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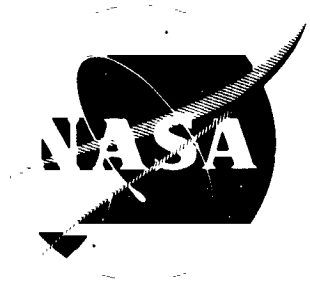

FLOW METER AND PROTOTYPE MERCURY FEED SYSTEM DEVELOPMENT

by

G. E. TRUMP

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

May 10, 1967

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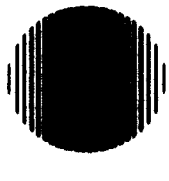

ELECTRO-OPTICAL SYSTEMS, INC.

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EOS 6969-Summary

SUMMARY REPORT

FLOW METER AND PROTOTYPE MERCURY FEED SYSTEM DEVELOPMENT

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February 25, 1967

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ABSTRACT

Work performed on a research and development program for mercury propellant feed systems and a mercury flow meter is reported. The development of laboratory model and prototype model feed systems and a laboratory control system is described. A novel flow meter which determines flow rate by measuring the thermal conductivity of mercury vapor has been developed. It was used to measure and control the flow rate during extended life tests of both the laboratory and prototype model propellant systems.

SUMMARY

This report describes work performed during the period 14 June 1965 to 5 February 1967 under Contract NAS3-7116. The objectives of the program were to develop a mercury propellant feed system which can serve as a prototype of a future flight rated system. The system is to deliver a controlled supply of mercury vapor to an ion engine.

A mercury propellant feed system utilizing positive pressure feed and porous metal phase separators was developed. A laboratory model was sucessfully tested for 1000 hours continuous operation. It had a capacity of 45 lbs mercury and utilized a stainless steel vaporizer with a porous stainless steel phase separator.

A prototype propellant system was developed from the basis design of the laboratory model. It had a slightly smaller propellant capacity and incorporated two important improvements: (1) small lightweight filling and pressurizing valves, and (2) a tantalum vaporizer with a porous tungsten phase separator. The prototype model was sucessfully tested for 1000 hours at a mercury vapor flow rate of 0.8 mg/sec. During this test the vaporizer operated at 200°C with an input power of approximately 6.1 watts.

A control system matched to the requirements of the laboratory and prototype propellant systems and the mercury vapor flow meter was developed. It was used in the long duration tests of the propellant systems where it proved to be reliable.

A novel flow meter which determines flow rate by measuring the thermal conductivity of mercury vapor was also developed. It was used as the flow rate sensor during the 1000 hour tests of both propellant systems.

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1. INTRODUCTION

This is the summary report on Contract NAS3-7116, Flow Meter and Prototype Mercury Feed System Development. It was a program to develop mercury feed systems and flow meters, demonstrate their performance through extended life tests, and deliver to NASA-LeRC similar units which will be compatible with the mercury thrustors under development there.

1.1 Contributors

Principal participants in the program and their respective areas of effort were:

F. A. Barcatta	Program Management
G. E. Trump	Feed System and Flow Meter Development
A. M. Schneider	Control Systems
S. Zafran	Quality Assurance

Other technical and engineering personnel who contributed to the program are S. R. King, J. T. Doyle, G. D. Seele, and A. N. Kosky.

1.2 Description of Program

The work described in this report was performed during the period 14 June 1965 to 5 February 1967. Major effort during the first 6 months of the program was on development of a laboratory model propellant system and a flow meter. During the second 6 months emphasis was on long duration system testing and the fabrication and testing of deliverable systems. The last portion of the program was devoted to the development and long duration testing of a prototype propellant system and the fabrication and functional testing of deliverable units.

During the first 6 months a majority of the development work was completed on the laboratory model feed system and a series of preliminary evaluation tests completed. Flow meter development during this time consisted of the fabrication and testing of a preliminary unit to determine feasibility followed by the fabrication of one flow meter for further evaluation.

During the second 6 month period, four laboratory model feed systems were fabricated. Three of these including their control systems were functionally tested and delivered. The remaining unit was retained for further testing. Two complete flow meter systems were fabricated and functionally tested. A 1000 hour life test of the laboratory feed system and a flow meter were successfully completed.

During the last 8 months of the contract, seven prototype feed systems were fabricated. One of these was successfully tested for 1000 hours. The other six units were functionally tested and delivered together with the two flow meter systems.

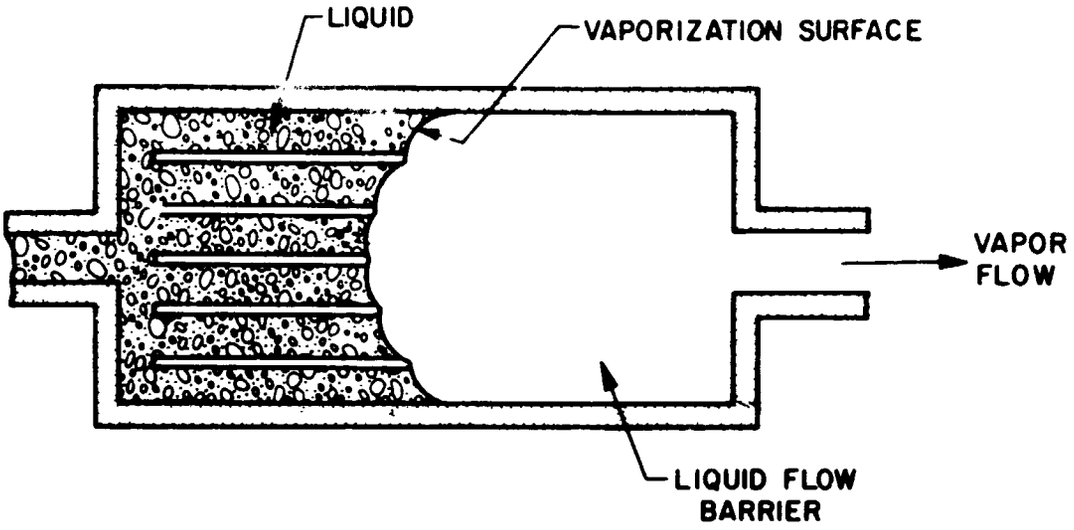
2. LABORATORY FEED SYSTEM DEVELOPMENT

Development of the laboratory model mercury feed system and its associated control system is described in this section. The design requirements and the general approach taken are described first. This is followed by a description of the developed hardware and finally by a discussion of some component development tests that were performed. Results of system tests are described in Section 4.

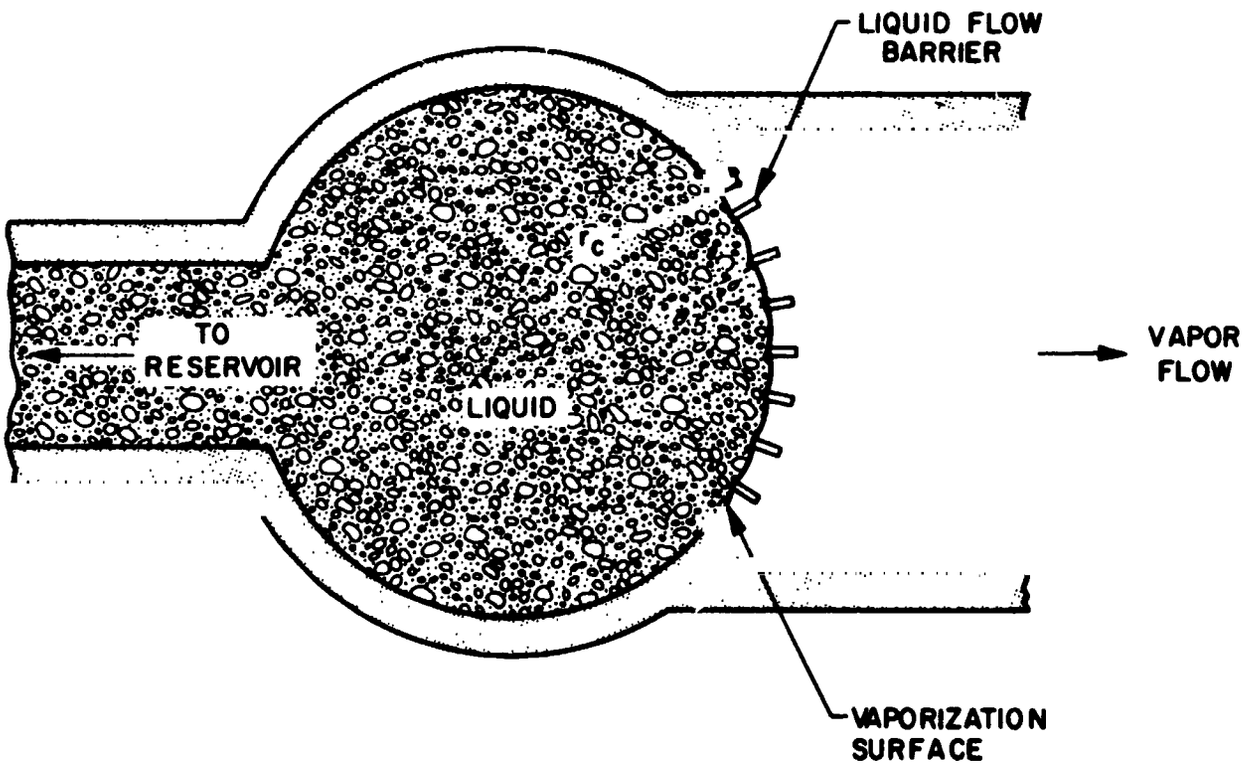
2.1 Design Requirements and General Approach

The specifications and goals of the laboratory feed system are that it provide a controlled flow of mercury vapor, be capable of operation under zero-gravity conditions, and be operated by an automatic control system. Required capacity is 45 pounds and the system should be capable of expelling 95 percent of the initial load. Flow rates controllable to an accuracy of ± 1 percent over the range from 2×10^{-4} grams per second to 2×10^{-3} grams per second are required. A life test demonstration of one unit for a minimum of 1000 hours in a vacuum environment of 1×10^{-6} torr is required. Three other units are to be fabricated, functionally tested and deliver to NASA-LeRC. Included with these units are their automatic control systems.

The general approach to the problem was to choose a mode of operation and control very similar to that which had been used so successfully in the past at this laboratory on cesium systems. This involves storing the propellant in liquid form and then maintaining liquid-vapor interfaces that are stable under both the one-g field of the laboratory and the near zero-g conditions of space. This is accomplished by providing a barrier to liquid flow between the stored liquid and the feed line to the engine. Figure 1 depicts the vaporizer region for a wetting liquid like cesium and a non-wetting liquid like



(a.) WETTING LIQUID



(b.) NON-WETTING LIQUID

Figure 1. Schematic of Vaporizer Region

mercury. In both cases surface tension forces are utilized to prevent liquid flow beyond the vaporization surface. For the case of interest here, the non-wetting case, the relation

$$\Delta P = \frac{2\sigma}{r} \qquad (1)$$

can be used to approximate the barrier cell size that is required. Here, ΔP is the pressure drop across a spherically shaped meniscus having a radius r and σ is the surface tension. If the cell radius, r_c in Fig. 1 , is chosen such that the calculated ΔP, using this radius, is greater than the upstream pressure of the liquid, extrusion of the liquid through the barrier is prevented. As an example, consider a typical case where the upstream pressure is 30 psi. This yields a required cell radius smaller than 4.55 microns. This calculated cell size is based on the assumption of uniform cylindrical cells in the barrier. However, to achieve such small cell size in actual practice, one normally turns to porous metals as a barrier material. Because the cell (pore) geometry is not well-defined, pore size calculations can only be used as a guide in the initial selection of the barrier material.

Evolution of vapor from the vaporization surface is accomplished by heating the immediate area by attaching a sheathed heater around the feed tube in the vicinity of the vaporizer. Control of the flow rate is accomplished simply by varying the power to the heater. This method of flow control lends itself quite readily to a closed-loop mode of operation where the ion beam current of the output of a flow meter, for example, is fed back through a simple control system to control the power to the vaporizer. Flow control in this manner has been shown to control the flow rate to within one percent.

The method chosen for liquid storage and delivery consists simply of storing the mercury in a spherical storage chamber containing a hemispherical elastomer diaphragm. Gas pressure applied behind the diaphragm forces the mercury from the reservoir as it is consumed. This method of storage provides positive assurance of propellant delivery independent of the external gravitational environment.

2.2 Hardware Description

The development of the feed system and its control system progressed through the development period with no major design changes or significant modifications. A description of the laboratory feed system and its control system follows.

Laboratory Feed System

An overall view of the laboratory feed system is shown in Fig. 2. Its components start at the left with a pressure chamber which is loaded at the beginning of a test with a preset pressure of dry nitrogen or argon gas. This gas acts through holes in the diaphragm support hemisphere on the elastomer diaphragm. Mercury is loaded into the reservoir through the reservoir fill valve. Mercury capacity is approximately 50 pounds. The vaporizer section is attached to the front end of the reservoir using an O-ring to provide a leak tight seal. A thermally actuated valve was originally considered as part of the vaporizer section. Its purpose was to prevent leakage of air into the reservoir prior to installation in the vacuum system. This valve was discarded in favor of an alternate approach to the problem which is to pressurize the reservoir to a pressure such that, at any time and under any fill conditions, the internal pressure will always be greater than one atmosphere. Since the pressure chamber volume was chosen equal to the reservoir volume, an initial pressurization in excess of two atmospheres is normally required.

A majority of the feed system is fabricated of 347 stainless steel in an all welded construction. A butyl rubber compound was chosen for the diaphragm because of the low gas permeability characteristics of this material. An O-ring is molded into the diaphgram to provide a seal between the reservoir halves. Also molded to the diaphragm are a series of ribs which act as passageways to prevent entrapment of mercury within the reservoir.

A photograph of the components of the reservoir appears in Fig. 3. An assembled unit is shown in Fig. 4.

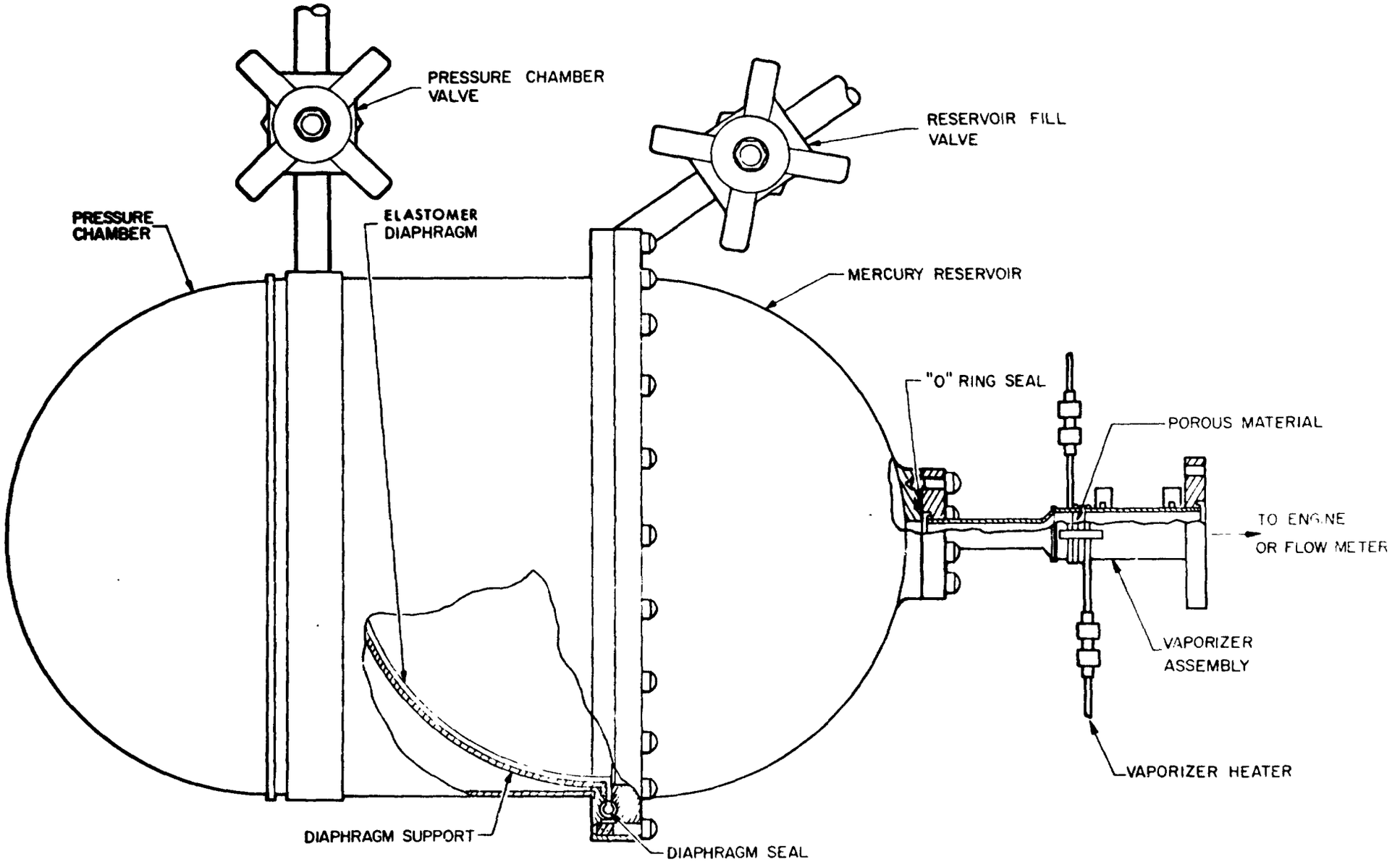


Figure 2. Laboratory H_g Feed System

Figure 3. Laboratory Feed System — Disassembled

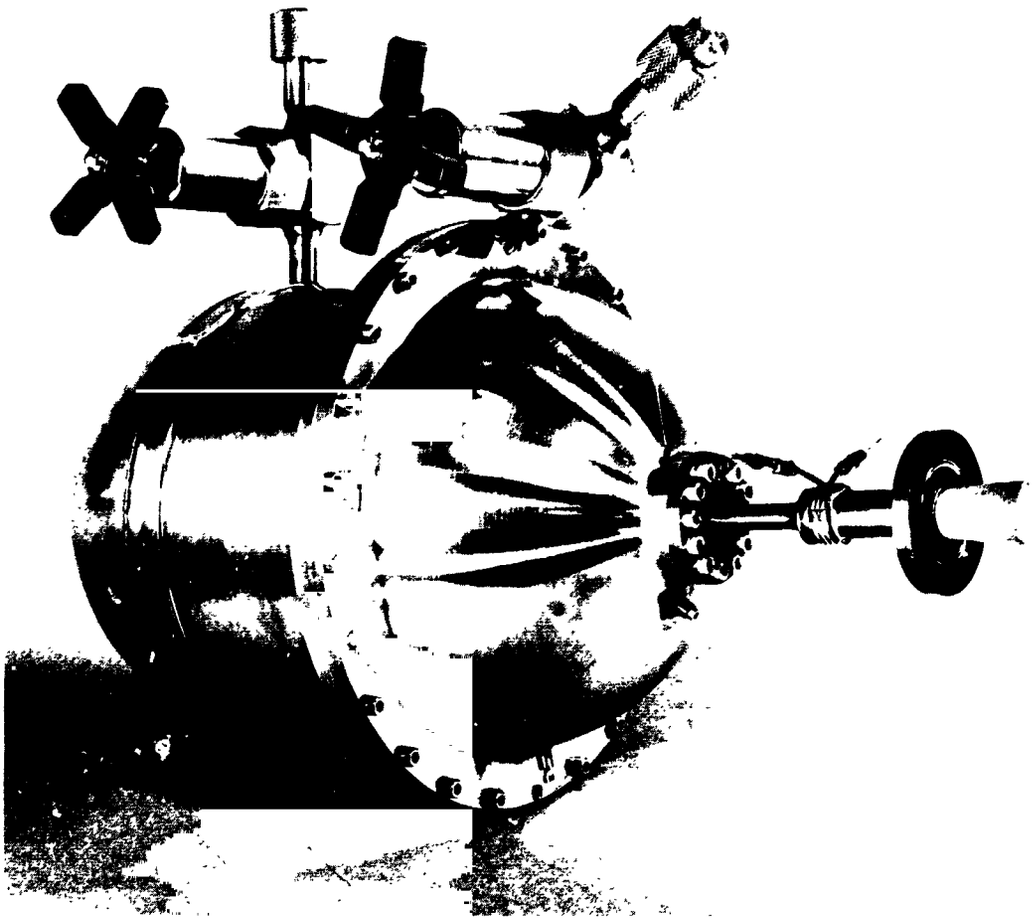


Figure 4. Laboratory Feed System – Assembled

Control System

Design of the feed control system followed very closely the basic design of similar units already in use at this laboratory. This was possible because the method used for flow rate control, control of the power to a sheathed heater on the vaporizer, is used on a majority of the feed systems now operating at this laboratory. This method of control has been found to be reliable and to control the flow rate to within one percent.

The basic control system is quite simple. A block diagram of the system is depicted in Fig. 5. Input from the flow rate sensor (flow meter, ion beam current or other source) is compared with the reference voltage at the input of the operational amplifier. If a difference exists between the two signals, an error signal appears at the output of the operational amplifier and drives the power controller to either increase or decrease the average power delivered to the vaporizer heater. An increase in flow rate above the reference setting would cause the vaporizer power to be reduced and conversely a low flow would cause a power increase. How closely the flow rate signal and reference signal coincide during steady-state operation is determined by the gain of the system. A high gain system as normally used forces the two signals to be quite close together. Essentially this means that the flow rate cannot depart to any great degree from the set point without experiencing a large corrective action. In practice the maximum usable gain is determined by stability considerations.

A full schematic of the laboratory feed control system is shown in Fig. 6. The flow rate signal is injected at the input of the operational amplifier, UPA-2, at terminal TB 101-3 and is compared there with the reference voltage. Reference voltage level is controlled by the ten-turn potentiometer R 104. The output of the operational amplifier drives one control element of the Robicon AC Power Controller. Output of the power controller is coupled to the vaporizer heater through a step-down transformer which reduces the vaporizer input voltage to a usable level and provides the necessary high voltage isolation for

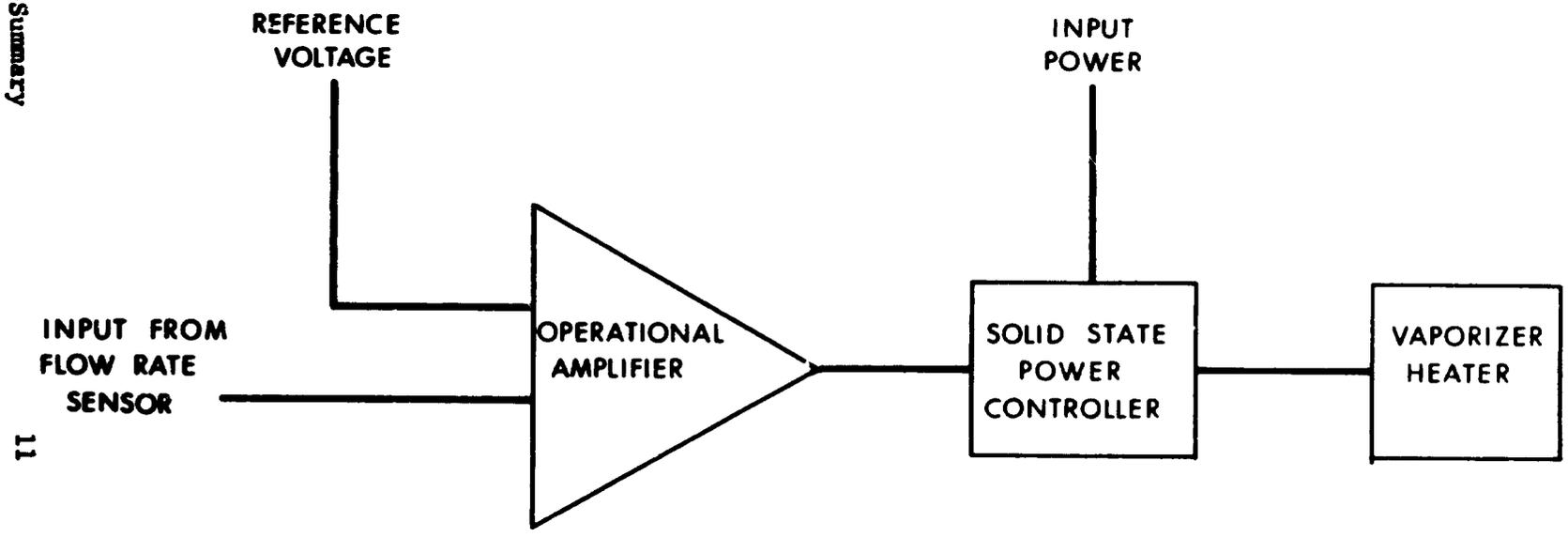


Figure 5. Feed Control System — Block Diagram

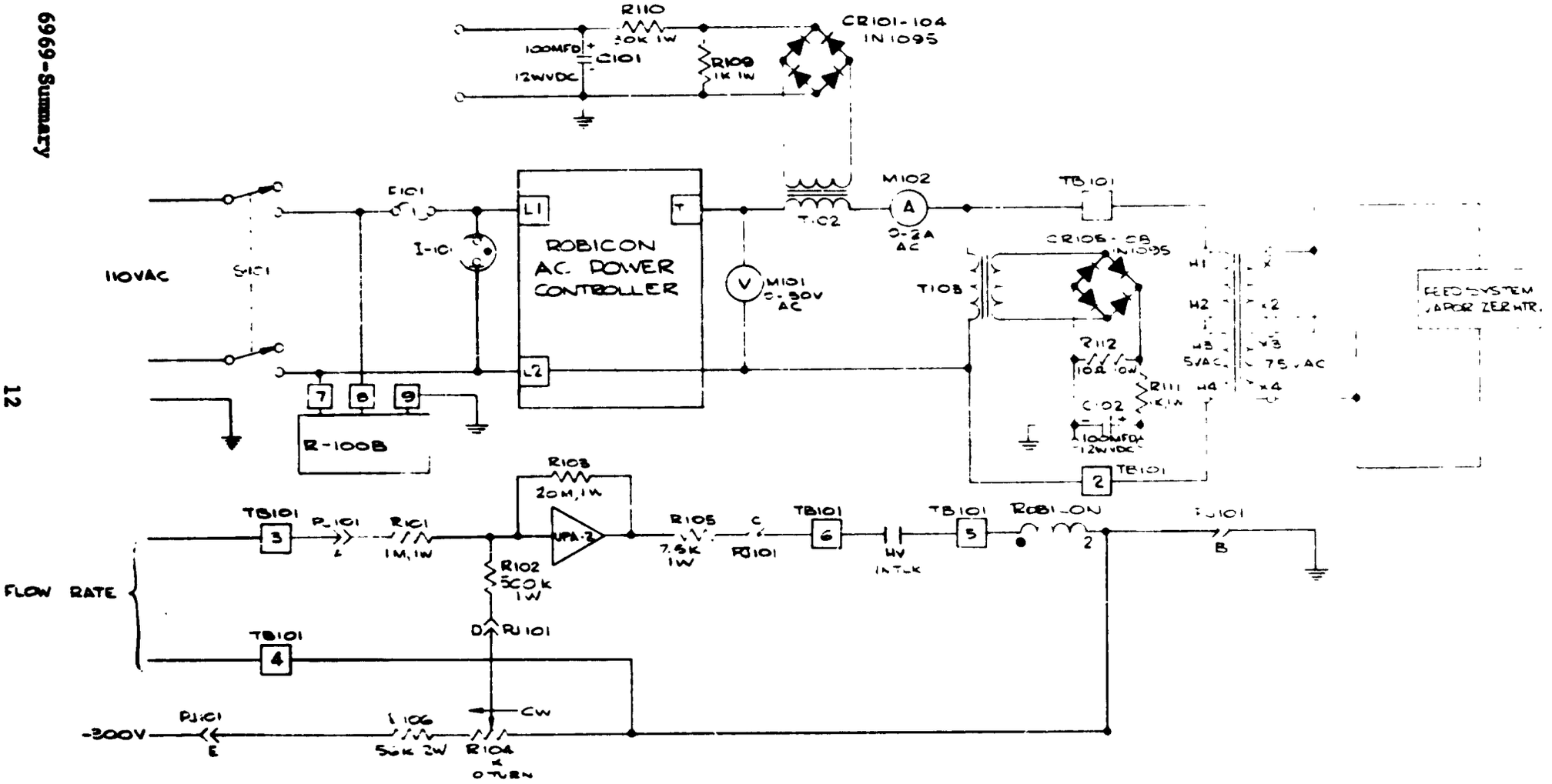


Figure 6. Laboratory Feed Control System Schematic

operation with an ion engine The operational amplifier has provisions which allow the use of various feed back elements to control gain or provide compensation to insure loop stability.

Additional provisions include full wave rectifiers coupled to the output circuit through current and voltage transformers T 102 and T 103, respectively, to provide dc output voltages proportional to vaporizer current and voltage. These are used to monitor and record power levels to the vaporizer. One other provision makes it possible to shut-off power to the vaporizer in the event of unstable engine operation. This is accomplished by inserting a relay contact at terminals TB 101-5 and TB 101-6. Opening of the circuit at this point reduces power to the vaporizer to zero.

A photograph of the completed unit is shown in Fig. 7 . Three of these units have been assembled and delivered. Check-out and functional testing was completed prior to their delivery. One additional breadboard unit, electrically similar to those just described, was fabricated early in the program. It has been used for system testing and was utilized in the 1000 hour tests of the laboratory and prototype feed systems.

2.3 Component Tests

Several tests were conducted to evaluate various components of the laboratory feed system. Three component areas were of major concern during the development period. These are: the vaporizer area and in particular its construction and the type and pore size of material that should be used for the porous plug, the diaphragm and its ability to properly expel the mercury propellant and the type of seals that should be used in the system.

Three vaporizer configurations have been tested. The first two configurations tested were of stainless steel and varied primarily in the manner in which the porous material was installed. The first configuration had a shoulder machined into the vaporizer tube to position the porous plug. The plug was held in place by a snap ring arrangement. The second configuration utilized a straight tube. In this modification

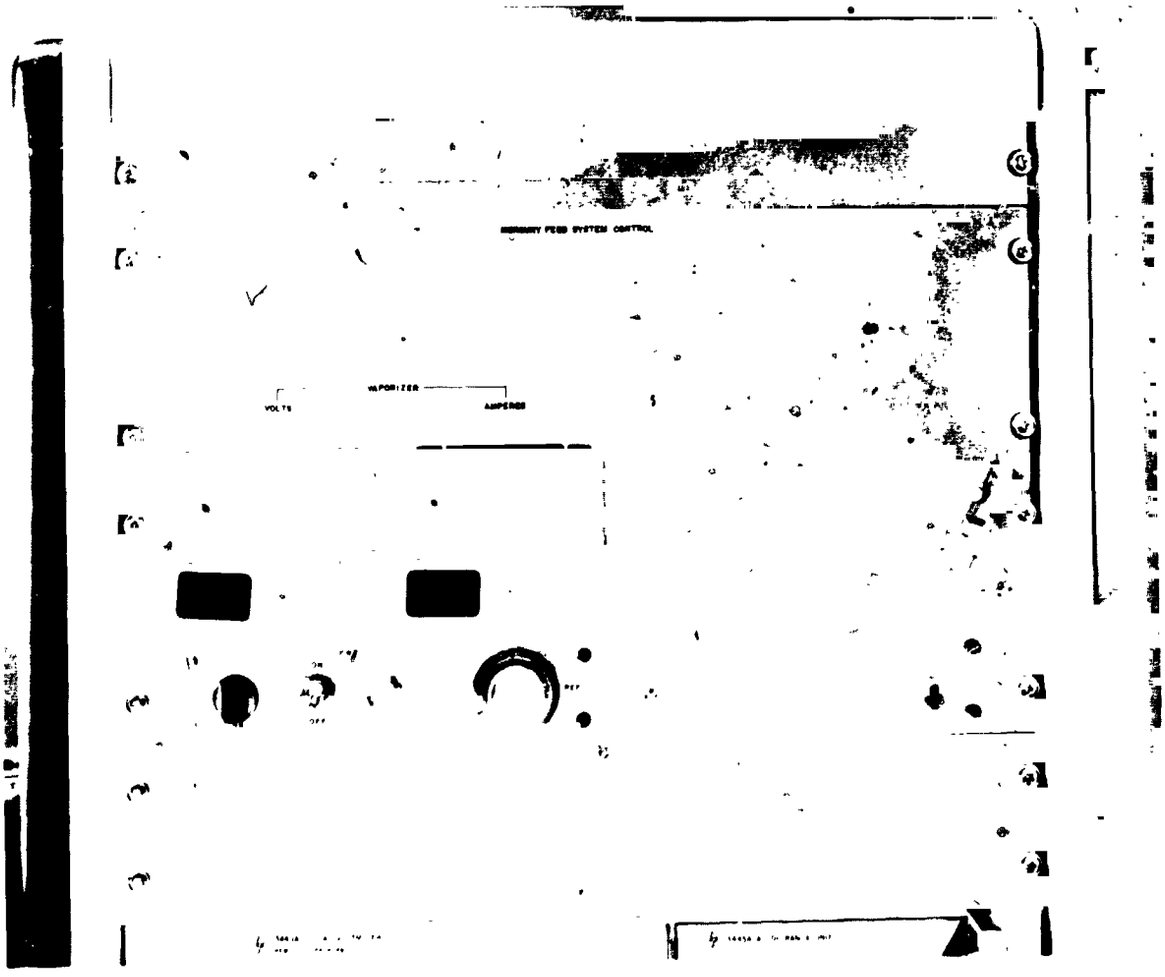


Figure 7. Laboratory Feed Control System

the porous material was actually formed in place within the tube and yielded the most successful of the stainless steel units. This configuration was used in the 1000 hour life test and on the deliverable units.

The third configuration employed a molybdenum tube, vapor plated around a porous tungsten disc. Since it is desirable to minimize heat transfer from the vaporizer downstream flange back to the porous plug, and from the porous plug back to the main body of the reservoir, stainless steel is the logical choice for the vaporizer body. However, the choice of tungsten for the porous meterial of the third unit dictated that a material, molybdenum in this case, with a low expansion coefficient be used for the vaporizer tube. In order to help minimize thermal conduction in this unit the tube diameter was reduced from 1/2 inch to 3/8 inch.

Preliminary tests of the tungsten unit were not particularly encouraging. High heat transfer rates away from the vaporizer plug necessitated the use of excessive amounts of power to achieve design flow rates. In one test a thermally isolating section fabricated of thin wall stainless steel tubing was inserted between the vaporizer and the reservoir. This reduced the heat transfer back to the reservoir to the point where it was possible to achieve the maximum flow rate with less than 50 watts. However, the heat conducted to the flow meter was still excessive, forcing the flow meter temperature above the control temperature of 200°C. This type of tungsten vaporizer was discarded in favor of the unit developed for the prototype feed system described in Section 5.

Typical performance of various vaporizers is shown in Fig. 8 and Fig. 9. Figure 8 shows vaporizer temperature versus mass flow rate for four stainless steel units and the tungsten unit. Figure 9 shows the power requirements of these same five units.

Of greatest importance in the selection of porous materials, aside from mercury compatibility consideration, is their ability to withstand the reservoir pressure and prevent extrusion of liquid mercury into the vapor feed tube. Original concepts were to use

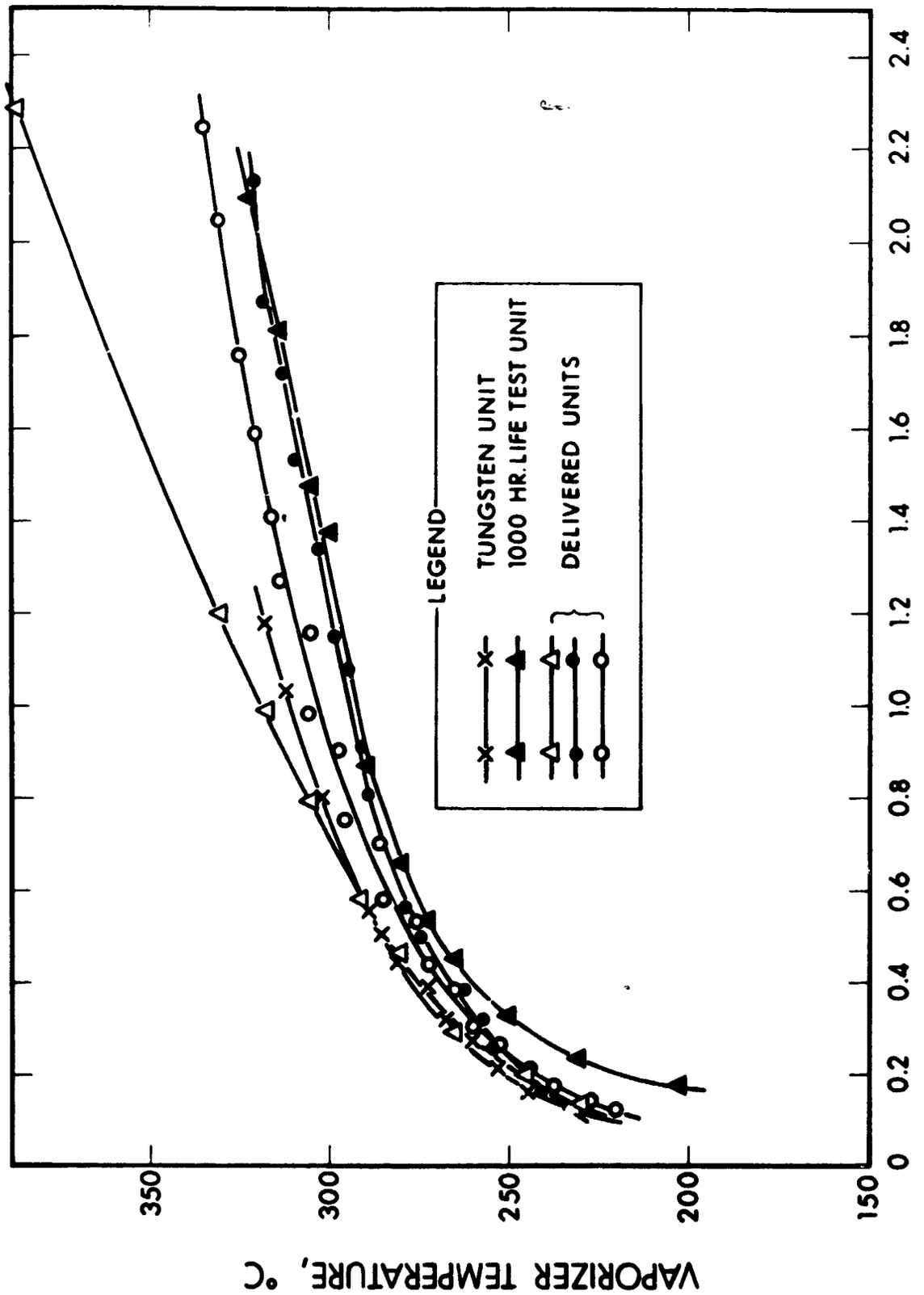


Figure 8. Vaporizer Temperature versus Mass Flow Rate

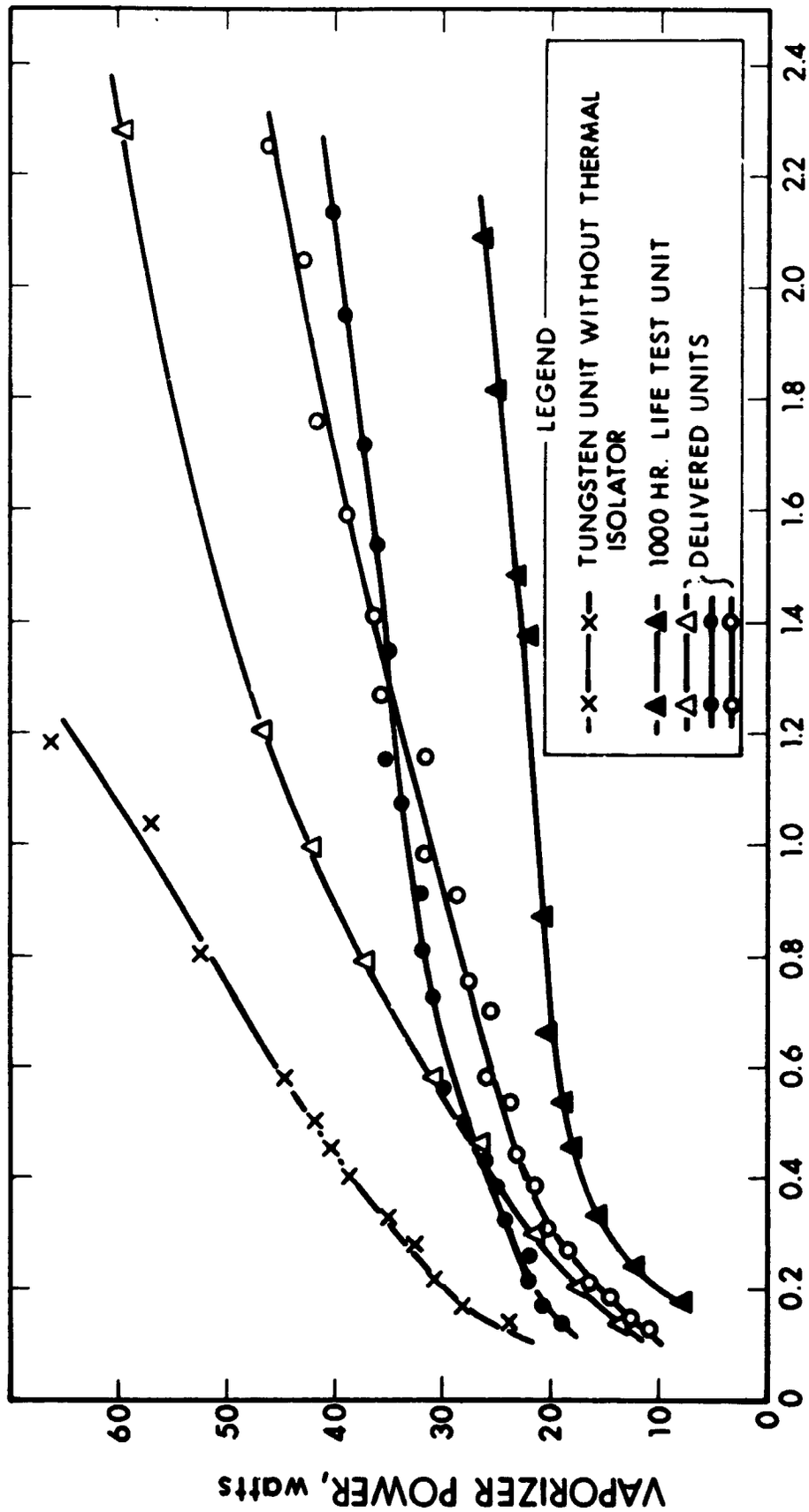


Figure 9. Vaporizer Power versus Mass Flow Rate

relatively large pore material and low reservoir pressure. However, deletion of the valve upstream of the vaporizer required that higher reservoir pressure (in excess of 30 psi) be used. This necessitated a series of extrusion tests to evaluate various grades of porous stainless steel.

The tests were performed by putting a small quantity of mercury above the porous disc and gradually increasing the gas pressure above the mercury until extrusion of mercury through the disc was observed.

The material tested was obtained from Asco Sintering Co. in five grades. The grade designation in this case is an indication of the size particles that the material will filter. The results of the tests are shown graphically in Fig. 10. Also shown is the calculated pressure that would be required to force mercury through a circular pore. Here the grade number was used as the pore radius in microns. Configuration number 9, as shown in Fig. 10, was finally arrived at. It was used in the life test and for the deliverable systems. Although not shown in Fig. 10, all of the tungsten units had extrusion pressures greater than 40 psi.

Evaluation of diaphragm folding characteristics and expulsion ability was carried out in a series of tests using a Lucite model fabricated to the same dimensions as the actual feed system hardware. Several diaphragms were fabricated for preliminary testing. These diaphragms were of two different Shore hardnesses, with and without, various fabric backings. Four diaphragms were first tested to determine the pressure difference that is required to force the diaphragm from one extreme to the other in the reservoir. These diaphragms had a Shore hardness of 45 and 60, with and without, a fabric backing. The maximum pressure required was approximately 10 torr which is small compared to the pressure required for operation of the feed system in the laboratory.

The 60 Shore hardness diaphragm (without fabric backing) was then used to determine the folding and expelling characteristics of the diaphragm. Approximately 40 pounds of mercury were loaded into

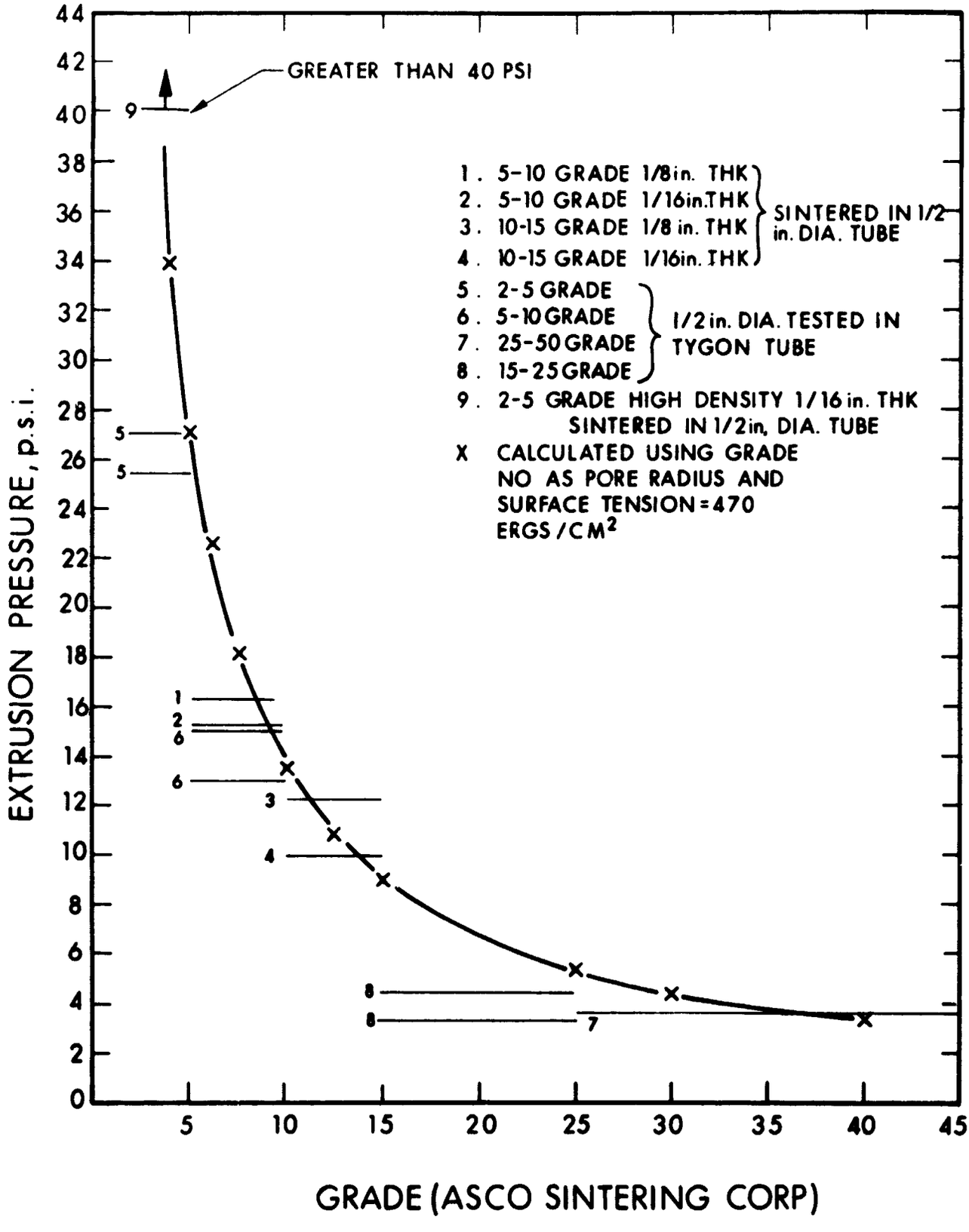


Figure 10. Extrusion Pressure versus Pore Size

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the reservoir model. The diaphragm was pressurized and photographs (Figs. 11-14) were taken with various quantities of mercury in the reservoir. For a particular quantity of mercury the pressure differential was adjusted to the value that the pressure chamber would supply during actual operation of the feed system. The pressure for these tests was varied from 5.05 psig to 3.25 psig as the mercury quantity went from 40 pounds to 0.

The pictures clearly showed the diaphragm folding and the ribs acting as expected. There is considerable "droop" to the diaphragm due to the weight of the mercury, but stretching was not evident. When the quantity of mercury had dropped to 30 pounds (Fig. 11), the diaphragm started to press against the front wall of the container at the top. As the quantity dropped further the ribs started to be seen and the amount of mercury between ribs decreased. The last picture taken (Fig. 12) showed the mercury almost completely expelled with the area along the sides of the ribs acting as canals for the remaining mercury. Figures 13 and 14 show a rear view of the diaphragm at 40 pounds and 20 pounds, respectively. As a result of these tests, the 60 Shore hardness diaphragm without fabric backing was chosen for general use.

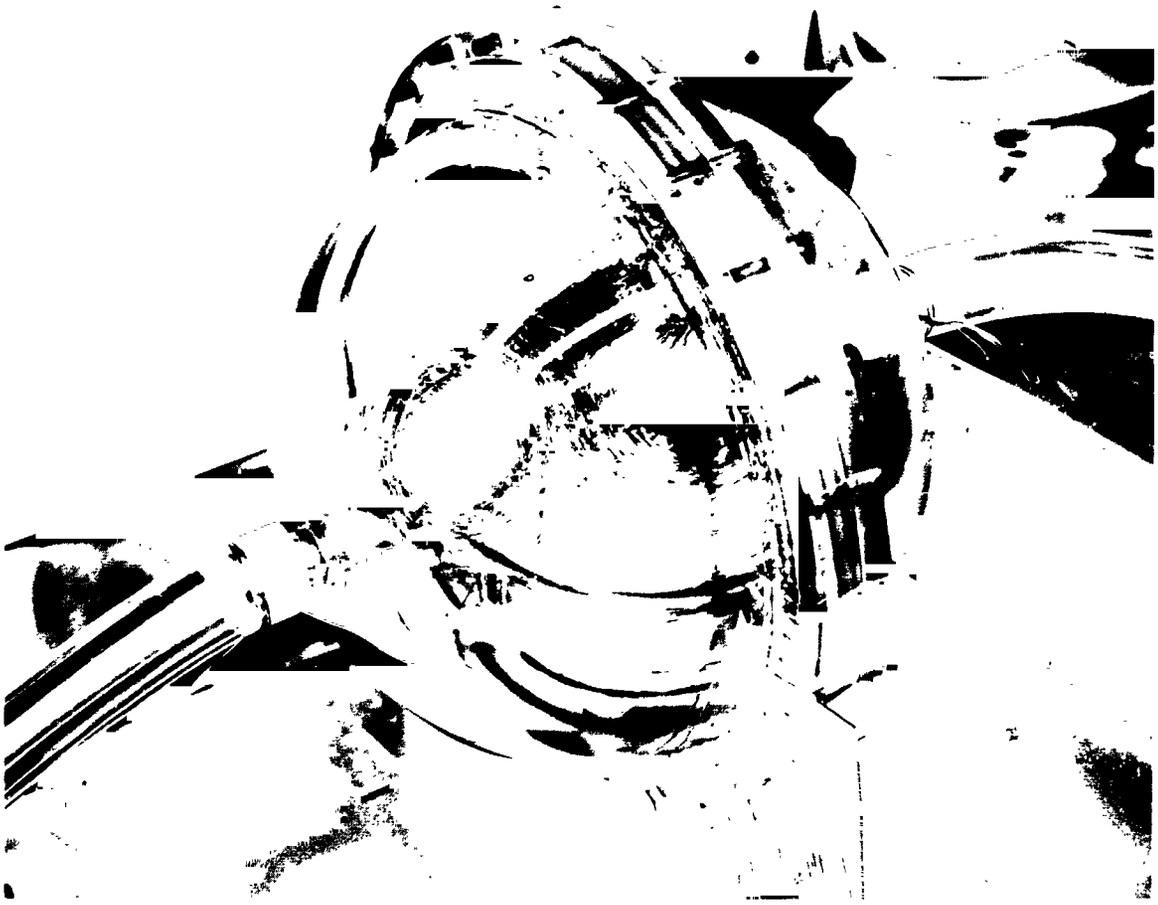

Figure 11. Diaphragm Expulsion Test — Front View at 30 Pounds

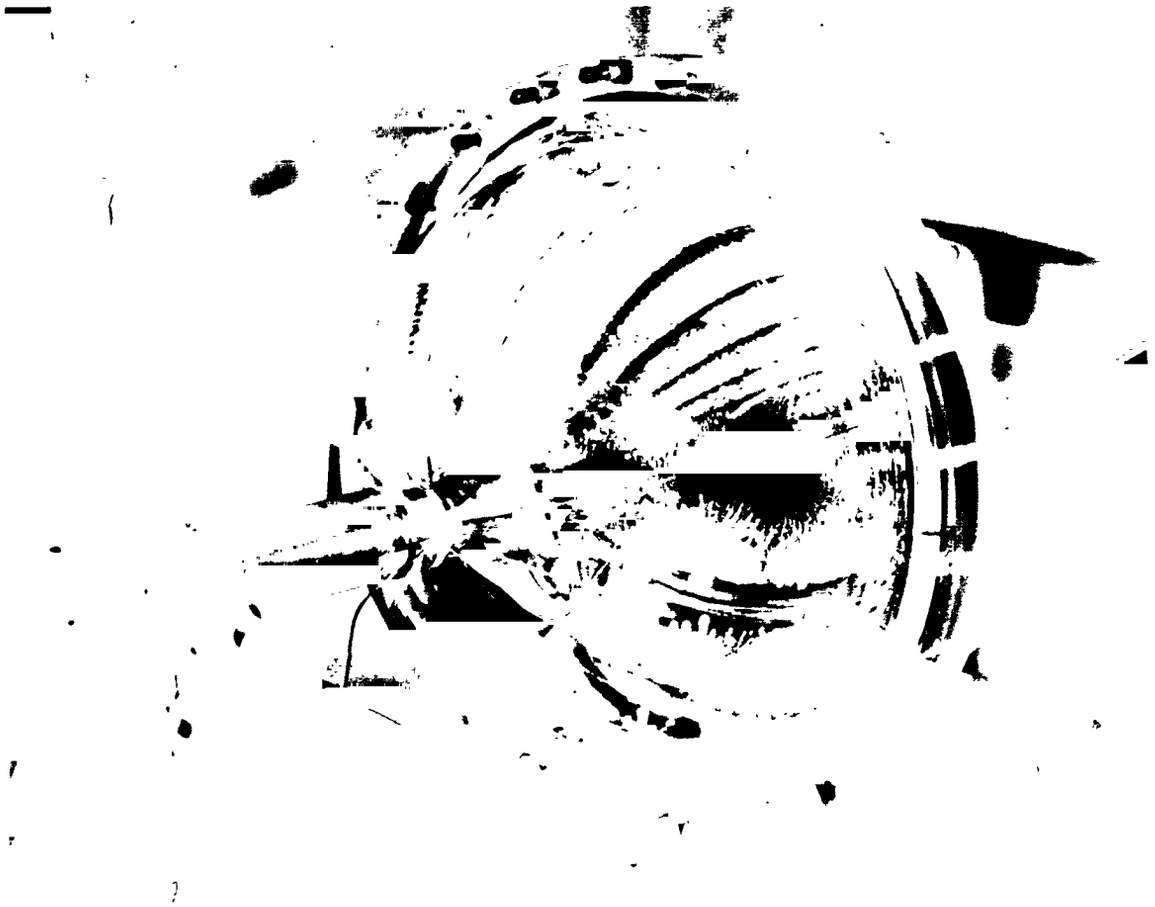

Figure 12. Diaphragm Expulsion Test - Front View Nearly Empty

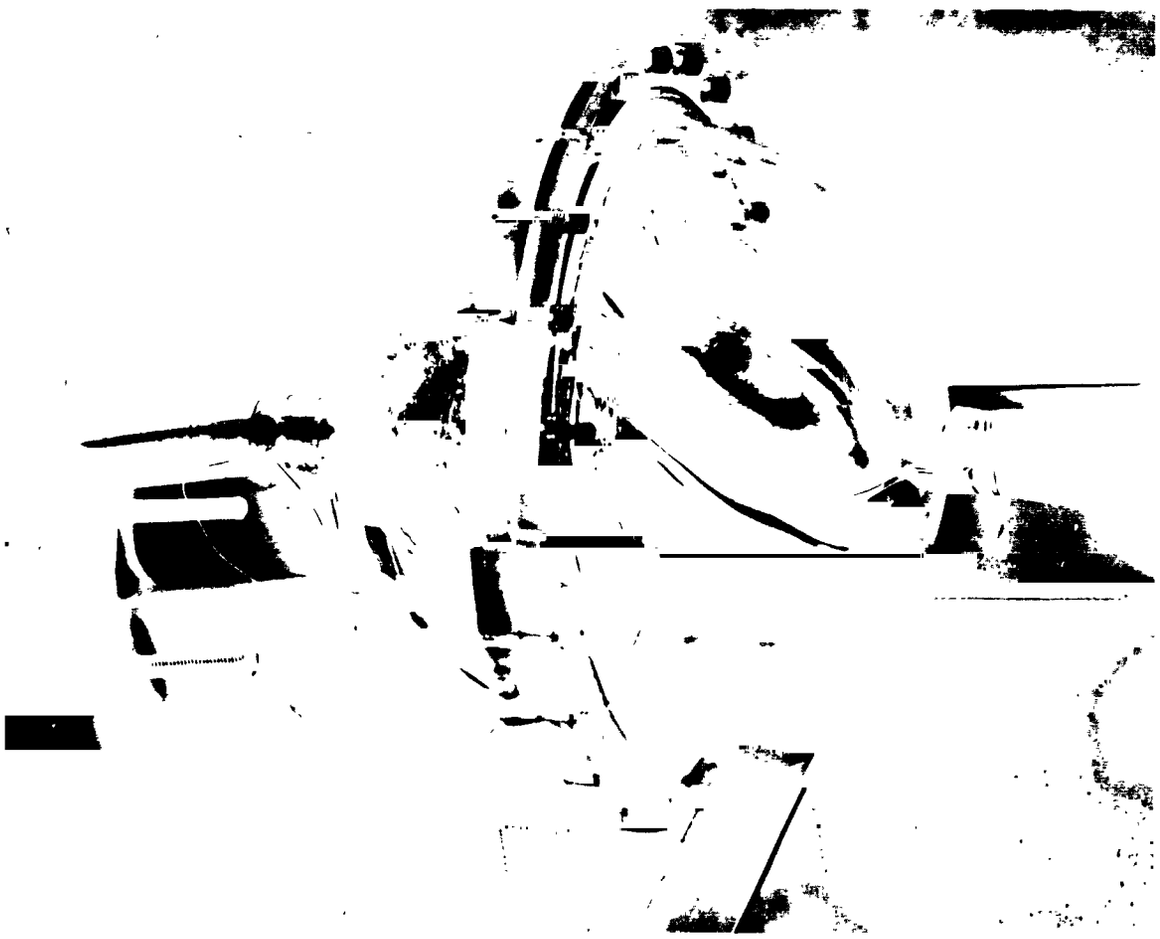

Figure 13. Diaphragm Expulsion Test - Rear View .) Pounds

Figure 14. Diaphragm Expulsion Test - Rear View at 20 Pounds

3. FLOW METER DEVELOPMENT

Development of a mercury flow meter and its associated control and measuring circuitry is described. The design requirements and general approach taken is discussed first, followed by the theory of operation and the results of preliminary feasibility tests of the concept finally chosen. A description of the developed hardware follows. System tests in which the flow meter is involved are discussed in the next section.

3.1 Design Requirements and General Approach

The basic requirements of the flow meter are that it have the capability of measuring and recording mercury vapor flow from 1×10^{-4} to 2×10^{-3} grams per second with an accuracy goal of ± 1 percent, and that it be compatible with the mercury feed systems to be developed on the program. Further, a dc output voltage corresponding to the flow rate and varying between zero and five volts over the flow rate range is to be provided. Compatibility with the mercury thrustors under development at NASA-LeRC is required. In addition, the flow meter is to be used with the feed systems in life tests and consequently should exhibit excellent reliability.

Many methods of flow measurement exist, and any one of a number of these could be utilized. However, the very low flow rates combined with the high accuracy goal tend to eliminate all but a few methods. Compatibility with mercury and operation in a hard vacuum environment further complicates the problem.

A first choice which must be made is whether to measure the flow in the liquid or vapor form. In general the measurement of liquid flow at these low rates usually involves the use of small bore capillary tubing which is susceptible to clogging or dimensional changes and is best avoided. In either case it is desirable to utilize a system with no moving parts in order to enhance reliability.

The measurement of vapor flow was picked as the better approach and a relatively standard method chosen for its determination. This is to determine the mercury vapor flow rate by measuring its pressure upstream of a critical orifice.

3.2 Theory of Operation

Under conditions of choked flow, the pressure downstream of the orifice has no effect on the flow through the orifice and consequently a measurement of the upstream pressure suffices to define the flow rate.

The mass flow rate, $\dot{m}$, for choked flow conditions is given by,

$$\dot{m} = \frac{AP}{T^{\frac{1}{2}}} \left(\frac{\gamma M}{R_o}\right)^{\frac{1}{2}} \left(\frac{2}{\gamma-1}\right)^{(\gamma + 1)/2(\gamma - 1)} \qquad (2)$$

where

A = orifice area (cm^2)

P = upstream pressure ($dynes/cm^2$)

T = upstream gas temperature (^oK)

R_o = gas constant 8.31×10^7 ergs/mole

M = molecular weight gm/mole

γ = ratio of specific heats.

The above equation indicates that for an accurate determination of the flow rate the gas temperature must be known or controlled to reasonable accuracy.

One additional factor which makes this method of measurement an attractive choice is the fact that the flow meter will be exhausting into a large distribution manifold and then through a series of large holes into the discharge chamber of the thrustor. Vapor flow impedance is expected to be extremely low through this path and consequently a very low back pressure is anticipated. In essence this means that the pressure upstream of the orifice can remain quite low and the orifice can still operate in the choked flow mode. The critical pressure ratio, the ratio of upstream pressure to pressure at the orifice throat at

which choking begins is given by

$$\frac{P}{P_t} = \left(\frac{\gamma + 1}{2}\right)^{(\gamma/\gamma-1)} \qquad (3)$$

where P_t is the pressure at the throat. For mercury vapor this ratio is about 2.05 and indicates that low pressure can be used in the flow meter and still maintain choked flow conditions. One major advantage derived from this is that a relatively large diameter orifice can be used which tends to reduce the effect of dimensional changes due to erosion and minimizes the possibility of obstruction by small particles. For an orifice diameter of 0.1 cm and a mass flow rate of 2×10^{-3} grams per second the upstream pressure calculated from Eq. 2 is approximately 3.5 torr.

Two methods were initially chosen as possible ways of measuring the upstream pressure. The first of these was to determine the temperature on a small thin-walled section of the flow meter at which condensation occurred -- that is, essentially to determine the dew point. Since there is a direct relationship between vapor pressure and temperature, if the dew point temperature could be accurately determined the pressure would be known. The main disadvantage of this scheme is that the dew point sensor would be required to cool to a temperature which was considerably below the temperature of a great majority of the surrounding hardware, especially the back plate of the thrustor which may operate as high as 350°C. Forced cooling, for example with a thermoelectric device, could be used but this would increase the mass of the sensor and considerably reduce its sensitivity and response.

The second method chosen is considerably less sensitive to the surrounding thermal environment. In this approach the pressure is found by the standard method of measuring the thermal conductivity of the gas. Pressure gages of this type for the measurement of low pressure were originally developed by Pirani and are now used extensively for pressure measurement in the range of 10^{-2} to 10 torr.

The measurement of pressure in a Pirani type device depends on the fact that the thermal conductivity of a gas at low pressures is directly proportional to the pressure. To make use of this phenomenon most Pirani pressure gages consist of a heated filament surrounded by a temperature controlled enclosure. As the pressure varies, the power conducted away from the filament varies. The variation in input power, filament temperature or filament resistance is used as an indication of the pressure. Gages of this type appear to be most sensitive in the pressure range from 10^{-2} torr to 1 torr. Much above this the thermal conductivity becomes independent of pressure and the sensitivity is reduced.

In the linear region of operation the power conducted per unit area from a filament running along the axis of a cylinder is given by

$$E_c = \alpha_r \Lambda_o P \left(\frac{273.2}{T_c}\right) (T_f - T_c) \qquad (4)$$

where

E_c = the conducted power per unit area (watts/cm^2)

= molecular heat conductivity at 0°C (watts/cm^2°K microbars)

P = pressure (microbars)

T_c = cylinder temperature (°K)

T_f = filament temperature (°K)

$$\alpha_r = \frac{\alpha}{1 + (1 - \alpha)\left(\frac{a}{r}\right)}$$

where α = accommodation coefficient

a = radius of the filament (cm)

r = radius of the cylinder (cm)

For the case of interest here where the filament radius is much smaller than the cylinder radius, the correction factor, α_r, approaches α.

In addition to power transfer by conduction, radiation from the filament must be taken into account in any performance calculation. As an approximation the relation for the total radiative transfer between infinitely long coaxial cylinders can be used. Total radiated power, Q, is given by

$$Q = \frac{\sigma A_f (T_f^4 - T_c^4)}{(1/\epsilon_f) + (A_f/A_c)(1/\epsilon_c - 1)} \qquad (5)$$

where

A_f = area of filament
A_c = area of cylinder
ϵ_f = emissivity of A_f
ϵ_c = emissivity of A_c
σ = Stefan-Boltzman constant.

For our case where A_c is much greater than A_f, equation 5 reduces to

$$Q = \epsilon_f \sigma A_f (T_f^4 - T_c^4) \qquad (6)$$

and the radiated power per unit area, E_R, becomes

$$E_R = \epsilon_f \sigma (T_f^4 - T_c^4) \qquad (7)$$

Figure 15 shows the calculated behavior for a constant filament temperature of 300°C and a cylinder temperature of 200°C. Filament dimensions are 0.001 inch x 0.50 inch x 6 inches. Filament resistance as a function of pressure for a constant input power of 2.5 watts is shown in Fig. 16. The use of a ribbon instead of a wire introduces negligable error in this calculation.

The calculated curves of Fig. 15 and Fig. 16 were based on the assumption of a linear variation in thermal conductivity throughout the pressure range. This is actually not the case, since at pressures much above 10^3 dynes/cm^2 the thermal conductivity becomes independent of pressure. Also at low pressures below 10 dynes/cm^2 very little change is observed.

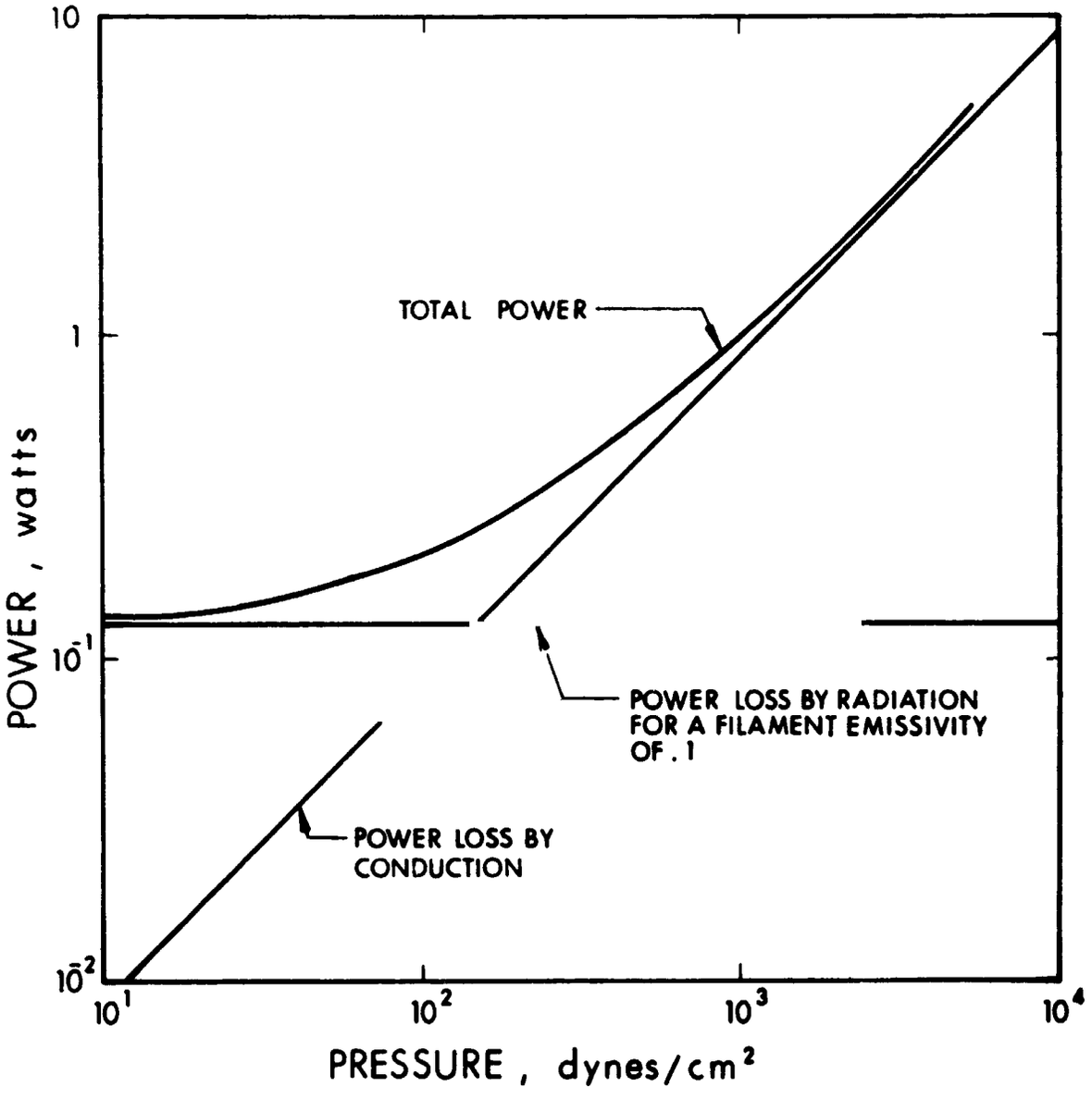

Figure 15. Power as a Function of Pressure for a Constant Filament Temperature of 300°C

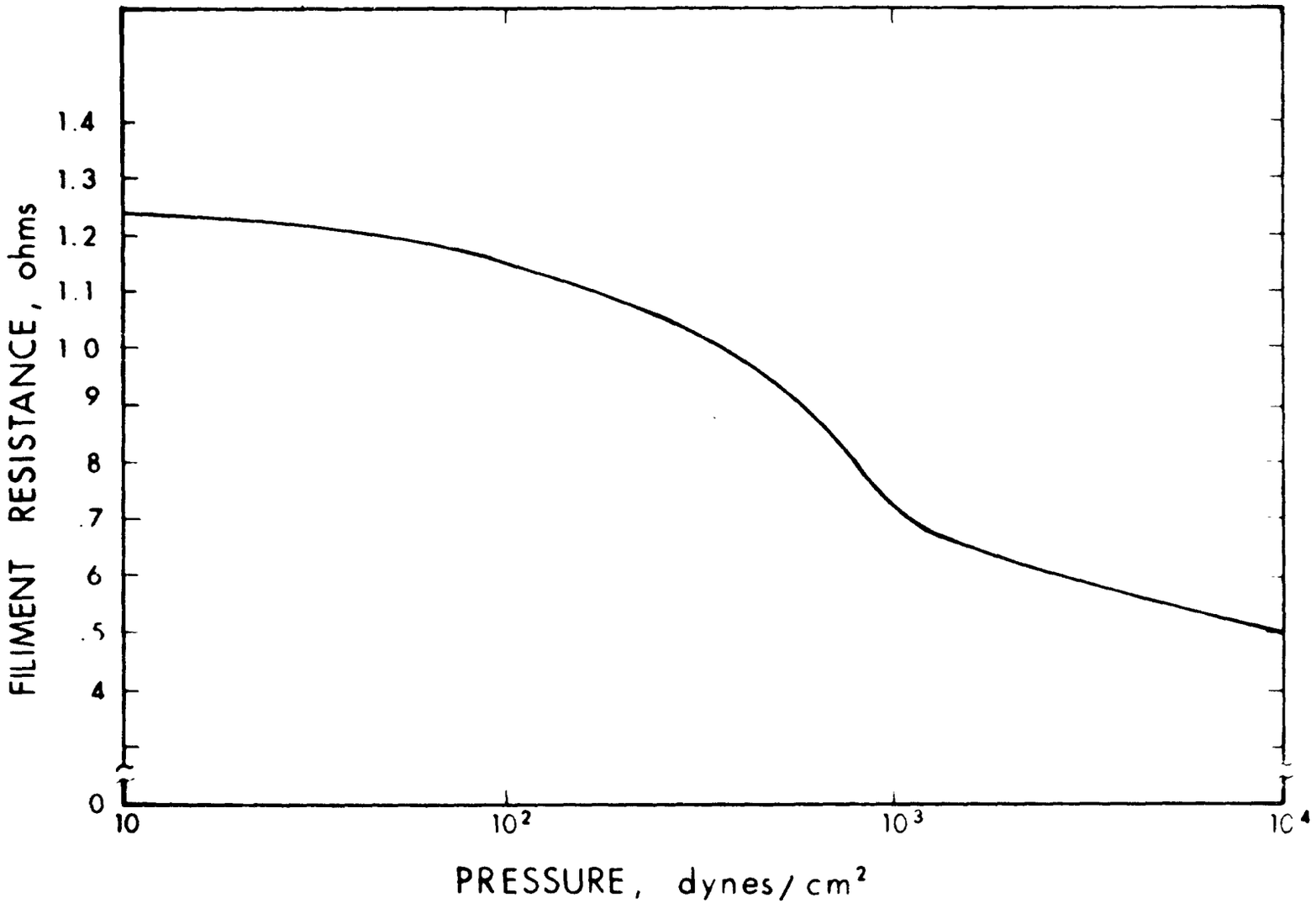

Figure 16. Filament Resistance as a Function of Pressure for a Constant Power Input of 2.5 Watts

In order to evaluate these effects and determine the most desirable operating pressure range, a Pirani test device was fabricated and tested. The construction of the test unit is shown in Fig. 17. Figure 18 shows the unit attached to the mercury boiler which provided mercury vapor for the test. The pressure within the test unit was calculated from the boiler temperature. Data were obtained for both constant filament voltage and constant filament current and the results are shown in Fig. 19 and Fig. 20, respectively. Greater sensitivity was achieved in the constant current mode. For example, at a constant filament current of 0.75 amperes a voltage change of about 100 mV is obtained in the pressure range of from 2×10^{-1} torr to 4 torr.

3.3 Hardware Description

Flow Meter

The flow meter consists basically of a temperature controlled cylinder with a critical orifice installed near one end. A heated filament is mounted along the axis of the tube. Construction details of the unit are shown in Fig. 21. A sheathed heater is brazed to the body along with a platinum temperature sensing element. The unit is then copper plated to a thickness of approximately 0.030 inch to minimize thermal gradients. The removable orifice plate facilitates filament installation and allows testing of various orifice sizes. A thin wall section downstream of the orifice plate thermally isolates the flow meter from the engine. The body is fabricated of stainless steel and is machined to accept copper seals at each end. A 0.003 inch dia. tungsten filament is used. Only one major design change was made on the unit. This was to replace the nickel temperature sensing element used on the first unit with one of platinum to increase reliability. At the same time the wire diameter was reduced to increase the resistance of the sensor from about 2 ohms at room temperature to about 15 ohms.

Four complete units were fabricated and used extensively in system tests. A completed unit is shown in Fig. 22.

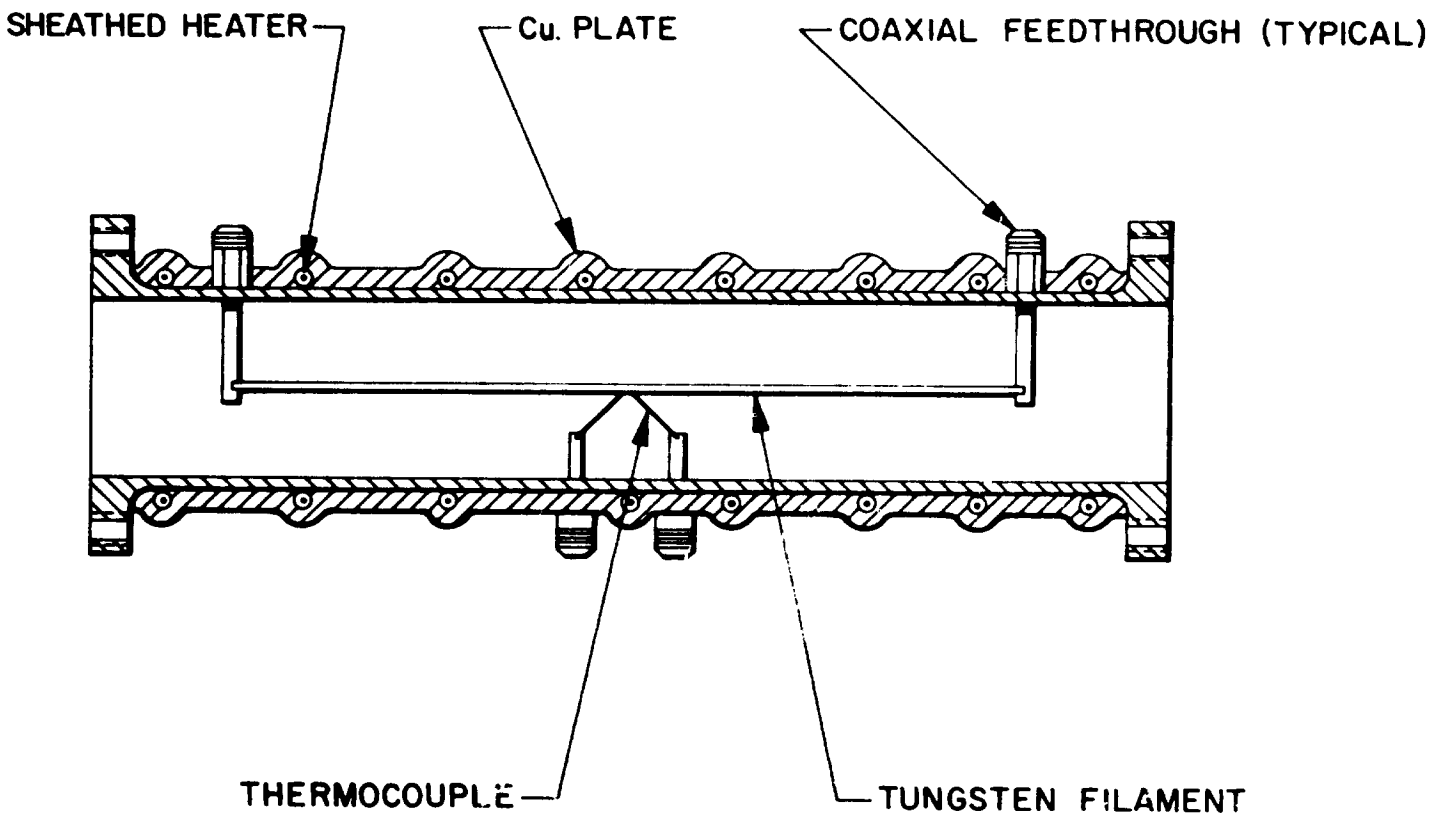

Figure 17. Pirani Test Device

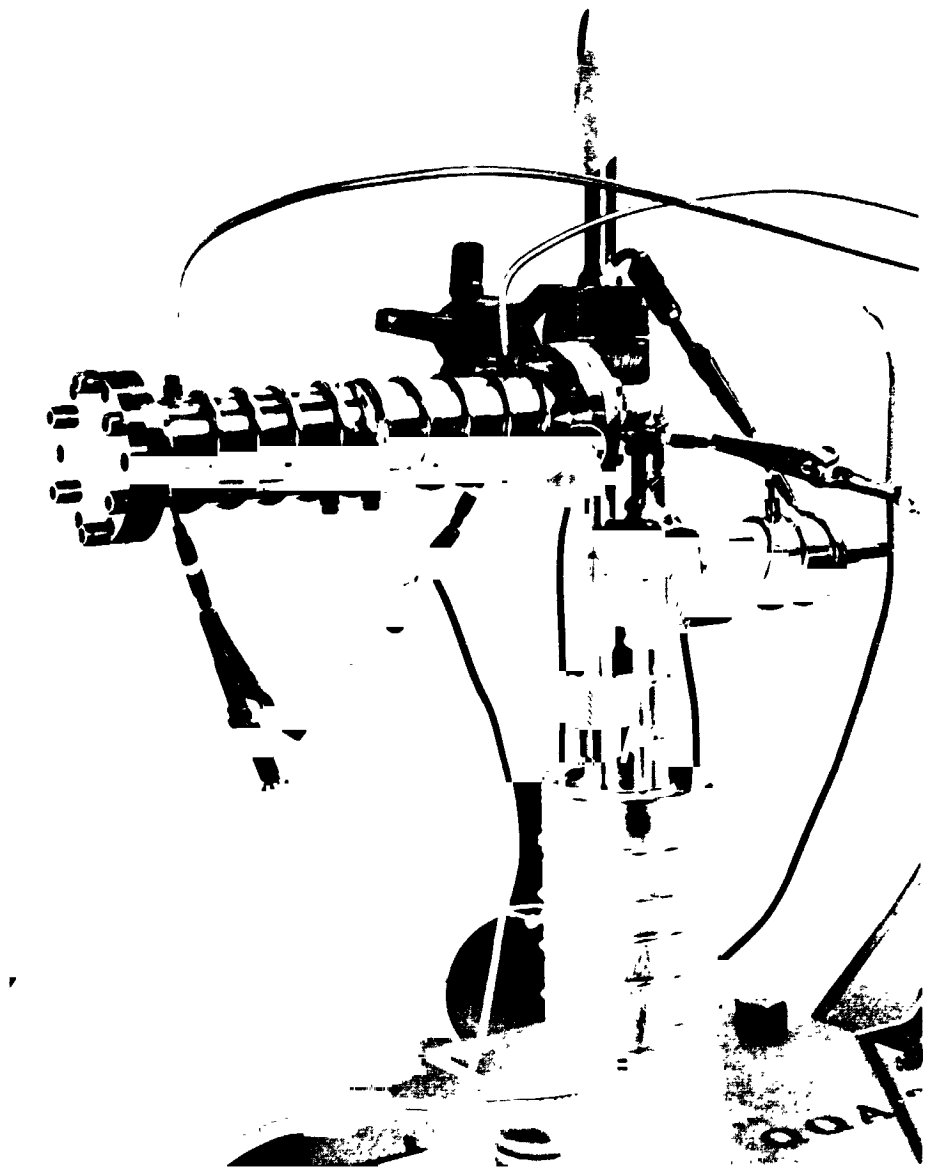

Figure 13. Pirani Test Assembly

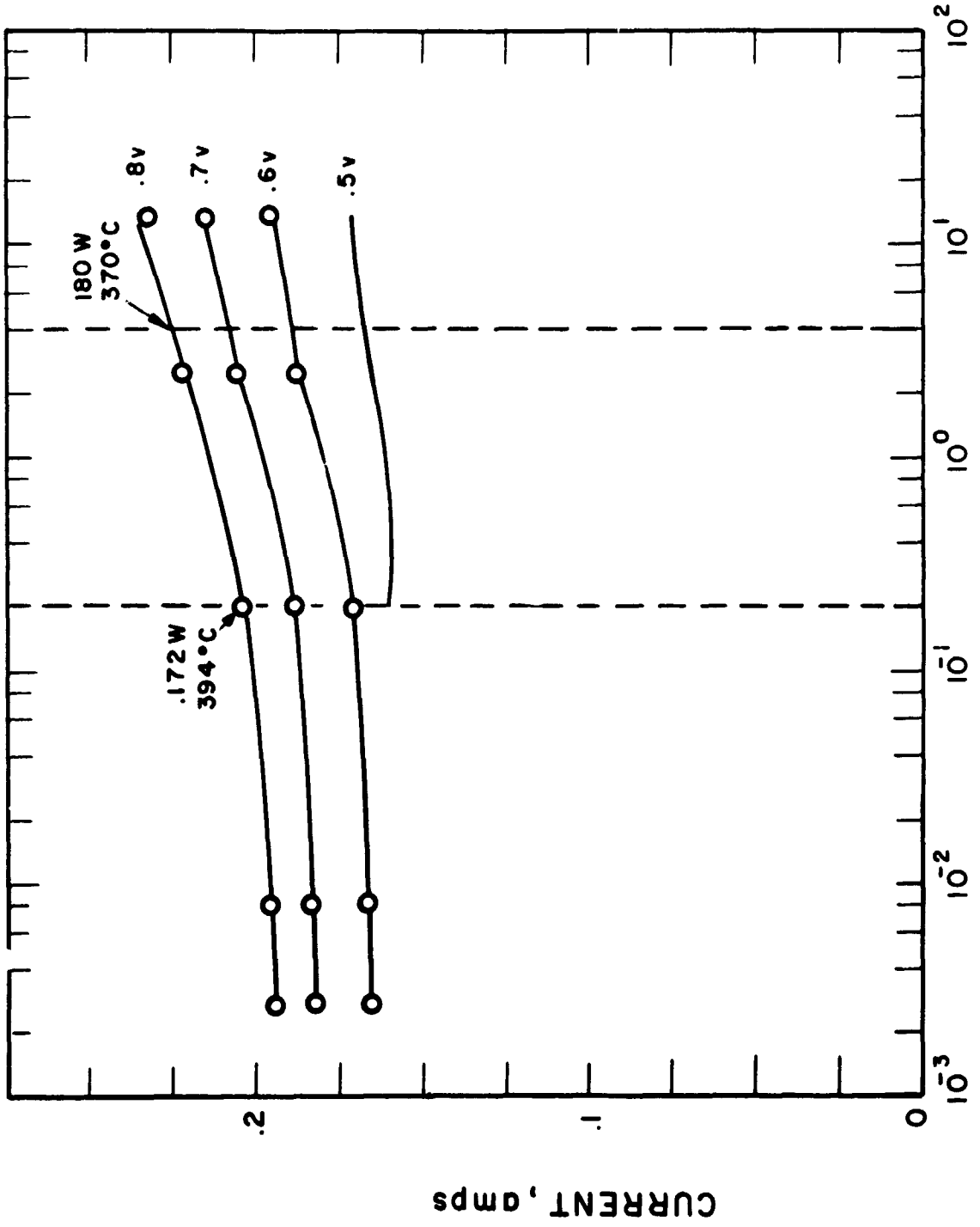

Figure 19. Pirani Characteristics - Constant Voltage

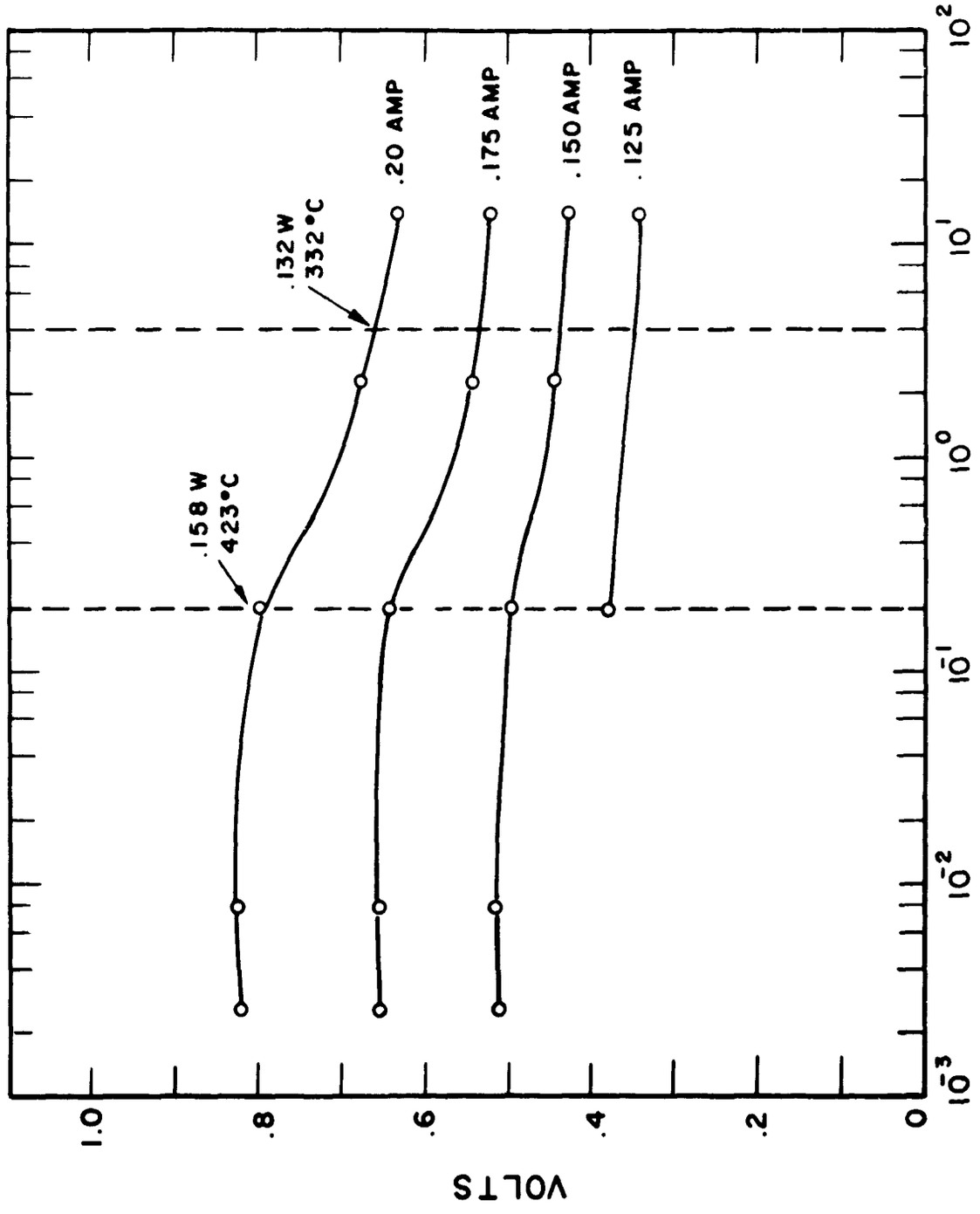

Figure 20. Pirani Characteristics - Constant Current

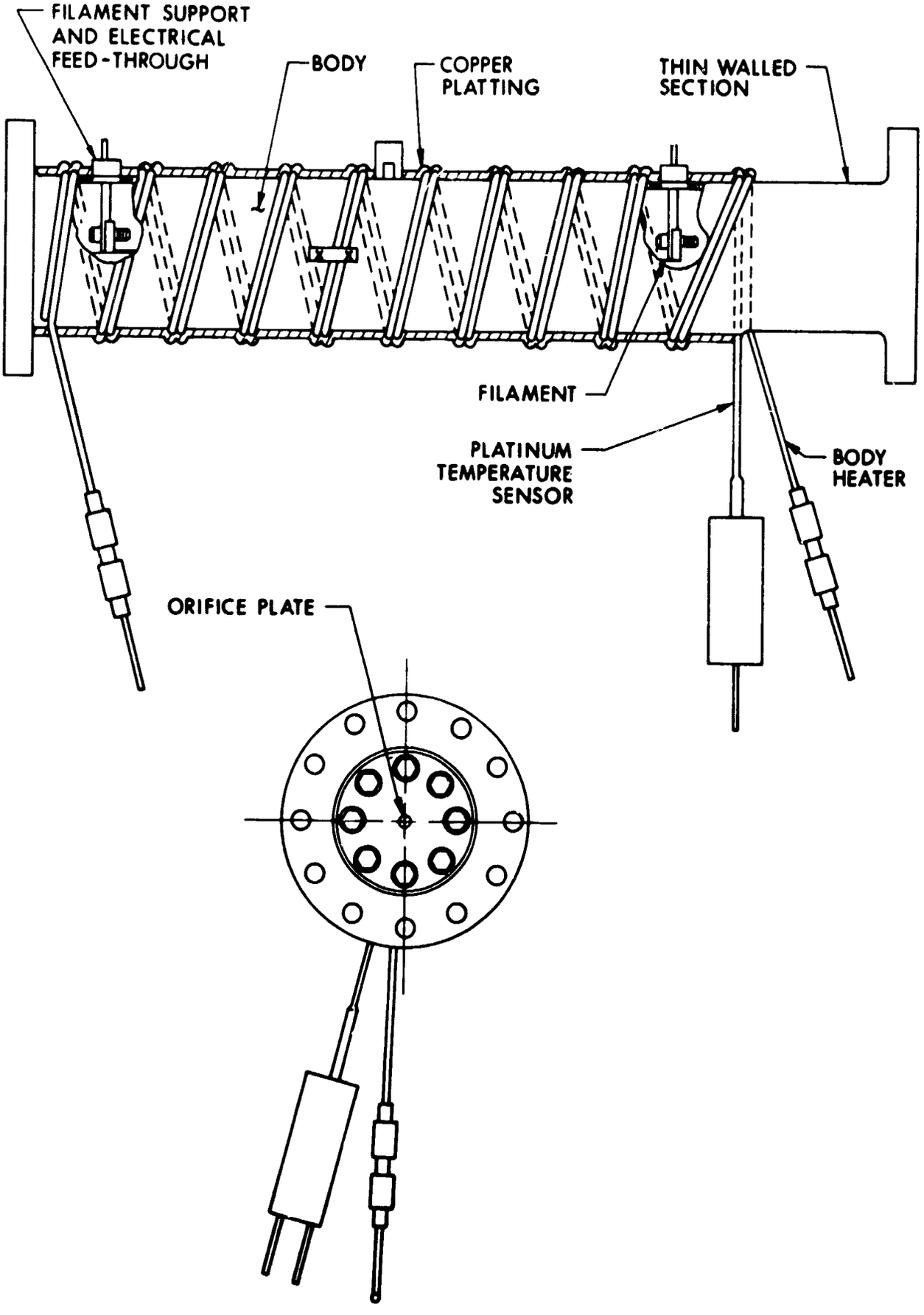

Figure 21. Flow Meter Details

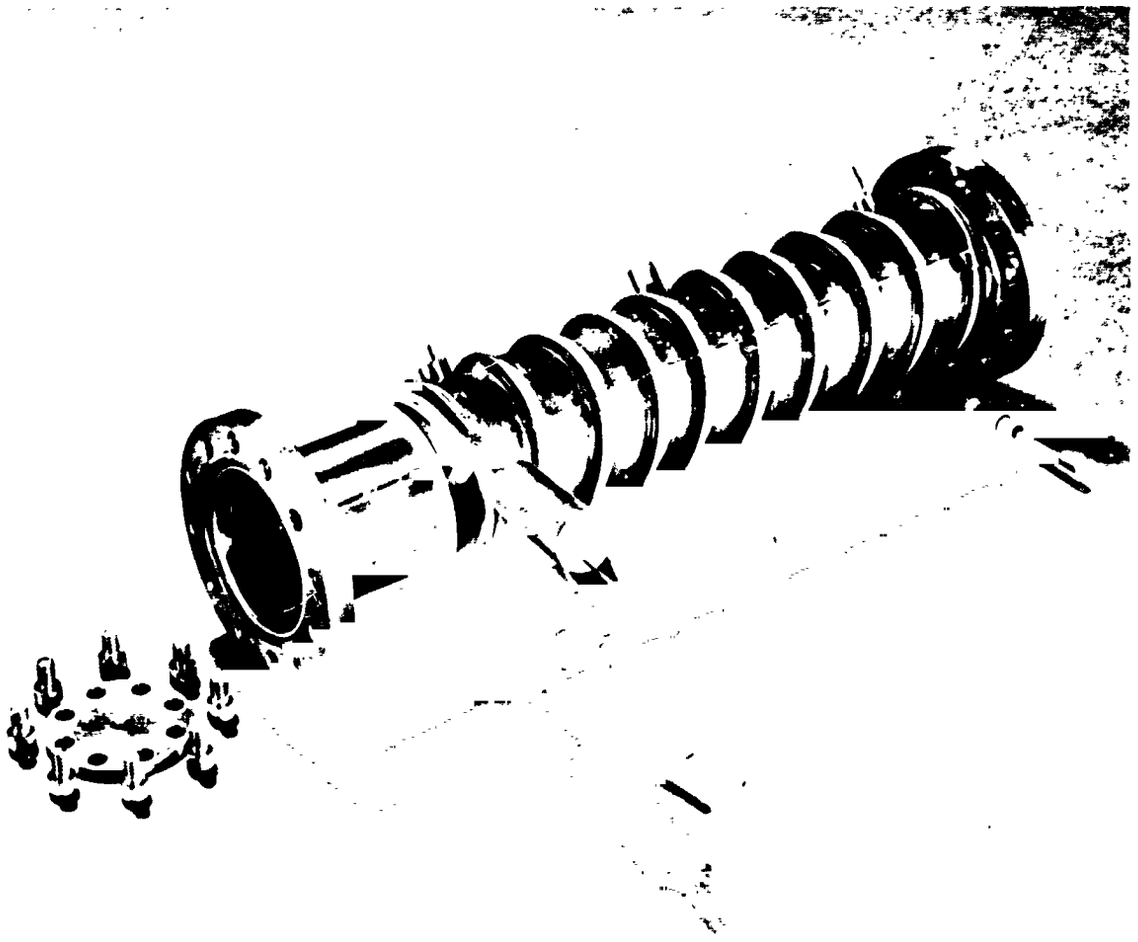

Figure 22. Mercury Flow Meter

Control and Measuring Circuits

Two main functions are required of the control circuitry. These are: to provide an electrical output which can be calibrated to read directly in mass flow rate and to maintain the body of the flow meter at constant temperature.

The importance of maintaining constant body temperature to obtain accurate flow measurements is readily apparent from an examination of Eqs. 2 and 4. From Eq. 2 we see that the mass flow rate through the orifice is inversely proportional to the half power of the gas temperature. It was assumed in the design of the flow meter that sufficient collisions will occur between the gas and the wall to bring about complete thermal equilibrium of the gas with the wall during its passage through the flow meter. Equation 4 shows that the amount of heat transferred by conduction from the filament to the wall is directly proportional to the temperature difference between the wall and filament. The temperatures chosen were a body temperature of approximately 200°C and a filament temperature at the higher flow rates of as low as 300°C. At low flow rates (low pressure) the filament temperature reaches approximately 450°C. At temperatures above this value radiation losses become appreciable. To achieve 1 percent overall accuracy, the body temperature therefore must be controlled to less than ± 1°C.

The method used to accomplish this is to compare the voltage developed across the body temperature sensor with that across a fixed reference resistor whose voltage is 180° out of phase with the voltage across the sensor. Three conditions can occur. If the resultant output is in phase with the sensor voltage, the flow meter body is too hot. Conversely for an output 180° out of phase with the sensor the flow meter could be too cool. Zero output would indicate that the sensor resistance and the reference resistance were equal and that the body temperature was correct. The output signal is amplified and drives a power controller which varies the power to the body heater in order to maintain it at a constant temperature.

The method of temperature control just described was found to be extremely sensitive; ± 0.1°C was easily maintained in breadboard tests of the circuit. Additional circuit details can be seen in the

complete flow meter schematic shown in Fig. 23. The body temperature control portion of this circuit occupies approximately the top third of the schematic.

Flow rate measurement is accomplished by determining the voltage change across the filament as the flow varies and is done by utilizing the filament at one element of a four arm bridge. Output of the bridge is amplified and then demodulated to provide a 0 to 5 volt dc signal corresponding to a flow rate of from 0 to 2×10^{-3} grams/sec.

The 0 to 5 volt output signal is read out on a digital voltmeter. It is also made available for recording and can be fed back to the feed control system to control the flow rate. The lower portion of the schematic of Fig. 23 gives additional details of the measuring circuit.

High voltage isolation of the entire unit is provided by a series of transformers which are shown in the dashed-in area at the right of the schematic. All of the components shown in the area are assembled in a separate unit which is to remain in a protected high-voltage area during thrustor operation.

One complete flow meter control unit was assembled early in the program and was used extensively in system testing including the 1000 hour life test of the laboratory feed system. Although the basic mode of operation of this unit is as described above, design changes have been made primarily to increase accuracy. These were incorporated into the two additional units that were assembled. Figure 24 shows a photograph of one of these. The unit at the left is the separate unit containing the transformers for high voltage isolation. The laboratory feed control system is also shown here mounted above the flow meter unit. One of these units was used during the 1000 hour test of the prototype feed system as described in Section 6.

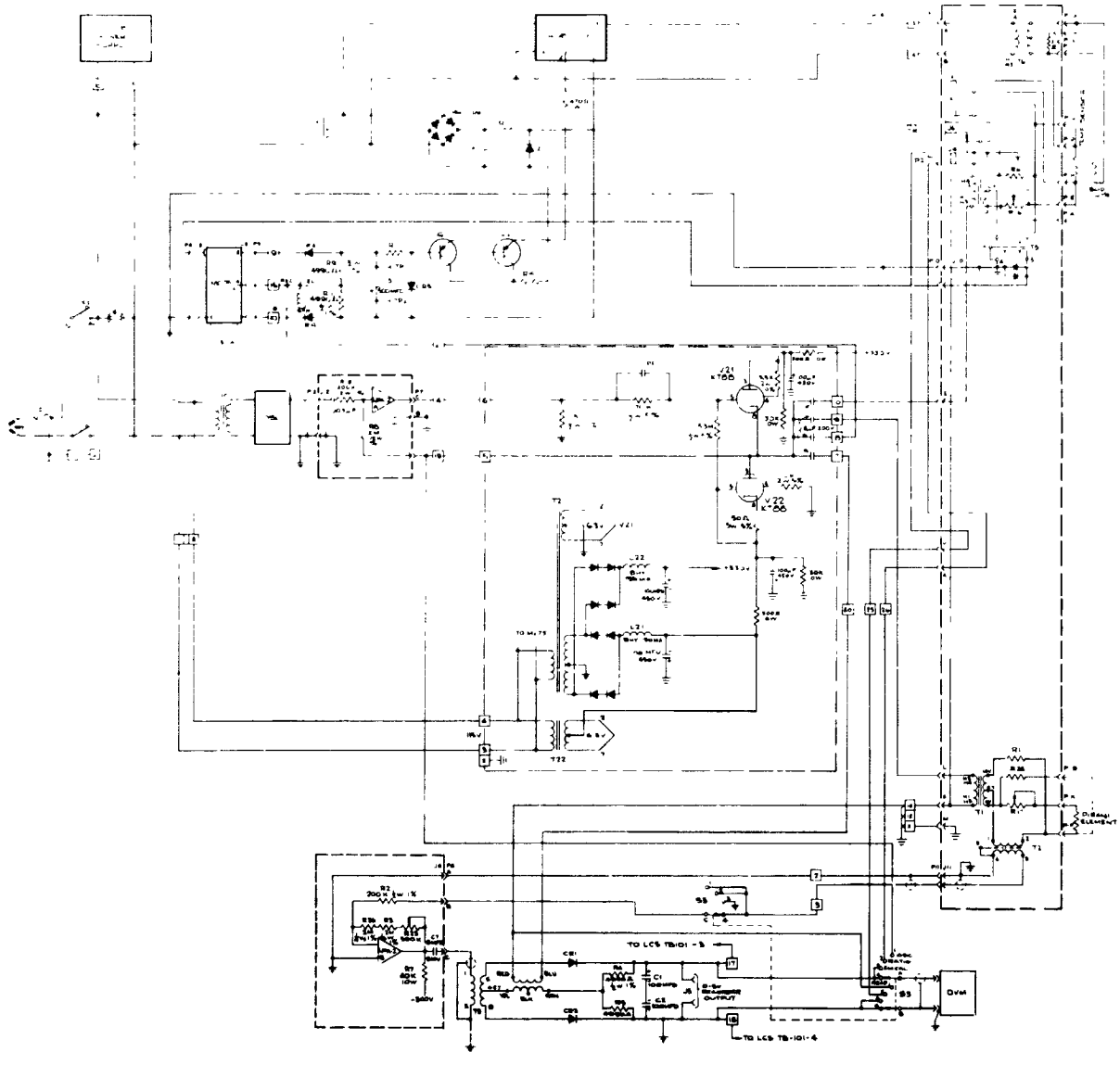

Figure 23. Flow Meter Control System Schematic

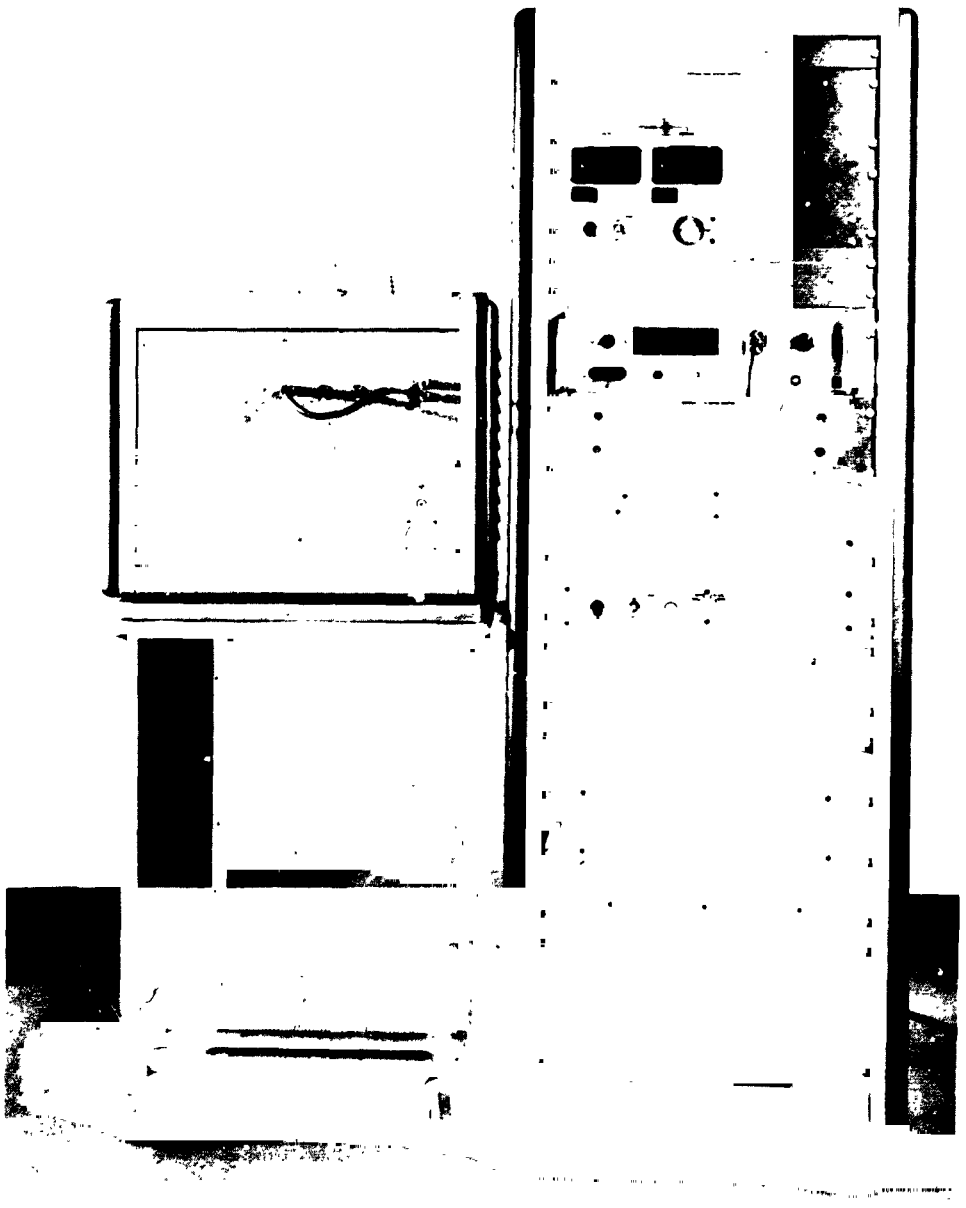

Figure 24. Feed and Flow Meter Control Systems

4. SYSTEM TESTS

A series of system tests was conducted using various test configurations. The results obtained are described in this section. Before proceeding to the various tests, a brief description of the test hardware will be presented.

4.1 Test Hardware

The general test setup that was used to evaluate the laboratory feed system and flow meter is shown schematically in the block diagram of Fig. 25. This particular method of testing, in a closed configuration was chosen to minimize the amount of mercury vapor that could escape into the vacuum chamber and so into the laboratory.

During operation mercury vapor emerging from the feed system flows through the flow meter and then through a heated line into either a collecting container or into the flow meter calibrator. A coolant line attached to the collection container is used to maintain the mercury vapor pressure within the container at a negligible level. Lines and valves between the flow meter and collector are maintained above the dew point with a series of sheathed heaters. Several iron-constantan thermocouples are used to monitor temperature. The collecting container can be fitted with an ion gage to monitor the internal pressure. A complete test assembly is shown in Fig. 26.

When a flow rate measurement is desired one of the valves to the calibrator is opened, the collecting container valve is closed, and collection begun in the calibrator.

Two methods of flow calibration have been tried. In the first method calibration is accomplished by allowing the mercury vapor to condense and collect in a small bore tube and electrically measuring the rate of rise of the liquid column. The device consists of a small bore stainless steel tube through which a 0.004 inch diameter resistance

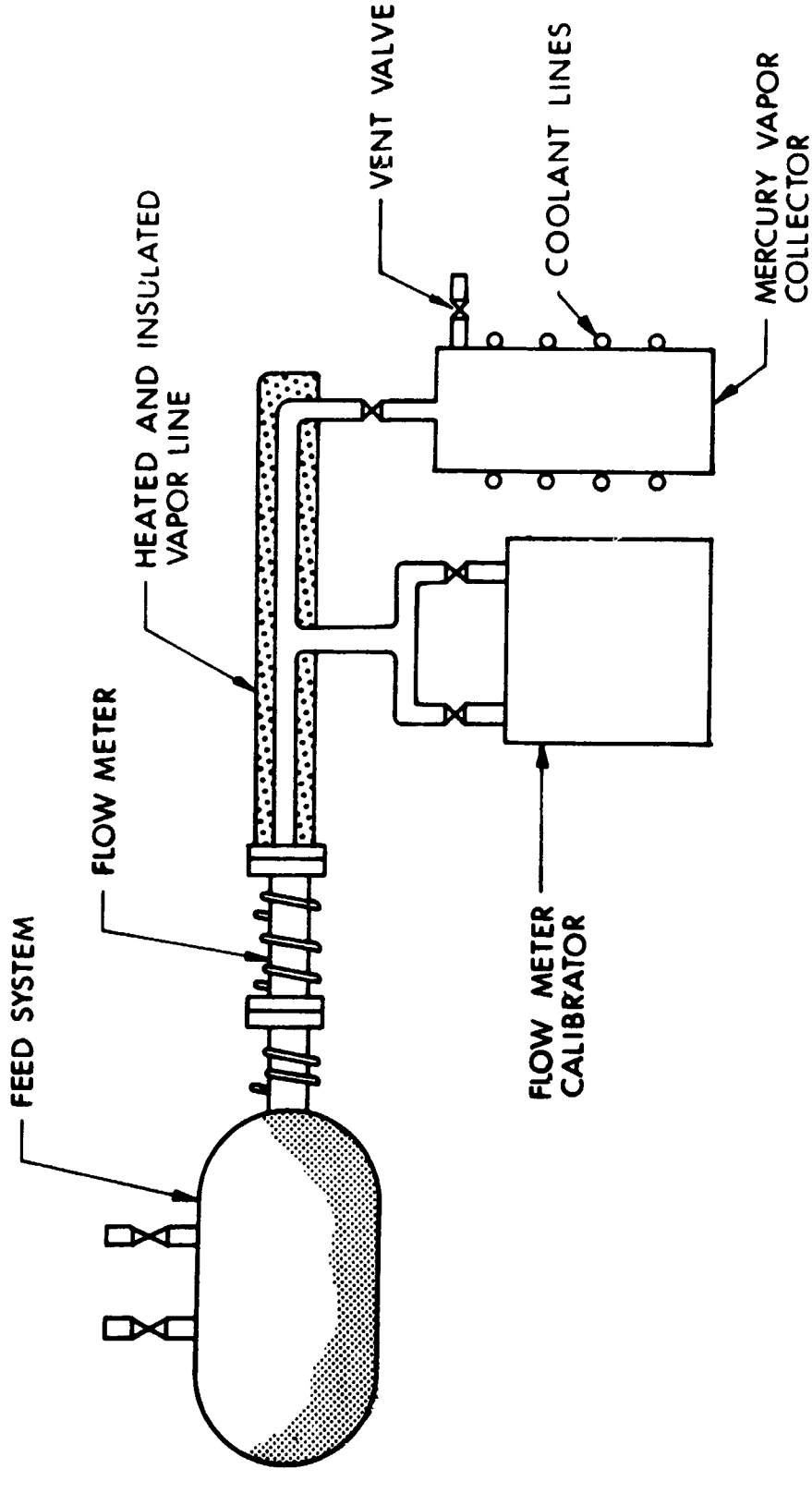

Figure 25. System Test Assembly Schematic

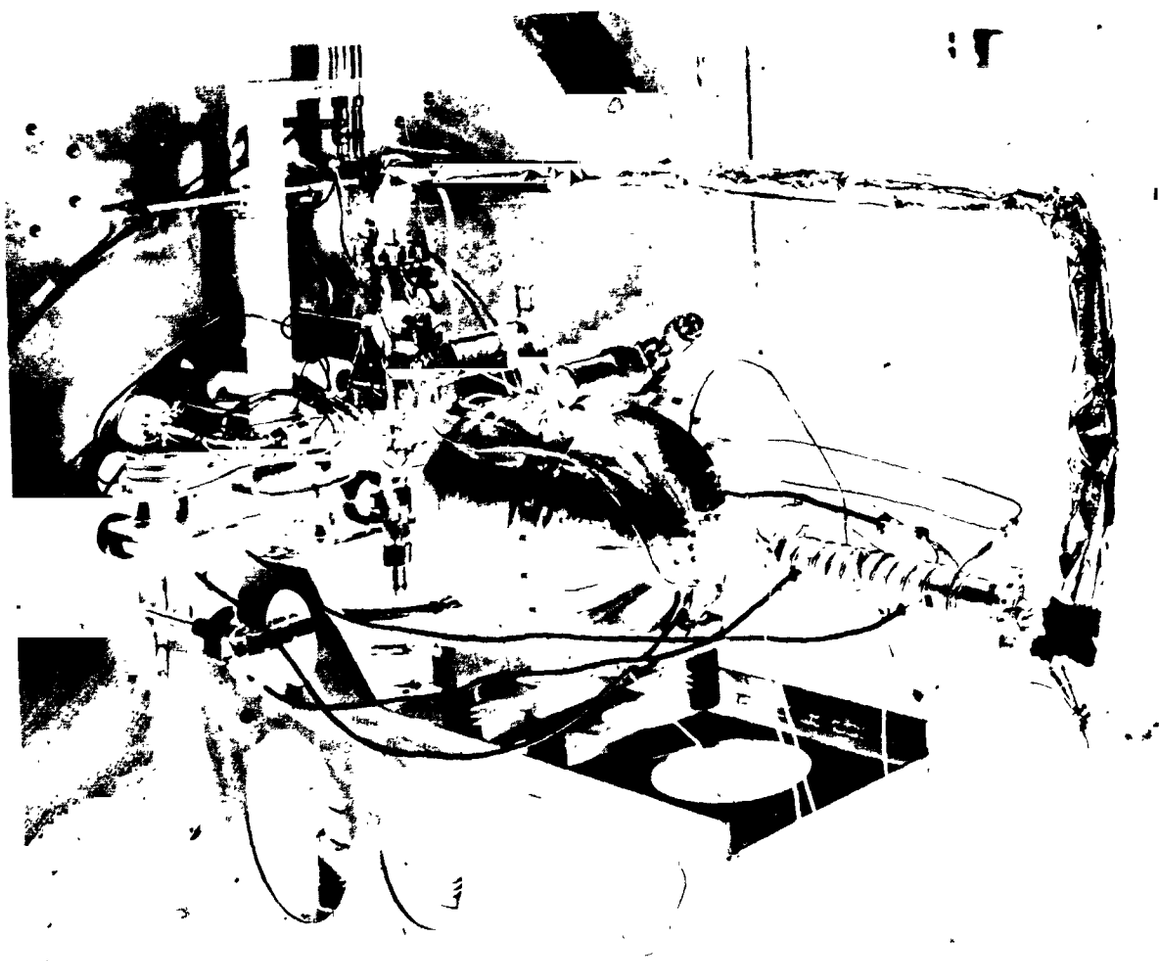

Figure 26. System Test Assembly

element is installed. When a flow rate reading is desired a valve at the bottom end of the tube is closed and the change in resistance of the element observed as a function of time. Because of the long calibration times required, up to several hours, the possibility of obstruction of the small bore tube by mercury droplets, and the sources of possible error, this method of calibration was rejected in favor of the inherently more accurate method finally chosen.

This method of flow rate calibration is depicted schematically in Fig. 27, A direct weight measurement is made over a known time period. Mercury vapor is first allowed to enter one collecting cup until a particular weight increment has been collected or alternately until a particular time has elapsed. The flow is then diverted to the other cup to again balance the mechanism. The advantage here is that repeated weight determinations can be made without exceeding the capacity of the force transducer. The force transducer used here has a full scale capacity of one gram although normally the flow rate measurement is made over only a small increment of total transducer capacity. Cooling for the collecting cups is accomplished by surrounding them with copper cups which are liquid nitrogen cooled. The collecting cups are of course completely free to move within the copper coolant cups. Adjacent surfaces are blackened to enhance heat transfer.

Transducer calibration is accomplished prior to a test by adding known weights to one of the cups and adjusting the output which is recorded on a strip chart recorder. Several attentuation positions on the transducer control unit allow it to be used for flow measurements throughout the flow range. The unit can be adjusted to give full scale indication for a weight change of 0.006 grams.

The first unit that was assembled used a standard knife edge at the balance point and utilized the beam and support stand from a commercial precision beam balance. Alignment problems plus excessive vacuum test chamber vibration led to the first modification. This change was to use a commercial flexure made by the Bendix Corp. at

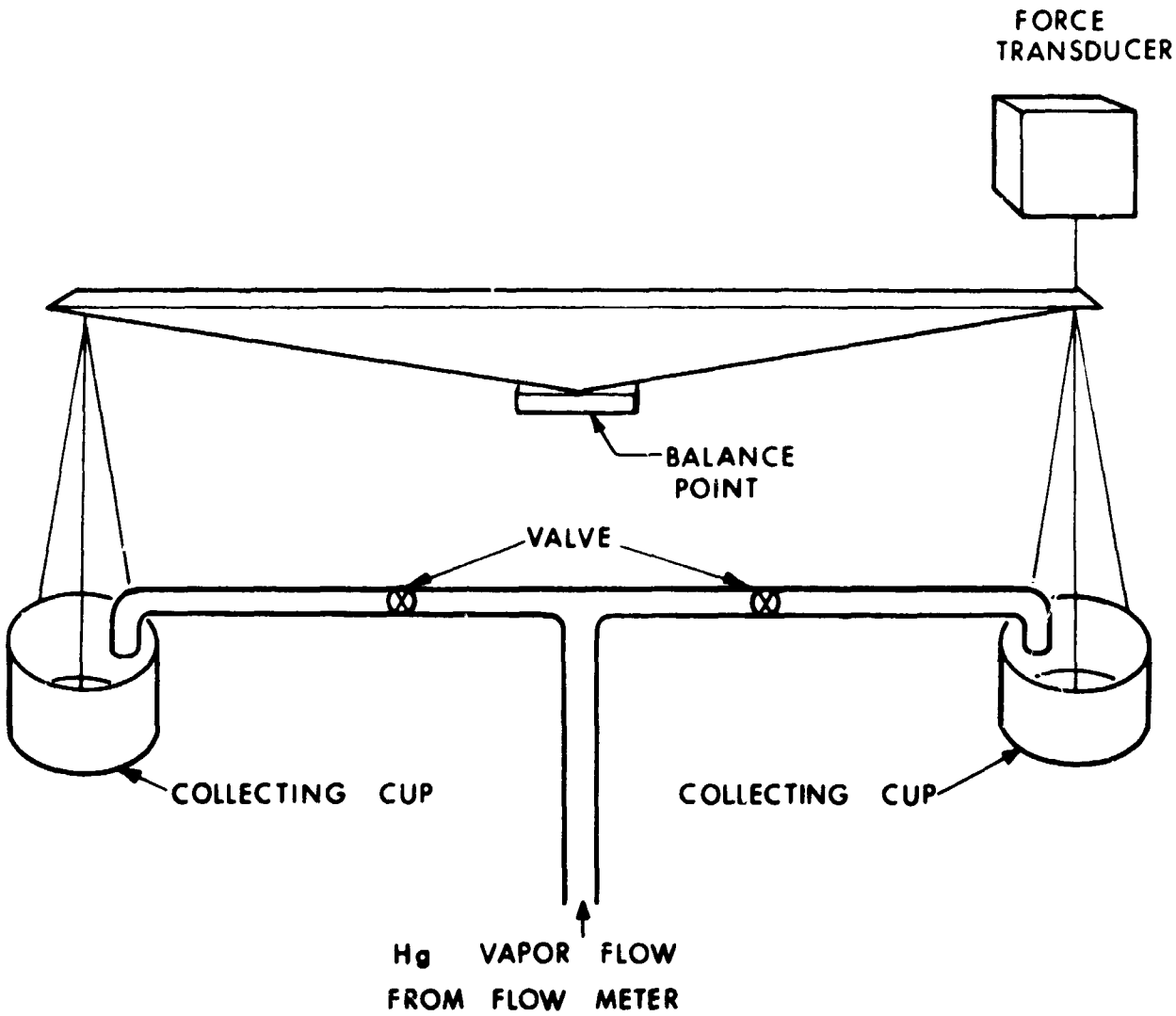

Figure 27. Flow Meter Calibrator

the beam pivot point in place of the knife edge. Although several modifications have been made to the unit including heat shielding on the collecting cups and resizing of the plumbing leading to the collecting cups, some discrepancy exists between the readings taken on either side. This is attributed to incomplete vapor condensation in the collecting cups and indicated that additional refinement was necessary. An actual calibration recording obtained with this unit is shown in Fig. 28.

4.2 Test Results

Complete system tests that have been conducted to date can be divided into two categories; those of a developmental nature and those conducted to functionally test deliverable hardware. Little more need be said here about the functional test other than that their purpose was to checkout the deliverable systems prior to delivery to NASA-LeRC. The same basic test arrangement was used for these tests as for the development tests.

All system tests of the laboratory system are summarized in Table I. The development tests, culminating with the 1000 hour life test, will be discussed further here. For the first test the SN-1 laboratory feed system was used. The vaporizer plug used in this assembly was a 25-50 grade stainless steel disc, press fit into the vaporizer. The diaphragm was 60 Shore hardness without fabric backing. Ten pounds of mercury were vacuum loaded into the reservoir. After loading the mercury the gas pressure in the pressure chamber was adjusted to an absolute pressure of 3.6 in. Hg. This is a sufficient pressure to force the full ten pounds into the vaporizer.

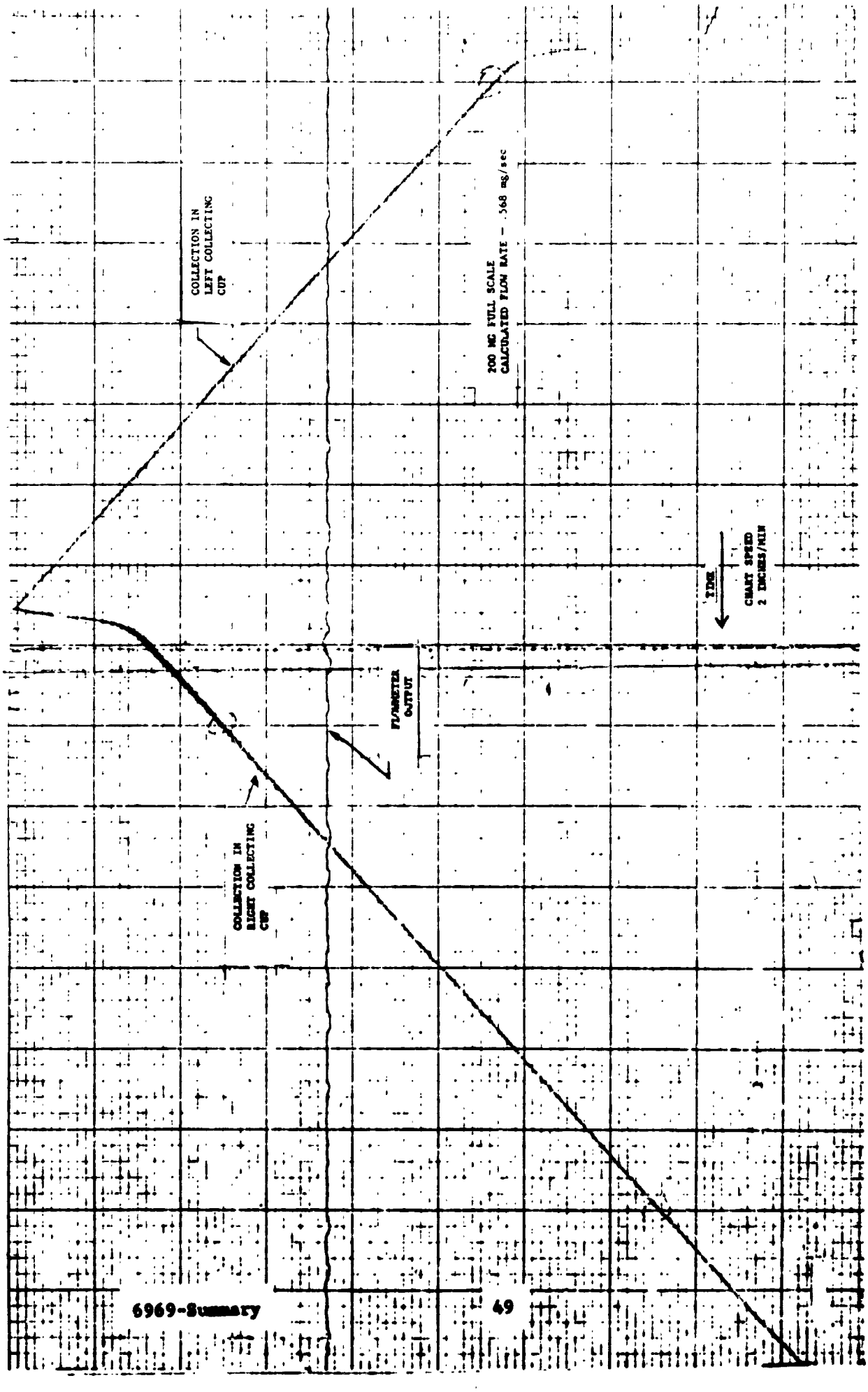

Figure 28. Calibration Recording

TABLE I

System Test Summary

Test	Date	Operating Time (hrs)	Test Function	Reason for Termination of Test and Comments
1	10/15 to 11/8	20	Press fit 25-50 grade porous SS vap plug. General test of feed system.	Mercury extruded through porous plug. Maximum flow rates obtained at less than 100°C and 5 watts vaporizer power.
2	11/15 to 11/18	25	Sintered in place porous SS vaporizer 10-15 grade.	Terminated to add flow meter to system. Maximum flow at 140°C and 8 watts.
3	11/18 to 11/29	246	Vaporizer from test No 2 and flow meter with 0.030 inch orifice.	Stopped to change to balance type calibrator and high pressure vaporizer. Observed gradual increase in vaporizer temperature during latter part of run.
4	12/6 to 12/21	113	High pressure vaporizer and flow meter with 0.060 inch orifice.	Stopped to change to flexure type calibrator. No increase in vaporizer temperature observed.
5	12/28 to 1/9	263	High pressure vaporizer and flow meter.	Terminated to prepare for high-voltage test. No increase in vaporizer temperature observed. Maximum flow at vaporizer temperature 290°C.
6	1/21 to 1/24	80	Evaluate high-voltage compatibility.	Terminated to prepare for 1000 hour life test. Found no effect due to high-voltage at 10 kV with 1200V ripple.
7	2/10 to 3/24	1014	Life test of all components. Used same vaporizer as tests 4, 5, and 6.	End of test. All components performed satisfactorily. However, found large discrepancy between integrated flow meter reading and total propellant consumed.

TABLE I (Continued)

System Test Summary

Test	Date	Operating Time (hrs)	Test Function	Reason for Termination of Test and Comments
8	3/16	6	Functional test of LFS-3 laboratory feed system and LCS-3 feed control system	All test objectives met. Units shipped 4/5/66
9	5/31	5	Functional test of LFS-4 laboratory feed system and LCS-4 feed control system.	All test objectives met. Units shipped 5/31/66.
10	5/26	4	Functional test of LFS-5 laboratory feed system and LCS-5 feed control system.	All test objectives met. Units shipped 5/31/66.

During the test the vaporizer was operated at temperatures from 100 to 200°C with the tube type calibrator used to determine the mass flow rate. With the 25-50 grade porous stainless steel vaporizer disc, the required flow rates were obtained at temperatures of less than 100°C and power levels of approximately five watts. After 20 hours of operation a large deviation from the expected flow rate was observed. When the system was disassembled a large quantity (5 cc) of mercury was found on the downstream side of the porous plug. A check on the extrusion pressure for this vaporizer showed a value of only 1 psi where before the test it had been approximately 3.8 psi. This is attributed to the fact that since the vaporizer disc had been pressed into the vaporizer tube, leakage around the periphery of the disc could have occurred. No extrusion has been observed in subsequent tests which used discs sintered in place.

The system was then reassembled for the second test using a vaporizer made from a section of tubing into which had been sintered a 10-15 grade stainless steel disc 1/16 inch thick. The pressure chamber pressure was set at 6.5 psia for tests with this vaporizer.

The maximum required flow rate was obtained with a vaporizer temperature of 140°C and a power level of 8 watts. Tests in this configuration were continued for a total of 25 hours. All portions of the system performed as expected during this time. This test was terminated in order to add the flow meter to the system and to use the flow meter and feed system control consoles in closed loop operation. All subsequent tests were conducted in the closed loop mode using the flow meter for flow rate sensing.

For the third test the feed system contained a diaphragm of 65 Shore hardness without fabric backing and was pressurized to 6.5 psia. The vaporizer contained a 10-15 grade porous stainless steel disc. The flow meter orifice was 0.030 inch diameter. The flow meter body temperature was approximately 200°C and the filament was first operated at approximately 300°C. Under the above conditions the

system was operated in a closed loop mode, i.e., the flow meter output was used to control the power to the vaporizer. The system worked as expected but did not appear to be as sensitive as required. The temperature of the flow meter filament was then raised to approximately 470°C. The sensitivity then appeared to be quite good. This system was then run for approximately 246 hours at various flow rates.

The vaporizer temperature for the maximum flow rate of 2×10^{-3} grams per second was approximately 200°C at a power level of approximately 20 watts. The data indicate that desired flow rates result from a pressure within the flow meter of about 2-20 mm Hg. where the output of the flow meter has a fairly flat slope. During the latter part of this test the vaporizer temperature was observed to gradually increase. It was not clear whether this was due to a malfunction in the vaporizer due to clogging or to an actual change in flow rate which was not recorded by the flow meter. The latter reason now seems more likely, however, since this phenomena was not observed in subsequent tests.

In the fourth test the flow meter orifice size was increased to 0.060 inch diameter to lower the upstream pressure to a more sensitive range. The high pressure (2-5 grade high density) vaporizer was installed. The balance type flow meter calibrator was also used for the first time. Pressure chamber pressure was set at 19 psia. This test was terminated after approximately 115 hours of operation to install the flexture type calibrator.

The fifth test was started on 28 December 1965. The test assembly was the same as used on test 4 except for the new calibrator. The best flow rate measurements were made with this calibrator although, as mentioned earlier, some discrepancy exists between the readings obtained in the two collecting cups.

The test continued for a period of 263 hours and was terminated in order to prepare for the high-voltage test. Primary purpose of the test was to obtain extended operating time on the vaporizer and to further evaluate the flow meter. The vaporizer used for this test consisted of a 2-5 grade high density porous stainless steel disc sintered into a

stainless tube. The flow meter used a 0.060 inch diameter orifice.

The gradual increase in vaporizer temperature observed in test 3 was not evident. Vaporizer temperature and power were relatively constant throughout the test. Maximum flow rates (2×10^{-3} g/sec) were obtained at a vaporizer temperature of 290°C. The test was terminated in order to prepare for the high voltage compatibility test.

The purpose of the sixth test was to determine the effect, if any, of applying high voltage with a large amount of ripple to the system and also to observe any transient effects when the high voltage supply was alternately switched on and off.

Tested were the LFS-1 feed system, the FM-2 flow meter, the LCS-3 laboratory feed system control console and the FMC-3 flow meter control console. The tests were performed in the 3 ft x 9 ft vacuum chamber at a pressure of less than 1×10^{-6} torr.

One side of the vaporizer heater, flow meter body heater, flow meter filament, and flow meter sensor element were attached to a common point which was then attached to the feed system and to the positive side of a high voltage power supply. There was approximately five pounds of mercury in the feed system at a pressure chamber pressure of approximately 17 psia.

The feed system and flow meter were operated in a closed loop mode at a flow rate of approximately 2 mg/sec. The high voltage was then switched on and off several times with no perceptible change in flow rate, vaporizer temperature or flow meter body temperature. The flow rate was then changed in a series of steps and allowed to regulate at each step. During these steps there was no indication of disturbance due to the high voltage. The applied voltage was 10 kV with a ripple of approximately 1200 volts peak to peak. The test was terminated to prepare for the 1000 hour life test.

The 1000 hour life test of the laboratory feed system was started on 10 February 1966 and completed on 24 March 1966. Total accumulated time was 1014 hours and 20 minutes. The system operated

continuously except for a brief period of about 5 minutes when a power cord supplying power to the control console was accidentally disconnected. The system utilized a stainless steel vaporizer. The run was originally attempted with a tungsten vaporizer, however it was found that a flow rate of only 2×10^{-5} grams/sec was obtainable at the full output power (70 watts) of the control system. The stainless steel vaporizer that replaced the tungsten unit is the one which had been used in previous tests and had already accumulated 456 hours of operation.

The test assembly consisted of the first feed system, LFS-1, with a stainless steel vaporizer, flow meter FM-2 which has a platinum temperature sensing element and a 0.095 inch diameter orifice and the breadboard feed and flow meter control units, LCS-1 and FMC-1, respectively. The feed system was loaded with 20 pounds of mercury and pressurized to 34 psia. It was attached to the flow meter and installed in a test assembly similar to that shown schematically in Fig. 25.

Mercury vapor is collected in a water cooled collector except for brief periods when the flow is diverted to the calibrator. The collector was weighed before the test. At the end of the test the mercury collected in both the collector and calibrator was measured to determine the total quantity consumed.

In addition to the instrumentation provided by the control consoles and the flow meter calibrator, eleven iron-constantan thermocouples were used to monitor temperatures on the test assembly. The outputs of these were recorded on a multipoint strip chart recorder. A two channel strip chart recorder recorded the flow meter output and the output of the flow meter calibrator. Vacuum chamber pressure was monitored with a standard ion gage and was recorded periodically in the log book.

The behavior as a function of test time of seven of the more important parameters is shown in Fig. 29 and Fig. 30. A brief discussion of each of these follows.

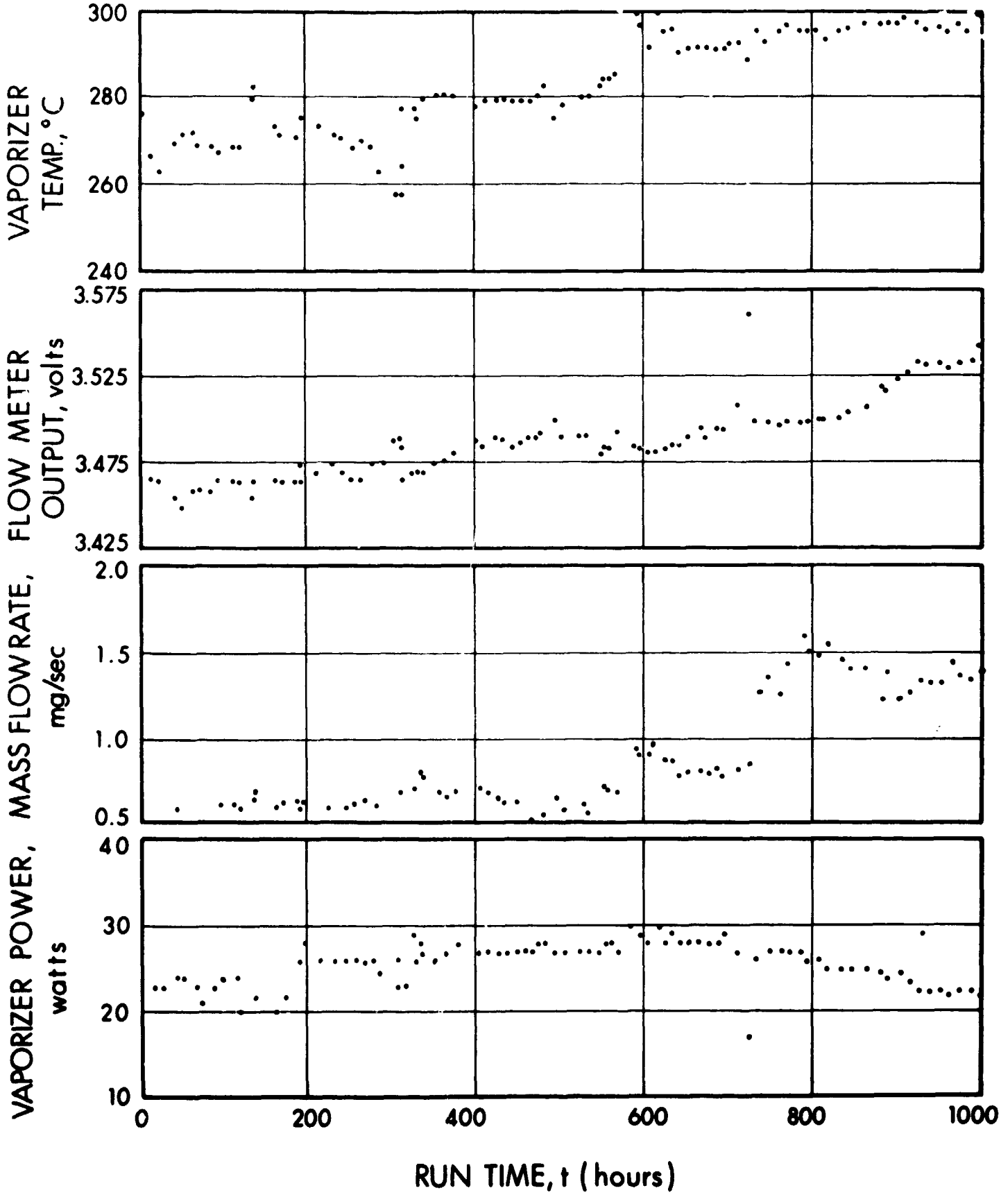

Figure 29. 1000 Hour Test Operating Parameters

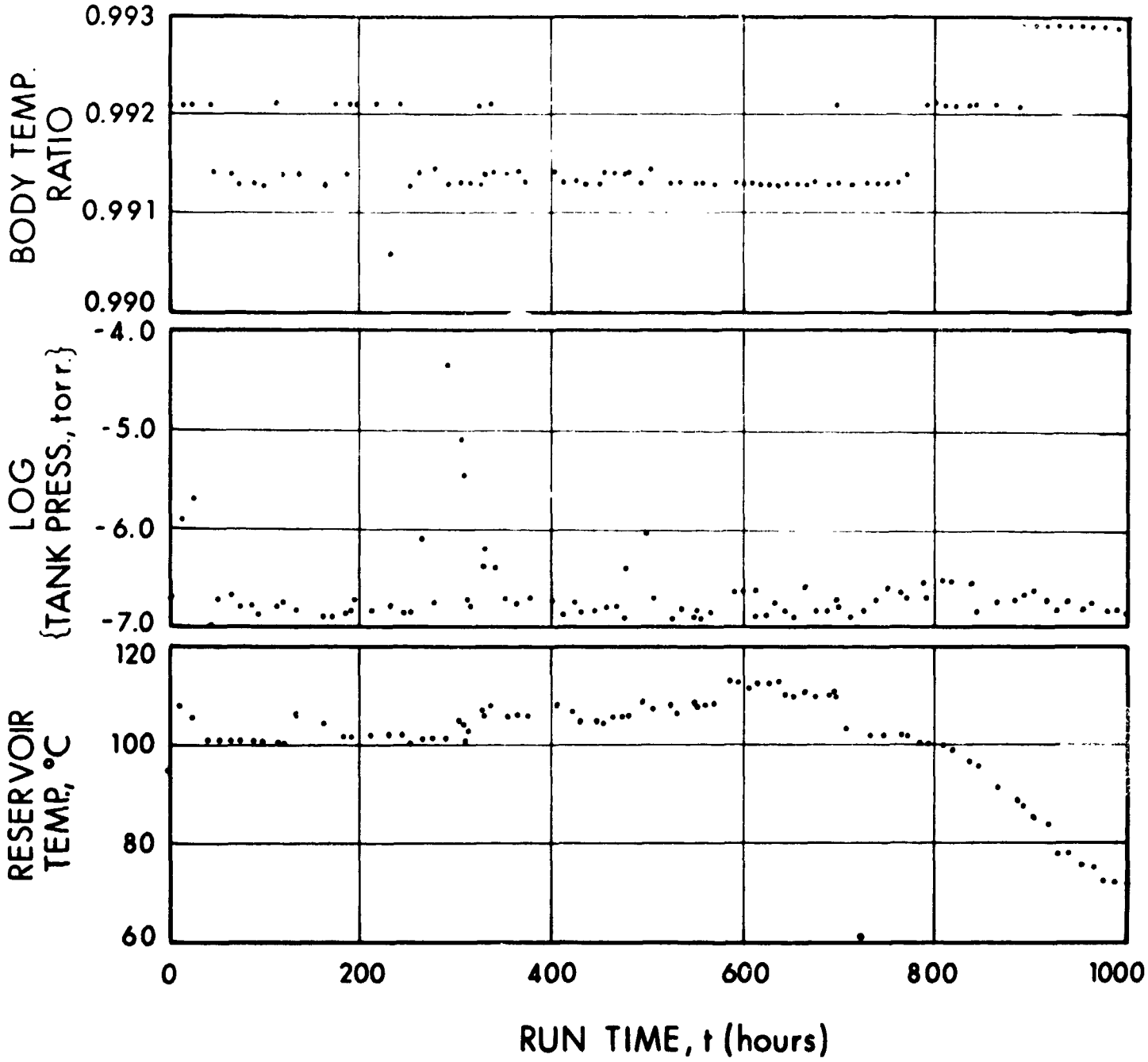

Figure 30. 1000 Hour Test Operating Parameters

The temperature of the vaporizer is measured with an iron-constantan thermocouple attached adjacent to the vaporizer heater and approximately 3/16 inch downstream of the vaporizer plug. Its output is recorded on a strip chart recorder.

The flow meter output is displayed on a digital volt meter and is recorded on a strip chart recorder. The values plotted in the figure are readings taken from the digital volt meter. Since short term variation of the output is about 20 mV, the values plotted are approximate averages.

The third plot of Fig. 29 shows the mass flow rate as measured with the calibrator. The values plotted here were obtained from the right side of the calibrator. A large total variation is observed here. However, the calibrator used shows a large discrepancy between the right and left side and suggests that the values obtained with the calibrator may be considerably in error.

The last plot of Fig. 29 shows the power supplied to the vaporizer heater. It is calculated from the current and voltage output of the control system. Since in the closed loop mode of operation the current and voltage fluctuate considerably the values plotted here are estimates of the input power.

The body temperature ratio (Fig. 30) is a measure of the stability of the flow meter body temperature. It is the ratio of the voltage across the platinum sensor and the voltage across a fixed reference resistor. A 1 percent variation of the ratio is equivalent to about a 6^{o}C variation of the body temperature.

Vacuum chamber pressure history is shown in the second plot of Fig. 30. The high pressure point at 290 hours occurred when the diffusion pumps were accidentally shut off. The run was not interrupted at this time.

The last plot shows reservoir temperature. It is measured with an iron-constantan thermocouple and recorded on a strip chart recorder.

At approximately 600 hours the vaporizer power and temperature and the mass flow rate increased rapidly. The reason for this increase is difficult to explain, as the flow meter output indicated no change in flow rate.

Of particular significance is the behavior at about 725 hours where the vaporizer power and flow meter output showed marked deviations from the general trend. This could indicate a momentary increase in the flow rate although a measurement with the calibrator of the mass flow rate at that time did not show a large change. However at the next data point, 737 hours, the measured flow rate had jumped to a new level.

During the last 200 hours the vaporizer power and reservoir temperature gradually increased. After the run it was determined that a majority of the mercury had been consumed. This accounts for the decrease in reservoir temperature and vaporizer power toward the end of the run since thermal conduction back into the reservoir was reduced.

Neglecting the one point at 725 hours the flow meter output remained constant to within ± 1.4 percent throughout the entire run. The body temperature ratio indicates that the flow meter body temperature was held constant to 1°C.

Following the run the system was disassembled and examined. The flow meter was clean with no discoloration. The vaporizer however showed some discoloration of the downstream face of the vaporizer plug. No mercury was visible on the downstream side.

The vaporizer was sectioned and photographed (Fig. 31). A majority of the discoloration that is seen occurred prior to the run during the fabrication of the unit. Some wetting was observed on the upstream face of the porous disc. In general the unit appeared to be in excellent condition with no evidence of erosion. A portion of the vaporizer disc was spectrographically analyzed. The result of the analysis is shown in Table II. Total operating time on the vaporizer exceeded 1450 hours.

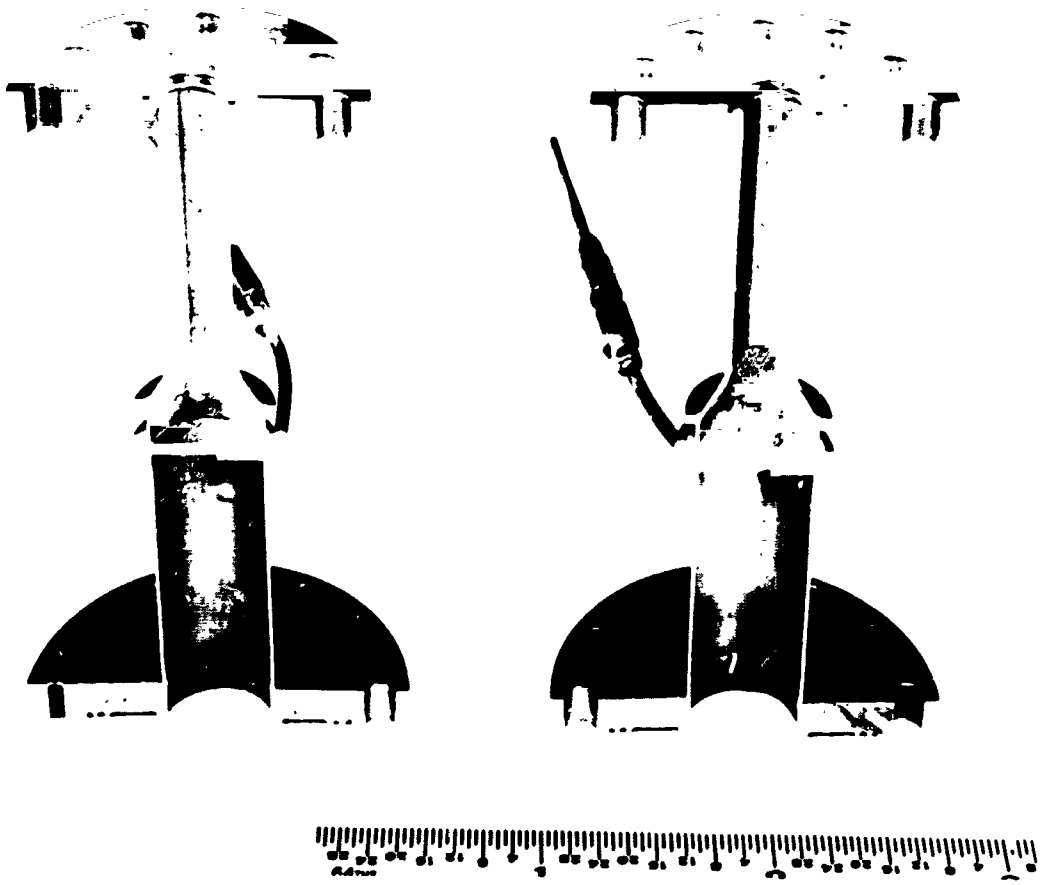

Figure 31. 1450-Hour Vaporizer - Internal View

TABLE II

Analysis of Stainless Steel Vaporizer After 1000 Hour Run

Element	Percent
Mn	.5
Si	.5
Mo	.5
Cu	.4
Cn	.004
Al	.001
Mg	.001
Cr	17.
Ni	9.5
Fe	Rem.

Wet Analysis

.02

The quantity of mercury consumed during the run was determined by measuring the quantity collected in the vapor collector and in the calibrator. This was 18.65 pounds, leaving approximately 1.35 pounds in the reservoir. The calculated average flow rate was 2.32 milligrams per second. This unexpectedly high flow rate was considerably above those measured with the calibrator. The explanation of the discrepancy is that a good portion of the mercury vapor entering the collecting cups of the calibrator is escaping. The problem was studied and new collecting cups with better collecting efficiency were fabricated.

A spectrographic analysis of the mercury collected during the run was performed. The procedure used was to evaporate the mercury sample to dryness and then spectrographically analyze the residue. The result of this analysis is shown in Table III. The only major contaminant was lead. No explanation for the lead content has been determined.

Following the test the flow meter was removed from the system and was found to be clean and dry. The filament resistance was 1.38 ohms where before the run it had been 1.40 ohms. This is a resistance change of about 1.5 percent but a difference in the ambient temperature when the resistance was measured could account for the difference. The filament diameter was measured and found not to have changed.

A measurement of the orifice size showed no change.

Following the run fixed resistors were substituted for the filament of the flow meter in order to determine the operating temperatures of the filament and the variation of filament resistance as a function of flow meter output. A resistance change of 0.687 ohm was measured over the range of 0.to 5 volts flow meter output. This corresponds to a change of 22 percent of the average operating resistance of the filament. The calculated filament temperature varied between 356°C and 253°C for a flow meter output of from 0 to 5 volts, respectively.

TABLE III

Analysis of Mercury After 1000 Hour Run

Element	P.P.M.
Lead	1.2 to 6
Silicon	.3
Antimony	.3
Iron	.3
Nickel	.03
Calcium	.03
Arsenic	.006
Chromium	.006
Boron	.003
Aluminum	.003
Manganese	.003
Magnesium	.0006
Bismuth	.0006
Copper	.0006
Barium	.0006
Silver	Trace
Other Elements	None Detected

5. PROTOTYPE FEED SYSTEM DEVELOPMENT

Development of the prototype model mercury feed system is described in this section. The design requirements are described first. This is followed by a description of the developed hardware and finally by a discussion of the porous tungsten vaporizer development tests that were performed. Results of system tests are described in Section 6.

5.1 Design Requirements

The specifications and goals of the prototype feed system are that it provide a controlled flow of mercury vapor and be capable of operation under zero-gravity conditions. Required capacity is 30 pounds and the system should be capable of expelling 98 percent of the initial load. Flow rates controllable to an accuracy of ± 1 percent over the range from zero to 1×10^{-3} grams per second are required at a power level of 18 watts or less. A life test demonstration of one unit for a minimum of 1000 hours in a vacuum environment of 5×10^{-6} torr is required. Six other units are to be fabricated, functionally tested and delivered to NASA-LeRC.

5.2 Hardware Description

Design of the prototype system is based on the design of the laboratory model and, except for size (30 lb capacity), vaporizer, and valving, is the same. A drawing of the reservoir is shown in Fig. 32. Pictures of the assembled and disassembled system are shown in Fig. 33. and Fig. 34.

The design consists of two equal volume chambers; a mercury chamber and a pressure chamber. The chambers are separated by an elastomer diaphragm which provides the rear liquid-vapor interface. Pressurizing the rear chamber forces the liquid mercury from the front chamber into the vaporizer. A porous tungsten disc in the vaporizer provides the front liquid-vapor interface. The pressure chamber is pressurized, as it is in the laboratory model, to approximately 34 psia.

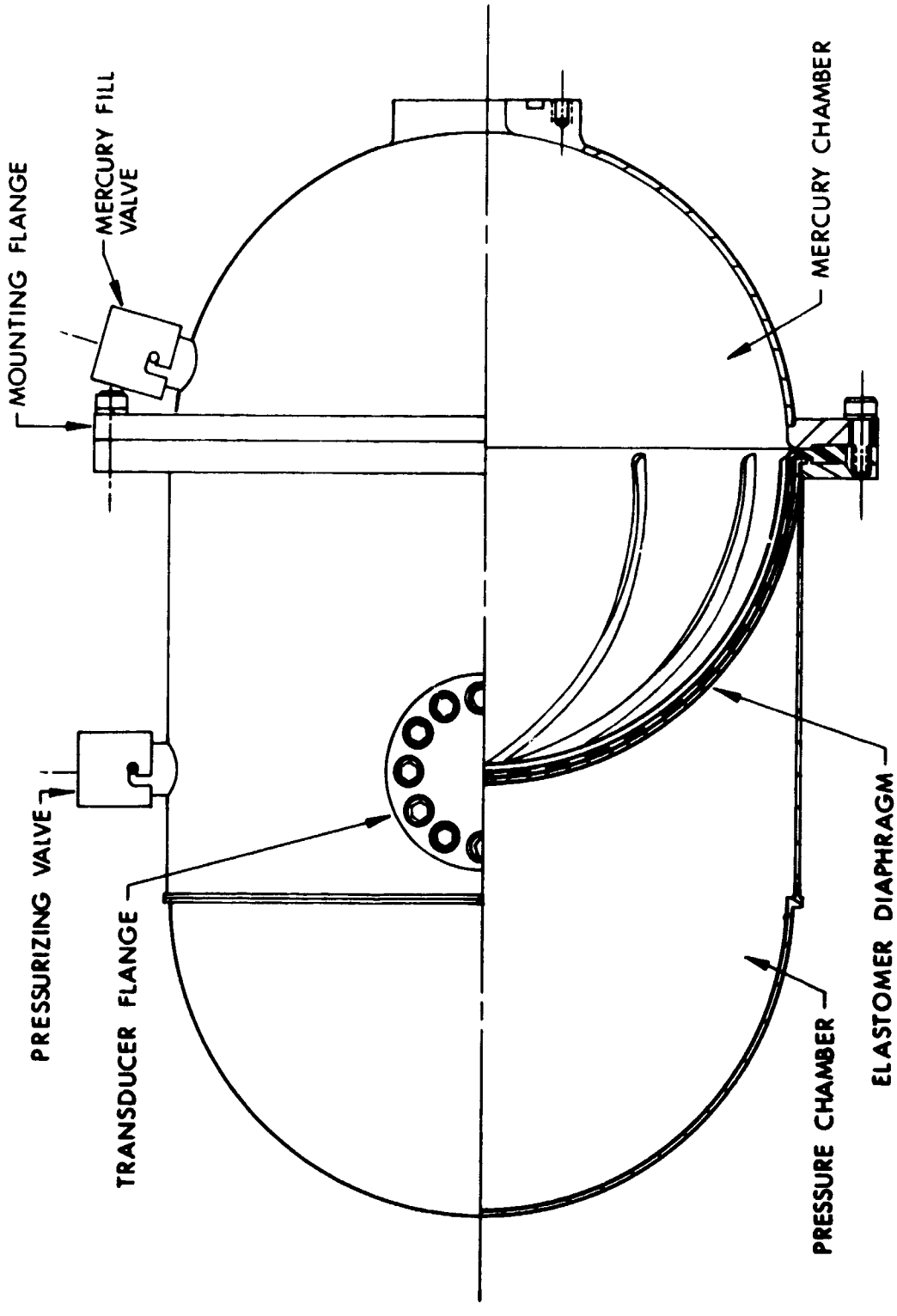

Figure 32. Prototype Mercury Reservoir

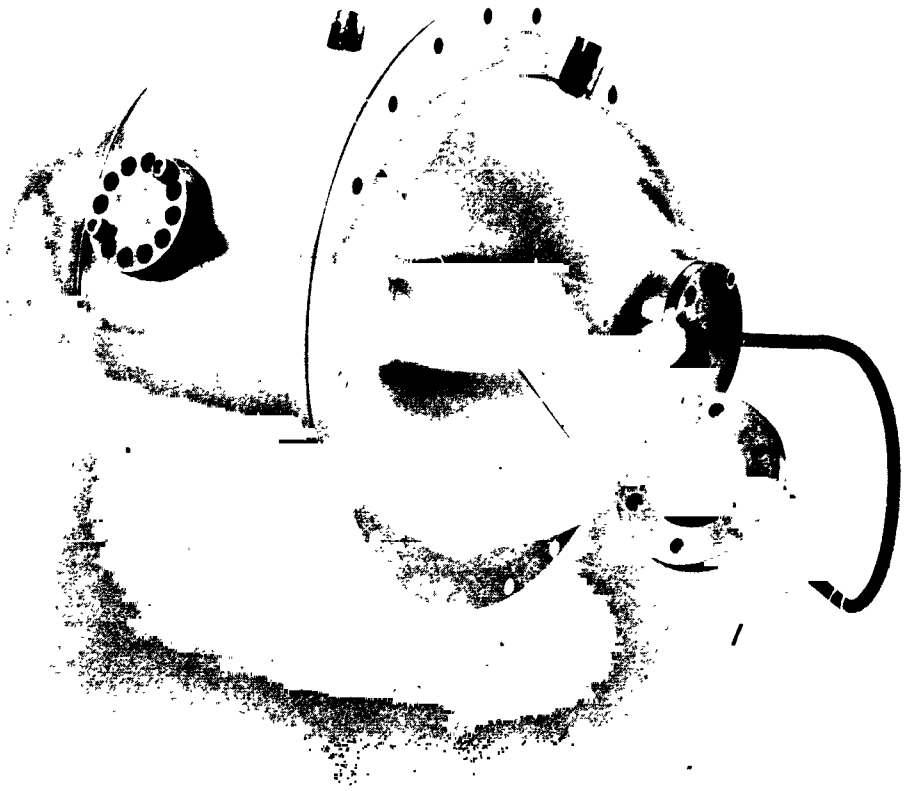

Figure 33. Prototype Mercury Feed System

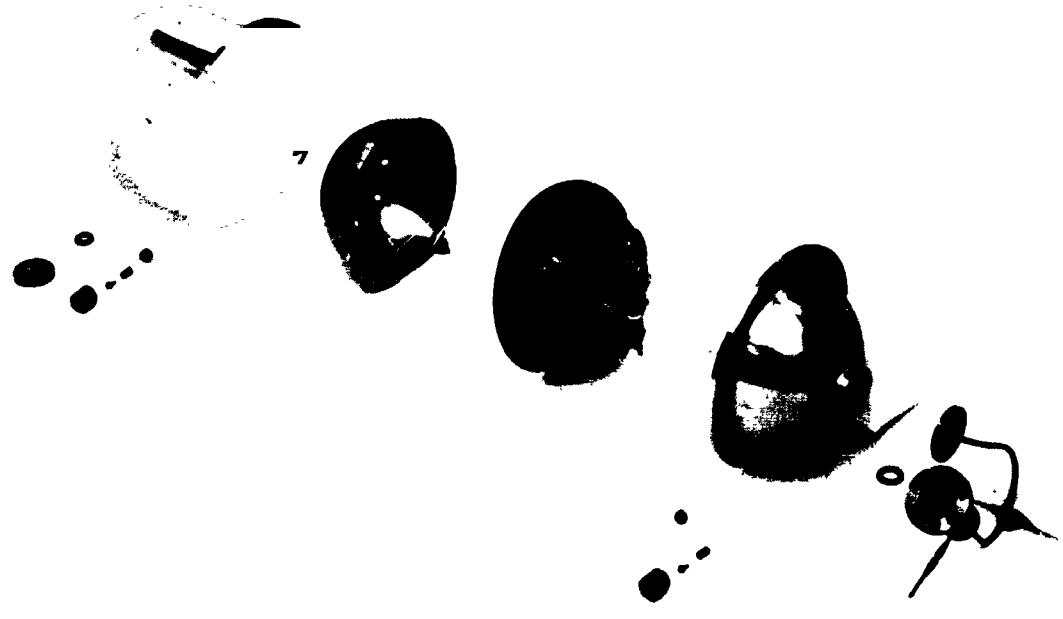

Figure 34. Prototype Mercury Feed System Disassembled

This pressure is sufficient to prevent air from entering the mercury chamber when the feed system is at atmospheric pressure.

All metal parts of the reservoir are made from 347 stainless steel. The diaphragm is made from a Butyl rubber compound. A flange is provided on the pressure chamber for the attachment of a pressure transducer should such a transducer be desired.

The valve design (Fig. 35) for the prototype feed system is based on the design of quick connecting air hose valves. A seal between mating parts is made before, during, and after the valve is opened. This coupling remains sealed until the valve has been completely closed. The same design is used for the mercury fill valve and for the pressurizing valve. The metal parts of the valve are made from 347 stainless steel, the spring is stainless steel and the o-ring is Buna N rubber. The valve is approximately 0.4 inch diameter and 0.5 inch long. A cap is provided to prevent unintentional opening of the valve.

The drawing of the prototype tungsten vaporizer is shown in Fig. 36. The vaporizer body is constructed entirely from tantalum to match the thermal expansion of the tungsten button. The porous tungsten button is electron beam welded in place. All body joints are also designed for electron beam welding. The heater sheath is tantalum and is brazed to the vaporizer chamber. Braze is also used as a seal where the heater wire passes through the vaporizer body.

5.3 Tungsten Vaporizer Tests

Further testing of porous tungsten vaporizer materials and fabrication techniques was performed during the prototype development period. One test was to determine the permeability of porous tungsten buttons made from angular and spherical powders. The results showed values for spherical powder from 0.82×10^{-6} to 1.15×10^{-6} $gm \cdot cm^{-1} \cdot sec^{-1} \cdot mm\ Hg^{-1}$ and values for angular powders from 0.975×10^{-6} to 1.35×10^{-6} $gm \cdot cm^{-1} \cdot sec^{-1} \cdot mm\ Hg^{-1}$. These values were determined using nitrogen gas. The average permeability values found were 1.01×10^{-6} for spherical powder buttons and 1.231×10^{-6} for angular powder buttons. The angular powder buttons have a 22 percent increase in permeability over that of

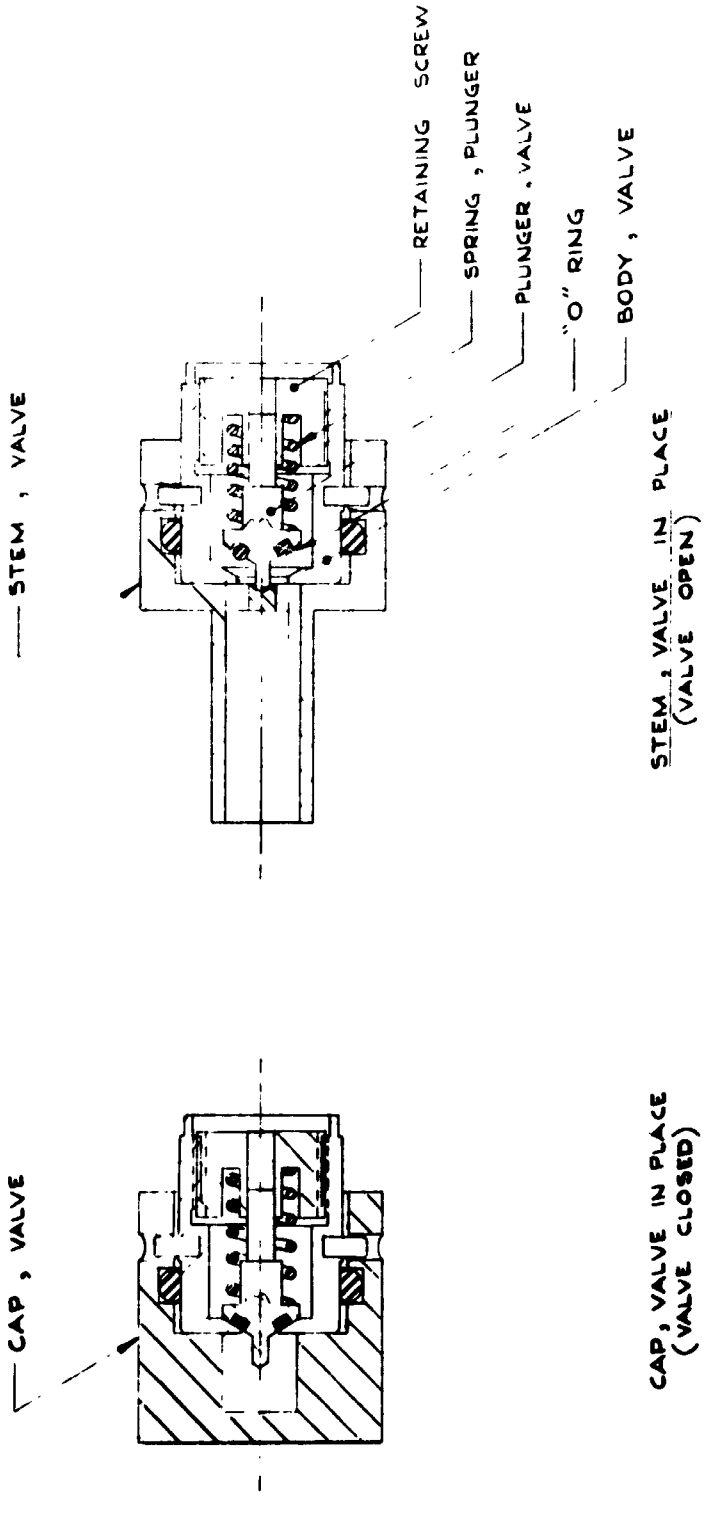

Figure 35. Prototype Valve

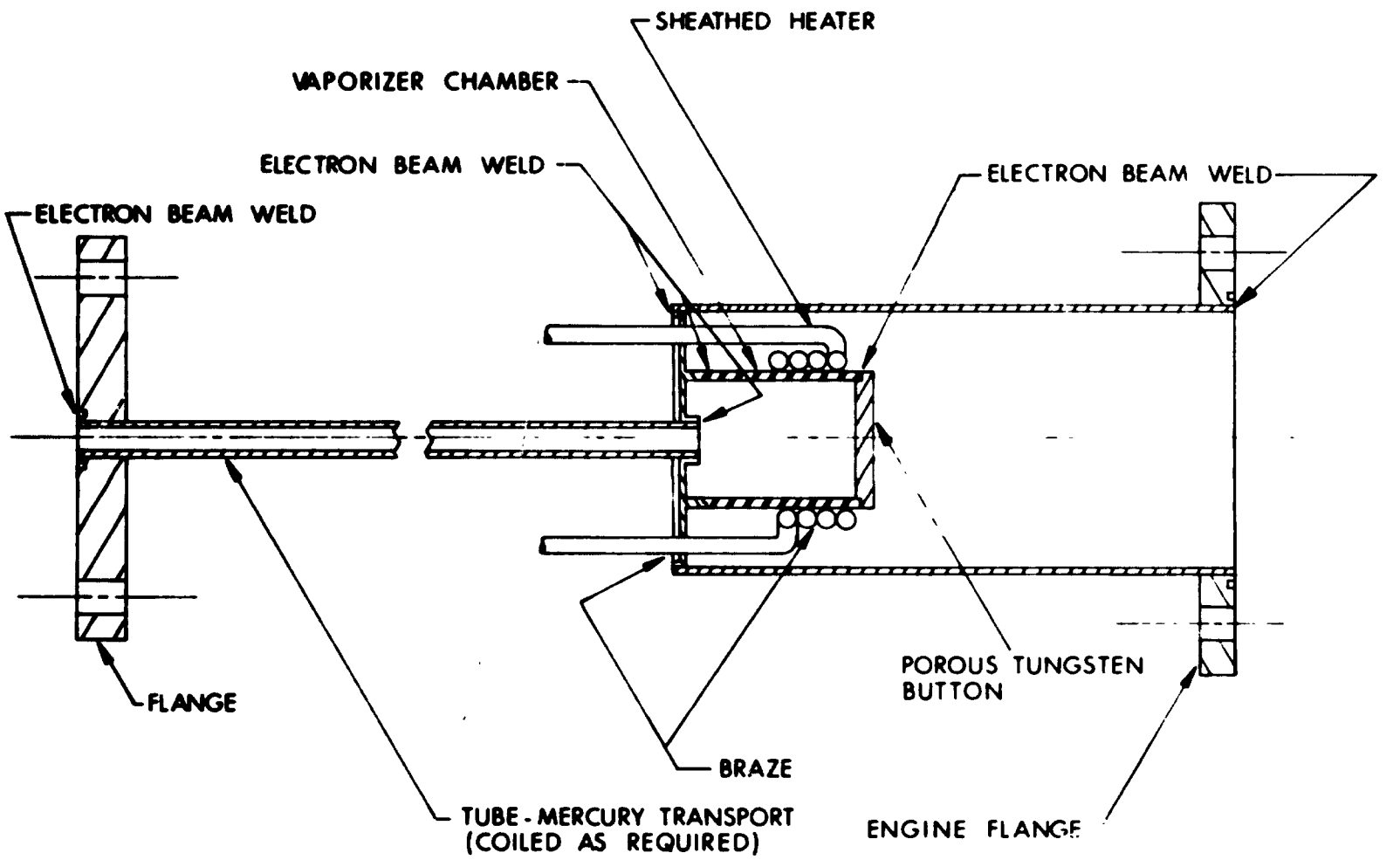

Figure 36. Prototype Vaporizer

the spherical powder buttons. The density of the spherical powder buttons was 77.2 percent and that for the angular powder was 68 percent.

These same buttons were then welded into tantalum tubes so that pressure required to extrude mercury liquid through the buttons could be determined. There was no extrusion at a pressure of 74 psig for either type button. Because of its better permeability the angular powder button was chosen for use in the prototype mercury vaporizer.

6. PROTOTYPE FEED SYSTEM TEST

A 1000 hour prototype feed system test was begun in November 1966. This test was conducted in the same manner as the laboratory system 1000 hour test. The test hardware, procedures, and results are described in this section.

6.1 Test Hardware

The same test hardware previously used for testing the laboratory feed system was used. One change however was made in the flow meter calibrating device. Figure 37 shows the collecting cups, cooling cups, and transducer. The collecting cups were fabricated from thick walled copper for greater thermal capacity. In addition, the top portion of each cup was heat shielded by alternating layers of fiberfrax and stainless steel foil. These modifications were made to increase the collecting efficiency and to allow a more accurate determination of the mass flow rate.

The feed system was operated in a closed loop mode with a deliverable mercury flow meter and control console, and the breadboard model vaporizer control.

6.2 Test Results

The feed system was loaded with 20 pounds mercury, pressurized to 35 psia and installed in a 5 ft x 12 ft test chamber. Once each day pertinent data was recorded and a flow rate determination made. Figure 38 shows data obtained versus time for vaporizer power and temperature, flow meter output, and calculated mass flow rate. In addition to this data flow meter temperature, flow meter body ratio, and tank pressure were recorded.

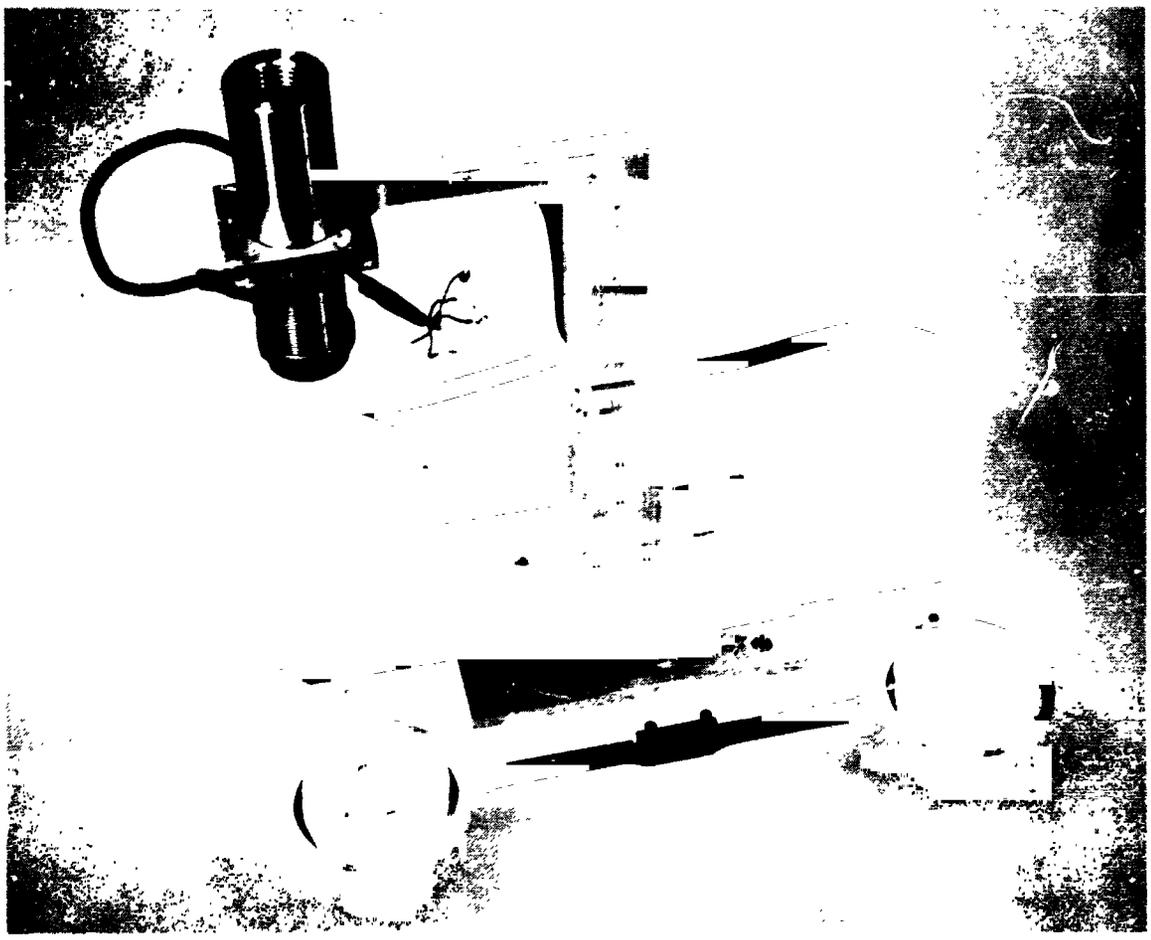

Figure 37. Calibrator Assembly

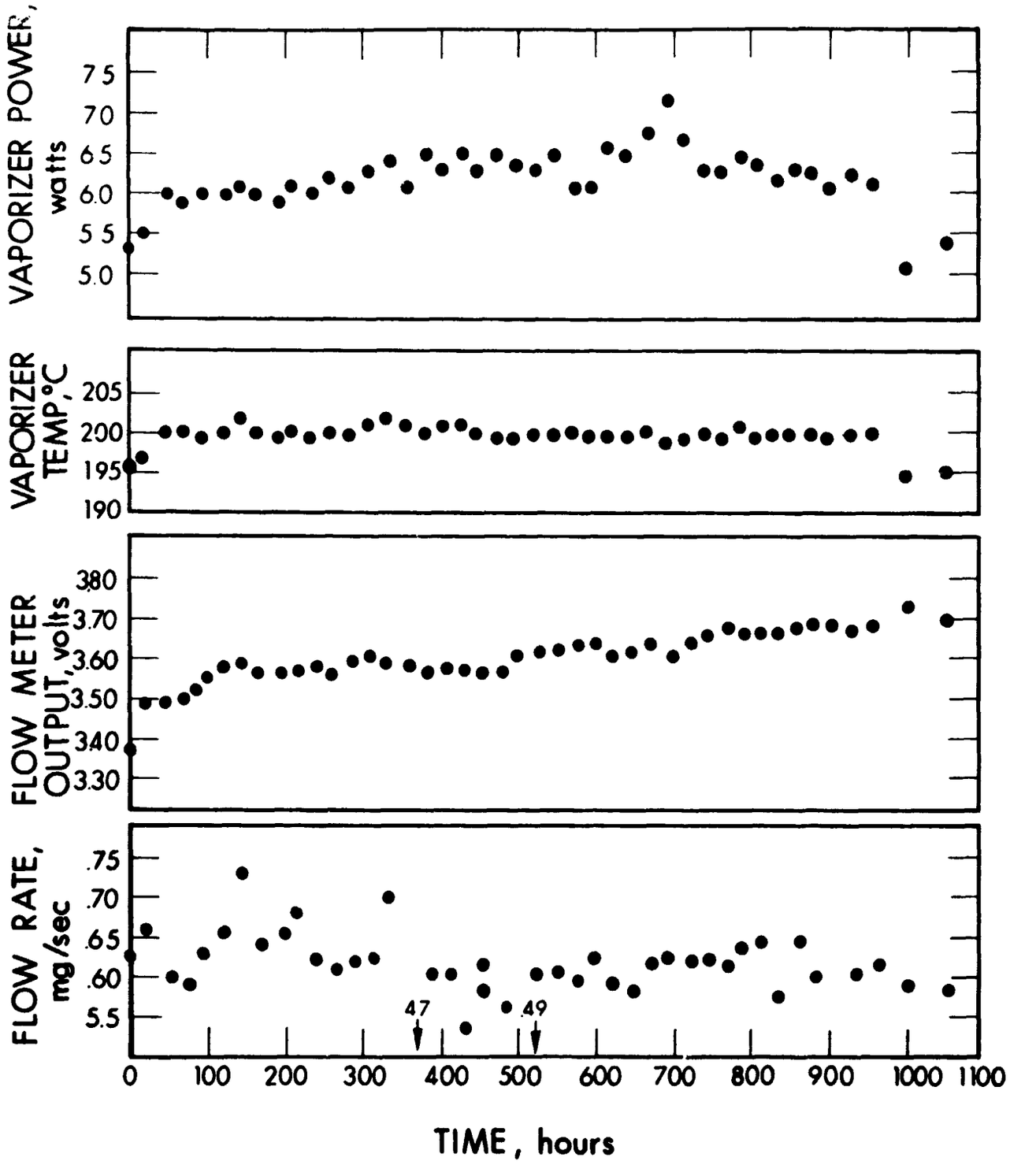

Figure 38. 1000 Hour Prototype Feed System Test Operating Parameters

The system was operated for a total of 1057 hours. The average flow rate determined by use of the calibrator was .61 mg/sec. The average flow rate calculated from the reservoir weight loss was .80 mg/sec. These values are much more consistant than those determined after the laboratory system test indicating a decided improvement in the calibrator collection efficiency.

Besides the collection efficiency problem one other factor affects the operation of the calibrator and best explains the change in performance near the end of the test. This is the difference in flow impedance between the two arms leading to the calibrating cups and that leading to the collecting reservoir. The impedance difference is large enough to cause the flow meter to indicate a higher flow rate during calibration. Because the system was operated in a closed loop mode, this higher apparent flow rate is fed into the control loop and the vaporizer power is reduced to obtain a constant flow meter output. When the flow is redirected into the collecting reservoir the flow meter indication decreases and the vaporizer power increases to compensate. The actual flow rate is then higher than indicated during calibration. An increase in plumbing diameter in the calibrator area would remove this problem.

The test was operated at a vacuum chamber pressure of 5×10^{-6} torr or less except for a period of about 10 hours commencing at approximately 350 hours accumulated operating time and a period of approximately 30 hours beginning at approximately 950 hours.

At 350 hours the foreline pressure safety meter failed. The diffusion pumps and gate valves were automatically turned off. The faulty meter was replaced and pumping was restored. During this time the tank pressure gradually increased to 2×10^{-4} torr.

At 950 hours the valve to the left collecting cup was accidentally left open. This caused the pressure to rise to the low 10^{-5} torr range. In order to rebalance the calibrator it was necessary to direct vapor flow into the right cup for an equal period of time. During this time

there was a decrease in the vaporizer temperature and power. The reason for this is most probably the increase in flow impedance during the time when flow is directed into the calibrator.

The vaporizer temperature was sampled by an iron-constantan thermocouple attached to the back plate of the vaporizer. The temperature recorded is lower than the temperature at the porous tungsten button due to some power lost in radiation. This error is only a few degrees due to the excellant thermal path involved. During the test the temperature stabilized at about 2' 0°C.

The vaporizer power was read on calibrated Weston ampere and volt meters. The power, well below the required 18 watts, varied between 6 and 6.5 watts during the test. Some of this variation is due to the adjustment of the vaporizer control to achieve a .65 mg/sec flow rate. There was no discernable trend toward either higher or lower power throughout the test.

The flow meter output is a dc voltage read on a digital voltmeter and is proportional to the mass flow rate. Since this test does not directly involve the testing of the flow meter the data is being taken for future reference only. The flow meter is however an important portion of the control loop and is being used as the reference signal for controlling the flow rate.

The flow rate is determined by measuring the increase in weight of a liquid nitrogen cooled collecting cup over a fixed period of time. This is identical to the system used on the laboratory feed system test. There is a difference in calculated flow rate between the left and right collecting cups probably caused by a poorer collection efficiency of the left cup. The data points shown are those calculated from data using the right cup only. Some of the variation is again due to adjustment of the vaporizer control to achieve the required .65 mg/sec flow rate.

Following the end of the run the feed system was disassembled and thoroughly examined. A sample of mercury was removed from the reservoir and spectrographically analyzed. There were no noticable increases in major constituents after the test. The vaporizer was

sectioned and was in perfect condition. There were no discolored areas, corrosion, erosion or wetting of the tungsten by mercury.

6.3 Conclusions

The successful tests of this type propellant system indicate that operating times far in excess of those corresponding to the propellant capacities used in the tests are feasible. In addition, flow rate control using a mercury vapor flow meter and a closed-loop control system was demonstrated. The narrow limits of variation of the vaporizer power and temperature demonstrated the high degree of stability and control of the system. In summary, the objectives of the program were met and the feasibility of the design approach and performance characteristics of the propellant system are established.

APPENDIX

QUALITY ASSURANCE

The quality assurance system employed to service the needs of this program closely paralleled the system concurrently in use on NASA-Lewis Contract NAS3-7112. Close cooperation between technical and product assurance personnel resulted in a flexible, efficient system for providing program support.

The basic system may be described as a shop traveller scheme. Quality information pertaining to fabricated articles and assemblies is entered on the traveller while work is in process. The traveller is ultimately placed in a permanent file as a record of actual detail part history. Supplementing shop traveller information are equipment logs containing test data and calibration records, and material certification files at receiving inspection. The shop travellers are instrumental in establishing quality criteria. Engineering drawings, test procedures, material and process specifications, and their respective revisions are prepared with the aid of the quality information on hand.

A1. QUALITY ASSURANCE PROGRAM FUNCTIONS

Quality assurance program functions pertained to the overall project activity and were not intended to be accomplished by any one department or group. Specific quality obligations were imposed on organizational elements other than the EOS Product Assurance Group which retained responsibility for the execution of product assurance policies and programs. A representative from Product Assurance was assigned to the project to work together with these other organizational elements. The representative assisted these groups in performing their quality assurance assignments. In this manner project and quality activity were continuously integrated.

A2. QUALITY ASSURANCE PROGRAM INFORMATION

LFS-3 final inspection report was prepared for a delivered laboratory-type mercury feed system including its control system.

LFS-4 and LFS-5 final inspection report was prepared for two delivered laboratory-type mercury feed systems including their control systems.

PFS-2 and PFS-3 final inspection report was prepared for two delivered prototype mercury feed systems.

PFS-4, 5, 6 and 7 Final inspection report was prepared for four delivered prototype mercury feed systems.

Equipment logs, including test and calibration data, were also prepared and maintained for each of the following:

Laboratory feed system S/N 1, S/N 3, S/N 4, S/N 5

Laboratory control system S/N 2, S/N 3, S/N 4, S/N 5

Flow meter S/N 2 and S/N 3

Flow meter control system S/N 1, S/N 3, S/N 4

Prototype feed system S/N 1, S/N 2, S/N 3, S/N 4, S/N 5, S/N 6, S/N 7.

One hundred and thirty seven shop travellers were processed during the contract period. Quality information contained on completed travellers was reviewed. Feed system vellums were revised in accordance with pertinent red-marks contained on the travellers.

A special parts processing instruction for preparation of 60 to 70 % dense tungsten components was issued.

The following test procedures were released:

6969-1) Laboratory Mercury Feed System

6969-3) Laboratory Feed Control System

6969-QAP-1, Rev. A) Inspection and Test Plan, Prototype Mercury Feed System.