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SIXTH

PROGRESS REPORT

AND PHASE I SUMMARY
PROGRAM TO DESIGN, FABRICATE,
TEST, AND DELIVER A THERMAL
CONTROL-MIXING CONTROL DEVICE
(CONTRACT NO. NAS8-~~32189~~)
31289

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Prepared by: T. S. Thurston/S. W. Haley

Approved by: L I Chambliss
L. I. Chambliss/Supvr., Documentation

T. G. Sutton
T. G. Sutton/Asst. Proj. Engr.

D. J. Schaffer
D. J. Schaffer/Sr. Proj. Engr.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

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1. INTRODUCTION AND SUMMARY

1.1 Introduction

This is the sixth monthly progress report which is presented as the Phase 1 summary on the program conducted by AiResearch Manufacturing Company of Arizona, a Division of The Garrett Corporation, for the George C. Marshall Space Flight Center, National Aeronautics and Space Administration, to design, fabricate, test, and deliver a thermal control-mixing control device as outlined in AiResearch Proposal 74-410766. The program was authorized by NASA Contract NAS8-31289 and is being accomplished under AiResearch Master Work Order 3409-248115-01-XXXX. The material in this report summarizes the program progress from initiation of the program on February 19, 1975, through August 20, 1975.

1.2 Summary of Phase I

Phase I of the program, which consisted of the development of a sensor capable of detecting temperature changes as a function of viscosity changes, has been completed. This type of sensor, consisting of an orifice bridge circuit, has resulted in a device with a threshold above internally generated noise of 0.8C (1.5F). Data was obtained using a "noise free" Freon source provided by an air pressurized bladder.

Tests conducted to operate the sensor from a typical Freon centrifugal pump system employing an air bubble accumulator for noise attenuation disclosed the sensor could be used only to sense temperature changes greater than 3.3C (6F) because of the excessively noisy output. This is attributed to the high frequency-pressure fluctuations in the Freon supply to the sensor.

An alternate sensor concept being developed under an AiResearch company-funded Research and Development program using a fluidic pin amplifier in conjunction with an expansion device will be used for the Phase III portion of this program. This concept will be employed since the sensor is not dependent on the fluid characteristics.

2. DESIGN AND EVALUATION OF TEMPERATURE SENSOR

2.1 Operation of the Orifice Bridge Type Viscosity Change Temperature Sensor

The orifice bridge sensor shown in Figure 1 consists of two types of restrictors, capillary (R_1 and R_4) and vortex (R_2 and R_3).

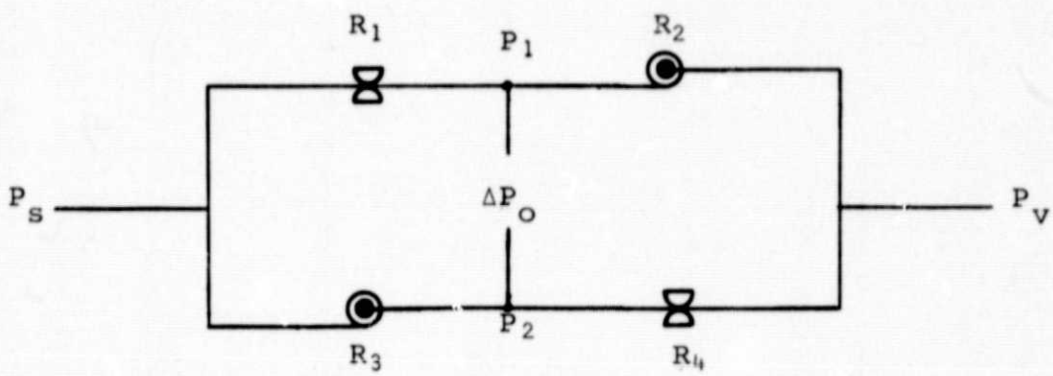

FIGURE 1

ORIFICE BRIDGE SENSOR

The effective resistance of the restrictors will change as a function of viscosity. The effect of viscosity change on a vortex restrictor is somewhat different than on a capillary restrictor. Two dissimilar restrictors placed in series like R_1 and R_2 in Figure 1 will produce a change in P_1 that is proportional to viscosity or temperature. By reversing the order of R_1 and R_2 relative to supply and vent, R_3 and R_4 would produce an opposite effect. In the orifice bridge circuit, the differential pressure, ΔP_o, represents a pressure gain twice that of the series restrictors.

The performance of the orifice bridge sensor with a noise-free power supply (Figure 2) is shown in Figure 3.

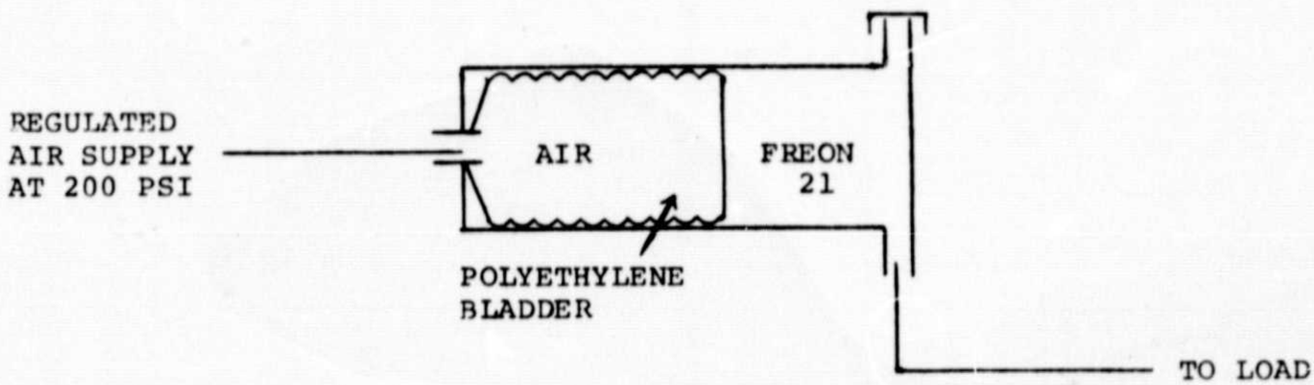

FIGURE 2

BLADDER USED IN NOISE-FREE POWER SUPPLY

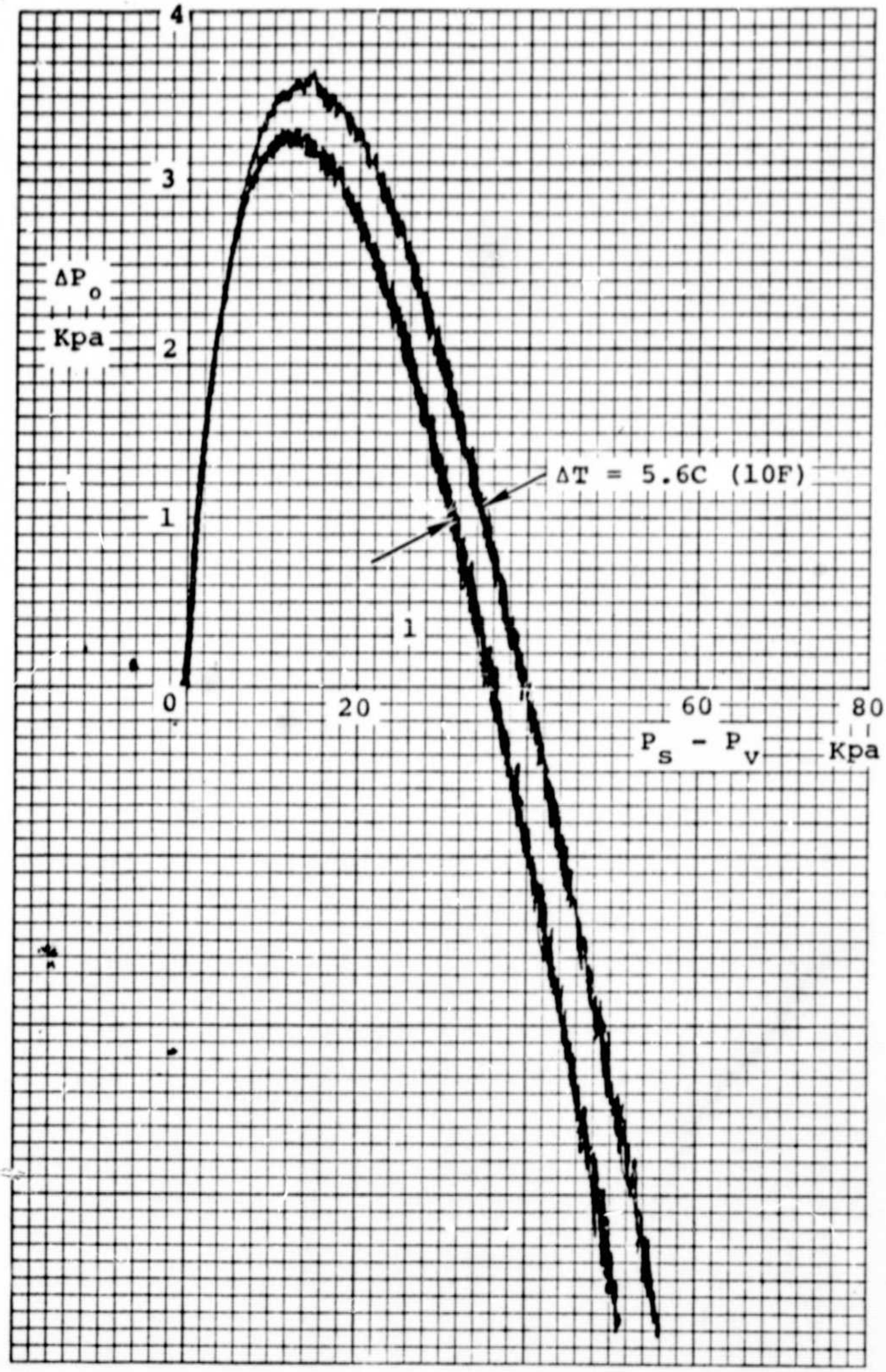

FIGURE 3

OUTPUT OF TEMPERATURE SENSOR

2.2 Analysis of the Orifice Bridge Viscosity Change Temperature Sensor

The analyses and theory presented herein were applied to a simple circuit employing two dissimilar restrictions connected in series as shown in Figure 4.

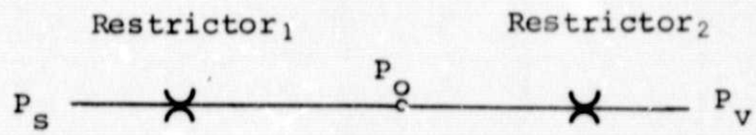

FIGURE 4

DISSIMILAR RESTRICTIONS
CONNECTED IN SERIES

where

P_s = Supply pressure

P_v = Vent pressure

P_o = Output pressure

Starting with the basic flow equation for incompressible flow through a restriction, and by assuming that the flow is dependent upon a Reynolds number, the following equation for flow along a differential length of a restriction is obtained.

$$\frac{-dP}{d\ell} = C_f \frac{\rho V^2}{2} = C_f \frac{\omega^2}{2\rho A^2}$$

where

dP = Differential pressure drop

$d\ell$ = Differential length

C_f = Flow coefficient (dependent on Reynolds number and restrictor geometry)

ρ = Fluid density

V = Fluid velocity

ω = Weight flow rate

A = Flow area

By separating the variables and integrating the equation along the length of the restriction, the incompressible theory yields:

$$\int_{P_i}^{P_o} -dP = \int_0^{\ell} \frac{\omega^2}{2A^2\rho} C_f \, d\ell = \frac{\omega^2}{2A^2\rho} \int_0^{\ell} C_f \, d\ell$$

where

P_o = Pressure downstream of restriction

P_i = Pressure upstream of restriction

T = Fluid temperature

P = Local pressure

where the term $\int_0^{\ell} C_f \, d\ell$ is proportional to the Reynolds number at the B power.

For Reynolds number similitude and fixed geometry

$$P_i - P_o \propto R_e^{\beta} \omega^2 T$$

where

R_e = Reynolds number

β = Assumed Reynolds number exponent

By substituting $\frac{\rho V d}{\mu}$ for R_e, assuming that $\mu \propto T^K$ and $\rho V \propto \omega$, and then solving the flow rate, we obtain:

$$\omega \propto (P_i - P_o)^{\eta} T^{\alpha}$$

where

$$\eta = \frac{1}{\beta + 2} \text{ and } \alpha = \frac{K\beta}{\beta + 2}$$

μ = Fluid viscosity

K = Exponent on viscosity temperature term

It is interesting to note that the pressure exponent, η, and the temperature exponent, α, are not independent.

Temperature gain, supply sensitivity, the determination of η and α, and bridge temperature sensors analyses follow.

2.2.1 <u>Temperature Gain</u>, $\frac{\partial P_o}{\partial T}$ - By adjusting the flow in the two series restriction to equal each other, then taking the partial derivitive with respect to temperature and solving for $\frac{\partial P_o}{\partial T}$, the following gain is obtained.

$$\text{Incompressible:} \quad \frac{\partial P_o}{\partial T} = \frac{\alpha_1 - \alpha_2}{T\left[\frac{\eta_1}{P_s - P_o}\right] + \left[\frac{\eta_2}{P_o - P_v}\right]} \qquad (1)$$

2.2.2 Supply Sensitivity, $\frac{\partial P_o}{\partial P_s}$, - By again adjusting the flow in the two series restrictions equal to each other, taking the partial derivitive with respect to P_s, and solving for $\frac{\partial P_o}{\partial P_s}$, the following is obtained.

$$\text{Incompressible:} \quad \frac{\partial P_o}{\partial P_s} = \frac{\eta_1}{\eta_2\left[\frac{P_s - P_o}{P_o - P_v}\right] + \eta_1} \qquad (2)$$

2.2.3 Determination of α and η - After defining the temperature gain and supply sensitivity above as functions of η and α for the two restrictions, the last step was to determine these values. Since α and η are both defined functions of β, the only required values were the values of β for each restriction. β can be determined from the flow/pressure data of each restriction.

NOTE: If η is known, β may be solved for and used to find α.

$$\text{Incompressible:} \quad \beta = \frac{1}{\eta} - 2$$

$$\alpha = \frac{K\beta}{\beta + 2} = K\eta\left(\frac{1}{\eta} - 2\right)$$

2.3 Bridge Circuit Performance

Using the previously derived equations for gain and supply sensitivity (and with all parameters defined at zero ΔP_o), the bridge circuit performance is defined as follows:

2.3.1 Gain

$$\text{Incompressible:} \quad \frac{\partial \Delta P_o}{\partial T} = \left[\frac{\alpha_1 - \alpha_2}{\eta_1 + \eta_2}\right]\left[\frac{P_s - P_v}{T}\right] \qquad (3)$$

where

$\left(P_s - P_o\right) = \left(P_o - P_v\right)$ for maximum gain.

2.3.2 Supply Sensitivity

$$\text{Incompressible:} \quad \frac{\partial \Delta P_o}{\partial P_s} = \frac{\eta_1 - \eta_2}{\eta_1 + \eta_2} \tag{4}$$

Since null of the bridge circuit occurs at a particular temperature, which is a function of supply pressure, the sensitivity of the set point temperature changes as a function of supply pressure, $\frac{\partial T_{set}}{\partial P_s}$, as defined below.

2.3.3 Setpoint Pressure Sensitivity

$$\frac{\partial T_{set}}{\partial P_s} = - \frac{\partial \Delta P_o}{\partial P_s} \quad \frac{\partial \Delta P_o}{\partial T}$$

$$\text{Incompressible:} \quad \frac{\partial T_{set}}{\partial P_s} = \left[\frac{T}{P_s - P_v}\right]\left(\frac{1}{2K}\right) \tag{5}$$

NOTE: The sensitivity of the setpoint temperature to supply pressure is a function of the sensitivity of the fluid viscosity to temperature and is independent of the flow characteristics of the restrictions used.

2.4 Bridge Circuit Operating on Freon 21

The gain of the bridge circuit shown in Figure 1 can be determined from the equation derived in the previous sections. The following values have been determined experimentally for Freon, capillary restrictors, and vortex restrictors.

Freon 21	$K = 2.38$
Capillary restrictors	$\beta_c = -0.37$; $\alpha_c = 0.54$; $\eta_c = 0.61$
Vortex restrictors	$\beta_v = 0.22$; $\alpha_v = -0.24$; $\eta = 0.45$

With (P_s - P_v) of 100KPA (14.5 psi) and a set point temperature of 283K (50F), the anticipated temperature sensor gain is approximately 0.26KPA/K (0.021 psi/F). The ancitipated set point pressure sensitivity is approximately 0.59K/KPA (7.32F/psi) for the same conditions.

Since an entire control band of 50 ±3F was specified, it is reasonable to allow ±0.56C (±1F) of sensor inaccuracy due to supply pressure variations. Solving Equation (5) for the allowable supply pressure variations, it was found that:

$$\Delta(P_s - P_v) = 2K \frac{\Delta T_{set}}{T_{set}} (P_s - P_v)$$

NOTE: The symbol, Δ, is used to represent allowable parameter variations.

Therefore, the allowable supply variation is 0.93 percent.

2.5 Performance of the Orifice Bridge Viscosity Change Temperature Sensor

The performance of the bridge circuit with a noise-free power supply was shown in Figure 3. The set point conditions of this sensor is approximately 283K (50F) with (P_s - P_v) at approximately 40KPA (5.8 psi). The temperature sensitivity of the sensor is approximately 1.25KPA/K (0.1 psi/F) and the set point pressure sensitivity is approximately 1.6K/KPA (20F/psi). These values were within 15 percent of those estimated by analysis.

The noise present on the output signal of the bridge circuit corresponds to approximately 0.8C (1.5F). This noise is assumed to be flow noise and could be reduced.

Figure 5 shows the performance of a bridge circuit which has approximately ±10KPA (±1.45 psi) noise in the supply pressure. The noise level generates approximately 6C variation in the temperature signal. This also makes it apparent that the noise on the supply pressure be eliminated to allow the sensor to operate within the prescribed control bands.

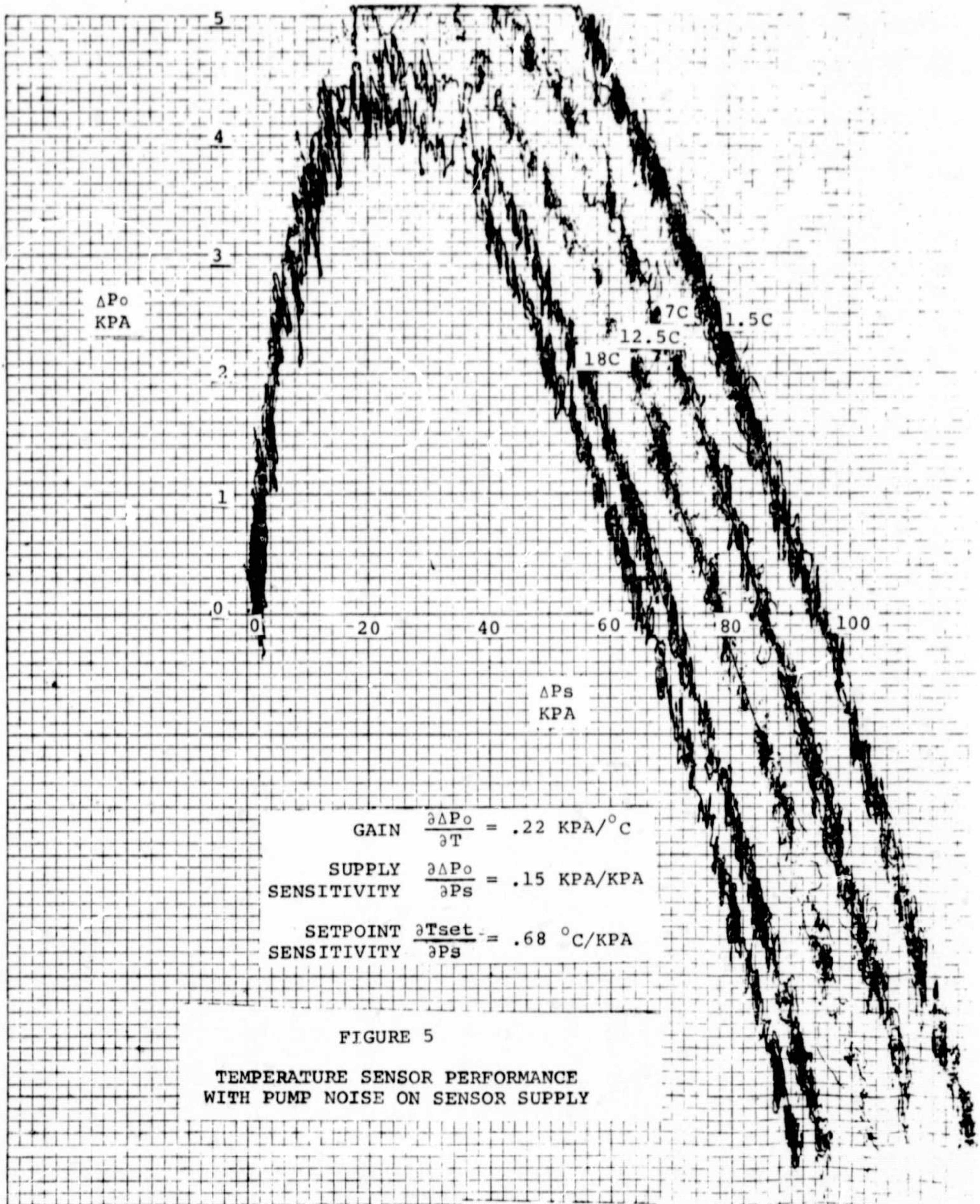

FIGURE 5

TEMPERATURE SENSOR PERFORMANCE
WITH PUMP NOISE ON SENSOR SUPPLY

3. DEVELOPMENT TESTING OF THE ORIFICE BRIDGE VISCOSITY CHANGE TEMPERATURE SENSOR

3.1 Argon-Freon Innerface Power Supply

Regulated argon was used to pressurize a Freon bottle, in the interest of saving time and expense, as shown in Figure 6. The pressurized Freon was used through a heat exchanger as the supply to the bridge circuit.

When the system was tested, the output of the sensor was too noisy to provide useful information needed in the sensor development. It was then discovered that the Freon was absorbing argon.

A conclusion made at this time was that the argon came out of solution in the passages of the bridge circuit. This was believed to be the cause of the noise in the sensor. The argon-Freon innerface power supply was abandoned at this time.

3.2 Freon Vapor Pressure Power Supply

The next approach in creating a power supply is shown in Figure 7. A pressure difference was produced by heating the supply reservoir and cooling the vent reservoir.

This method of producing a power supply also created noise on the sensor's output. It was concluded that the pressure which the sensor operated was too low to assure the Freon was not in two phases while in the passages of the sensor. At this point it was decided that all further Freon testing would be done with a 100KPA (14.5 psi) pressure differential with the supply pressure at 1400KPA (200 psig) to eliminate any problems associated with Freon being in two phases.

3.3 Freon Pump Power Supply

A pump had to be acquired that would operate in a Freon 21 environment because of the corrosive properties of Freon 21. Time to acquire this pump resulted in a delay in the program schedule.

A schematic diagram of the test setup is shown in Figure 8. A centrifugal pump is used in this system with a flow rate of 15.1 litre/min (4.6 gpm) at 1370KPA (200 psia). During testing, it was discovered that the pump was generating noise in the supply pressure. The amplitude of this noise is shown in Figure 9A and was approximately ±43KPA (±6 psi) at a frequency of 250 Hz. The sensor was unable to meet the sensitivities needed for this application with the noise level present in the Freon supply.

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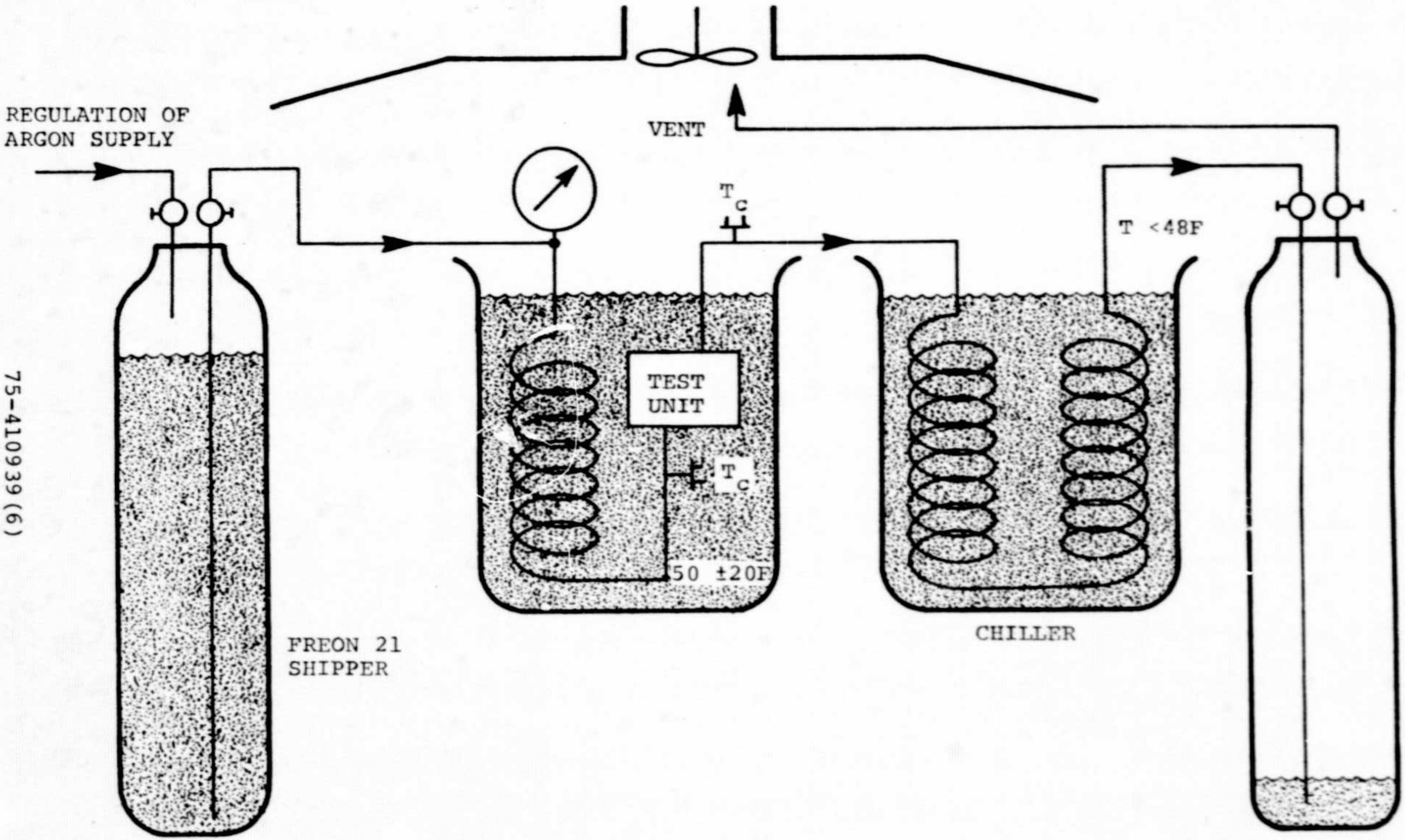


FIGURE 6

TEMPERATURE SENSOR TEST SETUP
PHASE I

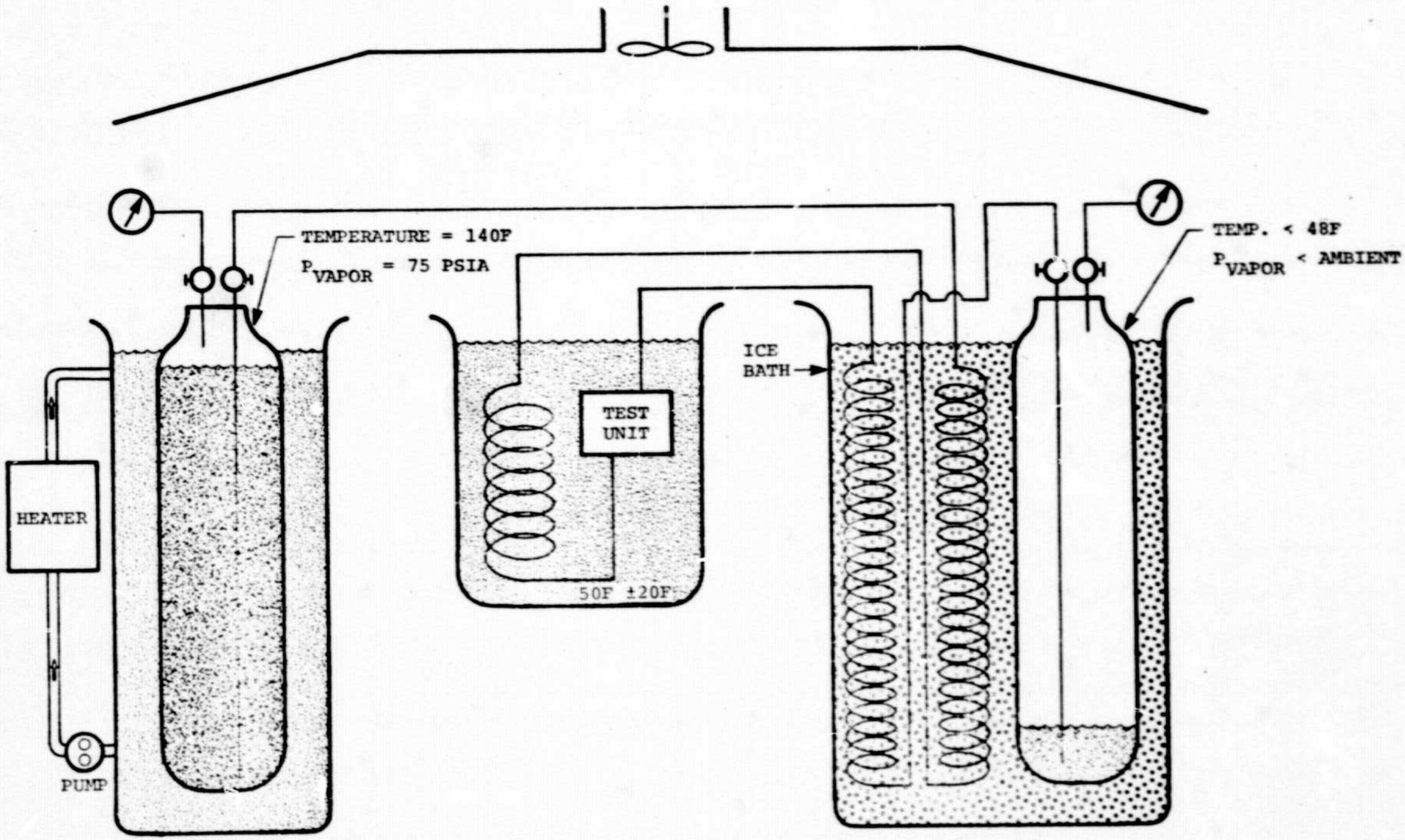


FIGURE 7

MODIFIED TEMPERATURE TEST SETUP
PHASE I

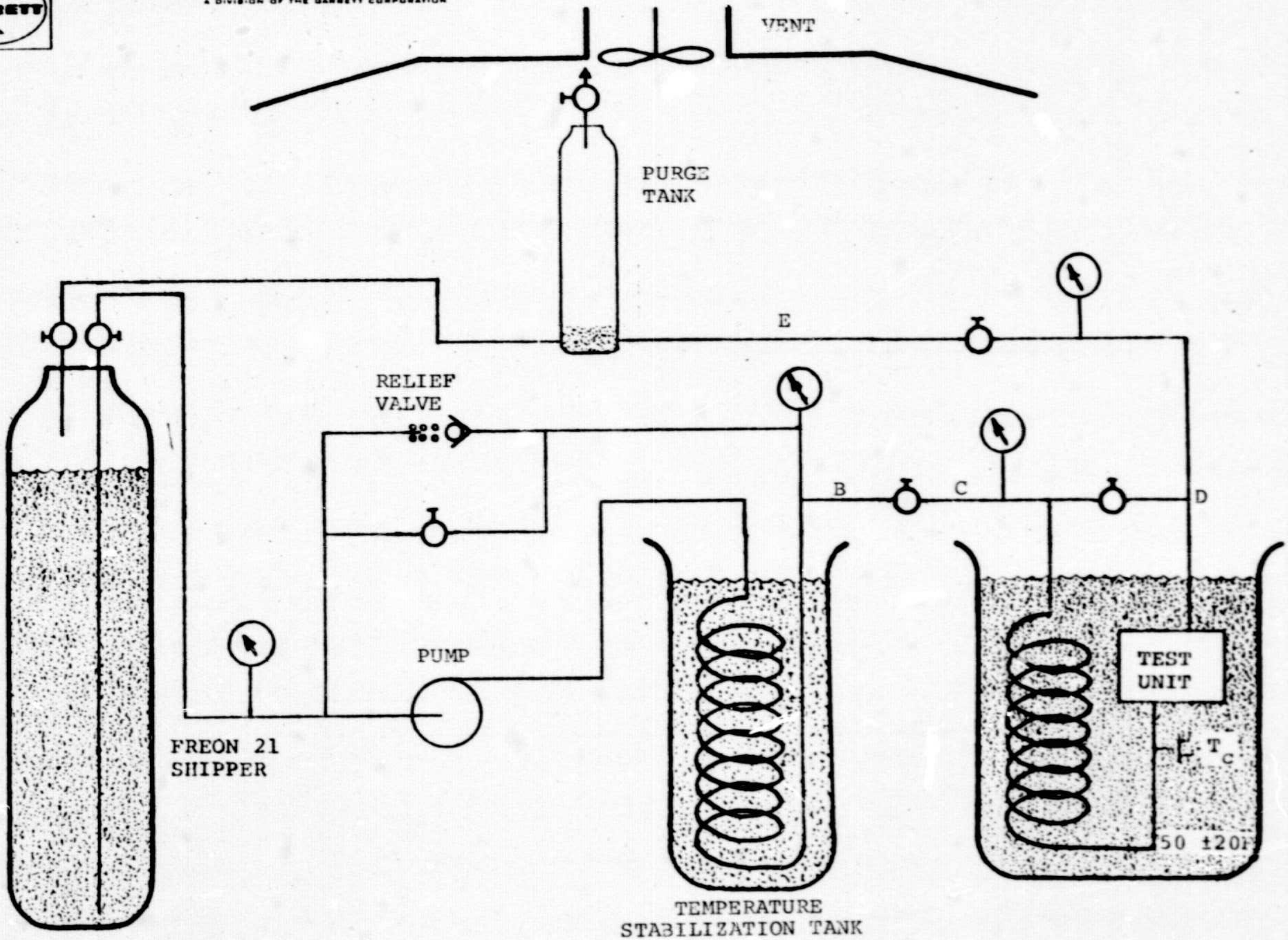
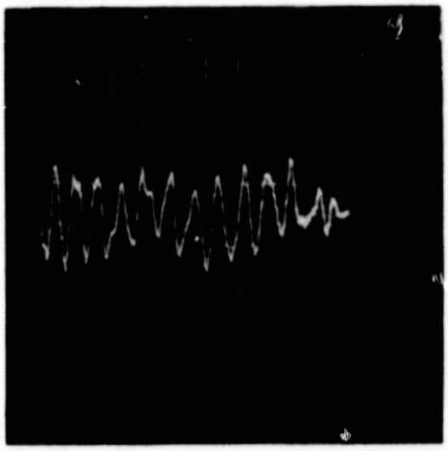


FIGURE 8

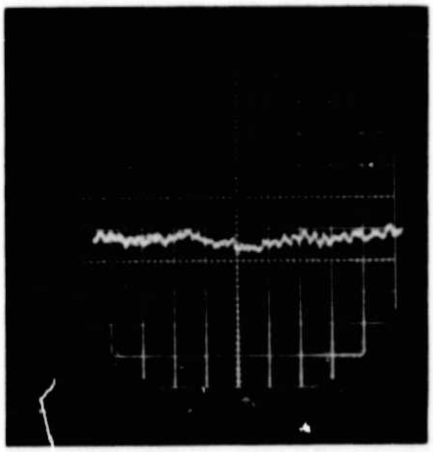
FREON PUMP POWER SUPPLY

SCALE: HORIZONTAL - 5 MS/DIV
VERTICAL - 35 Kpa/DIV (5 PSI/DIV)



A

FREON PUMP OUTPUT



B

OUTPUT WITH AIR BUBBLE IN A VOLUME AT THE PUMP OUTLET

FIGURE 9

FREON PUMP OUTPUT NOISE

The only way that the bridge type viscosity sensor will operate on Freon 21 to meet the design tolerances would be if the supply pressure noise level is below 0.93 percent of the bridge circuit differential pressure ($P_s - P_v$). Since there are no pumps available that can provide such a power supply, the only solution was to provide an acceptable level.

Various types of attenuation were investigated. The response requirement of an attenuator needed for this application immediately eliminated all mechanical accumulators with moving parts of appreciable mass. Off-the-shelf accumulators capable of high frequency response are typically of the bladder type; however, Freon 21 compatibility problems prevented the use of these accumulators.

An air bubble accumulator was introduced into the system at point B of Figure 8. Ideally the air bubble accumulator will provide the best filtering effect in that there is a negligible mass interface between the air and Freon. However, this type of accumulator can not be used in a real life system because the air is slowly absorbed into the Freon. This accumulator was used only to determine the approximate amount of filtering that could be achieved. The results of this type of filtering is shown in Figure 9B.

It is estimated that an accumulator with a polyethylene bladder which is not affected by the corrosive action of Freon 21 could be constructed with a noise amplitude of less than ±7KPA. A schematic diagram of the accumulator is shown in Figure 10.

3.4 Noise-Free Power Supply Using Polyethylene Bladder

A schematic diagram of the noise-free power supply is shown in Figure 11. This supply provides a noise-free pressure to the bridge for a short period of time. This is not a closed loop system and was used only to eliminate the supply pressure noise.

By eliminating the supply pressure noise, the temperature circuit may be tested and examined for its sensitivities, gain, and any other noise present in the circuit.

The remaining noise on the sensor output could be assumed to be the result of turbulent fluid flow in the sensor passages. The bridge output under this condition is shown in Figure 3, and reveals that the flow noise corresponds to approximately 1.5F (0.8C). This noise level was reduced from that found in previously built sensors by modifying the transfer passages within the fluidic stack. It can be assumed that further improvement in this area is possible.

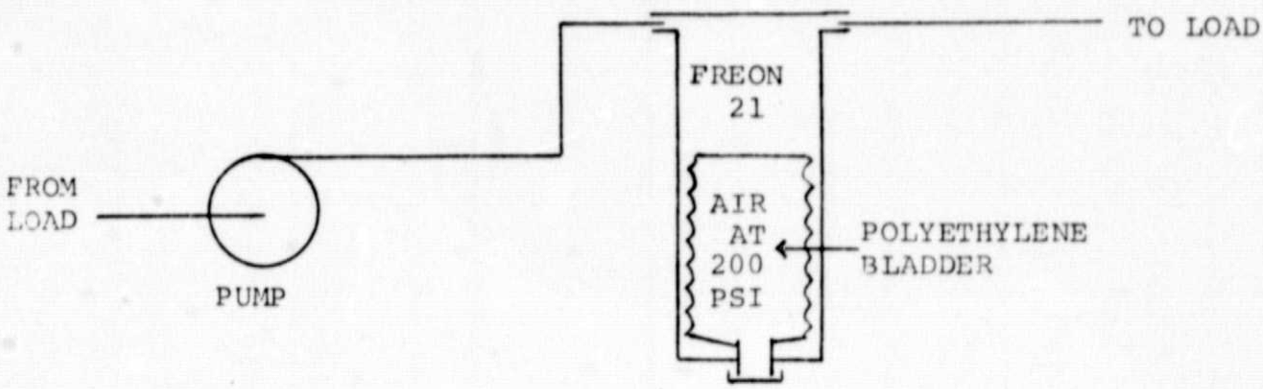


FIGURE 10

BLADDER USED IN NOISE ATTENUATOR

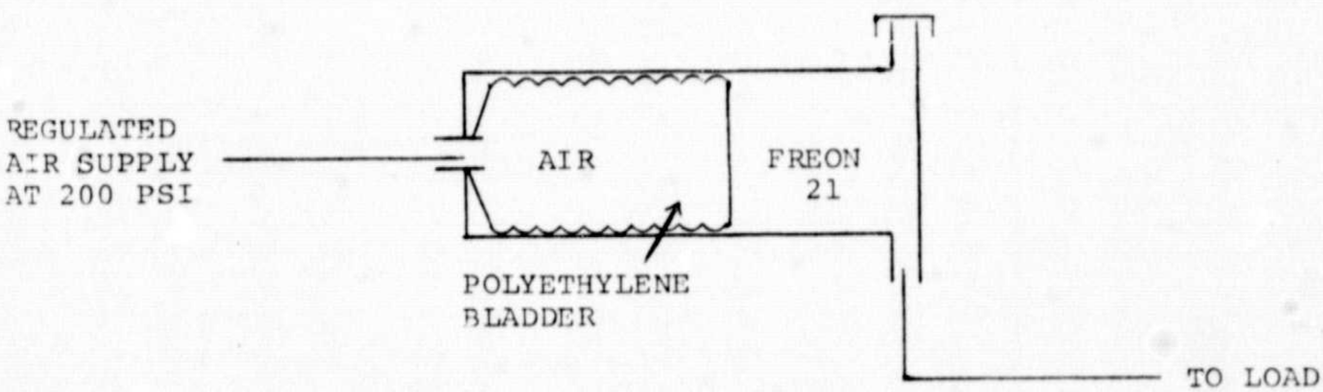


FIGURE 11

BLADDER USED IN NOISE-FREE
POWER SUPPLY

3.5 Material Compatibility Problem with Freon 21

In addition to problems experienced due to the characteristics of Freon affecting sensor performance, Freon 21 is found to be incompatible with all elastomers normally used for diaphragms, O-rings, and gaskets. For this reason, many items used in the test setup must be of special design, whereas common off-the-shelf items could be used with other fluid mediums.

4. CONCLUSIONS OF PHASE I PROGRAM

The pressure sensitivity of bridge circuit temperature sensors operating on Freon 21 is not compatible with the noise level on the pump output to achieve the desired control accuracy, even while using the most effective known methods of noise attenuation.

By filtering the supply such that pressure variation would be maintained within ±0.93 percent, a bridge-type temperature sensor could be developed with tolerances capable of controlling temperature to an estimated ±2.8C (±5F). An additional 0.56C (1F) would be added to the control tolerance for each additional 0.93 percent pressure variation in the supply.

It would be possible to test the system as required in Phase III by using a dual supply, i.e., a pump for the valves and pressurized supply for the sensor.

The temperature sensor desired for this system should be insensitive to supply variation, so that the effect of noise generation in the power supply is eliminated.

5. FUTURE WORK PLAN

Work will proceed with Phase II of the program to analyze the valve concepts and to select, design, fabricate, and test a valve.

6. SCHEDULE AND COST SUMMARY

6.1 Program Schedule

Figure 12 depicts the estimated time schedule for the various tasks in the program. The figure shows the most recent revisions based on completion of Phase I.

6.2 Program Cost

Figure 13 presents a comparison of estimated and actual program cost.

6.3 Program Man-hours Expended

The total man-hours expended on the program to date are as follows.

Engineering man-hours	733
Laboratory man-hours	224
Total	957

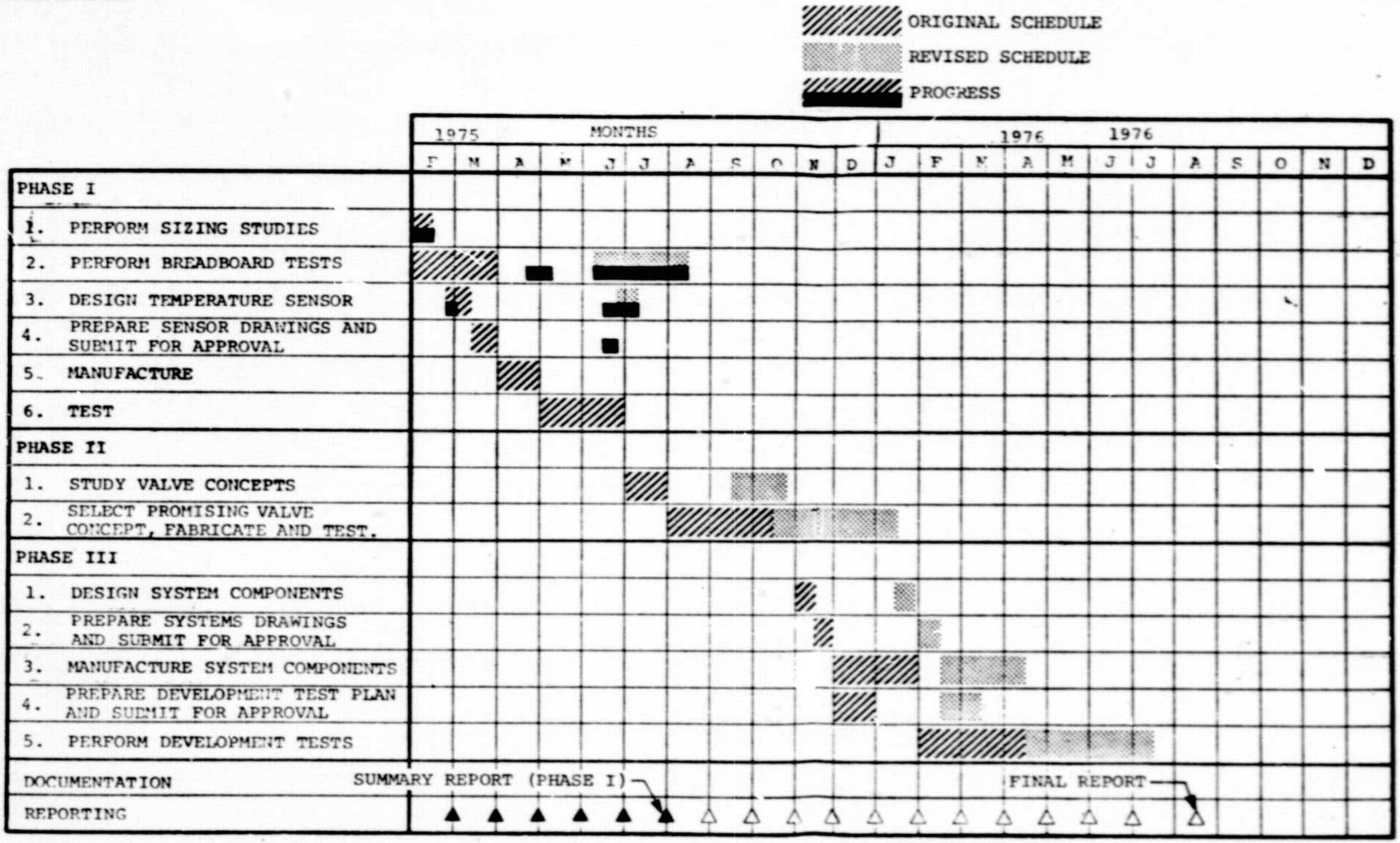


FIGURE 12

PROGRAM PLAN FOR THE DESIGN, FABRICATION, TESTING, AND DELIVERY OF A THERMAL CONTROL-MIXING CONTROL DEVICE

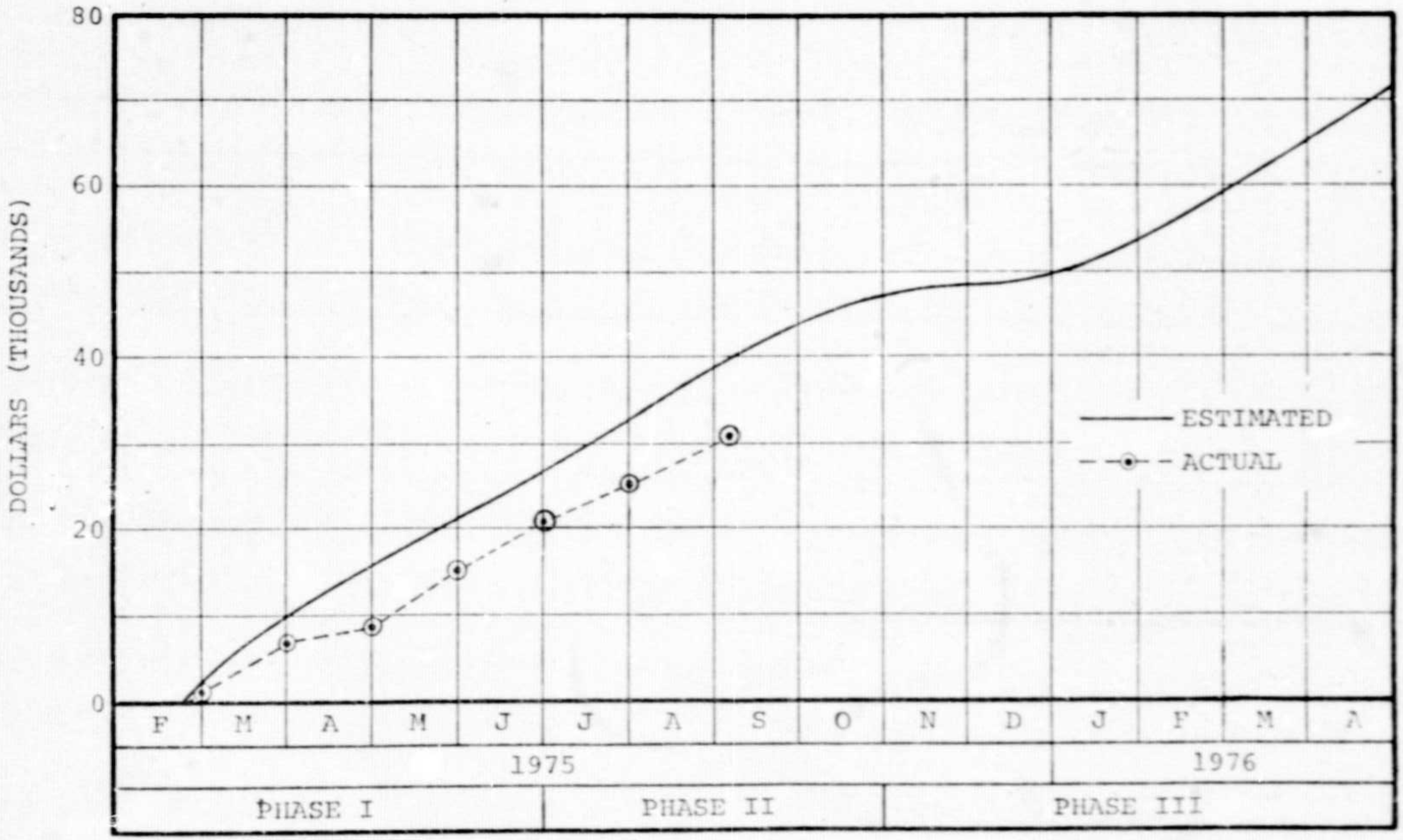


FIGURE 13

RATE OF EXPENDITURE
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