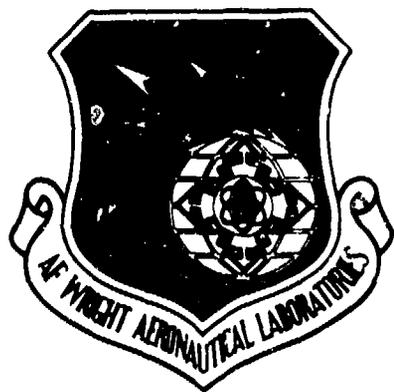


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AFWAL-TR-82-2120



**AUTOMATIC COMBUSTOR
CONTROLLER DEVELOPMENT AND
LIQUID-FUEL COMBUSTOR
DESIGN PROGRAM**

MECHANICAL TECHNOLOGY INCORPORATED
968 Albany-Shaker Road
Latham, New York 12110

January 1983

Final Report for Period FEBRUARY 1981 - SEPTEMBER 1982

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This technical report has been reviewed and is approved for publication.



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This technical report, prepared for the Aerospace Power Division, Aero Propulsion Laboratory, Wright-Patterson AFB, states design and test results of a combustor controller integrated with an existing 1kW free-piston Stirling engine. This report document also states the design of a liquid-fuel external heat system capable of operating with a 3kW free-piston Stirling engine.		

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The combustor controller design and development is directed at a controlled system that maintains the natural gas fired Stirling engine heater head temperature. In response to either load and/or stroke change of the Stirling engine, the basic controlled strategy, control system functions and system hardware is documented. The results and conclusion of steady state and transient testing of the controller with a free-piston Stirling engine are presented.

A liquid-fire external heat system includes evaluation of a monolithic free-piston Stirling engine GPU-3 heater head diesel combustor nozzle and design of a liquid-fueled external heat system that can integrate with a 3kW free-piston Stirling engine.

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PREFACE

This document contains the results of work performed for Wright-Patterson Air Force Base under Contract No. F33615-81-C-2007. The work effort was performed over two separate time periods. From February 1 through November 30, 1981, an automatic combustor controller was designed, fabricated, developed, and tested. The design of a potential multiliquid-fuel combustor that would integrate with a free-piston Stirling engine (FPSE) was performed from April 1 through September 30, 1982.

The major authors of this report, and their contributions are presented below:

Joseph Killough - definition/design of the automatic combustor controller;

Robert Lacy - fabrication, software, and development of the automatic combustor controller;

Thomas Moynihan - integration/test of the automatic combustor controller; baseline testing of an existing FPSE; and,

Roger Farrell - design of the multiliquid-fuel combustor.

As expected, the development of an automatic combustor controller and a liquid-fuel combustor for an FPSE provided the first step towards an integrated, militarized FPSE to be used for stand-alone, tactical field power.

Development efforts of this promising energy-conversion system are continuing under separate contracts.

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I. INTRODUCTION

This is a final report of the results of an eight-month contract awarded to Mechanical Technology Incorporated (MTI) by the Wright Patterson Air Force Base (WPAFB) Aero Propulsion Lab. The objective of this program was to develop and test components to adapt a free-piston Stirling engine (FPSE) for Air Force use at unattended remote and mobile sites. Emphasis of the work performed under this contract was centered on the development of an automatic combustor control system, and the design of a liquid-fueled combustor system that could eventually lead to unattended site operation.

A. OBJECTIVE

The major objective of this Automatic Combustor Controller Development and Liquid-Fuel Combustor Design Program was the development of an automatic combustor control system (a significant step towards the integrated engine-alternator control system) that would allow for unattended operation of an FPSE at Air Force remote and mobile sites. A second objective was the analytical evaluation and design of a multifuel combustor/heater head such that one engine system could use a variety of military logistic fuels.

B. BACKGROUND

The FPSE is an attractive power-conversion system because of its potential for long life, high reliability, and multifuel capability. A 1-kW FPSE/linear alternator, designed, fabricated, and tested by MTI under a separate program sponsored by the Department of Energy (DOE), has been modified to incorporate a natural-gas-fired combustor system and a monolithic-finned (tubeless) heater head*. The power conversion system has only two moving parts, whose motion is determined by their respective mass and gas springs. There is no physical connection between the dynamic components; the displacer and power pistons are supported by hydrostatic gas bearings with noncontacting clearance seals. The natural-gas combustor system has a recuperator to recover exhaust gas thermal energy, and a turbulent-mixing combustor in which natural gas and air are mixed

*Technology Demonstrator Engine (TDE)

and burned. The Inconel 617 heater head has both internal and external fins to augment transfer of thermal energy from the hot combustor gases to the internal helium working fluid. A layout of the TDE power conversion system is presented in Figure 1-1. This engine system has been designed to provide 1.4-kW (engine P-V power) and 1.0-kW electric output at 40-Bar charge pressure. As discussed in detail in References 1 and 2, the system has previously achieved:

- demonstration of the 1-kWe steady-state design power output;
- validation of analytical code predictions with test results; and,
- accumulation of 300 hours of operational test data.

The TDE is presently being used to demonstrate free-piston Stirling technology and to develop the FPSE so that its potential for a wide variety of applications can be realized. Demonstration of an automatic combustor control system, and a previous evaluation and design of a multifuel combustor heat system, enhances an earlier demonstration of a military FPSE. The automatic control system will be integrated with the TDE, and the liquid-fuel combustor design will be integrated with the FPSE* presently being developed by MTI.

C. SCOPE

The program was divided into five discrete elements to meet the overall program objectives. Detailed technical discussions of each major task are presented in Sections II through VI, respectively, of this report.

- Task 1 - Combustor Controller Characterization and Development - The purpose of this task is to specify, design, fabricate, and component-test a combustor controller that will maintain FPSE heater head temperatures with respect to varying airflow/fuel flow and/or load changes.
- Task 2 - Evaluation of Integrated FPSE Control - The combustor controller is one major element of an integrated system control that will provide unattended FPSE operation; the other is an FPSE power

*has similar features to the TDE, but has greater power capacity (3.0 kWe)

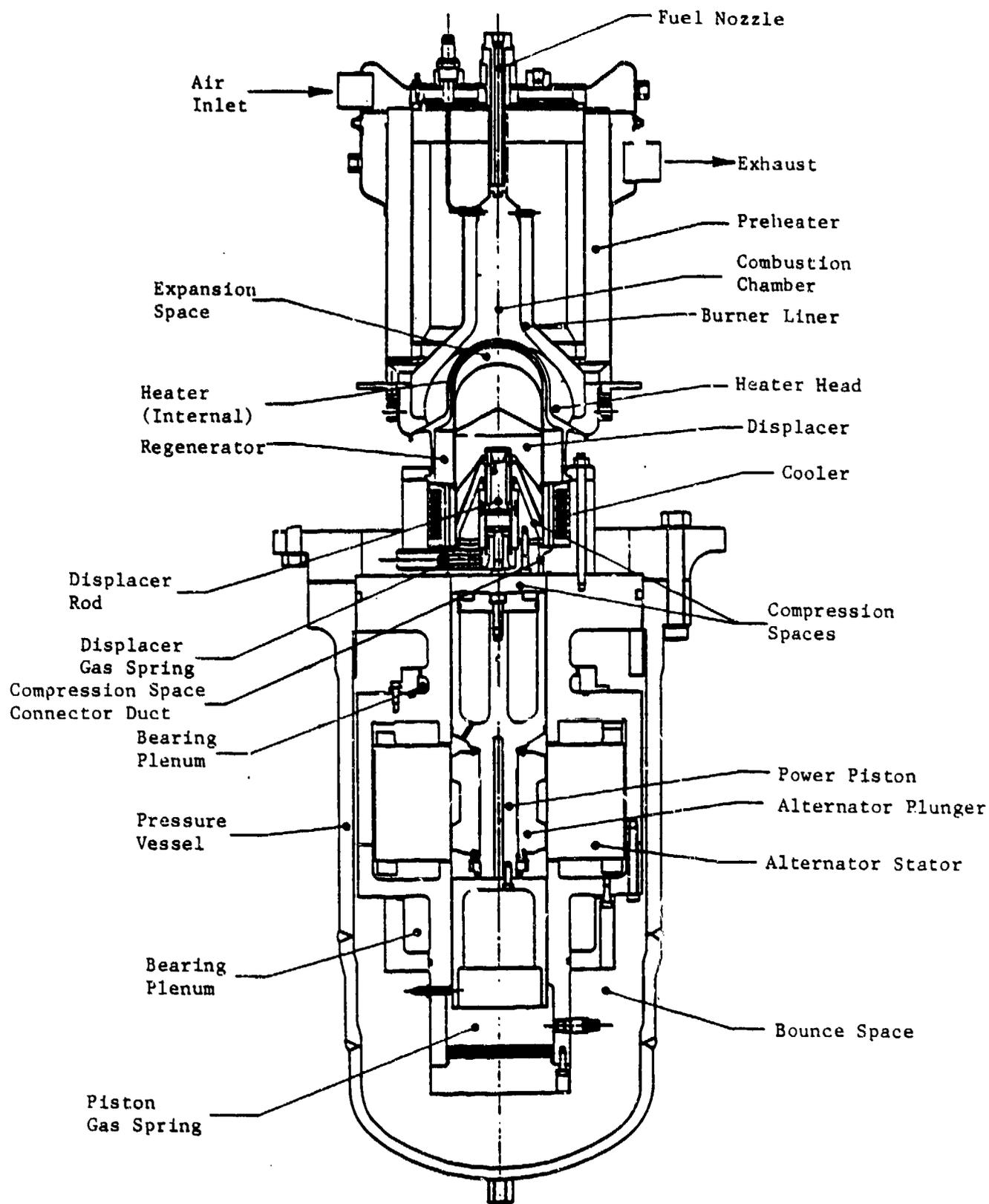


Figure 1-1 Technology Demonstrator Engine Layout

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control system that will maintain engine operation during load transient. A cursory evaluation of FPSE power control is performed.

- Task 3 - System Integration - The combustor controller developed in Task 1 is integrated and checked out as part of the FPSE control and test facility operation.
- Task 4 - Evaluation - The system is tested to evaluate combustor controller response to load changes.
- Task 5 - Liquid-Fuel Combustion Design - The potential of the FPSE will be analytically evaluated for multifuel operation. Based on the current natural-gas combustor technology, a design of a liquid-fuel combustor will be developed.

D. SUMMARY

The major directed thrust of this program, the development of an automatic combustor control system for an existing laboratory FPSE, was completed with great success. The remainder of the program studied other potential problems (including the design of a liquid fuel system) while using FPSE's at Air Force unattended sites. The major conclusions are:

- development of an engine power control is necessary to provide load-following capability for unattended operation;
- engine power control can and will interface with the WPAFB combustor controller;
- a control system can be developed to provide for unattended operation;
- a monolithic heater head such as used on the TDE can burn military logistic fuels;
- emissions of the present natural-gas-fired system are very low;

- development of a liquid-fuel system is required;
- design of a liquid-fuel combustor with multifuel capability is possible; and,
- an engine/alternator system can be developed to meet the requirements of the Air Force for unattended operation.

1. Combustor Controller

The combustor controller developed in this program performed as expected by:

- automatically maintaining heater head temperature with respect to air/fuel rates and/or engine load changes;
- providing start-up interlocking with the TDE facility;
- providing close-loop control of air/fuel ratio and temperature mean max with operator set capability;
- displaying key operating parameters;
- providing automatic shutdown; and,
- providing expansion capability to interface with power control system.

The demonstration range of performance parameters includes:

- | | |
|-----------------------|---------------------------------|
| • firing rate | 3-10 kW |
| • temperature | 200-500°C (error of only +10°C) |
| • system output power | 200 watts to 1 kW |
| • air/fuel ratio | 15:1 to 35:1 |

The combustor controller hardware is shown in Figures 1-2 to 1-4, and installed in the TDE facility in Figure 1-5.

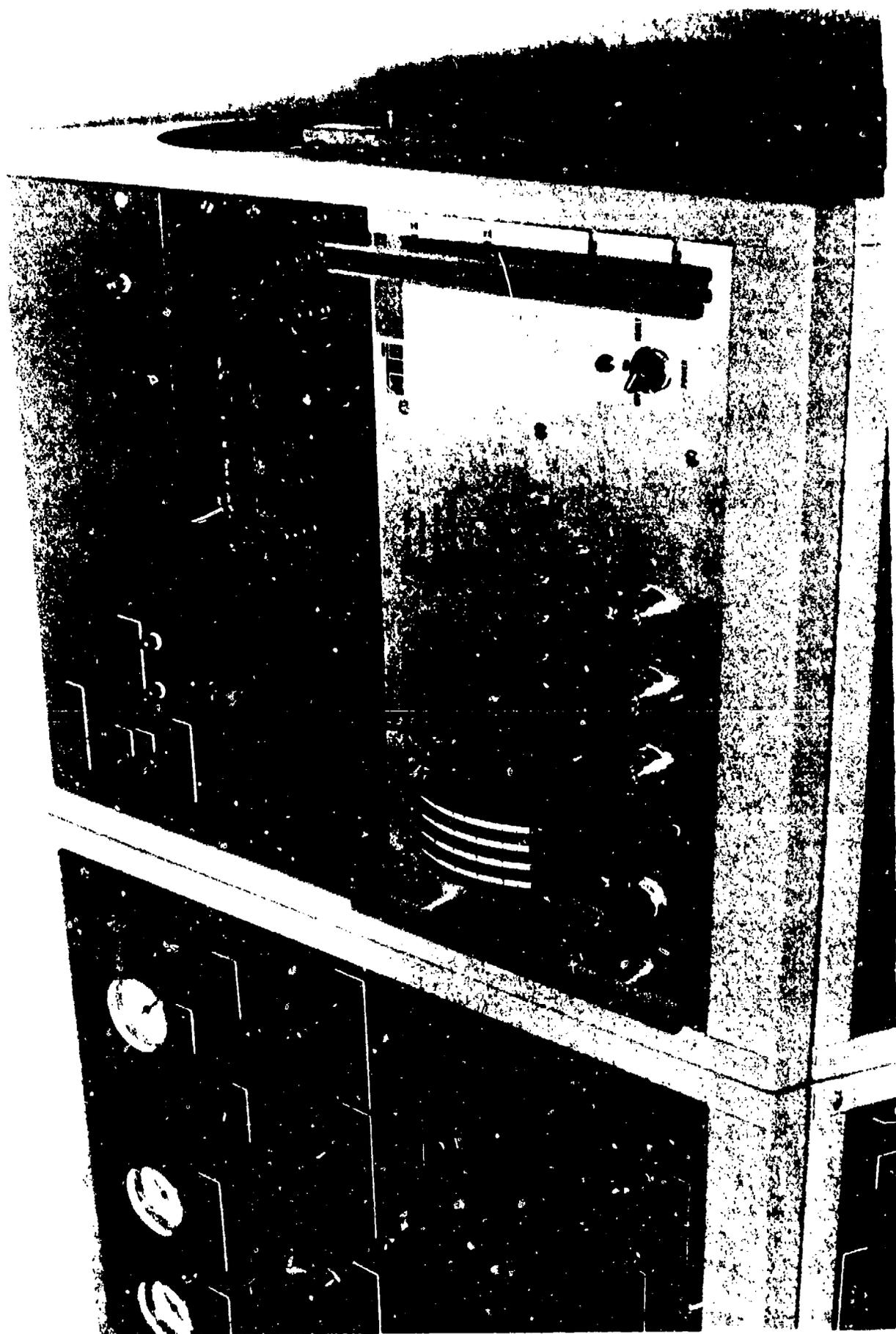


Figure 1-2 Automatic Combustor Controller

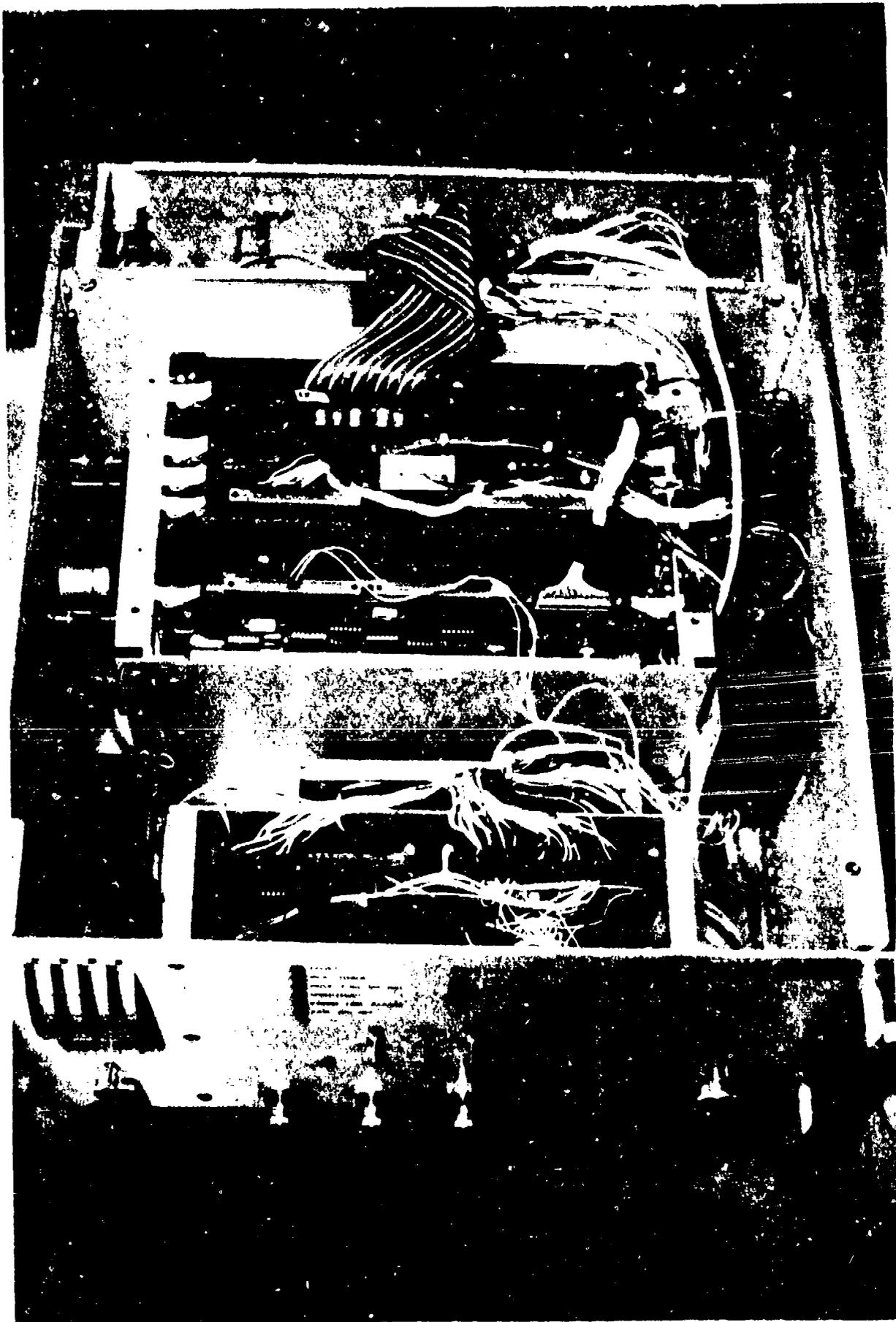


Figure 1-3 Interior of Automatic Combustor Controller

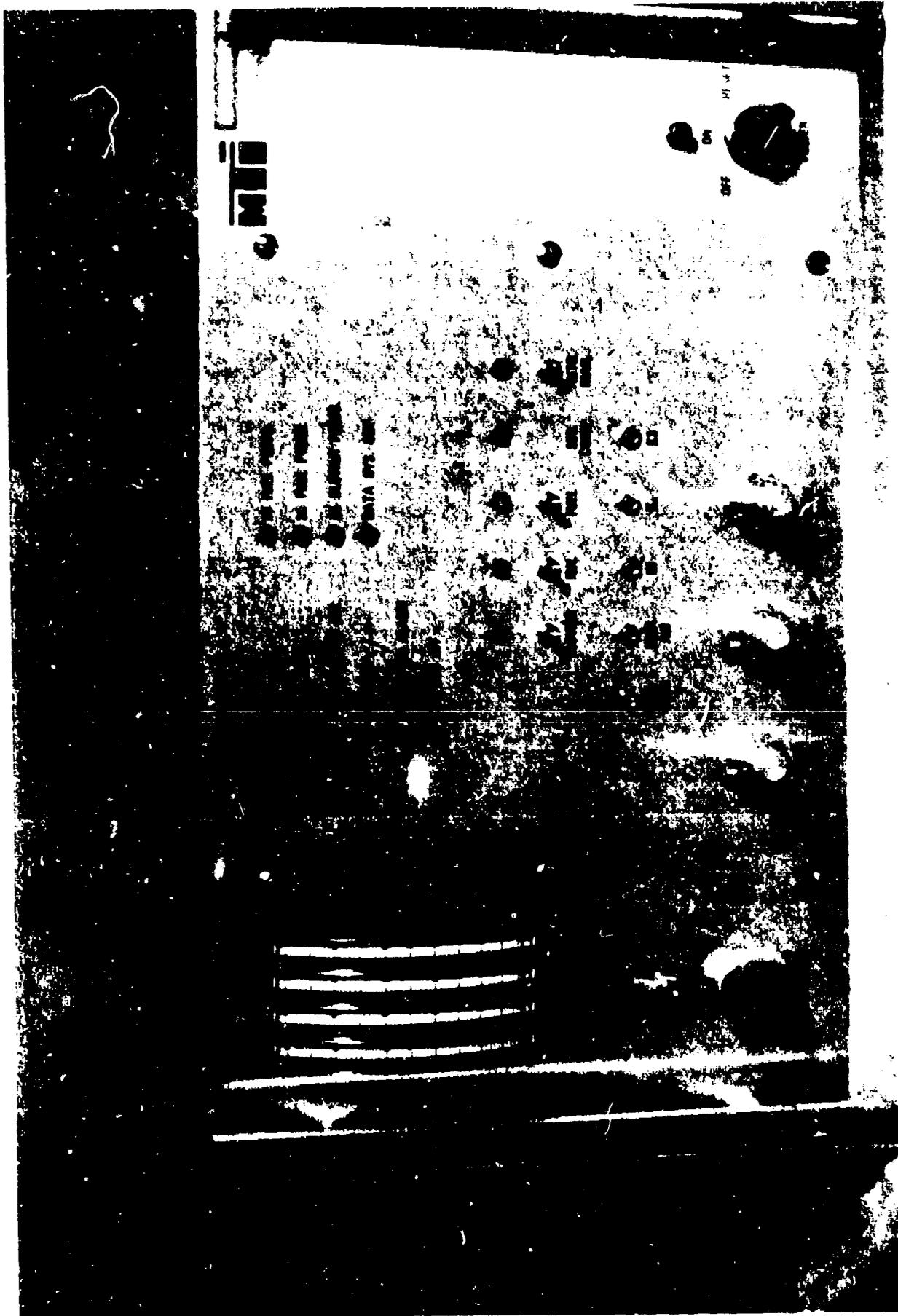


Figure 1-4 Input/Output Signals to Automatic Combustor Controller

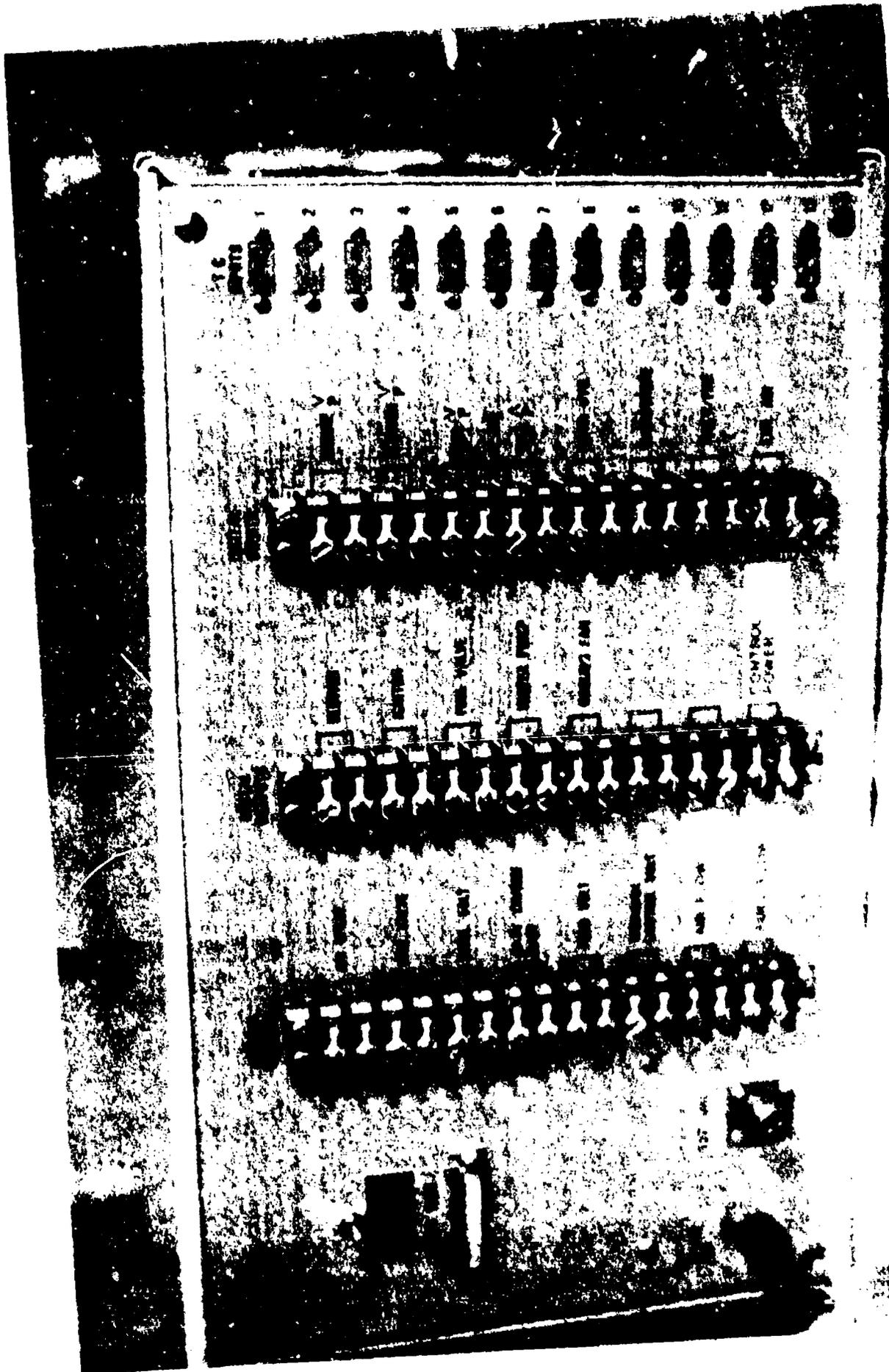


Figure 1-5 Automatic Combustor Controller Installed in
MTI TDE/FPSE Test Facility

2. Liquid-Fuel Combustor Design

The design of a liquid-fuel external heat system (shown in Figure 1-6), based on existing natural-gas combustor/external heat system technology, has the capability for multifuel use. The design of this combustor will be fabricated, tested, and developed under separate funding. This combustor design integrates with MTI's existing 3-kWe FPSE, designated as the Engineering Model (EM).

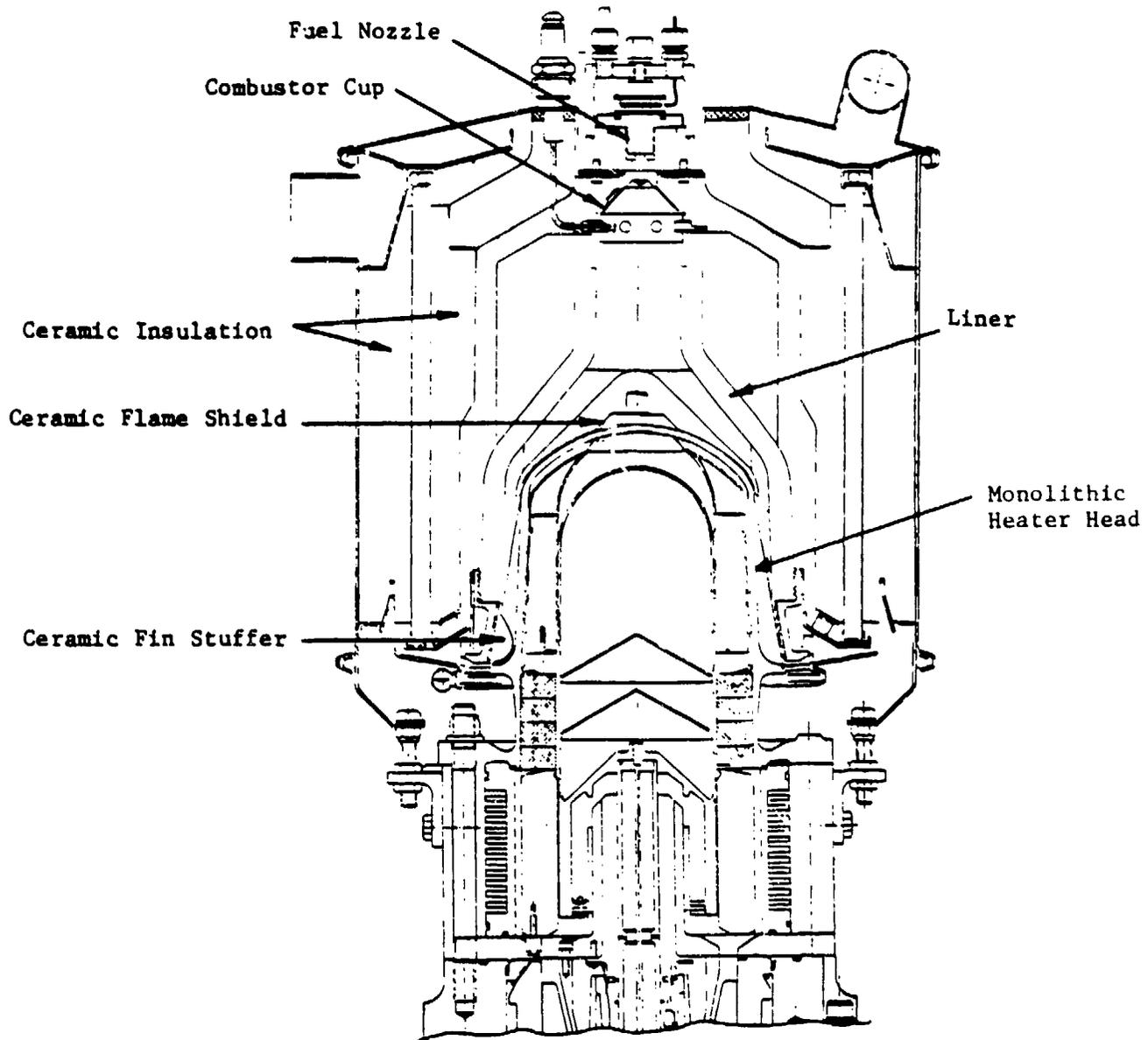


Figure 1-6 Liquid-Fueled Combustor and Fuel Nozzle

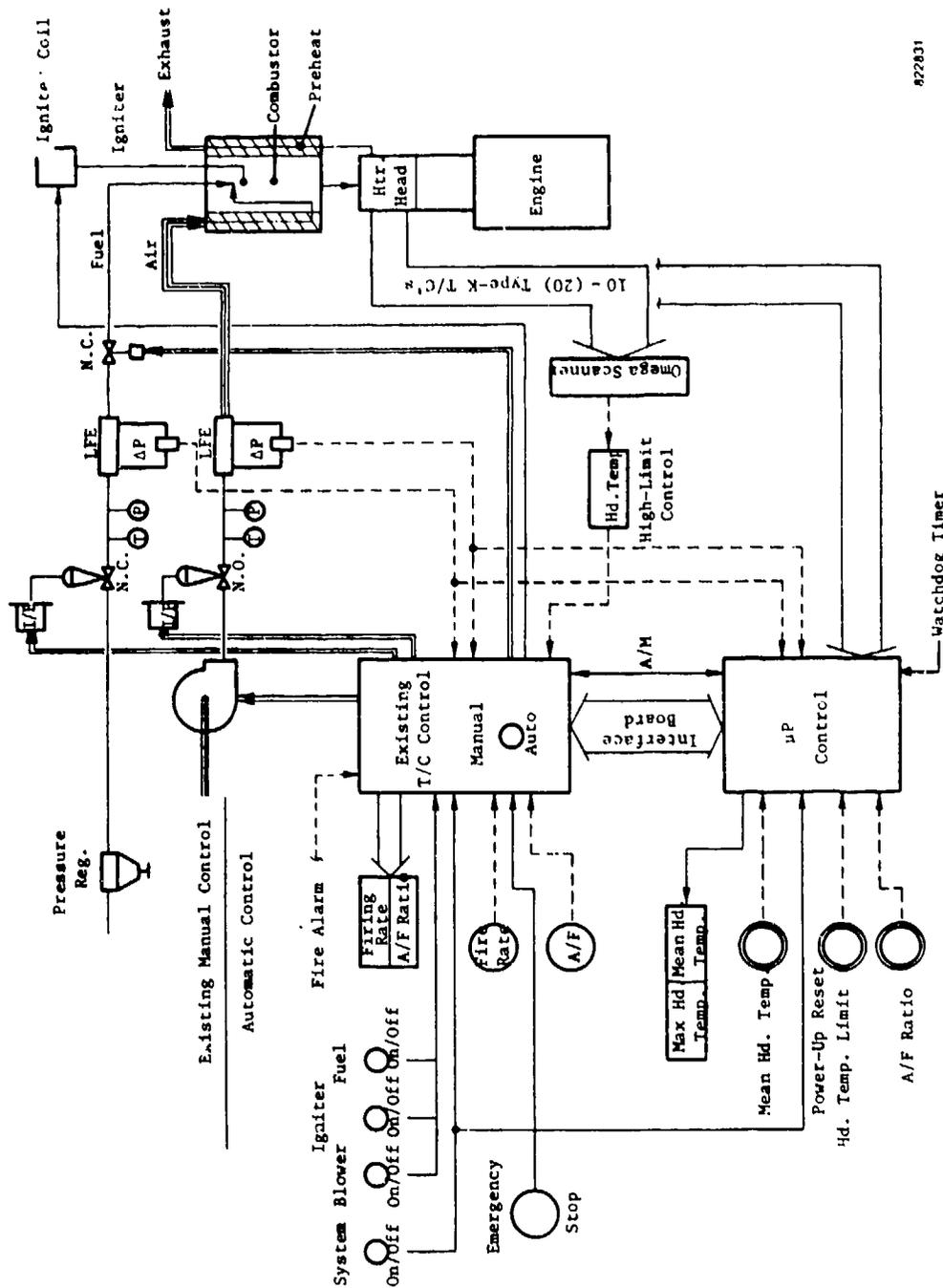
II COMBUSTOR CONTROL SYSTEM DEVELOPMENT

A. Characterization of Existing Manual Control Systems

The manual control system utilized on the 1-kW TDE incorporated two pneumatic-driven valves for gas and airflow, respectively. An operator monitors the heater head temperatures while manually adjusting air and gas (or both flows) to maintain a given temperature with respect to changing load requirements. A schematic of the present combustor control system is shown in Figure 2-1, along with the planned interface of the automatic system.

A desirable first step to moving the FPSE from the laboratory to an unattended operation site is automation of the combustor control system. This control system will utilize a microprocessor control that will provide both automatic and manual functions, with all basic control signals routed through the system, allowing for easy future expansion of the system, and closed loop control of the air/fuel ratio in the manual mode. In the automatic mode, heater head temperature will be used to control the firing rate of the combustor. Automatic shutdown will be provided in the event of relevant system problems. The basic signals and functions in the existing facility's manual control system will be contained in the new electronic combustion control system. The existing manual control will be electrically interchangeable with the new control system, allowing it to be used as backup. In order to define the requirements for the automatic system, determination of the characteristics of the present manual combustor control system was necessary. These include:

- system firing rate range;
- heater head temperature distribution;
- engine power versus heater head temperature at various strokes;
- airflow/fuel flow:
 - flow versus valve current (DC),
 - step response,
 - frequency response,
 - hysteresis;
- temperature versus air/fuel ratio; and,
- engine/combustor response to step-load change.



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Figure 2-1 FPSE Heater Head Temperature Control

The objectives of these tests are both steady-state and transient performance characterizations, with particular attention to heater head performance and transient heater/engine responses. Testing was performed with the TDE and test facility. The TDE configuration during combustor characterization testing was:

- 29.93-mm chrome-oxide rod versus hardened steel bearing;
- gas-fired finned heater head;
- TDE/alternator and piston spring assembly;
- screen regenerator; and,
- gas-fired combustor and preheater with monolithic heater head.

1. Performance Characterization

The TDE was run at the test conditions given in Table 2-1 to obtain the steady-state performance characteristics that correspond to the transient characterization points given in Table 2-2. Total cycle power and efficiency trends (shown in Figures 2-2 and 2-3) behaved as expected. At low strokes, the load stabilization control did not have sufficient gain to maintain stable operation, limiting low stroke operation. At high strokes, heater head characteristics limited the heat input, limiting high-stroke operation.

The dynamic response of the displacer (shown in Figures 2-4 and 2-5) indicates normal engine operation. The firing rate and heat input to the head are shown in Figures 2-6 and 2-7. The heater temperature distribution (Figure 2-8) shows the heater wall temperature dropping along the length of the head. This drop, an effect of the external fin characteristics, results in less heater head capability than if the temperature were uniform. These steady-state performance tests were necessary to define, set, and check steady-state control parameters.

2. Transient Characteristics

The transient test matrix given in Table 2-2 was run to evaluate engine characteristics and identify response parameters for the combustor/heater system controller. The measured responses indicate that the system time constant is ~4-5 minutes (significantly longer than the design response of the controller, which updates readings once per second). Transient response of the TDE system is presented in Figures 2-9 through 2-20. The transient system response did not

TABLE 2-1

PERFORMANCE MAP TEST MATRIX

Piston Stroke	Heater Temperature		
	(T = °C)		
	400	500	550
1.4	1*	6*	11*
1.6	2	7*	12*
1.8	3	8	13*
2.0	4	9	14
2.2	5	10	15

*Engine would not operate at given conditions.

TABLE 2-2

SUMMARY OF TRANSIENT TEST POINTS

Test Point	Initial Conditions		Control Transient	
	Heater Temperature	Piston Stroke	Firing Rate (kW)	Piston Stroke
1*	-	-	-	-
2	400	2.2	+1.0	Const.
3	500	2.2	+1.0	Const.
4	500	2.2	-1.0	Const.
5	400	2.2	- .75	Const.
6*	-	-	-	-
7*	-	-	-	-
8	372	2.2	Const.	-.2
9	425	2.0	Const.	+.2
10*	-	-	-	-
11	500	2.2	Const.	-.2
12	500	2.0	Const.	+.2

*Engine would not operate due to low temperature.

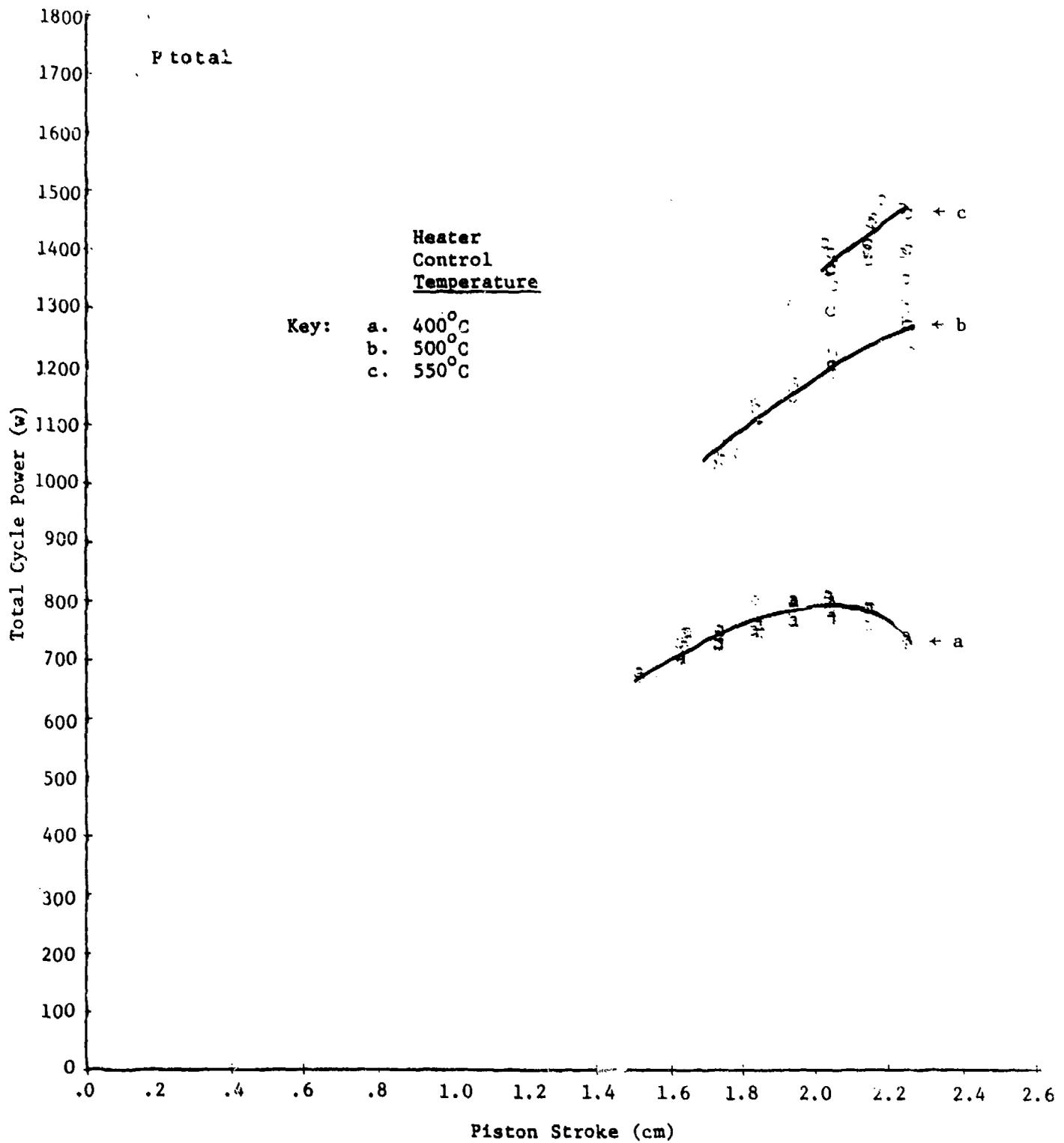


Figure 2-2 Total Cycle Power Versus Piston Stroke and Heater Control Temperature

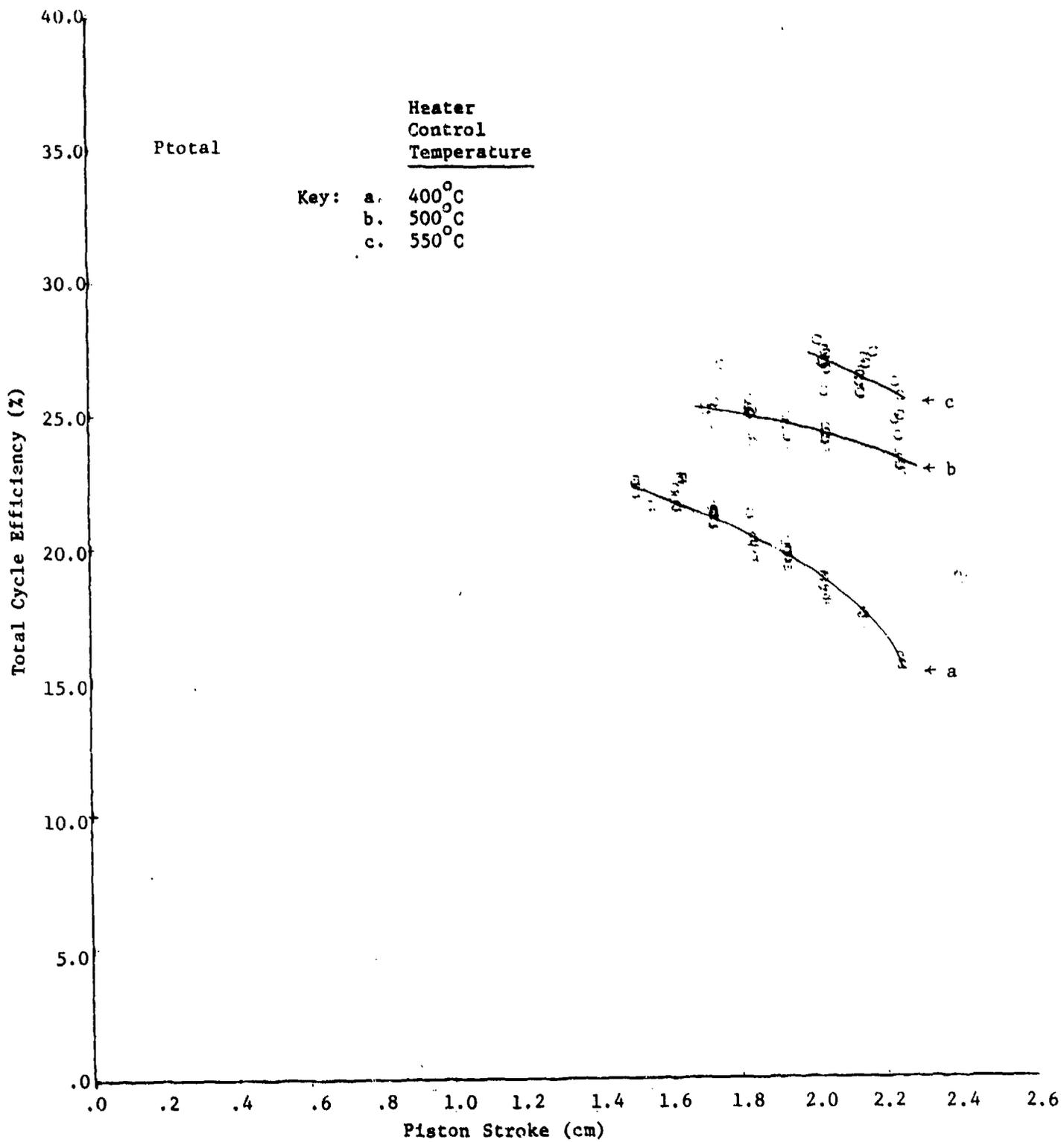


Figure 2-3 Total Cycle Efficiency Versus Piston Stroke and Heater Control Temperature

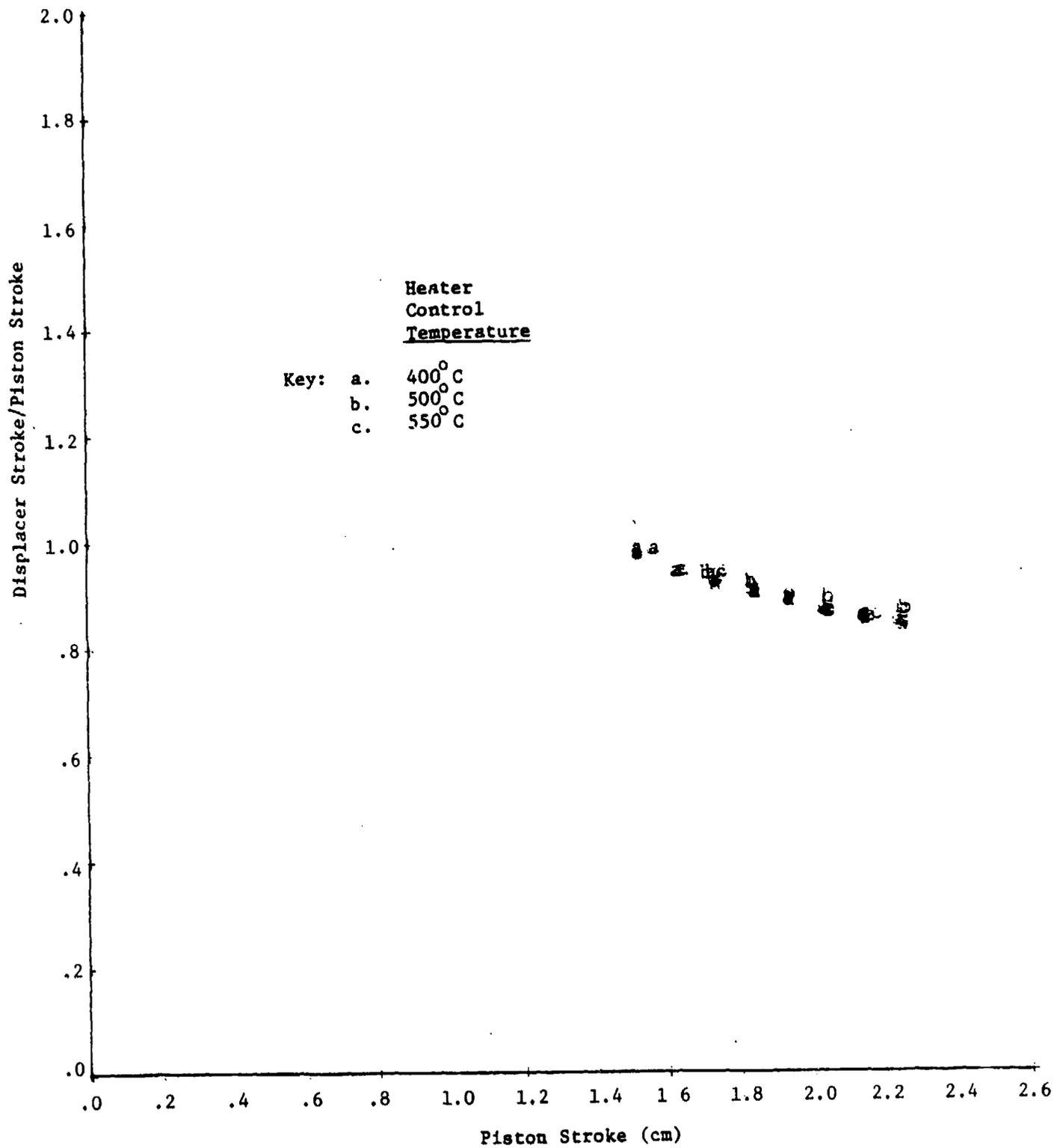


Figure 2-4 Displacer Stroke Ratio Versus Piston Stroke and Heater Control Temperature

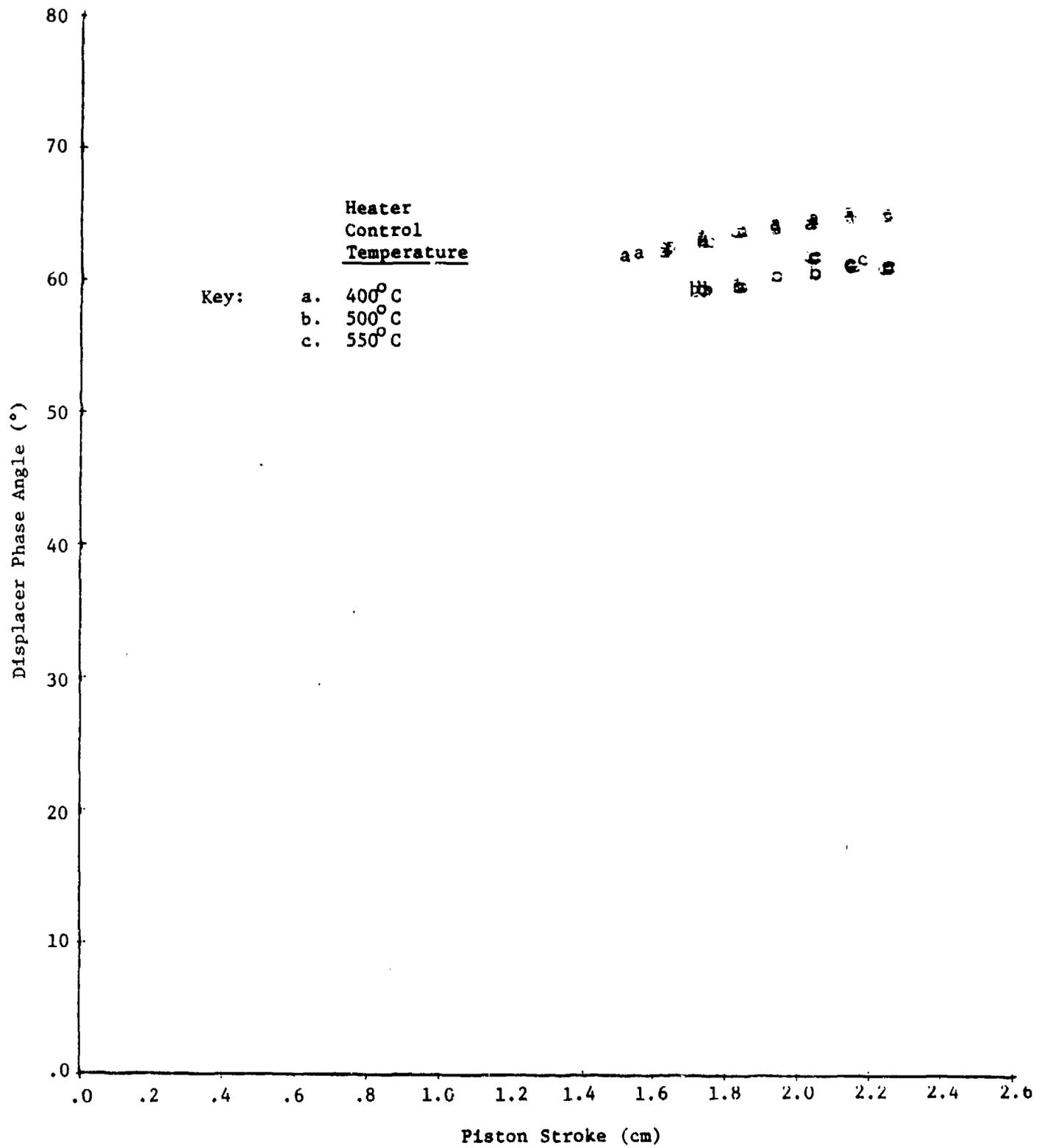


Figure 2-5 Displacer Phase Angle Versus Piston Stroke and Heater Control Temperature

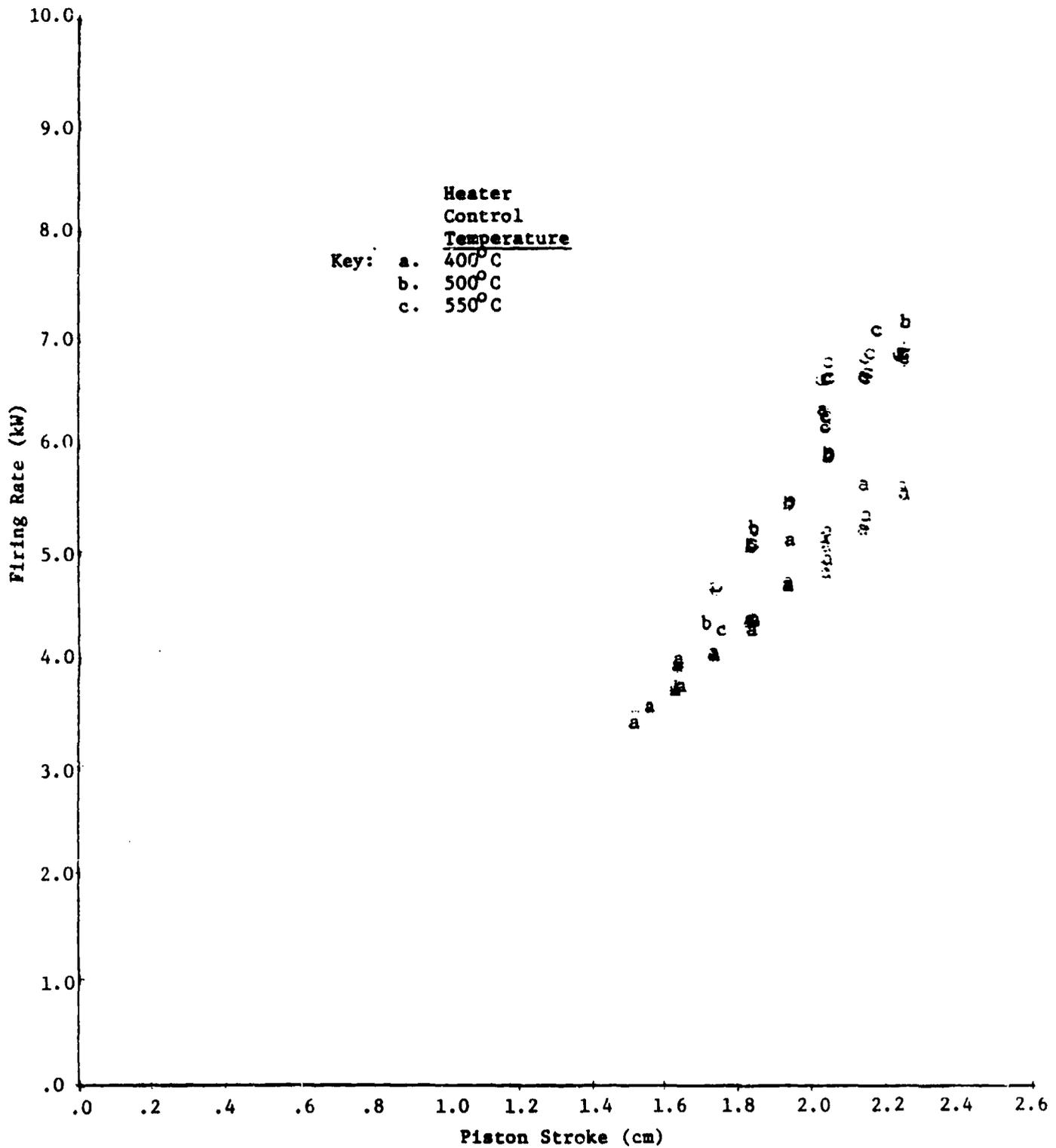


Figure 2-6 Firing Rate Versus Piston Stroke and Heater Control Temperature

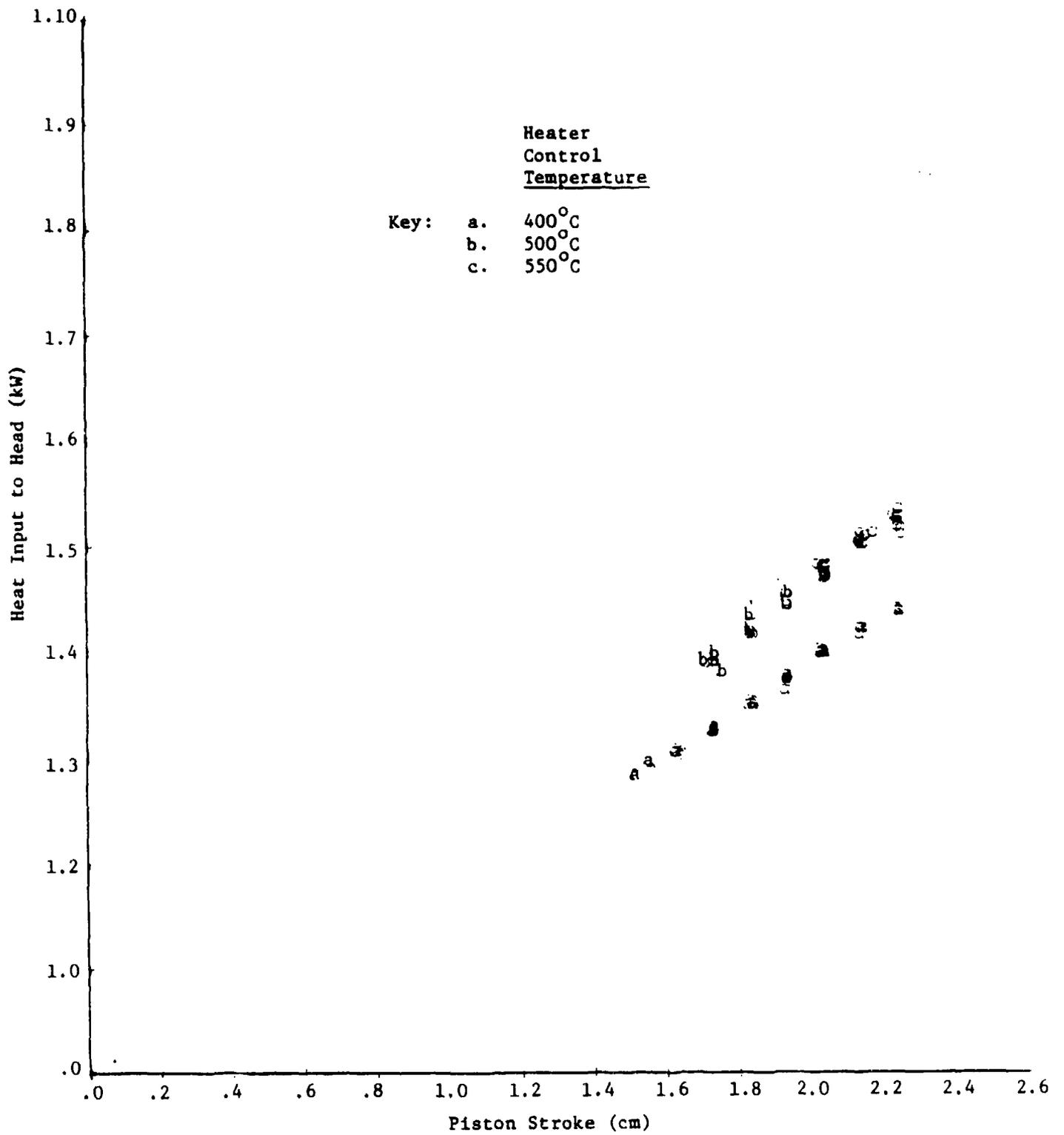


Figure 2-7 Heat Input to Engine Versus Piston Stroke and Heater Control Temperature

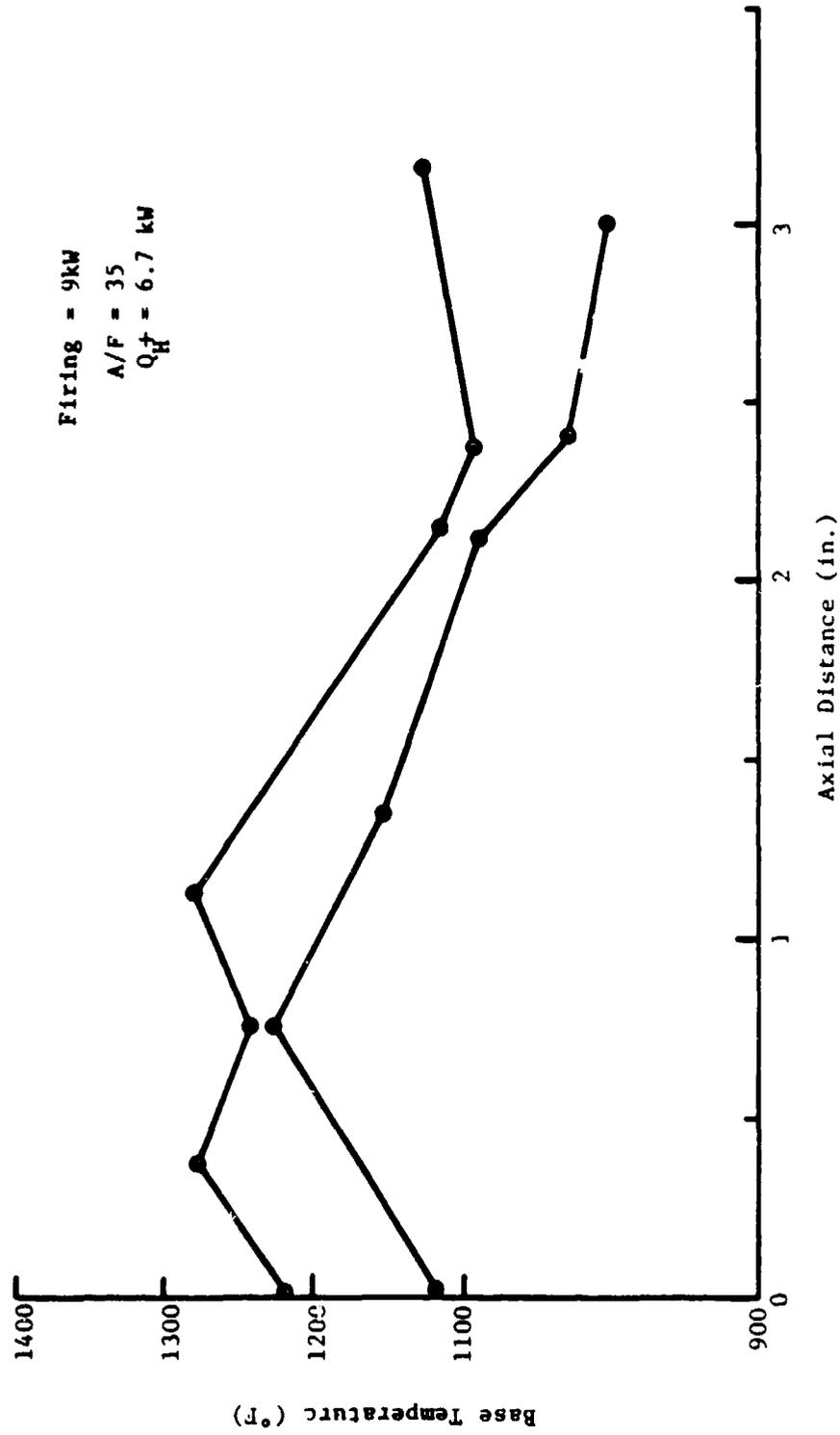


Figure 2-8 Heater Head Base Temperature Profile

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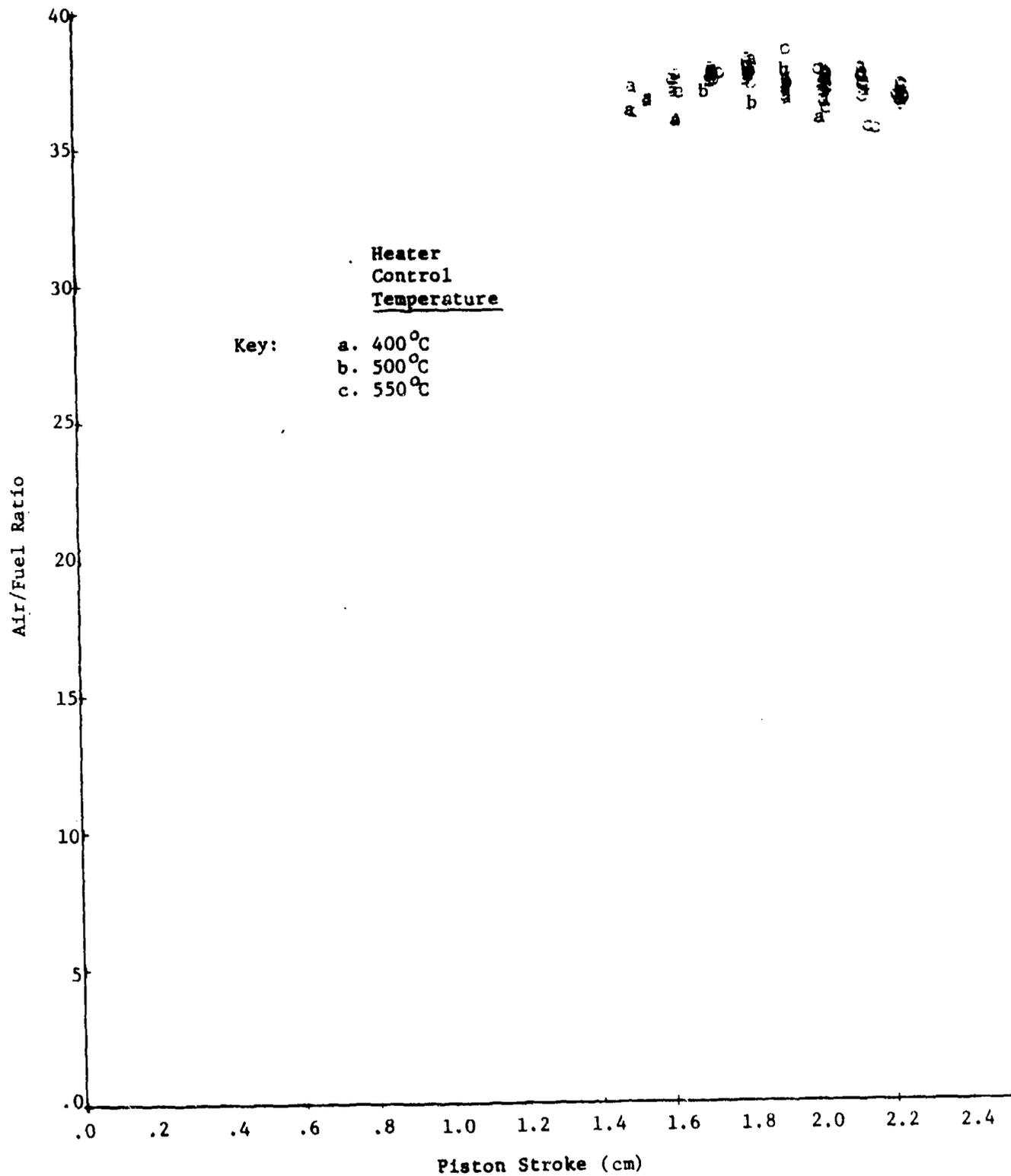


Figure 2-9 Air/Fuel Ratio Versus Piston Stroke

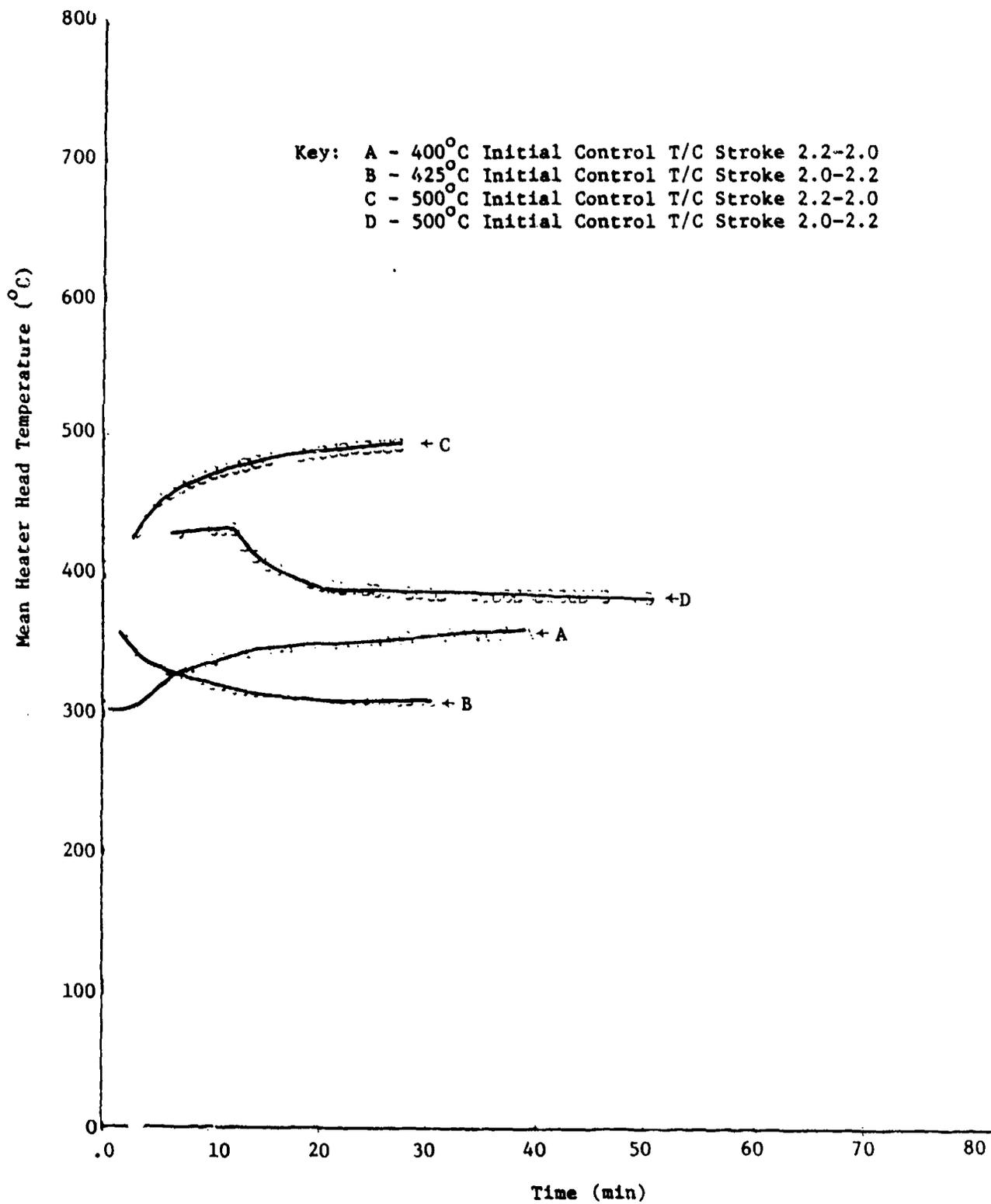


Figure 2-10 Mean Heater Head Temperature Versus Time (Fixed Firing Rate)

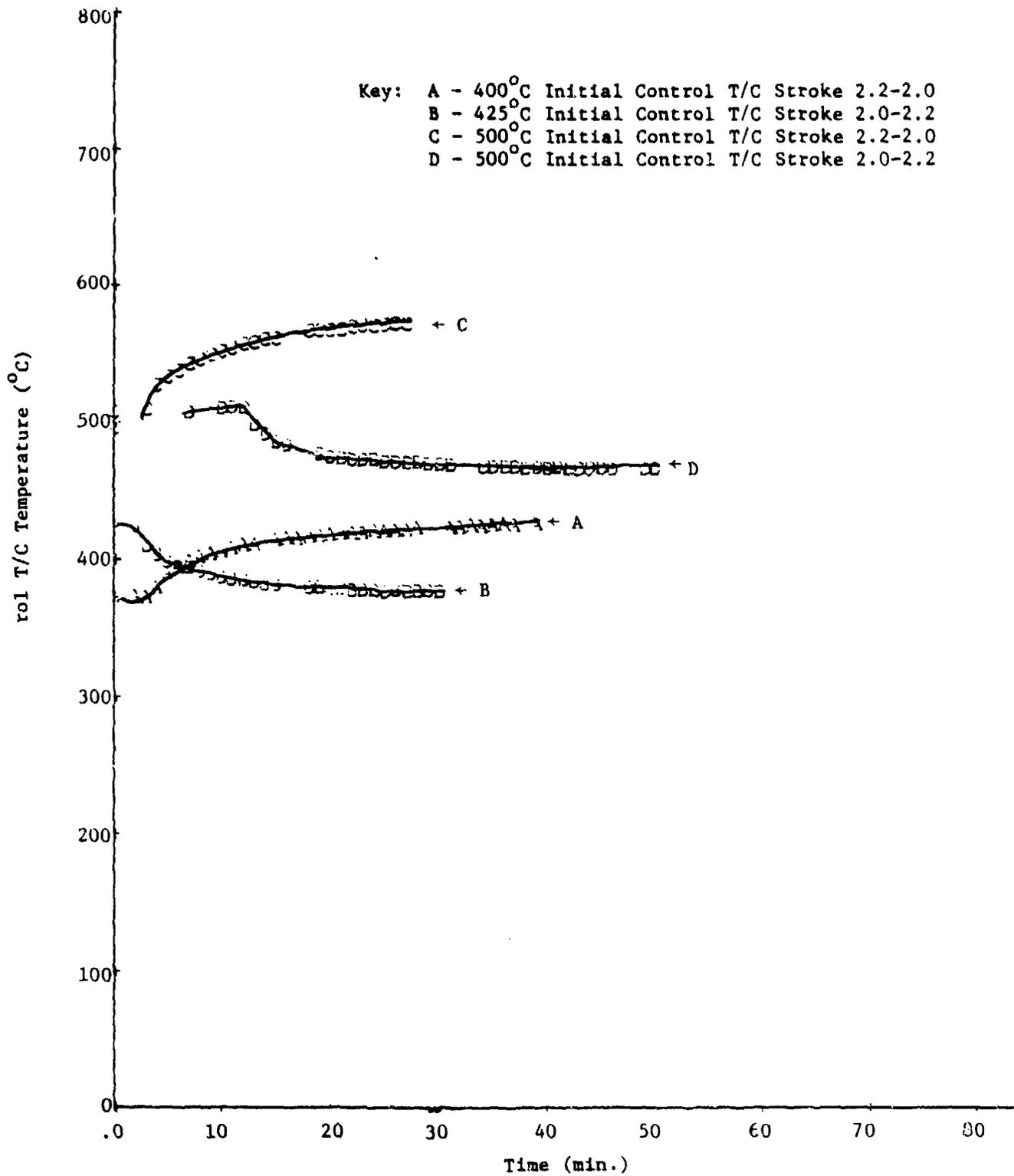


Figure 2-11 Control T/C Temperature Versus Time

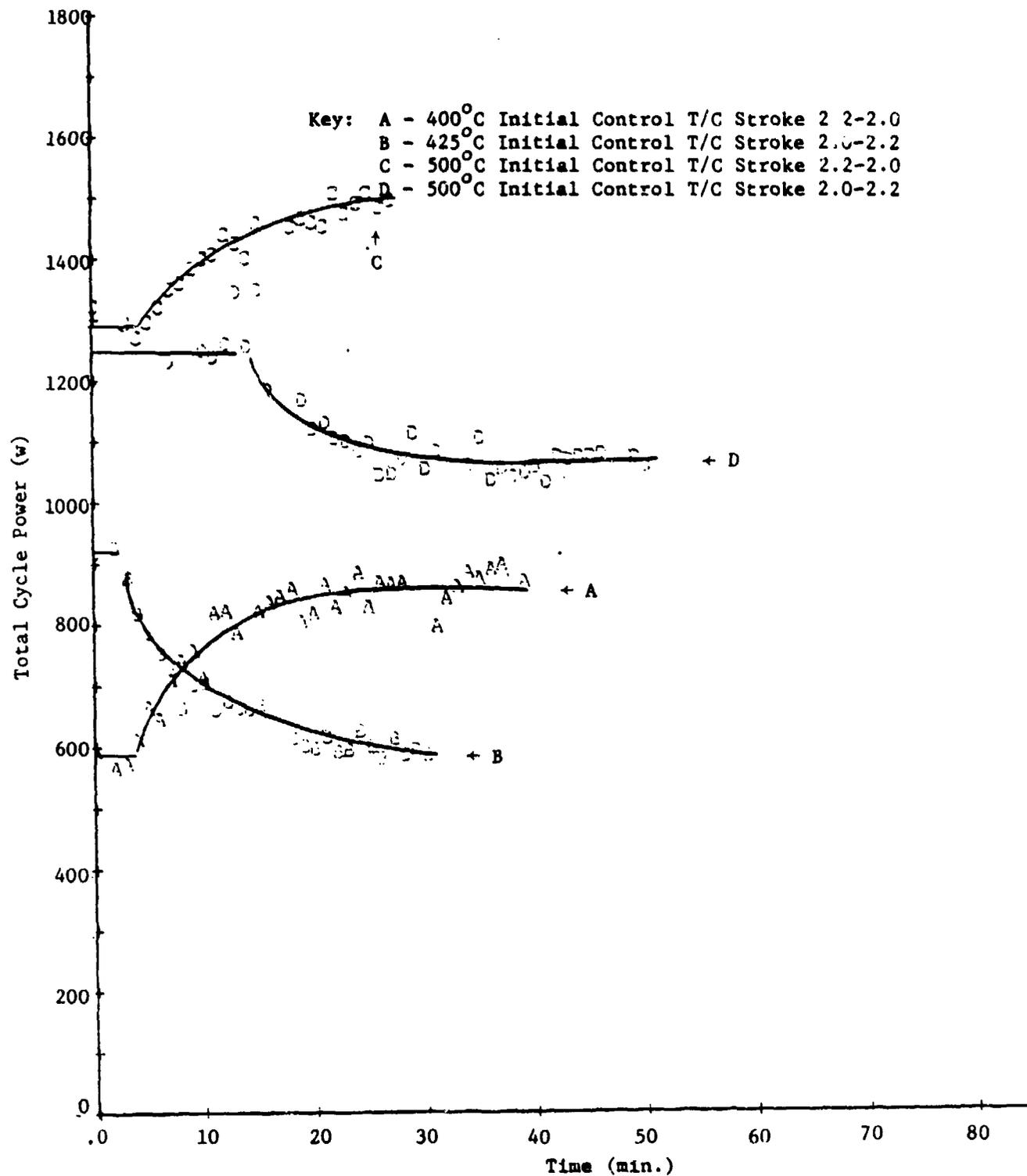


Figure 2-12 Total Cycle Power Versus Time

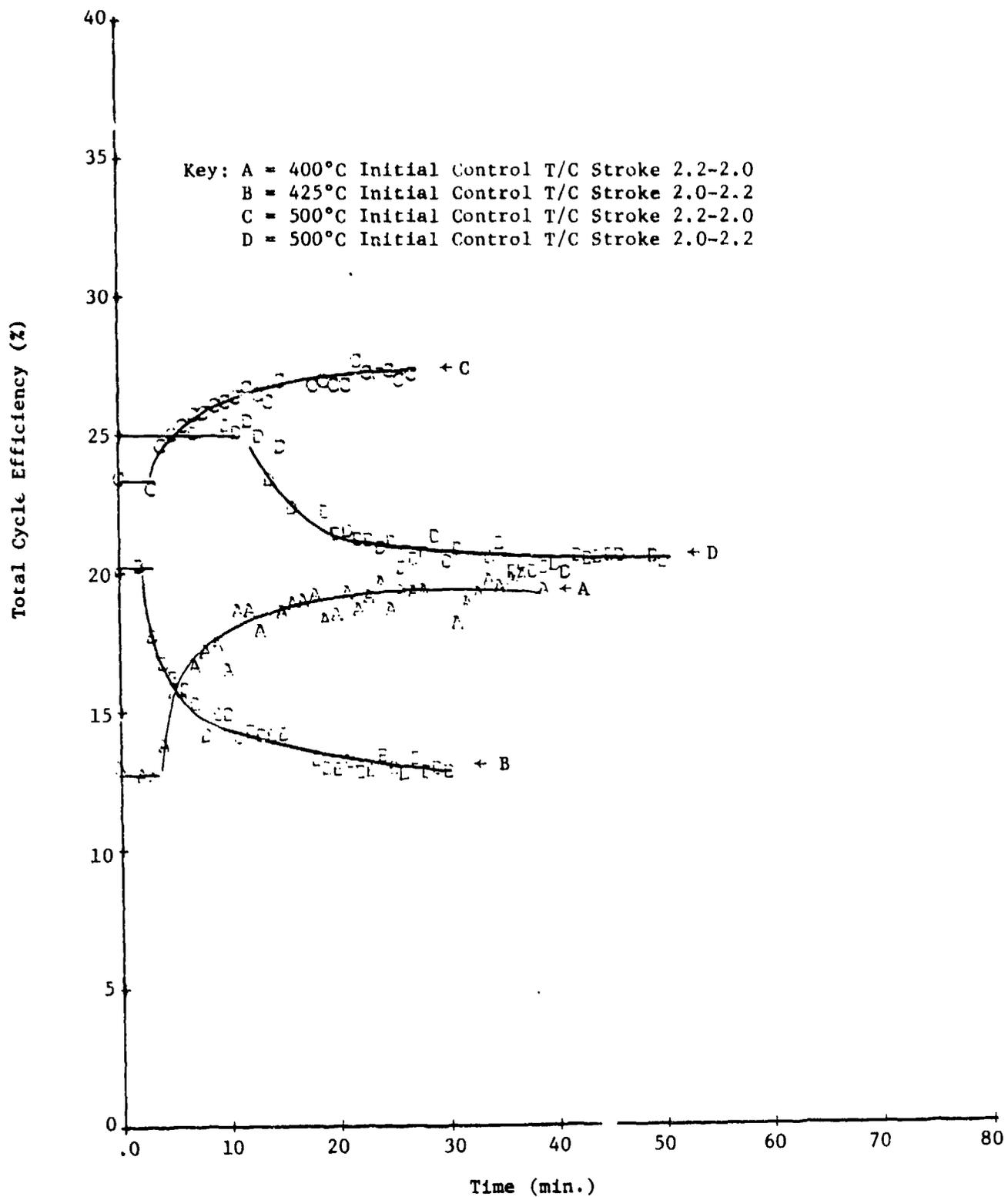


Figure 2-13 Total Cycle Efficiency Versus Time

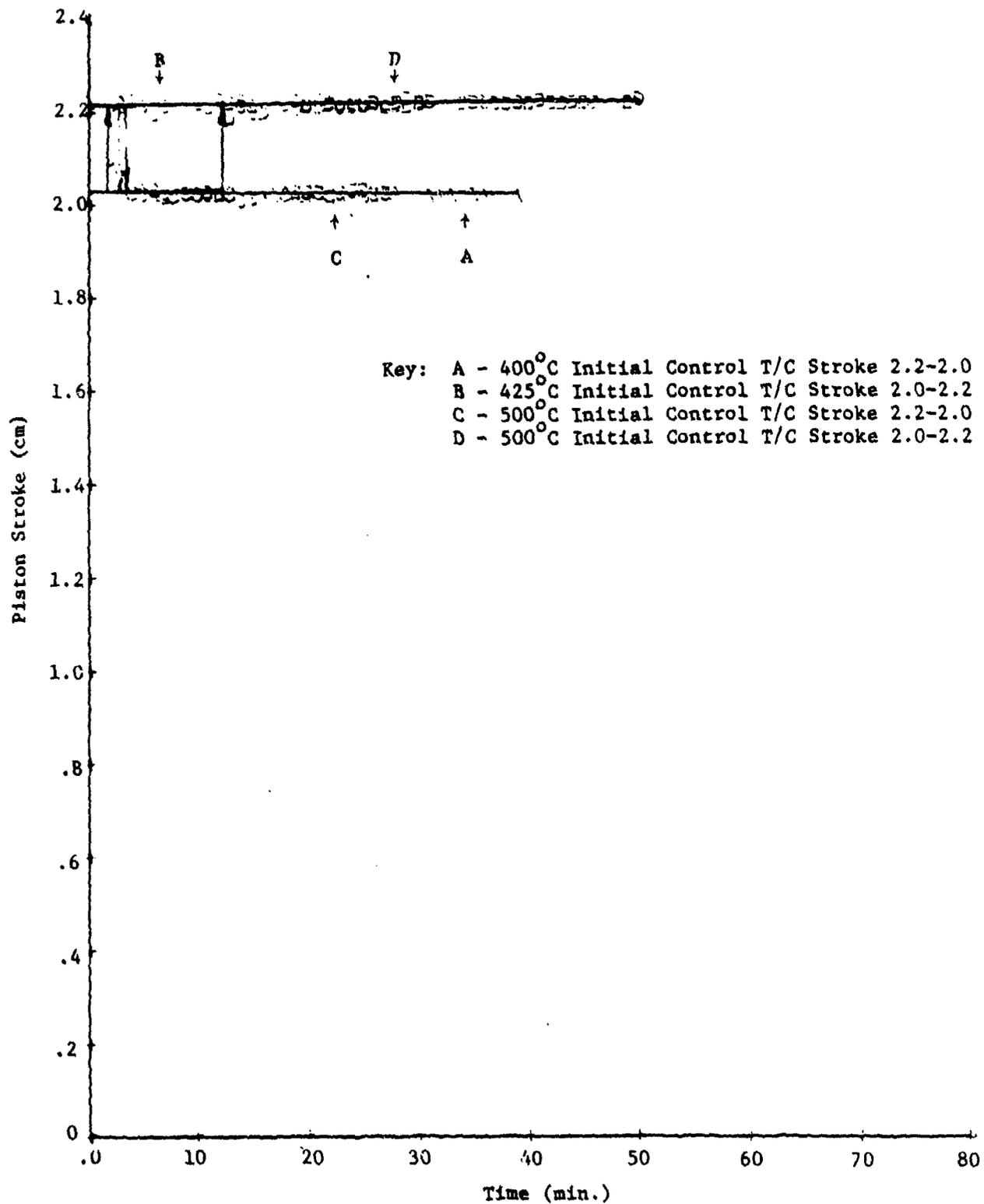


Figure 2-14 Piston Stroke Versus Time

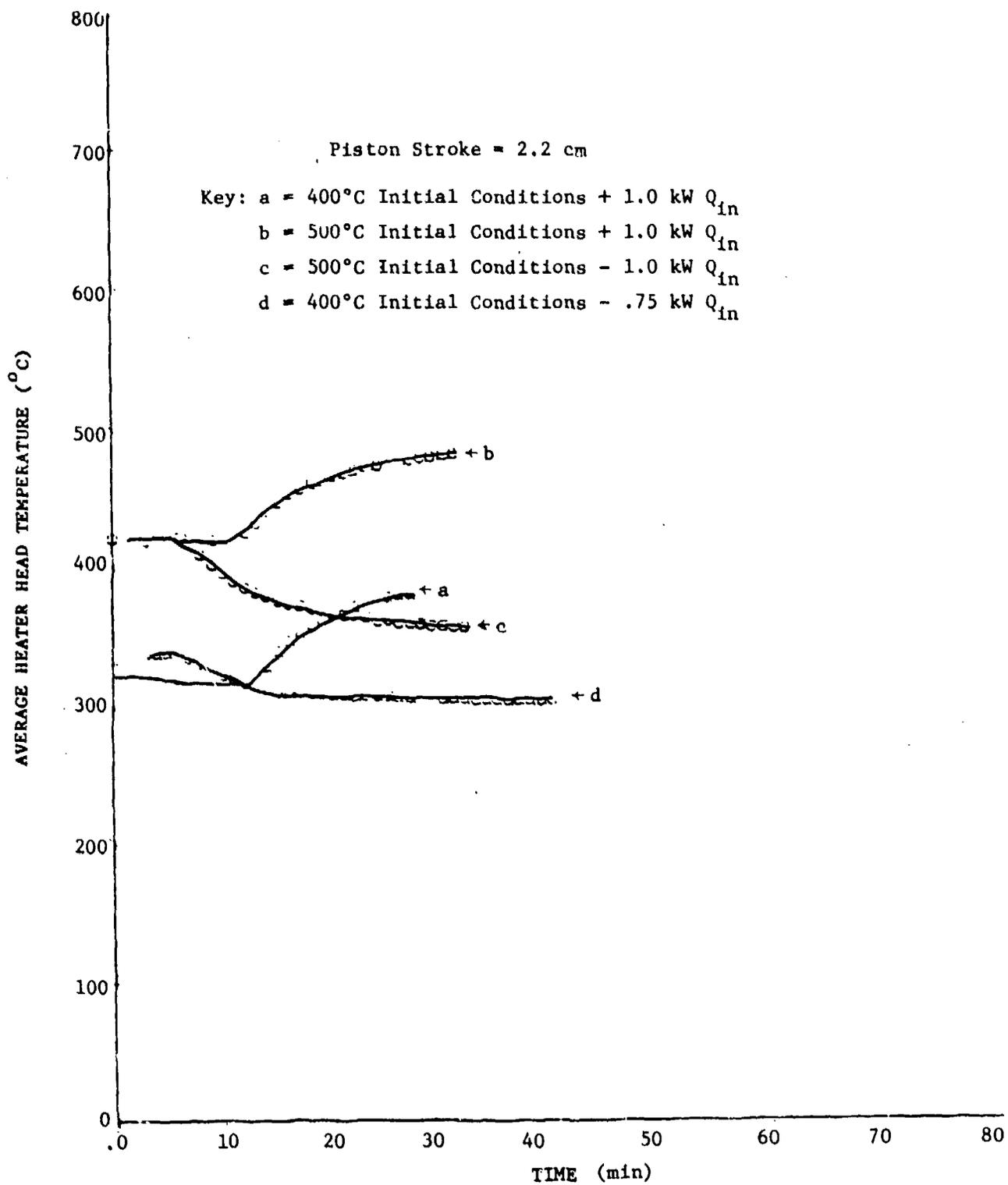


Figure 2-15 Average Heater Head Temperature Versus Time

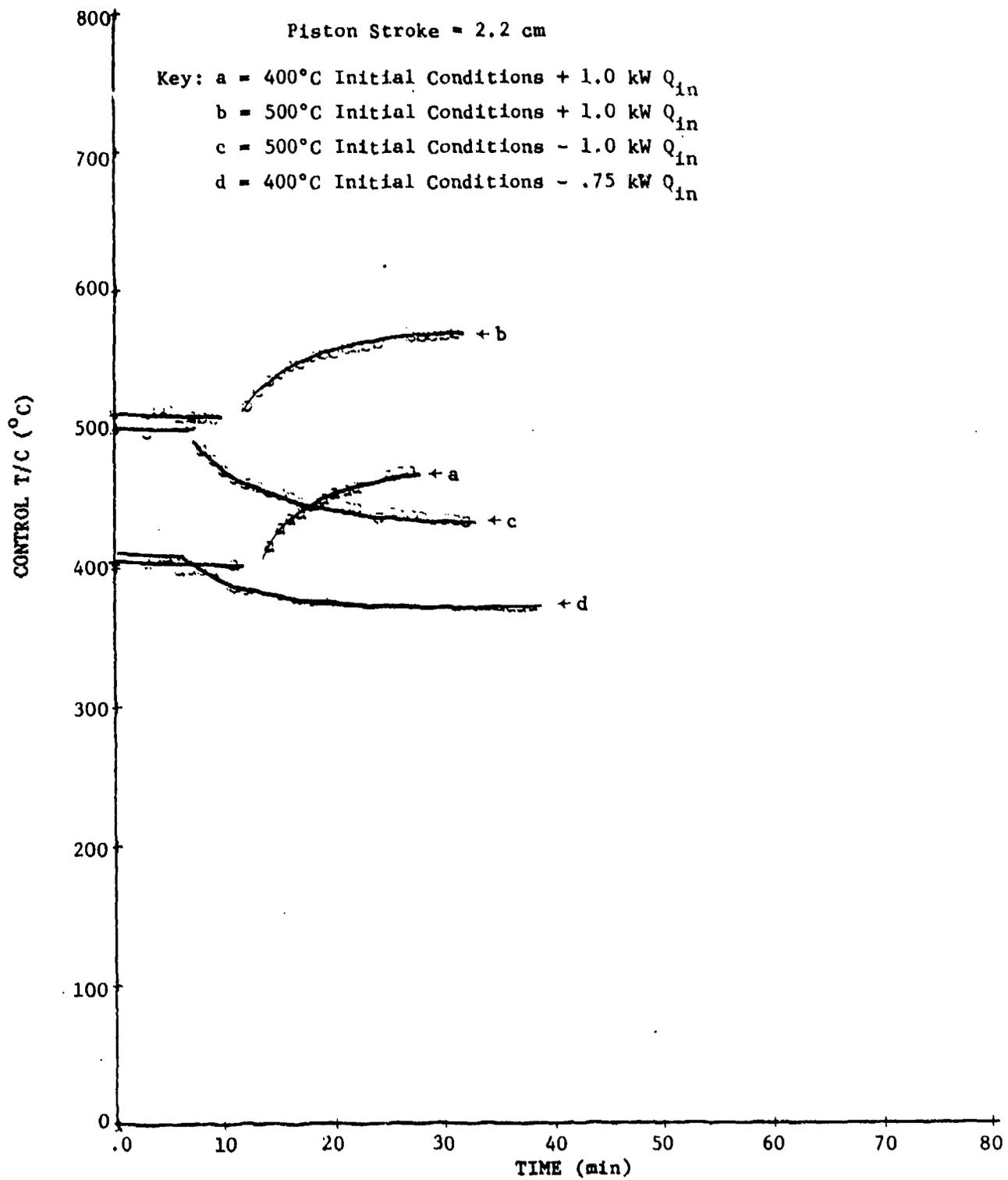


Figure 2-16 Control T/C Temperature Versus Time

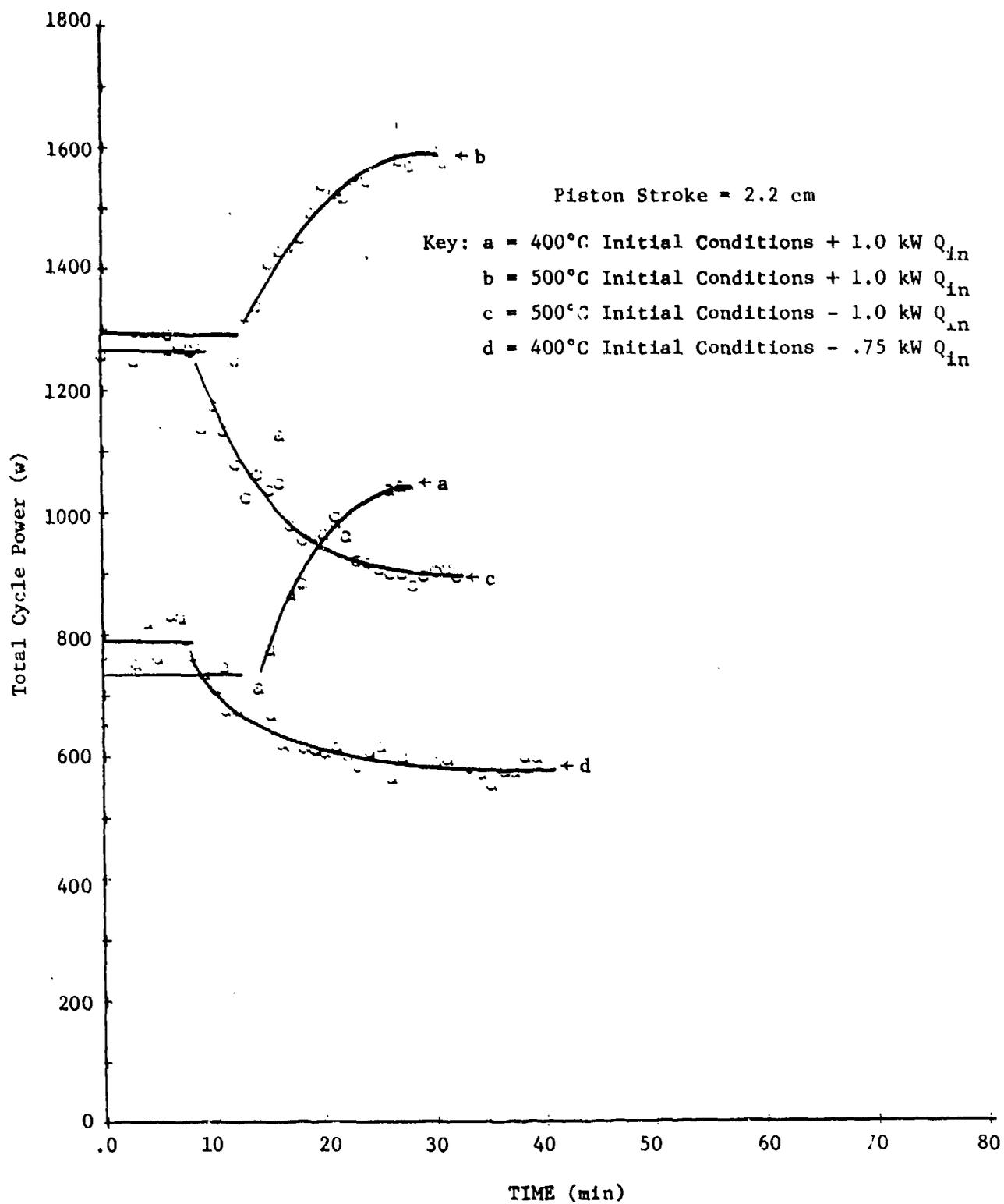


Figure 2-17 Total Cycle Power Versus Time

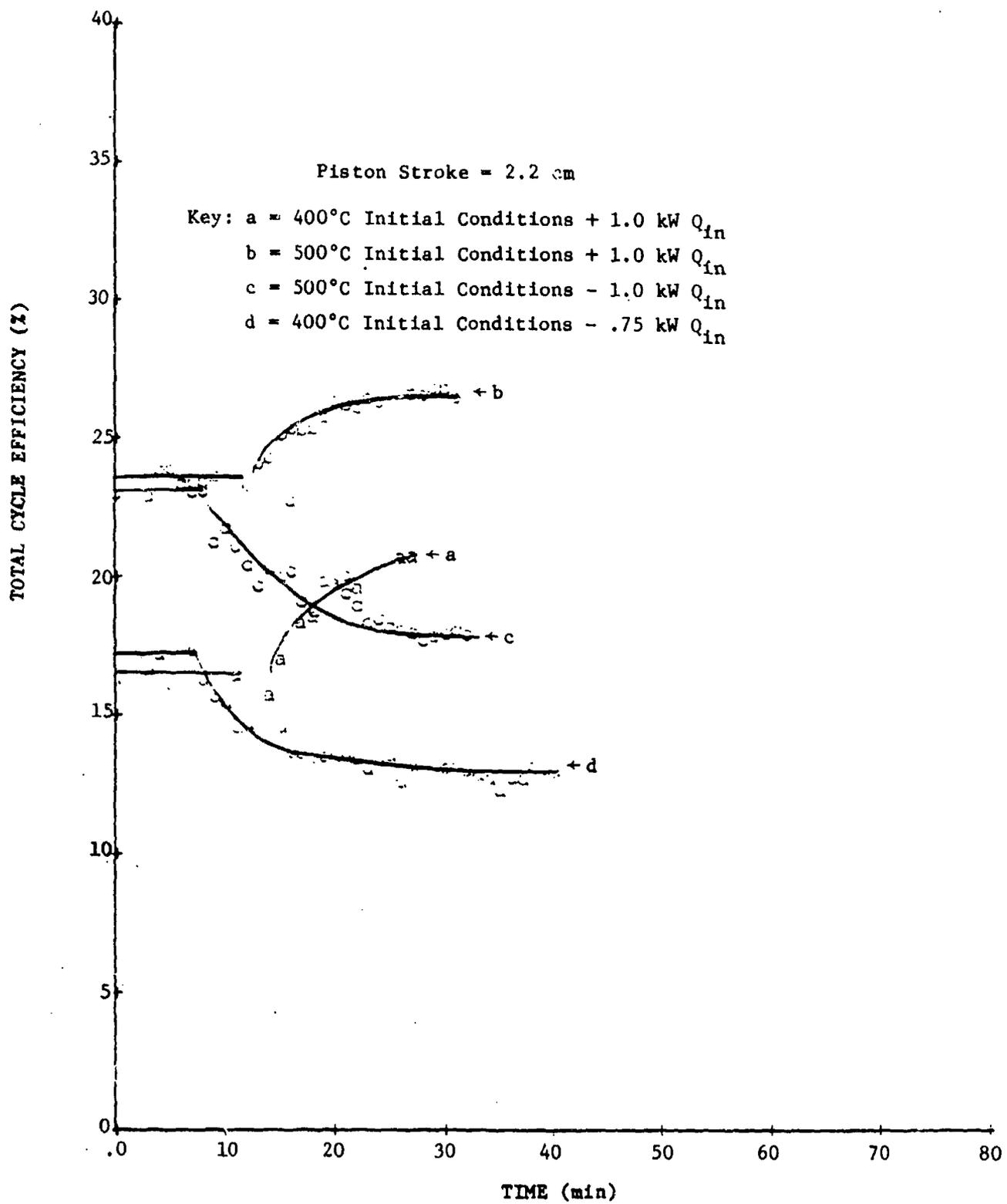


Figure 2-18 Total Cycle Efficiency Versus Time

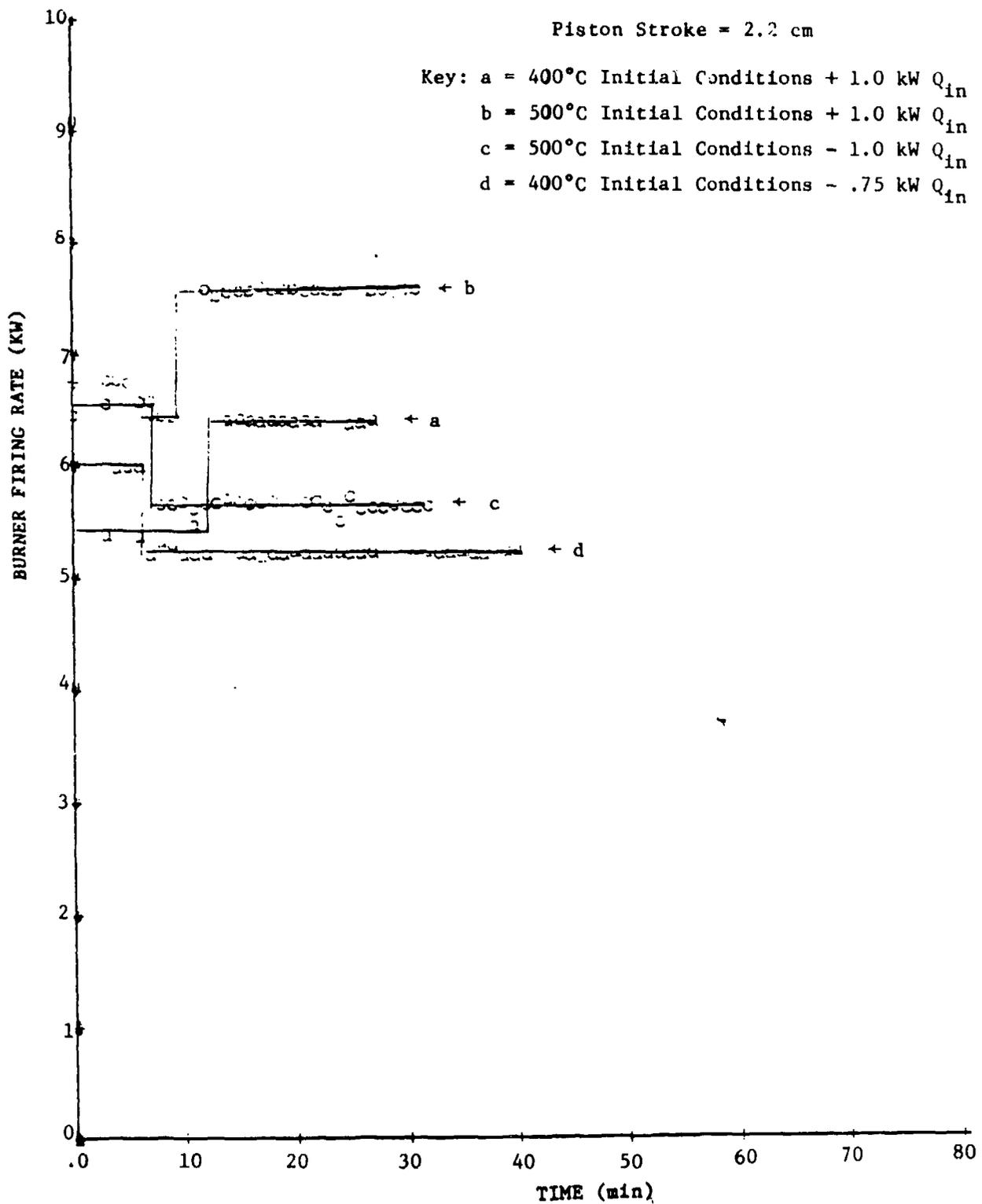


Figure 2-19 Burner Firing Rate Versus Time

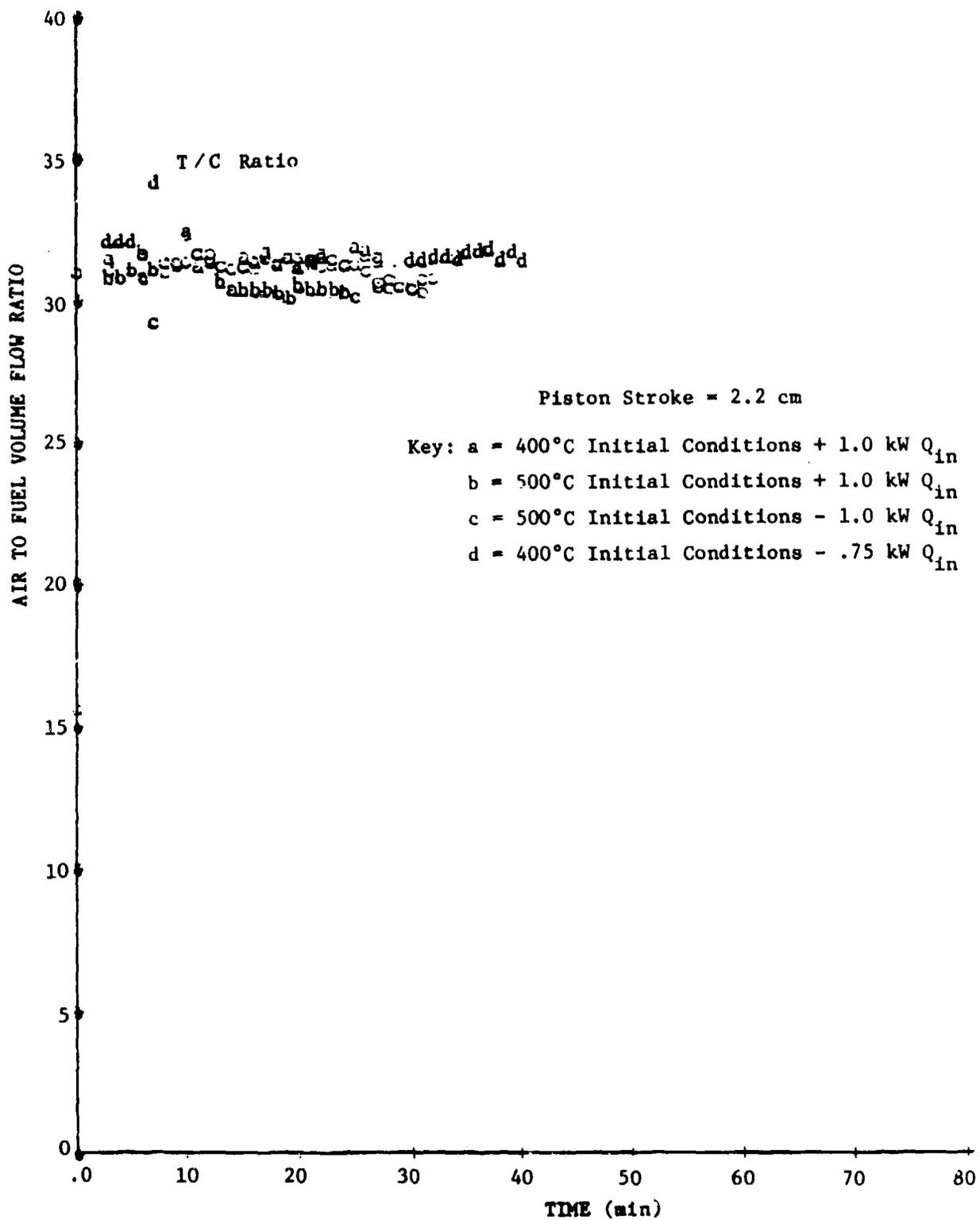


Figure 2-20 Air-To-Fuel Volume Flow Ratio Versus Time

require modification of the manual control hardware; however, testing showed heater head temperature to be the control parameter that could be used as the combustor control. Air/fuel flow could be adjusted automatically to maintain heater head temperature within a necessary control limit. Heater head temperature response was much longer than that of the airflow and/or fuel flow valves.

3. Fuel/Air Loop Characterization

Fuel/air loop testing was necessary to determine the response rates of the air/fuel valves, valve setting with respect to input voltage, and hysteresis in the valves themselves. Air/fuel loop testing is accomplished with:

- engine/combustor fully assembled;
- system at room temperature;
- flow restrictor on combustor outlet yielding 8-1/2" H₂O pressure drop to simulate hot combustor;
- nitrogen flowed in fuel loop (upstream of 40" H₂O); and,
- function generator connected to controller to modulate valves (full-scale valve motion caused by 0 to 10 V signal output)*.

Typical air/fuel valve transient response is shown in Figures 2-21 through 2-24. Based on transient testing of the air and fuel loops, flow versus valve input voltage characteristics are:

$$Q_{\text{air}}/V = 1.62/(1 + S/4.1) \pm 1.2 \text{ cfm/volt for air; and,}$$

$$Q_{\text{fuel}}/V = 0.027/(1 + S/3.77)(1 + S/5.03) \pm 0.013 \text{ cfm/volt for fuel;}$$

where: Q_{air} = airflow (cfm);
 Q_{fuel} = fuel flow (cmf);
 V = voltage; and,
 S = valve position.

*controller's voltage-to-current converters were used.

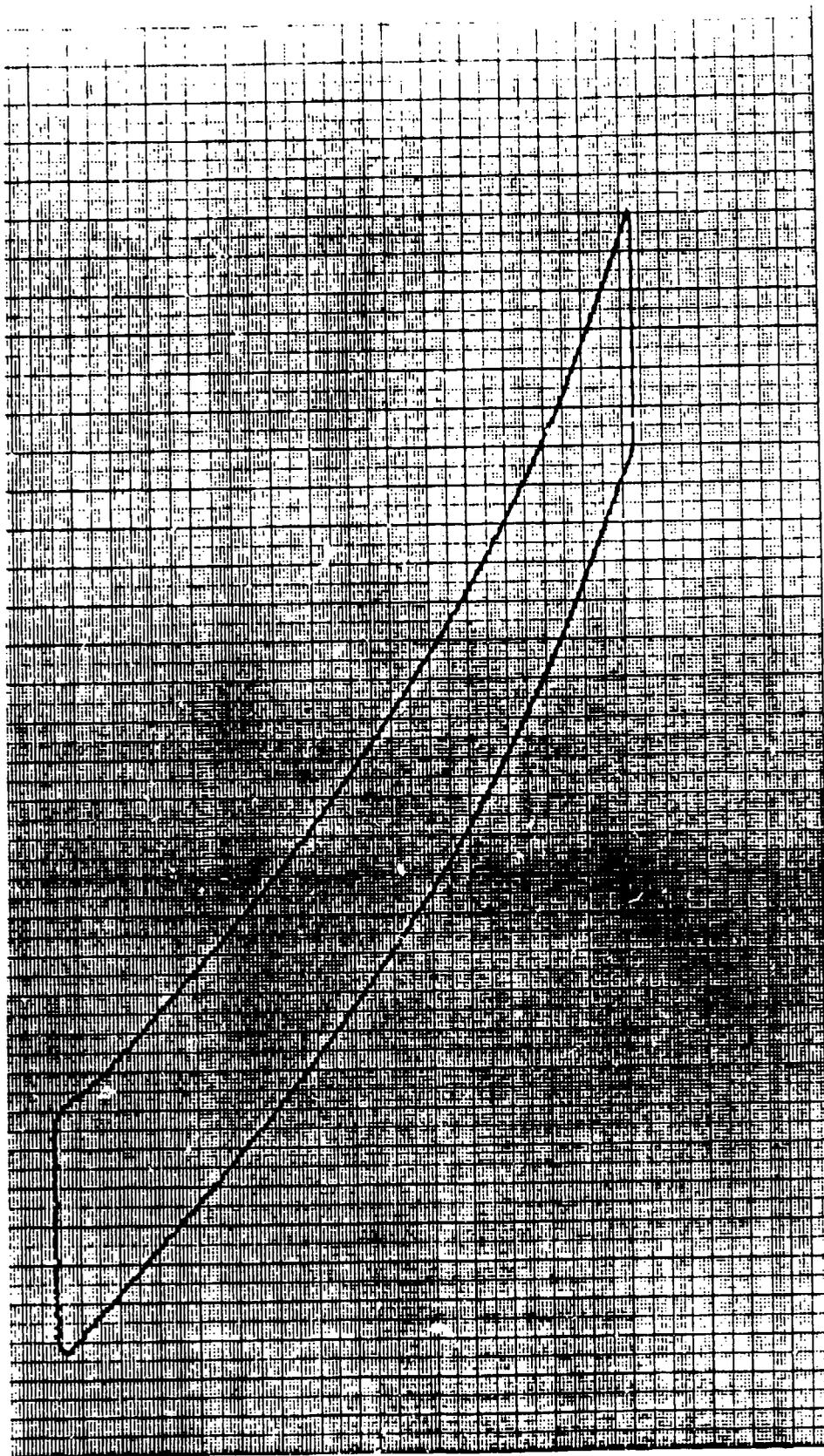


Figure 2-21 Airflow Versus Valve Input of 6 V_{pp} 0.1-Hz Triangle
0.25 V/cm Vertical and Horizontal

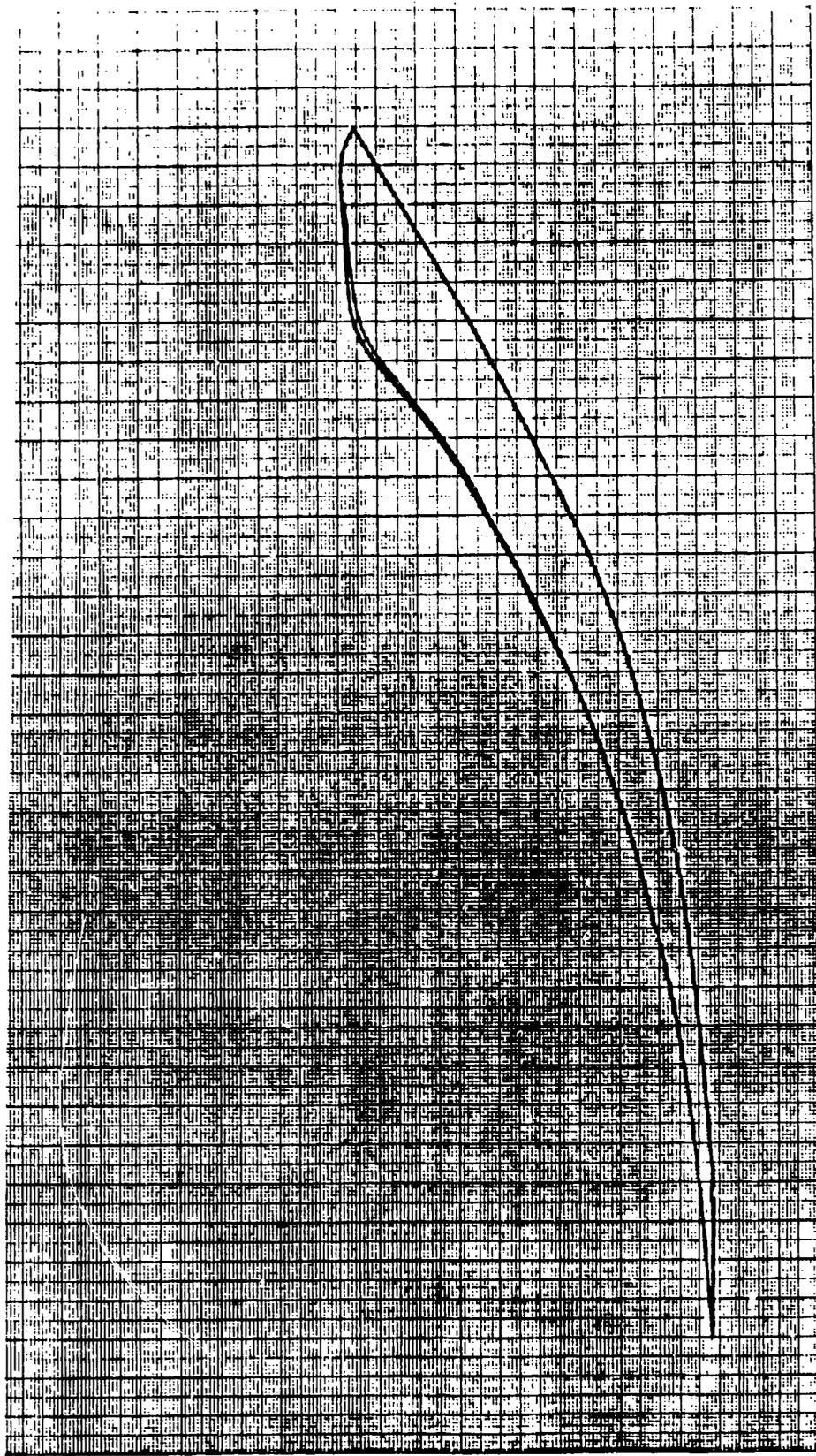


Figure 2-22 Fuel Flow Versus Valve Input of 6 V_{pp} 0.1-Hz Triangle
0.25 V/cm Vertical and Horizontal

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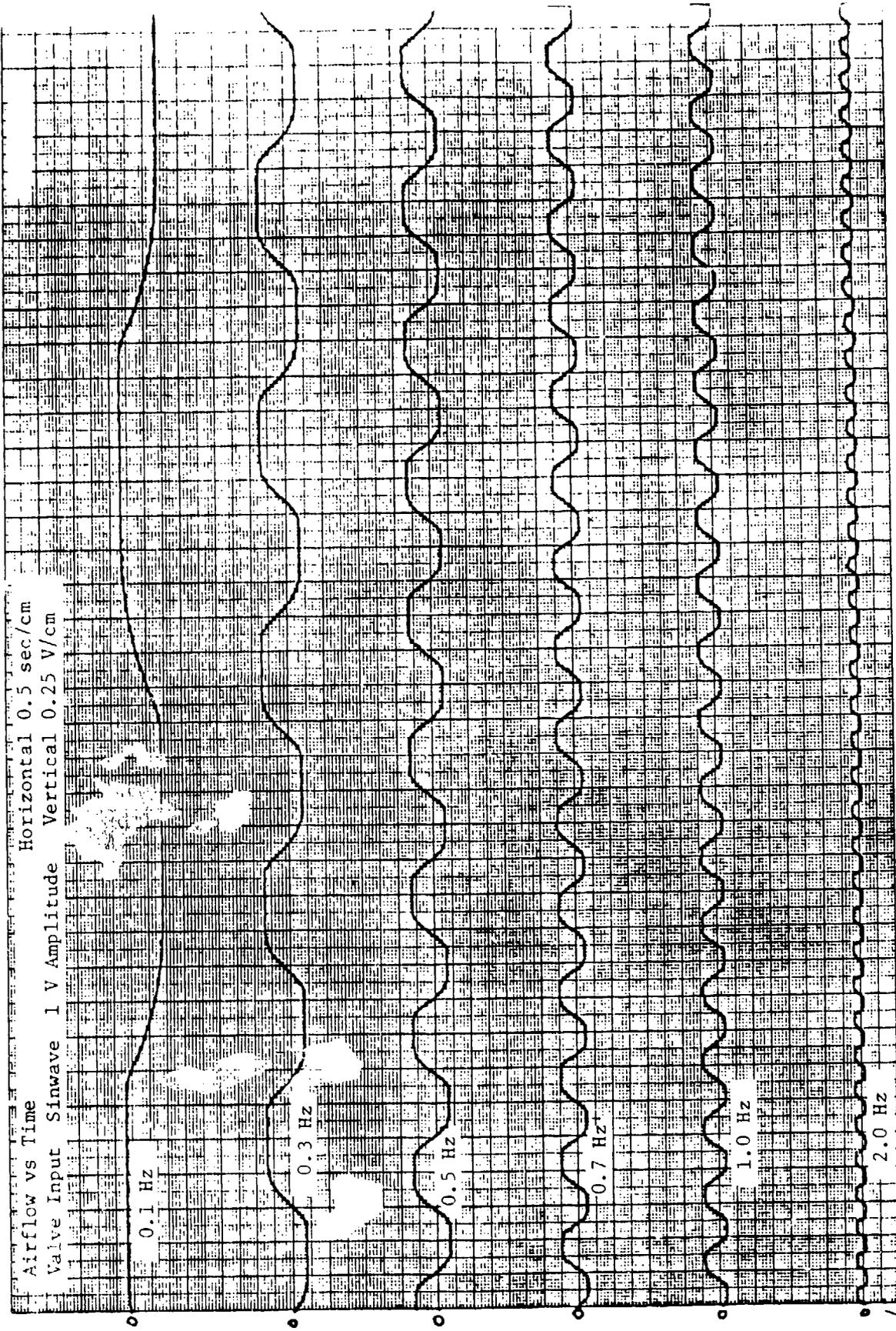


Figure 2-24 Airflow Versus Time Valve Input

B. DESIGN, FABRICATE, AND DEVELOP AUTOMATIC CONTROL SYSTEM

1. Basic Control Strategy

The automatic control system (shown schematically in Figure 2-25) is composed of three interconnected loops: heater head temperature, firing rate (fuel flow), and airflow. The airflow loop is slaved off the fuel flow to maintain air/fuel ratio; the firing rate loop will accept input from either the heater head temperature loop or an operator set point (manual mode). The air and fuel loops incorporate proportional integral-derivative control algorithms to stabilize operation, and have high and low flow rate bounds set at the limits of controllable flow through the system.

2. Control System Functions

The function of the combustor controller is to provide:

- start-up interlocking similar to the existing manual control;
- closed loop air/fuel ratio control (operator set);
- closed loop fuel flow control based on operator set point (manual mode) and head temperature (auto mode);
- automatic shutdown due to fuel pressure high or low, blower air pressure low, exhaust fan failure, fire alarm, emergency stop (operator), overtemperature, and command from HF Data Acquisition System (DAS);
- display: status of system monitors, firing rate, air/fuel ratio, and mean/max head temperatures;
- controls: firing rate, air/fuel ratio, max/mean head temperatures, blower, fuel, and igniter on/off, auto/manual, and emergency stop; and,
- watchdog timer.

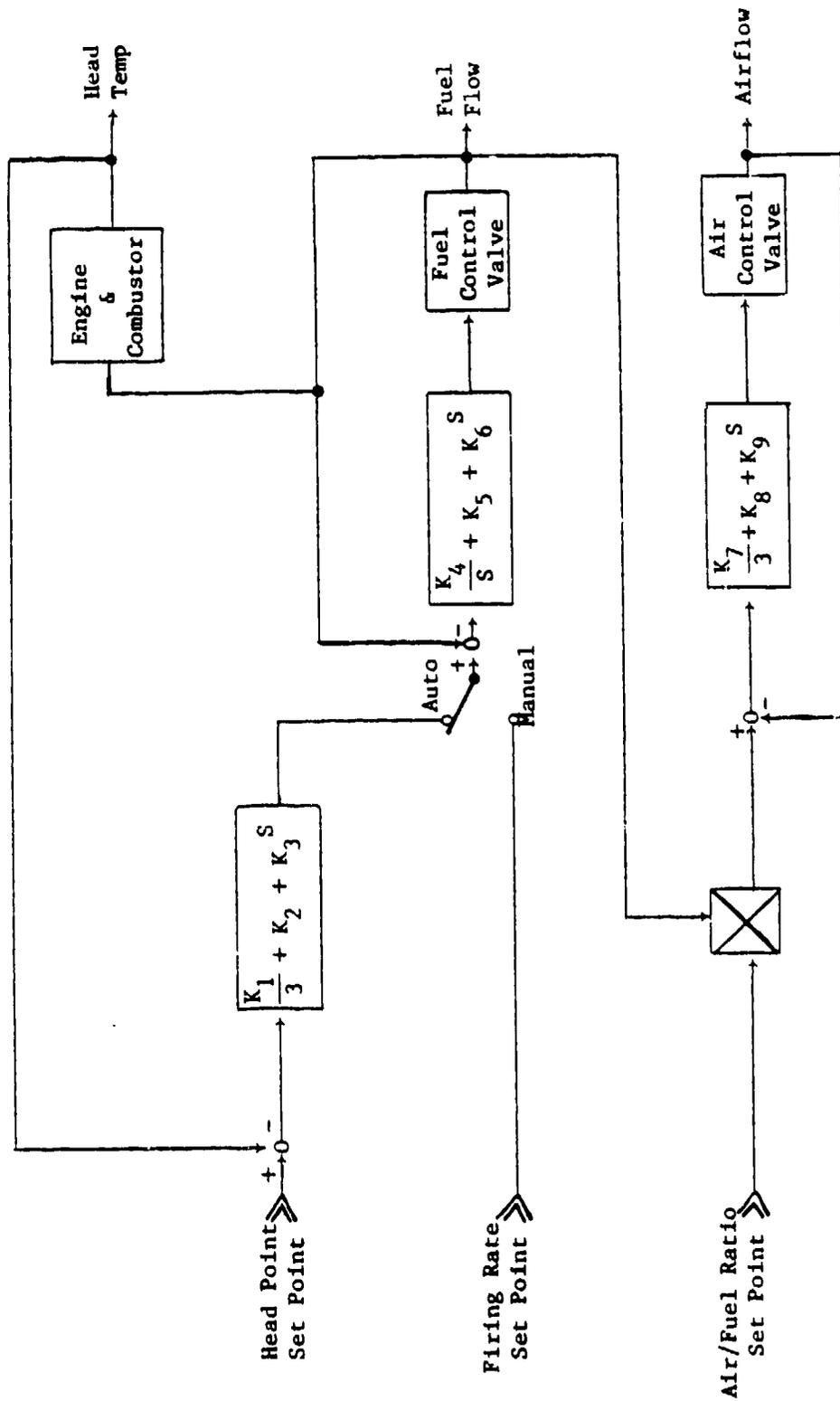


Figure 2-25 WPAFB Air/Fuel Controller Control Loop Structure

In addition, the combustor controller will allow for expansion to include automatic start-up sequencing, control based on mass flow rates, integration with power control, and transient power/head temperature control.

The combustor controller will also:

- leave existing manual control packages in place as backups;
- provide standard connectors for system monitors, relays, valves, and displays so that conversion from existing control to the new automatic control can be easily accomplished;
- route all signals through microprocessor control;
- provide emergency-stop function (button) to interrupt power to igniter relay, fuel valve/solenoid, and blower valve, and apply power to blower relay, assuring shutdown in the fail-safe mode; and,
- have tasks to fit controller to test cell to provide: in-line connectors for system monitors, relays, valves/displays, and thermocouples (T/C); additional overhead displays for mean and maximum head temperatures; and, a new system control panel.

A block diagram of the combustor controller is presented in Figure 2-26.

3. Control System Specification

Table 2-3 presents the control system specifications.

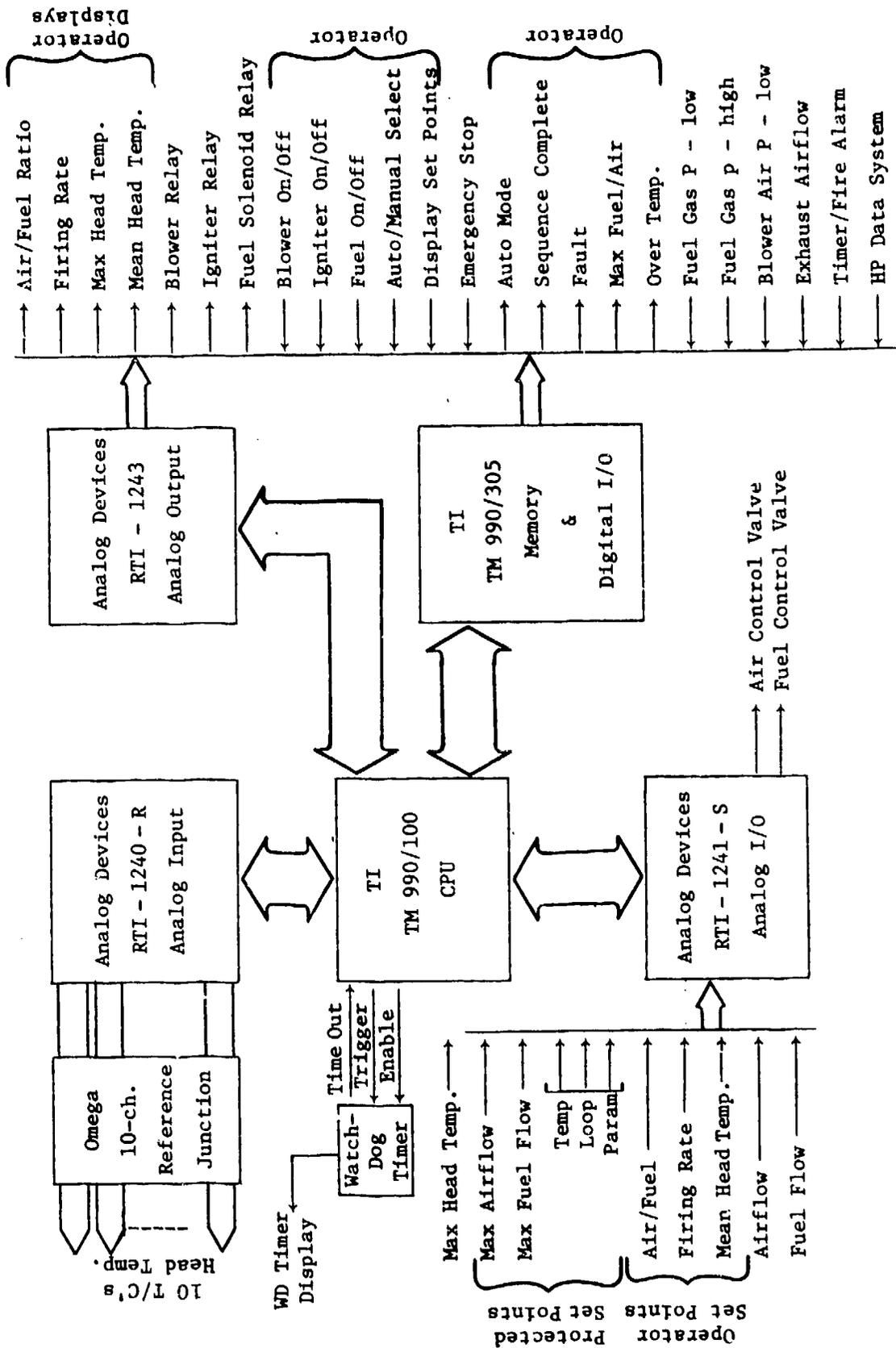


Figure 2-26 WPAFB Air/Fuel Controller System Block Diagram

TABLE 2-3
COMBUSTOR CONTROLLER SPECIFICATIONS

- I. Input/output - see following pages
- II. Monitor to provide:
 - A. Modification of parameters of running algorithms
 - B. Line assembler for writing short algorithms
- III. Protection to include:
 - A. Watchdog timer to reset system if CPU fails.
 - B. Emergency stop to act directly on system as well as CPU; will turn off igniter and fuel, and open air valve.
 - C. Shutdown due to presently installed system interlocks; being low fuel and high pressure, timer/fire alarm, and blower.
 - D. Shutdown command from HP-DAS
- IV. Control
 - A. Firing rate to be determined by operator in manual mode or by head temperature versus set point in automatic mode.
 - B. Airflow to be determined by firing rate and operator set air/fuel ratio.
- V. Manual/Auto
 - A. Manual mode to allow operator start-up of system, and provide closed loop temperature control.
- VI. Response/Accuracy (Goals)
 - A. Maintain temperature within $\pm 20^{\circ}\text{C}$ (steady-state power).
 - B. Maintain air/fuel ratio within $\pm 5\%$.

TABLE 2-3 (Cont'd)

<u>Signal Name</u>	<u>Input/ Output</u>	<u>Analog/ Digital</u>	<u>Range</u>
Head Temperature 1	I	A	0 → 40mV
2	I	A	
3	I	A	
4	I	A	
5	I	A	
6	I	A	
7	I	A	
8	I	A	
9	I	A	
10	I	A	
Ref. Junction Temperature	I	A	0 → 10V
Air/Fuel Ratio	I	A	
Firing Rate	I	A	
Maximum Head Temperature	I	A	
Mean Head Temperature	I	A	
Airflow	I	A	0-8V
Fuel Flow	I	A	0-8V
Blower Off	I	D	
Blower On	I	D	
Igniter Off	I	D	
Igniter on	I	D	
Fuel Off	I	D	
Fuel On	I	D	
Fuel Pressure Low	I	D	
Fuel Pressure High	I	D	
Blower Air Pressure Low	I	D	
Exhaust Airflow	I	D	
Timer/Fire Alarm	I	D	
Data System	I	D	
Emergency Stop	I	D	
Display Set Points	I	D	
Blower Starter Relay	O	D	120 VAC
Igniter Relay	O	D	120 VAC
Fuel Solenoid	O	D	120 VAC
Maximum Head Temperature	O	A	0-2V
Mean Head Temperature	O	A	0-2V
Air Valve Control	O	A	4-20mA
Fuel Valve Control	O	A	4-20mA
Sequence Complete	O	D	
Auto Mode	O	D	
<u>Auto Start Control</u>			
Start	I	D	
<u>Mass Flow Control</u>			
Upstream Air Temperature	I	A	0-40mV
Upstream Air Pressure	I	A	0-10V
Upstream Fuel Temperature	I	A	0-40mV
Upstream Fuel Pressure	I	A	0-10V

TABLE 2-3 (Cont'd)

<u>Signal Name</u>	<u>Input/ Output</u>	<u>Analog/ Digital</u>	<u>Range</u>
<u>Power Control</u>	J	A	
Output Voltage	I	A	
Output Current	I	A	
Battery Voltage	I	A	
Frequency	I	A	
Field Current	I	A	
Cooling Water Temperature	I	A	
Voltage Set Point	I	A	
Overstroke	I	D	
Low Engine Pressure	I	D	
Battery Rate of Charge	O	A	
Field Voltage	O	A	
Transfer Control Voltage	O	A	
Water Pump	O	D	
Cooling Fan	O	D	
Output Voltage Display	O	A	
Frequency Display	O	A	
Output Current Display	O	A	

TABLE 2-3 (Cont'd)

HP - Data System: (to be added later)

Data system used to monitor engine, auxiliaries, and shutdown in case of overstroke, overpower, loss of pressure, loss of coolant flow/excessive ΔT , and questionable engine dynamics.

Signal Description

Head Temperature 1...10 - Type K T/C's measuring combustor/head temperatures. T/C's are routed through a reference junction and a single-pole, low-pass passive filter (max signal = 41 mV \approx 1000°C).

Reference Junction Temperature - Output of a temperature sensor affixed to the T/C reference junction (sensitivity = 1mV/°C).

Air/Fuel Ratio Set Point - 0-10 V signal controlled by operator (specifies desired air/fuel ratio).

Firing Rate Set Point - 0-10 V signal controlled by operator (specifies desired firing rate (man) or maximum firing rate (auto)).

Max Head Temperature Set Point - 0-10 V signal controlled by operator (specifies temperature limit for all T/C's; if limit is exceeded, system will shut down).

Mean Head Temperature Set Point - 0-10 V signal controlled by operator (specifies desired mean of T/C readings).

Airflow - 0-8 V signal proportional to volumetric airflow (8V = 21.9 cfm).

Fuel Flow - 0-8 V signal proportional to volumetric fuel flow (8V = 1.25 cfm).

Max Airflow Set Point - 0-10 V signal (specifies maximum permissible airflow - protected set point).

Max Fuel Flow Set Point - 0-10 V signal (specifies maximum permissible fuel flow - protected set point)

Head Temperature Loop PID Control Parameters (3 signals) - 0-10 V signals (specifies constants to be used in temperature loop algorithm - protected set points).

The following six signals are active low TTL signals from momentary contact switches controlled by the operator. Only one signal may be active at a given time, or all will be ignored.

Blower Off - Turn combustor air blower off.

Blower On - Turn combustor air blower on.

Igniter Off - Turn igniter off.

Igniter On - Turn igniter on.

TABLE 2-3 (Cont'd)

Fuel Off - Close secondary fuel solenoid valve.

Fuel On - Open secondary fuel solenoid valve.

Fuel Pressure Low - Active low TTL signal indicating fuel supply pressure is low.

Fuel Pressure High - Active low TTL signal indicating fuel supply pressure is high.

Blower Air Pressure Low - Active low TTL signal indicating outlet air pressure from combustor blower is low.

Exhaust Airflow - 120 VAC signal which, when present, indicates test cell exhaust fan is working.

Timer/Fire Alarm - 120 VAC signal which, when present, indicates 15-minute exhaust fan timer has timed out, and that the fire alarm is not tripped.

Data System - Active low TTL signal from DAS commanding combustor shutdown.

Emergency Stop - Active low TTL signal controlled by operator, commanding combustor shutdown.

Display Set Points - Active low TTL signal controlled by operator, commanding mean and max head temperature set points to be displayed on control panel.

Auto - Active low TTL signal commanding switch from manual to automatic mode (operator controlled).

Manual - Active low TTL signal commanding switch from automatic to manual mode (operator controlled).

Blower Starter Relay - 10 mA current sink controlling solid-state relay (SSR) whose output is 120 VAC, and indicator lamp.

Igniter Relay - 10mA current sink controlling SSR whose output is 120 VAC, and indicator lamp.

Fuel Solenoid Relay - 10 mA current sink controlling SSR whose output is 120 VAC, and indicator lamp.

Max Head Temperature Display - 0-10 V output proportional to maximum head temperature.

Mean Head Temperature Display - 0-10 V output proportional to mean head temperature.

Air Valve Control - 4-20 mA current output to I/P converter for air control valve.

Fuel Valve Control - 4-20 mA current output to I/P converter for fuel control valve.

TABLE 2-3 (Cont'd)

Sequence Complete - 10 mA current sink on when start-up sequence completed and automatic mode can be entered.

Auto Mode Display - 10 mA current sink on when in automatic mode.

Max Fuel/Air Display - 10 mA sink on when airflow or fuel flow is at maximum allowed.

Overtemp Display - 10 mA current sink on when system is shut down due to excessive head temperature.

Fault - 10 mA current sink on when software error is detected.

Air/Fuel Display - 0-10 V output proportional to actual air/fuel ratio.

Firing Rate Display - 0-10 V output proportional to actual firing rate.

Watchdog Display - 10 mA current sink on when watchdog timer times out.

Timer/Fire Alarm Display - 10 mA current sink on when timer times out or fire alarm is activated.

Exhaust Air Off Display - 10 mA current sink on when exhaust air is detected off.

Hi/Lo Fuel Pressure Displays - 10 mA current sinks on when fuel pressure is detected high or low.

Low Blower Pressure Display - 10 mA current sink on when blower pressure is detected low.

4. System Software

The software will be comprised of five main modules:

1. System Monitor - This package will consist of modified versions of TIBUG and LBLA, and will allow monitoring and dynamic modification of all control loop parameters, as well as minor modifications to other software packages. This routine will execute during free time between other routines.
2. Initialization - This module will run immediately after a system reset, will initiate all control parameters, and will start the system and watchdog timers.
3. Thermocouple Package - This module will take four readings from each thermocouple, linearize the results, and check for bad T/C's or overtemperature. This routine is started by the main control module (4), and is driven from the end-of-conversion (EOC) interrupt of the T/C A/D converter. The module will be run once per second.
4. Main Control Module - This module will input all operator commands/set points and system status monitors or flow rates, compute new flow rates, and update valve positions and operator displays. This routine will run every 0.1 seconds, causing Module 3 to run every 1.0 seconds.
5. Shutdown Module - This routine will run whenever an abnormal condition demanding immediate shutdown occurs. (Note: This is not entered during normal, operator-controlled shutdown.)

Software developed for the combustor controller is provided under separate cover.

III. EVALUATION OF FPSE INTEGRATED CONTROL SYSTEM

The WPAFB combustor controller was designed to be upgraded in order to provide other necessary FPSE control functions in addition to the combustor controller that would eventually lead to stand-alone, unattended operation. These control functions can be divided into two areas: engine load control, and start/stop sequence.

A. ENGINE LOAD CONTROL

The engine load control for an engine-generator application must be designed to control the engine such that the output is maintained within specified tolerances of frequency, voltage, and power output. In addition, the load control must protect the system from adverse conditions such as load transients (both increasing and decreasing), momentary overloads, piston/displacer overstroke, and loss of load.

An uncontrolled FPSE typically responds to load changes by increasing and decreasing piston strokes; however, changing piston stroke results in changing voltage, making this unacceptable for an engine-generator system. Several mechanisms by which the engine stroke (and therefore output voltage) can be controlled as load is changed include:

- heater temperature;
- displacer spring damping;
- displacer spring stiffness;
- engine pressure; and,
- engine dead volume.

All of these mechanisms can be used to change the output power for a given stroke or voltage. Although the mechanisms for effecting the control concepts listed above have not been defined, some of their characteristics can be identified. In general, some performance penalty is associated with all control modes, and the control response to load transients is likely to be a problem with most of the above control modes. This is a particular problem for free-piston engines since they have relatively low inherent energy storage when compared to their output. Therefore, during fast-load transient, the engine may either shut down

(during up-load transients) or overstroke (during down-load transients) before the control system can provide control. In that case, this particular engine-generator application requires fast response to transient loads, and it may be necessary to isolate the engine/alternator system from the load by either a flywheel storage device or batteries that would provide power absorption/capability during fast transients until the engine power control system (displacer spring stiffness, pressure, etc.) can respond by changing the engine operating point to match the new load conditions. For unattended site operation, this load-following capability is considered necessary, as opposed to the fixed point operation.

Whatever engine power control is selected for the engine-generator system, the engine power feedback control loop can be incorporated into the WPAFB control microprocessor via software changes to provide a complete FPSE control system. (This would also require additional digital and analog I/O ports.) The most challenging task for implementing engine control will be designing and developing the control actuator into the engine proper.

B. START/STOP SEQUENCING

The task of start/stop sequencing is necessary for "one-button" startup/ shutdown of an engine system, and shutdown due to emergency conditions, which is ideally suited to a digital control such as the microprocessor-based WPAFB control. The controller in this case turns on the various subroutines necessary for engine start-up, and monitors the system to ensure proper response at each step. A microprocessor-based system can be easily used to evaluate several alternate start/stop sequences during the control development.

The start sequence for the engine system, shown in Figure 3-1, indicates the major steps that must be followed during start-up. Both hardware and software modifications will be required to implement this start sequence into the WPAFB control; however, the present controller's software can be modified to provide the combustor start-up (detailed in Figure 3-2), since the I/O signals have been incorporated in the present unit.

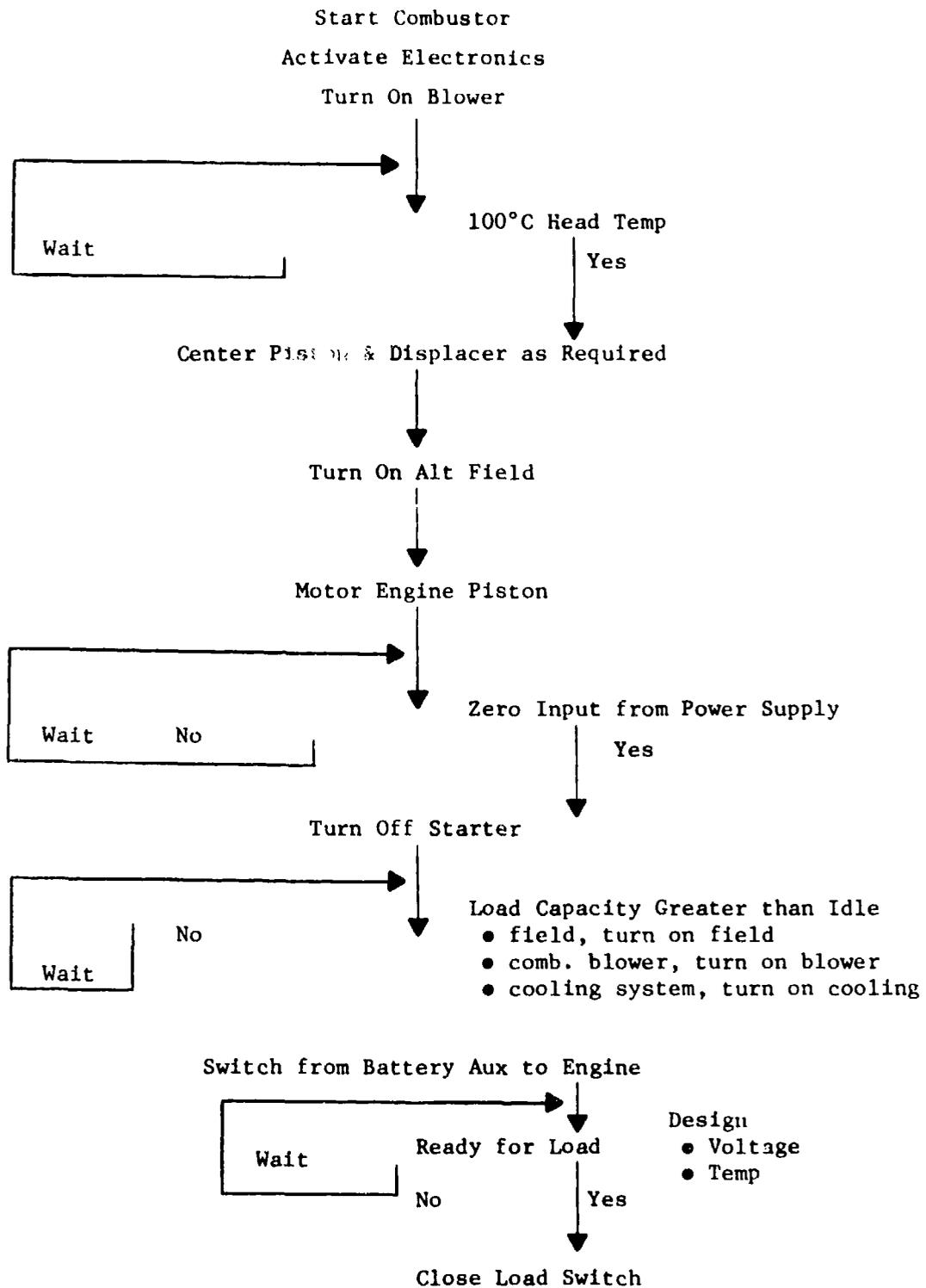


Figure 3-1 Engine Start-Up

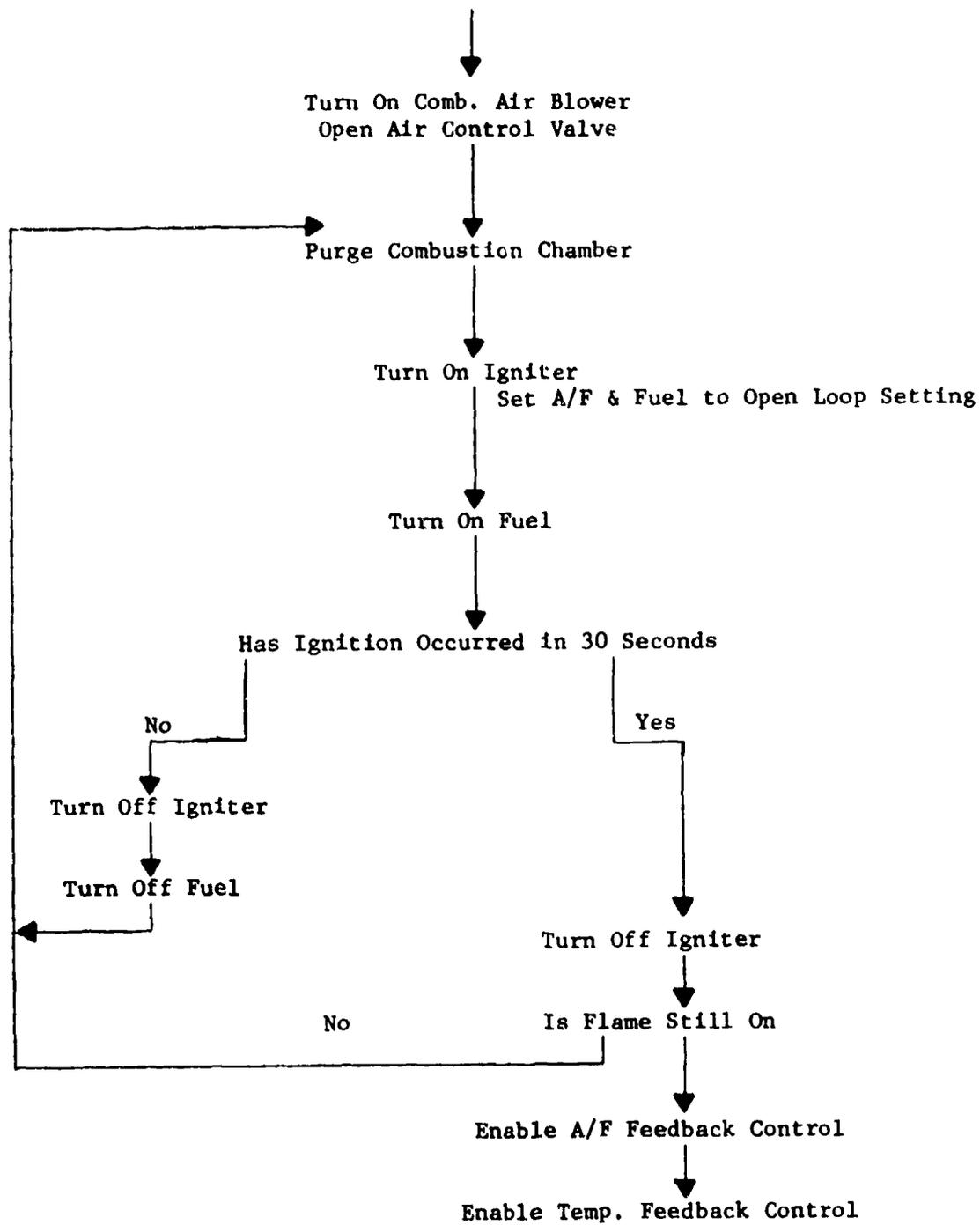


Figure 3-2 Combustor Start Sequence

The stop sequence for the engine, shown in Figure 3-3, indicates the major steps required for safe engine shutdown. Again, the combustor stop sequence can be implemented in the present control hardware with the addition of software changes.

The development of engine power control, including start-up and shutdown, is the next step to providing FPSE unattended operation.

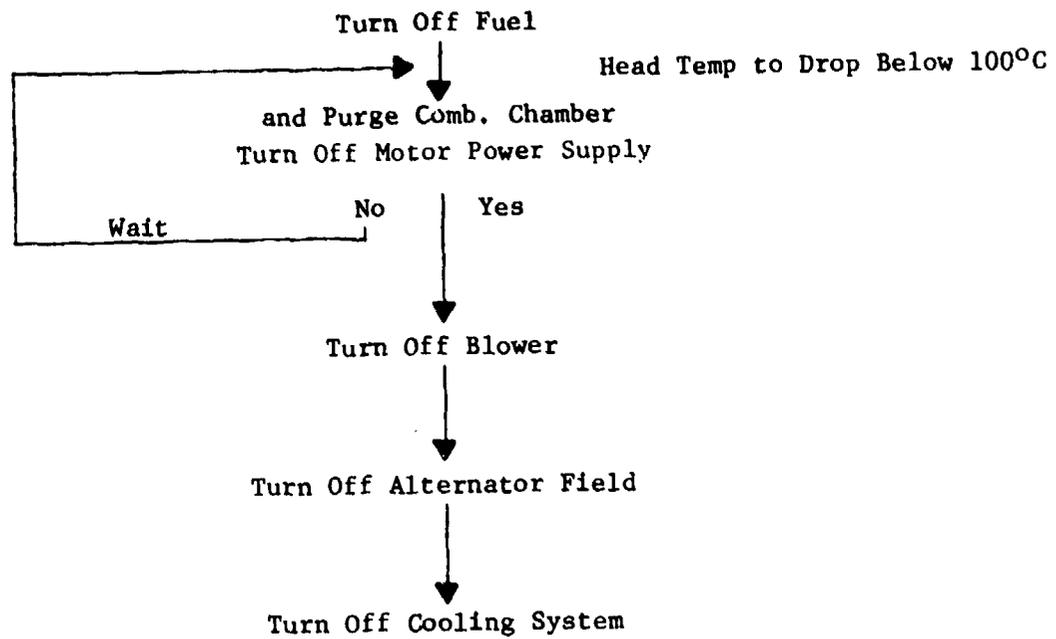


Figure 3-3 Engine Stop Sequence

IV. SYSTEM INTEGRATION

The combustor controller developed and component-tested (as described in Section 2.1) was integrated into the TDE test facility, thus identifying a number of minor problems that could not be addressed in the component bench-test. A number of small interactive problems with the controller, test facility, and engine that were identified and resolved before the start of the controller test evaluation include:

- Software Problems:
 - no limits were set on derived calculation values; and,
 - information was not properly transferred to memory.

- Air/Fuel Valve:
 - discrepancies noted between controller and system valve characteristics;
 - needed to recalibrate valve position versus voltage; and,
 - air valves only opened to 80% of full-open position.

- Sensors:
 - sensors were inappropriately calibrated;
 - error in measured airflow identified; and,
 - reset gain.

- Acoustic Resonance:
 - sensors operated with significant resonance;
 - needed to damp acoustic noise; and,
 - had to decouple combustion blower bypass from system.

The controller was tested in the manual mode after resolution of the above problems, and controller gains were adjusted to ensure a stable system. A time constant of 2 to 3 seconds was observed with respect to a step change in firing rate. Upon successful system integration, the controller was tested in the automatic mode to evaluate system operation.

V. TEST AND EVALUATION

A. SYSTEM TEST OF COMBUSTOR CONTROLLER

The objective of the WPAFB Digital Combustor Controller Tests was to demonstrate operation of the digital combustor controller, and to evaluate system response to load changes. Due to time constants within the program, the manual mode of controller operation was demonstrated with the TDE assembled with a 70%-porosity Metex regenerator, and the heater head loading was mapped while testing the performance of the TDE with the regenerator modification. The TDE was then reassembled in the baseline condition (91%-porosity, 100-mesh .001 wire screen) during which the start-up and automatic transient tests were conducted.

1. Steady-State Tests

The TDE characterization test matrix is shown in Table 5-1. Curves of total cycle power and efficiency, heat input to the engine, combustor firing range, and combustor efficiency are plotted in Figures 5-1 to 5-5. The test procedure was to hold T/C #12 (heater control temperature) constant at 400, 450, and 500°C while using the computer controller in the manual mode to vary the firing rate as the engine was stroked to each test point. These tests were necessary to ensure that the addition of the controller did not affect engine performance or power control. Based on these steady-state results, operation with the new controller was judged to be similar to previous TDE operation and, therefore, acceptable.

2. Transient Tests

The transient test matrix (shown in Table 5-2) was modified to:

- stay within the operating bounds of the TDE; and,
- allow continuous transient prints from terminal point to initial point of each transient.

Figure 5-6 shows the transient steps in controller mean temperature and piston stroke for the matrix in Table 5-2. Each step change in Figure 5-6 demonstrates the controller's ability to maintain mean head temperature. Figure 5-7 shows

TABLE 5-1

STEADY-STATE TEST POINT MATRIX

<u>Heater Head Control Temperature¹</u>	<u>Piston Stroke</u>
400°C	1.4
	1.6
	1.8
	2.0
	2.2
450°C	1.4
	1.6
	1.8
	2.0
	2.1
	2.2
	2.3
	2.4
500°C	1.6
	1.8
	2.0
	2.2
	2.4

- Notes: 1. The heater head control temperature was the highest reading head T/C (T/C #12) to be consistent with the ECUT Regenerator Test.
2. Manual mode of combustor control.

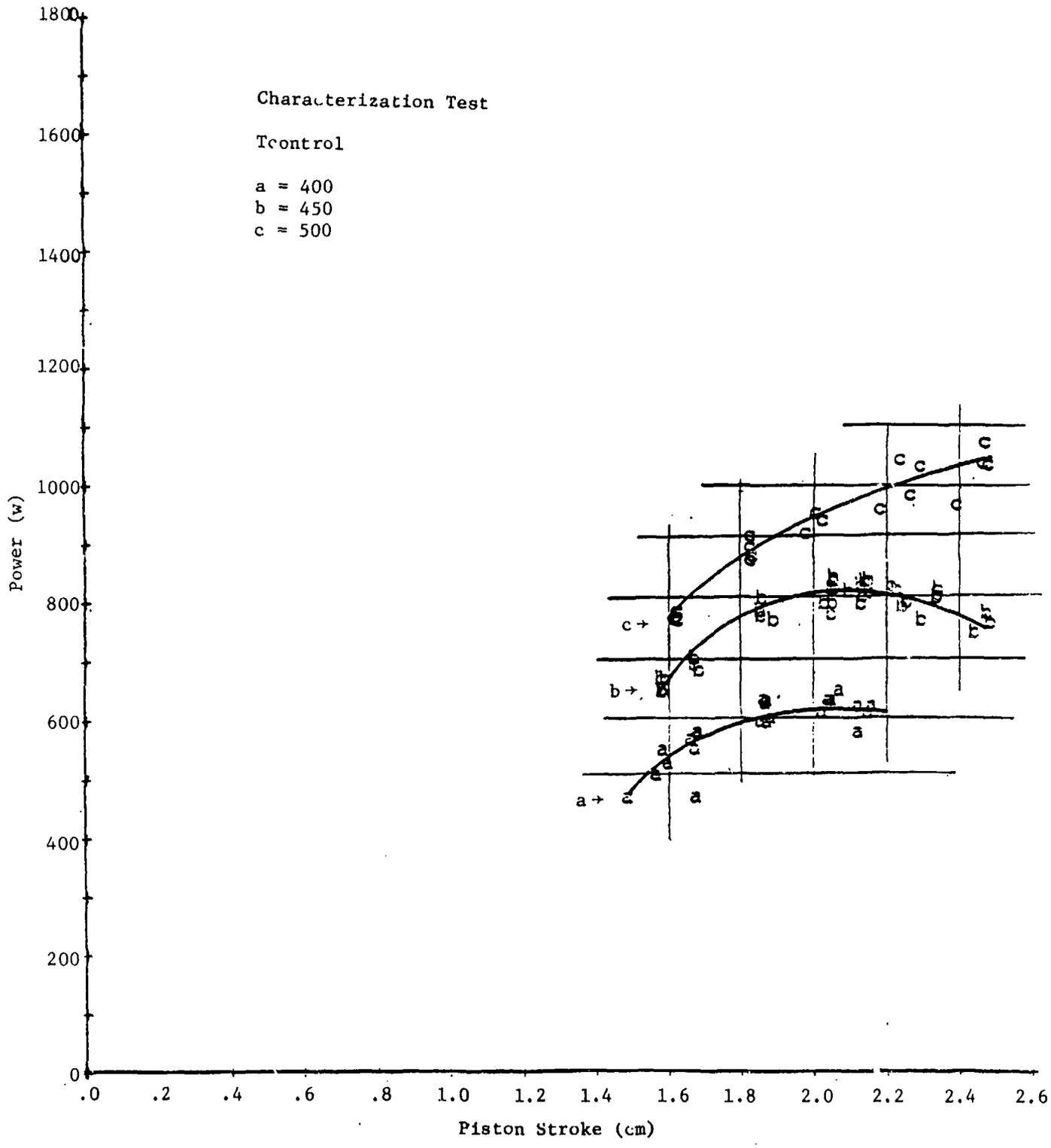


Figure 5-1 System Power Versus Piston Stroke

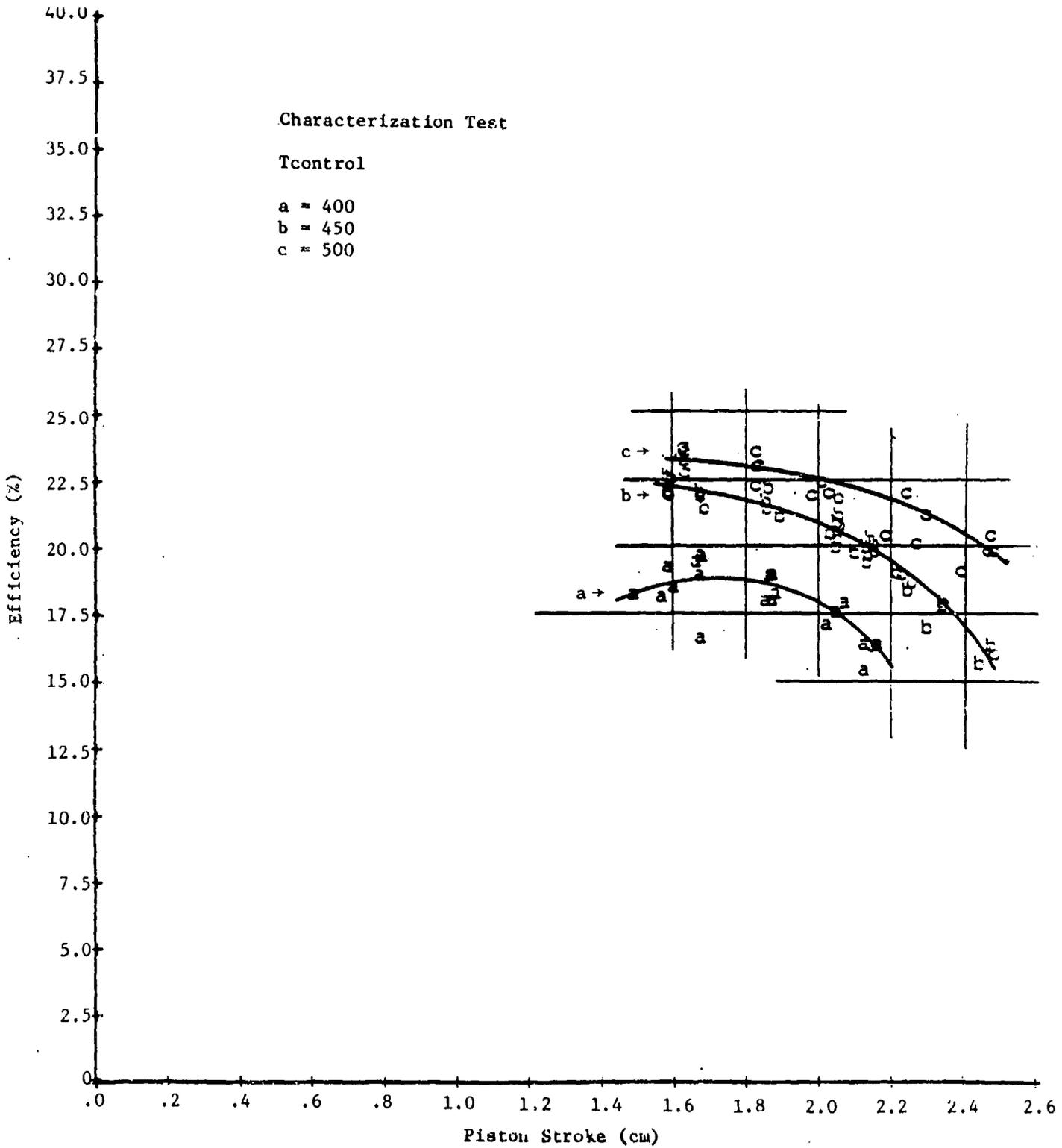


Figure 5-2 Total Efficiency Versus Piston Stroke

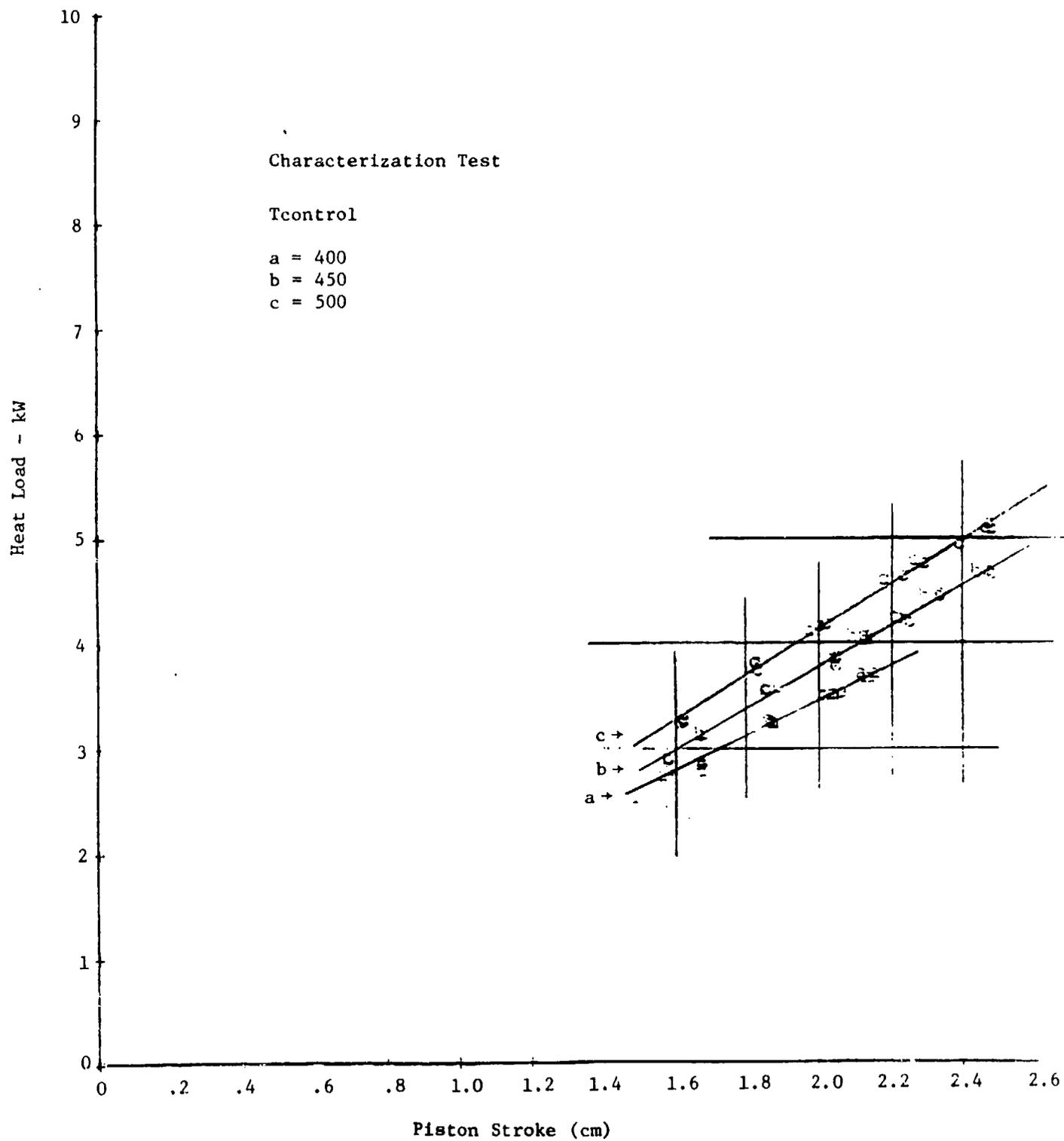


Figure 5-3 Heat Load Versus Piston Stroke

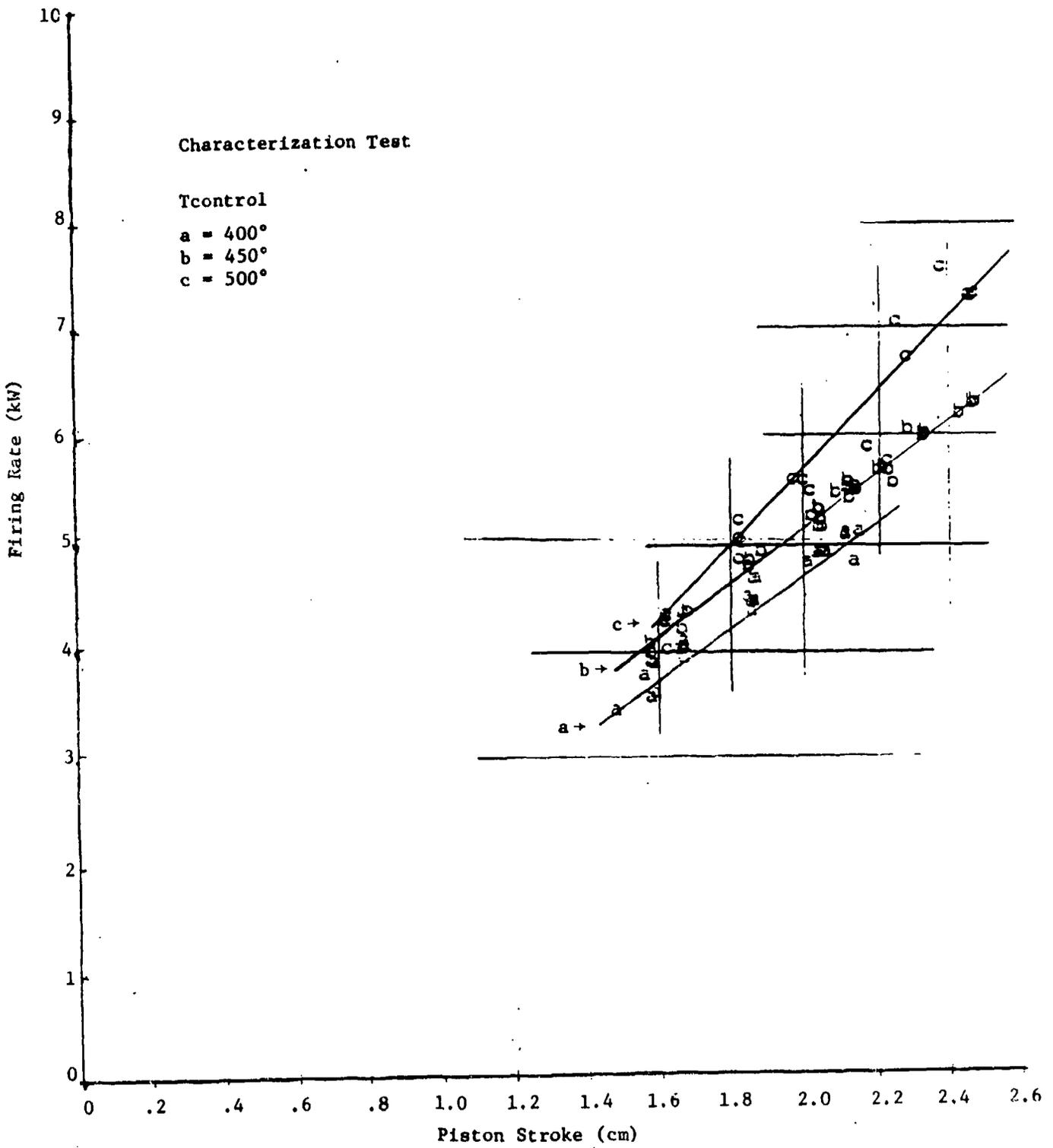


Figure 5-4 System Firing Rate Versus Piston Stroke

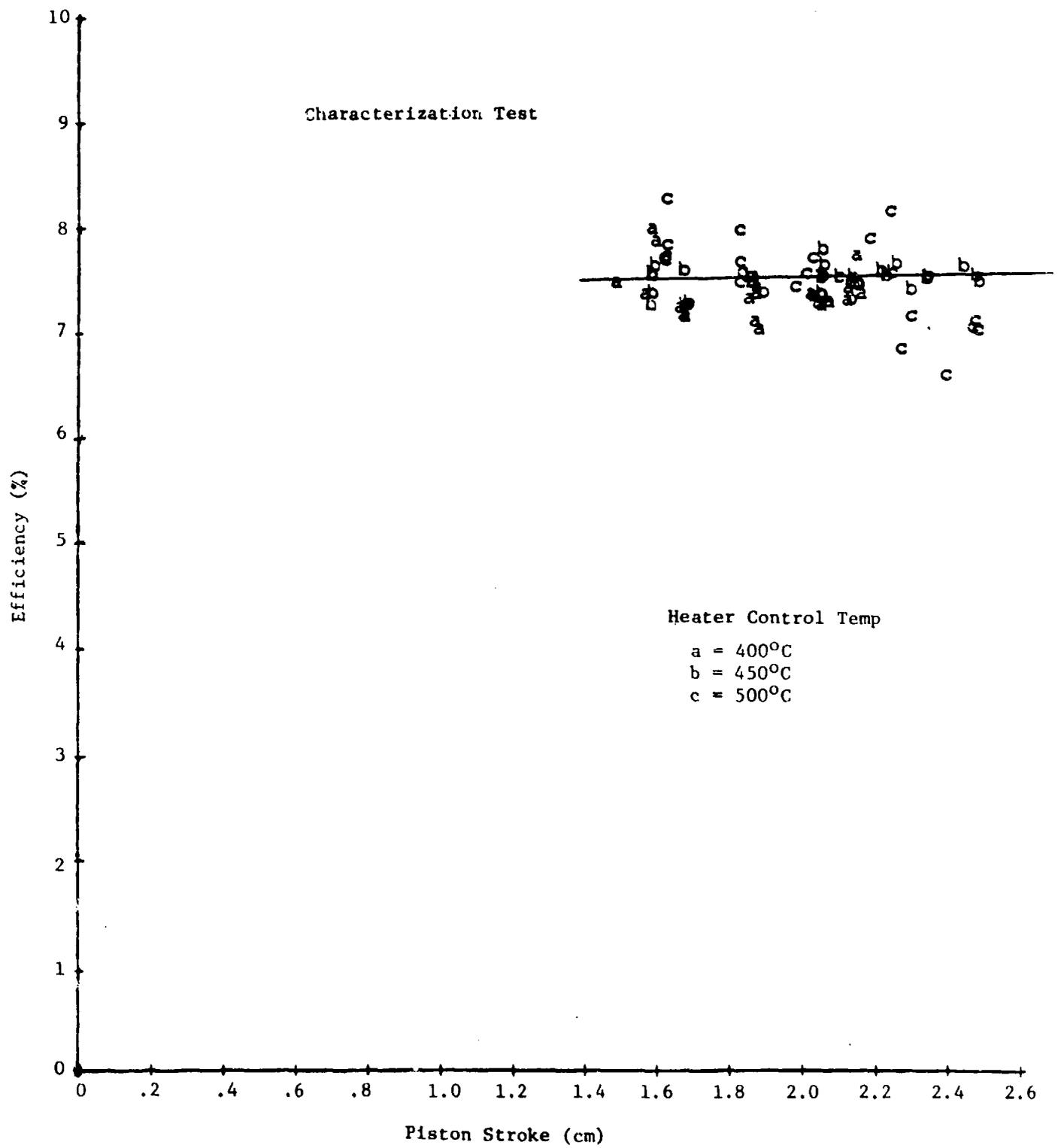


Figure 5-5 Combustor System Efficiency Versus Piston Stroke

TABLE 5-2

TRANSIENT TEST POINT MATRIX

Controller Mean Temperature (°C)	Piston Stroke (cm)	Transient Step	
		Temperature (°C)	Stroke (cm)
200	Start-up	Start-up	
400	2.0		+ .2
400	2.2	+50	
450	2.2	-50	
400	2.2		- .2
400	2.0	+50	
450	2.0		+ .2
450	2.2	+50	
450	2.2	-50	
400	2.2		- .2

Notes: 1. Automatic mode of combustor control

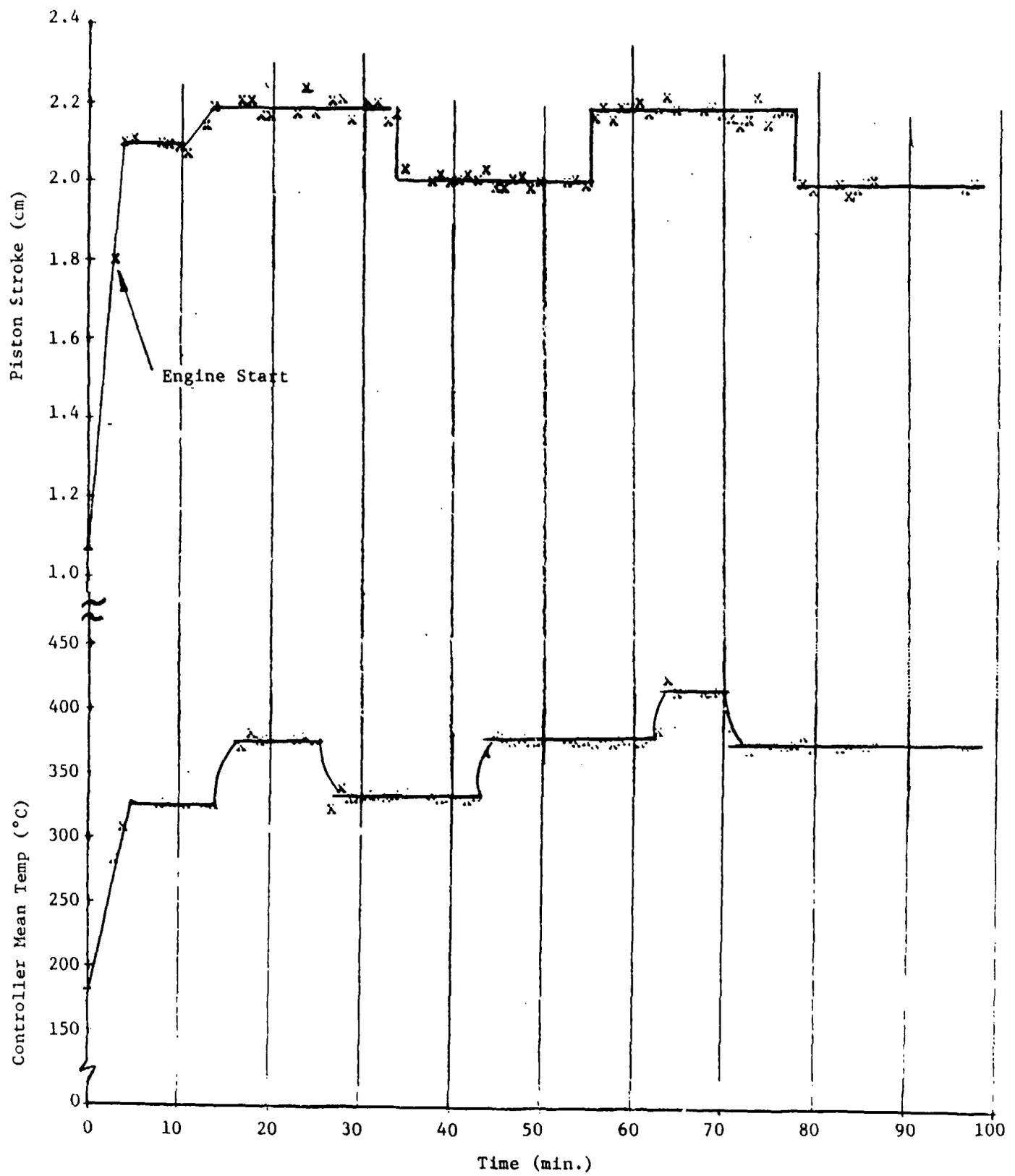


Figure 5-6 Controller Mean Temp. and Piston Stroke Versus Time

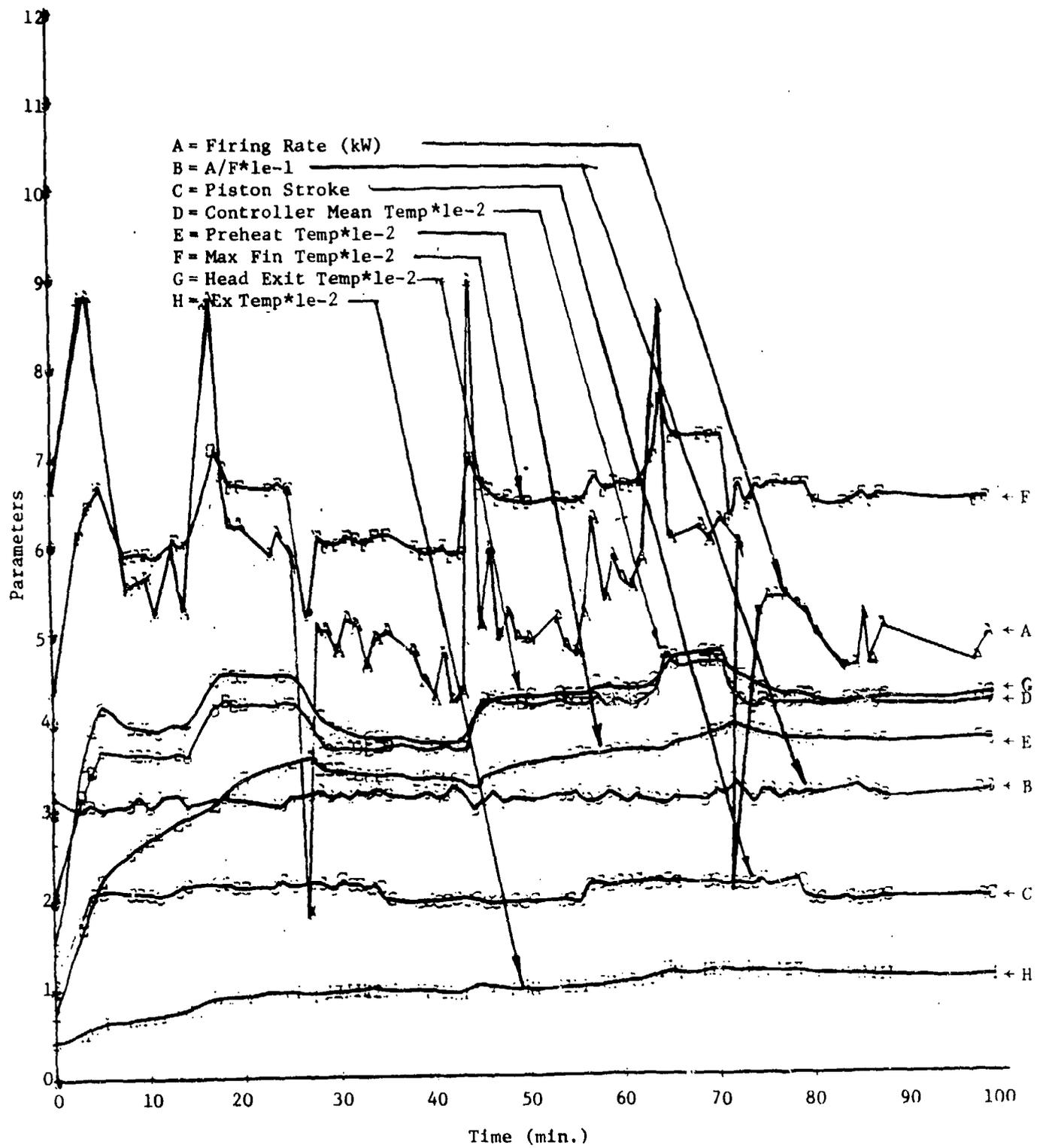


Figure 5-7 Various Parameters Versus Time

combustor system responses for these transient steps (see in Figure 5-8). The most radical change is in the firing rate as the controller opens the fuel valve to fully open for demands in increased mean temperature, and closes the fuel valve to 2 kW for decreased mean temperature demands. More severe transient steps were conducted during the gain-setting phase of the controller checkout tests. An engine start-up transient to steady state is illustrated by the burner system responses shown in Figure 5-8. The responses from a mean controller temperature step of 500 to 750°C are shown in Figure 5-9, and an A/F step of 30:1 to 20:1 is shown in Figure 5-10.

3. Conclusions

The combustor controller maintained heater head temperature in response to load changes of the system, and performed as expected by:

- automatically maintaining heater head temperature with respect to air/fuel rates and/or engine load changes;
- providing start-up interlocking with the TDE facility;
- providing close-loop control of air/fuel ratio and temperature mean max with operator set capability;
- displaying key operating parameters;
- providing automatic shutdown; and,
- providing expansion capability to interface with power control system.

The development of the combustor controller is the first phase that will lead to unattended FPSE operation. (A picture of the combustor controller as installed in the MTI TDE/FPSE test facility is shown in Figure 1-5, input/output signals to the combustor controller are shown in Figure 1-4, and the interior of the control is shown in Figure 1-3). The main features of the operating controller are:

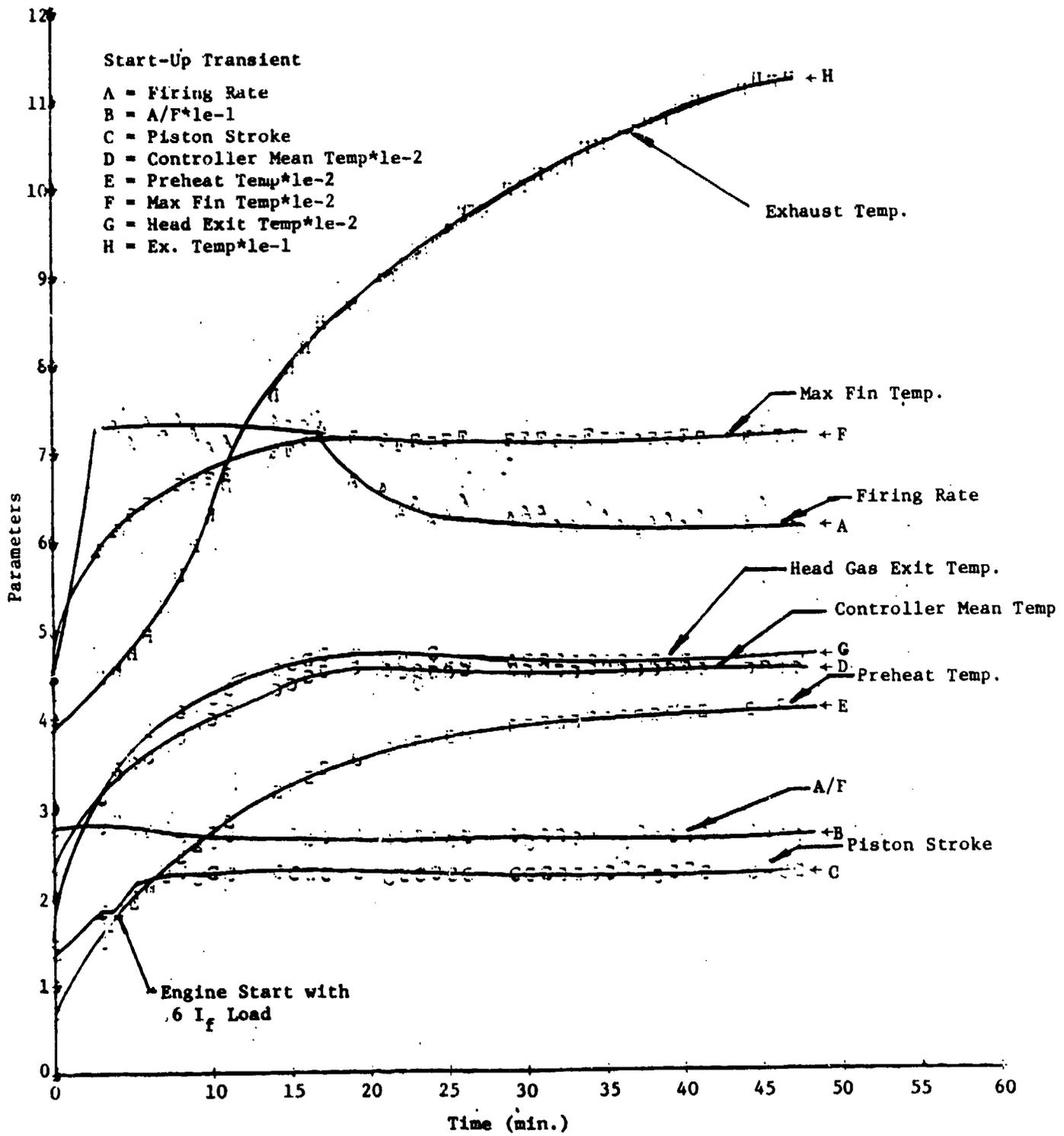


Figure 5-8 Various Parameters Versus Time

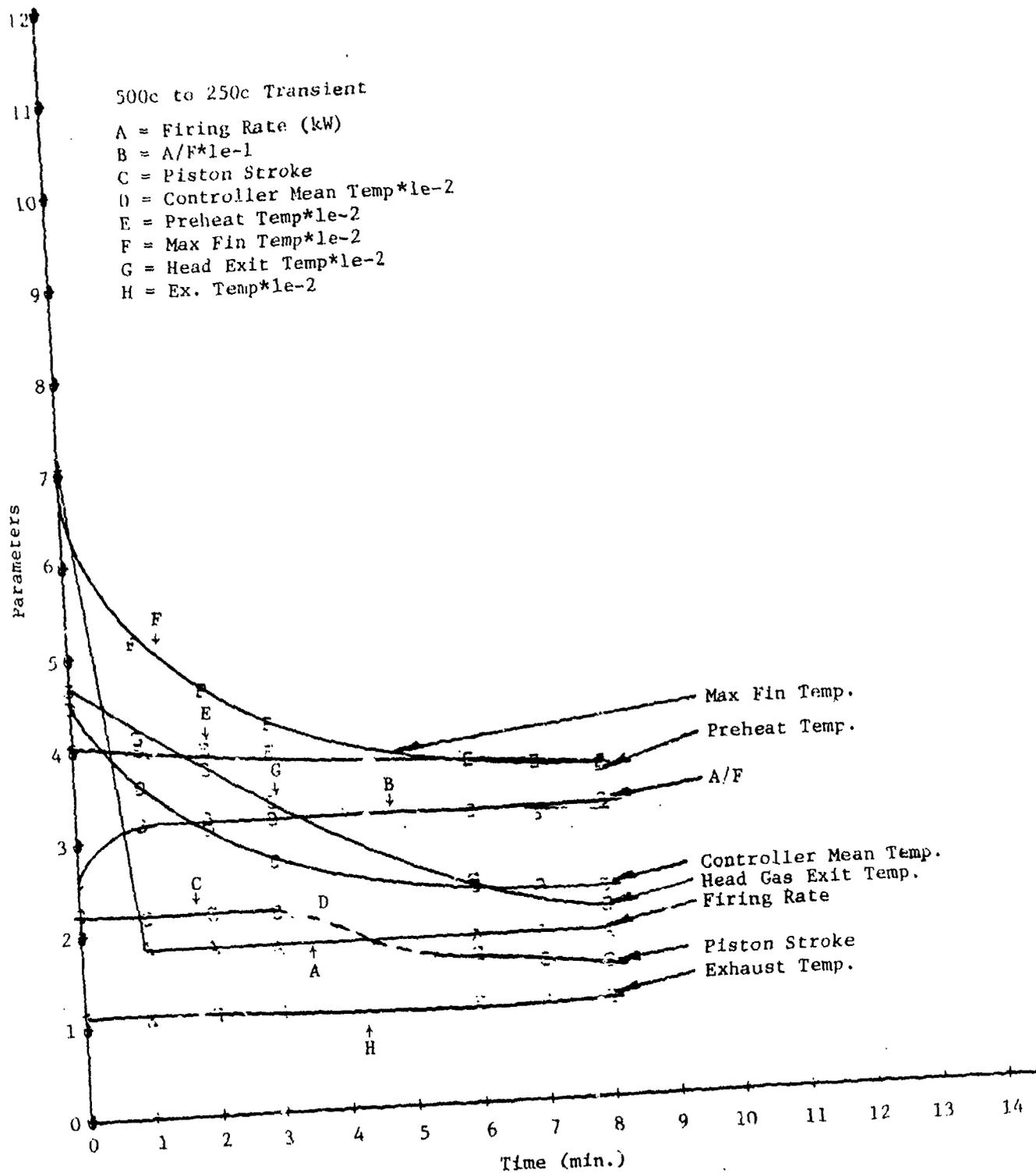


Figure 5-9 Various Parameters Versus Time

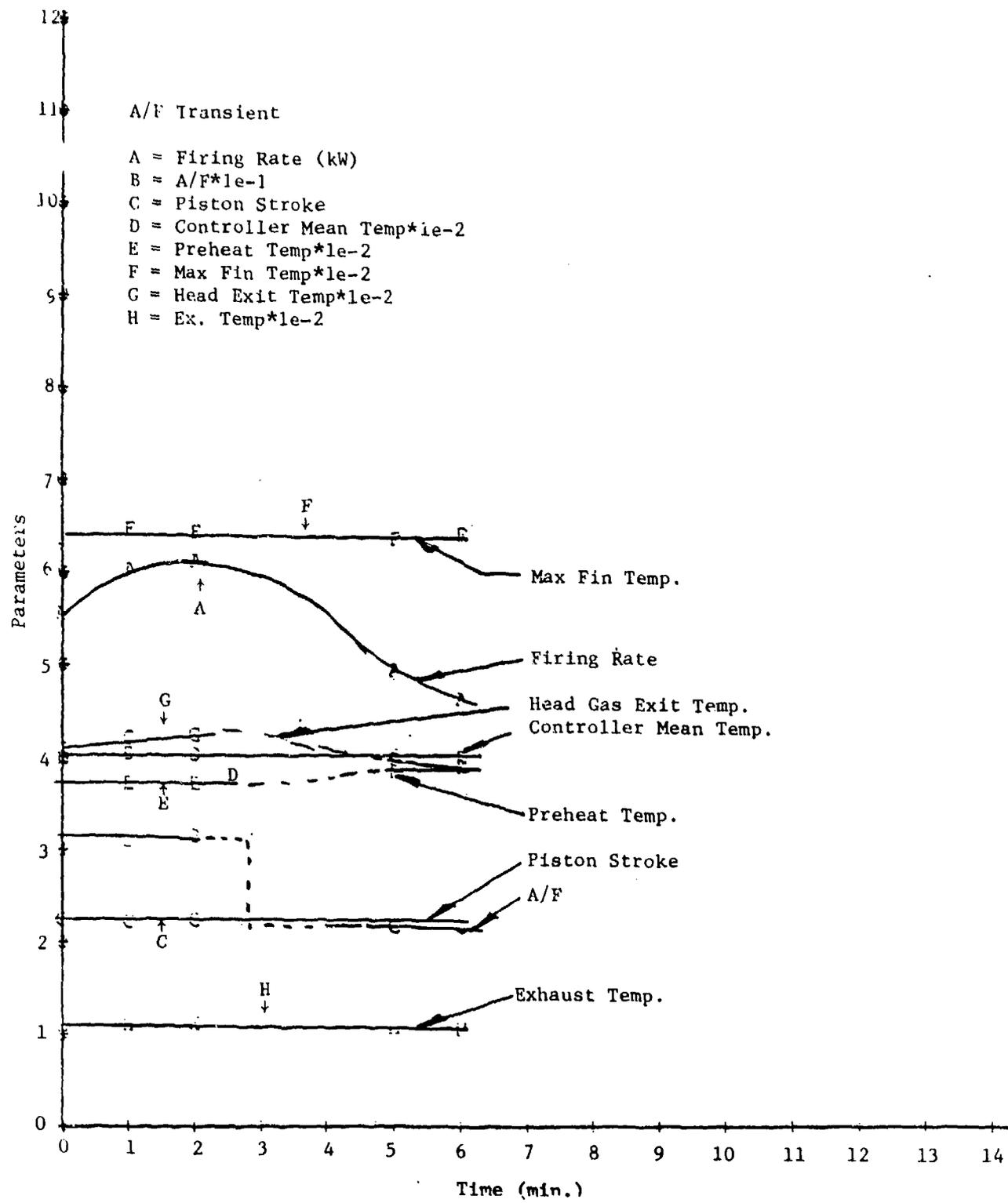


Figure 5-10 Various Parameters Versus Time

- start-up interlocking with facilities;
- closed loop air/fuel ratio control with operator set capability;
- closed loop airflow and fuel flow control;
- automatic control of heater head temperatures;
- display of key operating parameters;
- automatic shutdown in the event of key failures in the system; and,
- expansion capability to interface with power control system.

The range over which the controller has been tested includes:

- firing rate 2 to 10 kW
- temperature 200 to 500°C
- air/fuel ratios 15:1 to 35:1
- set temperature error $\pm 10^{\circ}\text{C}$ (versus goal of $\pm 20^{\circ}\text{C}$)

The above limitations in operating parameters are operating limits of the TDE and test facility, not a limitation of the controller. The controller performed as expected; other comments on the entire system performance are:

- the largest thermal inertia in the burner system is in the recuperator response;
- during light-off, the air valve is almost closed while the fuel valve is open (results in a very rich light-off of the order of 2-5 to 1; the burner does light, and soon after ignition, the air valve opens to the proper preset air/fuel ratio); and,
- an engine start from 200°C mean temperature was accomplished in 3 to 4 minutes with no difficulties during the transient.

VI. LIQUID-FUEL COMBUSTOR/EXTERNAL HEAT SYSTEM EVALUATION AND DESIGN

A. EVALUATION OF MONOLITHIC HEATER HEAD

In addition to the evaluation of the combustor controller, an analytical evaluation of the external combustion system*, with emphasis on the monolithic heater head, was performed to assess the adequacy of the system, and its potential for incorporating various military logistic fuels.

1. Performance of TDE Heater Head

The TDE utilizes a monolithic heater head (shown in Figure 6-1) in lieu of the traditional tubed design. The advantages of the monolithic heater head include elimination of the thin-wall tubes, elimination of the structure tube-to-head brazed or welded joints, and potential for a long-lived heater head.

The TDE heater head as fabricated exhibits an axial temperature distribution** (shown in Figure 6-2), as opposed to uniform temperature distribution, that limits its capability for peak temperatures and, hence, higher performance. The TDE heater head was the first monolithic heater head developed. Improvements in analytical techniques and imperical data from the head have led to improved heater head designs that will be built and tested as part of MTI's continuing FPSE Development Program. Subsequent testing of the EM monolithic heater head substantiates its much improved temperature distribution over that of the TDE head.

The problem with the TDE heater head is the external and internal leading fin geometry. The outside fins transfer too much heat to the base metal, while the internal fins are not capable of transferring the same amount of heat to the working gas. Hence, the leading base-metal temperature is too high, limiting temperature based on structural constraints. The mean heater head temperature

*consists of heater head, preheater, combustor, fuel nozzle, air/fuel control, fuel supply system

**discussed in Section IIA, and shown in Figure 2-8

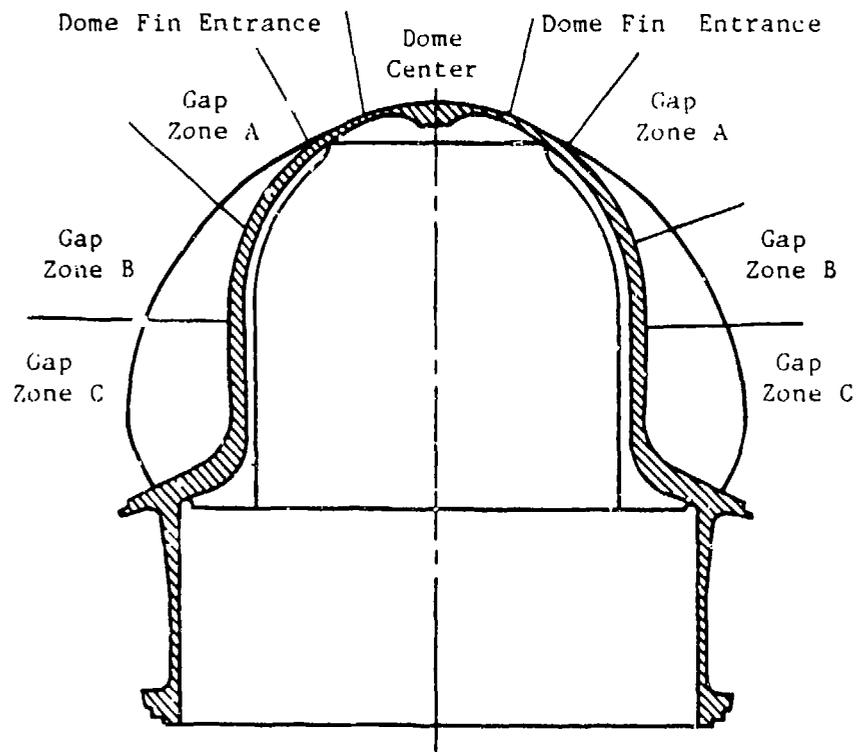
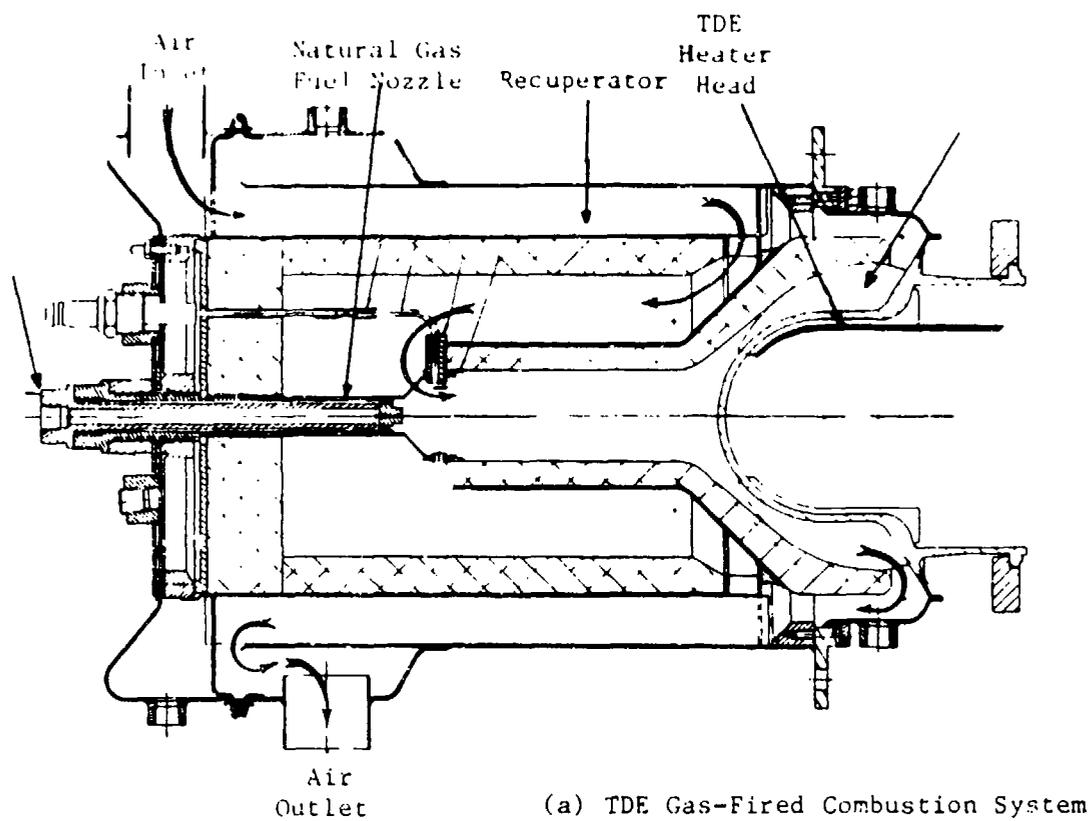


Figure 6-1(a) TDE Gas-Fired Combustion System
 (b) TDE Finned Heater Head

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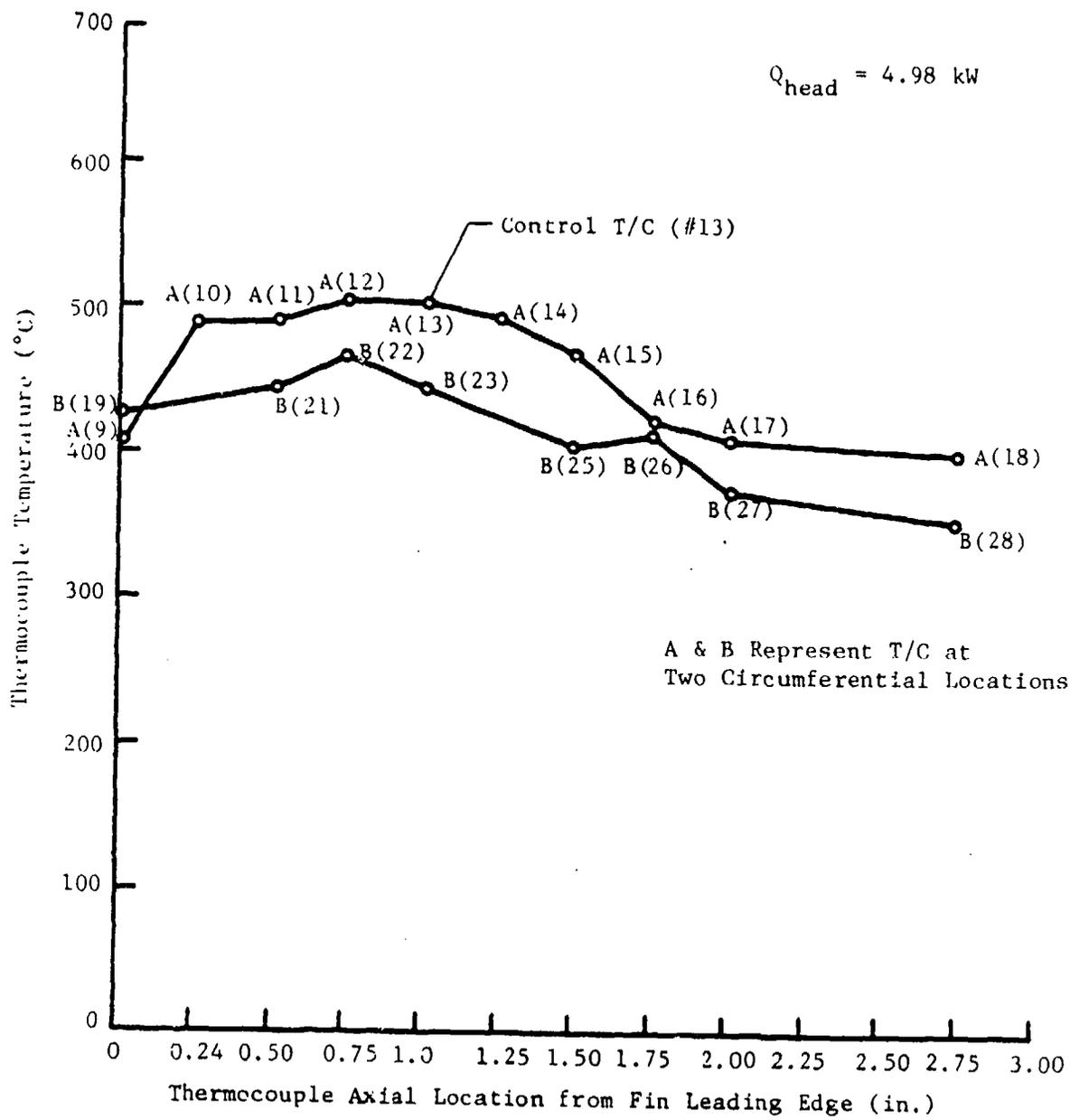


Figure 6-2 Heater Head Temperature Axial Distribution

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is considerably less than this peak heater head temperature. This can be seen in Figure 6-3 where, as stroke is increased (power increased), the leading edge fin temperature remains almost constant, while the dome (protected by a ceramic cup and indicative of expansion space temperature) continues to decrease. Development of a monolithic heater head that provides uniform temperatures is necessary so that maximum potential of the engine system with temperature can be realized. This has been accomplished with the development and test of the EM monolithic heater head.

2. Suitability of Monolithic Heater Head for Air Force Logistic Fuels

There is no known limitation for use of the monolithic heater head with USAF logistic fuels. The only concern would be high-temperature corrosion of the heater head; however, for the materials and peak temperature limits that would be selected for FPSE monolithic heater heads (i.e., Inconel 713 - 1400°F, Inconel 617 - 1200°F, and SS 316 - 1100°F), no significant corrosion would take place. In addition, MTI reviewed the entire external combustion system in a separate study, concluding that it is feasible to utilize gasoline, jet fuel, and diesel fuel in a single FPSE external-combustor-system design. The only disadvantage is that as sulfur content of the fuel increases (gasoline → jet fuel → diesel fuel), the amount of sulfuric acid in the exhaust products increases proportionately. As long as the acid remains in a gaseous state, no problem exists; however, if the exhaust is cooled below the dew point (~300°F), a corrosive condensate is introduced. If either the average exhaust gas temperature in the preheater or the local gas temperature in contact with a cool preheater wall are below 300°F, condensation occurs.

United Stirling of Sweden (USAB)* has experienced corrosion with the P-40 stainless steel preheater while using diesel fuel, but none with unleaded gasoline. Prevention of this would require reducing the preheater effectiveness (higher exhaust temperature and lower cycle efficiency), or using a material impervious to sulfuric acid (possibly ceramics); therefore, the conclusion is that not only is the monolithic heater head acceptable for multifuel use, but the entire

*major subcontractor to MTI's Automotive Stirling Engine (ASE) Development Program

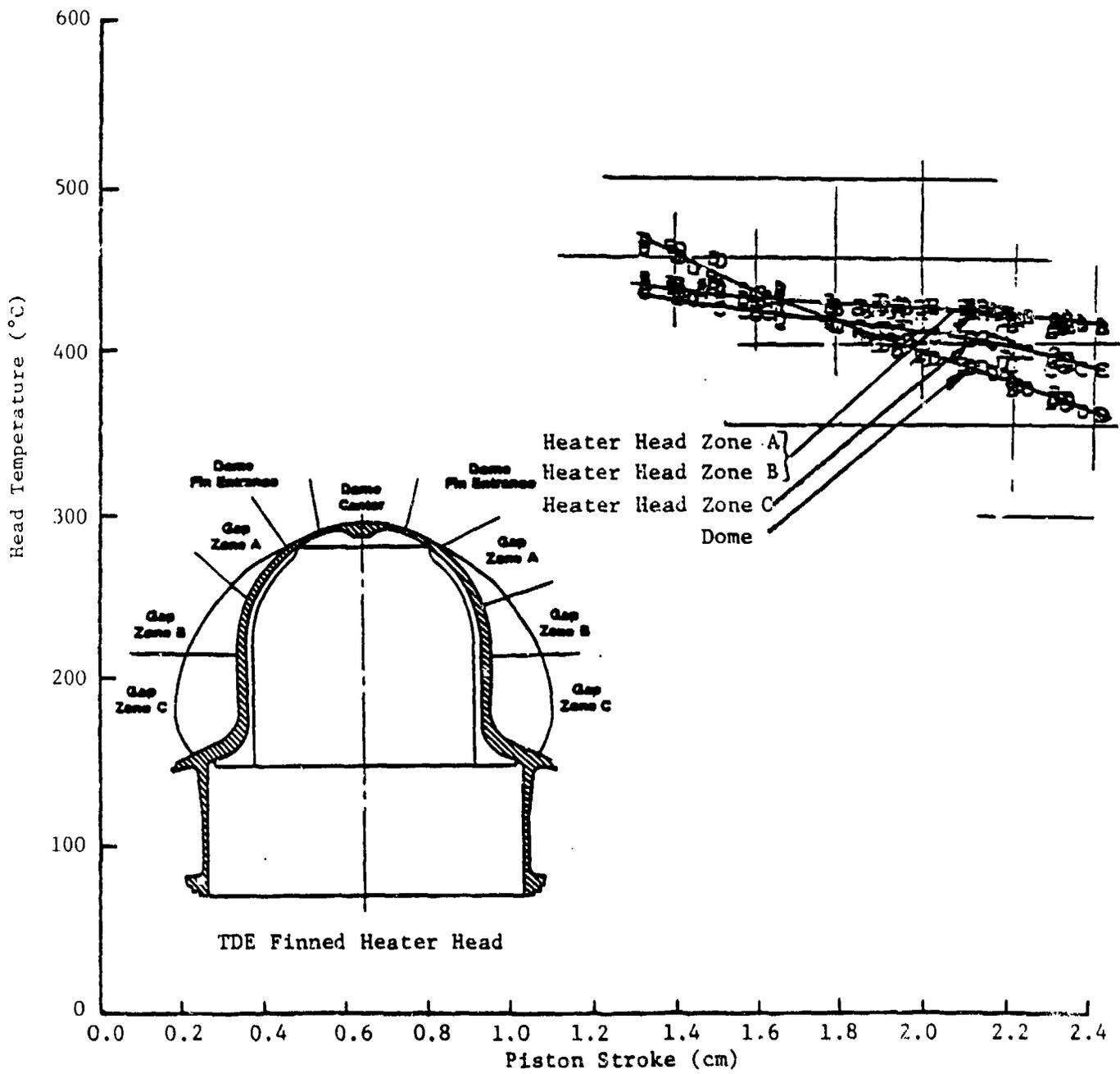


Figure 6-3 Average Heater Head Temperature Versus Piston Stroke

combustor system can be designed to be satisfactorily operated with Air Force logistic fuels.

B. EMISSIONS OF THE TDE EXTERNAL HEAT SYSTEM

Emissions of the TDE external heat system were taken and evaluated as part of this program. Gaseous emissions (NO_x , CO, and HC) were measured on November 3, 1981. A total of nine data points were taken using a matrix of air/fuel ratios (35, 30, and 20 by volume) and maximum heater head temperatures (400, 450, and 500°C) burning natural-gas fuel. The results are presented in Figures 6-4 and 6-5 on a volumetric and mass (Emissions Index) basis, respectively, as a function of Lambda (λ), which is defined as air/fuel divided by the stoichiometric (theoretical for complete combustion without excess air) air/fuel.

As illustrated in Figures 6-4 and 6-5, none of the gaseous emissions show any dependence on control temperature. The apparent scatter in CO is most likely due to the fact that the high-range CO analyzer (0-5000 PPM) had to be used because of the unavailability of the low CO instrument (0-500 PPM). For the formation of pollutants, relevant TDE parameters and their effects are:

Engine Parameter	Influences	Effects
Preheat Temperature	Flame Temperature	NO_x , CO, HC
Air/Fuel Ratio	Flame Temperature	NO_x , CO, HC
Airflow	Residence Time	NO_x , CO, HC
Heater Head Temperature	Catalytic Reaction	CO
Heater Head Heat Load	Reaction Rate	NO_x , CO

As maximum heater head control temperature is varied, preheat temperature, heater load (engine output), and mean head temperature vary, as illustrated in Figures 6-6 to 6-8; however, these variations are not very large. A larger variation in the temperature may have had a more noticeable influence on emissions. Similarly, heater head load (4.1-4.7 kW) and mean temperature (300-375°C) variations are small. A larger variation in heater head load can also be expected to influence emissions. For the test conducted, the dominant effect on emissions is due to variations in air/fuel and airflow.

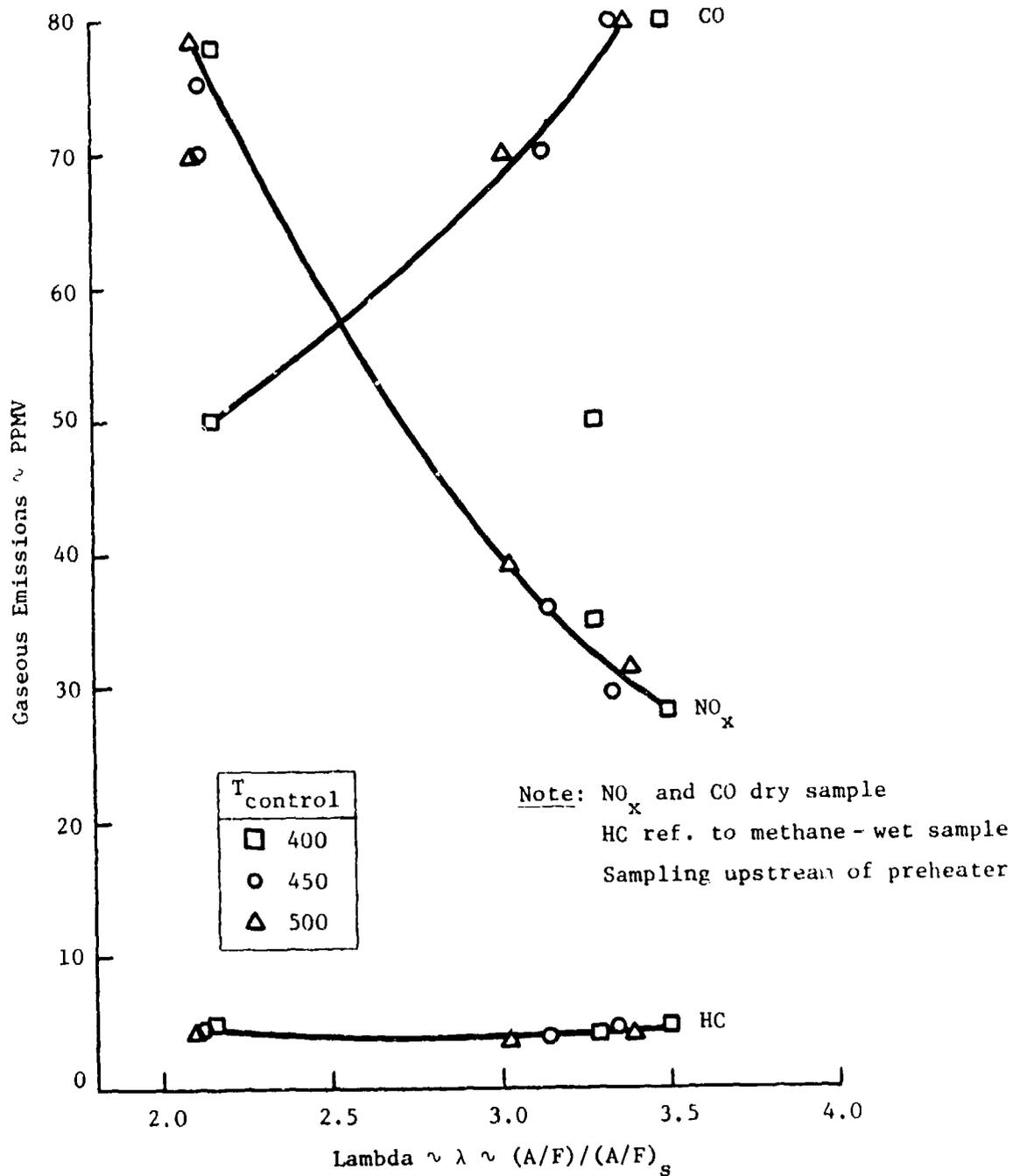


Figure 6-4 TDE Emissions - Lambda Versus Gaseous Emissions (Natural-Gas Fuel)

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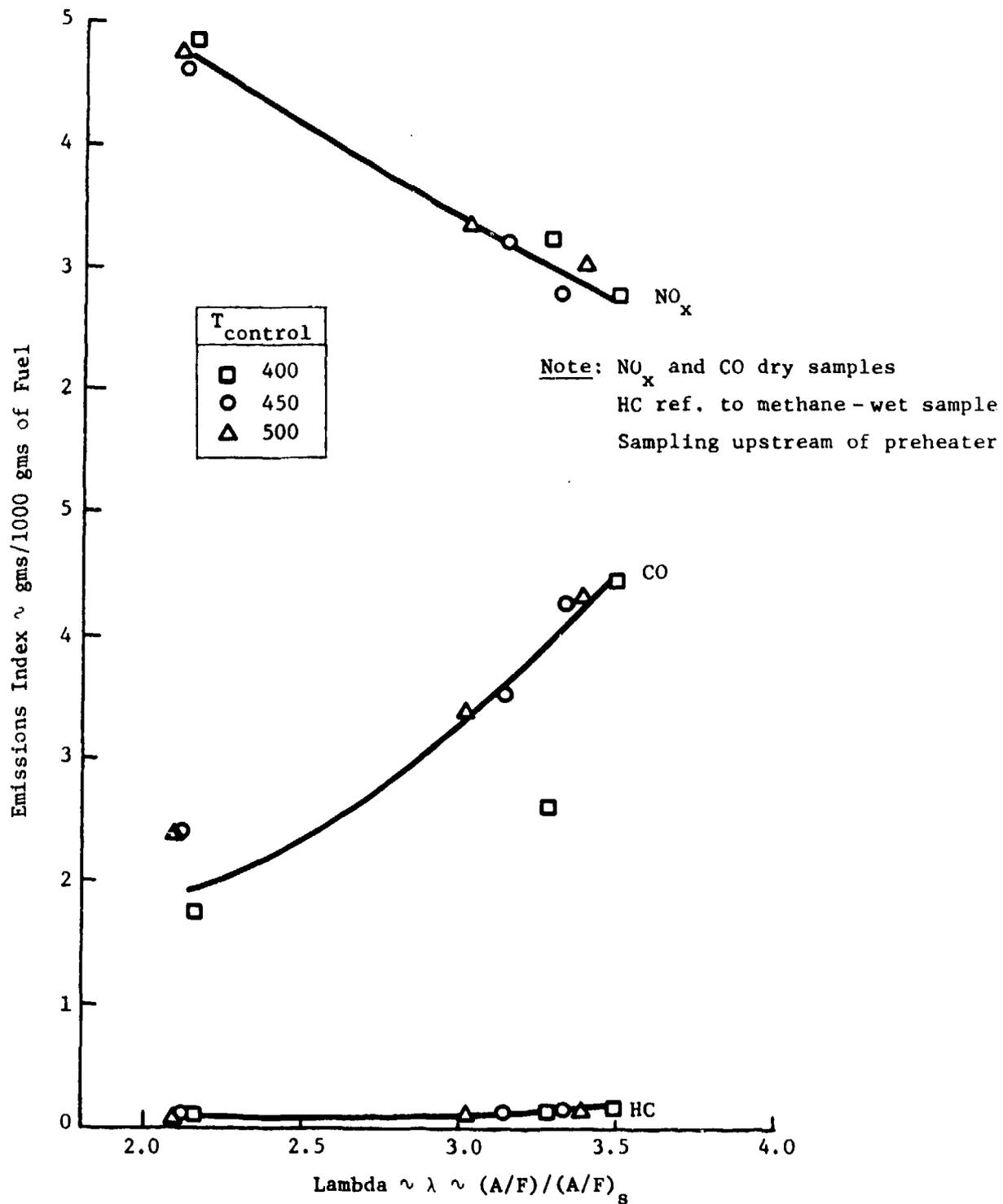


Figure 6-5 TDE Emissions - Lambda Versus Emissions Index (Natural-Gas Fuel)

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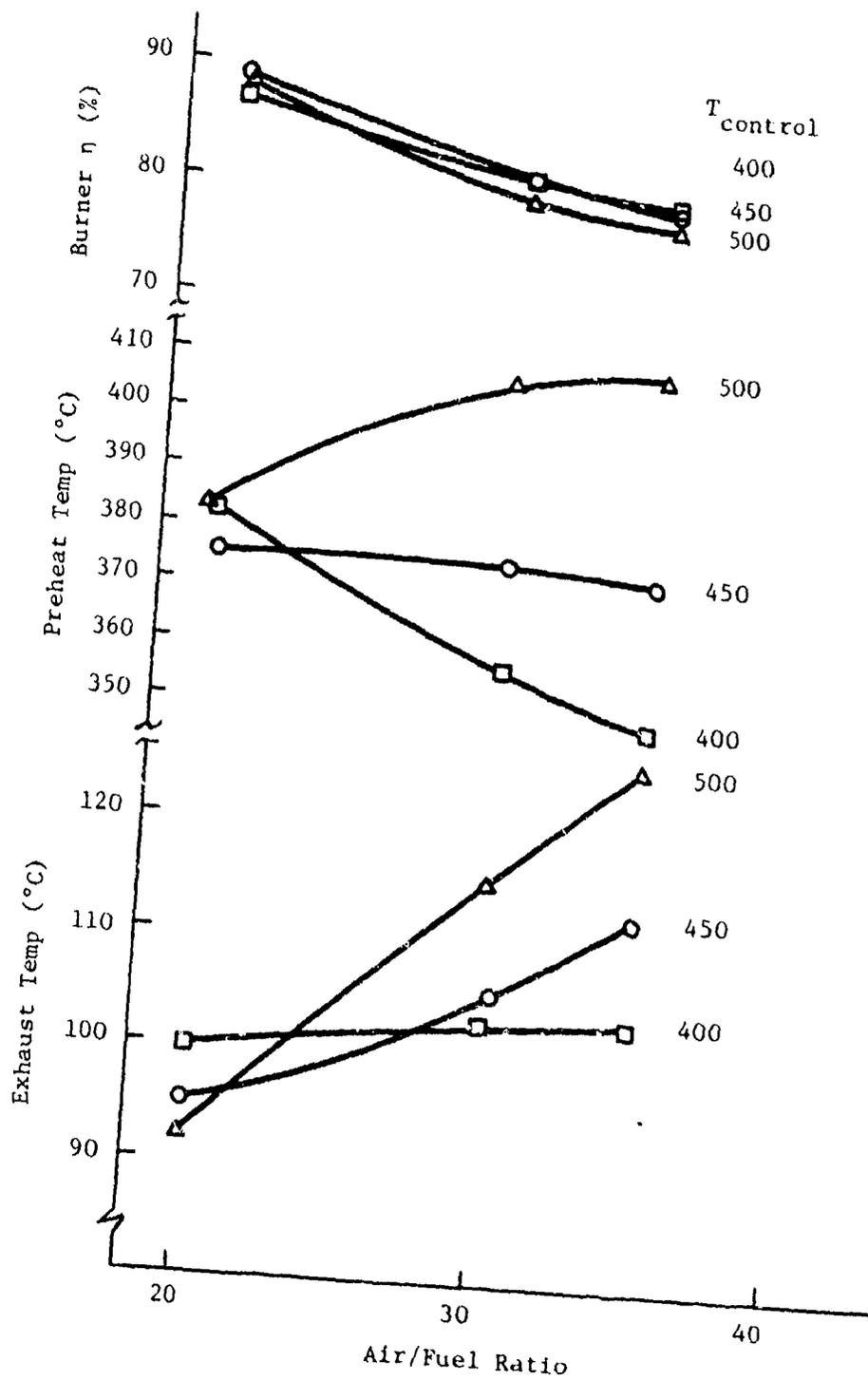


Figure 6-6 Exhaust Temp/Preheat Temp/Burner η Versus Air/Fuel Ratio

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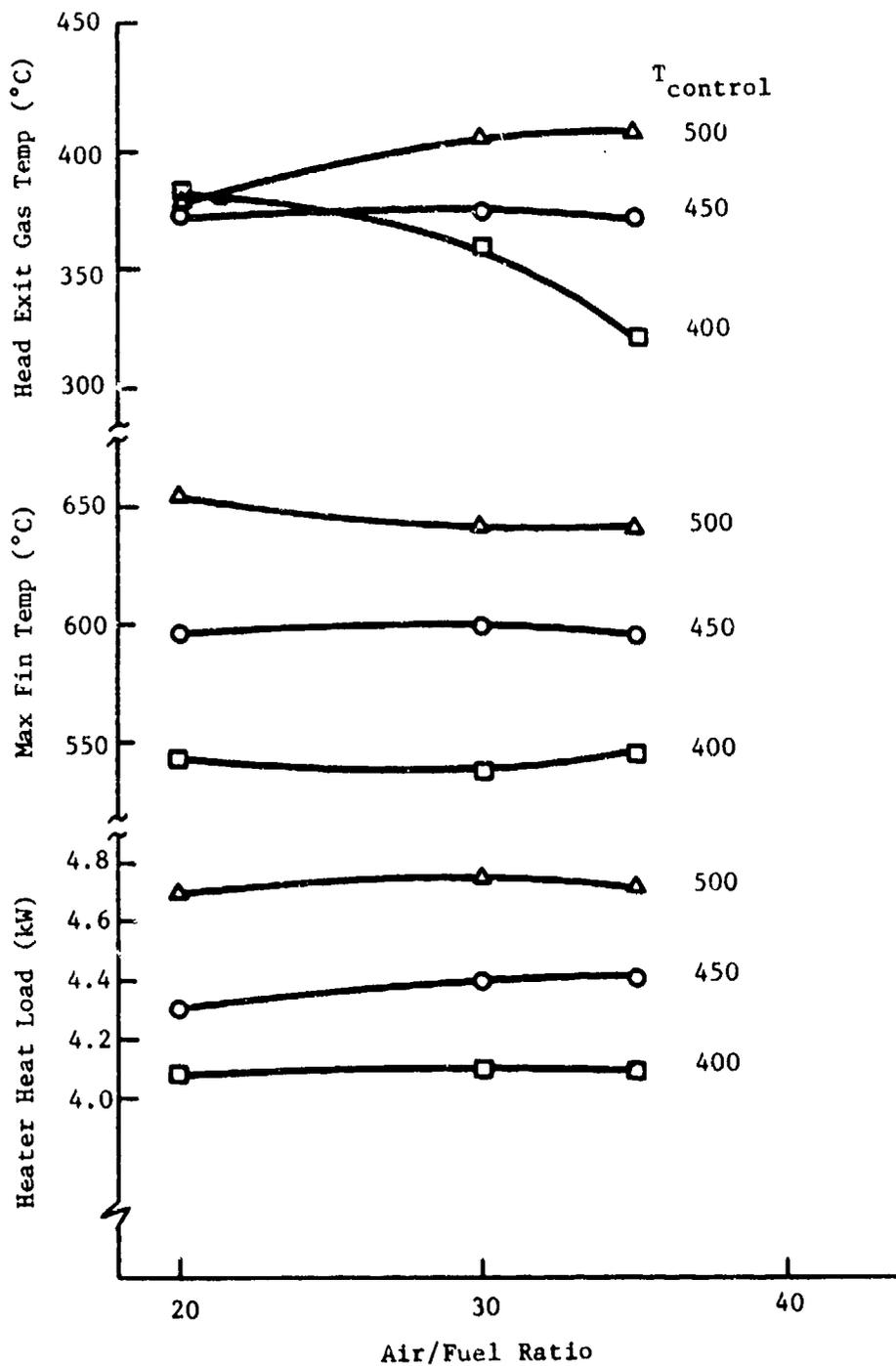


Figure 6-7 Heater Heat Load/Max Fin Temp/Head Exit Gas Temp Versus Air/Fuel Ratio

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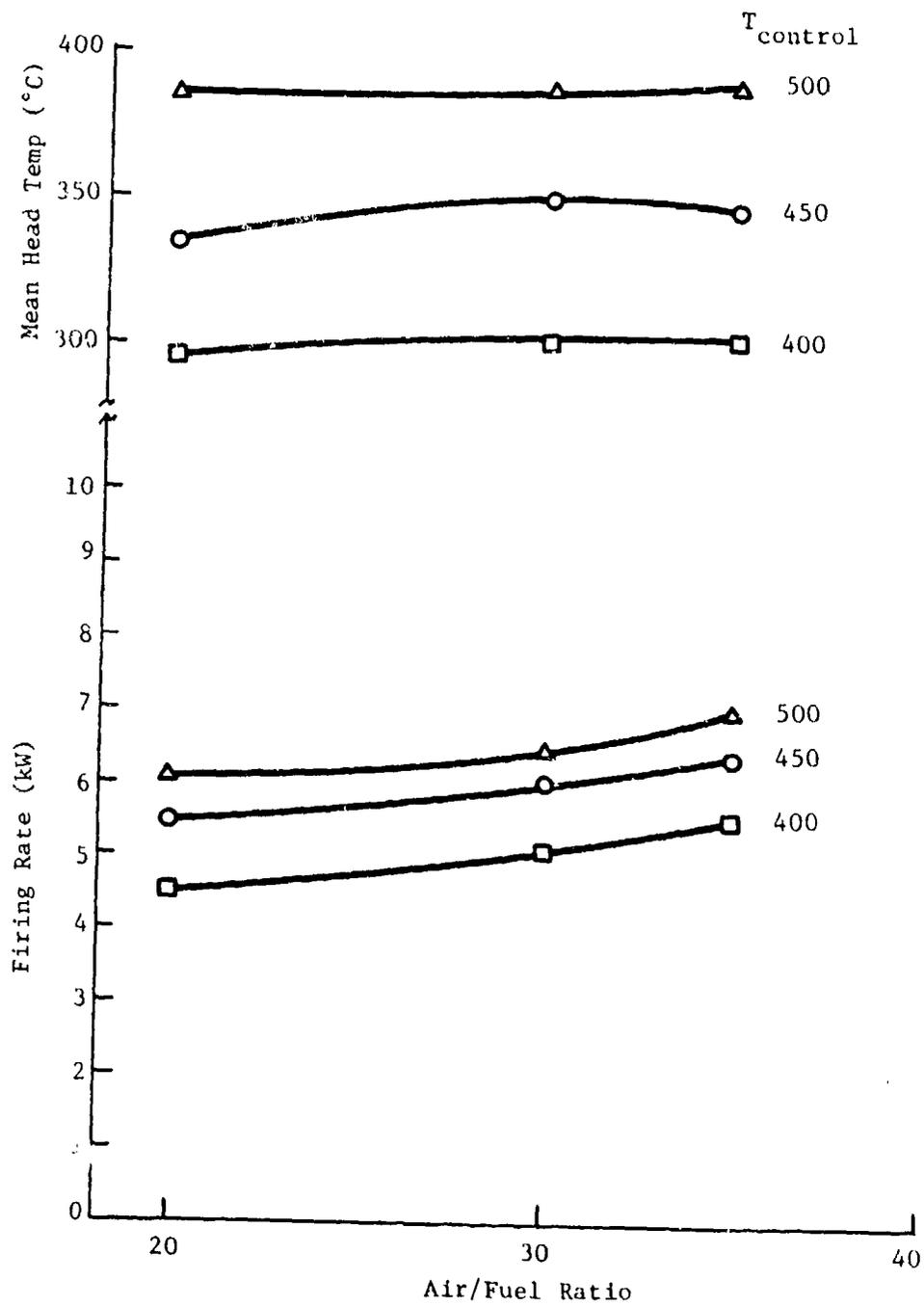


Figure 6-8 Area Weighted Mean Head Temperature and Firing Rate Versus Air/Fuel Ratio

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From Figures 6-4 and 6-5, a strong affect of air/fuel (λ) on CO and NO_x is noted, while HC is essentially constant. As λ increases, flame temperature decreases. Concurrently, airflow increases (fuel flow, i.e., "firing rate" in Figure 6-8 is nearly constant) and the residence time at that flame temperature decreases. The effect of both is to decrease NO_x - exponentially in the case of flame temperature, and linearly due to residence time. CO, whose oxidation to CO_2 is retarded by decreased flame temperature and residence time, exhibits the opposite trend. The extremely low and flat HC levels indicate a more than ample combustor reaction volume.

Overall emissions levels are extremely low in the case of NO_x and HC, but are reasonable for CO. Calculating a combustion efficiency based on the highest emissions levels of CO (80 PPM) and HC (5 PPM) yields an efficiency equal to 99.9%. It must be noted that the TDE is operated at extremely high λ 's (excess air), as compared to the General Motors GPU-3 Stirling engine (1.4-2.7) and MTL's ASE, P-40, or Mod I (1.15-1.4) engines.

Although beneficial to NO_x emissions, a penalty is paid in external heat system ("burner") efficiency, as shown in Figure 6-6. If the TDE were operated at a λ equal to 1.8, an efficiency of 90% is possible. This would, however, incur a penalty in NO_x emissions (Figure 6-4). The following conclusions can be made:

- small variations in preheat temperature, heater head load, and mean head temperature did not affect the emissions levels;
- as combustion becomes leaner (increasing λ), NO_x decreases and CO increases, as expected;
- emissions levels are extremely low, i.e., NO_x was less than 100 PPM, and CO and HC indicate a high combustion efficiency;
- the TDE data compares favorably to published emissions of the GPU-3 burning diesel fuel; and,
- the gas analyzer CO_2 measurements used to calculate λ agree reasonably well with those obtained with the gas chromatograph and the engine cell airflow/fuel flow.

C. GPU-3 DIESEL-COMBUSTOR TEST AND BASELINE EVALUATION

As a prelude to the design of a liquid-fuel combustion system that will integrate with the MTI FPSE designated Engineering Model, the combustor and fuel nozzle of the GPU-3 were tested and evaluated. The 10-hp GPU-3 was designed to operate on diesel fuel, lending its combustor performance information as a valuable baseline. The GPU-3 combustor and fuel nozzle (Figures 6-9 and 6-10) were supplied by NASA/MERADCOM.

The combustor cup has three air entry points:

- eight slots or louvers located on the conical dome;
- six tubes located on the cylindrical portion of the cup; and,
- an annulus, formed by the cup and liner.

The slots serve a dual purpose: 1) to cool the dome; and, 2) to impart swirl to the flow, creating a recirculatory region inside the cup for mixing and flame stabilization. The remainder of primary combustion air enters through the tubes. Air that flows in the annulus is used to cool the downstream cylindrical edge of the cup, thus completing the combustion process. The water-cooled fuel nozzle uses an external supply of pressurized air for atomization, and contains an igniter located in close proximity to the nozzle exit. The face of the nozzle also contains eight slots that are fed with a small amount of air via feed holes upstream of the combustor cup. The air corotates with that entering through the cup's dome slots, serving to purge the igniter and nozzle.

Prior to fired testing, the fuel nozzle was sprayed with diesel fuel and found to have an asymmetric pattern that was corrected by replacing the spin plug and cup. Atomizing air pressure was varied between 1.0 and 1.5 psig, with no effect on the diesel-fuel pressure versus flow characteristic or spray quality.

Evaluation of the GPU-3 hardware was performed in the MTI Free-Piston Combustor Rig (Figure 6-11), which uses an electric heater to supply preheated combustion air to burn diesel fuel. A portable diesel-fuel supply, control, and measurement system was designed and fabricated. Sheet-metal modifications were made to adapt the GPU-3 combustor and fuel nozzle to the rig. The GPU-3 combustor liner (Figure 6-9) was replaced with a 3.66-inch I.D., 10-inch long cylinder. The

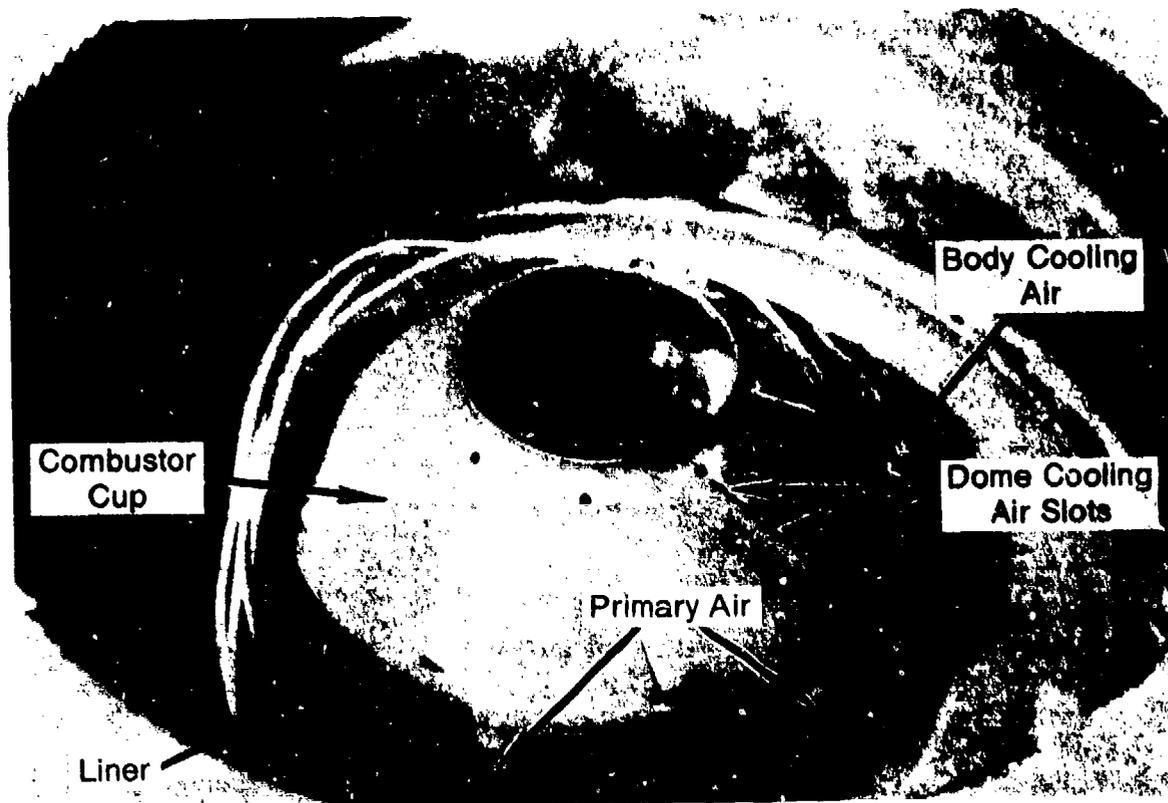


Figure 6-9 GMR Two-Piece Burner Assembly

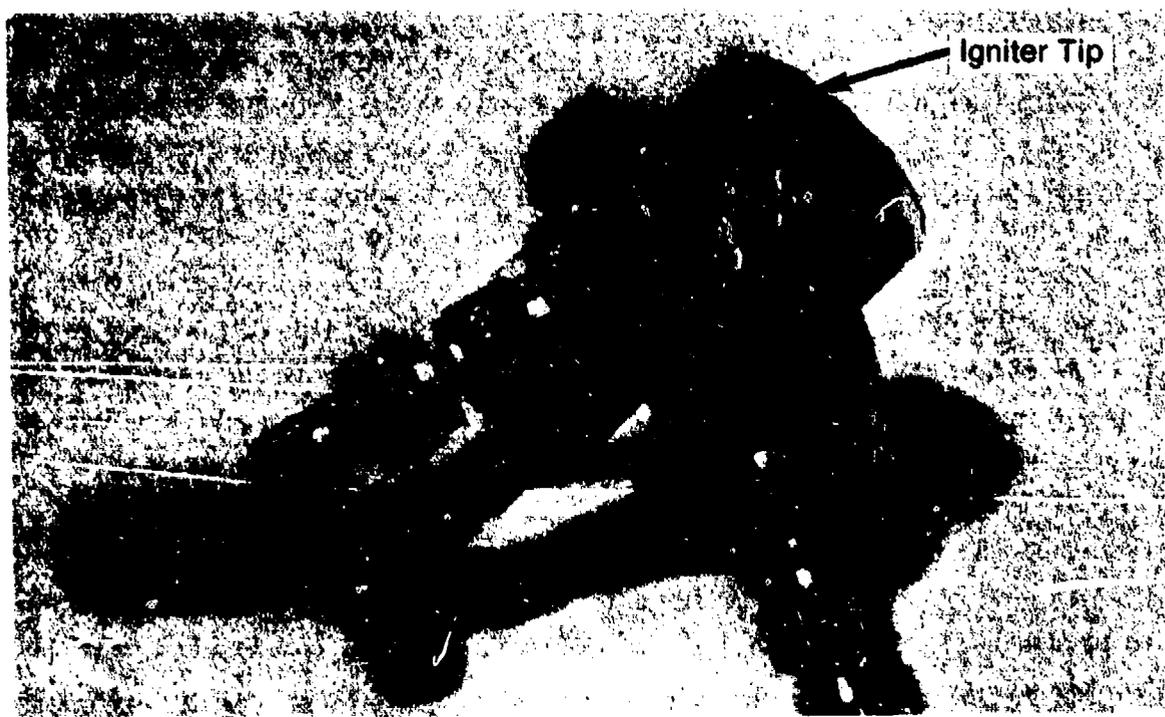


Figure 6-10 GMR Fuel Nozzle and Igniter Unit

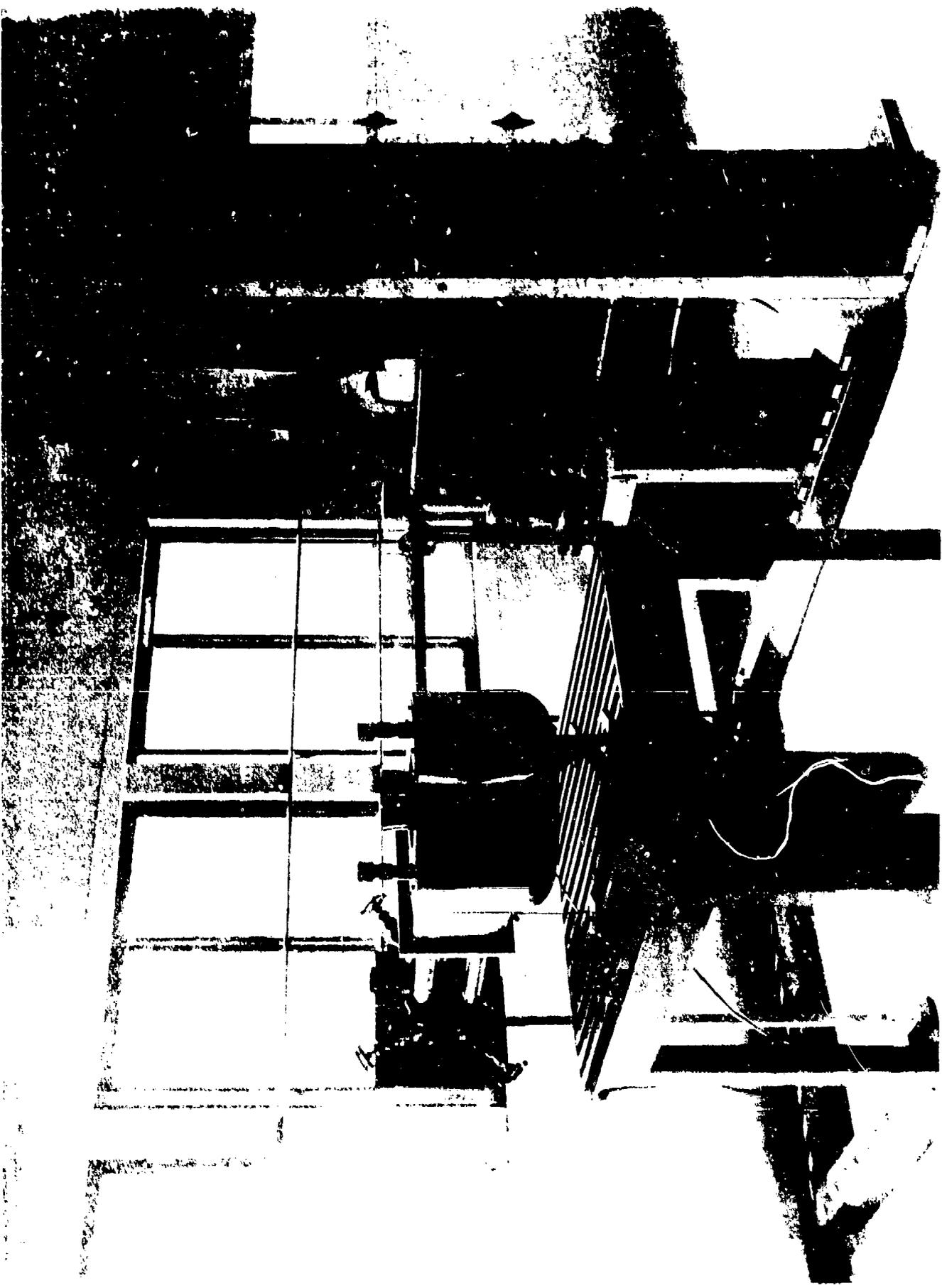


Figure 6-11 Free-Piston Combustion Rig

I.D. is the same as the engine liner to preserve the same cooling annulus flow. Due to the arrangement of the rig, the fuel nozzle and combustor were mounted upside down, e.g., nozzle pointing up, as compared to the engine. For ignition, the motor-driven engine power-supply system was mounted on the rig.

The combustor cup and liner were instrumented with thermocouples (three on the cup and four on the liner). Locations of the thermocouples are indicated in Figure 6-9 and in Table 6-1. The liner thermocouple locations are relative to the leading (upstream) edge. Rig instrumentation included flow measurements of air, atomizing air and fuel, air and fuel temperature, and combustor pressure drop. A bare-wire thermocouple mounted on a traversing rod was used to give an indication of axial-gas temperature profile within the combustor. Test conditions for the evaluation were determined from Table 6-1 (Reference 3), and input from NASA (Reference 4). Due to a limitation in airflow capacity, full-power GPU-3 condition could not be duplicated (24-kW versus 30-kW firing rate). The steady-state test results are given in Table 6-2 and Figures 6-12 through 6-19.

The conclusion is that both combustor cup and liner surface temperatures are too high for long life. Both pieces achieved temperatures in excess of 1900°F. Metallic pieces, even if made of high-quality stainless steel, would probably not survive for more than 100-200 hours. A second conclusion is that combustor pressure drop is too low ($\Delta P/P < 1\%$) and/or atomization is inadequate to mix fuel for completing the combustion reaction in a reasonably conservative volume (15 kW/liter). At higher fuel flows and $A/F \leq 25^*$, combustion was not completed within the liner volume, i.e., a luminous yellow flame with burning carbon particles or droplets was visible above the exit.

The measurements of combustor cup temperatures (Figures 6-12 to 6-14) indicate that the hottest region is in the cooling annulus, and that surface temperature is proportional to firing rate and inversely proportional to air/fuel ratio. Although the annulus is cooled, combustion gas temperature is higher than in the dome, causing high wall temperatures. This was confirmed by an examination of a used combustor cup where the most severe oxidation was observed on the trailing edge, i.e., the portion of the cup located in the annulus. The increase in

*GPU-3 nominal A/F = 25

TABLE 6-1

GMR GPU-3 ENGINE DYNAMOMETER PERFORMANCE
(SAE 680081)

Test No.	rpm	POWER (BHP)	LOAD (%)	EFFICIENCY (%)	AIRFLOW		FUEL FLOW		A/F	BURNER INLET	
					(lbm/hr)	(g/s)	(lbm/hr)	(g/s)		T (°F)	Qc (kW)
1	3000	2.48	30	8.9	114.0	14.4	3.84	0.484	27.10	80	20.6
2		4.72	50	13.9	118.0	14.9	4.66	0.587	25.30	249	25.0
3		4.84	↓	14.5	118.0	14.9	4.58	0.577	25.70	440	24.6
4		4.84		18.4	94.2	11.9	3.62	0.456	2.60	800	19.5
5		4.75	↓	20.4	78.3	9.9	3.20	0.403	24.50	994	17.2
6		4.72		22.6	75.5	9.5	2.86	0.360	26.40	1210	15.4
7		4.78	↓	21.9	89.3	11.2	3.00	0.378	29.80	1200	16.1
8		4.84		21.3	109.5	13.8	3.12	0.393	35.20	1200	16.8
9		4.83	↓	19.4	136.1	17.1	3.44	0.433	39.60	1150	18.5
10		4.91		23.4	58.1	7.3	2.87	0.362	20.20	1167	15.4
11		9.65	100	24.4	137.7	17.4	5.42	0.683	25.40	1350	29.1
12		9.69	100	25.6	108.5	13.7	5.20	0.655	29.90	1360	28.0

TABLE 6-2

GPU-3 COMBUSTOR EVALUATION TEST RESULTS

Date	Test Point	m _{aa}	m _a	m _f	A/F	λ	Q _c	I _a	Cup			Liner				ΔP	ΔP/P
									T21	T22	T23	T24	T25	T26	T27		
5/14/82	1	0.22	12.5	0.32	40.4	2.75	13.2	760	900	972	1354	948	1427	1352	1162	2.20	0.53
	2	0.30	8.8	0.35	25.9	1.76	15.0	1275	1526	1631	1833	1500	1752	1686	1731	1.60	0.37
5/17/82	3	→	11.0	0.36	31.7	2.15	15.4	1185	1415	1483	1804	1388	1727	1642	1659	2.10	0.48
	4	→	12.4	0.36	35.3	2.40	15.4	1225	1387	1560	1856	1374	1709	1644	1695	2.60	0.58
	5	→	12.4	0.42	30.2	2.06	18.0	1280	1433	1552	1887	1426	1767	1694	1743	2.75	0.62
	6	→	12.4	0.36	35.3	2.40	15.4	1340	1470	1592	1908	1463	1782	1716	1753	2.75	0.62
	7	→	12.4	0.48	26.4	1.80	20.5	1380	1572	1869	1935	1543	1877	1809	1860	2.85	0.64
	8	0.28	12.4	0.56	22.4	1.53	24.1	1380	1738	1931	1872	1560	1909	1848	1818	3.00	0.67
	9	0.29	7.0	0.36	20.3	1.38	15.4	1230	1672	1764	1774	1534	1790	1705	1705	1.00	0.24
	10	0.30	4.5	0.13	36.3	2.47	5.6	1010	1241	1308	1512	1244	1428	1385	1350	0.35	0.08
	11	0.30	4.4	0.18	26.0	1.77	7.8	1075	1448	1572	1648	1388	1588	1544	--	0.40	0.10
	12	0.29	4.4	0.24	19.7	1.34	10.3	1110	1453	1541	1678	1430	1624	1576	--	0.40	0.10
	13	0.29	4.4	0.16	29.6	2.00	6.8	1060	1306	1345	1565	1329	1516	1470	--	0.35	0.08

m_{aa} = atomizing airflow (g/s)
 m_a = combustor airflow (g/s)
 m_f = fuel flow (g/s)
 A/F = air/fuel mass ratio
 λ = A/F ÷ stoichiometric A/F
 Q_c = firing rate (kW)
 I_a = combustor inlet air temperature (°F)
 T21 = Combustor cup temperature near swirl slot (°F)

T22 = combustor cup temperature between swirl slot (°F)
 T23 = combustor cup temperature in cooling annulus (°F)
 T24 = combustor liner temperature at 0.375" (°F)
 T25 = combustor liner temperature at 2.875" (°F)
 T26 = combustor liner temperature at 5.375" (°F)
 T27 = combustor liner temperature at 7.875" (°F)
 ΔP = combustor pressure drop ("H₂O)
 ΔP/P = combustor pressure drop (%)

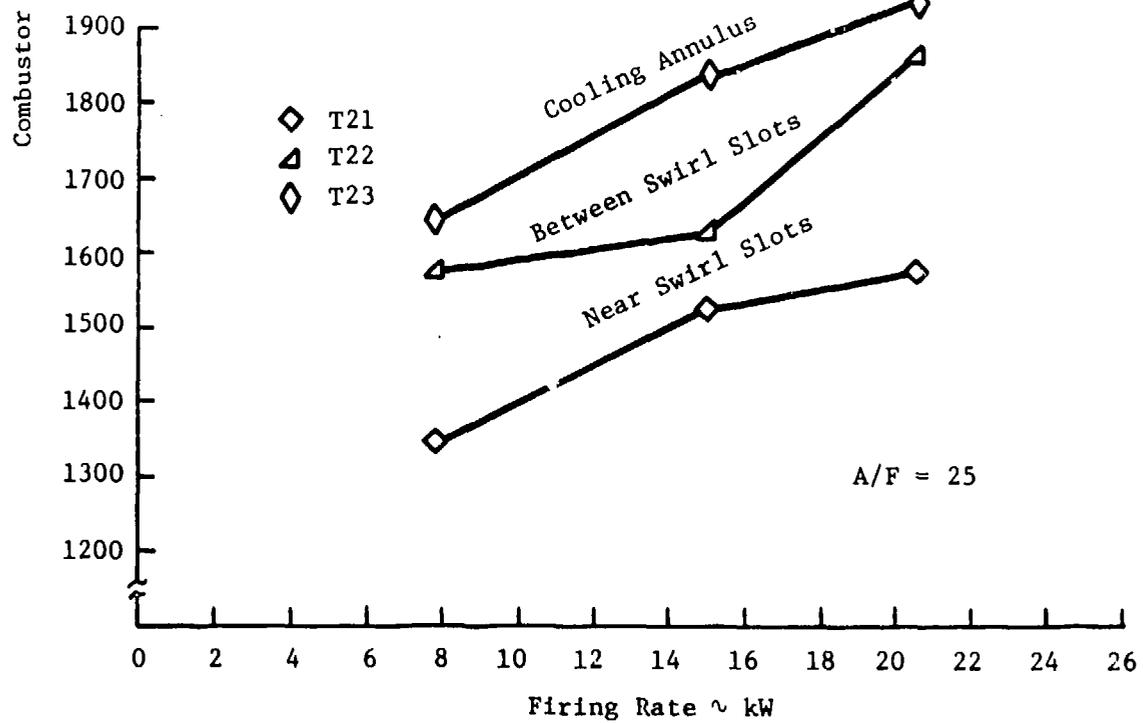
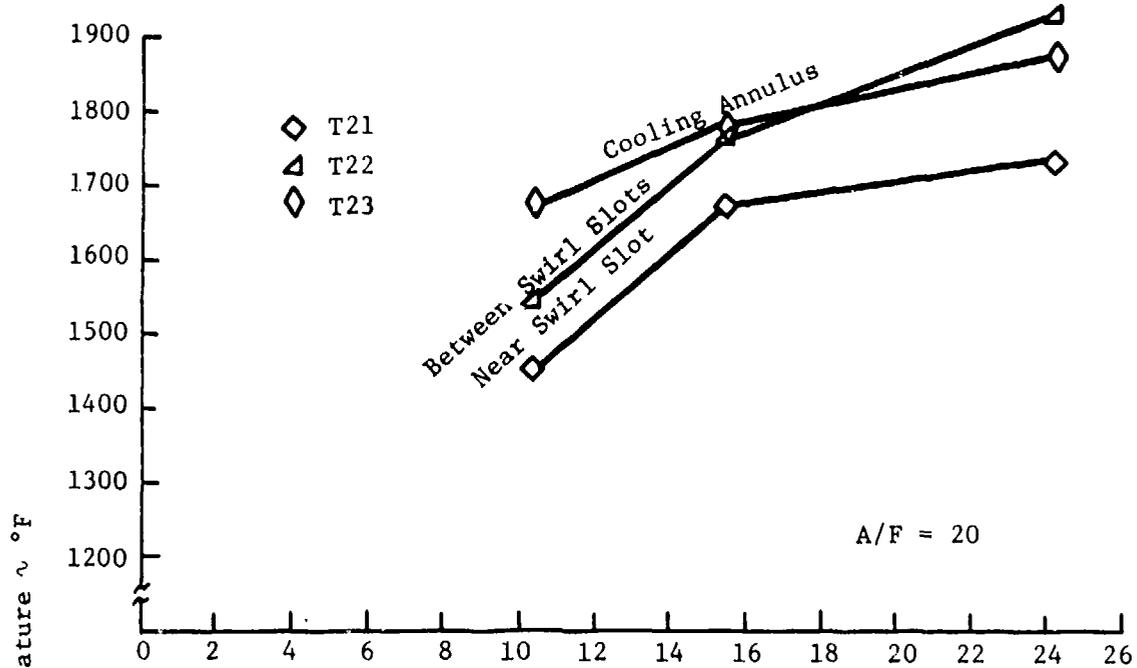


Figure 6-12 GPU-3 Combustor Evaluation
(Diesel Fuel)

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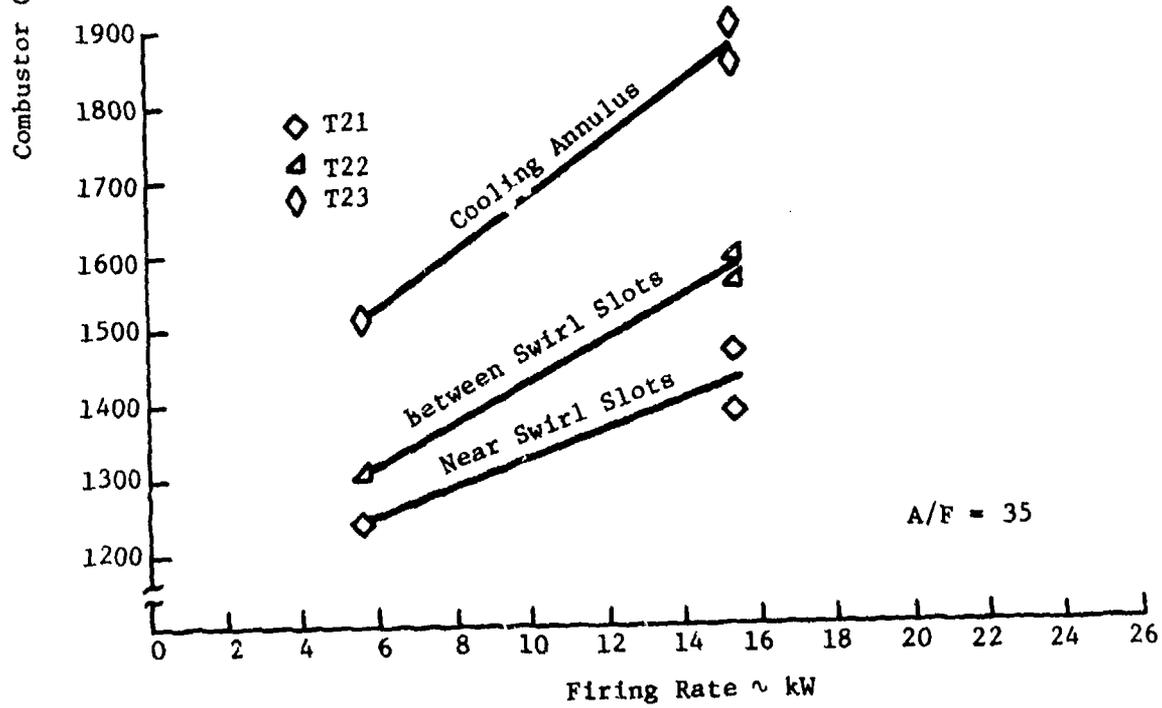
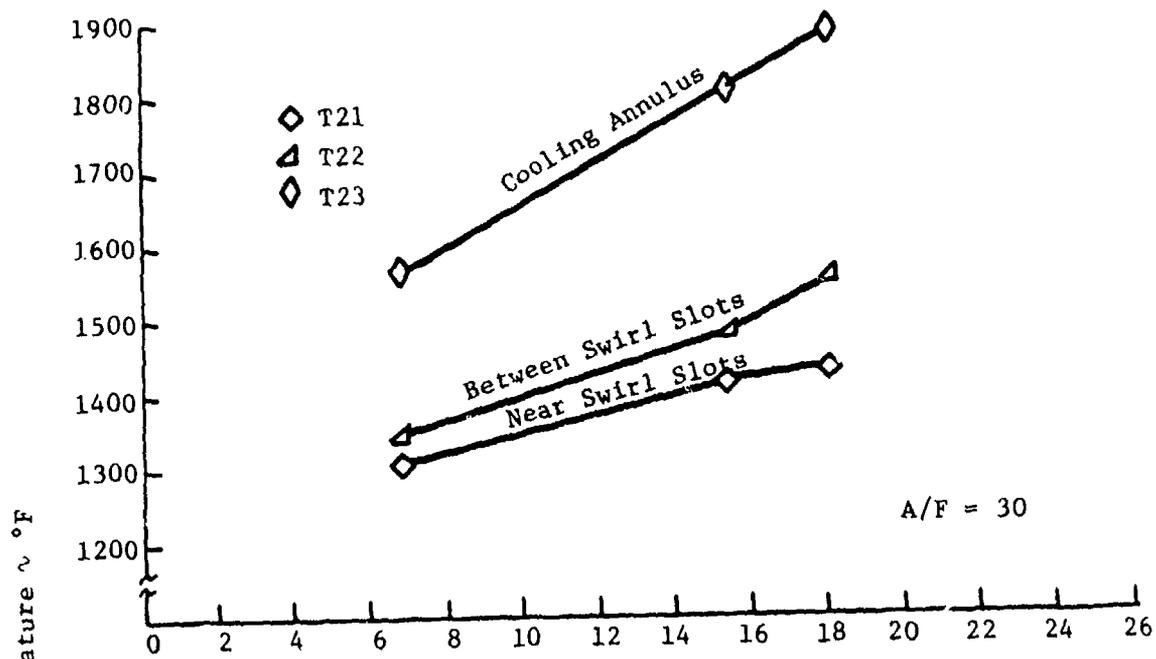


Figure 6-13 GPU-3 Combustor Evaluation
(Diesel Fuel)

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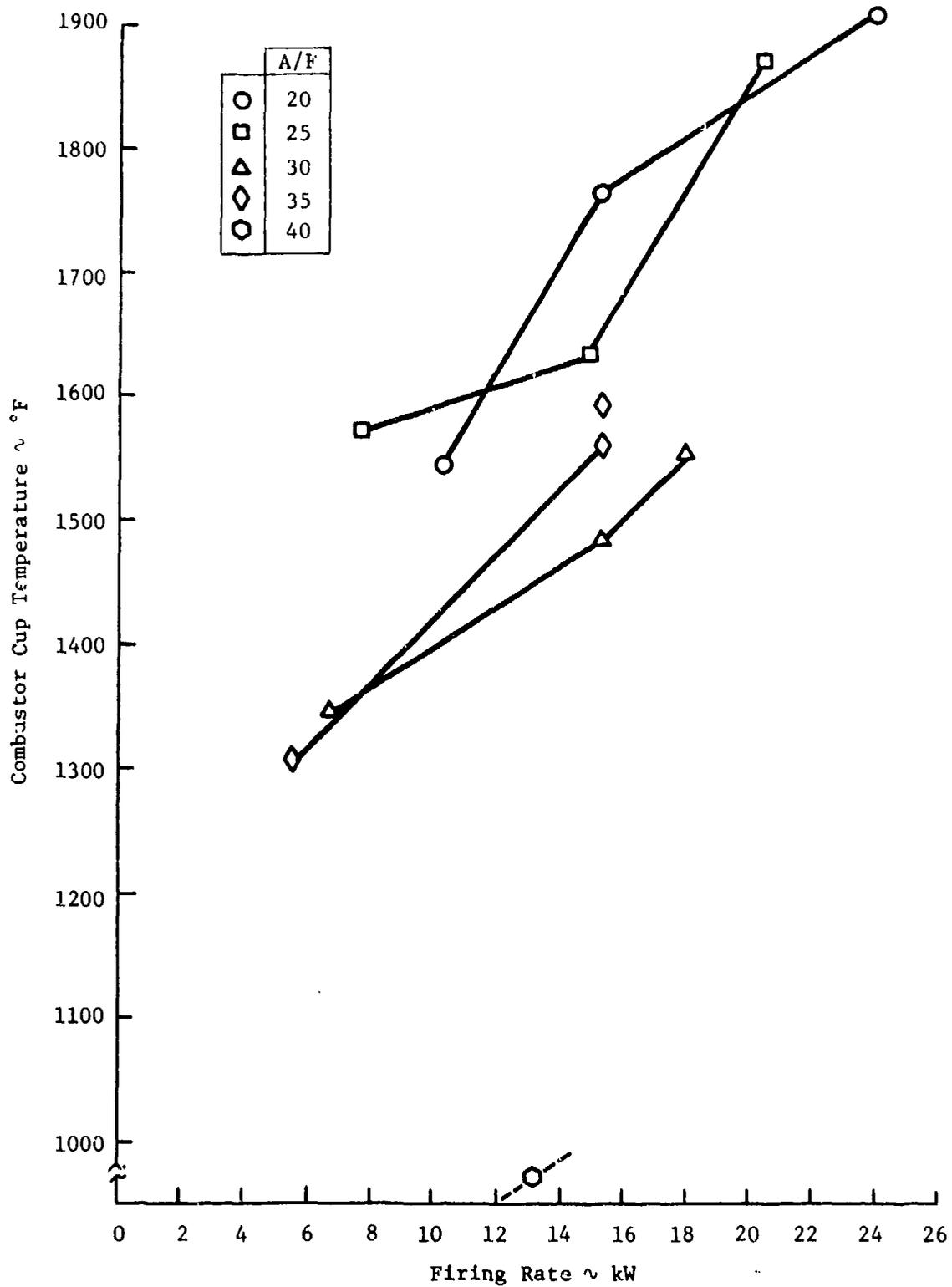


Figure 6-14 GPU-3 Combustor Evaluation (Combustor Cup Temperature Between Swirl Slots) (Diesel Fuel)

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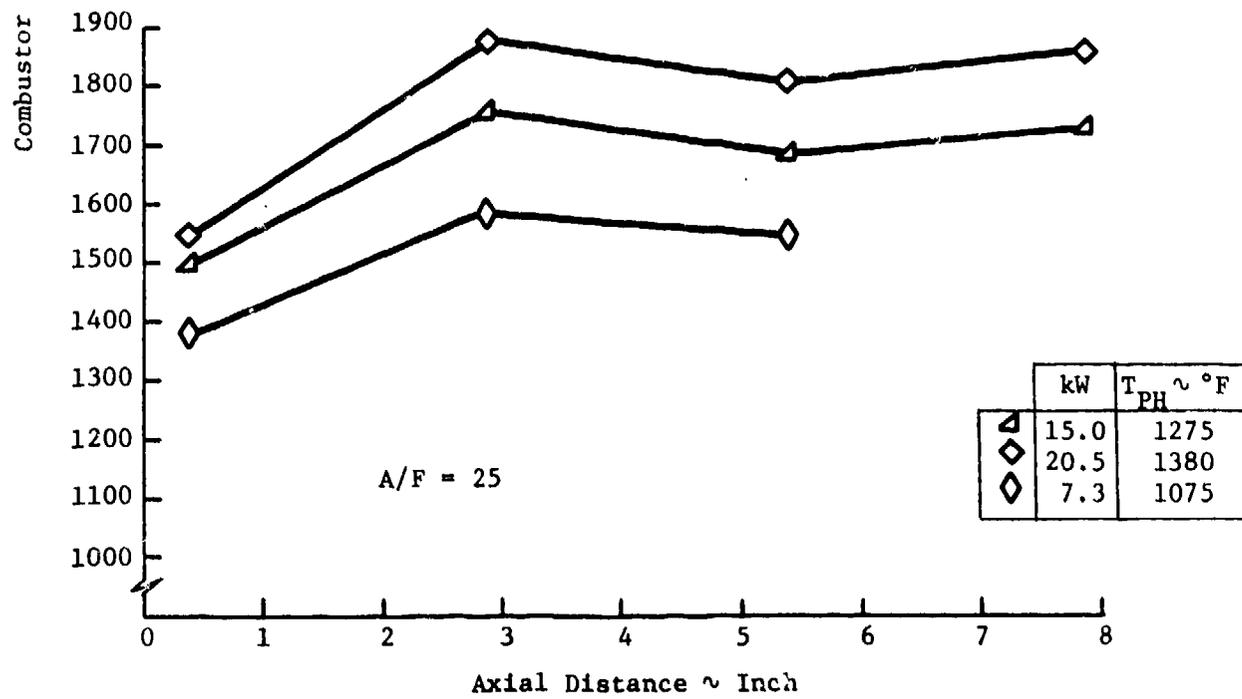
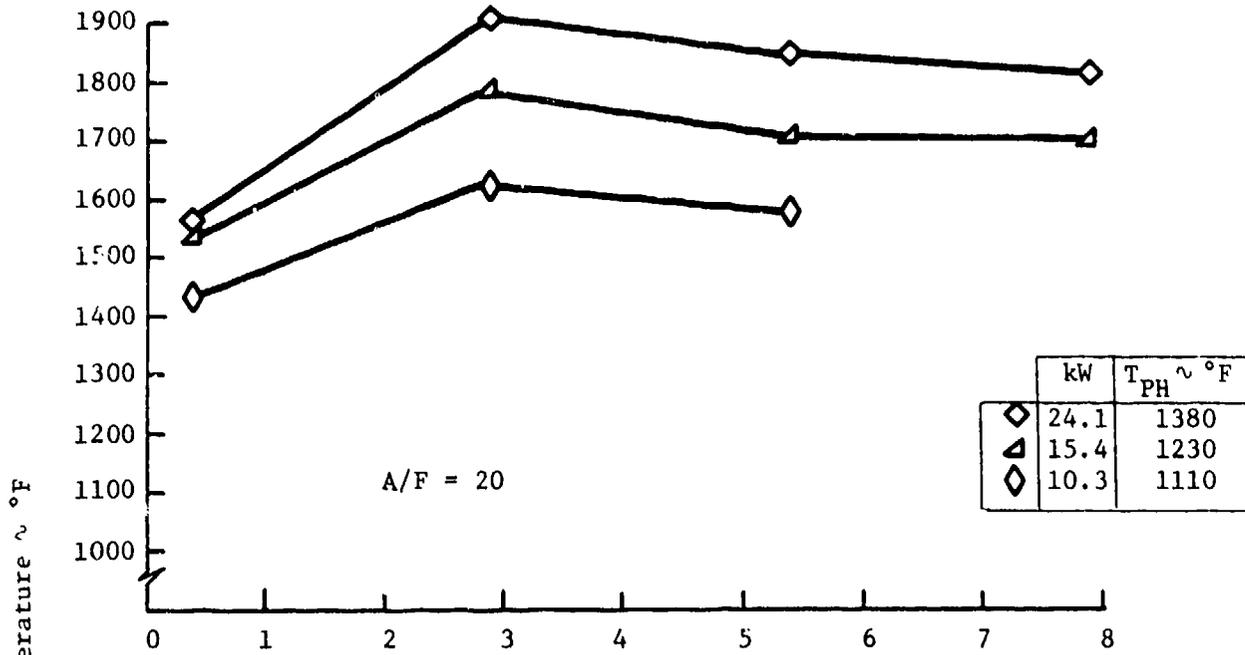


Figure 6-15 GPU-3 Combustor Evaluation
(Diesel Fuel)

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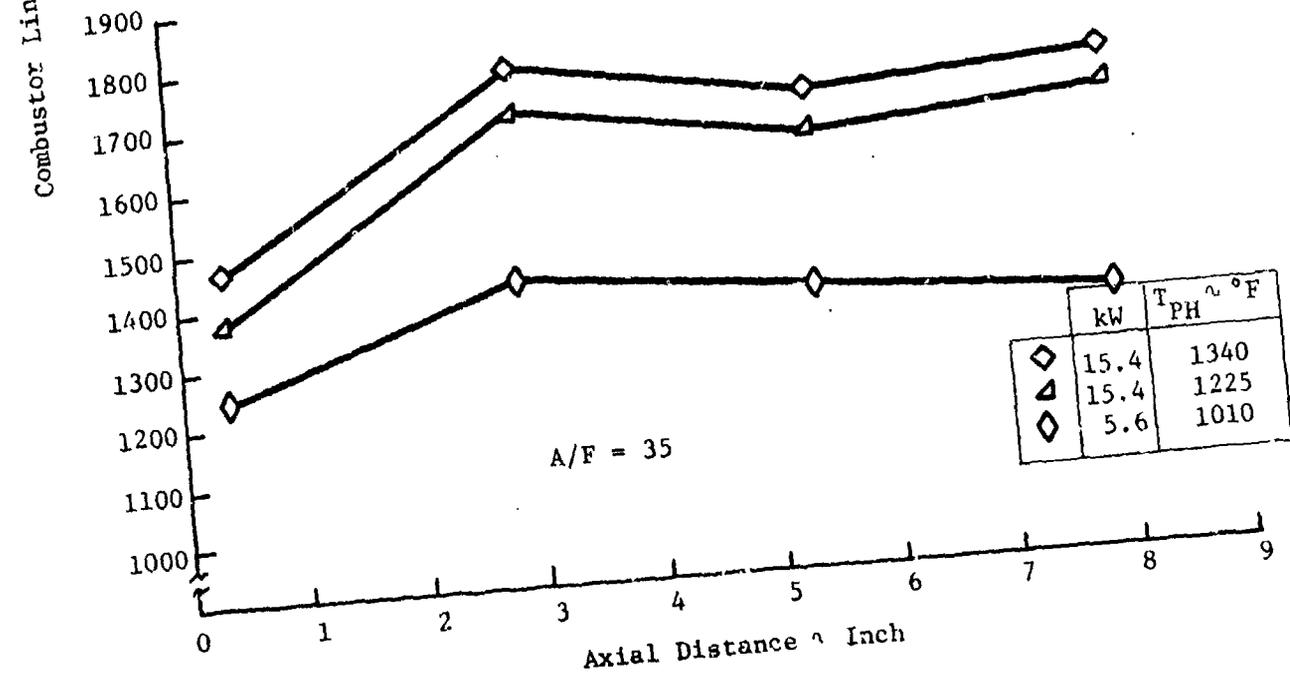
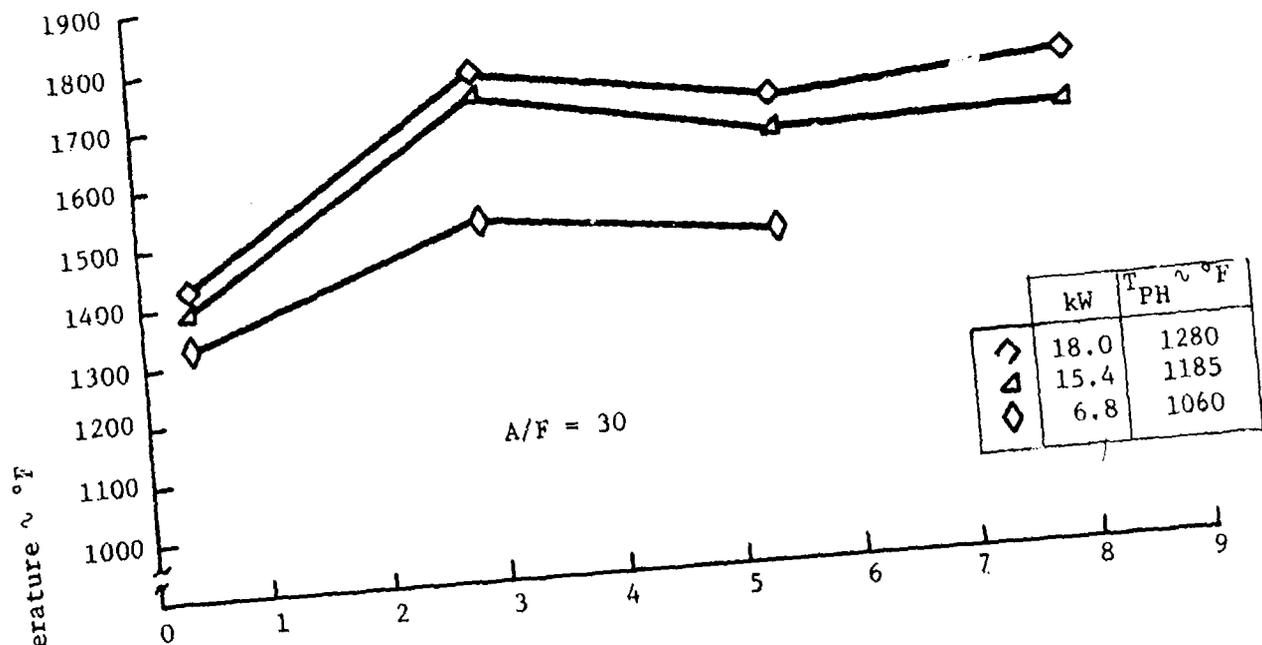


Figure 6-16 GPU-3 Combustor Evaluation
(Diesel Fuel)

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Combustor Liner Temp @ 2.875"

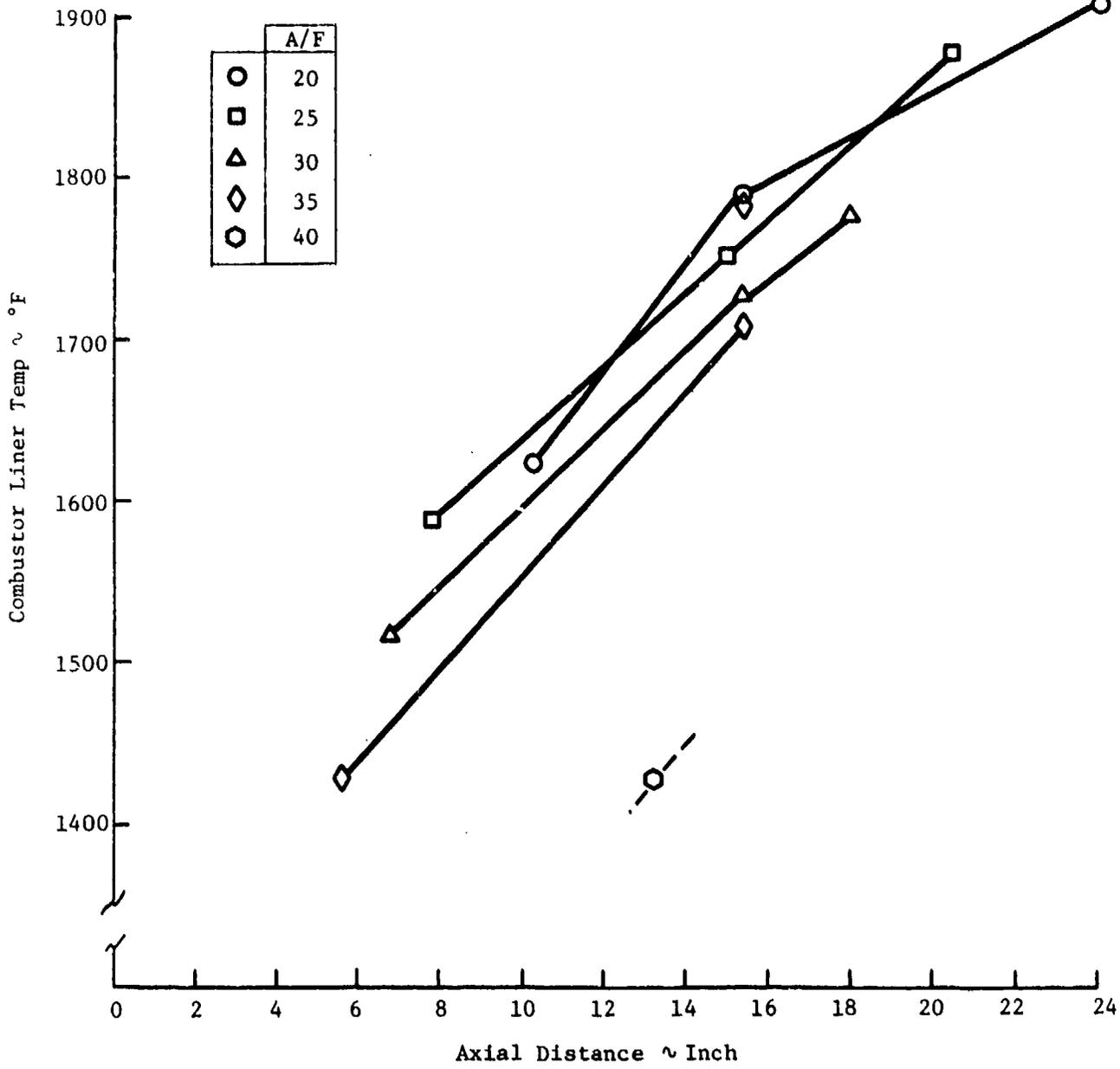


Figure 6-17 GPU-3 Combustor Evaluation (Diesel Fuel)

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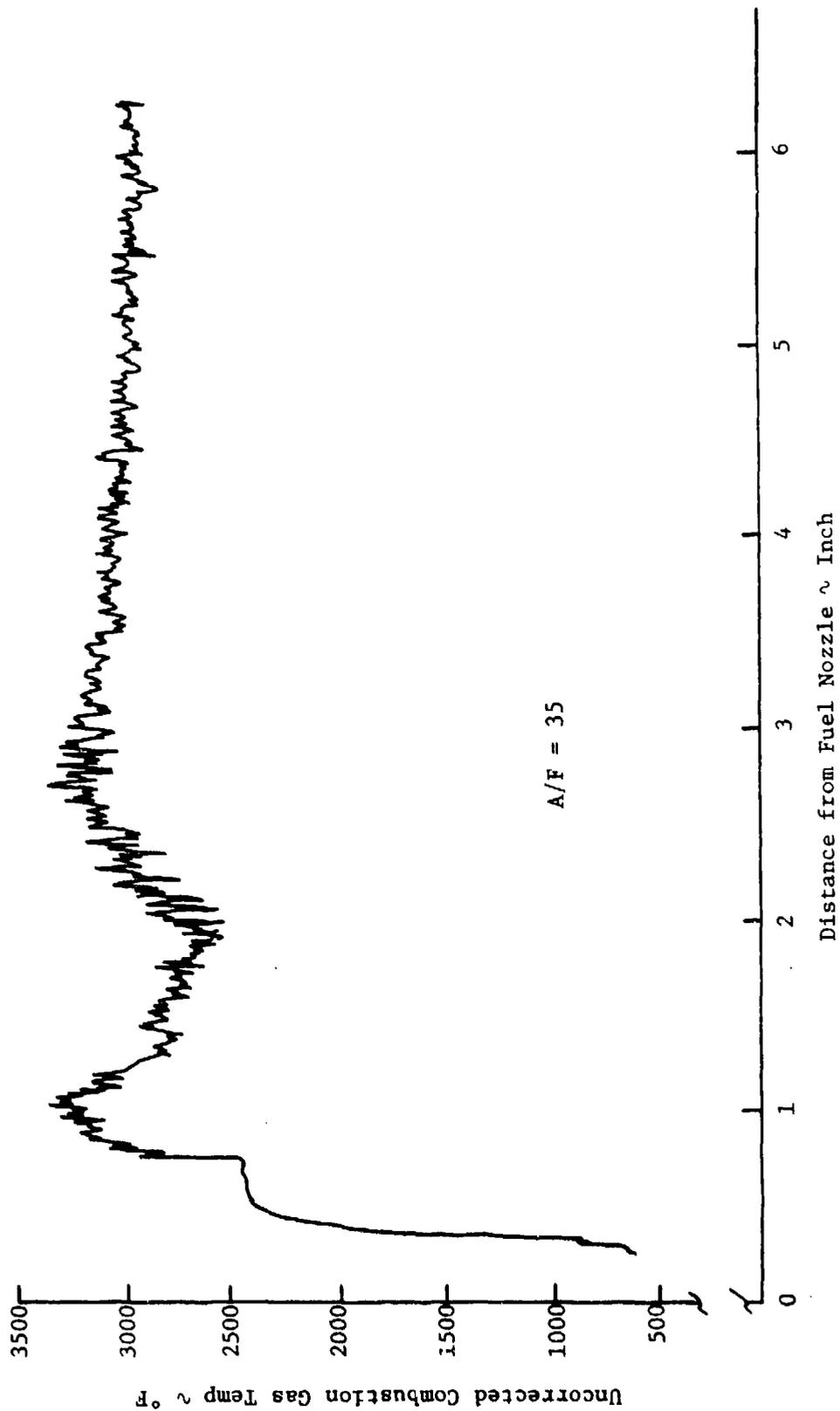
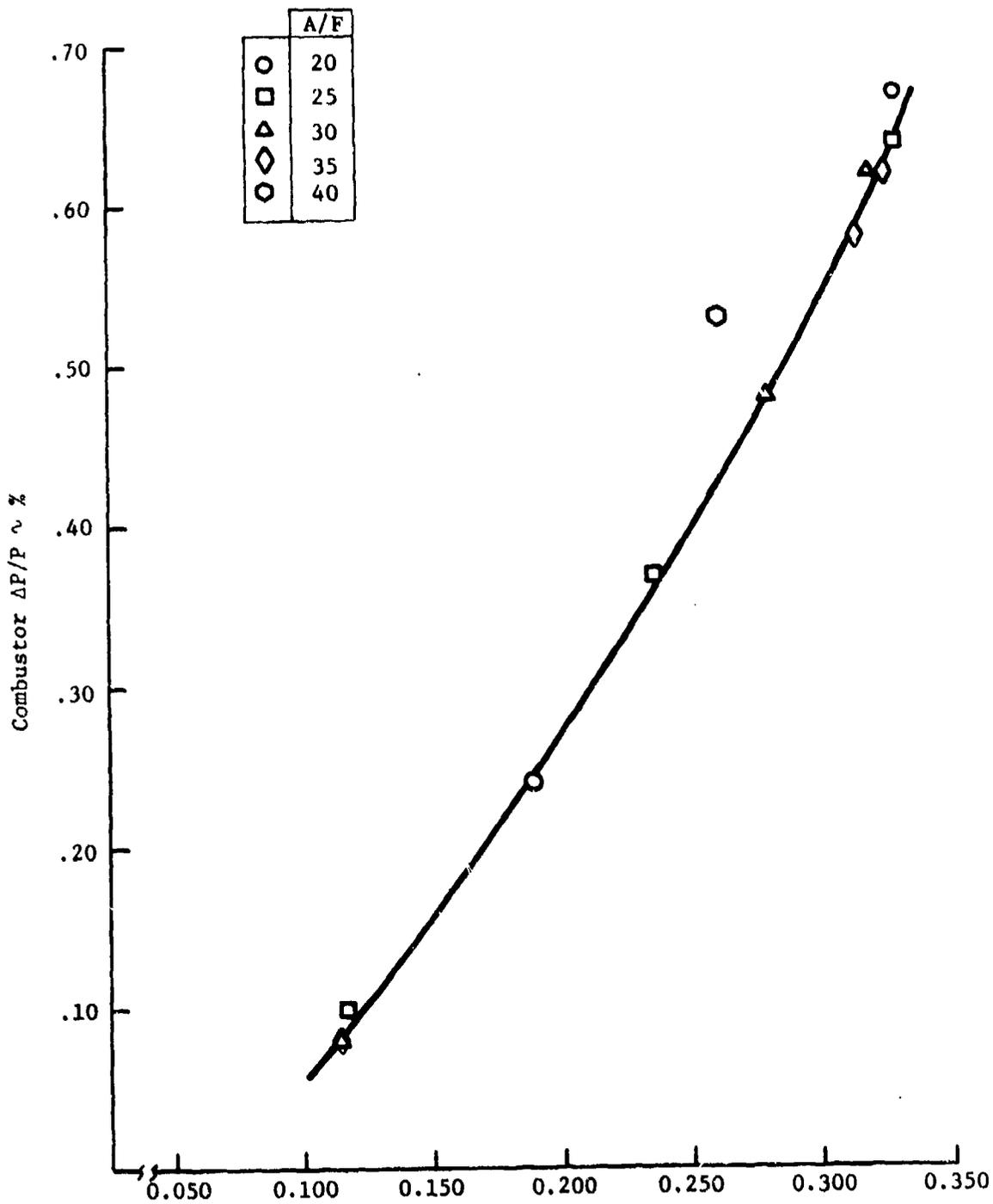


Figure 6-18 GPU-3 Combustor Evaluation
 Combustion Gas Temp Versus
 Axial Distance (I.P. #6)
 (Diesel Fuel; 15 kW)

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Figure 6-19 GPU-3 Combustor Evaluation
 Combustor Pressure Drop
 (Diesel Fuel)

surface temperature with firing rate and decreasing air/fuel ratio was due to higher combustor loading and flame temperature, respectively.

Combustor liner temperature is illustrated in Figures 6-15 to 6-17. The highest indicated temperature is at 2.875 inches, although the actual peak is probably between 0.375 and 2.875 inches. Once again, the trend is for surface temperature to increase with firing rate and decrease with air/fuel ratio.

A typical plot of the traversing thermocouple for test point 6 is shown in Figure 6-18. Although the absolute temperature is not accurate due to the large radiation error, the trend in gas temperature as a function of axial distance is indicated. The gas temperatures are consistent with the liner surface temperatures of Figures 6-15 through 6-17. Figure 6-19 shows % combustion drop versus corrected mass flow parameter. An increase in $\Delta P/P$ to the range of 2-4% would be beneficial to both combustion volume requirements and mixing.

Additional testing was conducted to determine ignition/blowout limits. In the former case, ignition was unsuccessfully attempted using the GPU-3 to the inverted position of the igniter, which allowed fuel to wet the igniter and prevent sparking. NASA experience indicates that ignition is easily achieved with the combustion system in its normal position. Rather than extensively modifying the rig to mount the test hardware in its designed orientation, a propane torch was used for ignition. Blowout testing yielded air/fuel ratios in excess of 100*, indicating good stability.

D. LIQUID-FUEL COMBUSTOR CUP AND NOZZLE DESIGN

The design of an EM-compatible liquid-fuel combustor and fuel nozzle is shown in Figure 6-20. The combustor cup is similar to that used on the TDE and EM natural-gas-fired engines (Figure 6-21), and represents a scaled-down version of the GMR-GPU-3 diesel-fueled combustor shown previously in Figure 6-9. The material is 310 stainless steel; however, based on the GPU-3 evaluation, this material will eventually be changed to ceramic because of the estimated 1900°F or higher surface temperatures. The high-surface temperatures are the result of

*A/F = 114 at 600°F combustor inlet temperature

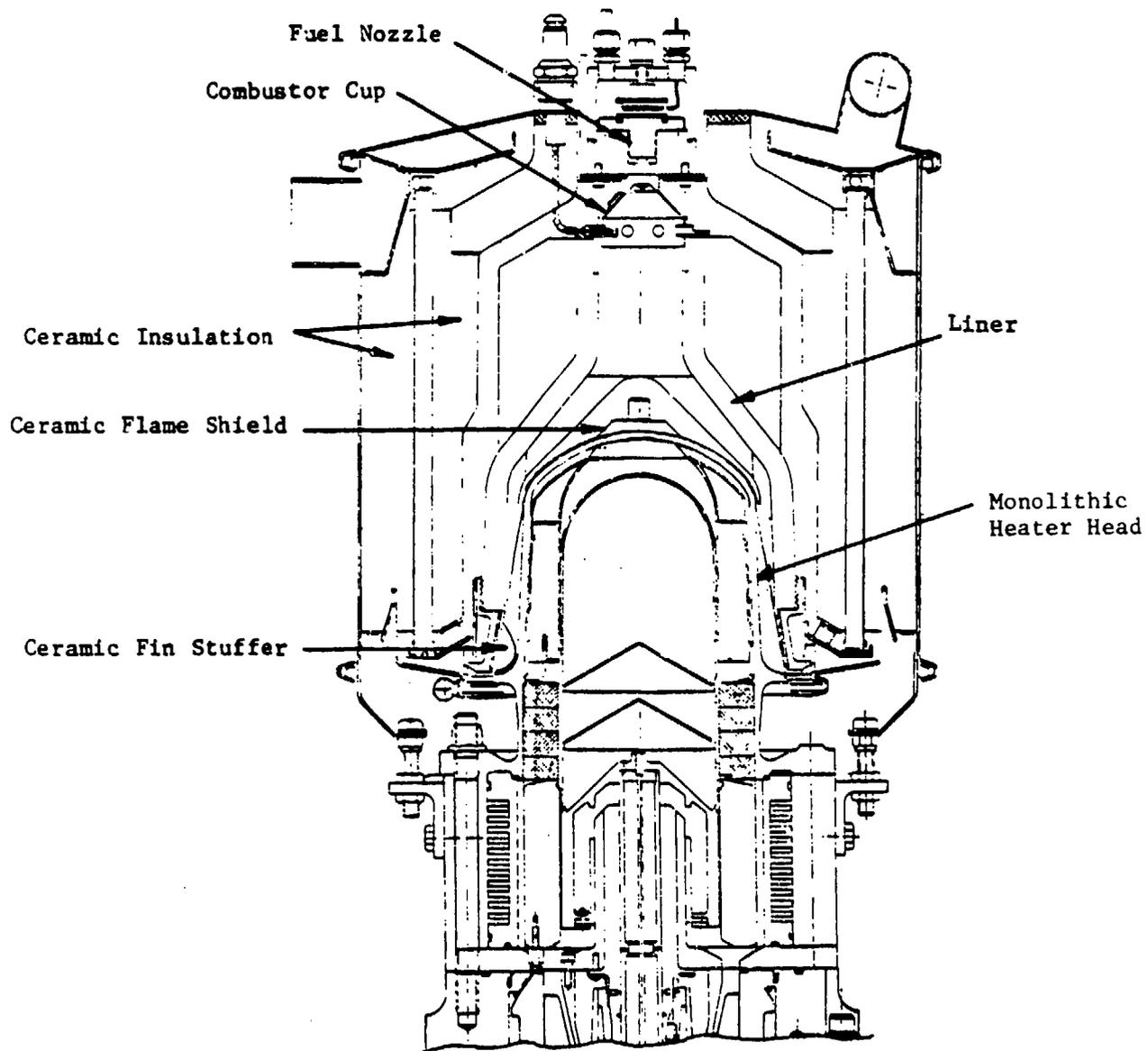


Figure 6-20 Liquid-Fueled Combustor and Fuel Nozzle

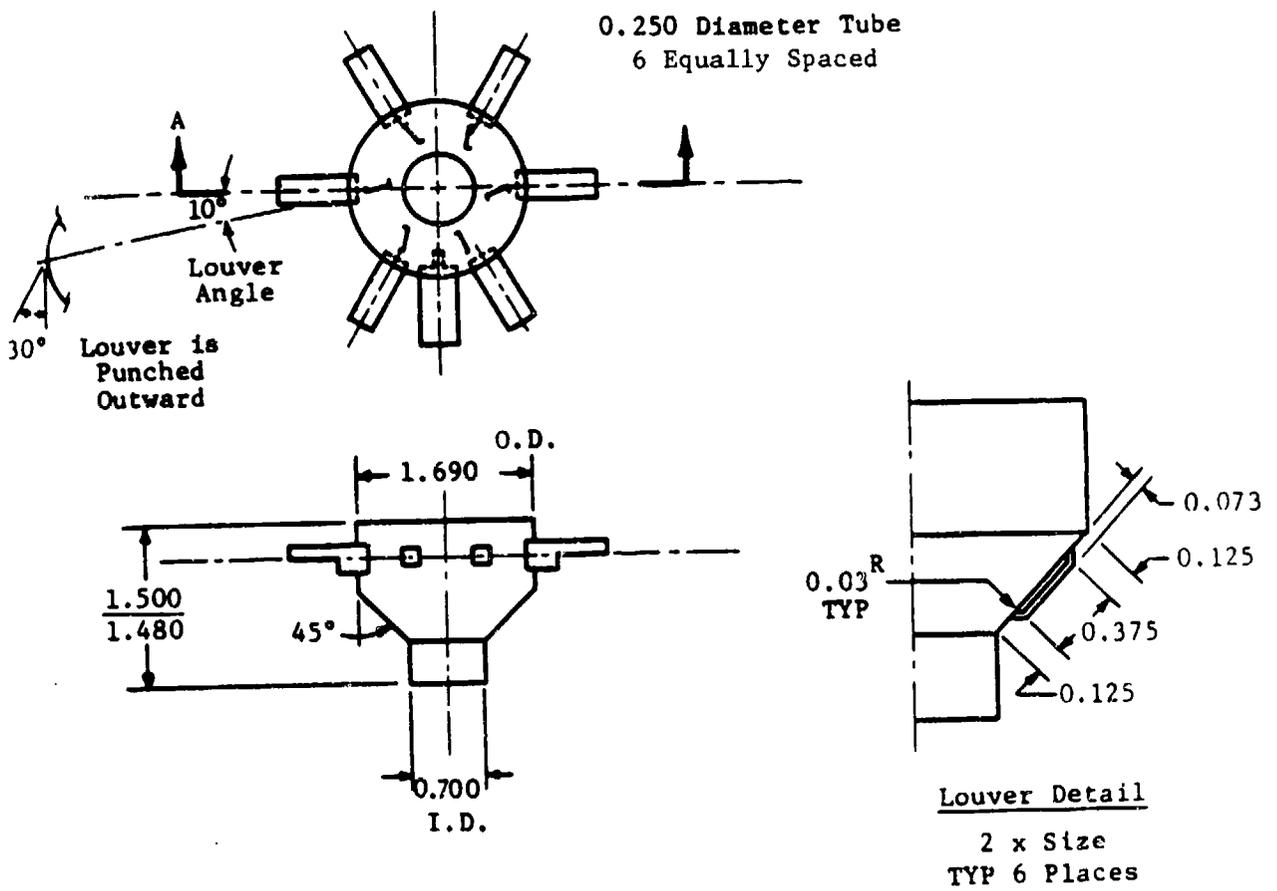


Figure 6-21 TDE Combustor Cup

a 1450°F combustion inlet air temperature and an increased flame temperature/luminosity of liquid fuel (as opposed to natural-gas). In the former case, the need to maximize external heat system efficiency by recouping energy from the combustion gases exiting the heater head results in high air temperatures into the combustor, reducing the ability to convectively cool the cup walls. The latter condition results from soot particles in liquid flames that give a characteristic yellow, more luminous flame, thereby increasing radiant loading and, because the carbon/hydrogen ratio is ~1/2 that of natural gas, leading to higher flame temperature/convective heat transfer to the combustor walls.

The combustor cup utilizes louvers on the cone portion of the cup for flame stabilization, cooling, and as a source of reaction air. The remaining combustion reaction air enters through six tubes. A seventh tube is utilized for the igniter. The remaining air convectively cools the cup by flowing through the annular gap between the cup and liner. Pressure drop is under 2%, but will probably be increased to improve mixing and reduce combustor volume.

Fuel nozzle requirements of the liquid-fuel combustor pose some unique requirements. Maximum fuel flow is ~0.4 gallons/hour (15-kW firing rate), falling within the range of domestic oil burner nozzles. Simple mechanical atomizers provide a turndown ratio of only 2:5 (inadequate for the 10:15 needed). A more sophisticated dual-orifice or piloted air-blast nozzle, typical of aircraft gas turbines, will provide the necessary turndown, but they are not feasible in the low flow range required because of the plugging tendency of small orifices (characteristic of these nozzles). It is possible to use an air-atomizing (air-assist) nozzle that utilizes an external supply of pressurized air for atomization. This type of nozzle has relatively large fuel passages and good turndown, and is, in fact, used on the GPU-3 (30-kW firing rate). The disadvantages of an air-atomized nozzle include the requirement to provide/drive an air compressor, and the reduction in external heat system efficiency. The latter condition results from cold atomizing air bypassing the preheater, and is most notable at low-power conditions.

Currently, the nozzle selected for experimental evaluation, shown in Figure 6-22 (manufactured by Sono-Tek Corporation in titanium or aluminum in two flow ranges: 0-1 and 0-3 GPH), uses two piezoelectric crystals to sonically atomize fuel. The advantages of this concept are wide turndown at low flows, extremely

SPECIFICATIONS

Model Number	STC 01-A	STC 03-A	STC 05-A	STC 06-A	STC 015-A	STC 016-A	STC 020-A	STC 021-A
Capacity (oil)—gph	0-1	0-1	0-3	0-3	0-3	0-1	0-1	0-1
Electrical Power Requirements ¹ —watts	10	6	7	10	8	7	11	7
Spray Shape	cylinder	cylinder	cylinder	cylinder	60° cone	60° cone	80° cone	80° cone
Median droplet diameter (oil)—microns	17	17	22	22	22	17	17	17
Nozzle Material ²	Ti	Al	Al	Ti	Al	Al	Ti	Al
Size (Inches)	1½ x 1 D	2¾ x 1 D	3¾ x 1½ D	2¾ x 1½ D	3½ x 1½ D	2¾ x 1 D	2¾ x 1 D	2¾ x 1 D
Weight (oz.)	1.7	1.5	3.8	4.2	3.5	1.3	1.4	1.3

¹ Power is supplied by a single transistor oscillator supplied with the nozzle. The oscillator can be adapted to either AC line current or low voltage DC operation.

² The Nozzle Material refers to the two metal cylinders which sandwich the piezoelectric crystals.



ST SONO-TEK
ULTRASONIC
ATOMIZING
NOZZLES

Sono-Tek Corporation
313 Main Mail
Poughkeepsie, NY 12601
(914) 471-6090

Figure 6-22 Sono-Tek Fuel Nozzle

fine droplet size, minimal electric power, and a 3/32-inch diameter passage that will not plug. A unique requirement for using the Sono-Tek nozzle is that mounting locations are limited to the fuel supply tube connection or nodal points; otherwise, atomization is adversely affected. Figure 6-23 illustrates the present mounting/interfacing arrangement design of the titanium EM ultrasonic fuel nozzle and combustor cup. The cavity around the nozzle ensures that no atomization energy is dissipated through contact with the adaptor and, if needed, provides a passageway to cool the nozzle. Unique features of this nozzle, relative to more conventional atomizers, are low pressure drop (<1 psi), a limitation on crystal temperature of 300°C, and low droplet momentum. This nozzle is believed to provide better atomization and mixing with combustion air than the air-atomized GPU-3 nozzle. Because of the low droplet velocity, care must be taken in designing how the air enters the combustor.

The fuel nozzle/combustor development work is being conducted using MTI's Free-Piston Combustor Test Rig. In addition to normal instrumentation to determine flows, temperatures/pressures of incoming fuel and air, combustor cup/liner sleeve temperature, axial gas temperatures, and gaseous emissions inside the combustor will be measured. During steady-state testing, engine load conditions from idle to maximum power were simulated by varying firing rate, air-to-fuel ratio, and combustor inlet air temperature. Additional testing will be conducted to determine ignition and blowout limits. Modifications to the nozzle and combustor will be made to meet the following design goals:

- maximum firing rate of 15 kW;
- adequate ignition and blowout margin;
- 10:1 turndown ratio;
- nonvisible exhaust plume;
- gas radial temperature profile of: $T_{\max} - T_{\text{mean}} / T_{\text{mean}} - T_{\text{in}} < .25$;
- combustor $\Delta P/P < 6\%$; and,
- combustor efficiency $> 99\%$.

E. CONCLUSIONS OF LIQUID-FUEL EXTERNAL HEAT SYSTEM DESIGN

In the liquid-fuel external heat system design and development effort, special emphasis will be placed on the preheater subcomponent. Since combustion chemical efficiency is near unity, the preheater is the main determinant of heat

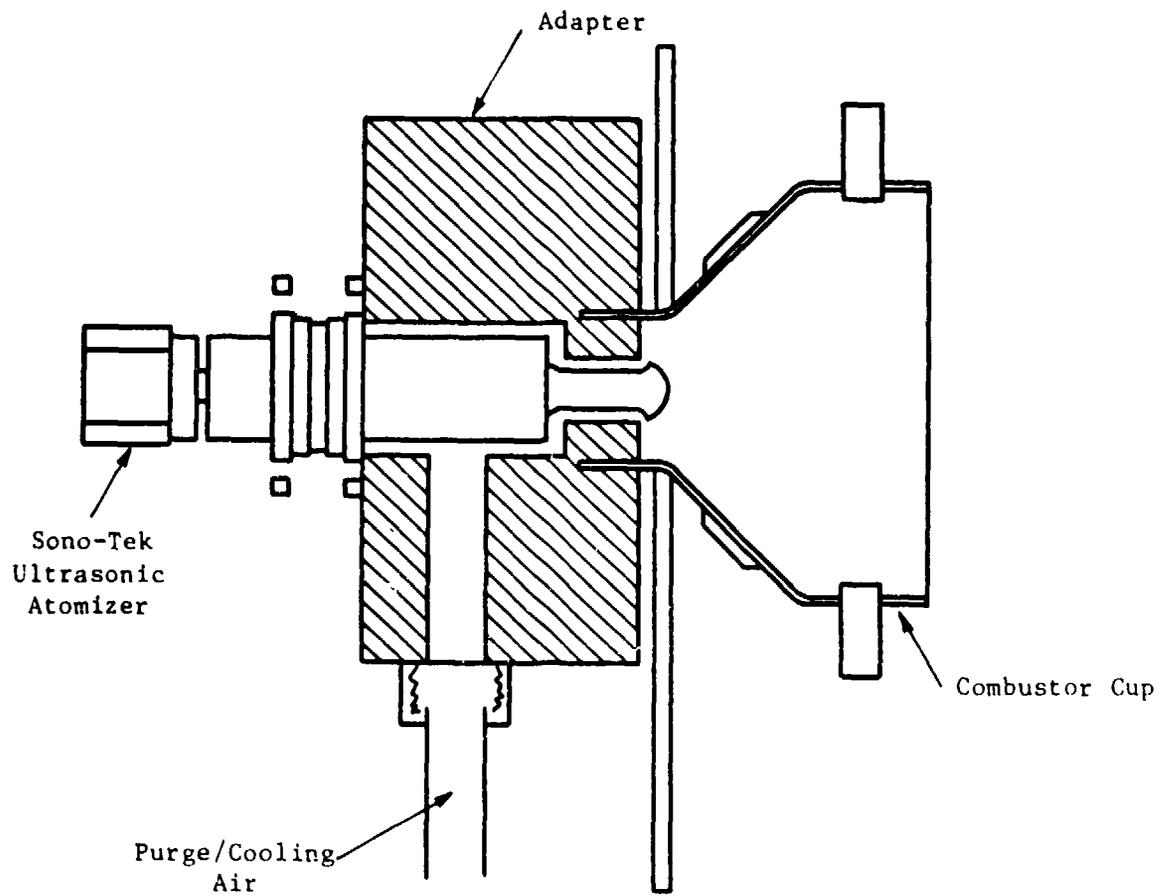


Figure 6-23 Proposed EM Diesel Fuel Nozzle and Combustor Cup

system efficiency, assuming heat lost through conduction to the cold parts of the engine, and convection losses to the environment, are minimized. Thermal isolation of the external heat system through the use of insulation is used to achieve minimal convection losses to the environment.

The natural-gas-fired EM uses a preheater consisting of a folded fin, 310 stainless-steel matrix sandwiched between two ceramic Kaowool cylinders. MTI's ASE Program experience with burning diesel fuel indicates that stainless-steel preheaters will corrode if the preheater matrix or average gas temperature in the matrix is below the sulfuric acid dew point (300°F). Further experience indicates that no problem exists with unleaded gasoline. For diesel fuel, increasing amounts of sulfur impose an increasingly corrosive environment. Two possible solutions to acid corrosion are to prevent acid condensation by raising the exhaust temperature, or to use an alternate matrix material. The first approach reduces efficiency; trade-off studies will be performed to determine the overall system effects.

Engine test experience with the EM Performance and Endurance Engines has led to refinements of the external heat system's overall design. Proposed changes to the combustor and fuel nozzle have already been discussed. The design refinements, also applicable to liquid-fuel operation, involved a change of material for the combustor liner, a different preheater fabrication technique, and detail design changes to the flame shield, combustor liner, and fin stuffer. (These pieces are identified in Figure 6-20.)

The combustor liner is currently made of Kaowool, and has a tendency to wear in a vibratory environment. The relatively soft and porous Kaowool will be replaced with a harder, mechanically stronger ceramic called Tabular™ (a mixture of aluminum oxide, silica, and mullite). This material is already used for the flame shield, where mechanical integrity at high temperature has been demonstrated. The method of attaching the liner to the external heat system has been changed to include a more positive, seal-threaded or clamped arrangement at the bottom, instead of the original method of preloading the liner with the combustor cover. The preheater end rings (U-shaped) will now be brazed directly to the folded fin matrix to eliminate a potential leakage path. A modification to the flame shield is the addition of locating ridges to more positively align the combustor to the heater head, thereby improving the circumferential uniformity

of heater head temperature profile. The change to a ceramic fin stuffer (used to enhance heat transfer at the bottom of the heater head) was to strengthen the locating pip, which has a tendency to break off.

As mentioned previously, the combustor cup itself will ultimately be made of ceramic. The feasibility of fabricating the cup out of ceramic Tabular™ has been confirmed through vendor contact. The change to ceramic, however, will not be made until aerodynamic development of the cup is completed in the Combustor Rig.

VII. CONCLUSIONS/RECOMMENDATIONS

The major objective of this WPAFB program (the design, fabrication, and test of an FPSE combustor controller) met or exceeded all expectations and goals. The combustor controller automatically maintains heater head temperatures with respect to air/fuel ratio and/or engine load changes, while operating effectively over the entire operating range of the TDE. The same controller system can be expanded to include the power control and provide for unattended operation.

The study evaluation of the FPSE for Air Force use (the secondary objective of the program) indicated that whatever the power control strategy of the engine/alternator system, it can be integrated with the combustor controller. In addition, the monolithic heater head design of the FPSE has the potential for use with military logistic fuels without any anticipated problems. The design of a liquid-fuel combustor that integrates with an FPSE has been completed, and is presented in this report.

Combustor controller development and FPSE evaluation for unattended operation provide the base from which FPSE's can be developed for Air Force use. To meet the particular requirements of the Air Force for its small engine-generator unattended site operation, the following efforts are recommended:

- development of a liquid-multifuel external combustor system using identical combustor control strategy developed herein for the natural-gas-fired system;
- integration of the selected FPSE power control with the combustor control;
- development of the start-up/shutdown capability of the system control (power control/combustor control); and,
- demonstration of a stand-alone, controllable FPSE.

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