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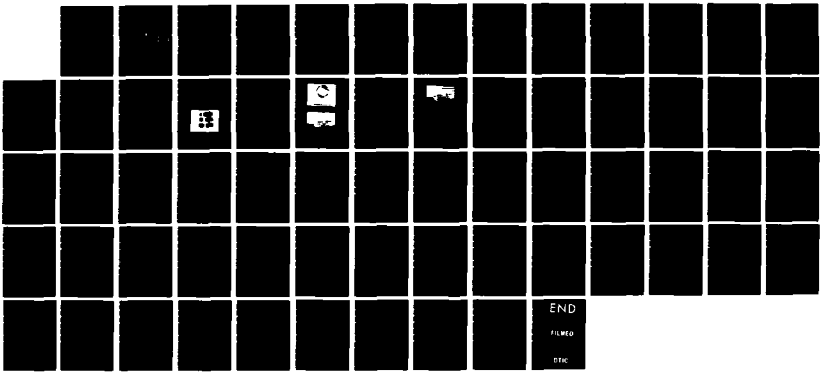

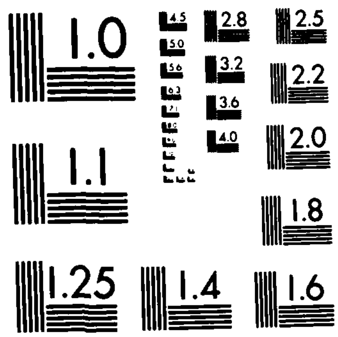

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

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AN EXPERIMENTAL INVESTIGATION
OF FUEL REGRESSION RATE CONTROL
IN SOLID FUEL RAMJETS

by

Ko, Bog Nam

December 1984

Thesis Advisor: D. W. Netzer

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An Experimental Investigation of Fuel Regression Rate Control in Solid Fuel Ramjets

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ABSTRACT

An experimental investigation was conducted to examine fuel regression rate control methods other than variable bypass air flow rates in the solid fuel ramjet. Air and oxygen injection at various axial locations within the fuel grain were examined as well as air, oxygen and ethylene injection through the step face. One inlet swirl design was also tested. Secondary gas injection was found to be inadequate for regression rate control. A small amount of inlet swirl resulted in a significant increase in fuel regression rate, indicating that variable inlet swirl may be a viable technique for providing in-flight fuel flow rate modulation in the solid fuel ramjet.

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I. INTRODUCTION

Ramjets operate with much higher specific impulse than rockets since ramjets use inlet air as a source of oxygen. Self-sufficient rockets, on the other hand, must carry their own oxidizer and bear the consequent penalty. Accordingly, although rockets must be chosen for propulsion outside of the atmosphere, and solid propellent rockets are unchallenged for short- range tactical applications, ramjets can generally outperform rockets in the medium and long range tactical environments.

Because the ramjet depends only on its forward motion at supersonic speeds to effectively compress intake air, the engine, in principle, can employ very few, if any, moving parts. It is therefore capable of simplicity, lightness of construction, and high flight speed not possible in other air-breathing engines. These features, plus the high thermal efficiency it can achieve, make the ramjet a particulary attractive choice for propelling vehicles at supersonic speeds.

One of the significant difference between rockets and ramjets is thrust at zero speed. Rockets can deliver thrust at any speed, whereas a ramjet requires an auxilary boost system to accelerate it to its supersonic operating regime so that its forward motion can compress the inlet air. To operate at practical efficiency a ramjet must be moving at about a Mach number of 1.5 or greater so that the margin of thrust over drag will be satisfactory.

The solid fuel ramjet(SFRJ) employs solid fuel for the combustor walls. Its distinguishing feature is the absence of fuel tankage, fuel delivery, and fuel control systems. The solid fuel ramjet offers this simplicity while providing excellent density impulse and combustion efficiency.

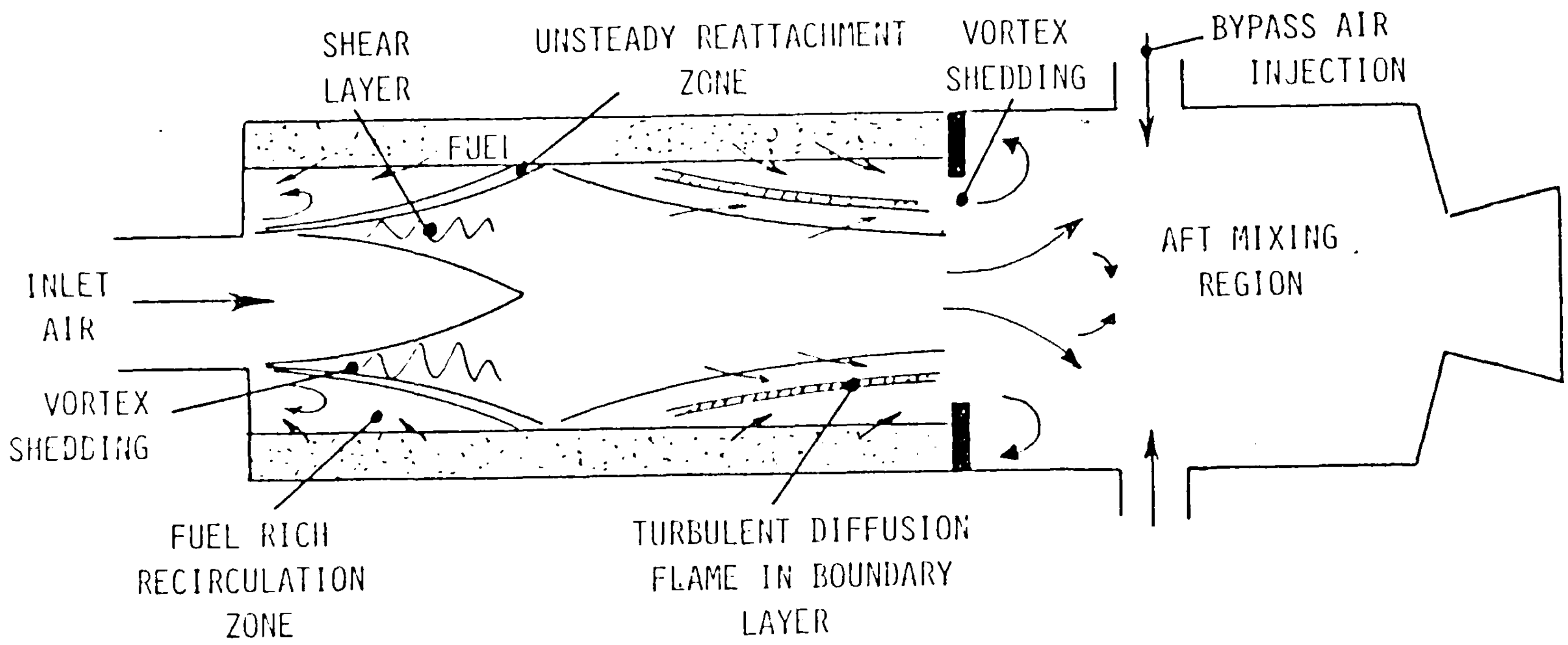

Figure 1.1 Schematic of the SFRJ.

flow was passed through a central swirl element which extended 0.5 inches into the combustor. The swirl was induced by machining six flutes with a twist of one turn in five inches. The latter resulted in an inlet swirl angle of approximately 5 degrees to the motor centerline.

During the normal ignition sequence, the air flow rate was set at the desired value before the ignition switch was activated. When the ignition circuit was activated, ethylene gas was introduced upstream of the fuel grain along with primary air flow. This mixture was ignited with an oxygen-ethylene torch which issued from the face of the step inlet. Normally, two to three seconds of ignition time was required for PMM combustion to sustain.

The step insert section was provisioned for variations in inlet diameters to make the sudden expansion. The fuel grain itself, when mounted in the motor, became the mid-body of the ramjet. The fuel grain (and injection ring, if used) mounted between the head-end assembly and the aft mixing chamber. The aft-mixing chamber had a length-to-diameter ratio of 2.9. The entire motor was held together by four threaded rods and nuts. The ramjet motor was then mounted on the thrust stand.

B. AIR SUPPLY SYSTEM

A schematic of the ramjet air supply system is shown in figure 3.2. From the air tanks, the air flows through a pressure regulator, a sonic choke, a vitiated air heater and finally to the head-end assembly. The air flow can be either vented into the atmosphere or vented through the ramjet motor by the control of two pneumatically operated valves. Two flexible air flow lines were used to connect the main air line to the air heater. The latter was mounted on the thrust stand.

III. DESCRIPTION OF APPARATUS

A. RAMJET MOTOR

The ramjet motor assembly used in this experiments was that used previously at NPS [Ref. 1, 2].

Figure 3.1 shows a schematic drawing of the ramjet, illustrating the main sections. These are, the head-end assembly, step insert section, fuel grain, aft mixing chamber and exhaust nozzle. For the tests with secondary injection, the injection ring was used.

The head-end assemly contains a central opening for the introduction of the primary air-flow, and ports for introduction of the ignition fuel and the igniter torch.

The fuel wall injection is shown in Figure 2.1, Figure 2.2 and Figure 2.3. Injection velocity varied between approximately 30 and 200 ft/sec as the injection mass flow rate was increased from 1% to 5 % of the inlet air flow. A nominal one dimensional flow port velocity was approximately 300 ft/sec.

For the face injection tests, air, oxygen or gaseous fuel was introduced using a differently designed step insert(Figure 2.4 and Figure 2.5). The injection was provided through eight equally spaced, 0.047 diameter holes. For an injection gas mass flow rate equal to 1 % of the inlet air flow rate the injection velocity was approximately 65 ft/sec.

To provide a swirl at the air inlet, a specially designed insert was used(Figure 2.6). This device was a tube-in-hole type injector. Approximately 43 % of the air flow passed through the outer annulus to maintain the recirculation region/flame holder. The other 57 % of the air where Pe = exit pressure of the nozzle

P_o = ambient pressure. Then for a choked converging nozzle, this equation can be simplified to

$$C_{F\,exp} = \sqrt{\left(\frac{2\gamma^2}{\gamma+1}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} + \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} - \frac{P_o}{\bar{P}_c} \qquad (2.13)$$

where R and γ are determined using PEPCODE

Then efficiency based on thrust is calculated from

$$\eta_{\Delta T_F} = \frac{C^{*2}_{exp} - C_a^{*2}}{C^{*2}_{th} - C_a^{*2}} \qquad (2.14)$$

where C^*exp = $\bar{F}\, g_c / (\dot{m}_t\, C_F exp)$

C^*a = $\bar{F} / (\dot{M}_{pi}\ C_F)$ (determined before ignition)

$\bar{F}$ = average thrust from analog record

$\bar{M}_{pi}$ = pre-ignition flow rate

$$Dth_{eff} = \sqrt{\frac{C^*_{air} \quad \dot{m}_{air}}{P_{ca} \quad \frac{\pi}{4} \quad g_c}} \tag{2.8}$$

Then temperature-rise comustion efficiency based on nozzle stagnation pressure can be calculated using c^*

$$\eta_{\Delta T_p} = \frac{C^{*\,2}_{exp} - C^{*\,2}_{a}}{C^{*\,2}_{th} - C^{*\,2}_{a}} \tag{2.9}$$

where C^*_a = characteritic exhaust velocity for air flow before ignition

C^*_{exp} = experimental characteristic exhaust velocity based on Pc, the average combustion pressure

C^*_{th} is obtained from equation(2.7) using γ, R and Tt from PEPCODE with inputs of Pc, Ta, $\dot{m}_{air}$, $\dot{m}_f$, $\dot{m}_{O_2}$ and $\dot{m}_{C_2H_4}$. The latter two flow rates are used in the vitiated air heater.

The thrust equation is

$$F = \dot{m}_t \, U_e + (P_e - P_o) \, A_e \tag{2.10}$$

where $\dot{m}_t = \dot{m}_{air} + \dot{m}_f + \dot{m}_{O_2} + \dot{m}_{C_2H_4}$

A thrust coefficient, C_F, can be defined such that

$$F = C_F \, P_t \, A_{th} \tag{2.11}$$

$$C_{F_{exp}} = \sqrt{\left(\frac{2\gamma^2}{\gamma-1}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left\{1-\left(\frac{P_e}{\overline{P_c}}\right)^{\frac{\gamma-1}{\gamma}}\right\}} + \left(\frac{P_e - P_o}{\overline{P_c}}\right)\frac{A_e}{A_{th}} \tag{2.12}$$

based on thrust. The one dimensional continuity equation ($\dot{m} = \rho A V$) can be expressed in terms of the chamber stagnation properties for a choked converging nozzle

$$\dot{m}_t = \frac{P_t \, A_{th_{eff}}}{\sqrt{R \, T_t}} \sqrt{g_c \gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{2.5}$$

where $\dot{m}_t$ = total flow rate

P_t = P_c, chamber pressure(for low Mach number)

Ath_{eff} = effective nozzle throat area

R = gas constant

The characteristic exhaust velocity, c^* is defined as

$$c^* = \frac{P_c \, A_{th} \, g_c}{\dot{m}_t} = \frac{F \, g_c}{C_F \, \dot{m}_t} \tag{2.6}$$

where C_F = thrust coefficient

For a sonically choked exhaust nozzle,

$$c^* = \sqrt{\frac{g_c}{\gamma} \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}} R \, T_t} \tag{2.7}$$

Using pre-test air flow through the motor, equations (2.6)and (2.7) can be used to determine the effective exhaust nozzle throat diameter(Dtheff)

$$\overline{Df} = \sqrt{\frac{4\,\Delta W}{\pi\,\rho\,L} + \overline{Di}^2} \qquad (2.2)$$

where ΔW = weight change

L = length of the fuel grain

ρ = density of the fuel grain

$\overline{Di}$ = average intial port diameter of the PMM grain

The average fuel regression rate was then computed using

$$\dot{r}_{avg} = \frac{\overline{Df} - \overline{Di}}{2\,t_b} \qquad (2.3)$$

The mixture ratio, chamber pressure and motor air inlet temperature were used as input into the Naval Weapons Center(NWC) China Lake, Ca., Propellant Evaluation Program(PEPCODE) computer program to obtain the theoretical adiabatic combustion temperature and the combustion gas properties(γ and R). This temperature was used to calculate temperature rise combustion efficiencies based on thrust and based on nozzle stagnation pressure, where

$$\eta_{\Delta T} = \frac{T_{t\,exp} - T_a}{T_{t\,th} - T_a} \qquad (2.4)$$

and $T_{t\,exp}$ = combustor stagnation temperature

$T_{t\,th}$ = theoretical combustor temperature

T_a = inlet air temperature

Experimental values of combustor stagnation temperatures were calculated in two ways, one based on pressure and one

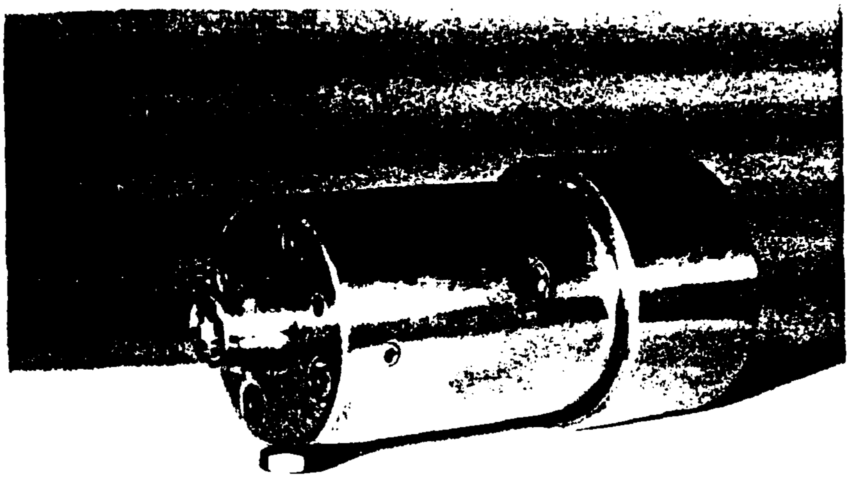

Figure 2.6 Swirl Element Inlet Injector.

Temperatures were only recorded digitally. Average values of the thrust and chamber pressure were determined using a compensating polar planimeter on the analog record.

The mass flow rate of air was obtained by using sonically choked nozzles. Average fuel mass flow rate was calculated by using the weight loss during the burn time

$$\dot{M}f = \frac{\Delta W}{t_b} \qquad (2.1)$$

where ΔW = weight change during the run

tb= burn time

The average internal diameter of the fuel grain was measured prior to the run. The final average diameter was determined based on weight loss and fuel length by using

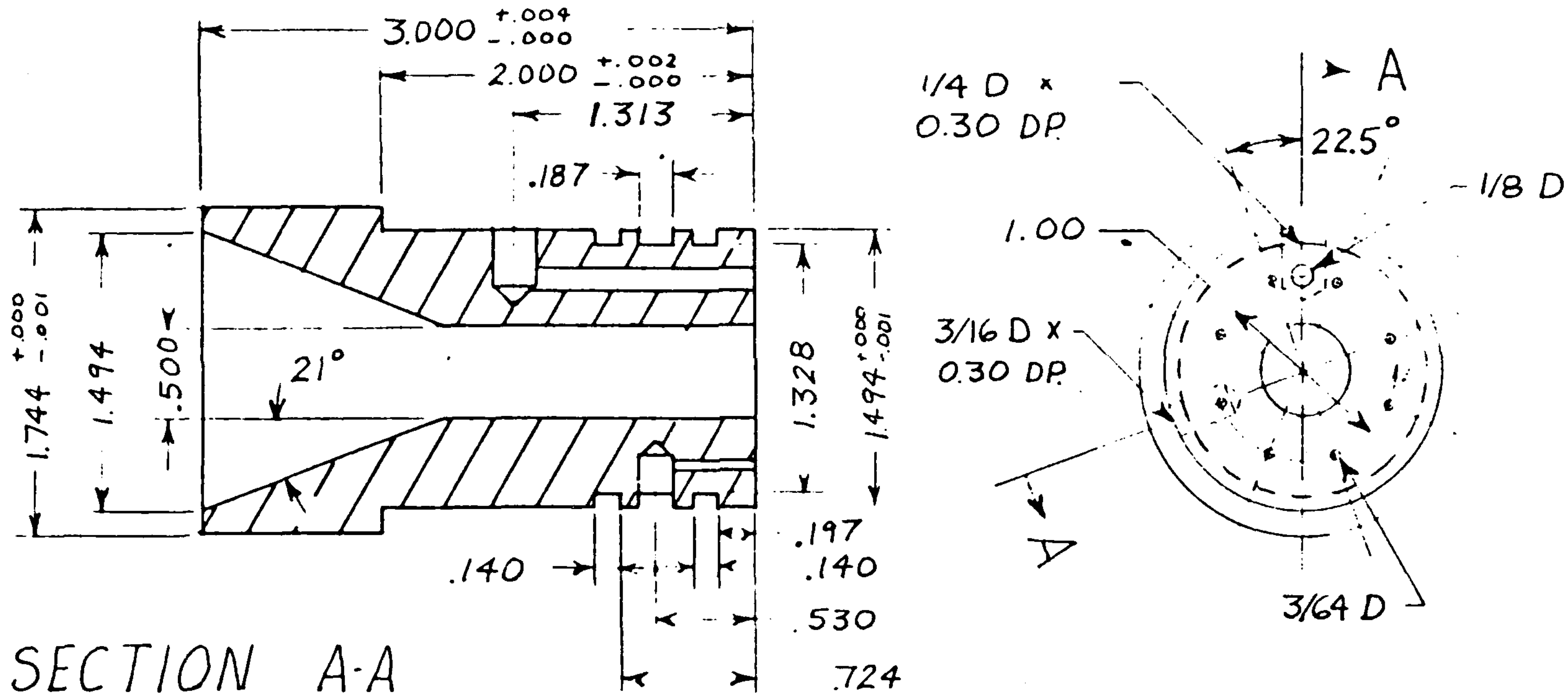

Figure 2.5 Drawing of Step Insert for Gaseous Injection.

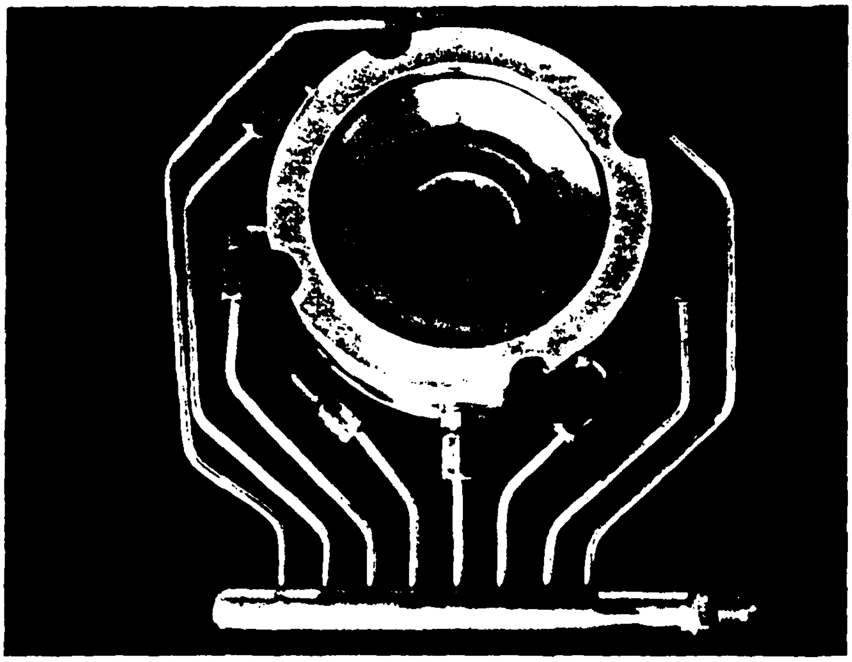

Figure 2.3 Injection Ring for Side Wall Injection.

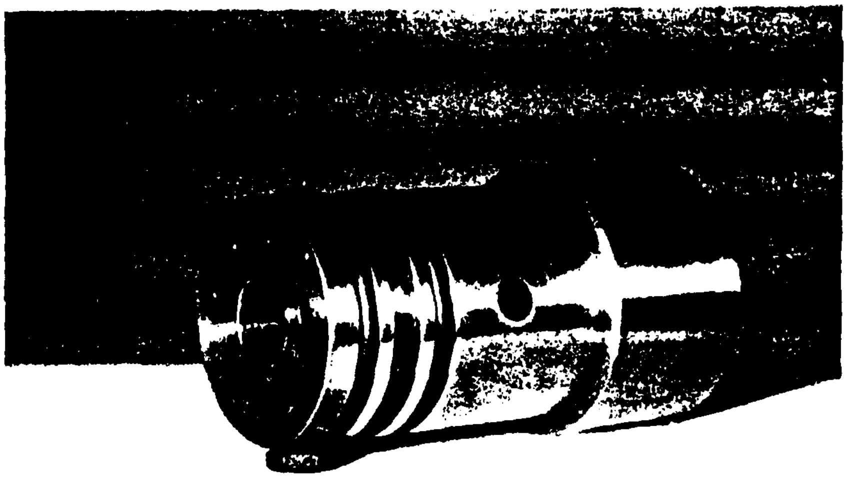

Figure 2.4 Step Insert For Gaseous Face Injection.

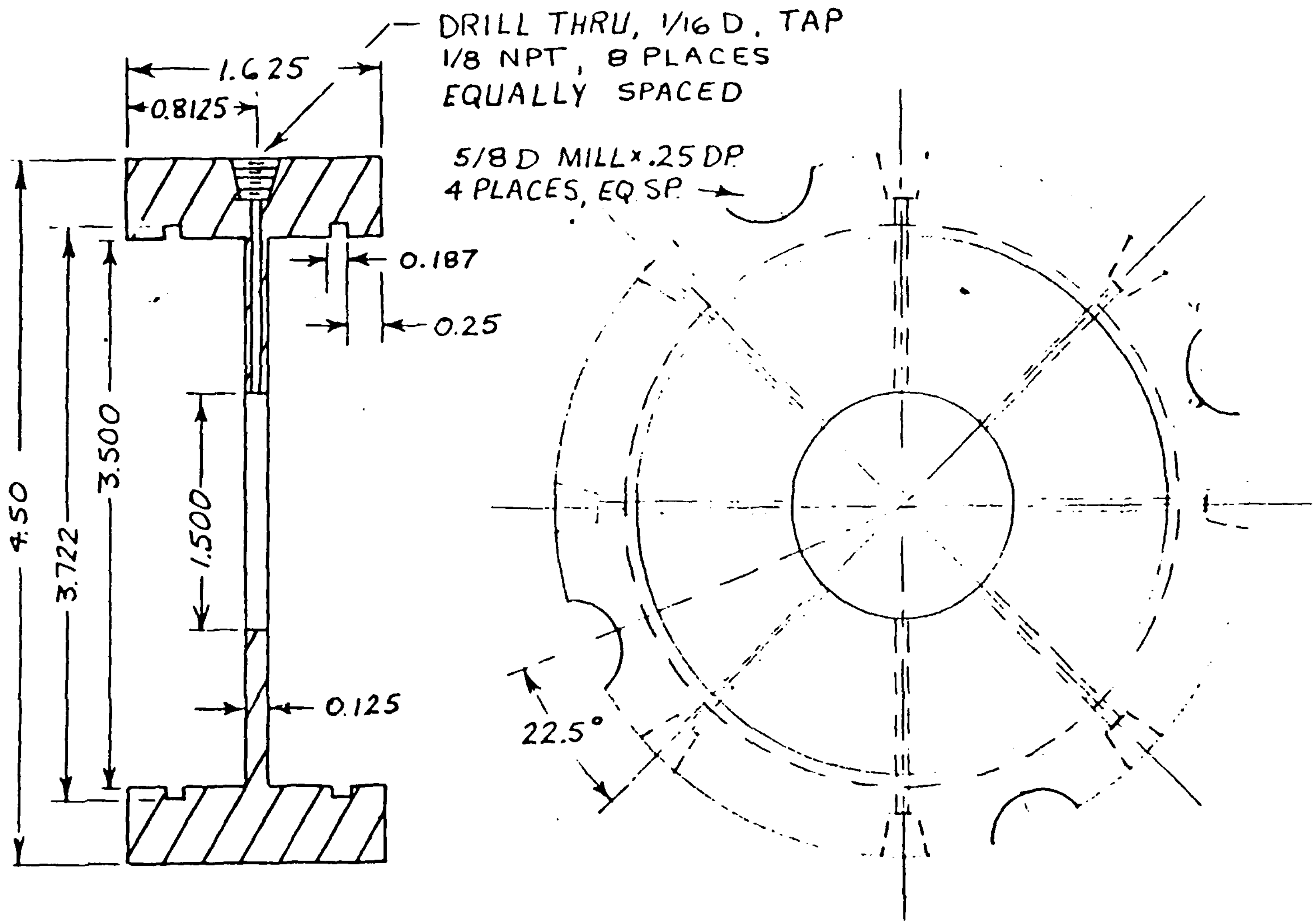

Figure 2.2 Drawing of Injection Ring for Side Wall Injection.

conditions found to significantly affect chamber pressure(or thrust) were further evaluated using full-length burn times of approximately 30 seconds (in order to accurately determine regression rate and combustion efficiency).

B. DATA COLLLECTION METHOD

The data collected during the regression rate control tests consisted of air flow rates, oxygen, air or fuel flow rates for the injection, motor head-end and chamber pressures, weight changes of the fuel grain, pre-ignition air flow time, ignition time, burning time, purge time, thrust and ignition gas flow rate. All pressures and the thrust were recorded both digitally and analog.

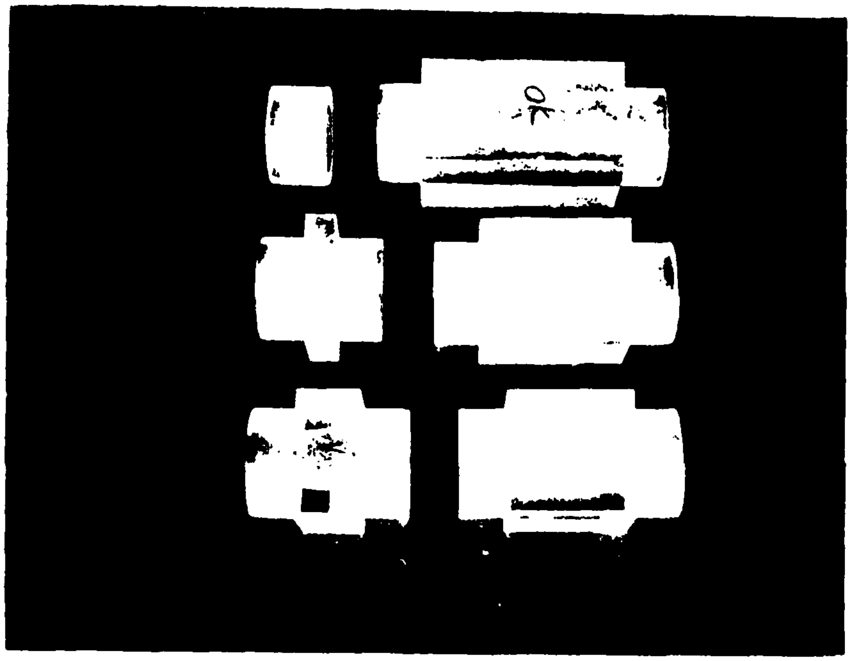

Figure 2.1 Fuel Configurations for Side Wall Injection.

II. METHOD OF INVESTIGATION

A. TEST CONDITITIONS AND METHODS

The experimental investigation was begun by selecting several configurations for regression rate control through the utilization of secondary injection. It was decided to examine secondary injection at three locations through the fuel grain wall: in the recirculation zone(flame holder area), just downstream of flow reattachment and further downstream within the region of the developing boundary layer (in which is located a turbulent diffusion flame). In addition, gaseous injection on the inlet step face and inlet air swirl were examined.

Polymethylmethacrylate(PMM) was used as the fuel and had a nominal length of 12 inches and an internal diameter of 1.5 inches. A sudden expansion inlet was used which provided an inlet step height of 0.49 inches.

Flow reattachment normally occurs between 7 and 8 step heights(i.e, 3.5 - 4 inches). Thus the three injection location chosen where 2, 5, and 8 inches from the head end(See Figure 2.1).

The injection ring was designed to provide radial injection through eight equally spaced, 0.0625 inches diameter holes(See Figure 2.2 and Figure 2.3).

Gaseous injection was also used through the inlet step face as shown in Figure 2.4 and Figure 2.5.

Swirl was provided to the inlet air flow through the use of a swirl element inlet injector(Figure 2.6).

Initial screening tests of short duration were made in which no injection or swirl was used, followed by tests with various amounts of gaseous injection or swirl. Those oscillations. Therefore, other fuel regression rate control techniques should be persued.

One possible alternative technique is the use of variable swirl at the air inlet. Increased swirl may increase the regression rate. This technique would require a vane control device. Another possibility is the use of secondary injection of air, oxygen or gaseous fuel into one or more locations within the combustor. This may lead to both increased fuel regression rate and combustion efficiency. If oxygen were used it would require an auxillary supply system. Therefore, it would be a practical possibility (to maintain simplicity) for a one-time augmentation in thrust(at take-over from booster, at terminal maneuver, etc).

In this investigation tests were conducted to examine the effects of secondary gaseous injection and inlet air swirl on regression rate and combustion efficiency.

A new ramjet thrust stand was installed in the combustion laboratory and required calibration and certification. A second part of this investigation was to conduct tests using high temperature inlet air and then to ensure that combustion efficiencies based on thrust and based on measured chamber pressure were in agreement.

Fig 1.1 shows a schematic of a SFRJ combustor. One inherent problem with the SFRJ is the dependence of fuel regression on the air mass flux through the fuel grain. The fuel regression rate generally behaves according to

$$\dot{r} = k\left(\frac{\dot{M}air}{Ap}\right)^{x} f\left(Tair,P\right) \qquad (1.1)$$

where $\dot{r}$ = fuel regression rate

Mair = air flow rate

Ap = port area

f(Tair,P)= a weaker function of inlet air temperature and pressure

x is between .3 and .6

If the air flow rate increases or decreases, then the fuel flow rate varies in the correct direction, but not enough to maintain design fuel-air ratio. This can significantly affect propulsive thrust.

The range of application and the performance of the SFRJ could be significantly improved if fuel regression rate could be controlled in some manner. Perhaps the most obvious method for fuel regression rate control is to use variable bypass air flow.

Bypass designs are often desired in order to increase fuel loading, and can also improve combustion efficiency. A valve in the bypass line could be used to vary the bypass ratio, thus producing changes in the fuel flow rate according to equation 1.1. (since only the fuel port air mass flux affects the regression rate). However, combustion efficiency may vary significantly with the amount of bypass air and a control valve must be used in the inlet air ducting. In addition, flow coupling may lead to undesired

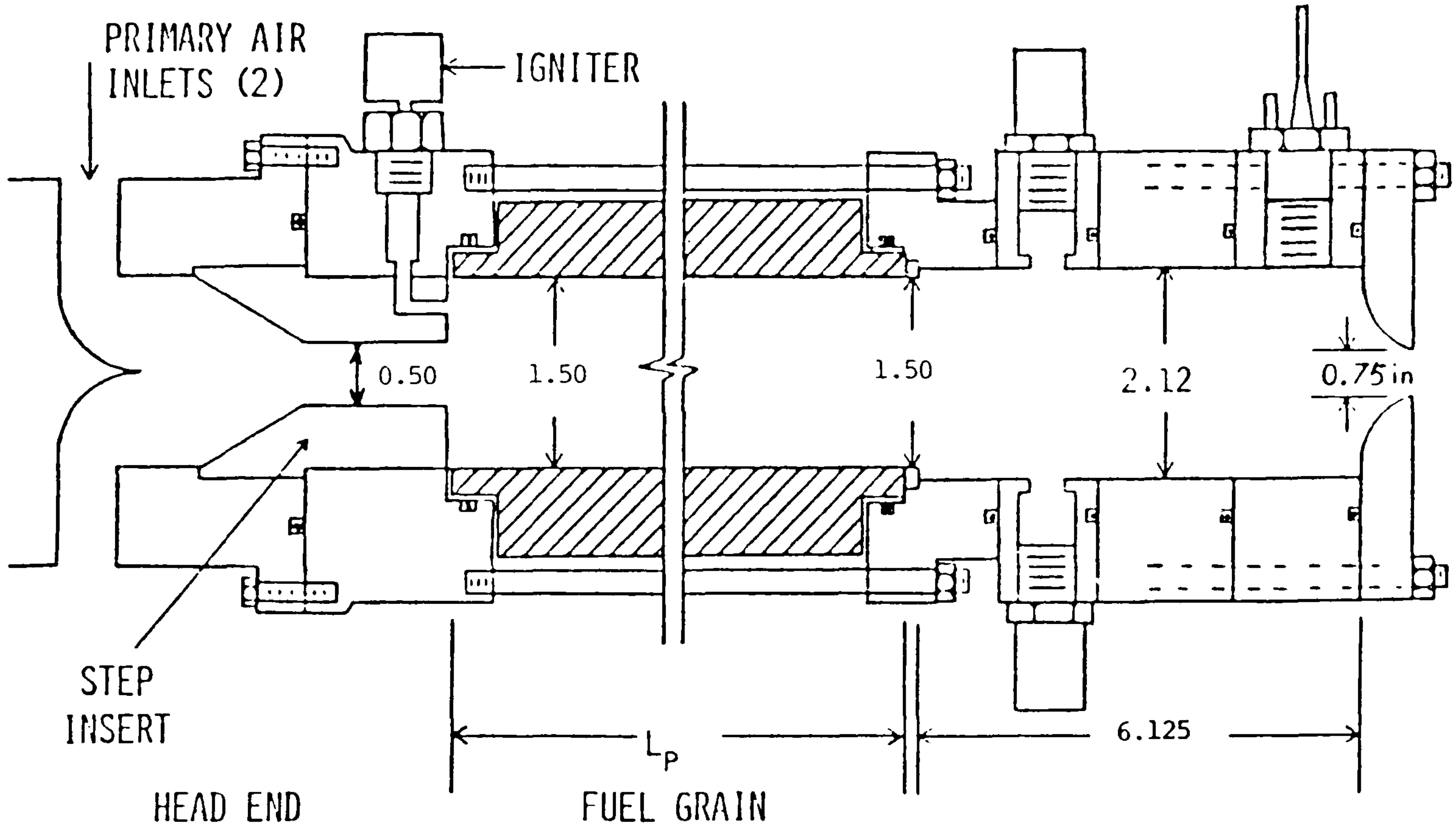

Figure 3.1 Schematic of the SFRJ Motor.

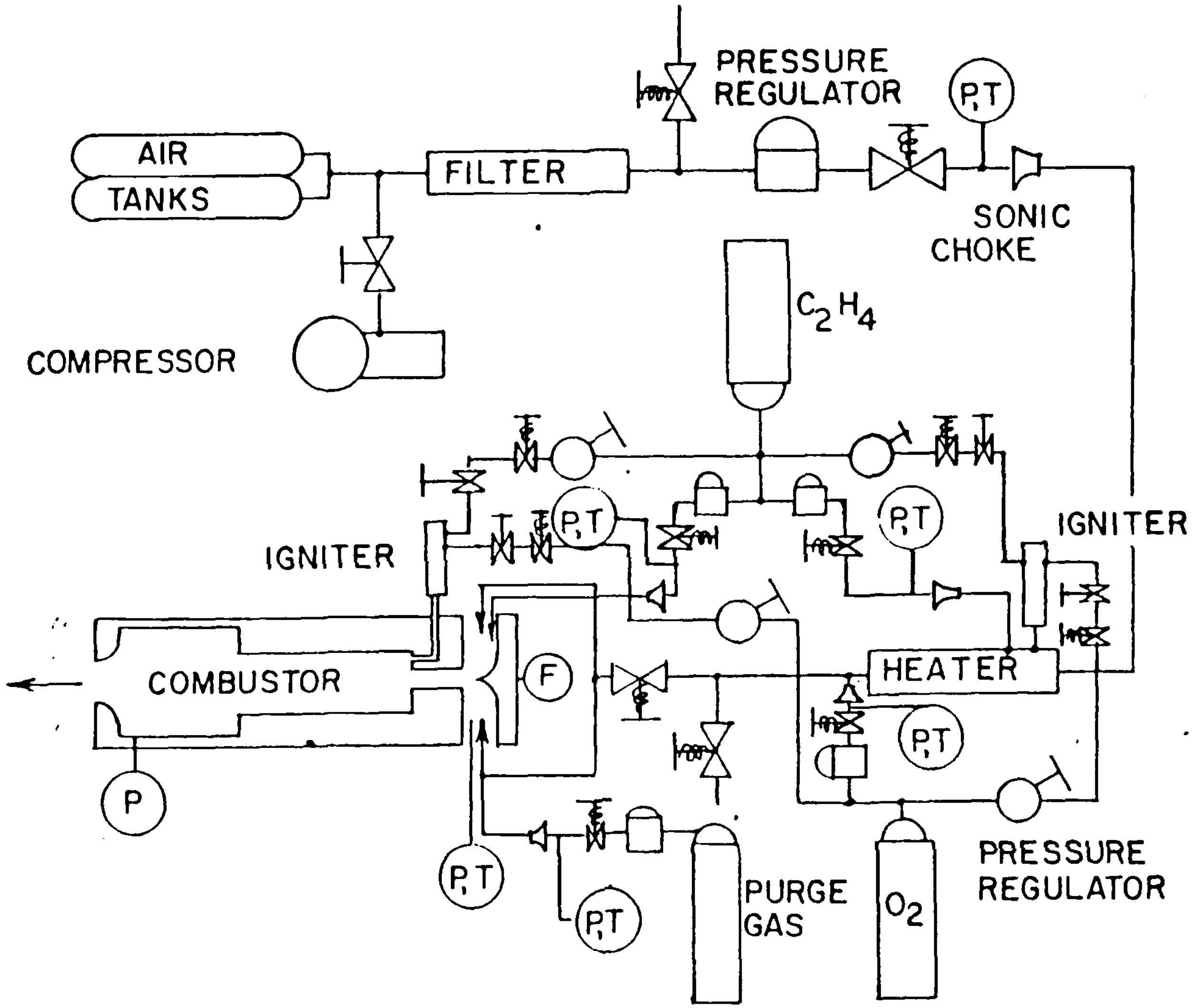

Figure 3.2 Schmatic of Air Supply System.

C. AIR HEATER

To simulate actual flight condition, air should be heated to the appropriate stagnation temperature. In this investigation ethylene gas used in the air heater. The oxygen in the air which is consumed during the heating must be replaced before injection into the ramjet cumbustor. Figure 3.2 shows a schematic diagram of the air heater. The air heater and the ramjet motor assembly were mounted together on the thrust stand.

D. DATA ACQUSITION AND CONTROL SYSTEM

The primary instrumentation used in this investigation consisted of various individual pressure transducers and thermocouples and a strain gage load cell for the thrust measurement. All transducer outputs were recorded both with a Honeywell 1508 Visicorder and HP-9836S computer using a HP-3054A AUTOMATIC DATA AQUISITION/CONTROL SYSTEM. A timing reference signal was provided to the analog record by feeding a 10 Hz signal from a laboratory signal generator to the timing channel of the Visicorder. During the test, the HP-9836S computer system was used to record the temperatures, and thrust, and calculate the flow rates of the ignition gas, purge gas, air heater ethylene and oxygen, air and secondary injection gas. It was necessary to record the PMM fuel grain weight and inner diameter before and after each run. The fuel grain weight was measured using a balance. All thermocouples used were chromel vs alumel (type K) with electronic ice points.

The computer was used to both control the test sequence and to provide data aquisition during the experiment. Figure 3.3 is a block diagram of the computer program. (See Appendix A. for a complete listing). Data aquisition for all fourteen channels were recorded every 0.5 seconds.

```
| Variable definitions and nomenclature                    |
------------------------------------------------------------
                             |
------------------------------------------------------------
| Transducer calibrations                                  |
|   main air sonic choke pressure                          |
|   chamber pressure                                       |
|   motor head pressure                                    |
|   air heater fuel sonic choke pressure                   |
|   oxygen make-up sonic choke pressure                    |
|   ignition fuel sonic choke pressure                     |
|   purge gas sonic choke pressure                         |
|   thrust transducer                                      |
------------------------------------------------------------
                             |
------------------------------------------------------------
| Pre-run input                                            |
|   test number, date                                      |
|   fuel I.D                                               |
|   fuel dimensions and weight                             |
|   air heater fuel type                                   |
|   motor throat diameter                                  |
|   ignition delay time                                    |
|   ignition time                                          |
|   buring time                                            |
|   purge time                                             |
|   sonic choke diameters, discharge coefficients          |
|   gas contants and desired flow rates                    |
------------------------------------------------------------
                             |
------------------------------------------------------------
|  Flow rates set-up                                       |
|   main air                                               |
|   heater fuel                                            |
|   make-up oxygen                                         |
|   ignition fuel                                          |
|   purge gas                                              |
------------------------------------------------------------
                             |
------------------------------------------------------------
|  Test and data collection                                |
|  pressures and temperature  in voltages                  |
------------------------------------------------------------
                             |
------------------------------------------------------------
|  Data extraction                                         |
|  pressures, temperatures and flow rates                  |
------------------------------------------------------------
                             |
------------------------------------------------------------
|   Print results                                          |
------------------------------------------------------------
```

Figure 3.3 Block Diagram of the Computer Data Aquisition/Control Program.

IV. EXPERIMENTAL PROCEDURES AND TEST CONDITIONS

A. TRANSDUCER CALIBRATION

A dead-weight tester was used for the calibration of all pressure transducers. Initially all transdusers were checked for linearity and the Visicorder(analog) display positions were labeled. For the computer data aquisition, voltages corresponding to atmospheric pressure and the maximum pressure were measured. From these readings a calibration constant (K) was determined for each transducer.

$$K = \frac{V_{pmax} - V_{po}}{P_{max}} \tag{4.1}$$

where Vpmax = voltage reading at the applied maximum pressure

V_{po} = voltage reading at atmospheric pressure

Pmax = maximum applied pressure

The thrust transducer was calibrated in-place by appliying known weights to the transducer through a pulley system attached to the thrust stand.

B. FLOW RATES SET-UP

By use of the computer, the gas flow rates could be set up before the hot firing. These were determined from short duration flows using the equation

$$\dot{M} = \frac{C_d \; K_m \; P_t \; \frac{\pi}{4} \; D_{choke}^2}{\sqrt{T_t}} \tag{4.2}$$

where km = constant (a function of R and γ)

Cd = discharge coefficient

P_t = total pressure of the gas flow

Dchoke = sonic choke diameter

T_t = total temperature of the gas flow

C. TEST SEQUENCE

1. Thrust Stand Calibration

The thrust stand was calibrated to determine the difference between the measured thrust and the actual or theoretical thrust. The measured thrust can be in error primarily due to the variation in flex-line stiffness with changing pressure levels. The process was begun by dead-weight calibration of the load cell. Cold air was then flowed through the motor with a choked exhaust nozzle. Measured thrust was recorded and compared to the theoretical thrust. The latter was calculated using Equations (2.11) and (2.13). This was repeated for increasing air flow rates and for three different exhaust nozzle throat diameter. An additional test was made using hot air (1200° R) and a 12 inches long HTPB fuel grain. This test was conducted in order to compare the temperature rise combustion efficiency determined by using chamber pressure and by using thrust.

2. Fuel-wall Injection Tests

For the fuel-wall injection tests, three injection location were used as discussed above. Each test lasted for approximately six seconds, three seconds without injection and three seconds with injection. Air injection mass flows of 2, 5 and 7 percent of the main air flow rate were used. For oxygen injection, 1.5, 2 and 5 percent were used. Those conditions which resulted in the greatest increases in chamber pressure/thrust were repeated with full duration(30 sec) tests.

3. Face Injection Tests

In these experiments a twelve inches long cylindrically perforated PMM fuel grain was used. Air injection flow rates of 2, 5 and 7 percent of the main air flow rate were examined.For oxygen injection, 1.5, 2 and 5 percent were used. Ethylene was also used with 0.5, 1.25 and 2.5 percent. Testing methods were identical to those discussed above for fuel-wall injection.

4. Inlet Air Swirl Tests

Several inlets were initially tried which induced swirl to the entire inlet air flow. Swirling the entire flow apparently distroys the flameholding recirculation zone, and resulted in no ignition. The tube-in-hole injector discussed above was then tested using a twelve inch PMM fuel grain.

V. RESULTS AND DISCUSSION

Summaries of the experimental results obtained during the initial screening tests are presented in Table 1 and Table 2 for fuel-wall and inlet step-face injection respectively. Results from the subsequent full duration tests are presented in Table 3.

A. FUEL WALL INJECTION

In data presented in Table 1 shows that air injected through the fuel grain surface was generally detrimental to combustion. Air injection rates up to approximately 7 % of the inlet air flow rate had little if any effects on combustion pressure when introduced downstream of flow reattachment. Small amounts of air injected into the recirculation zone appeared to provide small improvements. The injected air was quite cold (approximately 500°R) and therefore could have had a quenching effect on the boundary layer combustion. Use of "in-flight" high air should be examined in the future.

Unheated oxygen injection resulted in significant increases in combustion pressure, especially when introduced into the recirculation zone in small amounts. Based on these screening test results two additional tests were conducted with test times of approximately 30 seconds. These tests were made to examine the effects of 1 % oxygen injection into the recirculation region.

In these tests, a total grain length of fourteen inches was used; two inches of PMM , then the injection ring and then twelve inches of PMM. One test(Table 3, no. 30) was made without injection and one with (Table 3, no.29).

Oxygen injection resulted in approximately a 5 % increase in in fuel regression rate (when adjusted for the different air flowrate) but a decrease of 21 % in combustion efficiency. The recirculation zone is generally fuel rich. Thus, oxygen injection should increase the "flame-holder" temperature. This was evident during the test from increased flame luminosity.

It is not clear at this point why the combustion efficiency decreased or, for that matter, why the precence of the ring alone increased combustion efficiency. The oxygen injection velocity was approximately 30 ft/sec which is less than 30 % of typical recirculation zone, near-wall velocities. However, the injected oxygen may have penetrated the shear layer.

Further testing would be benificial, especially using HTPB, but at this point it does not appear that fuel wall injection of small amounts of air or oxygen is a viable method for providing fuel mass flowrate control since combustion efficiency was decreased significantly and the increase in regression rate was small.

B. INLET STEP FACE INJECTION

The data from the screening tests with step-face injection are presented in Table 2. Unheated air had no significant effect on combustion pressure. Oxygen injection resulted in increased flame luminosity in the recirculation zone but apparently did not significantly affect downstream combustion (even though the overall equivalence ratio was approximately 0.7). Injection of ethylene resulted in significant increases in combustion pressure.

A full duration test (Table 3, no. 28) was conducted using 1 % of ethylene with an injection velocity of approximately 65 ft/sec. Comparison of the results with those for no injection (Table 3, no. 27) showed that only a small increase occurred in fuel regression rate.

Some of the ethylene apparently escaped the recirculation region and burned downstream in the central air or in the aft mixing region, resulting in little effect on regression rate.

C. INLET AIR SWIRL

Only one test was conducted using inlet air swirl (Table 3, no. 31). Approximately 43 % of the air was injected axially to maintain the recirculation zone flame holding ability. This could be reduced to perhaps only 10 - 20 %, resulting in more air with swirl. The amount of swirl was also intentionally kept small (5 degrees from the axial direction) to determine if regression rate was sensitive to the swirl.

The small amount of swirl increased the fuel regression rate by 15 %. This resulted in an increase in equivalence ratio ratio from 0.69 to 0.79 . Some non-uniformity in regression rate was also evident.

These initial results indicate that fuel regression rate is quite sensitive to inlet air swirl. Further testing is necessary using varying amounts of swirl, but the technique appears viable for in-flight fuel mass flow modulation.

D. THRUST STAND CALIBRATION

The results from the cold-flow tests for comparison of measured and calculated thrust are in Figure 5.1. Excellent agreement was attained. A least-square fit of the data resulted in the following equation for relating measured thrust to the "actual" thrust

$$Fa = 1.0149 \times Fm + 0.4 \qquad (5.1)$$

where Fa = actual thrust, based on Pc and throat diameter

Fm = measured thrust

A test was then coducted (Table 3, no. 32) in which HTPB fuel was used with an inlet air temperature of approximately 1200 R. This test was made in order to compare the combustion efficiencies based on chamber pressure and based on thrust. The two efficiencies were within 5 %, with the value based on Pc being greater. This difference is not large when it is realized that small errors in determining F and Pc from the analog traces are squared when calculating C for the efficiency based on thrust determination.

TABLE 1

Fuel Wall Injection Results

test number	$\dot{M}air$ (Lbm/sec)	$\dot{M}inj$ (Lbm/sec)	$\dot{M}inj/\dot{M}air$ %	$\Delta Pc/Pc$ %	Injected gas
8 inches and 4 inches configuration					
1	0.192	0.004	2.1	0	air
2	0.193	0.0029	1.5	0	air
3	0.205	0.0042	2.1	0	air
4	0.202	0.014	6.9	5.0	air
5	0.196	0.014	7.1	5.0	air
6	0.200	0.001	0.5	1.6	oxygen
7	0.197	0.002	1.0	3.3	oxygen
8	0.192	0.0039	2.0	3.4	oxygen
9	0.197	0.004	2.0	3.7	oxygen
5 inches and 7 inches configuration					
10	0.202	0.01	4.95	3.5	air
11	0.208	0.001	0.48	1.7	oxygen
12	0.202	0.003	1.5	3.3	oxygen
2 inches and 10 inches configuration					
13	0.200	0.004	2.0	3.3	air
14	0.200	0.01	5.0	5.1	air
15	0.205	0.01	5.0	2.5	oxygen
16	0.209	0.0011	0.54	2.5	oxygen
17	0.182	0.0033	1.8	4.4	oxygen
18	0.198	0.0038	1.9	4.6	oxygen

TABLE 2

Step Face Injection Result

Test number	$\dot{M}_{air}$ (Lbm/sec)	$\dot{M}_{inj}$ (Lbm/sec)	$\dot{M}_{inj}/\dot{M}_{air}$ %	$\Delta Pc/Pc$ %	Injected gas
19	0.196	0.003388	2.0	3.0	air
20	0.201	0.0104	5.0	4.0	air
21	0.209	0.00099	0.5	0.0	oxygen
22	0.143	0.00095	0.65	0.0	oxygen
23	0.205	0.00105	0.5	4.0	ethylene
24	0.201	0.00264	1.25	5.9	ethylene
25	0.203	0.00513	2.5	5.0	ethylene

TABLE 3

Summary of Experimental Data

Test number	27	28	29	30	31	32
Condition	nominal	1 % C_2H_4 face injection	1 % O_2 recirculation zone	same as 29 without injection	inlet air swirl	nominal
Fuel	PMM	PMM	PMM	PMM	PMM	HTPB
Initial weight (Lbm)	6.01	6.035	6.645	6.013	5.583	1.664
Final weight (Lbm)	5.448	5.471	5.972	5.410	5.169	1.165
Length (in)	11.933	11.848	13.838	14.013	11.761	12.170
Dp, intial (in)	1.500	1.502	1.501	1.503	1.502	1.538
$D_{th_{eff}}$ (in)	0.739	0.739	0.737	0.744	0.737	0.938
Fuel Density (Lbm/cu.in)	0.0426	0.0426	0.0426	0.0426	0.0426	0.0332
f stoichiometric	0.121	0.121	0.121	0.121	0.121	0.0737
Burn time (sec)	33.1	33.1	33.4	33.1	34.3	9.9
$\dot{M}air$ (Lbm/sec)	0.203	0.202	0.203	0.185	0.202	0.498
Tair, inlet (R)	546	538	501	563	504	1172
$\dot{M}f$ (Lbm/sec)	0.0169	0.0171	0.0201	0.0182	0.0194	0.0504
$\dot{r}$ (in/sec)	0.0062	0.0063	0.00634	0.0058	0.0071	0.0225

```
6550   ENTER 722;Vphf
6560   OUTPUT 709;"AC10"
6570   OUTPUT 722;"T3"
6580   ENTER 722;Vthf
6590   CLEAR 709
6600   OUTPUT 709;"DC10,0"
6610   PRINT "MANUALLY TURN OFF AIR 'HEATER GAS' SWITCH"
6620   BEEP
6630   DISP "HIT CONTINUE TO PROCEED"
6640   PAUSE
6650   OUTPUT 709;"DO10,0"
6660   Phf=(Vphf-Vphf0)*Kphf+Pbar
6670   Volts=Vthf
6680   GOSUB Tcalc
6690   Thf=T
6700   Mhf=Kmhf*Cdhf*Phf*.7854*(Dhfchoke^2)/(Thf^.5)
6710   PRINT USING "@"
6720   PRINT USING "4A,DD.DDDDD";"Mhf=";Mhf
6730   PRINT USING "12A,DD.DDDDD";"Mhf DESIRED=";Mhfd
6740   Ratio=Mhf/Mhfd
6750   PRINT USING "19A,D.DDD,2X,4A,DDDD.DD,1A";"Mhf/ Mhf DESIRED=";Ratio,"Thf="
;Thf,"R"
6760    Pg=Phf-Pbar
6770    PRINT USING "5A,DDDD.DDD,4A,3X,4A,DDDD.DD,1A,4A,DDDD.DD,1A";"Phf= ";Pg;"P
sig","Thf=";Thf;"R"
6780    INPUT "IS HEATER FUEL FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$
6790    IF Xx$="Y" THEN GOTO Phffin
6800    Phfnew=(Phf*Mhfd/Mhf)-Pbar
6810    PRINT USING "13A,DDDD.DD,4A";"RESET Phf TO";Phfnew;"Psig"
6820    DISP "HIT CONTINUE AFTER RESET OF Phf"
6830    PAUSE
6840    GOTO Phfset
6850 Phffin:!
6860     DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
6870     PAUSE
6880 Phfskip:     !
6890     PRINT USING "@"
6900     INPUT "DO YOU WANT TO PRESET THE HEATER OXYGEN FLOW RATE?(Y/N)",Zz$
6910     IF Zz$="N" THEN GOTO Phoskip
6920     !************************************************************************
6930     PRINT "SET THE DESIRED VALUE OF Pho USING THE HAND LOADER/PRESSURE GAGE"
6940     !************************************************************************
6950     DISP "HIT CONTINUE WHEN READY"
6960     PAUSE
6970 Phoset:!
6980           PRINT "MANUALLY TURN ON AIR 'HEATER GAS' SWITCH"
6990           DISP "HIT CONTINUE TO PROCEED"
7000           PAUSE
7010           OUTPUT 709;"AC4"
7020           OUTPUT 722;"T3"
7030           ENTER 722;Vpho
7040           OUTPUT 709;"AC11"
7050           OUTPUT 722;"T3"
7060           ENTER 722;Vtho
7070           CLEAR 709
7080           OUTPUT 709;"DC10,0"
7090           PRINT "MANUALLY TURN OFF AIR 'HEATER GAS' SWITCH"
7100           BEEP
7110           DISP "HIT CONTINUE TO PROCEED"
7120           PAUSE
7130           OUTPUT 709;"DO10,0"
7140           Pho=(Vpho-Vpho0)*Kpho+Pbar
7150           Volts=Vtho
7160           GOSUB Tcalc
7170           Tho=T
7180           Mho=Kmho*Cdho*Pho*.7854*(Dhochoke^2)/(Tho^.5)
7190           PRINT USING "@"
7200           PRINT USING "4A,DD.DDDDD";"Mho=";Mho
```

```
5900   IF Xx$="Y" THEN GOTO Dtheffcalc
5910   Panew=(Pa*Maird/Mair)-Pbar
5920   PRINT "RESET Pa TO";Panew;"Psig"
5930   DISP "HIT CONTINUE AFTER RESET OF Pa"
5940   PAUSE
5950   GOTO Paset
5960 Dtheffcalc:                ! CALCULATE EFFECTIVE THROAT DIAMETER, CHARACTERIS
TIC EXHAUST VELOCITY, THRUST BOTH THEORETICAL AND MEASURED
5970   Cstar=(Gc*Rair*Ti*((Gammaair+1)/2)^((Gammaair+1)/(Gammaair-1))/Gammaair)^
.5
5980   Cfair=.7396+.5283-(14.7/Pc)
5990   Dtheff=(((Cstar*Mair)/(.7854*Pc*Gc))^.5)
6000   PRINT "Cstarair(BASED ON Ti)=";Cstar,"(ft/sec)"
6010   PRINT "Cfair=";Cfair
6020   PRINT "Dtheff=";Dtheff,"(in)"
6030   PRINT "Pco=";Pc,"Psia"
6040   PRINT "Ti=",Ti," R"
6050   F=(Vf-Vf0)*Kf
6060   Fair=Cfair*Pc*.7854*(Dtheff^2)
6070   PRINT "Fair(BASED ON Pc)=";Fair,"(Lbf)"
6080   PRINT "Fair(MEASURED)=";F,"(Lbf)"
6090   IF Ko=0 THEN GOTO 6170
6100   INPUT "DO YOU WANT PRINTOUT OF POST RUN DATA?(Y/N)",Yy$
6110   IF Yy$="N" THEN GOTO Finish
6120 Headingprint: !
6130     PRINTER IS 701
6140     PRINT USING "6/"
6150     PRINT "                 ****** POST RUN DATA COLD AIR, CHOKED ****** "
6160     GOTO Preprint
6170   INPUT "DO YOU WANT PRINTOUT OF PRE-RUN DATA?(Y/N)",Xx$
6180   IF Xx$="Y" THEN GOTO Preprint
6190   GOTO Skipprint
6200 Preprint:   !
6210     PRINTER IS 701
6220     IF Ko=1 THEN GOTO 6240
6230     PRINT "                         **** PRE-RUN DATA, USING COLD AIR ONLY AND CHO
KED FLOW ****"
6240     PRINT ""
6250     PRINT USING "12A,2X,8A   ";"TEST DATE IS",Date$
6260     PRINT "Cstarair(BASED ON Ti)=";Cstar,"(ft/sec)"
6270     PRINT "Cfair=";Cfair
6280     PRINT "Dtheff=";Dtheff,"(in)"
6290     PRINT "Pco=";Pc,"Psia"
6300     PRINT "Ti=",Ti," R"
6310     PRINT "Fair(BASED ON Pc)=";Fair,"(Lbf)"
6320     PRINT "Fair(MEASURED)=";F,"(Lbf)"
6330     PRINT "Mair=";Mair,"Lbm/sec"
6340     PRINTER IS 1
6350     IF Ko=1 THEN GOTO Finish
6360 Skipprint: !
6370   DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
6380   PAUSE
6390 Paskip:   !
6400   PRINT USING "@"
6410   INPUT "DO YOU WANT TO PRESET THE HEATER FUEL FLOW RATE? (Y/N)",Zz$
6420   IF Zz$="N" THEN GOTO Phfskip
6430 !*************************************************************************
6440  PRINT "SET THE DESIRED VALUE OF Phf USING THE HAND LOADER/PRESSURE GAGE"
6450 !*************************************************************************
6460  DISP "HIT CONTINUE WHEN READY"
6470  PAUSE
6480 Phfset:!
6490   PRINT USING "@"
6500   PRINT "MANUALLY TURN ON AIR 'HEATER GAS' SWITCH"
6510   DISP " HIT CONTINUE TO PROCEED"
6520   PAUSE
6530   OUTPUT 709;"AC3"
6540   OUTPUT 722;"T3"
```

```
5250  IF Zz$="Y" THEN GOTO Nochange
5260 Changevariable:!
5270  PRINT "INPUT VARIABLE NAME= CORRECTED VALUE"
5280  PRINT "A STRING VARIABLE MUST BE ENCLOSED IN QUOTATION MARKS"
5290  DISP "HIT EXECUTE AND THEN CONTINUE AFTER CORRECTION "
5300  PAUSE
5310  GOTO Change1
5320 Nochange:!
5330  !*********************************************************************
5340  ! B. FLOW RATE SET-UPS
5350  !*********************************************************************
5360  PRINT USING "@"
5370  INPUT "DO YOU WANT TO PRESET THE AIR FLOW RATE?(Y/N)",Zz$
5380  IF Zz$="N" THEN GOTO Paskip
5390  PRINT "SET THE DESIRED VALUE OF Pa(psig) USING THE HAND LOADER /PRESSURE G
AGE"
5400  PRINT USING "3/"
5410  PRINT "THE HAND LOADER SHOULD BE 20 PSIG MORE THAN DESIRED PRESSURE"
5420 Paset: !
5430  PRINT USING "3/"
5440   PRINT "MANUALLY INITIATE AIR FLOW BY TURNING 'MAIN AIR' TO 'ON' AND PUSHI
NG 'PRI'      ON CONTROL PANEL"
5450   DISP "HIT CONTINUE WHEN READY"
5460   PAUSE
5470   WAIT 3
5480   OUTPUT 709;"AC2"
5490   OUTPUT 722;"T3"
5500   ENTER 722;Vpa
5510   OUTPUT 709;"AC9"
5520   OUTPUT 722;"T3"
5530   ENTER 722;Vta
5540   OUTPUT 709;"AC0"
5550   OUTPUT 722;"T3"
5560   ENTER 722;Vpc
5570   OUTPUT 709;"AC8"
5580   OUTPUT 722;"T3"
5590   ENTER 722;Vti
5600   OUTPUT 709;"AC5"
5610   OUTPUT 722;"T3"
5620   ENTER 722;Vf
5630   CLEAR 709
5640   OUTPUT 709;"DC10,1"      ! DIGITALLY CLOSE CIRCUIT 1
5650   WAIT 1
5660   OUTPUT 709;"DO10,1"      ! DIGITALLY OPEN CIRCUIT 1
5670   BEEP
5680   PRINT "TURN OFF 'MAIN AIR'"
5690   DISP "HIT CONTINUE TO PROCEED"
5700   PAUSE
5710   Pa=(Vpa-Vpa0)*Kpa+Pbar
5720   Pc=(Vpc-Vpc0)*Kpc+Pbar
5730   Volts=Vta
5740   GOSUB Tcalc               ! CONVERSION FROM VOLTAGE TO TEMPERATURE
5750   Ta=T
5760   Volts=Vti
5770   GOSUB Tcalc               ! CONVERSION FROM VOLTAGE TO TEMPERATURE
5780   Ti=T
5790   Mair=Kmair*Cdair*Pa*.7854*(Dairchoke^2)/(Ta^.5)
5800   PRINT USING "@"
5810   PRINT USING "5A,2X,DDD.DDDDD";"Mair=";Mair
5820   PRINT USING "14A,DDD.DDD";"Mair DESIRED=";Maird
5830   Ratio=Mair/Maird
5840   PRINT USING "20A,D.DDD,2X,3A,1X,DDDD.DD,1A,3X,3A,DDDD.DD,1A";"Mair/DESIRE
D Mair=";Ratio,"Ta=";Ta,"R","Ti=";Ti;"R"
5850   Pg=Pa-Pbar
5860   PRINT USING "4A,DDDD.DD,4A";"Pa =";Pg;"Psig"
5870   PRINT USING "4A,DDDD.DD,1A";"Ta =";Ta;"R"
5880   IF Ka=1 THEN GOTO Dtheffcalc             ! DETERMINE PRE-RUN OR POST-RUN
5890   INPUT "IS AIR FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$
```

```
4680  INPUT "THE AIR CHOKE DISCHARGE COEFFICIENT",Cdair
4690  INPUT "THE AIR HEATER FUEL CHOKE DISCHARGE COEFFICIENT",Cdhf
4700  INPUT "THE AIR HEATER OXYGEN CHOKE DISCHARGE COEFFICIENT",Cdho
4710  INPUT "THE IGNITION GAS CHOKE DISCHARGE COEFFICIENT",Cdif
4720  INPUT "THE PURGE GAS CHOKE DISCHARGE COEFFICIENT",Cdp
4730  INPUT "THE AIR HEATER FUEL FLOW RATE CONSTANT,Kmhf",Kmhf
4740  INPUT "THE IGNITION GAS FLOW RATE CONSTANT, Kmif",Kmif
4750  INPUT "THE PURGE GAS FLOW RATE CONSTANT, Kmp",Kmp
4760  INPUT "GAMMA FOR HEATER FUEL,Gammahf",Gammahf
4770  INPUT "GAMMA FOR IGNITION FUEL, Gammaif",Gammaif
4780  INPUT "GAMMA FOR PURGE GAS, Gammap",Gammap
4790  INPUT "GAS CONSTANT FOR HEATER FUEL,Rhf(ft.lbf/lbm.R)",Rhf
4800  INPUT "GAS CONSTANT FOR IGNITION FUEL,Rif(ft.lbf/lbm.R)",Rif
4810  INPUT "GAS CONSTANT FOR PURGE GAS, Rp(ft.lbf/lbm.R)",Rp
4820  INPUT "THE AIR CHOKE DIAMETER,Dairchoke (in)",Dairchoke
4830  INPUT "THE HEATER FUEL CHOKE DIAMETER,Dhtfuchoke(in)",Dhfchoke
4840  INPUT "THE IGNITION OXYGEN CHOKE DIAMETER,Dhtoxchoke(in)",Dhochoke
4850  INPUT "THE IGNITION FUEL CHOKE DIAMETER,Dignfuchoke(in)",Difchoke
4860  INPUT "THE PURGE CHOKE DIAMETER,Dpurgechoke(in)",Dpchoke
4870  INPUT "THE DESIRED MASS FLOW RATE OF AIR,Maird(lbm/sec)",Maird
4880  INPUT "THE DESIRED MASS FLOW RATE OF heater FUEL,Mhfd(lbm/sec)",Mhfd
4890  INPUT "THE DESIRED MASS FLOW RATE OF heater OXYGEN,Mhod(lbm/sec)",Mhod
4900  INPUT "THE DESIRED MASS FLOW RATE OF IGNITION FUEL,Mifd(lbs/sec)",Mifd
4910  INPUT "THE DESIRED MASS FLOW RATE OF PURGE,Mpd(lbm/sec)",Mpd
4920  INPUT "THE INJECTION GAS,Injectgas",Injectgas$
4930  !************************************************************************
4940  !*    CHECK THE INPUT DATA      *
4950  !************************************************************************
4960 Chancel:  !
4970  PRINT USING "@"
4980  PRINT USING "14A,9A,5X,14A,9A,5X,14A,9A,2X,14A,DDDD.DDDD";"Testno=";Testno
$,"Date=";Date$,"Fuelid$=";Fuelid$,"Pbar=";Pbar
4990  PRINT USING "14A,9A,5X,14A,9A,5X,14A,9A,5X,14A,9A";"Heaterfuel=";Heaterfue
l$,"Ignitionfuel=";Ignitionfuel$,"Purge gas=";Purgegas$
5000  PRINT USING "14A,DDDDDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Wtfi=";W
tfi,"Do=";Do,"Lo=";Lo
5010  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Di=";Di,"Dth=";Dth
5020  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD,2X,14A,DDDD.D
DDD";"Tma=";Tma,"Tmi=";Tmi,"Tmb=";Tmb,"Tmp=";Tmp
5030  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Dairchoke=";Dairchoke,"Dhtfu
choke=";Dhfchoke
5040  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Dhtoxchoke=";Dhochoke,"Dignf
uchoke=";Difchoke
5050  PRINT USING "14A,DDDD.DDDD";"Dpurgechoke=";Dpchoke
5060  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Cdair=";Cda
ir,"Cdh=";Cdhf,"Cdho=";Cdho
5070  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Cdp=";Cdp,"Cdif=";Cdif
5080  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Gammahf=";G
ammahf,"Gammaif=";Gammaif
5090  PRINT USING "14A,DDDD.DDDD";"Gammap=";Gammap
5100  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Rhf=";Rhf,"
Rif=";Rif,"Rp=";Rp
5110  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Kmhf=";Kmhf
,"Kmif=";Kmif,"Kmp=";Kmp
5120  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Kmho=";Kmho,"Kmair=";Kmair
5130  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Maird=";Maird,"Tid=";Tid
5140  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD,2X,14A,DDDD.D
DDD";"Mhfd=";Mhfd,"Mhod=";Mhod,"Mifd=";Mifd,"Mpd=";Mpd
5150  PRINT "INJECTION GAS IS",Injectgas$
5160  !************************************************************************
5170  !*  VARIABLE CORRECTION
5180  !************************************************************************
5190  PRINT USING "4/"
5200  PRINT "CHECK ALL VALUES"
5210  DISP "HIT 'CONTINUE' TO PROCEED TO CORRECTION OR NEXT SUBROUTINE"
5220  PAUSE
5230  INPUT "VARIABLE OK? (Y/N)",Zz$
5240  IF Zz$="N" THEN GOTO Changevariable
```

```
4000  Kpp=Ppmax/(Vppmax-Vpp0)
4010  PRINT "Kpp=";Kpp
4020  BEEP
4030  INPUT "READING OK? (Y/N)",Zz$
4040  IF Zz$="N" THEN GOTO Ppmaxcal
4050 Fcal: !
4060        IF Ff=0. THEN GOTO Endcal
4070  !*****************************************************************
4080  PRINT "**CALIBRATION OF F, THE THRUST STAND LOAD CELL**"
4090  !*****************************************************************
4100 F0cal:  !
4110  PRINT "****ZERO CALIBRATION****"
4120  PRINT "INSURE THAT THE 'ZERO' TARE WEIGHT IS ON THE TRAY"
4130  DISP "HIT CONTINUE WHEN READY"
4140  PAUSE
4150  REMOTE 709
4160  OUTPUT 709;"AC5"
4170  OUTPUT 722;"T3"
4180  ENTER 722;Vf0
4190  PRINT "Vf0=";Vf0
4200  INPUT "READING OK? (Y/N)",Zz$
4210  IF Zz$="N" THEN GOTO F0cal
4220 Fmaxcal:  !
4230  PRINT USING "@"
4240  PRINT "****CALIBRATION****"
4250  PRINT "APPLY MAXIMUM WEIGHT TO THE TRAY"
4260  INPUT "ENTER THE MAXIMUM WEIGHT IN LBS",Fmax
4270  DISP "HIT CONTINUE WHEN READY"
4280  PAUSE
4290  REMOTE 709
4300  OUTPUT 709;"AC5"
4310  OUTPUT 722;"T3"
4320  ENTER 722;Vfmax
4330  PRINT "Vfmax=";Vfmax,"Fmax=";Fmax
4340  Kf=Fmax/(Vfmax-Vf0)
4350  PRINT "Kf=";Kf
4360  BEEP
4370  INPUT "READING OK? (Y/N)",Zz$
4380  IF Zz$="N" THEN GOTO Fmaxcal
4390 Endcal:  !
4400  PRINT "THIS ENDS THE CALIBRATIONS "
4410  !*****************************************************************
4420  !(3) PRE-RUN INPUTS, FLOW RATE SET-UP
4430  !*****************************************************************
4440  !A. PRE-RUN INPUTS
4450  !*****************************************************************
4460 Inputvariables:  !
4470  INPUT "DO YOU WANT TO INPUT NEW VARIABLES (Y/N)",Yy$
4480  IF Yy$="N" THEN GOTO Nochange
4490  PRINT "INPUT THE FOLLOWING TEST VARIABLES"
4500  PRINT "STRING VARIABLES MUST BE ENCLOSED IN QUOTATION MARKS"
4510  INPUT "THE TEST IDENTIFICATION NUMBER,A STRING VARIABLE",Testno$
4520  INPUT "TODAY'S DATE AS MO.DAY.YEAR,A STRING VARIABLE ",Date$
4530  INPUT "THE BAROMETRIC PRESSURE",Pbar
4540  INPUT "THE FUEL IDENTIFICATION,A STRING VARIABLE ",Fuelid$
4550  INPUT "THE AIR HEATER FUEL TYPE,A STRING VARIABLE ",Heaterfuel$
4560  INPUT "THE SFRJ IGNITION FUEL TYPE,A STRING VARIABLE ",Ignitionfuel$
4570  INPUT "THE PURGE GAS TYPE,A STRING VARIABLE ",Purgegas$
4580  INPUT "THE INITIAL FUEL GRAIN WEIGHT (LBM)",Wtfi
4590  INPUT "THE INITIAL FUEL GRAIN INTERNAL DIAMETER (IN)",Dp
4600  INPUT "THE INITIAL FUEL GRAIN LENGTH (IN)",Lp
4610  INPUT "THE AIR INLET DIAMETER (IN)",Di
4620  INPUT "THE MOTOR THROAT DIAMETER (IN)",Dth
4630  INPUT "THE DESIRED AIR INLET TEMPERATURE (R)",Tid
4640  INPUT "THE DESIRED IGNITION DELAY TIME (SEC)",Tma
4650  INPUT "THE DESIRED IGNITION TIME (SEC)",Tmi
4660  INPUT "THE DESIRED BURN TIME (SEC)",Tmb
4670  INPUT "THE DESIRED PURGE TIME (SEC)",Tmp
```

```
3320  ENTER 722;Vphomax
3330  PRINT "Vphomax=";Vphomax,"Phomax=";Phomax
3340  Kpho=Phomax/(Vphomax-Vpho0)
3350  PRINT "Kpho=";Kpho
3360  BEEP
3370  INPUT "READING OK? (Y/N)",Zz$
3380  IF Zz$="N" THEN GOTO Phomaxcal
3390 Pifcal:!
3400  !*********************************************************************
3410  PRINT "**CALIBRATION OF Pif, THE SFRJ IGNITION FUEL PRESSURE TRANSDUCER**"
3420  !*********************************************************************
3430 Pif0cal:  !
3440  PRINT "****ZERO CALIBRATION****"
3450  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3460  DISP "HIT CONTINUE WHEN READY"
3470  PAUSE
3480  REMOTE 709
3490  OUTPUT 709;"AC6"
3500  OUTPUT 722;"T3"
3510  ENTER 722;Vpif0
3520  PRINT "Vpif0=";Vpif0
3530  INPUT "READING OK?  (Y/N)",Zz$
3540  IF Zz$="N" THEN GOTO Pif0cal
3550 Pifmaxcal:  !
3560  PRINT USING "@"
3570  PRINT "****CALIBRATION****"
3580  PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3590  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Pifmax
3600  DISP "HIT CONTINUE WHEN READY"
3610  PAUSE
3620  REMOTE 709
3630  OUTPUT 709;"AC6"
3640  OUTPUT 722;"T3"
3650  ENTER 722;Vpifmax
3660  PRINT "Vpifmax=";Vpifmax,"Pifmax=";Pifmax
3670  Kpif=Pifmax/(Vpifmax-Vpif0)
3680  PRINT "Kpif=";Kpif
3690  BEEP
3700  INPUT "READING OK? (Y/N)",Zz$
3710  IF Zz$="N" THEN GOTO Pifmaxcal
3720 Ppcal: !
3730  !*****************************************************************
3740  PRINT "**CALIBRATION OF Pp, THE SFRJ PURGE GAS PRESSURE TRANSDUCER**"
3750  !*****************************************************************
3760 Pp0cal:  !
3770  PRINT "****ZERO CALIBRATION****"
3780  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3790  DISP "HIT CONTINUE WHEN READY"
3800  PAUSE
3810  REMOTE 709
3820  OUTPUT 709;"AC7"
3830  OUTPUT 722;"T3"
3840  ENTER 722;Vpp0
3850  PRINT "Vpp0=";Vpp0
3860  INPUT "READING OK?  (Y/N)",Zz$
3870  IF Zz$="N" THEN GOTO Pp0cal
3890 Ppmaxcal:  !
3890  PRINT USING "@"
3900  PRINT "****CALIBRATION****"
3910  PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3920  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Ppmax
3930  DISP "HIT CONTINUE WHEN READY"
3940  PAUSE
3950  REMOTE 709
3960  OUTPUT 709;"AC7"
3970  OUTPUT 722;"T3"
3980  ENTER 722;Vppmax
3990  PRINT "Vppmax=";Vppmax,"Ppmax=";Ppmax
```

```
2640  WAIT 2
2650  OUTPUT 722;"T3"
2660  ENTER 722;Vphmax
2670  PRINT "Vphmax=";Vphmax,"Phmax=";Phmax
2680  Kph=Phmax/(Vphmax-Vph0)
2690  PRINT "Kph=";Kph
2700  BEEP
2710  INPUT "READING OK? (Y/N)",Zz$
2720  IF Zz$="N" THEN GOTO Phmaxcal
2730 Phfcal:!
2740  !*******************************************************************
2750  PRINT "**CALIBRATION OF Phf, THE AIR HEATER FUEL PRESSURE TRANSDUCER**"
2760  !*******************************************************************
2770 Phf0cal:  !
2780  PRINT "****ZERO CALIBRATION****"
2790  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2800  DISP "HIT CONTINUE WHEN READY"
2810  PAUSE
2820  REMOTE 709
2830  OUTPUT 709;"AC3"
2840  OUTPUT 722;"T3"
2850  ENTER 722;Vphf0
2860  PRINT "Vphf0=";Vphf0
2870  INPUT "READING OK?  (Y/N)",Zz$
2880  IF Zz$="N" THEN GOTO Phf0cal
2890 Phfmaxcal:  !
2900  PRINT USING "@"
2910  PRINT "****CALIBRATION****"
2920  PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
2930  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Phfmax
2940  DISP "HIT CONTINUE WHEN READY"
2950  PAUSE
2960  REMOTE 709
2970  OUTPUT 709;"AC3"
2980  OUTPUT 722;"T3"
2990  ENTER 722;Vphfmax
3000  PRINT "Vphfmax=";Vphfmax,"Phfmax=";Phfmax
3010  Kphf=Phfmax/(Vphfmax-Vphf0)
3020  PRINT "Kphf=";Kphf
3030  BEEP
3040  INPUT "READING OK? (Y/N)",Zz$
3050  IF Zz$="N" THEN GOTO Phfmaxcal
3060 Phocal:!
3070  !*********************************************************************
3080  PRINT "**CALIBRATION OF Pho, THE AIR HEATER OXYGEN PRESSURE TRANSDUCER**"
3090  !*********************************************************************
3100 Pho0cal:  !
3110  PRINT "****ZERO CALIBRATION****"
3120  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3130  DISP "HIT CONTINUE WHEN READY"
3140  PAUSE
3150  REMOTE 709
3160  OUTPUT 709;"AC4"
3170  OUTPUT 722;"T3"
3180  ENTER 722;Vpho0
3190  PRINT "Vpho0=";Vpho0
3200  INPUT "READING OK?  (Y/N)",Zz$
3210  IF Zz$="N" THEN GOTO Pho0cal
3220 Phomaxcal:  !
3230  PRINT USING "@"
3240  PRINT "****CALIBRATION****"
3250  PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3260  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Phomax
3270  DISP "HIT CONTINUE WHEN READY"
3280  PAUSE
3290  REMOTE 709
3300  OUTPUT 709;"AC4"
3310  OUTPUT 722;"T3"
```

```
1960  Kpa=(Pamax)/(Vpamax-Vpa0)
1970  PRINT "Kpa= ";Kpa
1980  BEEP
1990  INPUT "READING OK? (Y/N)",Zz$
2000  IF Zz$="N" THEN GOTO Pamaxcal
2010 Pccal:!
2020  !*******************************************************************
2030  PRINT "**CALIBRATION OF Pc, THE SFRJ MOTOR CHAMBER PRESSURE TRANSDUCER**"
2040  !*******************************************************************
2050 Pc0cal:  !
2060  PRINT "**** ZERO PRESSURE ****"
2070  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2080  DISP "HIT CONTINUE WHEN READY"
2090  PAUSE
2100  REMOTE 709
2110  OUTPUT 709;"AC0"
2120  WAIT 2
2130  OUTPUT 722;"T3"
2140  ENTER 722;Vpc0
2150  PRINT "Vpc0=";Vpc0
2160  BEEP
2170  INPUT "READING OK?  (Y/N)",Zz$
2180  IF Zz$="N" THEN GOTO Pc0cal
2190 Pcmaxcal:  !
2200  PRINT USING "@"
2210  PRINT " **** CALIBRATION  ****"
2220  PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
2230  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Pcmax
2240  DISP "HIT CONTINUE WHEN READY"
2250  PAUSE
2260  REMOTE 709
2270  OUTPUT 709;"AC0"
2280  WAIT 2
2290  OUTPUT 722;"T3"
2300  ENTER 722;Vpcmax
2310  PRINT "Vpcmax=";Vpcmax,"Pcmax=";Pcmax
2320  Kpc=Pcmax/(Vpcmax-Vpc0)
2330  PRINT "Kpc= ";Kpc
2340  BEEP
2350  INPUT "READING OK? (Y/N)",Zz$
2360  IF Zz$="N" THEN GOTO Pcmaxcal
2370 Phcal:!
2380  !*******************************************************************
2390  PRINT "**CALIBRATION OF Ph, THE SFRJ MOTOR HEAD-END PRESSURE TRANSDUCER**"
2400  !*******************************************************************
2410 Ph0cal:  !
2420  PRINT "****ZERO PRESSURE****"
2430  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2440  DISP "HIT CONTINUE WHEN READY"
2450  PAUSE
2460  REMOTE 709
2470  OUTPUT 709;"AC1"
2480  WAIT 2
2490  OUTPUT 722;"T3"
2500  ENTER 722;Vph0
2510  PRINT "Vph0=";Vph0
2520  BEEP
2530  INPUT "READING OK?  (Y/N)",Zz$
2540  IF Zz$="N" THEN GOTO Ph0cal
2550 Phmaxcal:  !
2560  PRINT USING "@"
2570  PRINT "****CALIBRATION****"
2580  DISP "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
2590  INPUT "ENTER THE MAXIMUM PRESSURE IN Psig",Phmax
2600  DISP "HIT CONTINUE WHEN READY"
2610  PAUSE
2620  REMOTE 709
2630  OUTPUT 709;"AC1"
```

```
1350            IF Volts)=.00609 AND Volts(.00831 THEN T=((Volts-.00609)/.000022
2)+740
1360            IF Volts)=.00831 AND Volts(.01056 THEN T=((Volts-.00831)/.000022
5)+840
1370            IF Volts)=.01056 AND Volts(.01285 THEN T=((Volts-.01056)/.000022
9)+940
1380            IF Volts)=.01285 AND Volts(.01518 THEN T=((Volts-.01285)/.000023
3)+1050
1390            IF Volts)=.01518 AND Volts(.01752 THEN T=((Volts-.01518)/.000023
4)+1150
1400            IF Volts)=.01752 AND Volts(.01988 THEN T=((Volts-.01752)/.000023
6)+1260
1410            IF Volts)=.01988 AND Volts(.02225 THEN T=((Volts-.01988)/.000023
7)+1360
1420            IF Volts).02225 THEN GOTO Toohigh
1430      RETURN
1440 Toohigh:      !
1450              PRINT "TEMPERATURE SET AT 1460 R"
1460              PRINT "I=",I
1470              T=1460
1480              BEEP 500,.1
1490              WAIT .1
1500              BEEP 700,.1
1510              RETURN
1520 Transcal: !
1530  !****************************************************************
1540  !(2) TRANSDUCER CALIBRATIONS
1550  !****************************************************************
1560  !THERE ARE 6 PRESSURE TRANSDUCERS AND ONE LOAD CELL FOR THRUST  WHICH
1570  !MUST BE CALIBRATED. TRANSDUCER LINEARITY MUST BE VERIFIED BEFORE THIS
1580  !CALIBRATION PROCEDURE IS EMPLOYED. THE ORDER OF CALIBRATION IS AS
1590  !FOLLOWS: Pa, Pc, Ph, Phf, Pho, Pif, Po, F
1600  !THE FOLLOWING TWO LINES SET UP 722 AND 709 FOR DATA ACQUISITION"
1610  CLEAR 709          ! CLEAR 3497A DATA AQUISITION/CONTROL UNIT
1620  CLEAR 722          ! CLEAR 3456A DIGITAL VOLTMETER
1630  REMOTE 709         ! MAKE 3497A  UNIT TO REMOTE MODE
1640  OUTPUT 722;"L1R31STNZ11OSTIT4QX1"  ! 10 READING PER TRIGGER AND STORE
1650 Pacal: !
1660  !****************************************************************
1670  PRINT "** CALIBRATION OF Pa, THE AIR SONIC CHOKE PRESSURE TRANSDUCER"
1680  !****************************************************************
1690 Pa0cal:  !
1700  PRINT " ***** Z E R O   P R E S S U R E *****"
1710  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
1720  DISP "HIT CONTINUE WHEN READY TO TAKE ZERO READING"
1730  PAUSE
1740  REMOTE 709
1750  OUTPUT 709;"AC2"     ! AQUIRE CHANNEL 2
1760  WAIT 2
1770  OUTPUT 722;"T3"     ! INITATE SINGLE TRIGGER
1780  ENTER 722;Vpa0      ! READ VOLTAGE
1790  PRINT "Vpa0=";Vpa0
1800  BEEP
1810  INPUT "READING OK? (Y/N)",Zz$
1820  IF Zz$="N" THEN GOTO Pa0cal
1830 Pamaxcal:  !
1840  PRINT USING "@"      ! CLEAR SCREEN
1850  PRINT "     ***** C A L I B R A T I O N  ****x"
1860  PRINT "APPLY MAXIMUM PRESSURE USING THE DEAD-WEIGHT TESTER"
1870  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Pamax
1880  DISP "HIT CONTINUE WHEN READY"
1890  PAUSE
1900  REMOTE 709
1910  OUTPUT 709;"AC2"
1920  WAIT 2
1930  OUTPUT 722;"T3"
1940  ENTER 722;Vpamax
1950  PRINT "Vpamax=";Vpamax,"Pamax= ";Pamax
```

```
690  !  Tma            TIME BETWEEN SFRJ AIR FLOW AND IGNITION, sec
700  !  Tmb            BURN TIME AFTER Tmi, sec
710  !  Tmi            IGNITION DURATION AFTER Tma, sec
720  !  Tmp            PURGE DURATION AFTER Tmb, sec
730  !  Tp             TEMPERATURE, PURGE GAS SONIC CHOKE, R
740  !  Wtfi           INITIAL FUEL GRAIN WEIGHT, Lbm
750  !
760  !
770  BEEP 1000,.1
780  PRINT USING "@"
790  PRINT USING "6/"
800  PRINT "                1.2 Volts MAXIMUM into Acquisition System!!!"
810  ! THE RECORDED VARIABLES (VOLTAGES) AND LOCATIONS ARE:
820  ! (NOTE: THE MAXIMUM ALLOWABLE VOLTAGE INTO THE SYSTEM IS 1.2 VOLTS)
830  !
840  ! VARIABLE                          3497 DACU SCANNER NUMBER 0_
850  !
860  ! Pa --------                       2 ----------------------
870  ! Pc                                0
880  ! Ph                                1
890  ! Phf                               3
900  ! Pho                               4
910  ! Pif                               6
920  ! Pp                                7
930  ! F                                 5
940  ! Ta                                9
950  ! Thf                               10
960  ! Tho                               11
970  ! Ti                                8
980  ! Tif                               12
990  ! Tp                                13
1000 !
1010 !
1020 !ALL FLOW RATES ARE CALCULATED USING THE ONE-DIMENSIONAL, ISENTROPIC
1030 !FLOW EXPRESSIONS WITH FIXED PROPERTIES. SMALL SONIC NOZZLES HAVE
1040 !MEASURED DISCHARGE COEFFICIENTS. THE AIR FLOW NOZZLE USES AN ASSUMED
1050 !DISCHARGE COEFFICIENT (Cd) OF 0.97.
1060 !
1070 !M (LBM/SEC)=Cd*P*A*Km/T^.5
1080 !
1090 !Km IS THE GAS-DEPENDENT SONIC CHOKE FLOW RATE CONSTANT
1100 !
1110 !Km=SQR((Gamma*Gc/R)*(2/(Gamma+1))^((Gamma+1)/(Gamma-1)))
1120 !
1130 ! APPROPRIATE CONSTANTS ARE:
1140 !
1150 ! GAS     MOLECULAR WT.   GAS CONST.    CP     GAMMA     Km
1160 !
1170 ! AIR        29.0          53.3       .240     1.40     .5320
1180 ! O2         32.0          48.3       .217     1.40     .5589
1190 ! CH4        16.03         96.4       .593     1.32     .3876
1200 ! C2H4       28.03         55.1       .400     1.22     .4985
1210 ! ARGON      39.9          38.7       .124     1.67     .6626
1220 !
1230 !ALL THERMOCOUPLES USED ARE CHROMEL vs ALUMEL (TYPE K) WITH
1240 !ELECTRONIC ICE POINTS. TEMPERATURE READINGS (VOLTAGES) ARE
1250 !CONVERTED TO DEGREES RANKINE (R) PER "INDUSTRIAL INSTRUMENTATION" BY
1260 !D.P. ECKMAN (PAGE 369). THIS CALCULATION IS PERFORMED IN SUBROUTINE
1270 !Tcalc. TEN VOLTAGE INTERVALS ARE USED BETWEEN 460 AND 1460 R.
1280 Gc=32.174
1290 Ko=0            !  POST RUN CONTROL FLAG
1300 GOTO Transcal
1310 Tcalc:      !
1320         IF Volts(.00153 THEN T=((Volts+.00068)/.0000220)+460
1330         IF Volts)=.00153 AND Volts(.00382 THEN T=((Volts-.00153)/.000023
0)+560
1340         IF Volts)=.00382 AND Volts(.00609 THEN T=((Volts-.00382)/.000022
7)+660
```

APPENDIX A

COMPUTER PROGRAM FOR EXPERIMENT CONTROL AND DATA REDUCTION

```
10   !SFRJTEST
20   !SOLID FUEL RAMJET DATA ACQUISITION AND DATA REDUCTION PROGRAM,
30   !THIS PROGRAM IS DIVIDED INTO FIVE PARTS:
40   !      (1) VARIABLE DEFINITIONS AND NOMENCLATURE
50   !      (2) TRANSDUCER CALIBRATIONS
60   !      (3) PRE-RUN INPUTS,FLOW SET-UPS
70   !      (4) THE TEST SEQUENCE AND DATA COLLECTION
80   !      (5) POST-RUN OPERATIONS
90   !*********************************************************************
100  !(1) VARIABLE DEFINITIONS AND NOMENCLATURE
110  !*********************************************************************
120  !  SYMBOL              DEFINITION
130  !  A                  ANALOG CHANNEL NUMBER
140  !  Cdair              DISCHARGE COEFFICIENT, AIR SONIC CHOKE
150  !  Cdhf               DISCHARGE COEFFICIENT, HEATER  FUEL SONIC CHOKE
160  !  Cdho               DISCHARGE COEFFICIENT, OXYGEN MAKE-UP SONIC CHOKE
170  !  Cdif               DISCHARGE COEFFICIENT, IGNITION FUEL SONIC CHOKE
180  !  Cdp                DISCHARGE COEFFICIENT, PURGE GAS SONIC CHOKE
190  !  Cf                 THRUST COEFFICIENT
200  !  Cstarth            THEORETICAL C*, FT/SEC
210  !  Cstarair           C* FOR AIR FLOW BASED ON Dtheff
220  !  Dairchoke          AIR SONIC CHOKE DIAMETER
230  !  Date$              Test Date  Mo-Dav-Yr
240  !  Dhfchoke           AIR HEATER FUEL SONIC CHOKE DIAMETER
250  !  Dhochoke           OXYGEN MAKE-UP SONIC CHOKE DIAMETER
260  !  Di                 MOTOR INLET DIAMETER, IN.
270  !  Difchoke           IGNITION FUEL SONIC CHOKE DIAMETER
280  !  Dp                 MOTOR FUEL PORT DIAMETER,IN.
290  !  Dpchoke            PURGE GAS SONIC CHOKE DIAMETER
300  !  Dth                MOTOR EXHAUST NOZZLE THROAT DIAMETER,IN.
310  !  Dtheff             EFFECTIVE THROAT DIAMETER,IN.
320  !  F                  THRUST
330  !  Fuelid$            FUEL IDENTIFICATION
340  !  Gc                 GRAVITATIONAL CONSTANT (32.174)
350  !  Heaterfuel$        FUEL IDENTIFICATION
360  !  Ignitionfuel$      SFRJ IGNITION FUEL I.D
370  !  Kmair              AIR SONIC CHOKE FLOW RATE CONSTANT
380  !  Kmhf               HEATER FUEL SONIC CHOKE FLOW RATE CONSTANT
390  !  Kmho               OXYGEN MAKE-UP SONIC CHOKE FLOW RATE CONSTANT
400  !  Kmif               IGNITION FUEL SONIC CHOKE FLOW RATE CONSTANT
410  !  Kmp                PURGE GAS SONIC CHOKE FLOW RATE CONSTANT
420  !  Lp                 FUEL GRAIN LENGTH, IN.
430  !  Mair               AIR FLOW RATE, LBM/SEC
440  !  Maird              DESIRED AIR FLOW RATE, Lbm/sec
450  !  Mhf                HEATER FUEL FLOW RATE, Lbm/sec
460  !  Mhfd               DESIRED HEATER FUEL FLOW RATE Lbm/sec
470  !  Mho                HEATER OXYGEN FLOW RATE, Lbm/sec
480  !  Mhod               DESIRED HEATER OXYGEN FLOW RATE, Lbm/sec
490  !  Mif                IGNITION FUEL FLOW RATE, Lbm/sec
500  !  Mifd               DESIRED IGNITION FUEL FLOW RATE, Lbm/sec
510  !  Mp                 PURGE GAS FLOW RATE, Lbm/sec
520  !  Mpd                DESIRED PURGE GAS FLOW RATE, Lbm/sec
530  !  Pa                 PRESSURE, AIR SONIC CHOKE, Psia
540  !  Pbar               BAROMETRIC PRESSURE, Psia
550  !  Pc                 PRESSURE, CHAMBER, Psia
560  !  Ph                 PRESSURE, MOTOR HEAD-END, Psia
570  !  Phf                PRESSURE, HEATER FUEL SONIC CHOKE, Psia
580  !  Pho                PRESSURE, HEATER OXYGEN SONIC CHOKE, Psia
590  !  Pif                PRESSURE, IGNITION FUEL SONIC CHOKE, Psia
600  !  Pp                 PRESSURE, PURGE GAS SONIC CHOKE, Psia
610  !  Purgegas$          PURGE GAS I.D
620  !  Ta                 TEMPERATURE, AIR SONIC CHOKE, R
630  !  Testno$            TEST I.D NO.
640  !  Thf                TEMPERATURE, HEATER FUEL SONIC CHOKE, R
650  !  Tho                TEMPERATURE, OXXYGEN MAKE-UP SONIC CHOKE, R
660  !  Ti                 TEMPERATURE, MOTOR AIR INLET, R
670  !  Tid                TEMPERATURE, DESIRED MOTOR AIR INLET, R
680  !  Tif                TEMPERATURE, IGNITION FUEL SONIC CHOKE, R
```

VI. CONCLUSIONS AND RECOMMENDATIONS

Additional tests using fuel-wall and step face injection of oxygen, gaseous fuel and/or heated air should be conducted to verify the initial results found in this investigation. However, the initial data from this investigation indicates that gaseous injection is not a viable tecnique for fuel regression rate control.

Fuel regression rate was found to be quite sensitive to small amounts of inlet air swirl without large changes in combustion efficiency. Additional testing is recommended.

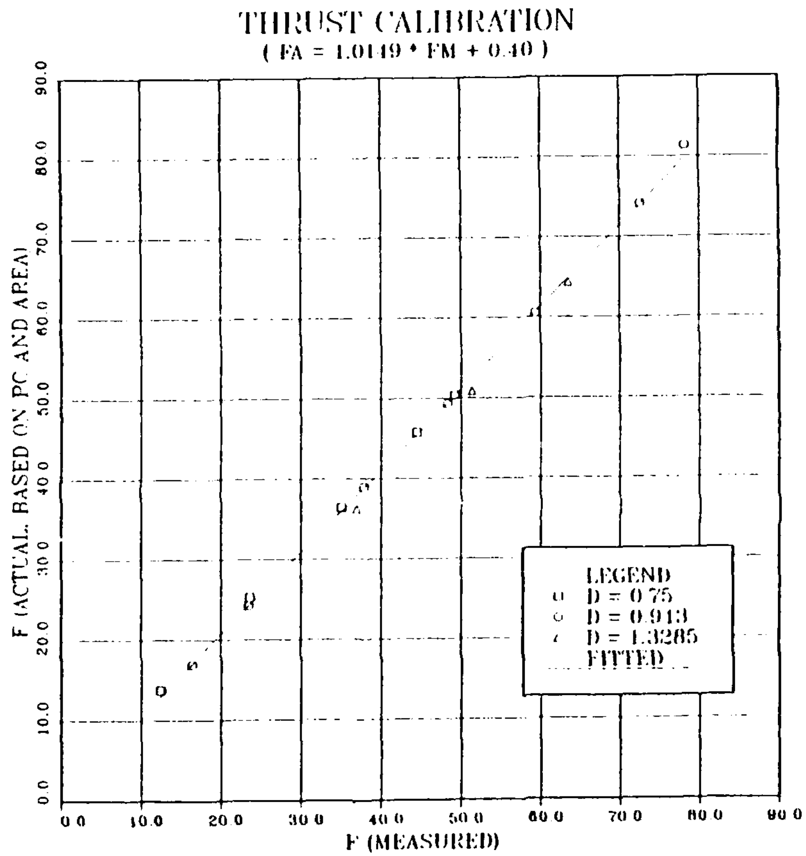

Figure 5.1 Thrust Calibration Curve, Measured vs Actual.

Table 3

Summary of Experimental Data (cont'd.)

Test number	27	28	29	30	31	32
ϕ	0.69	0.70	0.82	0.81	0.79	1.374
Pc (psia)	55.4	59.1	57.7	55.9	55.8	101.8
PEPCODE results						
Tth (°R)	3398	3917	3737	3724	3662	4283
γ	1.265	1.254	1.256	1.256	1.258	1.257
R (ft Lbf/Lbm°R)	56.18	55.93	54.93	53.27	55.68	56.82
Efficiency (based on Pc, analog)	83.4	81.5*	78.9	100	85.5	82.7 (78.7)**

* based on Pc, digital
** based on F , analog

```
7210        PRINT USING "11A,DD.DDDDD";"Mairinject=";Mho
7220        PRINT USING "18A,DD.DDDDD";"Mho DESIRED=";Mhod
7230        Ratio=Mho/Mhod
7240        PRINT USING "30A, DDDD.DDDD,3X,4A,DDDD.DD,1A";"Mho/Mho DESIRED=",Rat
io,"Tho=";Tho,"R"
7250        Pg=Pho-Pbar
7260        PRINT USING "5A,DDDD.DD,1X,5A,5X,4A,DDDD.DD,1X,2A";"Pho=";Pg;"Psig"
;"Tho=";Tho;"R"
7270        INPUT "IS THE HEATER OXYGEN FLOW RATE ENOUGH? (Y/N)?",Xx$
7280        IF Xx$="Y" THEN GOTO Phofin
7290        Phonew=(Pho*Mhod/Mho)-Pbar
7300        PRINT USING "14A,DDDD.DD,1X,4A";"RESET Pho  TO ";Phonew;"Psig"
7310        DISP "HIT CONTINUE AFTER RESET OF Pho"
7320        PAUSE
7330        GOTO Phoset
7340 Phofin:!
7350   DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
7360   PAUSE
7370 Phoskip:   !
7380   PRINT USING "@"
7390   INPUT "DO YOU WANT TO PRESET THE IGNITION FUEL FLOW RATE?(Y/N)",Zz$
7400   IF Zz$="N" THEN GOTO Pifskip
7410   !*****************************************************************
7420   PRINT " SET THE DESIRED VALUE OF Pif USING THE HAND LOADER/PRESSURE GAGE"
7430   !*****************************************************************
7440   DISP "HIT CONTINUE  WHEN READY"
7450   PAUSE
7460 Pifset:!
7470   PRINT "MANUALLY TURN ON ' IGN. GAS ' SWITCH"
7480   DISP " HIT CONTINUE WHEN READY"
7490   PAUSE
7500   OUTPUT 709;"AC6"
7510   WAIT 1
7520   OUTPUT 722;"T3"
7530   ENTER 722;Vpif
7540   OUTPUT 709;"AC12"
7550   OUTPUT 722;"T3"
7560   ENTER 722;Vtif
7570   BEEP
7580   PRINT "MANUALLY TURN OFF 'IGN GAS' SWITCH"
7590   DISP "HIT CONTINUE TO PROCEED"
7600   PAUSE
7610   Pif=(Vpif-Vpif0)*Kpif+Pbar
7620   Volts=Vtif
7630   GOSUB Tcalc
7640   Tif=T
7650   Mif=Kmif*Cdif*Pif*.7854*(Difchoke^2)/(Tif^.5)
7660   PRINT USING "@"
7670   PRINT USING "4A,DD.DDDDD";"Mif=";Mif
7680   PRINT USING "15A,DD.DDDDD";"Mif DESIRED=";Mifd
7690   Ratio=Mif/Mifd
7700   PRINT USING "17A,D.DDD,3X,4A,DDDD.DDD,1A";"Mif/Mif DESIRED=";Ratio,"Tif="
;Tif,"R"
7710   Pg=Pif-Pbar
7720   PRINT USING "4A,DDDD.DD,1X,4A,5X,4A,DDDD.DD,1X,1A";"Pif=";Pg;"Pisg";"Tif=
";Tif;"R"
7730   INPUT "IS THE SFRJ IGNITION FUEL FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$
7740   IF Xx$="Y" THEN GOTO Piffin
7750   Pifnew=(Pif*Mifd/Mif)-Pbar
7760   PRINT USING "12A,DDDD.DD,1X,4A";"RESET Pif TO";Pifnew;"Psig"
7770   DISP "HIT CONTINUE AFTER RESET OF Pif"
7780   PAUSE
7790   GOTO Pifset
7800 Piffin:!
7810   DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
7820   PAUSE
7830 Pifskip:   !
7840   PRINT USING "@"
```

```
7850   INPUT "DO YOU WANT TO PRESET THE PURGE FLOW RATE? (Y/N)",Zz$
7860   IF Zz$="N" THEN GOTO Ppskip
7870   !****************************************************************
7880   PRINT "SET THE DESIERD VALUE OF Pp USING THE HANDLOADER/PRESSURE GAGE"
7890   !****************************************************************
7900   DISP "HIT CONTINUE WHEN READY"
7910   PAUSE
7920 Ppset: !
7930    CLEAR 709
7940    OUTPUT 709;"DC10,1"
7950    WAIT 2
7960    OUTPUT 709;"AC7"
7970    OUTPUT 722;"T3"
7980    ENTER 722;Vpp
7990    OUTPUT 709;"AC13"
8000    OUTPUT 722;"T3"
8010    ENTER 722;Vtp
8020    OUTPUT 709;"DO10,1"
8030    Pp=(Vpp-Vpp0)*Kpp+Pbar
8040    Volts=Vtp
8050    GOSUB Tcalc
8060    Tp=T
8070    Mp=Kmp*Cdp*Pp*.7854*(Dpchoke^2)/(Tp^.5)
8080    PRINT USING "@"
8090    PRINT USING "3A,DD.DDDDD";"Mp=";Mp
8100    PRINT USING "13A,DD.DDDDD";"Mp DESIRED=";Mpd
8110    Ratio=Mp/Mpd
8120    PRINT USING "16A,D.DD,3X,3A,DDDD.DD,1A";"Mp/Mp DESIRED =";Ratio,"Tp=" Tp
,"R"
8130    BEEP
8140    Pg=Pp-Pbar
8150    PRINT USING "3A,DDDD.DD,1X,4A,3X,4A,DDDD.DD,1X,1A";"Pp=";Pg;"Psig","Tp="
;Tp;"R"
8160    INPUT "IS THE PURGE GAS FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$
8170    IF Xx$="Y" THEN GOTO Ppfin
8180    Ppnew=(Pp*Mpd/Mp)-Pbar
8190    PRINT USING "16A,DDDD.DD,1X,4A";"RESET Pp TO";Ppnew;"Psig"
8200    DISP "HIT CONTINUE AFTER RESET OF Pp"
8210    PAUSE
8220    GOTO Ppset
8230 Ppfin: !
8240 Ppskip:    !
8250          PRINT "THIS COMPLETES PRE-RUN SET-UP"
8260 !*****************************************************************
8270 ! (4) THIS PORTION OF THE PROGRAM RUNS THE TEST AND COLLECTS THE DATA
8280 !*****************************************************************
8290 !
8300   PRINT USING "@"
8310   DISP "SET TIMEDATE BY PRESSING K19 AND UPDATE, THEN EXECUTE, THEN HIT CON
TINUE"
8320   BEEP
8330   PAUSE
8340   CLEAR 709
8350   CLEAR 722
8360   ! THE FOLLOWING PROGRAMS THE 3456A DVM
8370   OUTPUT 722;"L1Z0D0F10STDP0FL0R3.10STI1STN501T4QX1"
8380   PRINT "THE DESIRED RUN TIMES AND DELAYS NOW BE INPUT"
8390   INPUT "ENTER Tma,Tmi,Tmb,Tmp SEPARATED BY COMMA,THEN HIT CONTIUE",Tma,Tmi
,Tmb,Tmp
8400   Tshut=Tma+Tmi+Tmb+Tmp+1        ! ONE MORE SECOND FOR TAIL PART READING
8410   T4=Tma+Tmi
8420   T5=T4+Tmb
8430   T6=T5+Tmp
8440   OPTION BASE 1
8450   DIM In(600,14)                 ! STORAGE DEFINITION
8460   J=1
8470   A=1                            ! CONTROL FLAGS
8480   A1=0
```

```
8490   A2=0
8500   A3=0
8510   A4=0
8520   V14=0
8530   PRINT USING "@"
8540   DISP "TO INITIATE RUN, PUSH 'PRI-AIR SWITCH' "
8550 Monitor:    ! WAIT UNTIL INITIATE
8560             OUTPUT 709;"AC14"
8570             OUTPUT 722;"T3"
8580             ENTER 722;V14
8590             IF V14)=.5 THEN GOTO Startrun   ! IF INITIATE RUN, IT WILL GIVE
 0.8 VOLTS
8600             GOTO Monitor
8610 Startrun: !
8620           T0=TIMEDATE
8630           ON CYCLE .5 GOSUB Data
8640           ON DELAY Tshut GOTO Shutdown
8650 Timewait: ! WAIT 0.5 SECOND
8660           A=A+1
8670           GOTO Timewait
8680 Data: !   READ ALL DATA EVERY 0.5 SECONDS
8690      OUTPUT 709;"AC0AF0AL13"
8700      FOR I=1 TO 14
8710      OUTPUT 722;"T3"
8720      ENTER 722 USING "#,K";In(J,I)
8730      OUTPUT 709;"AS"
8740      NEXT I
8750      J=J+1
8760      T1=TIMEDATE
8770      IF A1=1 THEN GOTO Tmabypass
8780       IF DROUND(T1-T0,3))=Tma THEN
8790         OUTPUT 709;"DC10,2"
8800         OUTPUT 709;"DC10,3"
8810         A1=1
8820       END IF
8830 Tmabypass: !
8840      T1=TIMEDATE
8850      IF A2=1 THEN GOTO T4bypass
8860        IF DROUND(T1-T0,3))=T4 THEN
8870         OUTPUT 709;"DO10,2"
8880         OUTPUT 709;"DO10,3"
8890         A2=1
8900        END IF
8910 T4bypass: !
8920      T1=TIMEDATE
8930      IF A3=1 THEN GOTO T5bypass
8940        IF DROUND(T1-T0,3))=T5 THEN
8950         OUTPUT 709;"DC10,1"
8960         A3=1
8970        END IF
8980 T5bypass: !
8990      T1=TIMEDATE
9000      IF A4=1 THEN GOTO T6bypass
9010        IF DROUND(T1-T0,3))=T6 THEN
9020         OUTPUT 709;"DO10,1"
9030         OUTPUT 709;"DC10,0"
9040         A4=1
9050      END IF
9060 T6bypass: !
9070           GOTO 9080    !*  THIS NUMBER WILL BE CHANGED WHEN RENUMBER.
9080    RETURN
9090 Shutdown:   !
9100             OFF CYCLE
9110             Jmax=J-1
9120             PRINT USING "@"
9130             PRINT " TEST COMPLETE, TURN OFF 'MAIN-AIR', AND TURN OFF 'HEATER
 GASES'"
9140             BEEP
```

```
9150 !***********************************************************************
9160 !*  (5) POST-RUN OPERATION
9170 !***********************************************************************
9180            DISP "HIT CONTINUE TO PROCEED TO DATA REDUCTION"
9190            PAUSE
9200            OUTPUT 709;"D010,0"
9210            PRINTER IS 701
9220  PRINT USING "3/"
9230  PRINT "                    ****  PRE-RUN INPUT   **** "
9240  PRINT USING "2/"
9250  PRINT USING "14A,9A,5X,14A,9A,5X,14A,9A,2X,14A,DDDD.DDDD";"Testno=";Testno
$,"Date=";Date$,"Fuelid$=";Fuelid$,"Pbar=";Pbar
9260  PRINT USING "14A,9A,5X,14A,9A,5X,14A,9A,5X,14A,9A";"Heaterfuel=";Heaterfue
l$,"Ignitionfuel=";Ignitionfuel$,"Purge gas=";Purgegas$
9270  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Wtfi=";Wtfi
,"Dp=";Dp,"Lp=";Lp
9280  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Di=";Di,"Dth=";Dth
9290  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD,2X,14A,DDDD.D
DDD";"Tma=";Tma,"Tmi=";Tmi,"Tmb=";Tmb,"Tmp=";Tmp
9300  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Dairchoke=";Dairchoke,"Dhfu
choke=";Dhfchoke
9310  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Dhtoxchoke=";Dhochoke,"Dignf
uchoke=";Difchoke
9320  PRINT USING "14A,DDDD.DDDD";"Dpurgechoke=";Dpchoke
9330  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Cdair=";Cda
ir,"Cdh=";Cdhf,"Cdho=";Cdho
9340  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Cdp=";Cdp,"Cdif=";Cdif
9350  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Gammahf=";G
ammahf,"Gammaif=";Gammaif
9360  PRINT USING "14A,DDDD.DDDD";"Gammap=";Gammap
9370  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Rhf=";Rhf,"
Rif=";Rif,"Rp=";Rp
9380  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Kmhf=";Kmhf
,"Kmif=";Kmif,"Kmp=";Kmp
9390  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Kmho=";Kmho,"Kmair=";Kmair
9400  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Maird=";Maird,"Tid=";Tid
9410  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD,2X,14A,DDDD.D
DDD";"Mhfd=";Mhfd,"Mhod=";Mhod,"Mifd=";Mifd,"Mpd=";Mpd
9420  PRINT "INJECTION GAS IS ",Injectgas$
9430  PRINT USING "3/"
9440  PRINT "                    ****  DATA  EXTRACTED   ****          "
9450  PRINT ""
9460  PRINT "FLOW RATES IN Lbm/sec, PRESSURE IN Psia, TEMPERATURE IN R"
9470  PRINT ""
9480  ! HEADING PRINT
9490  PRINT USING "9A,1X,6A,3X,6A,4X,6A,4X,6A,4X,6A,4X,6A,5X,6A,4X,6A,4X,10A";"T
ime(sec)"," Mair"," Mhf"," Mho"," Mif"," Mp"," Ti","F(Lbf)"," Pc"," Ph","Ta"
9500  FOR J=1 TO Jmax
9510  FOR I=1 TO 14
9520    IF I=1 THEN
9530      Vpc=In(J,I)
9540      Pc=(Vpc-Vpc0)*Kpc+Pbar
9550    END IF
9560    IF I=2 THEN
9570      Vph=In(J,I)
9580      Ph=(Vph-Vph0)*Kph+Pbar
9590    END IF
9600    IF I=3 THEN
9610      Vpa=In(J,I)
9620      Pa=(Vpa-Vpa0)*Kpa+Pbar
9630    END IF
9640    IF I=4 AND Ht=1. THEN
9650      Vphf=In(J,I)
9660      Phf=(Vphf-Vphf0)*Kphf+Pbar
9670    END IF
9680    IF I=5 AND Ht=1. THEN
9690      Vpho=In(J,I)
9700      Pho=(Vpho-Vpho0)*Kpho+Pbar
```

```
9710   END IF
9720   IF I=6 AND Ff=1 THEN
9730      Vf=In(J,I)
9740      F=(Vf-Vf0)*Kf
9750   END IF
9760   IF I=6 AND Ff=0 THEN
9770      F=0
9780      END IF
9790   IF I=7 THEN
9800      Vpif=In(J,I)
9810      Pif=(Vpif-Vpif0)*Kpif
9820      IF Pif<=(Ph+20) THEN
9830            Pif=0.
9840            END IF
9850    END IF
9860    IF I=8 THEN
9870      Vpp=In(J,I)
9880      Pp=(Vpp-Vpp0)*Kpp+Pbar
9890      IF Pp<=(Ph+20) THEN
9900           Pp=0.
9910           END IF
9920    END IF
9930    IF I=9 THEN
9940      Volts=In(J,I)
9950      GOSUB Tcalc
9960      Ti=T
9970     END IF
9980     IF I=10 THEN
9990       Volts=In(J,I)
10000      GOSUB Tcalc
10010      Ta=T
10020    END IF
10030    IF I=11 AND Ht=1. THEN
10040      Volts=In(J,I)
10050      GOSUB Tcalc
10060      Thf=T
10070    END IF
10080    IF I=12 AND Ht=1. THEN
10090      Volts=In(J,I)
10100      GOSUB Tcalc
10110      Tho=T
10120    END IF
10130    IF I=13 THEN
10140      Volts=In(J,I)
10150      GOSUB Tcalc
10160      Tif=T
10170    END IF
10180    IF I=14 THEN
10190      Volts=In(J,I)
10200      GOSUB Tcalc
10210      Tp=T
10220    END IF
10230   NEXT I
10240   T=J/2
10250   Mair=Kmair*Cdair*Pa*.7854*(Dairchoke^2)/(Ta^.5)
10260   Mhf=Kmhf*Cdhf*Phf*.7854*(Dhfchoke^2)/(Thf^.5)
10270   Mho=Kmho*Cdho*Pho*.7854*(Dhochoke^2)/(Tho^.5)
10280   Mif=Kmif*Cdif*Pif*.7854*(Difchoke^2)/(Tif^.5)
10290   Mp=Kmp*Cdp*Pp*.7854*(Dpchoke^2)/(Tp^.5)
10300   PRINT USING "2X,DD.DD,3X,DD.DDD,4(3X,D.DDDDD),5(3X,DDDD.DD)";T,Mair,Mhf,M
ho,Mif,Mp,Ti,F,Pc,Ph,Ta
10310   NEXT J
10320   PRINTER IS 1
10330   PRINT USING "@"
10340   INPUT "DO YOU WANT TO MAKE POST-RUN AIR CALCULATION? (Y/N)",Yy$
10350   IF Yy$="Y" THEN Ko=1
10360   IF Yy$="N" THEN GOTO Finish
10370   GOTO Paset  ! TO CALCULATE THE EFFECTIVE THROAT DIAMETER
```

```
10380 Finish: !
10390  PRINT "DATA OUTPUT IS COMPLETE"
10400  DISP "SECURE TEST CELL !!!"
10410  LOCAL 709                        ! RETURN LOCAL MODE
10420 END
```

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