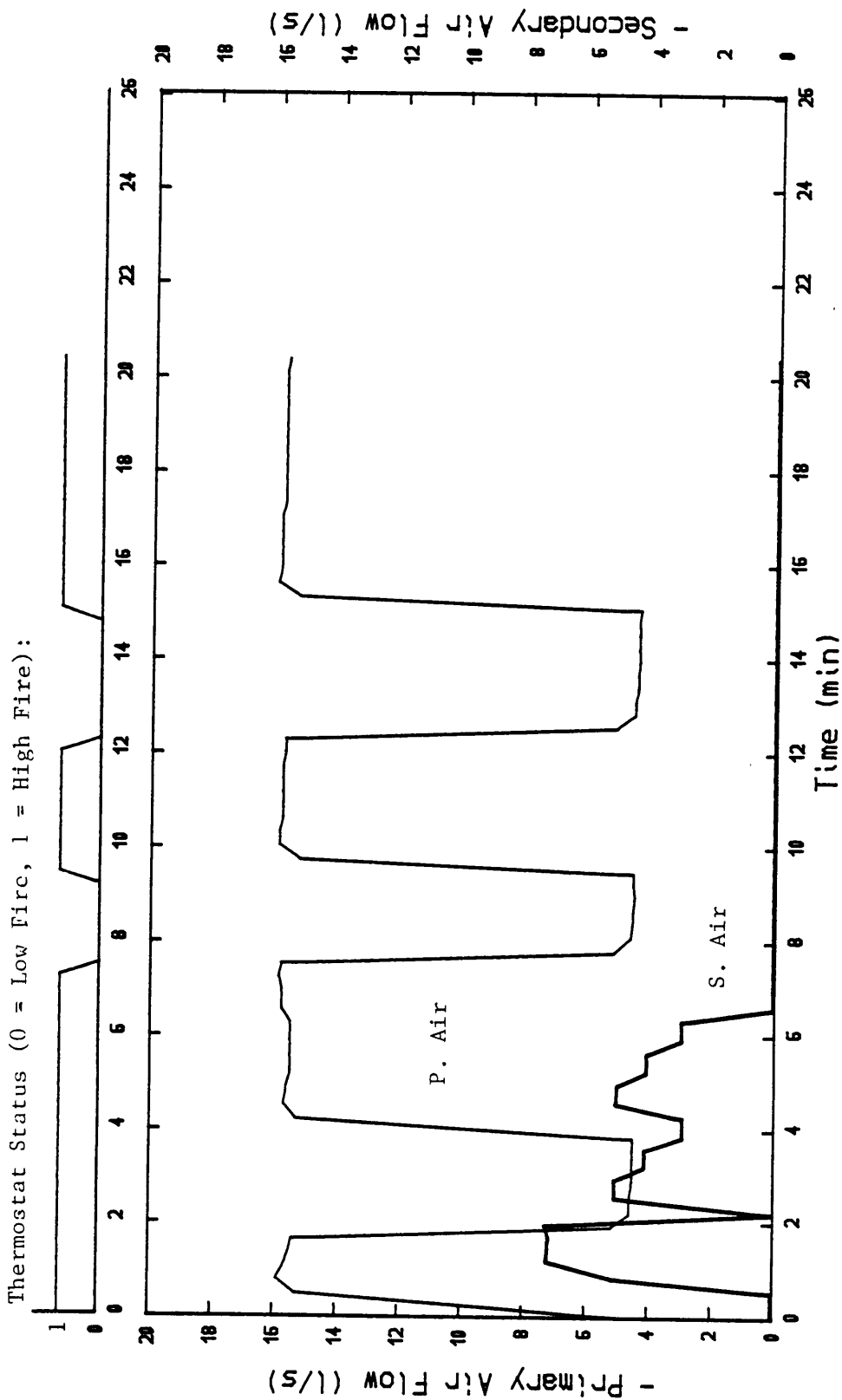Using Baled Slash for Fuel (Test I)
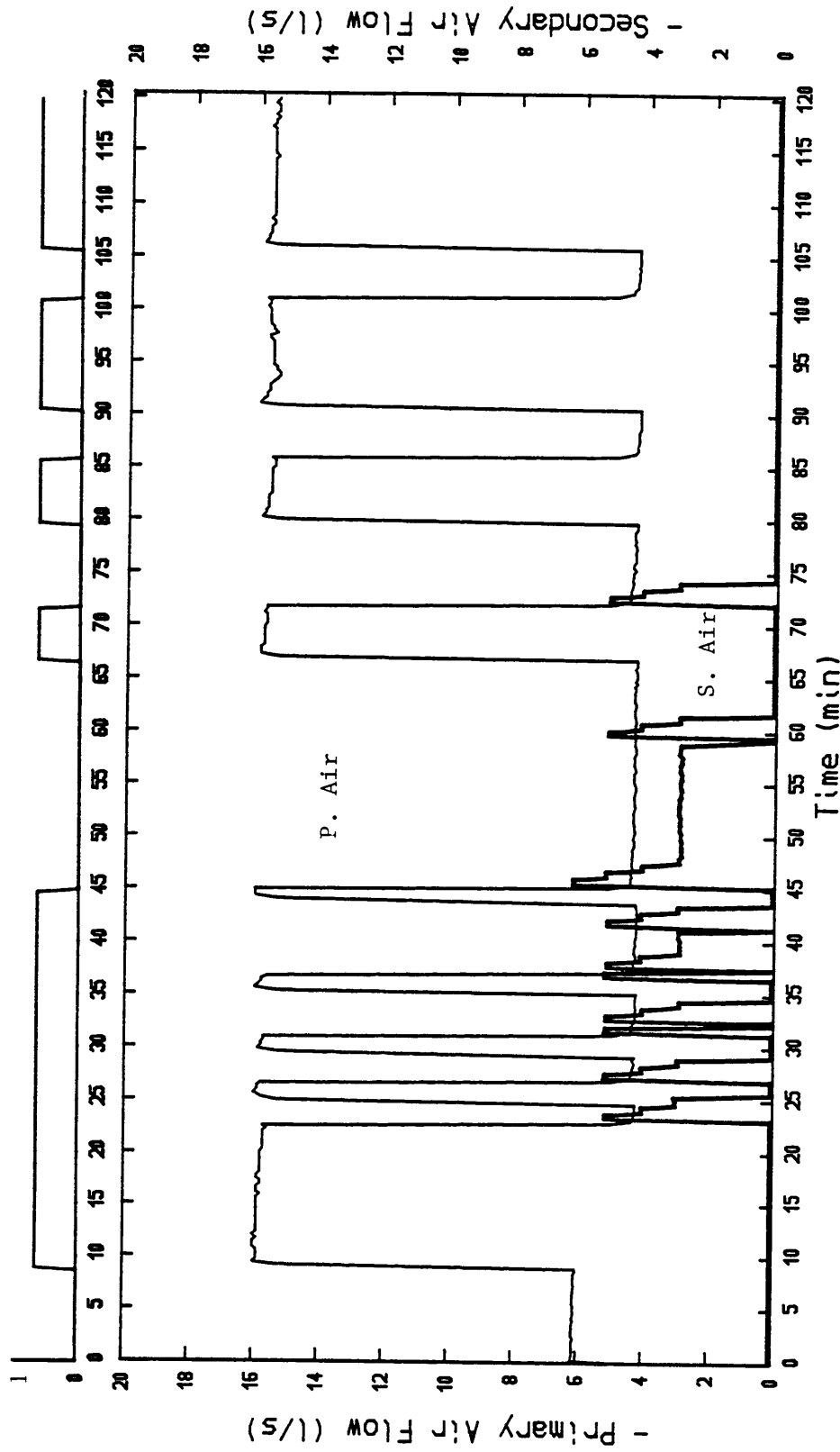
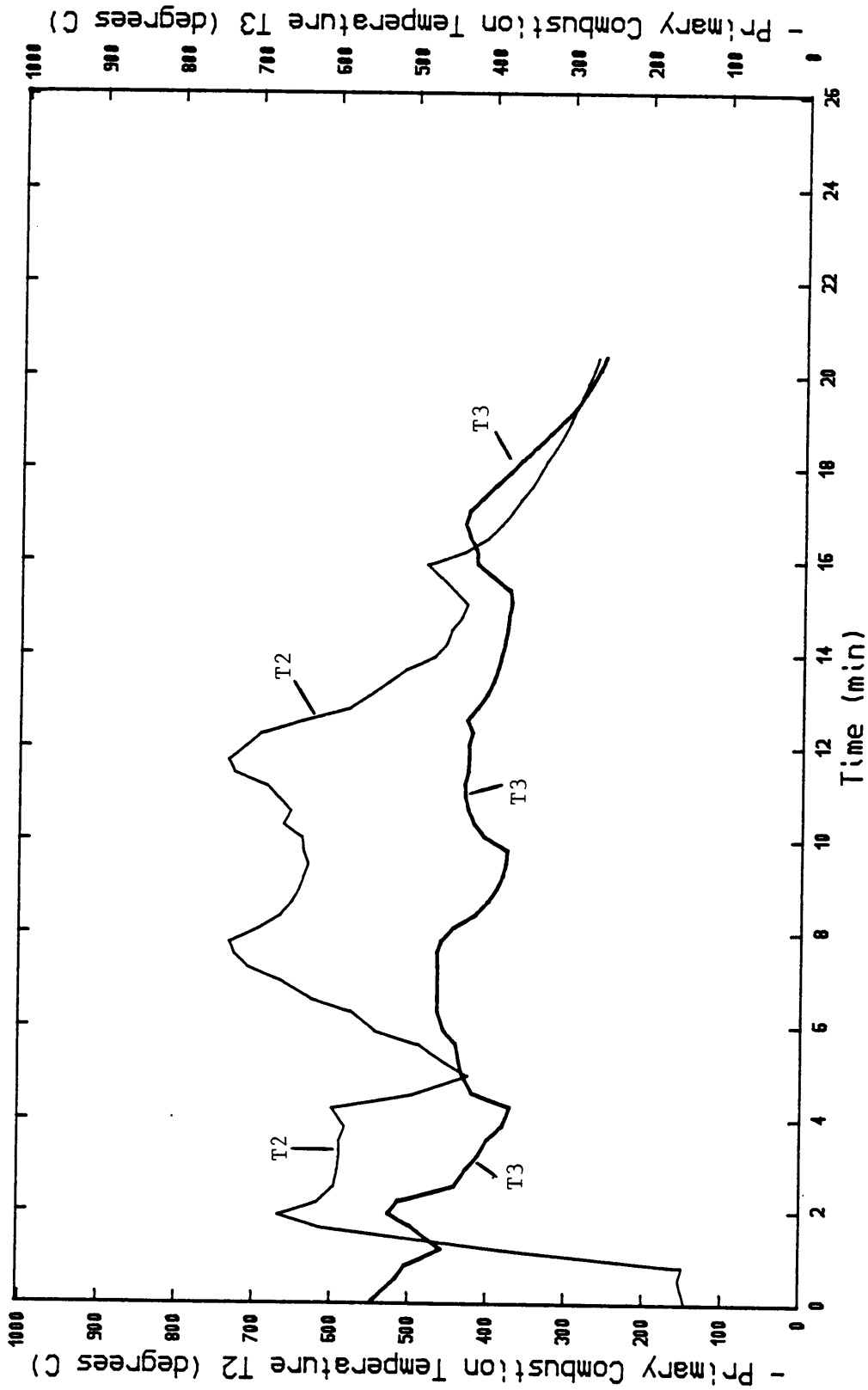Figure 98  Primary and Secondary Air Flows During Performance Test Using Baled Slash for Fuel (Test I)
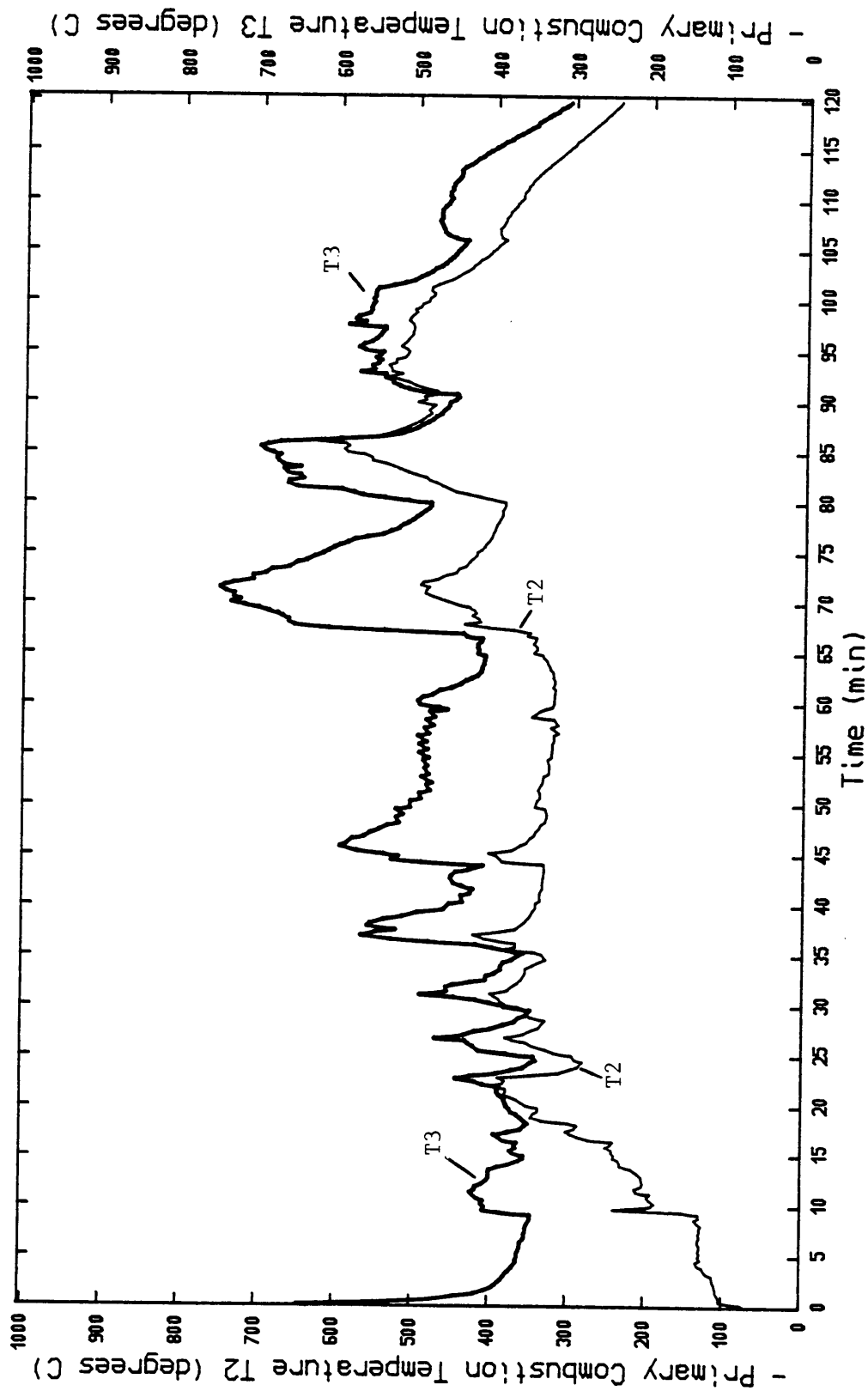
Figure 99  Primary Combustion/Gasification Temperatures, T2 and T3, During Performance Test Using Baled Slash for Fuel (Test 1)
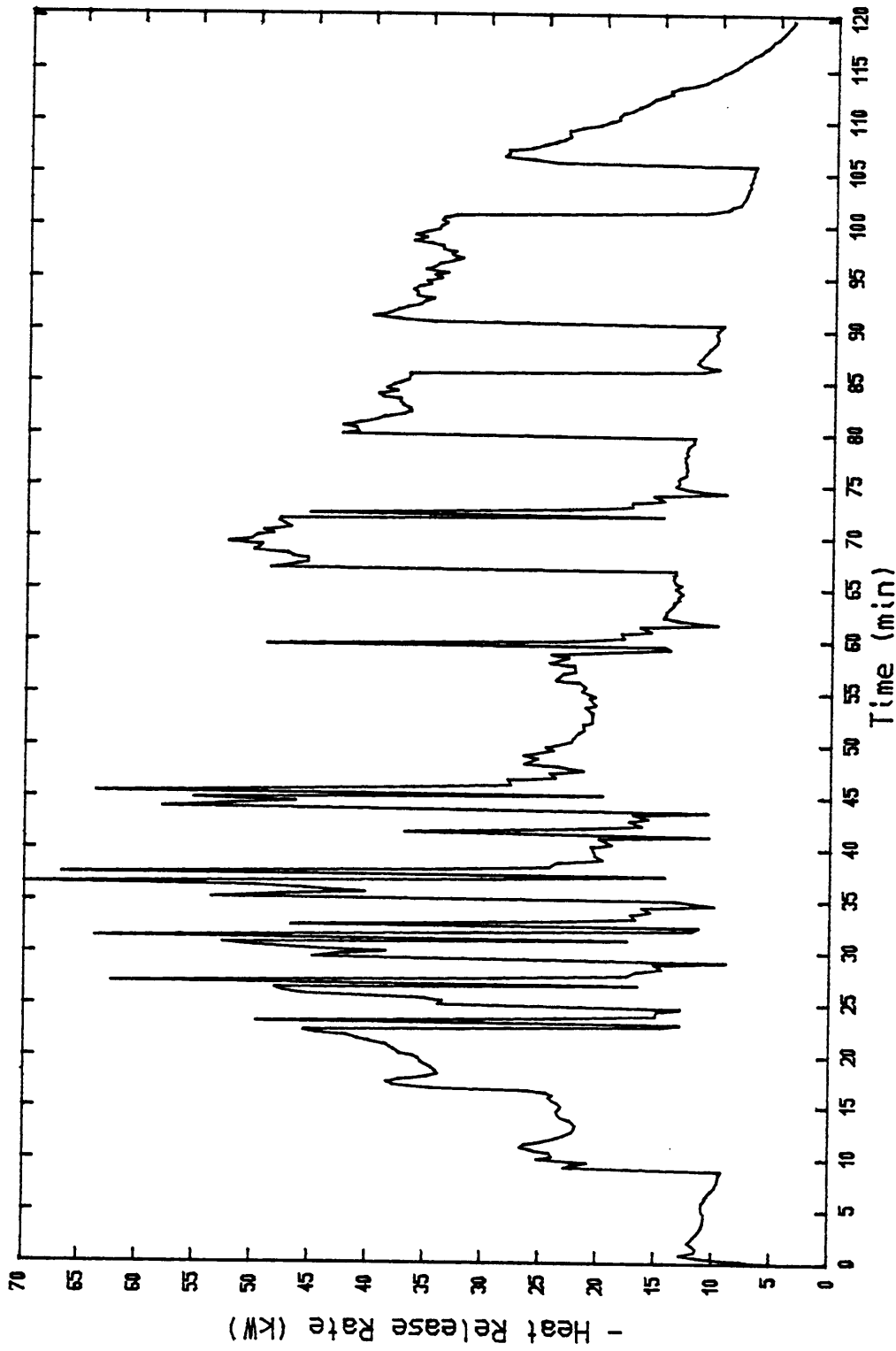
Figure 100  Heat Release Rate During Performance Test Using Baled Slash for Fuel (Test 1)
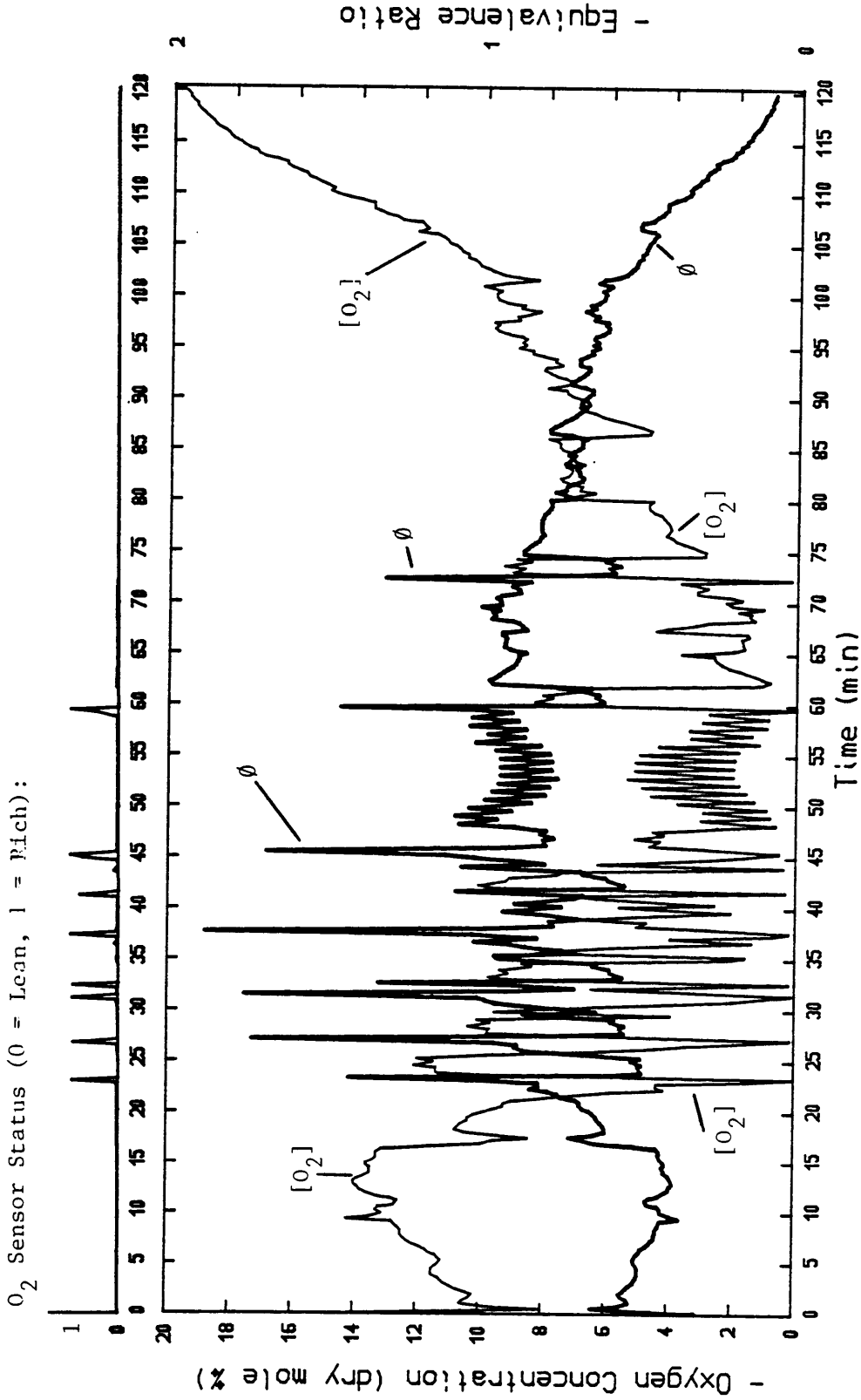
Figure 101  Oxygen Concentration and Equivalence Ratio During Performance Test Using
Baled Slash for Fuel (Test 1)
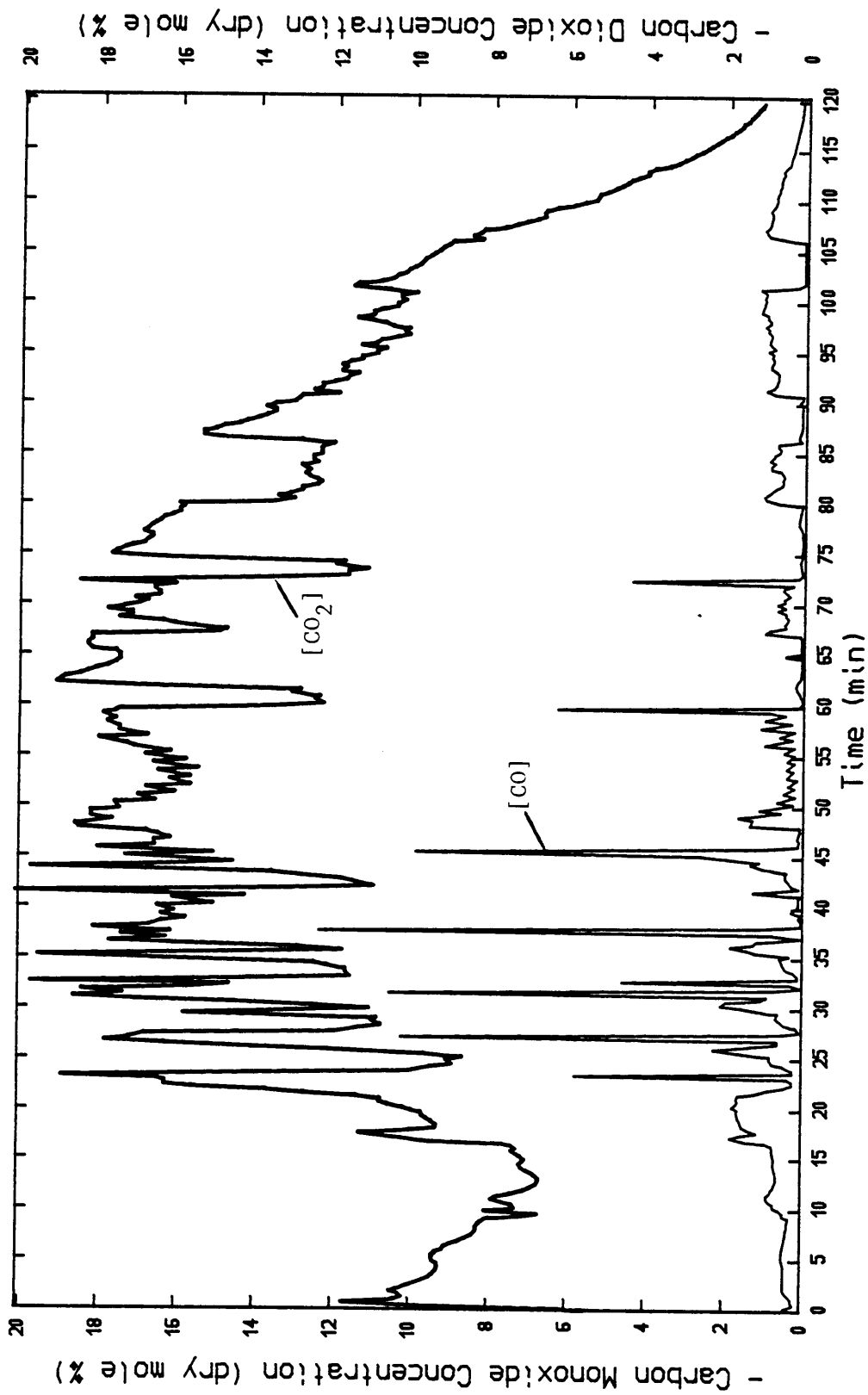
Figure 102  Carbon Monoxide and Carbon Dioxide Concentrations During Performance Test
Using Baled Slash for Fuel (Test 1)
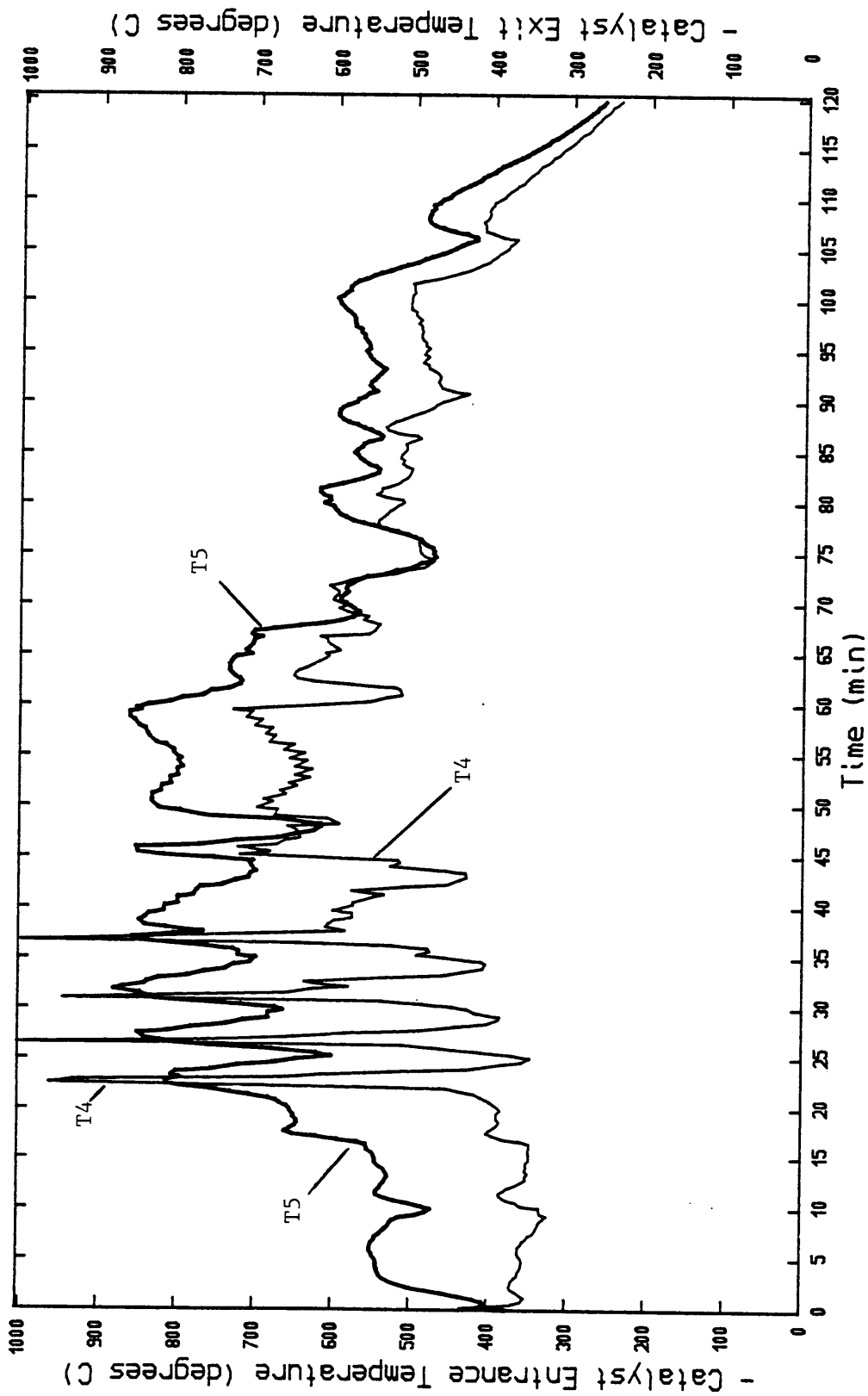
Figure 103  Catalyst Entrance and Exit Temperatures, T4 and T5, During Performance Test Using Baled Slash for Fuel (Test 1)

Prototype Catalytic Combustor/Gasifier Performance Test
Using Baled Slash for Fuel (Test II--Reduced High Fire
Set Point)
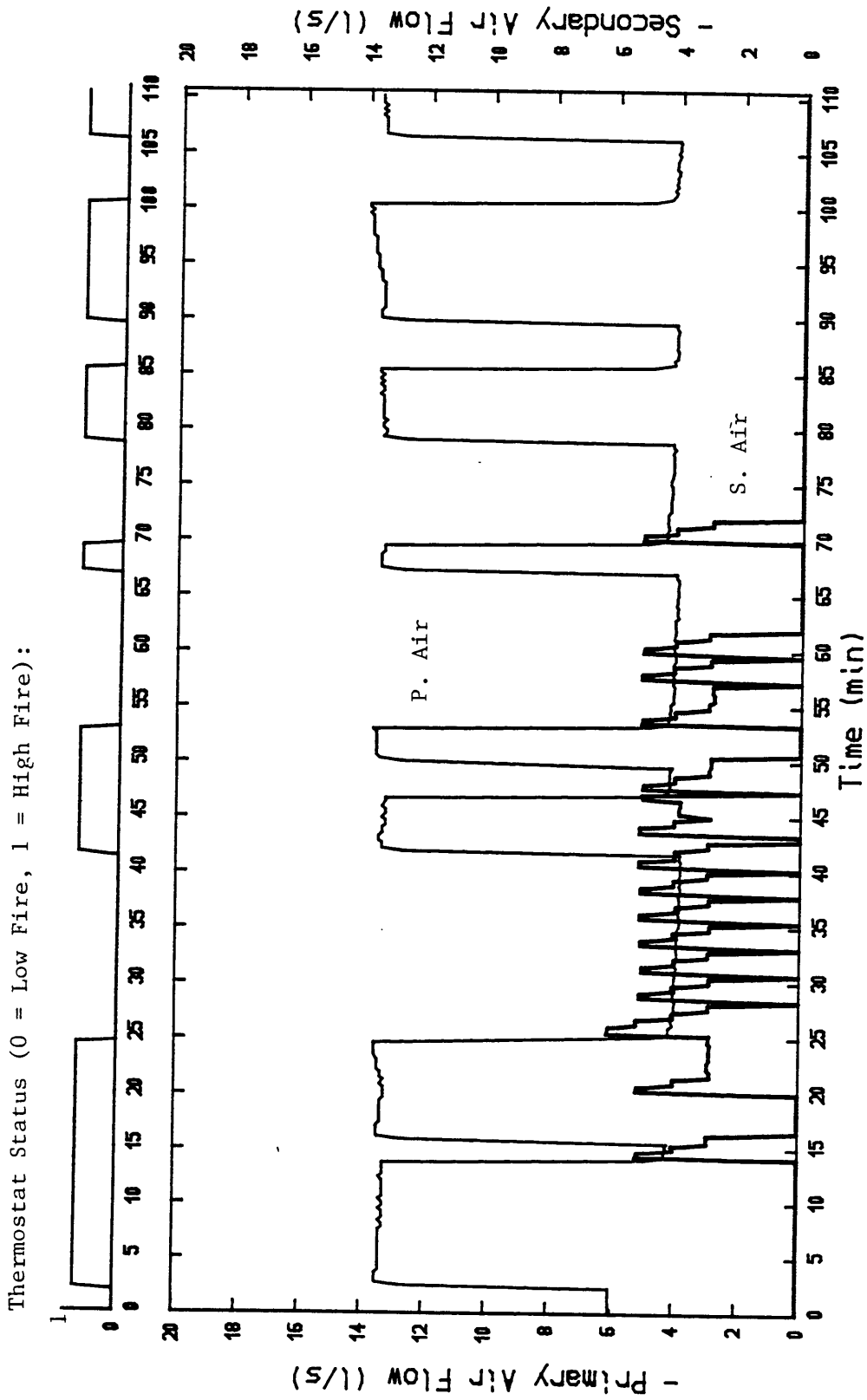
Figure 104  Primary and Secondary Air Flows During Performance Test Using Baled Slash
for Fuel (Test II--Reduced High Fire Set Point)
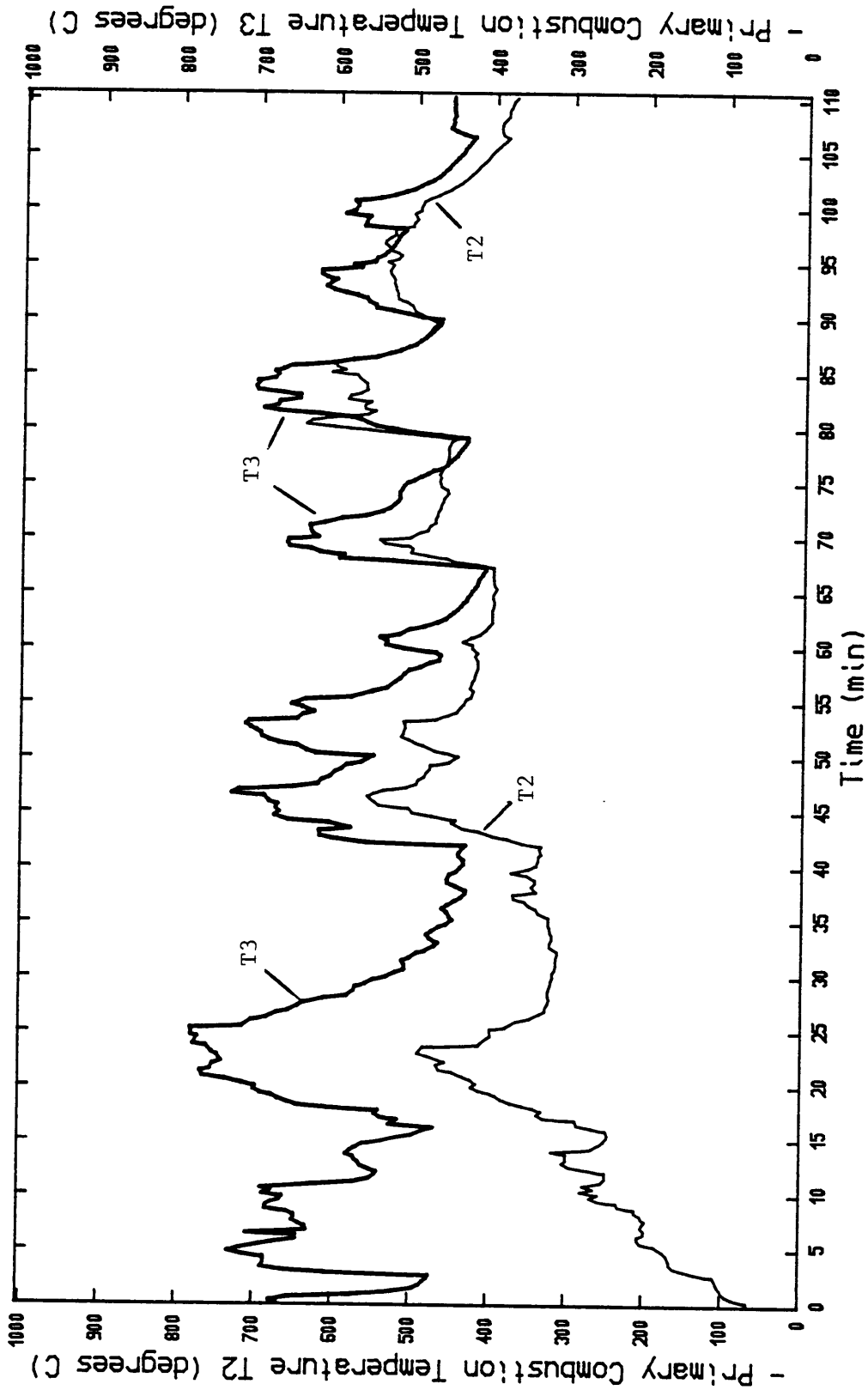
Figure 105  Primary Combustion/Gasification Temperatures, T2 and T3, During Performance Test Using Baled Slash for Fuel (Test II--Reduced High Fire Set Point)
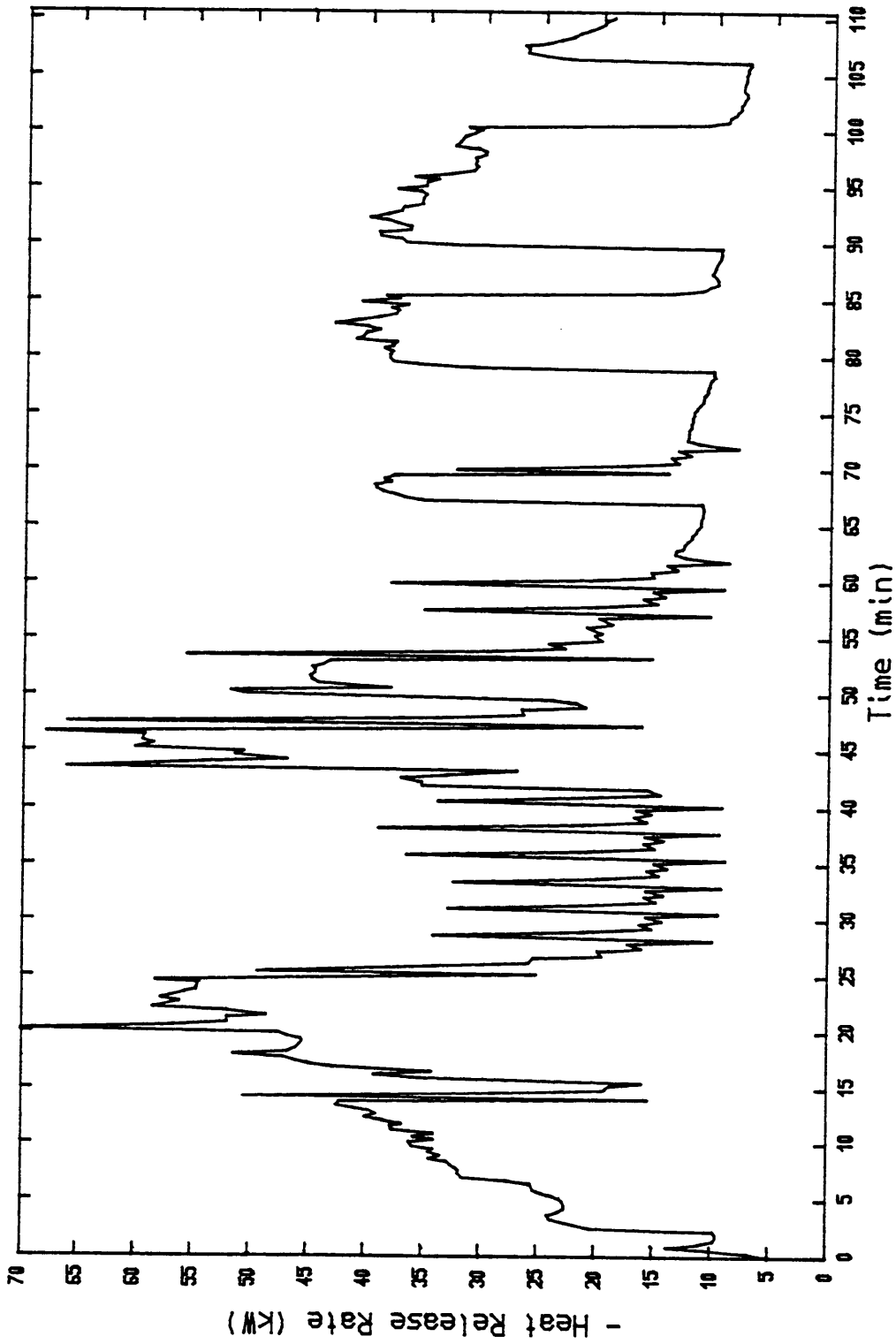
Figure 106  Heat Release Rate During Performance Test Using Baled Slash for Fuel
(Test II--Reduced High Fire Set Point)

252
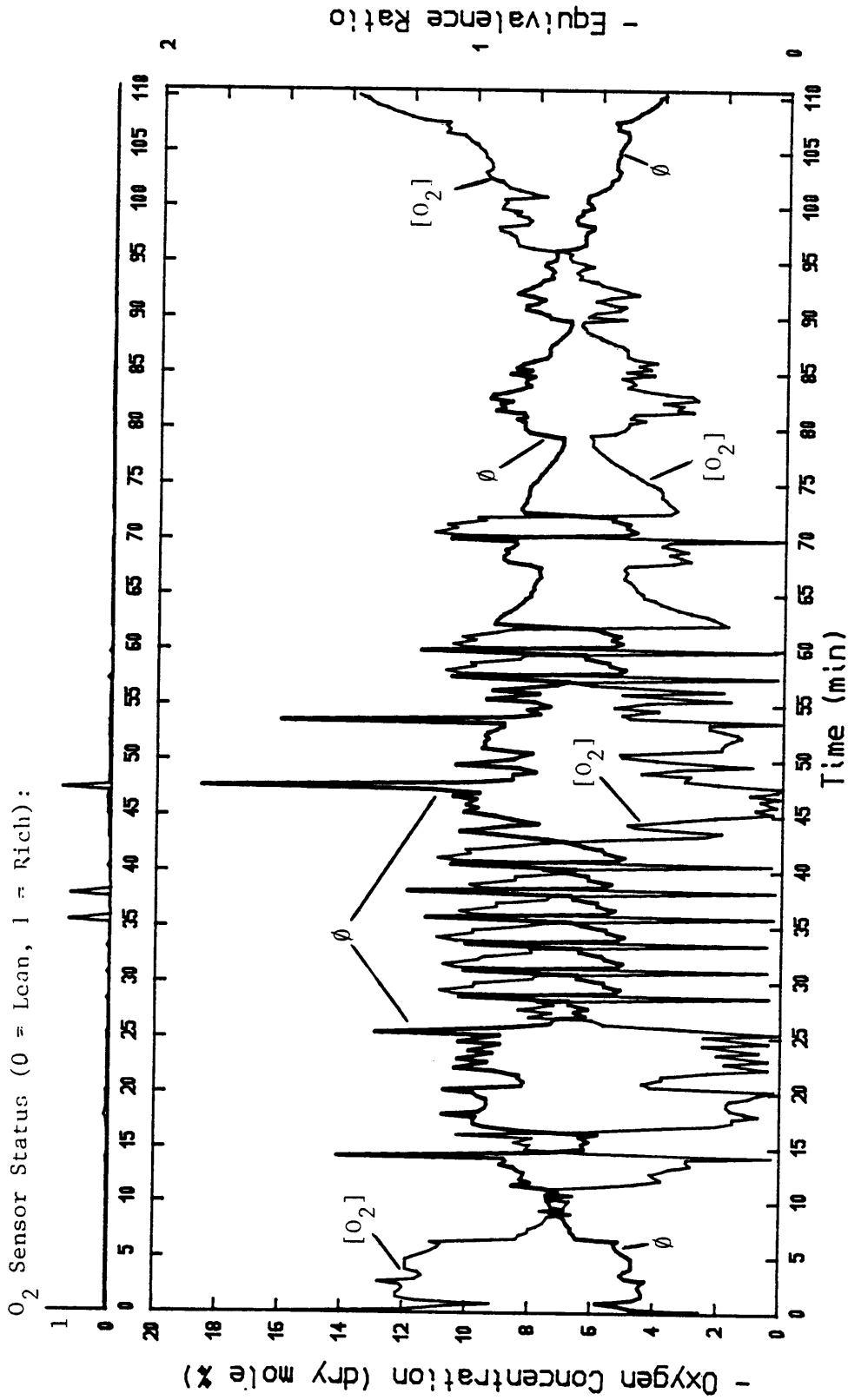


Figure 107   Oxygen Concentration and Equivalence Ratio During Performance Test Using Baled
Slash for Fuel (Test II--Reduced High Fire Set Point)
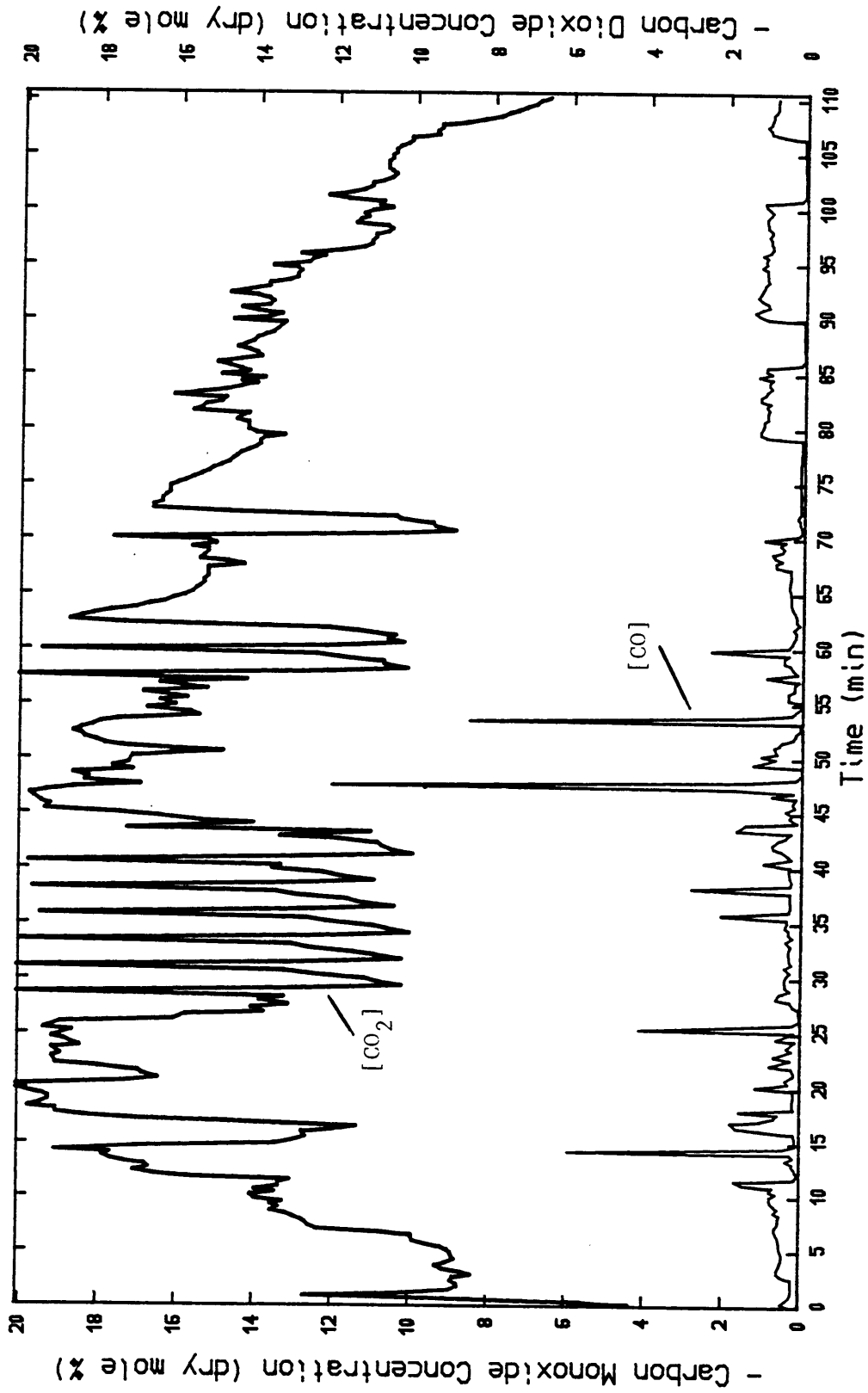
Figure 108  Carbon Monoxide and Carbon Dioxide Concentrations During Performance Test Using Baled Slash for Fuel (Test II--Reduced High Fire Set Point)

254
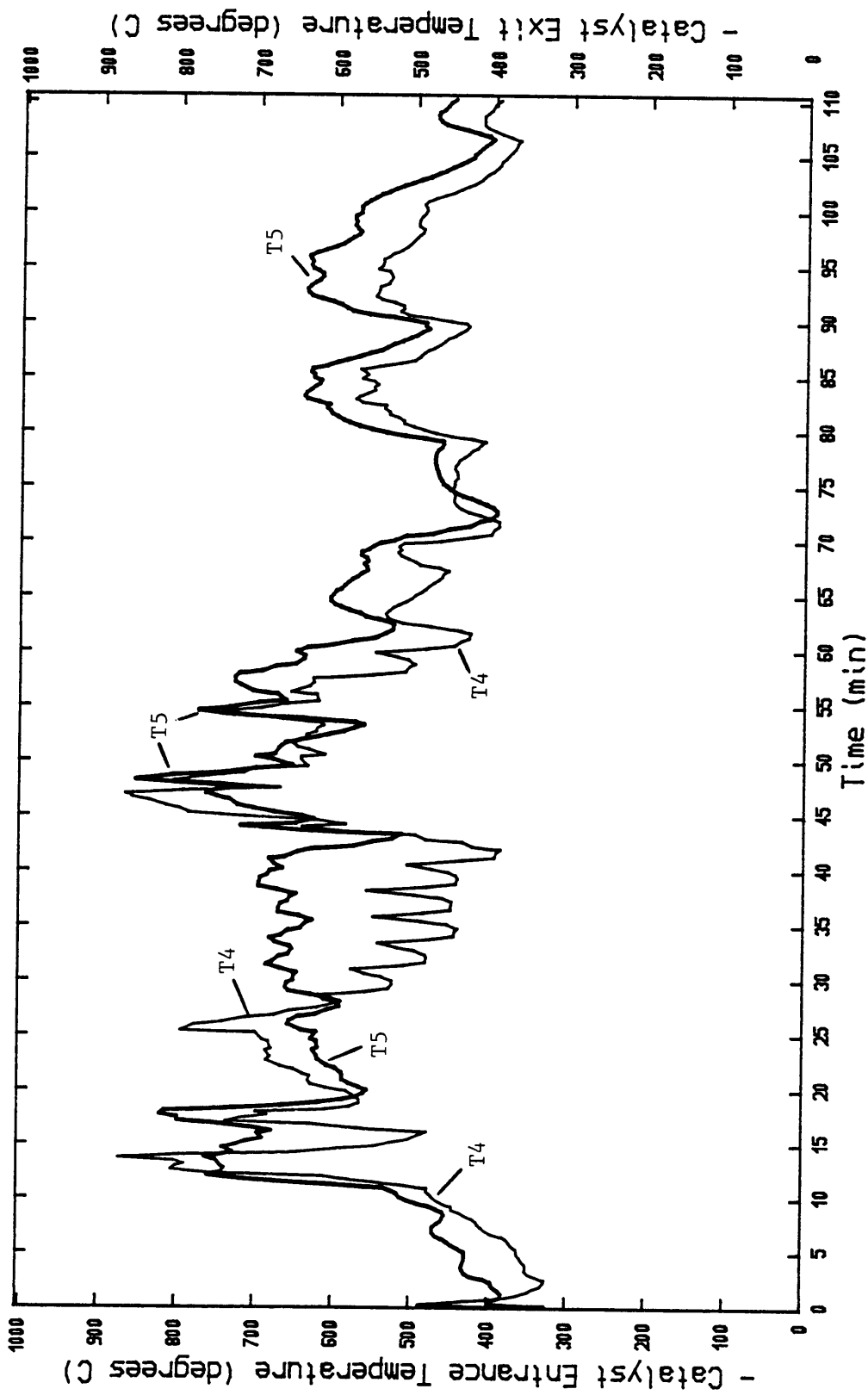


Figure 109  Catalyst Entrance and Exit Temperatures, T4 and T5, During Performance Test Using Baled Slash for Fuel (Test II--Reduced High Fire Set Point)

Prototype Catalytic Combustor/Gasifier Performance Test
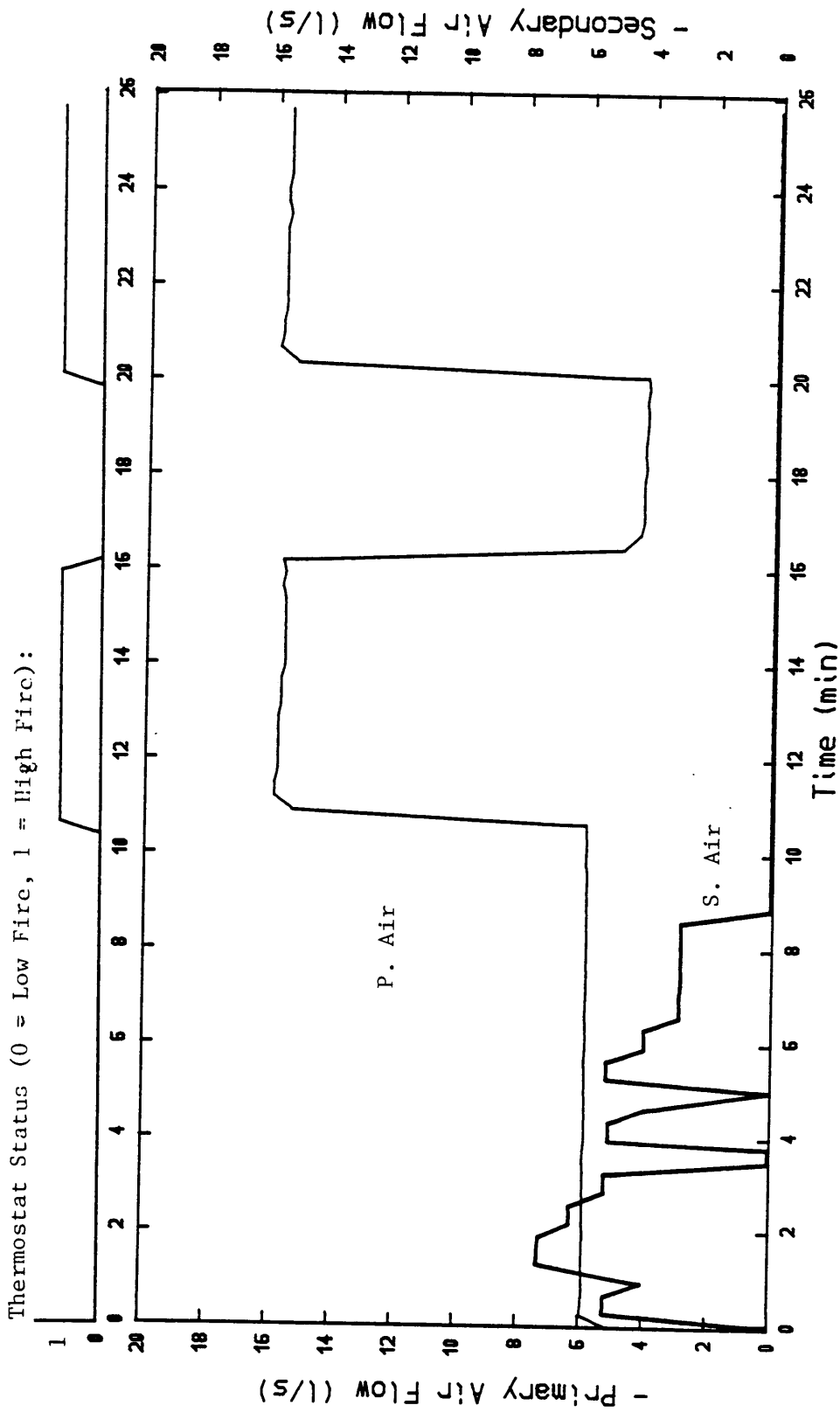Using Corn Fodder for Fuel (Test I)

256



Figure 110   Primary and Secondary Air Flows During Performance Test Using Corn Fodder for Fuel (Test I)

Figure 111  Primary Combustion/Gasification Temperatures, T2 and T3, During Performance Test Using Corn Fodder for Fuel (Test I)
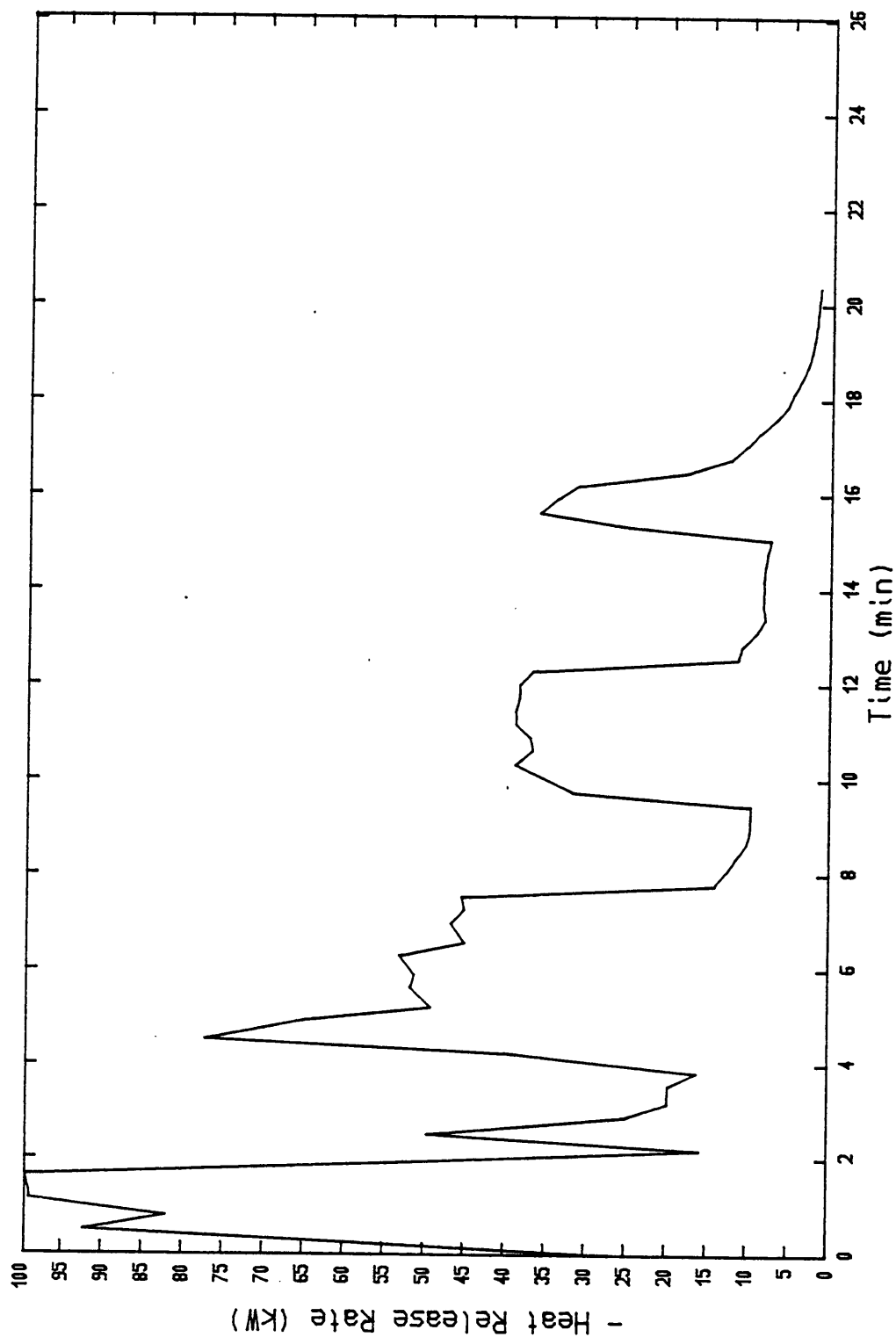
Figure 112  Heat Release Rate During Performance Test Using Corn Fodder for Fuel (Test I)

259
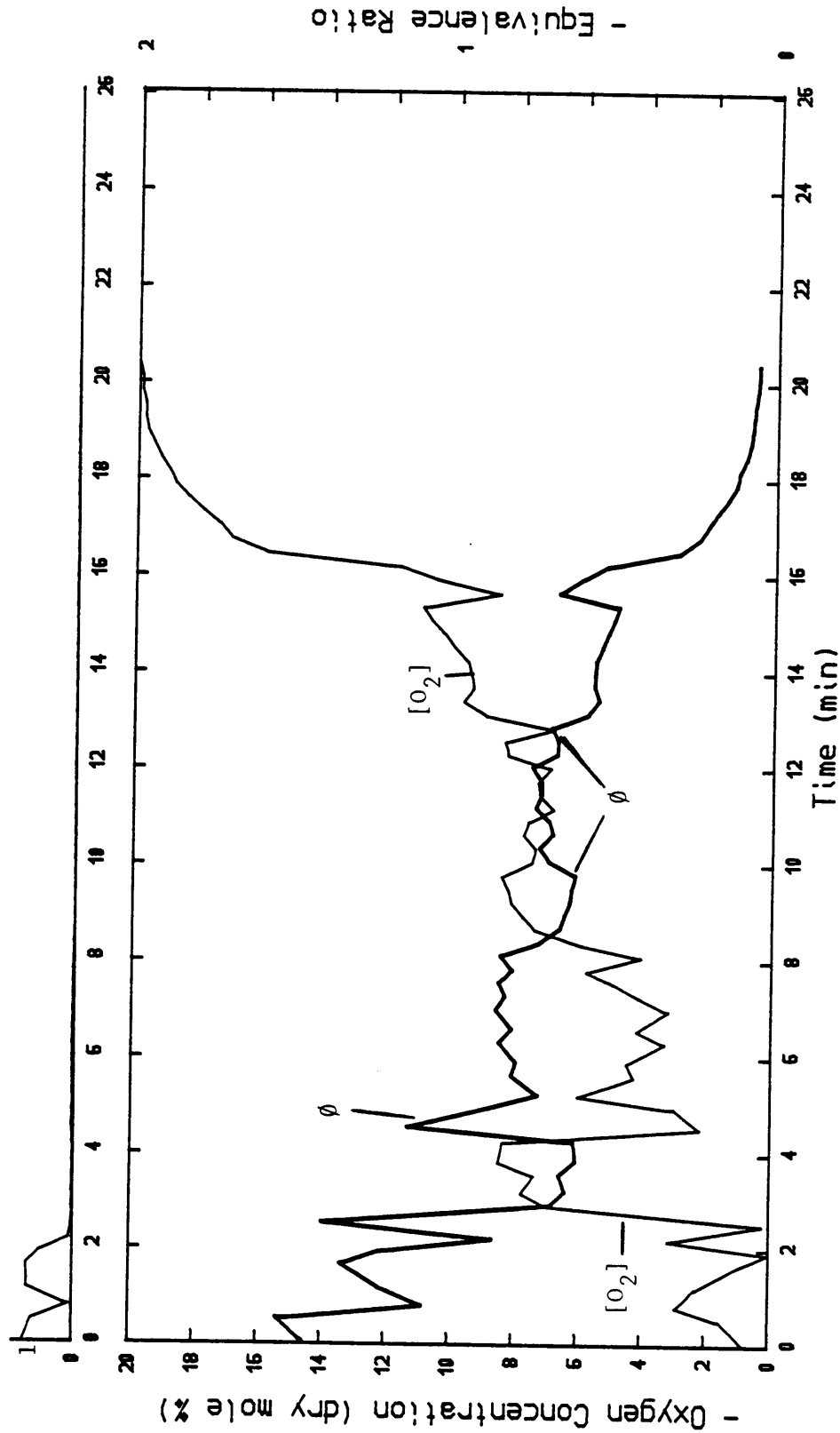


Figure 113  Oxygen Concentration and Equivalence Ratio During Performance Test Using
Corn Fodder for Fuel (Test I)
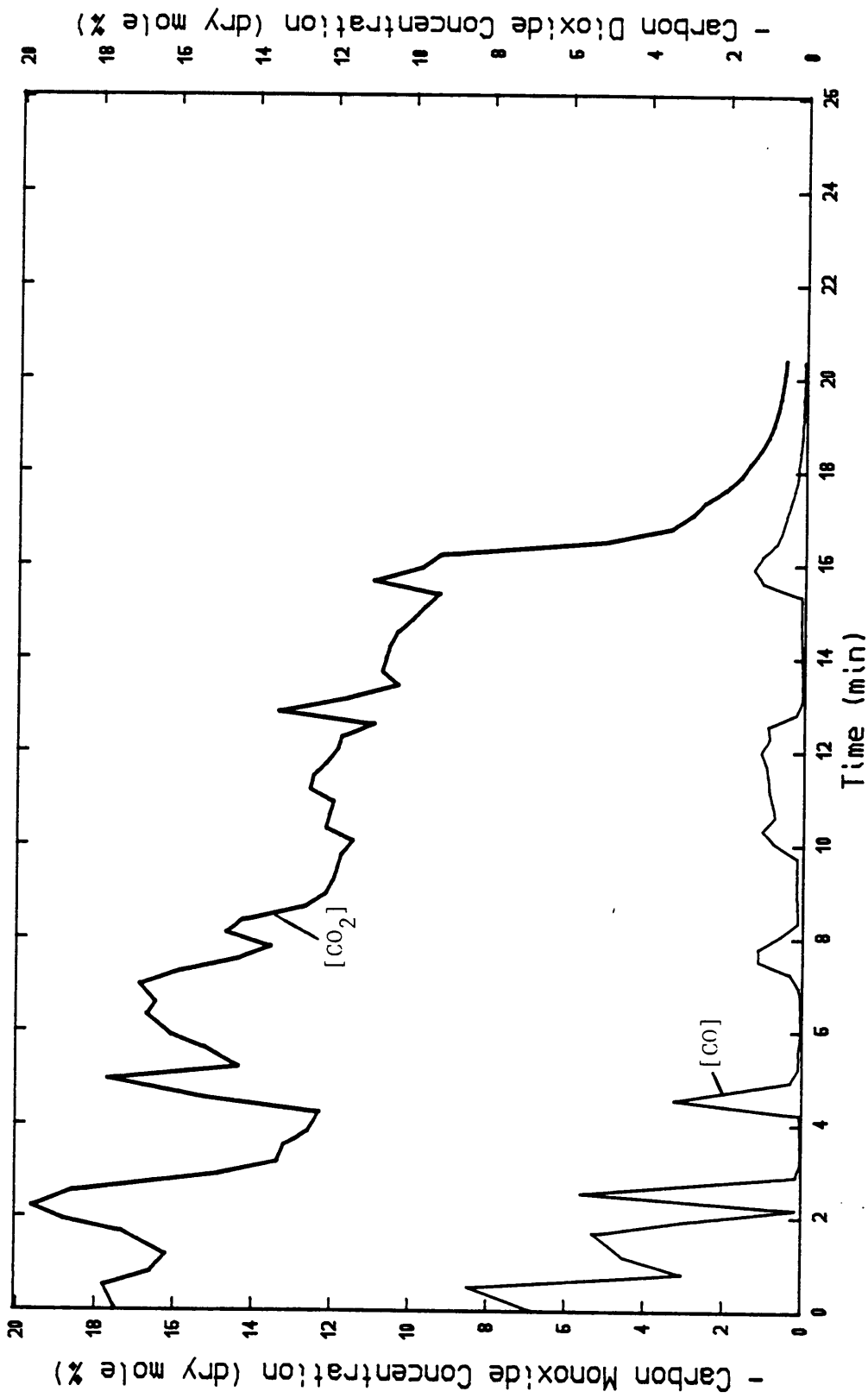
Figure 114  Carbon Monoxide and Carbon Dioxide Concentrations During Performance Test Using
Corn Fodder for Fuel (Test I)
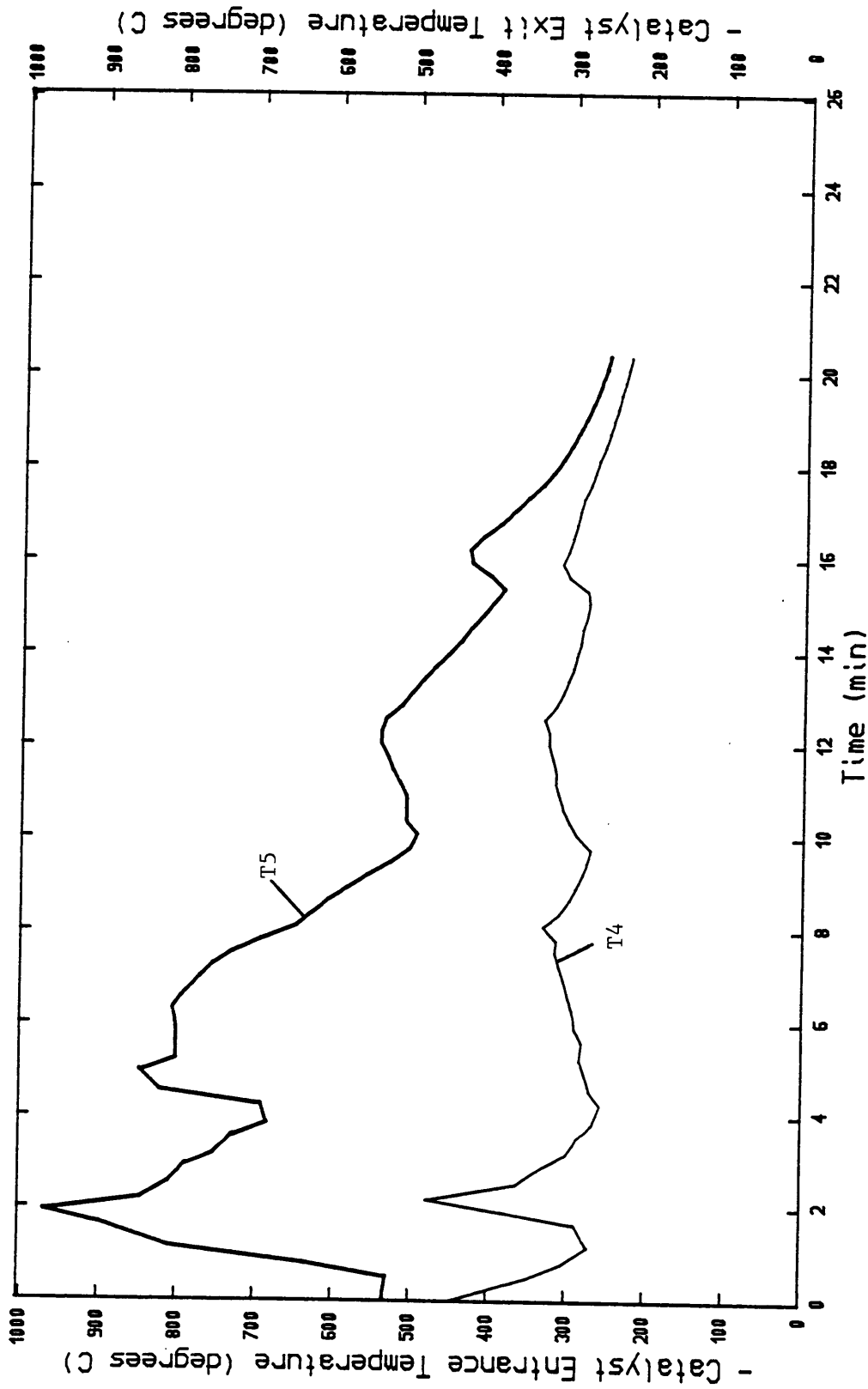
Figure 115  Catalyst Entrance and Exit Temperatures, T4 and T5, During Performance Test Using Corn Fodder for Fuel (Test I)

Prototype Catalytic Combustor/Gasifier Performance Test
Using Corn Fodder for Fuel (Test II)

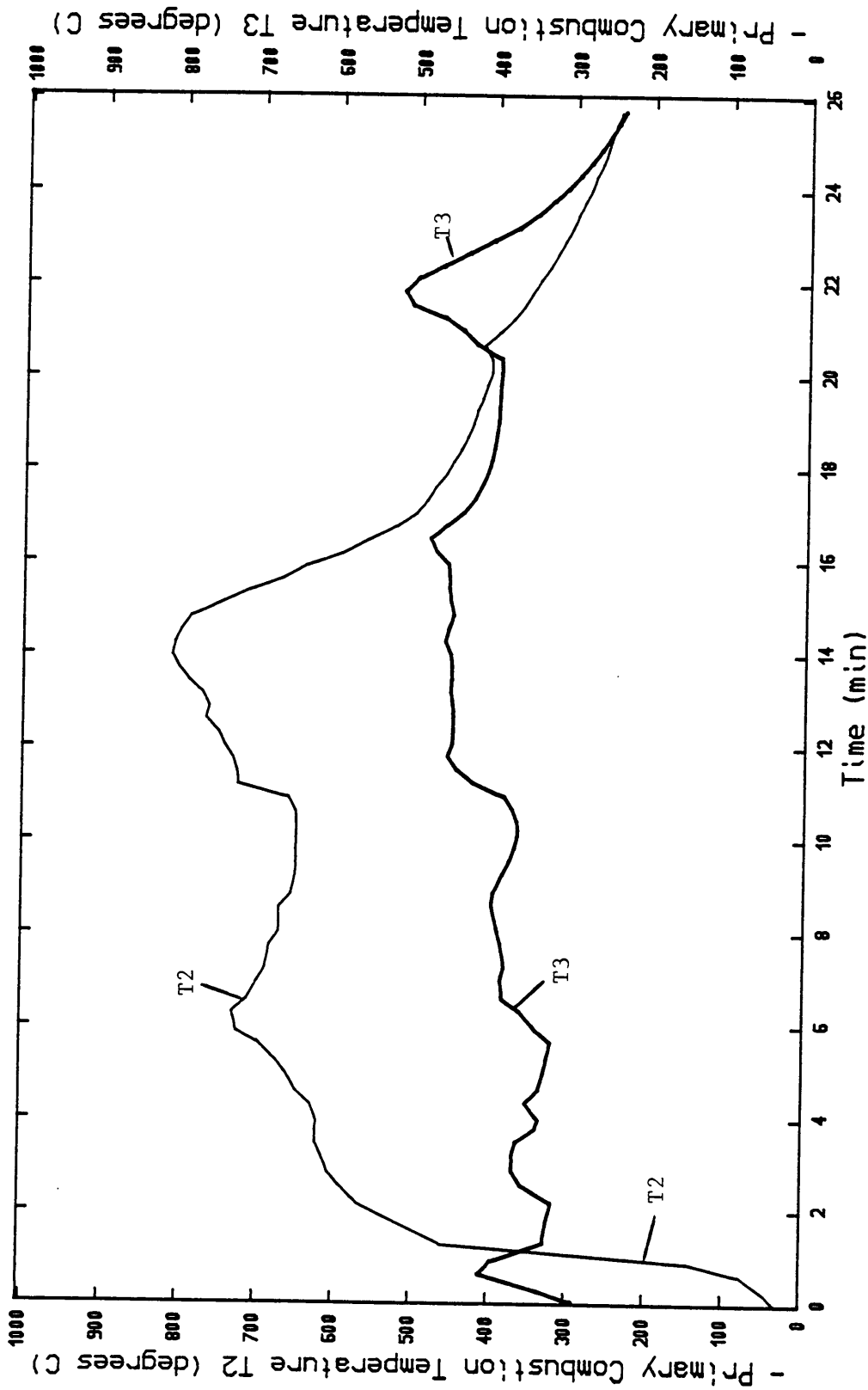Figure 116  Primary and Secondary Air Flows During Performance Test Using Corn Fodder for Fuel (Test II)

Figure 117  Primary Combustion/Gasification Temperatures, T2 and T3, During Performance Test Using Corn Fodder for Fuel (Test II)
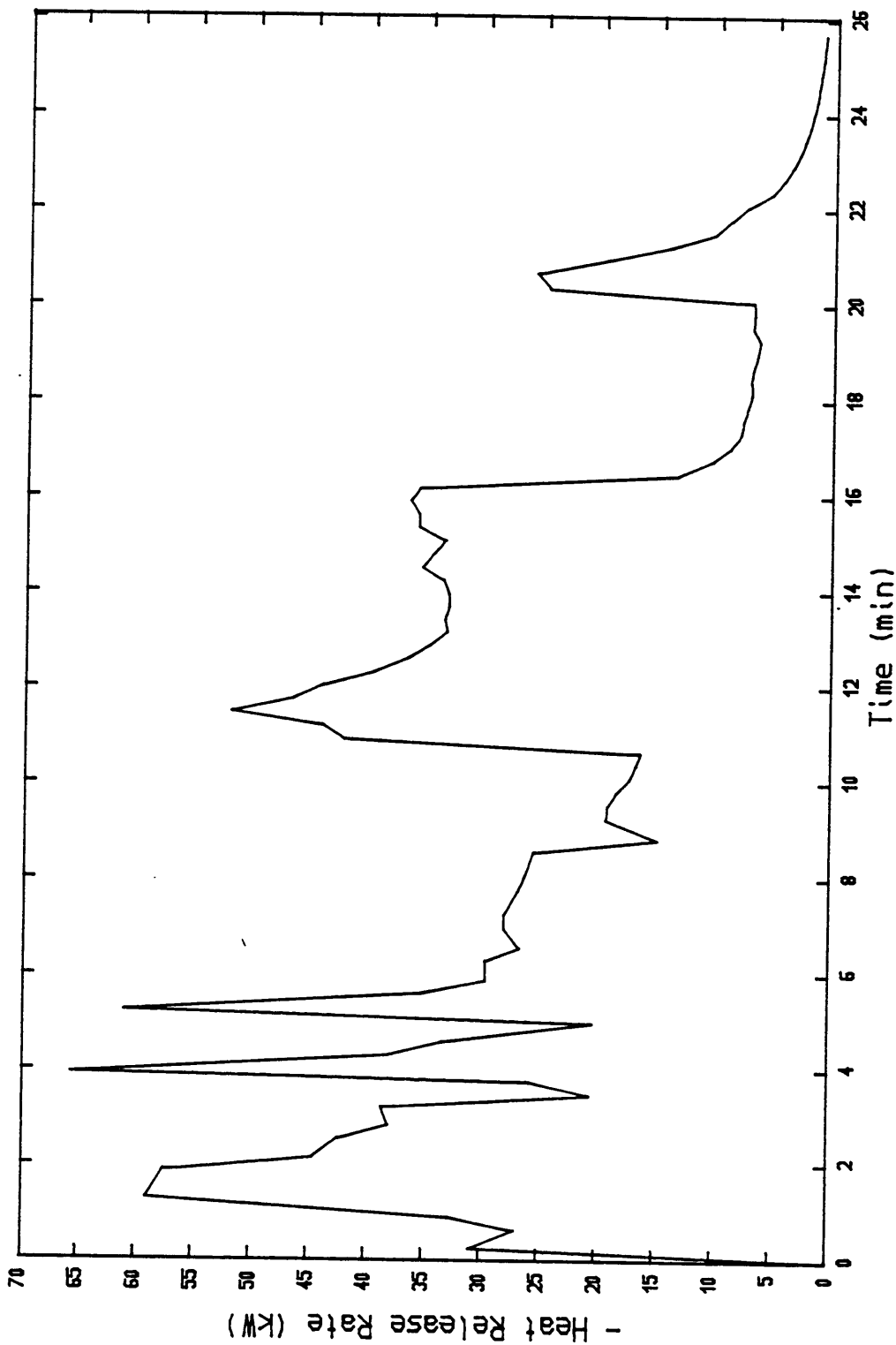
Figure 118  Heat Release Rate During Performance Test Using Corn Fodder for Fuel (Test II)
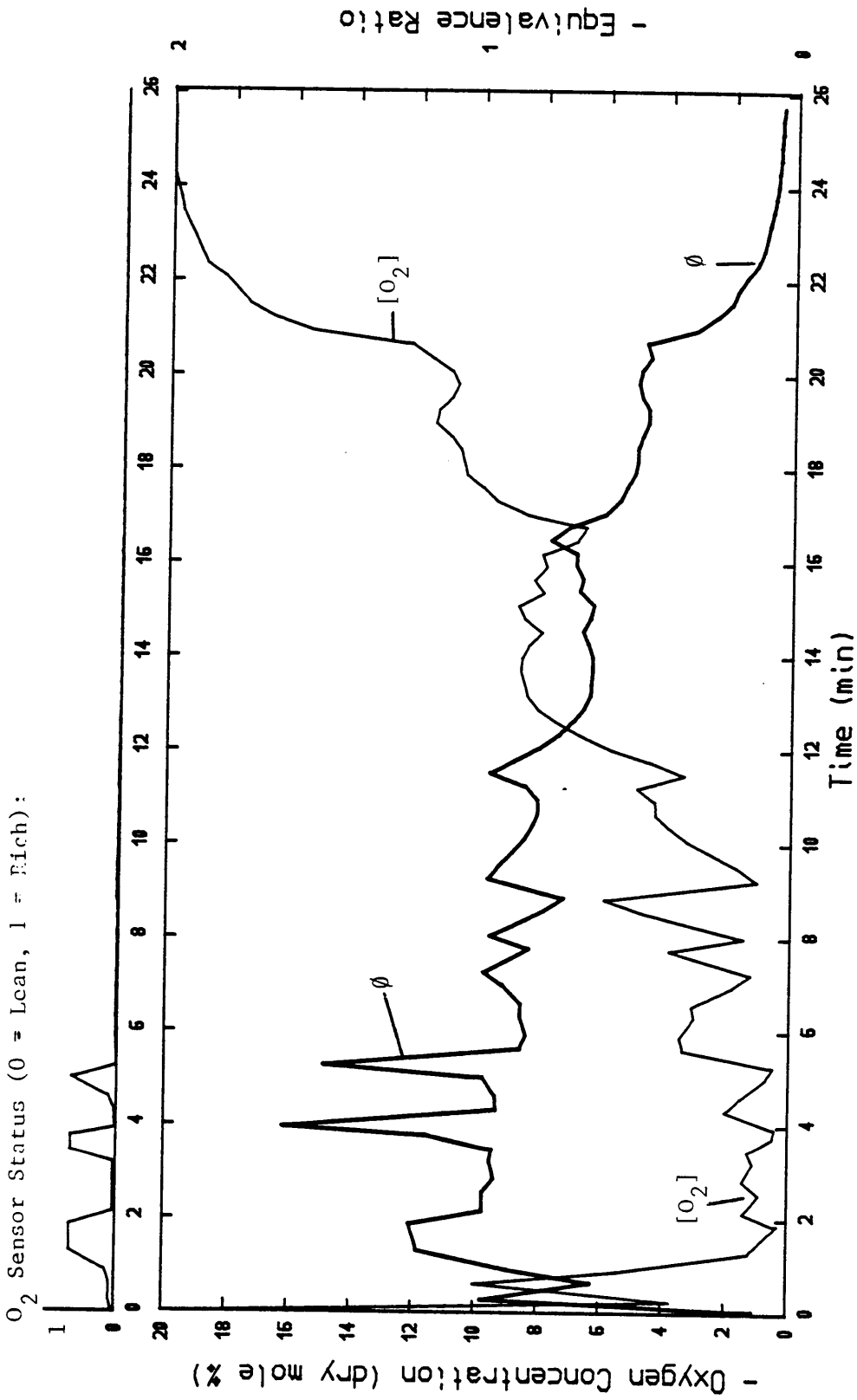
Figure 119  Oxygen Concentration and Equivalence Ratio During Performance Test Using Corn Fodder for Fuel (Test II)
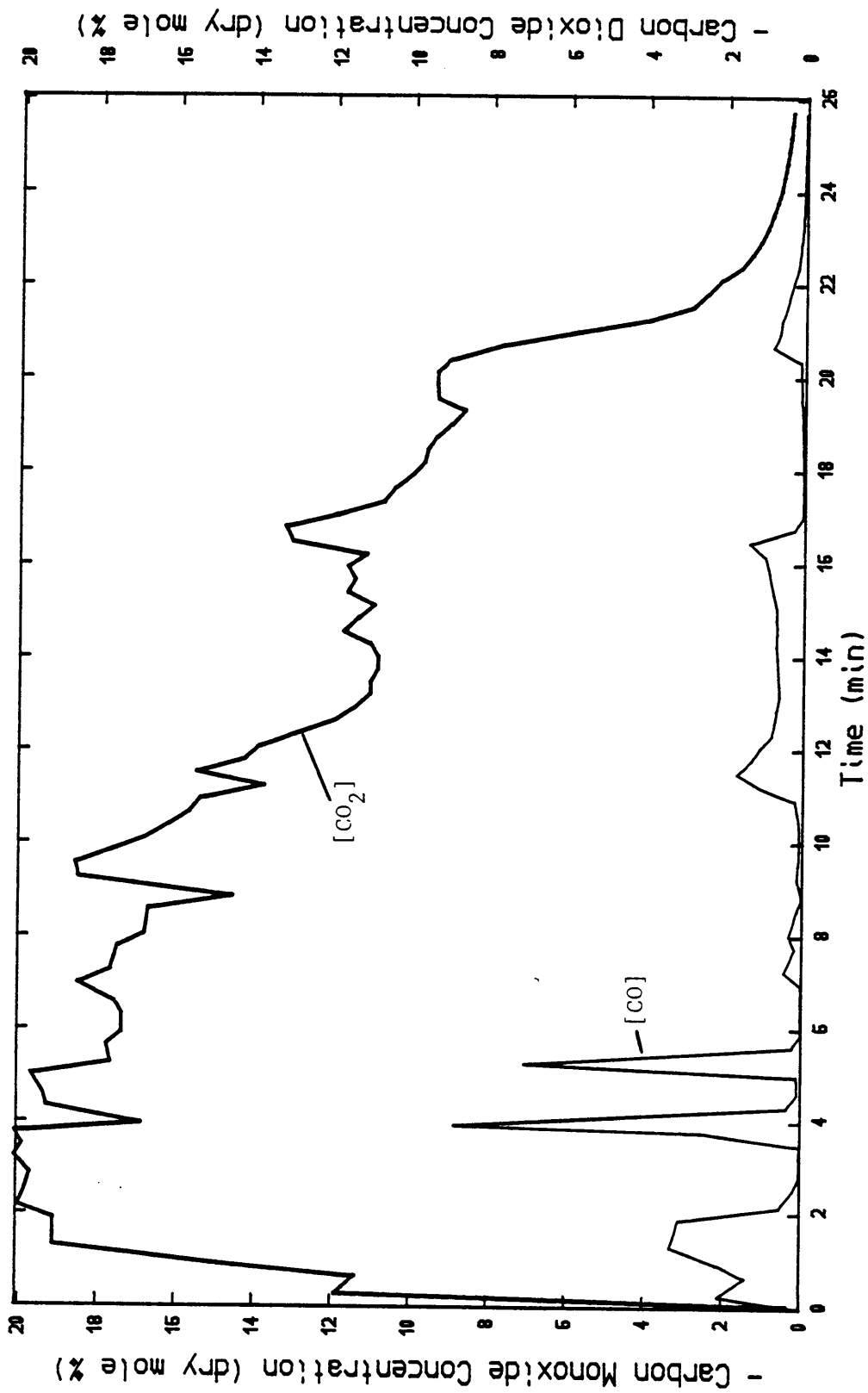
Figure 120  Carbon Monoxide and Carbon Dioxide Concentrations During Performance Test Using Corn Fodder for Fuel (Test II)
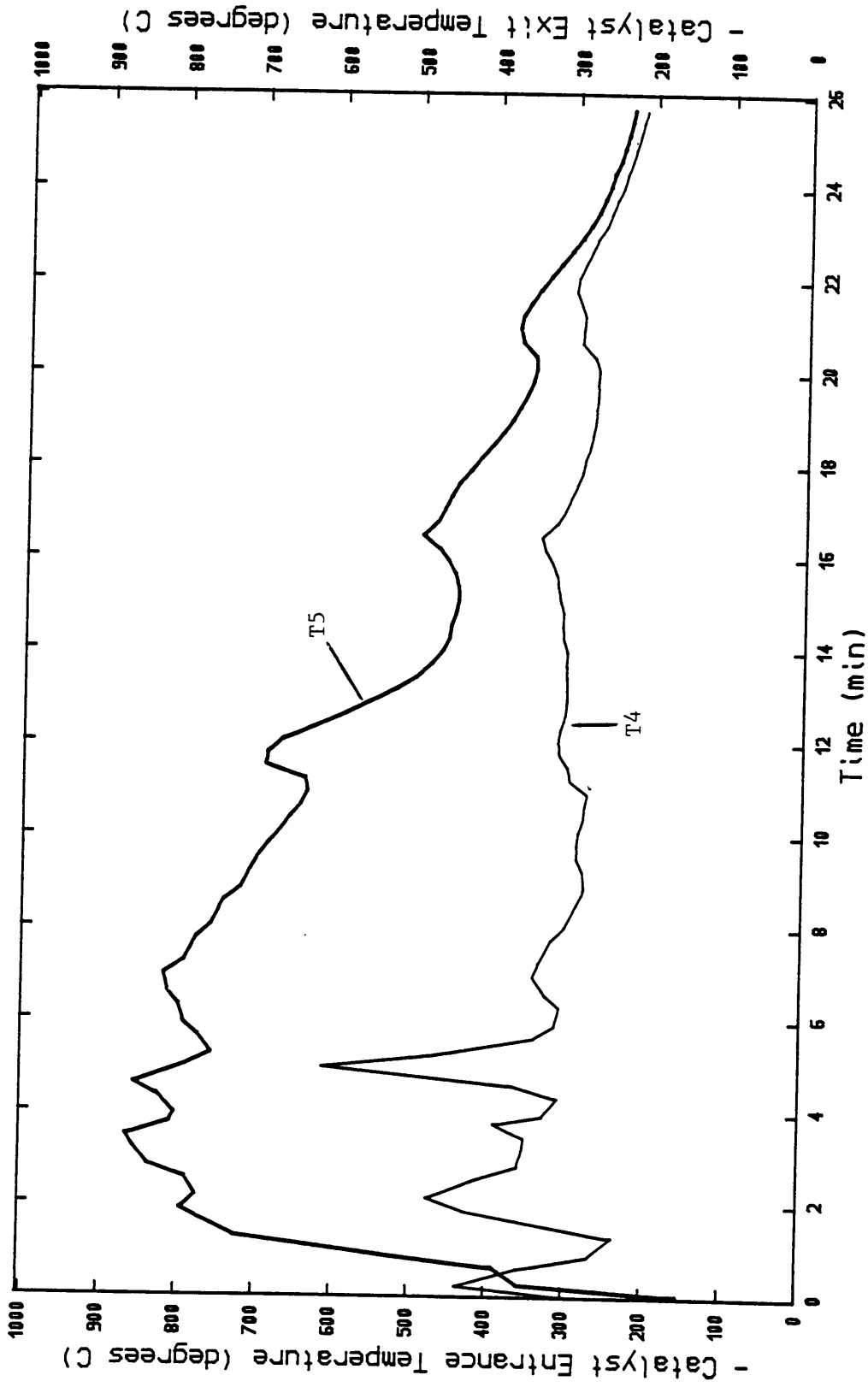
Figure 121  Catalyst Entrance and Exit Temperatures, T4 and T5, During Performance Test Using Corn Fodder for Fuel (Test II)

# STUDY OF BIOMASS COMBUSTION CHARACTERISTICS FOR THE DEVELOPMENT OF A CATALYTIC COMBUSTOR GASIFIER

by

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(ABSTRACT)

The research reported here explored a "new" approach to biomass energy conversion for small-scale process heat applications. The conversion process uses close-coupled catalytic combustion to burn combustibles in effluent generated by primary combustion or gasification of biomass fuels. Computer control of primary and secondary air flow rates allow control of the devices output power while maintaining fuel-lean or stoichiometric conditions in the effluent entering the catalytic combustion zone. The intent of the secondary combustion system is to ensure "clean" exhaust (i.e., promote complete combustion).

A small-scale combustor/gasifier was built and instrumented. Characteristics of combustion were studied for three biomass fuels so that primary and secondary air flow control strategies could be devised. A bang-bang type controller was devised for primary air flow control. Secondary air was controlled based on feedback signals from an inexpensive automobile exhaust gas oxygen sensor. The control strategies and catalytic combustion were implemented on prototype combustor/gasifier and the device was tested with good results.

Power turn down ratios of 4 to 1 and 3 to 1 were achieved. The zirconia-type automobile exhaust gas oxygen sensors adapted well to the combustion environment of biomass fuels at least for short periods (long term durability tests were not conducted). The secondary air control

system was able to maintain fuel-lean flows for the most part and, the secondary combustion system provided reductions of approximately three-fourths in carbon monoxide emissions.