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FREE-PISTON STIRLING ENGINE

DEMONSTRATOR TEST PLAN

Prepared for

Division of Fossil Fuel Utilization

Department of Energy

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DISCLAIMER

INTRODUCTION

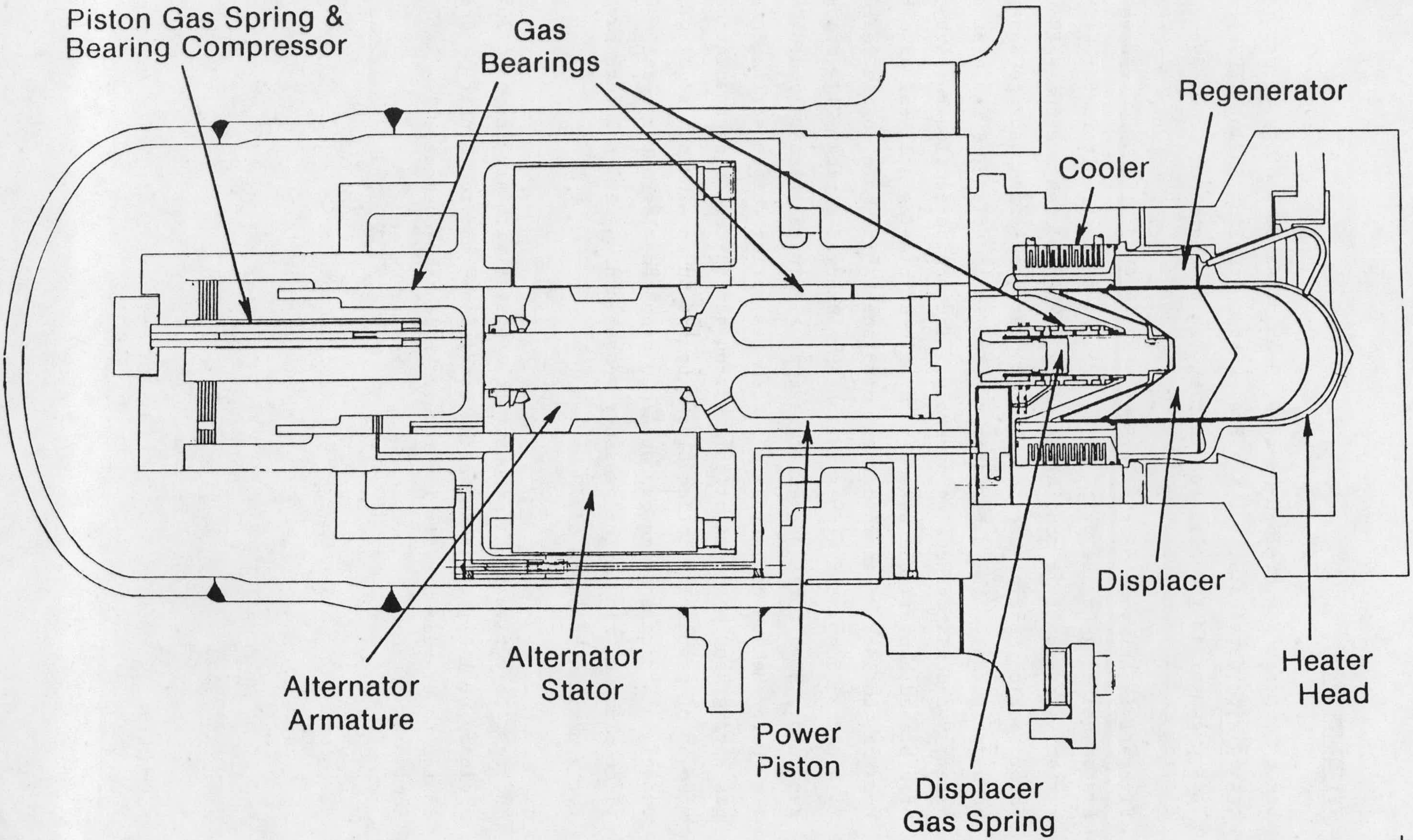
Under Contract No. EY-76-C-02-2764, Mechanical Technology Incorporated is tasked with developing a 1 KWe Free-Piston Stirling Engine (FPSE) Power System. This document is the plan for testing the demonstrator power system.

Figure 1 is a layout of the demonstrator system. The test hardware is a Free-Piston Stirling Engine prime mover driving a linear alternator. The demonstrator system is basically a modular assembly. The modules are the reciprocating alternator section, engine section, heater head insulation package assembly, and the pressure vessel. The alternator section is comprised of the piston plunger assembly and piston housing assembly. The engine section has subsections made up of a brazed heater head assembly, displacer bearing and seal assembly, cooler housing, cooler, regenerator, and displacer. The main engine features include: 1) a posted displacer with a variable volume gas spring; 2) a stacked screen regenerator; 3) a three segment tube type electrical heater head; 4) a counter-cross flow water-helium cooler; 5) a ported gas spring compressor integral with piston gas spring; and 6) an adjustable piston gas spring. The insulation package is made up of precut insulation blocks housed in an aluminum housing. The pressure vessel is a single piece cap attached over the alternator section with a single piece clamping ring. The pressure vessel and engine enclosure have been designed for a maximum pressure of 70 bar.

The test objective is to demonstrate a system with greater than 30% overall efficiency at 1 KW, 45 hz operating conditions, and to identify and isolate engine losses to provide a basis for future engine improvements.

FIGURE 1

Demonstrator Layout



TEST FACILITY

Figures 2 and 3 show the Stirling Engine Test Facility and the Data Acquisition System. The demonstrator will be tested in an 8 x 12 x 10 cell of concrete block construction. The operator has visual contact with the test engine through shatter proof protection windows. All control is accomplished remotely at the operator's console (Figure 4). The variac primary controls engine power input and is turned on or off by two push buttons (Item 2). The variac primary voltage and amperage are displayed by analog voltage and amp meters (Item 4). Of primary interest to the operator is the oscilloscope (Item 3), which has the relative displacer position on the vertical axis with the piston position on the horizontal. As the engine operates, the scope tracing will appear as a loop (Figure 5), providing the operator with a visual indication of the engine internal dynamics.

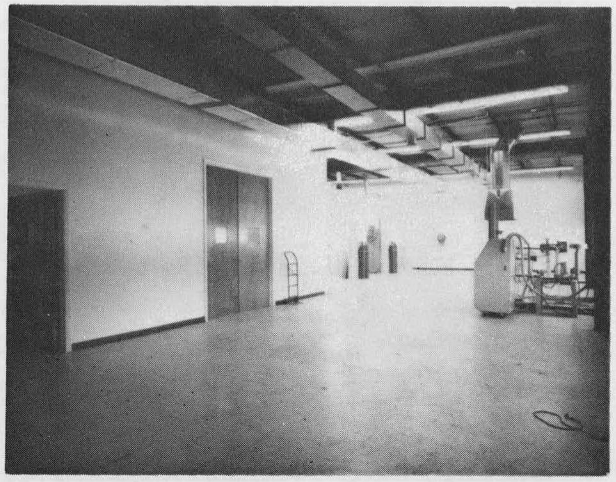
Prior to charging with the working fluid, a vacuum is pulled on the pressure vessel by selecting the valving with Items 7, 10, and 11. Once the vacuum has been established, the engine is charged with valve operation of Items 8 and 9. Helium supply pressure can be continuously monitored by the pressure gage showing the bounce space pressure.

Engine cooling water control is provided by Items 14 and 15 (by-pass valve and pump switch). The coolant supply pressure is monitored by Item 13. The flow is displayed on the overhead panel (Figure 6) with a conditioned signal from the HP frequency counter.

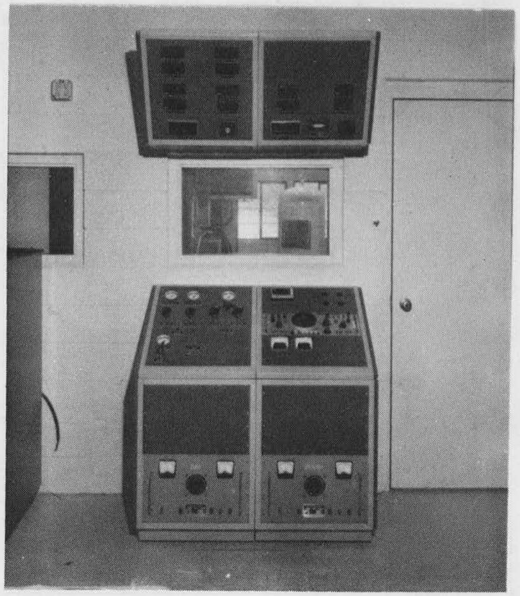
The overhead panel allows the operator to monitor the alternator field current, load current and voltage, and the power output. Engine dynamics of piston/displacer phase angle, frequency, piston stroke, and the displacer stroke are also displayed on the overhead panel. Heater head temperatures are manually selected by the temperature selector and individually displayed. A temperature controller automatically monitors the heater head temperature and cuts out the heater power in the event of an overtemperature.

FIGURE 2

MTI Stirling Engine Lab View From Southeast Corner



JPL Test Cell with Overhead Instrumentation Panel



JPL Test Cell

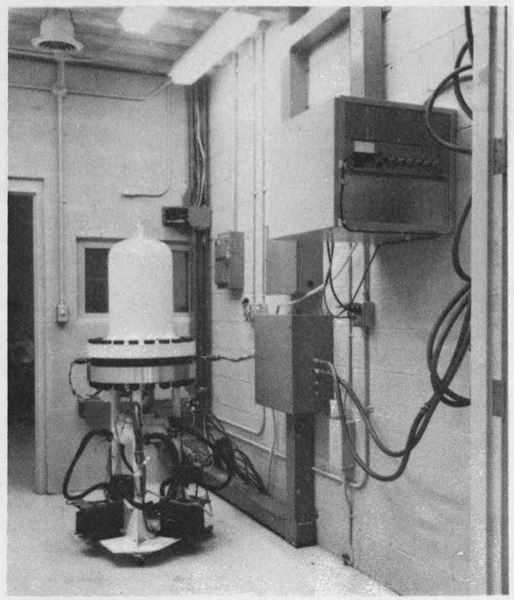
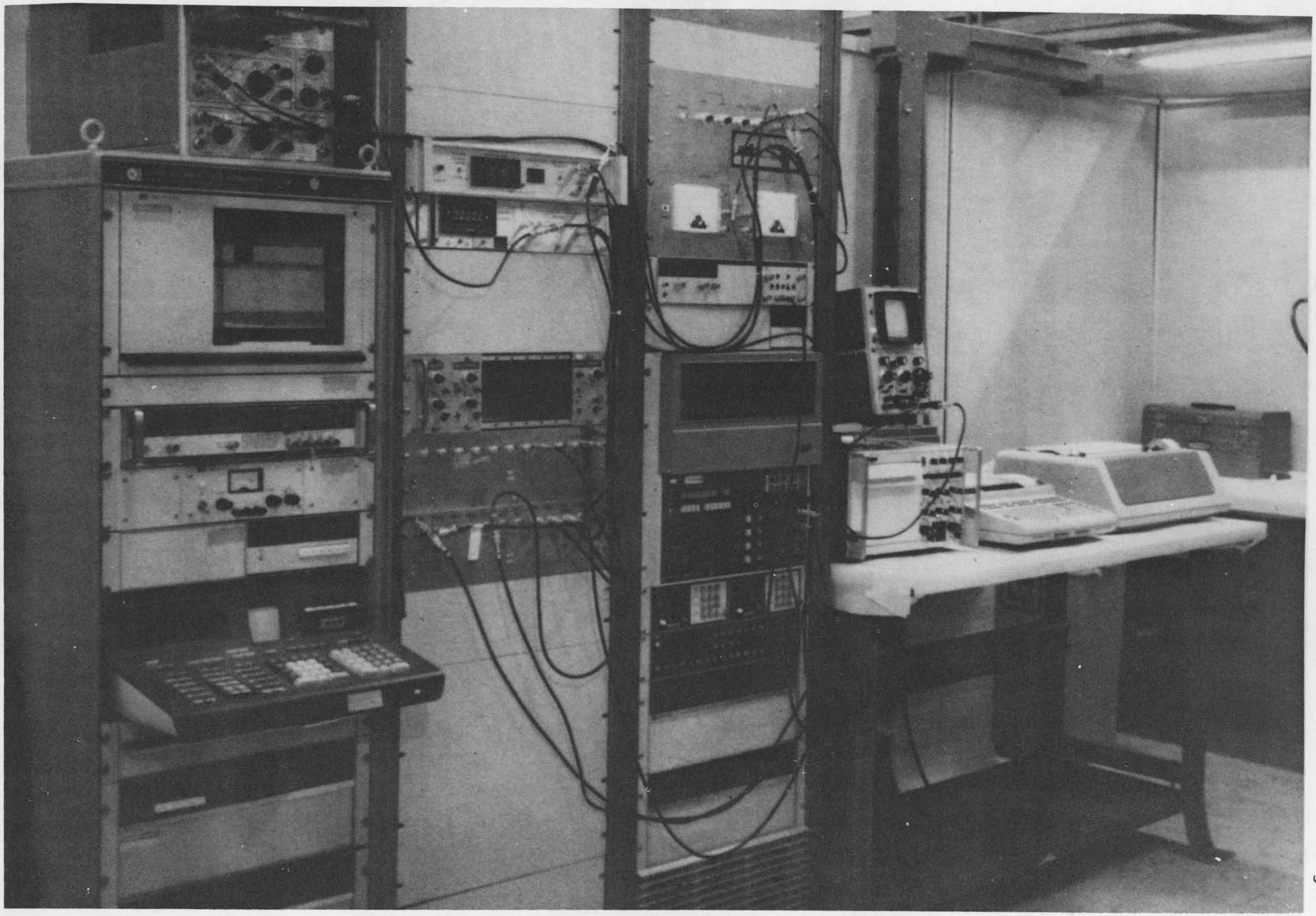


FIGURE 3

Free-Piston Stirling Engine Instrumentation



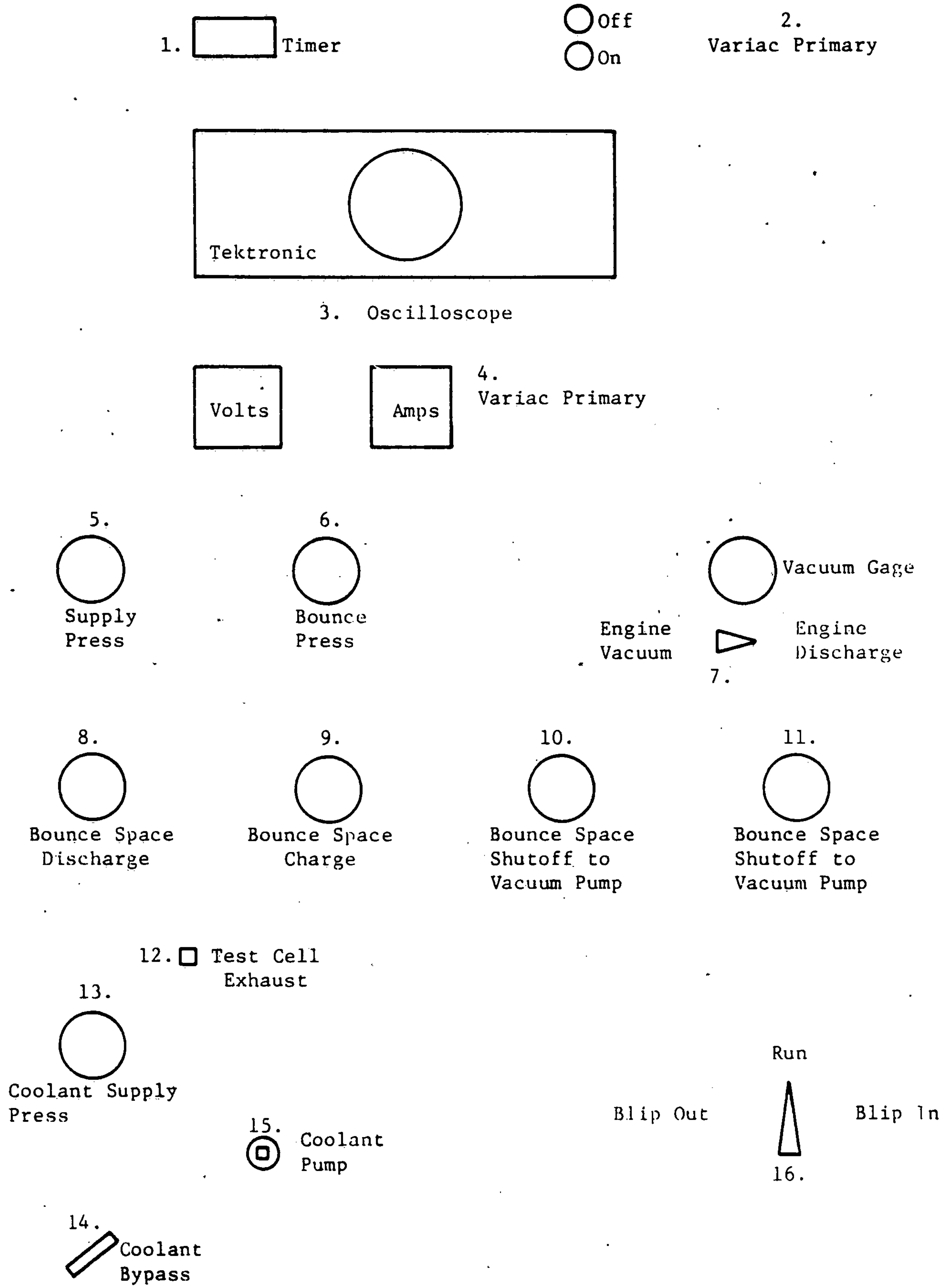


Fig. 4 Test Facility
Operator's Control Console

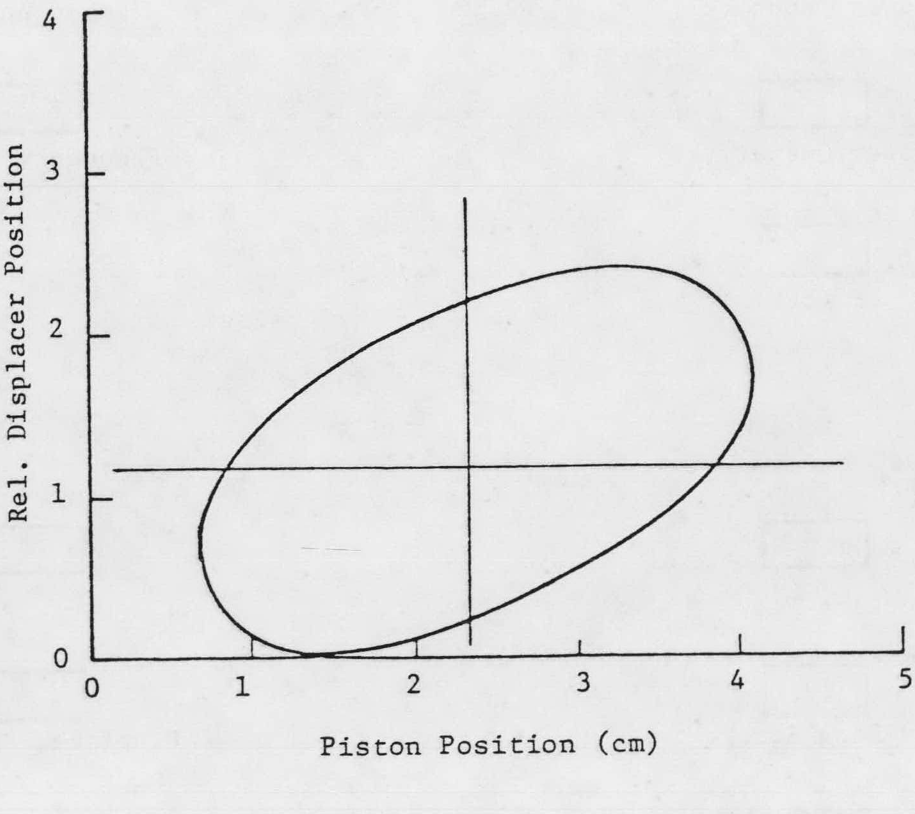


Figure 5 Displacer Phase Diagram

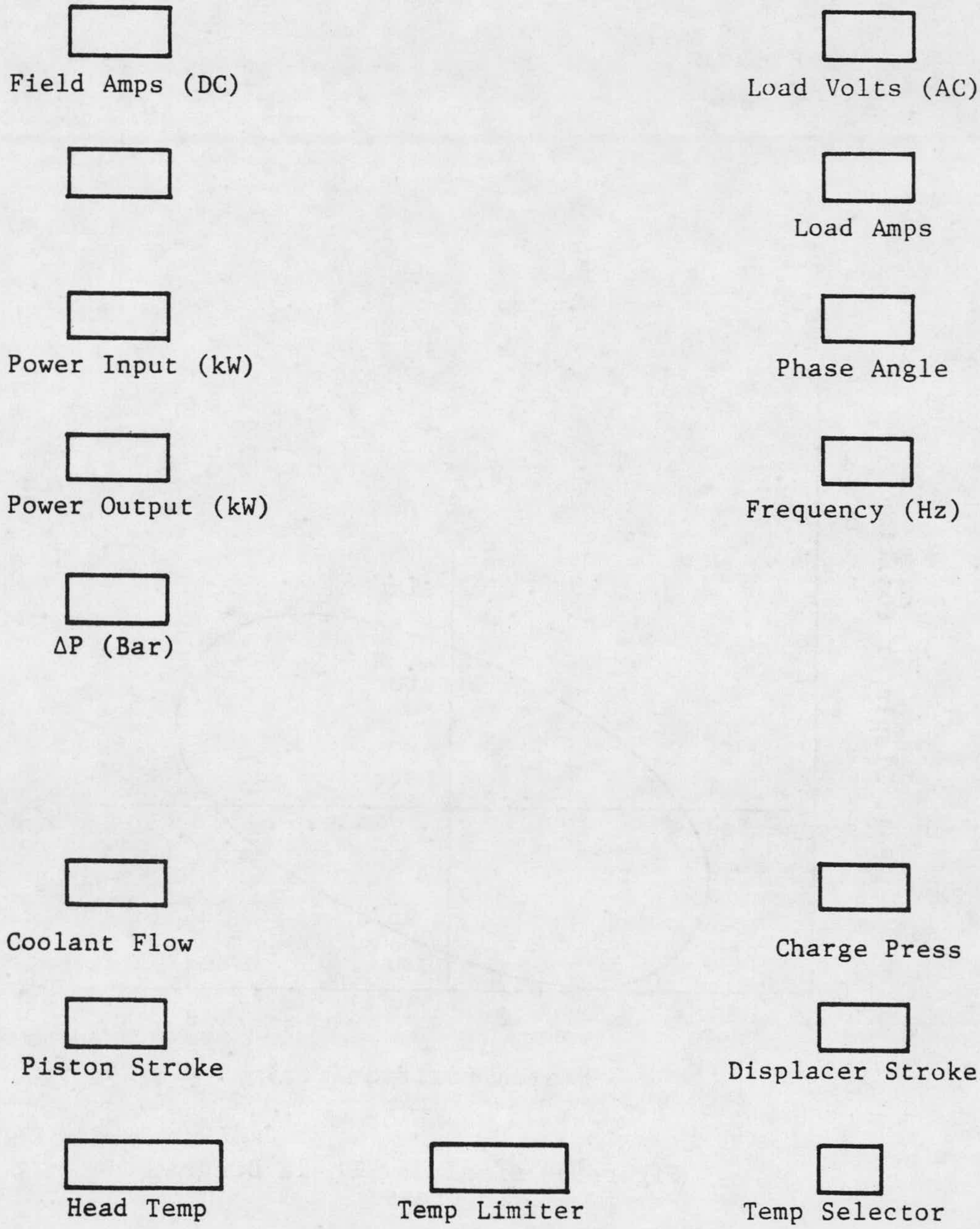


Fig. 6 Test Facility
Overhead Console

TEST PROCEDURES

I. Pressure Vessel Leak Check

The DOE FPSE pressure vessel has been designed for 70 bar operation while the engine design point is for 40 bar operation. Prior to any testing, it will be checked for possible leaks. Parting surface "o" ring seals exist at the piston housing to pressure vessel, engine/displacer assembly to piston alternator, water cooler, and heater head to water cooler interfaces. Dimensional checks at assembly will be performed to insure "o" ring pinch is adequate at each interface. There are 17 instrument pass-throughs and an external gas bearing pump inlet/outlet at the pressure vessel. Two instrument pass-throughs and two variable volume control rods pass through the cooler housing. All of the above constitute possible leakage sources.

Procedure

1. Turn on scope with piston displacer relative position signals on.

2. Turn on alternator stator load integrator.

3. Remove displacer gas spring T/C and install gas start solenoid. Leave water hook-up disconnected.

4. Monitoring the stator load integrator and scope position signals, pressurize the engine to 10 bar and watch for unusual piston and/or displacer motion and transient load signals at the load cells.

5. Observe pressure vessel pressure reading for rapid decline indicative of gross leakage.
   a) Check all parting surfaces and pressure pass-throughs for leaks and correct if necessary.

6. Observe all pressure reading signals for deviation from each other.

7. After any leaks have been corrected, disturb the displacer and observe scope for free motion of the piston and displacer.

8. Increase charge pressure to 40 bar in 10 bar increments, repeating the above checks.

9. Check water connections for helium leakage.

II. Engine Bearing Compressor Checkout

During the initial build, the internal gas spring pump will be plugged. Initial tests of the DOE FPSE will be conducted using the external gas bearing supply pump to ensure positive bearing feed. The purpose of this test is to check out the external bearing supply system.

Procedure

1. Charge engine and pump loop to 10 bar.

2. Actuate pump and observe charge pressure for equilibrium.

3. Observe bearing ΔP for indication of flow. (Off design ΔP curves are to be defined).

4. Without alternator field excitation, disturb displacer with helium charge to gas spring and observe freedom of piston and displacer motion.

5. Energize piston forward capacitance position probes and observing relative motion, energize DC field with 23 volts (2.5 amps of field current results in 1 KW output at 45 hz).

6. With the above alternator field current, disturb the displacer and observe piston and displacer motion.

7. Increase charge pressure to 40 bar and set bearing ΔP (to be determined).

8. Repeat the piston and displacer motion checks without the alternator field and again with the field energized.

III. Engine Motoring Checkout

The alternator motoring system will be checked out prior to the addition of heat to the engine. The objectives will be to define control procedures, establish required power input, and define the engine start up sequence. To minimize power input, it will be desirable to motor the engine at or near its natural frequency.

Procedure

1. Charge engine to 20 bar pressure and set water flow at .5 gpm.

2. Set engine bearing ΔP as determined from bearing checkout tests.

3. Set alternator DC field current to approximately 1 amp (approximately 9 volts).

4. Set AC output load at zero ohms.

5. Set AC oscillator at 32 hz, 5 amps (approximately 73 volts), and energize.

6. Observe piston peak-to-peak stroke and adjust motoring inputs to control stroke to 70% maximum (.7 in. or 1.8 cm).

7. Observe heater head temperature and discontinue motoring if heater temperature drops 20°F.

8. Repeat the above motoring check out tests for 30, 35, and 40 bar charge pressure and record the most favorable oscillator settings for off design system frequency and control.

IV. Low Power Mechanical Checkout Tests

The purpose of the low power checkout tests is to establish control and preliminary operating characteristics of the engine. As the engine has an adjustable displacer gas spring, results from these low power system checks will also be used to establish gas spring settings for the demonstrator tests. To prevent any mechanical damage to the engine, these tests will be of short duration and the dynamics will be recorded and played back later for evaluation.

Procedure

1. Shut off helium charge bottle and bearing pump accumulator bottle.
2. Disconnect cooling water lines and purge water cooler of any water with shop air.
3. Open external bearing supply inlet and outlet lines to pressure vessel.
4. Evacuate pressure vessel and external bearing pump and plumbing.
5. Shut off vacuum pump inlet connection and turn off vacuum pump.
6. Charge pressure vessel to 20 bar.
7. Open bearing pump accumulator bottle and bring up charge pressure to 20 bar. Set bearing ΔP (determined from bearing tests) by adjusting pump air regulator
8. Connect cooling water lines and set water flow at 1 gpm.
9. Energize heat input variac and start warming engine to 450°C.
10. Step through all instrumentation channels and check signal integreties.
11. Check each analog recorder for proper readings.
12. As the heater temperature approaches 450°C, set alternator load resistor to zero ohms.

13. Set alternator DC field current at 1 amp. Start recorder.

14. Set AC oscillator at 32 hz, 5 amps, and energize, motoring alternator.

15. Decrease oscillator current and bring in AC load resistance as the alternator stroke increases. Maintain stroke to 1.8 cm.

16. As engine becomes the predominate drive, disconnect AC oscillator and increase load resistance to maintain the 1.8 cm stroke.

17. Reset engine heater head temperature to 450^{o}C.

18. Take first data point.

19. Observe engine stability by observing phase diagram, piston and displacer stroke, alternator apparent power, voltage, and engine frequency.

20. Change alternator load resistance from initial setting (to be determined by controlling stroke) to -.5, .5, and 1 ohm.

21. Observe engine stability, readjust heater head temperature to 450^{o}C, and adjust cooling water flow to maintain 10^{o}C. Take data point at each load setting.

22. Record all analog display readings on operator's data sheet.

23. Turn off heater input power and, maintaining constant engine phase by adjusting the alternator load and preventing engine overstroke, allow the engine to coast down as the heater cools. Observe any unusual stability regimes and record as they occur.

24. When engine has stopped, reduce the alternator field current and observe that the engine does not restart.

25. Continue to reduce the field current until the engine has cooled sufficiently to prevent start up upon eliminating the alternator load entirely.

26. Shut down external bearing supply pump.

27. When heater has cooled to below 300^{o}F, turn off cooling water and disconnect lines.

28. Review preliminary data and provide engine tuning adjustments as deemed necessary, and recheck engine performance.

V. Engine Mapping Tests

The purpose of these tests is to provide sufficient engine mapping from lower power settings to allow extrapolation of these data to predict design point performance. In order to minimize the number of runs, three point curve resolution will be implemented following the run schedule outlined in Table I. As there are seven independent engine controls, fixing control variables at each data point is necessary to reduce scatter in the data and to provide the correct parameters for cross plottings.

Procedure

1. The first tests will be initiated at the 20 bar, 450^{o}C heater temperature point.

2. Start engine by the procedures outlined in the low power mechanical checkout tests.

3. Allow engine to stabilize by monitoring energy balance residuals from data output.

4. Take data points following the point schedule outlined in Table I.

5. Shut down engine in accordance with the procedures outlined in the low power mechanical checkout tests.

6. Fixed parameters will be gas spring volume controls, alternator reactance power (nulled to zero with load capacitor), and engine cold space temperature. (Controlled with cooling water by-pass flow).

TABLE I

Heater Temp - 450°C
Charge Press - 20 bar

Load Resistance - 5Ω
Field Current - 1, 1.75, 2.5 amps

Load Resistance - 10Ω
Field Current - 1, 1.75, 2.5 amps

Load Resistance - 15Ω
Field Current - 1, 1.75, 2.5 amps

Heater Temp - 450°C
Charge Press - 30 bar

Heater Temp - 450°C
Charge Press - 40 bar

Heater Temp - 550°C
Charge Press - 20 bar

Heater Temp - 550°C
Charge Press - 30 bar

Heater Temp - 550°C
Charge Press - 40 bar

Heater Temp - 650°C
Charge Press - 20 bar

Heater Temp - 650°C
Charge Press - 30 bar

Heater Temp - 650°C
Charge Press - 40 bar

VI. Engine Design Point Performance Test

The purpose of this test is to demonstrate the design point operating performance of the engine. The expected conditions for design point operation are given in Table II.

Procedure

1. Start engine in accordance with the procedure outlined in the low power mechanical test procedure.

2. Once started, increase the charge pressure to 40 bar, observing engine stability and controlling the engine stroke to 1 inch, varying the load resistance.

3. Set load resistance to 14.5Ω or to a value to control the stroke to 1 inch with a DC field current of 2.5 amps.

4. Null out reactive power with load capacitor.

5. Increase heater temperature to 700^{o}C, observing to control the stroke to 1 inch.

6. Take data readings until steady state is attained.

7. Once on point, record all the data parameters outlined in instrumentation section.

TABLE II

DESIGN POINT CONDITIONS

Piston P-V Power	— 1423 watts
Frequency	— 45 hz
Charge Pressure	— 40 bar
Displacer Stroke	— 2.69 cm
Piston Stroke	— 2.54 cm
Engine Phase	— 18.76^{o}
Heater Temperature	— 700^{o}C
Alternator DC Volts	— 22.9 volts
Alternator DC Current	— 2.5 amps
Alternator AC Volts	— 121.9 volts
Alternator AC Current	— 8.2 amps
Alternator Power	— 1000 watts
Load Resistance	— 14.47 ohms
Load Capacitance	— 150.5 mf

INSTRUMENTATION & DATA REDUCTION

INTRODUCTION

The DOE FPSE is instrumentated to provide data for determining the overall engine package efficiency, component losses, heater head temperature distribution, energy input, pressures, and dynamics. Defining the thermodynamic boundary A (Figure 7) as the net heat into the engine, then the system efficiency is η_{sys} = alternator power out/net power in. Defining the thermal boundary B (Figure 8), η_{sys} = alternator power out/(heat rejected + alternator power out). This gives two checks on the efficiency calculation. To further isolate internal component losses, the engine is instrumented to determine displacer gas spring power, piston gas spring power, engine shaft power, piston P-V power, and internal T/C's in the working space and the regenerator side of the cooler are also provided.

HEATER HEAD HEAT INPUT

The heater head heat input to the working gas is accomplished through 48 tubes brazed in a three circuit segmented ring. The thin wall heater tubes constitute the primary resistance path and provide the major portion of heating. Where mechanical connections are provided at the thermal guards, local power input losses will occur. The three segment heater scheme is to reduce the effects of imposed impedance from input connections from current source to current source due to voltage splits and thereby provide a more even power distribution to the heater tubes. To obtain the closest power input point to the heater head, the input voltage is measured across the T/C closest to the heater head on the thermal guards for each segment (Figure 9). The input current is measured using three Midwest Electric Products Model No. 6 CT, 120B current transformers with 2000 to 5 ratio. The power-in signal is conditioned by an FW Bell Watt Transducer and fed into the designated channel on the HP 3495 scanner. It will be determined if any significant reactive power components exist and, if not, the CT and voltage signals will be read-in directly without power multiplication.

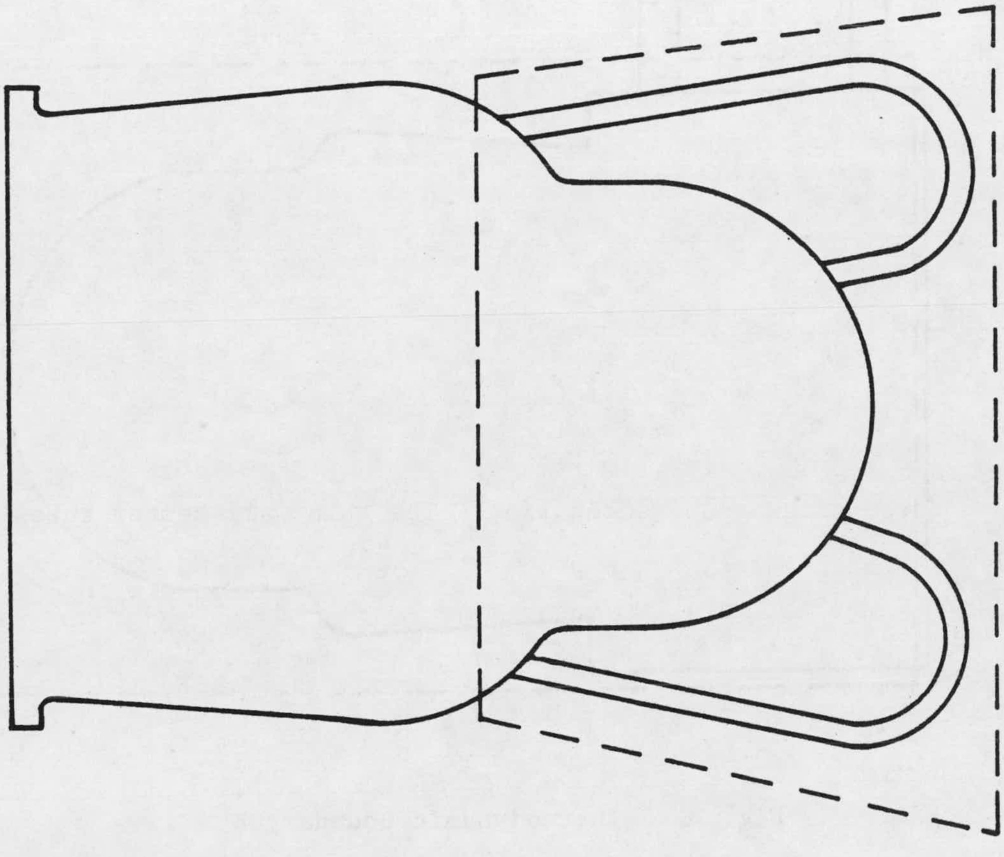


Fig. 7 Thermodynamic Boundary A

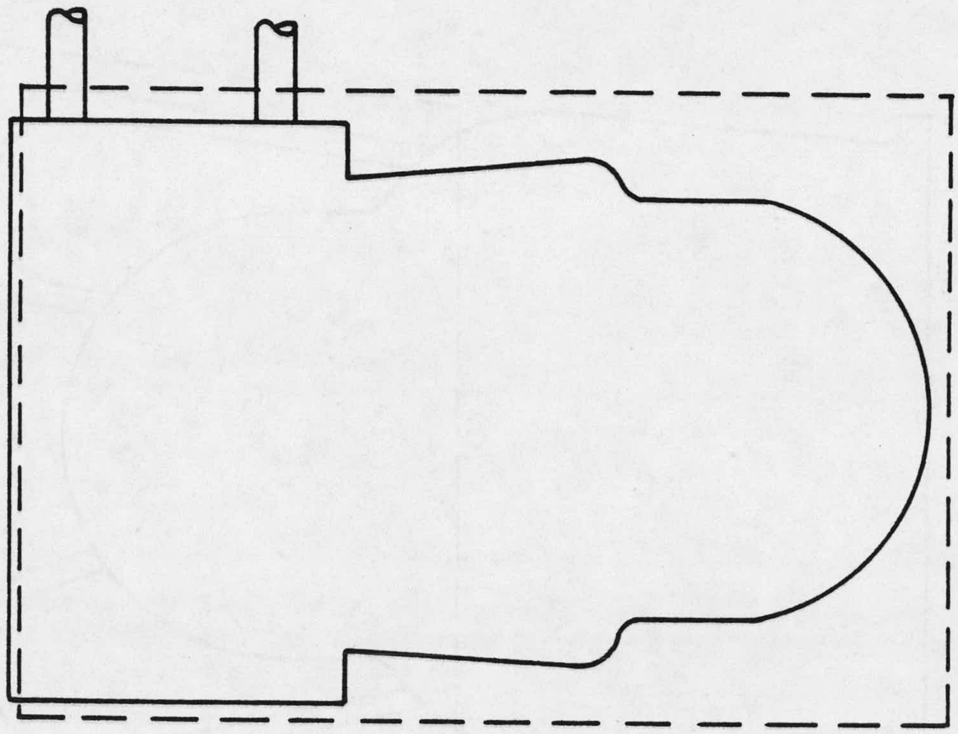


Fig. 8 Thermodynamic Boundary B

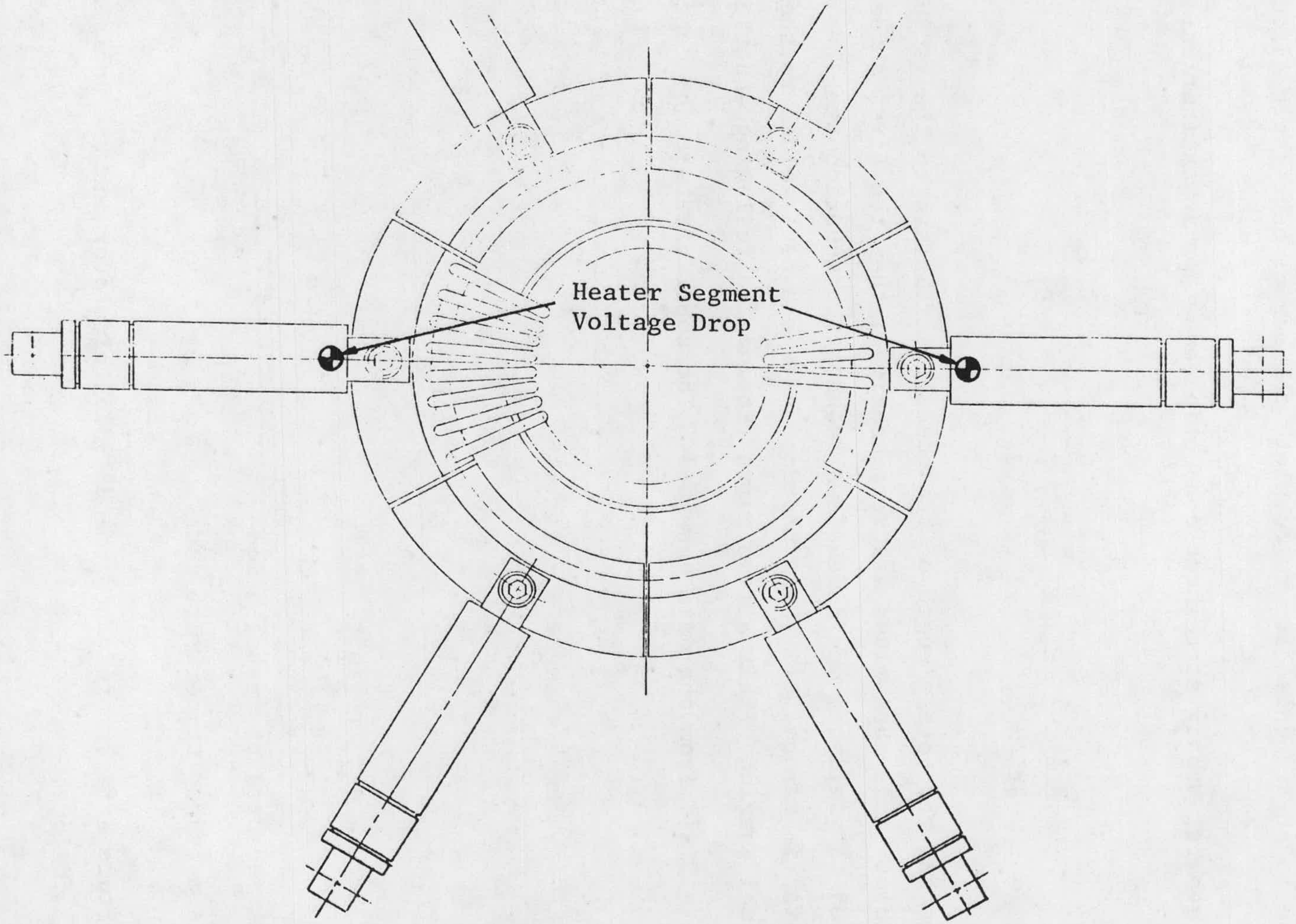


FIGURE 9 Engine Power Input Measurement

HEATER HEAD HEAT INPUT LOSSES

As the thermal guards themselves are conductors and due to the high input current, heat generation and conduction losses of the thermal guards must be corrected out of the power-in measurements. Also, conduction losses, through the insulation package, have to be accounted for to complete the engine heat input calculation.

Writing the general steady state heat conduction equation in cylindrical coordinates:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T^2}{\partial Z^2} + \frac{\dot{q}}{k} = 0;$$

and assuming that the total length of the conductor relative to the radius is large (the input leads themselves are very massive), then the first three terms can be dropped to yield the one dimensional conduction equation that has a solution form which is parabolic. Three thermocouples are tack welded to the thermal guards in equal spacing. This allows curve fitting the following equation form: $ax^2 + bx + c = T(x)$, from the data obtained. The coefficients to be determined are:

$$ax_o^2 + bx_o + c = T_o$$

$$ax_1^2 + bx_1 + c = T_1$$

$$ax_2^2 + bx_2 + c = T_2$$

Where: x_i is measured at installation

T_i is measured temperature data

These temperature data are fed into the HP 9825 calculator and the coefficients are solved as follows:

$$\begin{Bmatrix} a \\ b \\ c \end{Bmatrix} = \begin{bmatrix} X \end{bmatrix}^{-1} \begin{Bmatrix} T \end{Bmatrix}$$

Since the conduction loss over the length of the thermal guard is $q_{tg} = -kA\ dT/dX$, dT/dX can be found from the coefficient solution $2ax + b$ and $q_{tg} = -kA\ (2aL + b)$ for the length of the thermal guard (k is assumed constant over the length for the mean temperature).

The insulation conduction loss is calculated assuming the cylindrical insulation package can be approximated by one dimensional spherical shell conduction corrected by a shape factor:

$$q_{cin_s} = -.725\ k\ \sqrt{A_o A_i}\ \frac{T_i - T_o}{r_o - r_i}$$

T_i = highest temperature at the heater head.

T_o = lowest temperature at the insulation OD.

r_o & r_i = chosen to approximate the spherical shell.

A_o = actual outside area of insulation package.

A_i = approximated hemispherical area of heater over the tubes.

Then the net heat input to the engine for efficiency calculations is:

$$\dot{Q}_{power} - \dot{Q}_{tg} - \dot{Q}_c = \dot{Q}_{net\ in}$$

$\dot{Q}_p$ = measured power input.

$\dot{Q}_{tg}$ = conduction loss at thermal guards.

$\dot{Q}_c$ = conduction loss at insulation.

ALTERNATOR POWER OUT (FIGURE 10)

The alternator power out is measured by voltage signals and two API current transformers input to a Signal Transformer watt meter, where these input values are summed vectorily and the output fed into the HP 3495 scanner. Then, the system efficiency based on heat input can be calculated as:

$$\frac{\text{Alternator Powerout}}{\dot{Q}_{net\ in}} .$$

The alternator load system contains a tuning capacitor with the load resistor that is used to null the reactive component. For engine analysis, the alternator phase angle can be found as $\alpha = 90 - \kappa$, where κ is found with the Dranetz phase meter with piston stroke as the reference and resistive voltage as the input signal.

ENGINE HEAT REJECTION (FIGURE 11)

The engine heat is rejected to a cooling water loop as part of the test facility. The engine cooler is a counter cross flow, water to helium, unmixed heat exchanger. The heat rejection is calculated as $\dot{q}_{rej} = \dot{m}\ C_p \Delta T$ of the cooling water. The water mass flow is measured with a Bearingless flow meter which has a frequency response fed into the HP 5328 frequency counter and fed into the HP 3495 scanner through a relay multiplexer. The cooling water ΔT is sensed by two HyCal RTD probes ($16^{\circ}C$ range) and conditioned by a HyCal Model CT-825-A amplifier. The conditioned output is then fed into the HP scanner.

The engine efficiency based on engine heat rejection is then:

$$\frac{\text{Powerout}}{\text{Powerout} + \dot{Q}_{rej}}$$

This then provides two checks on the measured engine efficiency.

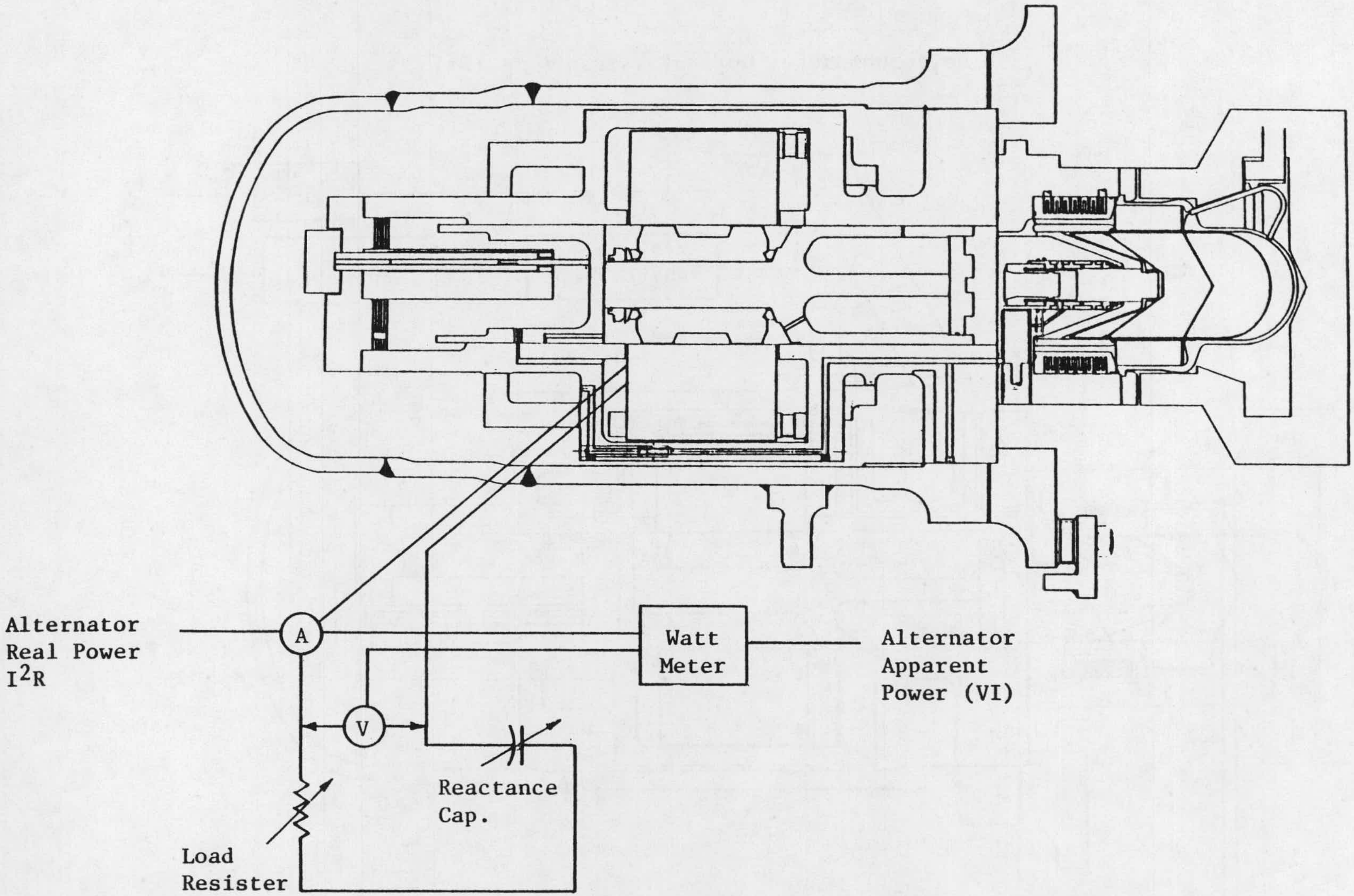


Fig. 10 Alternator Instrumentation

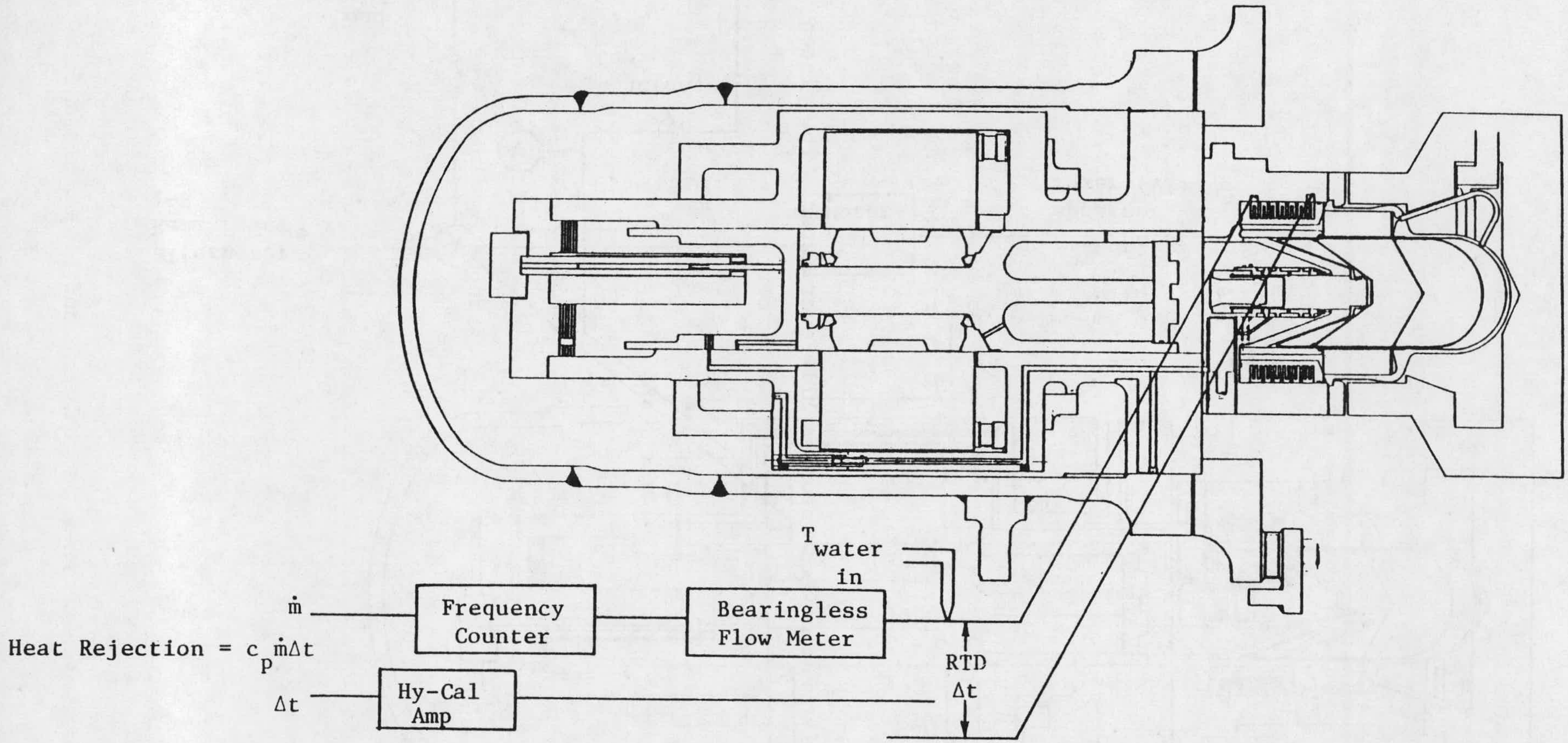


Fig. 11 Heat Rejection Instrumentation

ENGINE ENERGY BALANCE

The engine energy balance can be stated algebraically as:

$$\dot{Q}_{net\ in} + \dot{Q}_{out} + \dot{Q}_{rejected} + \dot{Q}_{losses} = \varepsilon;$$

where ε is the energy balance residual and results from experimental error. It may not be possible to account for the losses individually in an overall balance since, depending on the cooler wall temperature, some of the heat generated by losses will be rejected through the pressure vessel.

The net heat in, powerout, and rejected heat parameters have been previously discussed. For analytical evaluation, the engine is instrumented for determining the gas spring pumping losses and shaft power delivered to the alternator, engine P-V power, and displacer gas spring losses. The net shaft power delivered to the alternator is sensed by the stator reaction force and integrating this signal with the piston shaft velocity signal. The stator reaction force is measured with Kistler 9021 load cells preloaded at 4000 lb. force beneath the stator at the piston housing mount. The load cells are input to Kistler 5001 charge amplifiers with the amplifier output fed into the MTI Power Meter. The piston velocity is sensed by a Trans Tek 112-001 velocity transducer and fed into the MTI Power Meter and integrated with the force. Stator accelerations are summed out of the load values by two Kistler 816 accelerometers conditioned by a Kistler 5001 charge amplifier and fed to the power meter. The power meter output is fed to the HP 3495 scanner. This net power will not account for any eddy currents that may occur in the alternator plunger. Also, gas spring housing deflections which may influence the force cell outputs are neglected. The alternator efficiency can then be taken as the alternator power out/the input shaft power and would be a loss in the energy balance (Figure 12).

The thermodynamic power (P-V) delivered to the piston can be calculated by:

$$P = \pi\ f\ P\ A\ x\ \sin\phi;$$

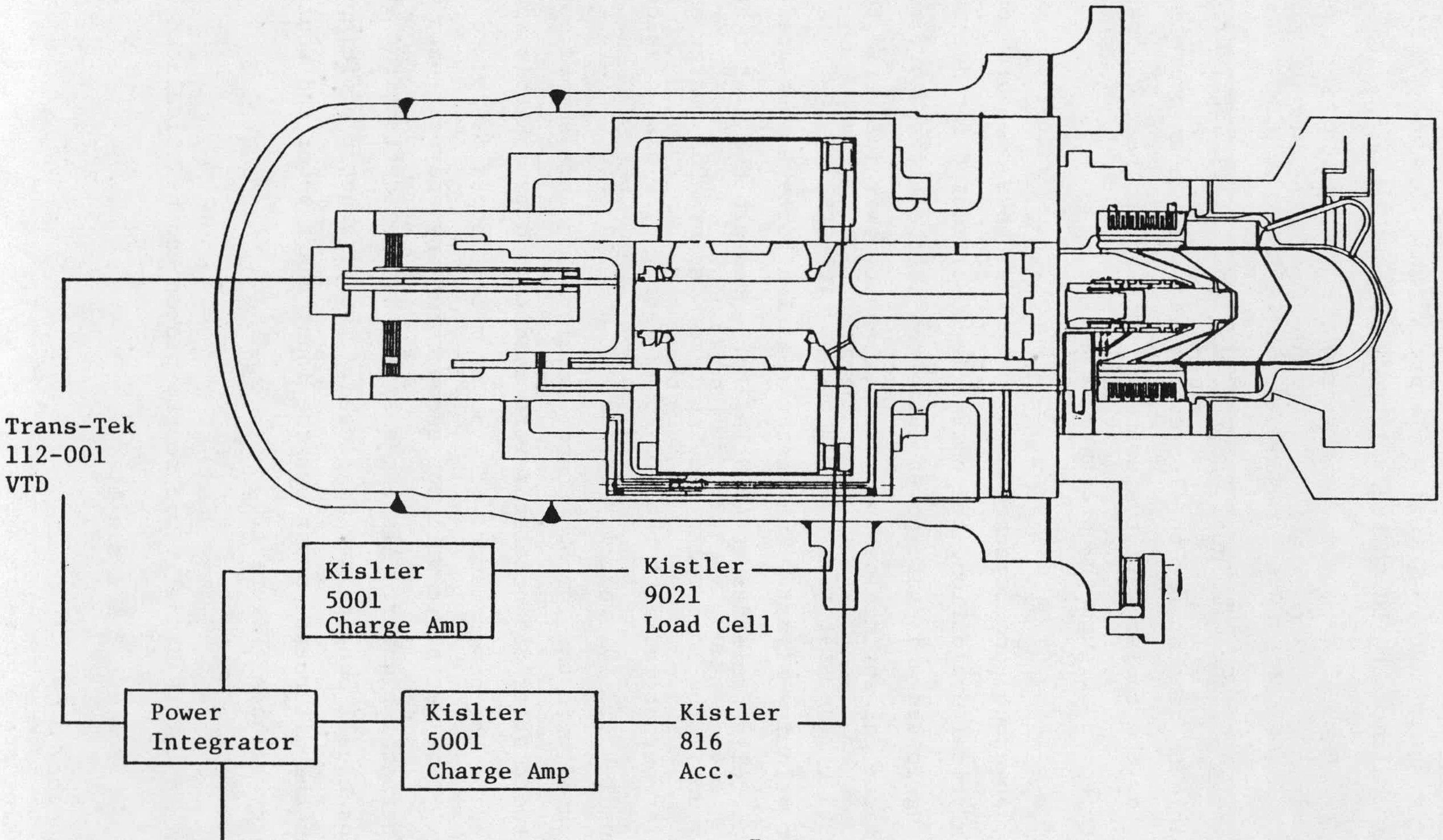
where: f = frequency

P = working space pressure amplitude

A = piston area

X = piston amplitude

ϕ = phase angle between the pressure and piston position



Shaft Power into Alternator $P_S = \frac{1}{\tau} \oint^{\tau} F_s \dot{x}_p dt$

Fig. 12 Shaft Power into Alternator

The engine frequency is taken from the velocity probe and conditioned by the HP 5328 frequency counter. The working space pressure is sensed by a Kistler 4045 piezoresistive transducer with bridge elements powered by a Kistler 4601 amplifier. The phase angle is obtained by input signals from the piston position used as a reference signal with the pressure signal from the 4601 through an AC coupler, both input in the Dranetz phase meter. The piston position is sensed by MTI CP10 10 mil capacitance probes conditioned by a Wayne-Kerr DIMEQ TE 200 amplifier. The AC outputs from the pressure and piston position signals are read by HP 3455 voltmeter as true RMS voltages. The calculation will correct the AC RMS values to amplitude values assuming sinusoidal wave forms (Figure 13).

As a check to this method of measuring P-V power, the working space dynamic pressure signal will be read into the MTI Power Meter with the velocity signal and integrated in the same manner as the stator reaction power was attained. The output signal (which is the result of a vector operation) will be multiplied by the appropriate scaler in the software.

A third method would be to take the pressure and piston position signals in real time through the scanner multiplexor and read these data into the calculator by two System Volt Meters. Reading would be taken over a few cycles and stepped to provide P-V data in real time (Figure 14). These signals can also be recorded on tape and fed back for Fourier analysis to determine higher order harmonics.

The piston and displacer gas spring losses can be determined in the same manner as the piston thermodynamic work. These losses are expected to be small relative to the engine power, and instrument resolution may not allow their use in the energy balance equation. Then, the equation balance can be found by:

$$\dot{Q}_{net\ in} + \dot{Q}_{out} + \dot{Q}_{rejected} + \dot{Q}_{pgs} + \dot{Q}_{dgs} + \dot{Q}_{alt\ loss} = \varepsilon;$$

where: $\dot{Q}_{net\ in}$ = net heater input power

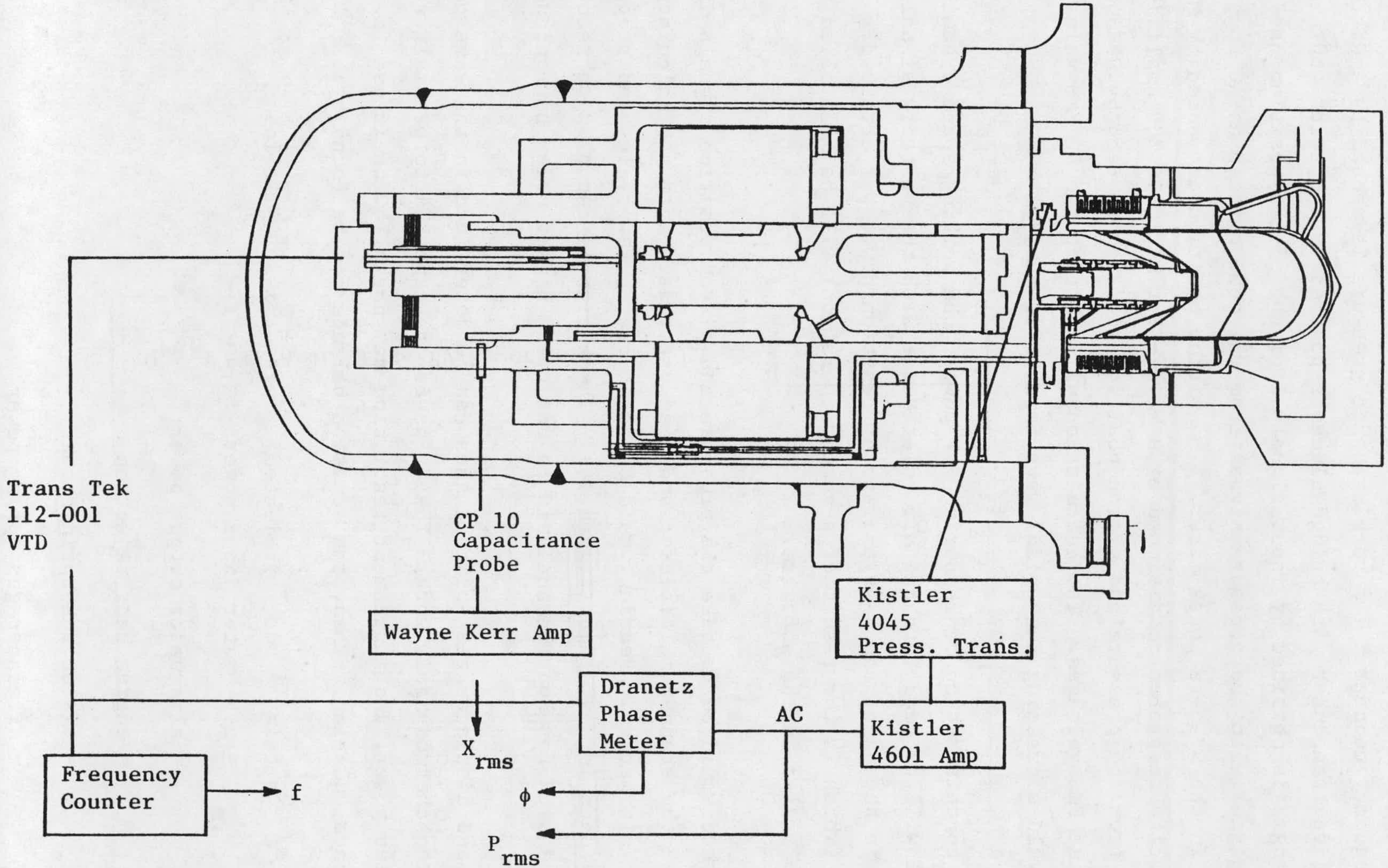
$\dot{Q}_{out}$ = alternator output power

$\dot{Q}_{rejected}$ = engine heat rejection

$\dot{Q}_{pgs}$ = piston gas spring power

$\dot{Q}_{dgs}$ = displacer gas spring power

$\dot{Q}_{alt\ loss}$ = powerout $\left(1 - \dfrac{\text{Powerout}}{\dot{Q}_{st}}\right)$



$$\dot{Q}_{PV} = \pi f P A \text{ x } \sin\phi$$

Fig. 13 Engine PV Power with Phase Meter

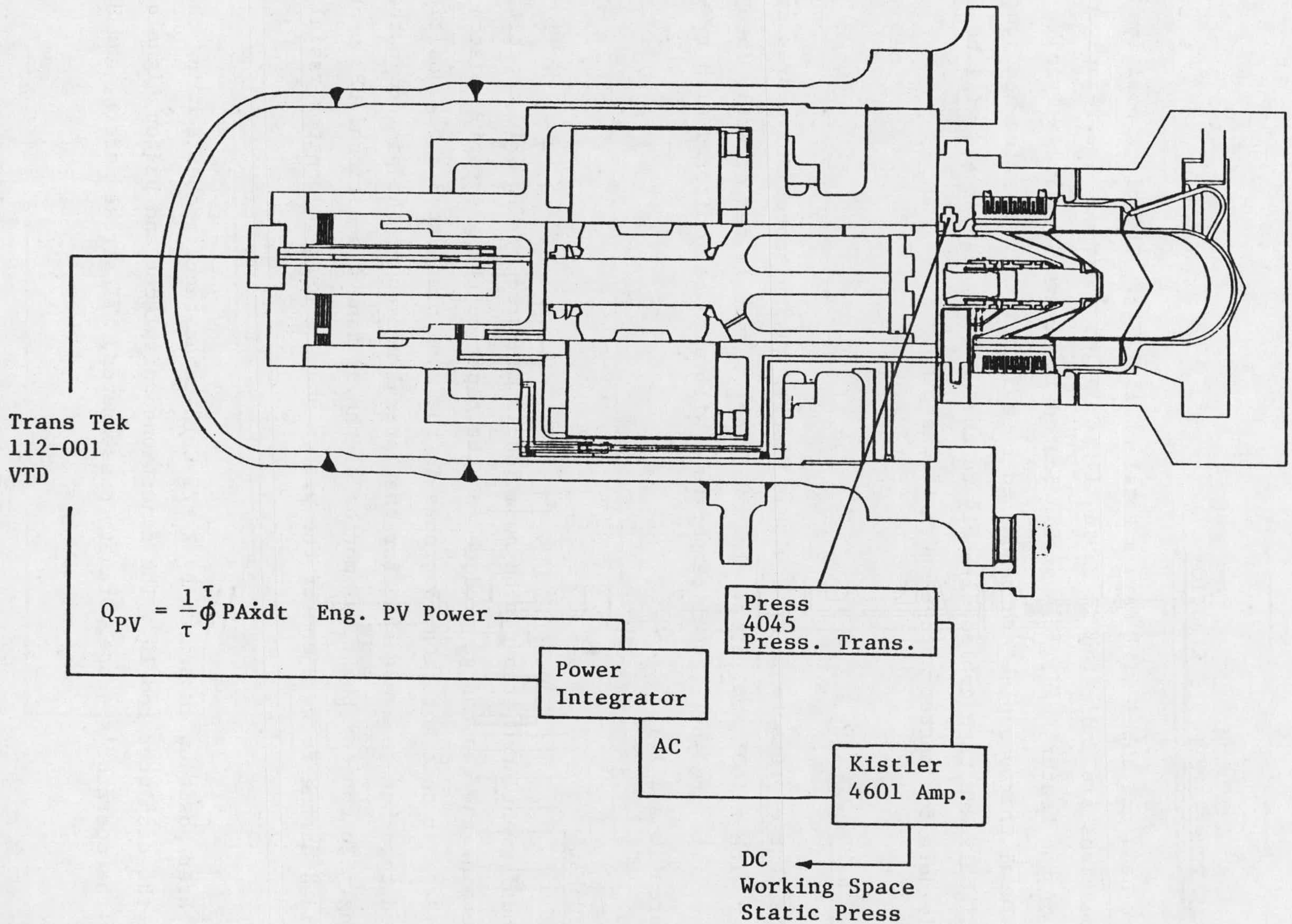


Fig. 14 Engine PV Power
with Power Integrator

Instrumentation to determine the pumping losses of the heat exchangers are not provided and an analytical correction would be required to close the heat balance loop.

HEATER HEAD TEMPERATURE DISTRIBUTION

The heater head and tubes will have a total of 15 T/C's. The clock position and engine locations are indicated in Table III for all the T/C's. The relative position of the heater head T/C's are indicated in Figure 15. Omega Type K Chromel Alumel thermocouples are connected to a 52 point HyCal reference junction. The T/C signals are then cabled directly to the HP 3495 scanner and will be used to provide data for heater head temperature mapping.

PRESSURE VESSEL

The engine charge pressure is read with a Kistler 4045 piezoresistive pressure transducer with a 4601 amplifier. The amplifier output is fed directly into the HP scanner. The pressure vessel temperature will also be monitored with a Type K T/C (Figures 16 and 17).

ENGINE DYNAMICS

As previously mentioned, the piston position is measured by MTI CP10 capacitance probes sensing the gap change produced by the taper on the gas spring piston (Figure 18). At this location, 3 probes in the same plane at 3 clock positions are summed together to compensate for the lateral motion of the piston in the gas spring. To monitor the total motion of the piston, 2 additional CP5 probes are provided at the forward end of the piston and are used to monitor radial motion.

The displacer position is sensed by 2 MTI CP10 capacitance probes sensing the taper on the displacer rod ID. The conditioned displacer and piston signals are input to the operator's scope, Dranetz phase meter, MTI stroke meters, and HP scanner.

TABLE III

INSTRUMENT HOOK-UP SHEET

Probe Type	Probe Name	P/N	Engine Clock Position	Test Cell Number	Engine Location
T/C	THHO	SCASS-062G-12		1	Heater Head
"	THH.4A	"	11:00	2	
"	THH.4B	"	5:00	3	
"	THH1.3A	SCASS-062G-16	11:00	4	
"	THH1.3B	"	5:00	5	
"	THH2.35A	"	11:00	6	
"	THH2.35B	"	5:00	7	
"	THT.25A	SCASS-062G-12	11:00	8	Heater Tube
"	THT.25B	"	5:00	9	
"	THT.26A	"	11:00	10	
"	THT.26B	"	5:00	11	
"	THT2.15A	SCASS-062G-16	11:00	12	
"	THT2.15B	"	5:00	13	
"	THT3.0A	"	11:00	14	
"	THT3.0B	"	5:00	15	
"	TG1A.94	SCASS-062G-12	12:00	16	Thermal Guard
"	TG1B2.47	"	12:00	17	
"	TG1C4.0	"	12:00	18	
"	TG2A.94	"	2:00	19	
"	TG2B2.47	"	2:00	20	
"	TG2C4.0	"	2:00	21	
"	TG3A.94	"	4:00	22	
"	TG3B2.47	"	4:00	23	
"	TG3C4.0	"	4:00	24	
"	TG4A.94	"	6:00	25	
"	TG4B2.47	"	6:00	26	
"	TG4C4.0	"	6:00	27	
"	TG5A.94	"	8:00	28	
"	TG5B2.47	"	8:00	29	
"	TG5C4.0	"	8:00	30	
"	TG6A.94	"	10:00	31	
"	TG6B2.47	"	10:00	32	
"	TG6C4.0	"	10:00	33	

TABLE III CONTINUED

Probe Type	Probe Name	P/N	Engine Clock Position	Test Cell Number	Engine Location
T/C	TRG3.8A	SCASS-062G-12	11:00	34	Regenerator Wall
"	TRG3.8B	"	5:00	35	
"	TRG4.75A	"	11:00	36	
"	TRG4.75B	"	5:00	37	
"	TRG5.7A	"	11:00	38	
"	TRG5.7B	"	5:00	39	
"	TDGS9.5	SCASS-062G-12	9:00	40	Disp. Gas Spring
"	TCUS6.2	SCASS-040G-12	11:00	41	U/S Cooler
"	TWS9.6	"	11:00	42	Working Space
				CI	
Pressure	PSDGS9.5	4075 A100	12:00	a	Disp. Gas Spring
"				b	
"				c	
"				d	
"	PSW9.5	4045 A100	3:00	e	Working Space Pressure
"				f	
"				g	
"				h	
"				i	
"	PPV12.5	4045 A100	7:30	j	Press. Vessel
"				k	
"				l	
"				m	
"				n	
"	PCD27.0	4045 A100	8:00	o	Comp. Discharge
"				p	
"				q	
"				r	
"				s	
"	PSPGS29.5	4045 A100	3:00	t	Piston Gas Spring
"				u	
"				v	
"				w	
"				x	

TABLE III CONTINUED

Probe Type	Probe Name	P/N	Engine Clock Position	Test Cell Number	Engine Location
Capacitance	CPDX9.2A		12:00	Wayne Kerr Amp.	Displacer
"	CPDX8.2B		6:00		
"	CPPO12.5A	CP5	11:30	"	Forward Piston Orbit
"	CPPO12.5B	CP5	2:30	"	
"	CPPO12.5C	CP5	5:30	"	
"	CPPX26.5A	CP10	11:30	"	Rear Piston Orbit & Piston Displacer
"	CPPX26.5B	CP10	2:30	"	
"	CPPX26.5C	CP10	5:30	"	
Accelerometer	AC16.8A	816A	12:30		Stator Accel.
"	AC16.8B	816A	5:30		
Load Cell	LCM8.0A	9041	10:30		Engine Mount
"	LCM8.0B	9041	1:30		
"	LCM8.0C	9041	6:00		
"	LCS16.8A	9021	12:00		Stator Mount
"	LCS16.8B	9021	5:00		
"	LCS16.8C	9021	7:00		
Velocity	VP30.	112-001	2:00		Piston Velocity

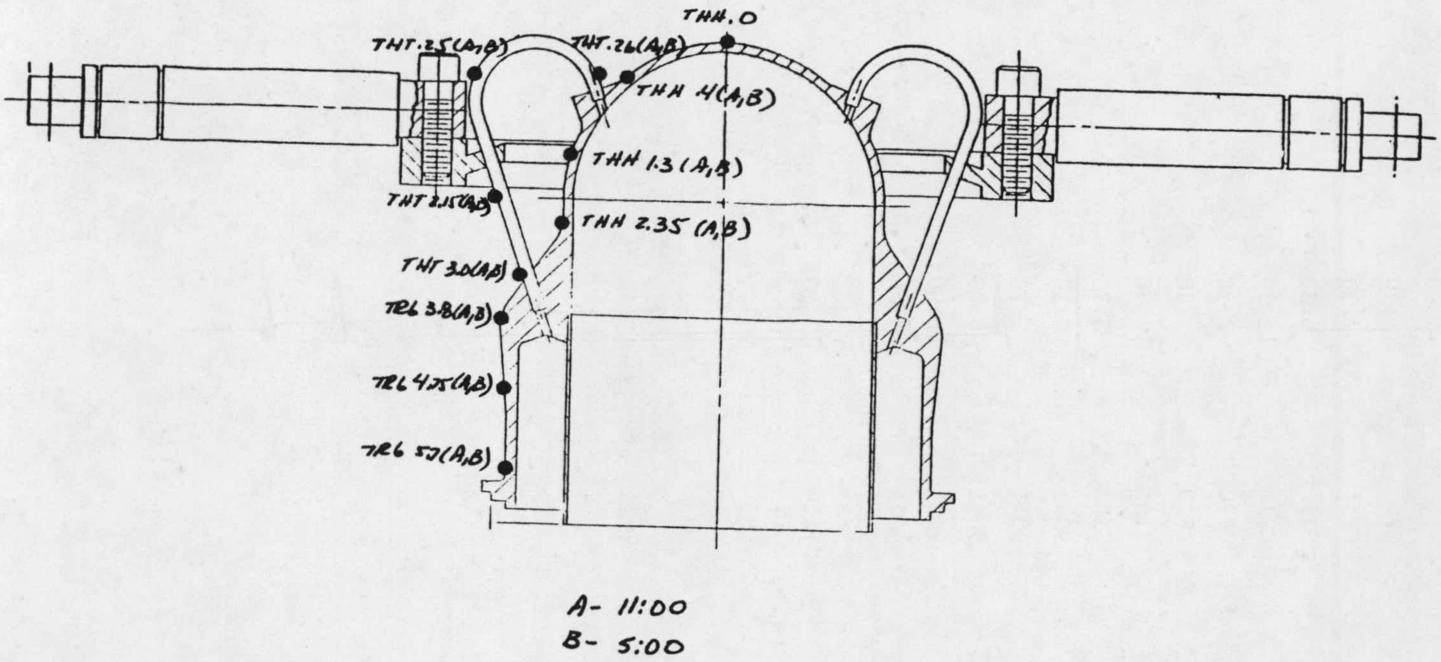


Figure 15 Heater Head Thermocouple Location

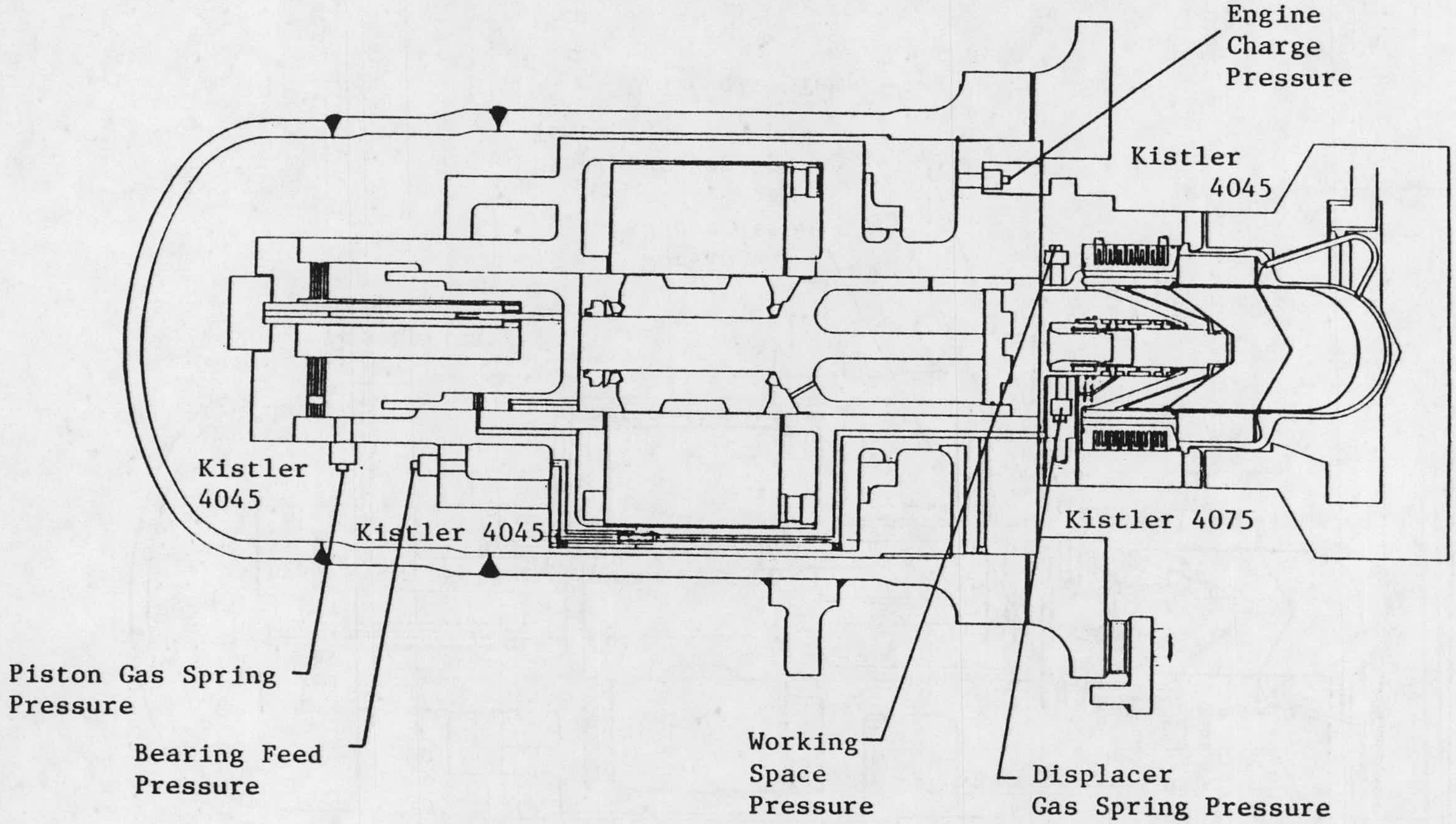


Fig. 16 Engine Pressures

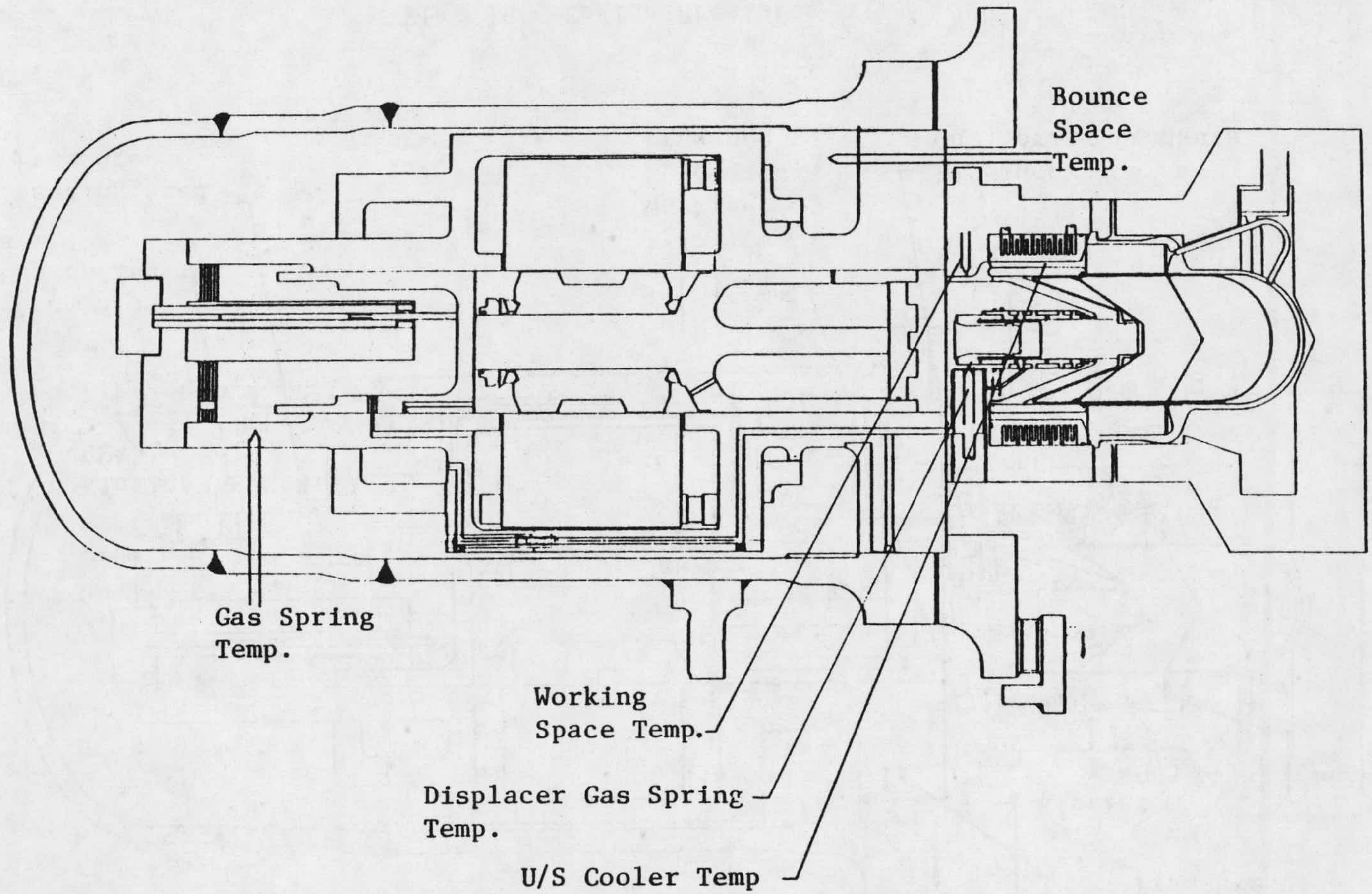


Fig. 17 Engine Temperatures

The engine dynamic load transmitted through the mount is sensed by 3 Kistler 9041 load cells located between the engine and the engine mount. The output signals from the load cells are summed with two Kistler 816 accelerometers and conditioned with a Kistler 5001 charge amplifier (Figure 18). Static mean pressure in the gas spring volumes, working space, pressure vessel, and compressor discharge are provided for determining engine pressure balance evaluation.

Figure 19 is an overall instrumentation schematic and the channel allocations, sensitivities, and ranges are listed in Table IV.

Figure 20 is the flow chart for the software computer routine (HP 9825 calculator) that will be programmed to perform the indicated calculations from the new engine data as collected. The actual equations are contained in Tables V and VI.

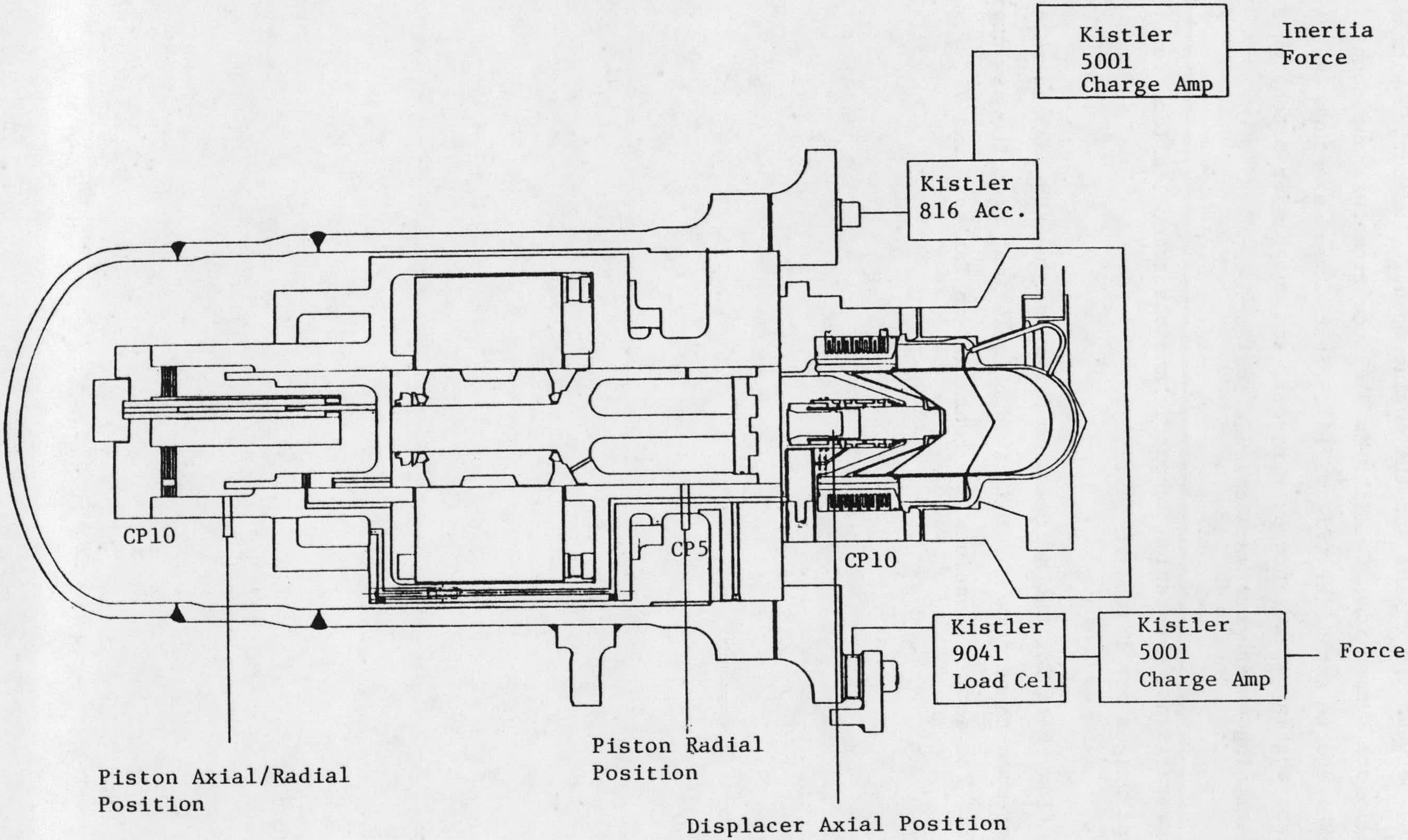


Fig. 18 Engine Dynamics

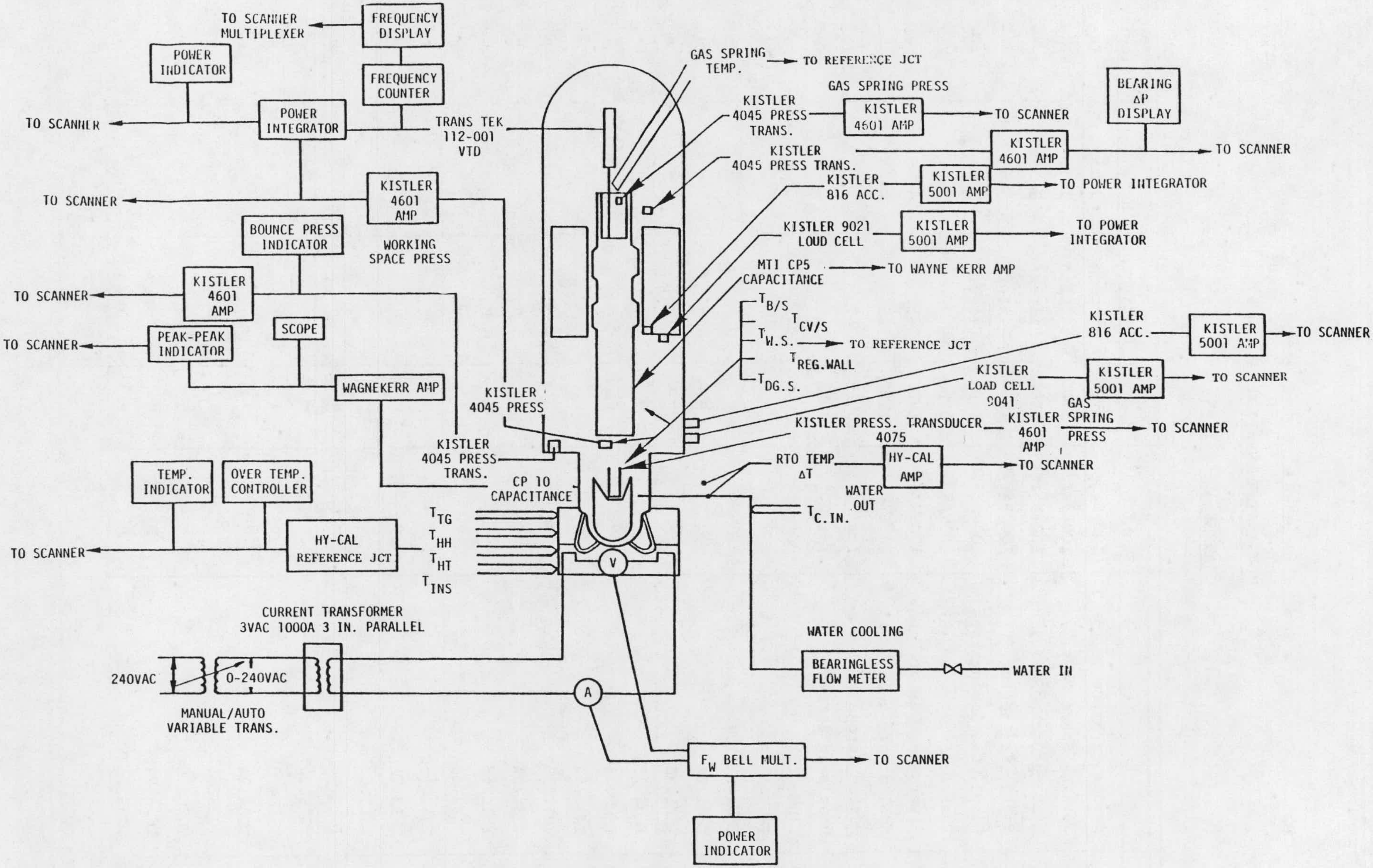


FIGURE 19 INSTRUMENTATION SCHEMATIC

TABLE IV

DOE INSTRUMENTATION

CHANNEL ALLOCATION

Channel No.	Parameter	Sensitivity	Range	Instrument	Instrument	Operators Display
0	Bounce Pressure	100 Bar/V	1VDC	-------	3455	Yes
1	Working Space Pres.	100 Bar/V	1VDC	Filter*	3455	---
2	Beaving Dschg Spring Pres	100 Bar/V	1VDC	Filter*	3455	---
3	Piston Gas Spring Pres	100 Bar/V	1VDC	Filter*	3455	---
4	Displ. Gas Spring Pres	100 Bar/V	1VDC	Filter*	3455	---
5	Phasemeter	100^{o}/V	10VDC	-------	3455	Yes
6	Alternator Stator Power	1000W/V	1VDC	3455	----	Yes
7	Coolant ΔT	20^{o}C/V	1VDC	3455	----	---
8	Piston Stroke	1cm/V	10VDC	3455	----	Yes
9	Displacer Stroke	1cm/V	10VDC	3455	----	Yes
10	THHO (T1)	^{o}C/mV	.1VDC	3455	----	Yes
11	THH.4A (T2)	"	"	"	"	"
12	THH.4B (T3)	"	"	"	"	"
13	THH1.3A	"	"	"	"	"
14	THH1.3B	"	"	"	"	"
15	THH2.35A	"	"	"	"	"
16	THH2.35B	"	"	"	"	"
17	THT.25A	"	"	"	"	"
18	THT.25B	"	"	"	"	"
19	THT.26A	"	"	"	"	"
20	THT.26B	"	"	"	"	---
21	THT2.15A	"	"	"	"	"
22	THT2.15B	"	"	"	"	"
23	THT3.0A	"	"	"	"	"
24	THT3.0B	"	"	"	"	"
25	TG1A.94	"	"	"	"	"
26	TG1B2.47	"	"	"	"	"
27	TG1C4.0	"	"	"	"	"
28	TG2A.94	"	"	"	"	"
29	TG2B2.47	"	"	"	"	"
30	TG2C4.0	"	"	"	"	"
31	TG3A.94	"	"	"	"	"
32	TG3B2.47	"	"	"	"	"

TABLE IV CONTINUED

Channel No.	Parameter	Sensitivity	Range	Instrument	Instrument	Operators Display
33	TG3C4.0	°C/mV	1VDC	3455	----	---
34	TG4A.94	"	"	"	"	"
35	TG4B2.47	"	"	"	"	"
36	TG4C4.0	"	"	"	"	"
37	TG5A.94	"	"	"	"	"
38	TG5B2.47	"	"	"	"	"
39	TG5C4.0	"	"	"	"	"
40	TG6A.94	"	"	"	"	"
41	TG6B2.47	"	"	"	"	"
42	TG6C4.0	"	"	"	"	"
43	T1NS1	"	"	"	"	"
44	T1NS2	"	"	"	"	"
45	T1NS3	"	"	"	"	"
46	T1NS4	"	"	"	"	"
47	TRG3.8A	"	"	"	"	"
48	TRG3.8B	"	"	"	"	"
49	TRG4.75A	"	"	"	"	"
50	TRG4.75B	"	"	"	"	"
51	TRG5.7A	"	"	"	"	"
52	TRG5.7B	"	"	"	"	"
53	TDGS9.5	"	"	"	"	"
54	TCUS6.2	"	"	"	"	"
55	TWS9.6	"	"	"	"	"
56	TPGS	"	"	"	"	"
57	TBS	"	"	"	"	"
58	------					
59	------					
60	DC Alternator Current	10A/V	.1VDC	3455	-----	Yes
61	DC Alternator Voltage	10V/V	10VDC	3455	-----	Yes
62	AC Alternator Current	10A/V	1VAC	3455	-----	Yes
63	AC Alternator Voltage	10V/V	10VAC	3455	-----	Yes
64	AC Input Voltage - S1	1V/V	10VAC	3455	-----	Yes*
65	AC Input Current - S1	10A/V	1VAC	3455	-----	Yes*
66	AC Input Voltage - S2	1V/V	10VAC	3455	-----	----
67	AC Input Current - S2	10A/V	1VAC	3455	-----	----
68	AC Input Voltage - S3	1V/V	10VAC	3455	-----	----
69	AC Input Current - S3	10A/V	1VAC	3455	-----	----

TABLE IV CONTINUED

Channel No.	Parameter	Sensitivity	Range	Instrument	Instrument	Operators Display
70	Engine Frequency	H2/H2	10^{-5}sec	Frequency Counter	------	Yes
71	Coolant Flow Rate	H2/H2	1KHZ	Frequency Counter	------	Yes
72	Lbs. Displacer Position	--------	-----	Phasemeter Sig	------	----
73	AC Working Space Pres	--------	-----	Phasemeter Sig	------	----
74	Stator Force	--------	-----	"	------	----
75	AC Coil Current	--------	-----	"	------	----
76	AC Working Space Pres	10 Bar/V	1VAC	Power Multiplier	3455	----
77	AC Piston Gas Spring Pres	10 Bar/V	1VAC	"	"	----
78	AC Displacer Gas Spring Pressure	10 Bar/V	1VAC	"	"	----
79	AC Alternator Volts-Inap	--------	----	---------	------	----
Display	Input Power					Yes
	ΔP (Bearing Discharge-Bounce Pressure)					Yes

Figure 20 Data Reduction Flow Chart

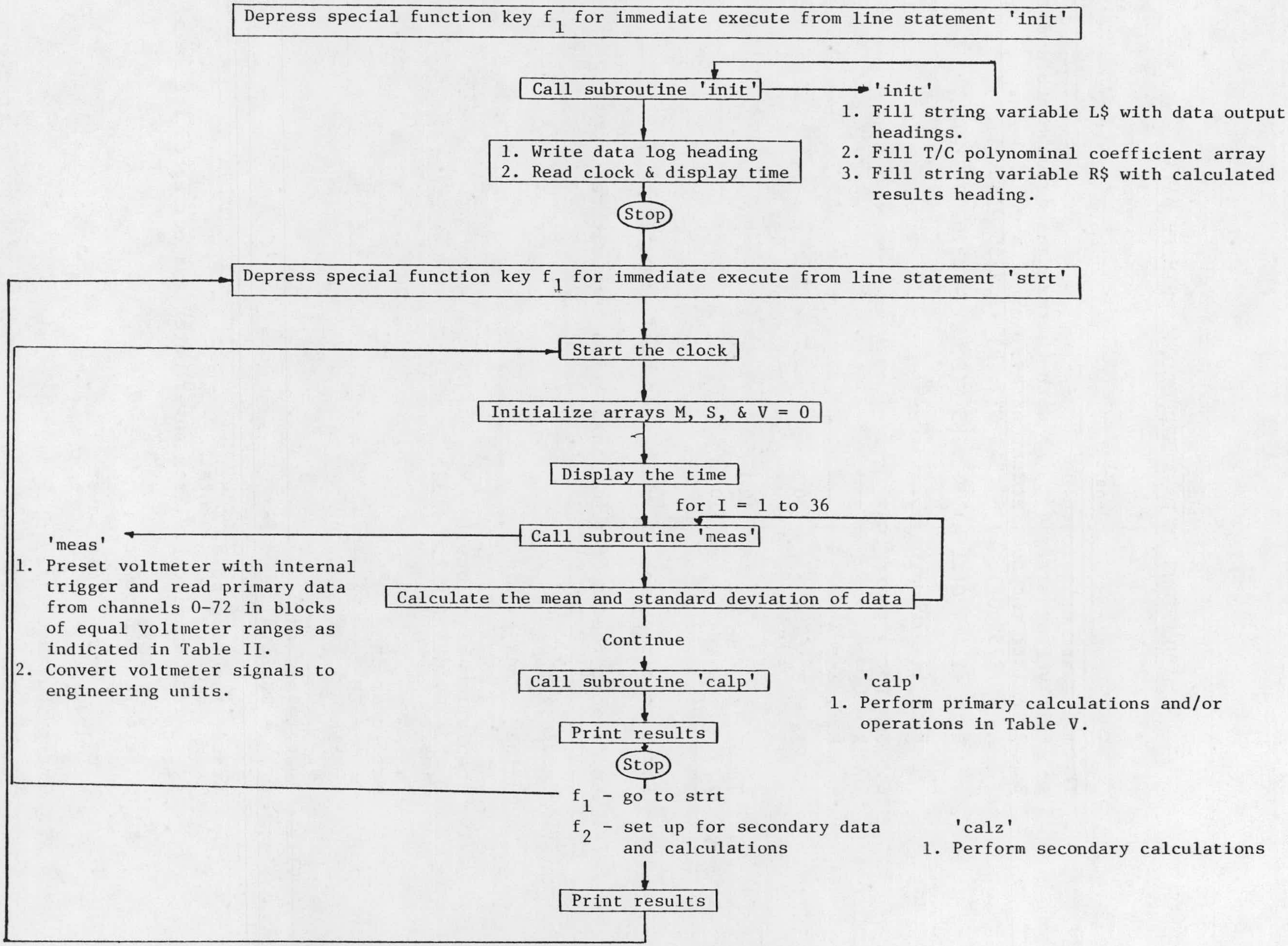


TABLE V

CALCULATIONS IN DATA REDUCTION (PRIMARY DATA)

I. Thermal guard heat loss

A. Fill vector array G(i, k) with thermal guard temperature data

B. Calculate the coefficient arrays A & B, x = 0

$A_i = .2755\ G(1, k) - .549\ G(2, k) + .2735\ G(3, k)$

$B_i = -1.114\ G(1, k) + 1.485\ G(2, k) - .3707\ G(3,k)$

$R_i = (.45108\ A_i + B_i)\ (-.0224)$

C. Sum total guard loss

$X = 0$

$R_i + X = X$

$\Sigma x = R_{TOT}$

II. Total input power

A. $Q_{TOT} = \Sigma V_i I_i$

III. Enter sort routine for max heater head temperature

IV. Enter sort routine for min insulation temperature

V. Insulation ΔT

$\Delta t_{ins} = T_{max} - T_{min}$

VI. Insulation heat loss

$Q_{ins} = -.1625\ (\Delta t\ 1.8 + 32)$

VII. Net power in

$Q_{net} = \Sigma V_i I_i + \Sigma x + Q_{ins}$

VIII. Heat rejection

$Q_{clt} = \dot{m} c_p\ \Delta t_{cooler}$

IX. Stator reaction power Q_{stat}

Q_{stat} read in directly from power meter and corrected for gain

X. Alternator I^2R power

$V_{rms_{load}}\ I_{rms} = Q_{clt}$ power

XI. Energy balance

$Q_{net} - Q_{clt} - Q_{stat} = \varepsilon$

XII. Engine efficiency based on heat input

$$\eta_{HTR} = \frac{Q_{stat}}{Q_{net}}$$

TABLE V CONTINUED

XIII. Engine efficiency based on heat rejection

$$\eta_{alt} = \frac{Q_{stat}}{Q_{stat} + Q_{clt}}$$

XIV. Enter sum routine for average heater temperature

$$T_{avg} = \frac{\Sigma T_{Heat}}{N}$$

XV. Alternator efficiency

$$\eta_{alt} = \frac{Q_{alt_{real}}}{Q_{stat}}$$

XVI. System efficiency based on heat rejection

$$\eta_{sys} = \frac{Q_{alt_{real}}}{Q_{alt_{real}} + Q_{clt}}$$

XVII. System efficiency based on heat input

$$\eta_{sys} = \frac{Q_{alt_{real}}}{Q_{net}}$$

XVIII. Average cooler temperature

$$T_{cool\ in} + \frac{\Delta t_{clt}}{2} = T_{cool\ avg}$$

XIX. Load resistance

$$R = \frac{V_{rms}}{I_{rms}}$$

XX. Piston gas spring

$$K_p = 617.53\ P_{pgs}$$

XXI. Displacer gas spring

$$K_d = 90.596\ P_{dgs}$$

XXII. Piston thermal loss

$$Q_{pt} = 3.9 \sqrt{((T_{pgs}\ 1.8 + 32) + 460)\ f\ P_{pgs}}\ .033\ X_p^{\,2}$$

XXIII. Displacer thermal loss

$$Q_{dt} = .84 \sqrt{((T_{dgs}\ 1.8 + 32) + 460)\ f\ P_{dgs}}\ .056\ X_D^{\,2}$$

TABLE VI

CALCULATIONS IN DATA REDUCTION (SECONDARY DATA)

I. Alternator reactive power

$$\alpha = \frac{\pi}{2} - K$$

K - current phase with piston

II. Alternator power factor

$$P_f = \cos \alpha$$

III. Alternator apparent power

$$P_{app} = \frac{P_{real}}{P_f}$$

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