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1.0 SUMMARY

This is the final report of the work performed under contract to NASA Manned Space Flight Center on the design and test of an all mechanical Mass Flow Controller. The program involved design, development, manufacture of four MFC units and a test program using inert gas as the test medium. The unit controlled the pressure within ± 1 percent. An analytical method is described for relating the control pressure error with error in mass flow.

2.0 INTRODUCTION

Control of the mass flow rate is essential for controlling the fuel-oxidizer mixture ratio or controlling the thrust level of a rocket engine. In a rocket engine designed for a constant thrust level, the flow rate of the propellants must be maintained essentially constant. When gaseous propellants are used, it becomes more difficult to maintain a constant flow rate than when liquid propellants are used. In a typical rocket engine system using gaseous propellants, both the pressure and temperature of the propellant supply will vary. The function of a mass flow controller is to compensate for these variations as required to maintain the flow rate constant.

An all mechanical approach to mass flow control is illustrated in Figure 1. In this approach a fixed flow restriction is combined with a temperature biased absolute pressure regulator. The pressure regulator maintains a constant control pressure, Po, so long as the temperature of the propellant does not change, even though the propellant inlet pressure varies. Under these conditions the pressure at both ends of the fixed flow restriction is constant and the flow rate is therefore constant. When the propellant temperature changes, the temperature biased pressure regulator alters the control pressure proportionally so as to maintain the flow rate constant through the fixed restriction.

The equation for subsonic gas flow through a fixed restriction can be approximated by the equation

$$\omega = \frac{2g}{R} \quad CA \sqrt{\frac{Pc\,(Po-Pc)}{ZT}} \quad \ldots\ldots\ldots\ldots \quad (1)$$

It can be seen that the flow rate through the fixed restriction will be constant if the term under the radical is maintained constant. This term is constant when the pressure drop, Po - Pc, is caused to vary with the absolute temperature, T. This is easily seen when Pc and Z are constant; actually these two terms vary somewhat with temperature, which requires minor modification to the proportionality maintained between Po - Pc and T.

DEFINITIONS OF SYMBOLS

A	Flow area of throttling element, in^2
A_b	Bellows area, in^2
C	Coefficient of discharge, dimensionless
C_b	Specific heat of bellows, $\frac{BTU}{LB - {}^oR}$
F	Force, lbs
g	Conversion Factor, $\frac{LB_m\ ft}{LB_f - sec^2}$
h	Film Coefficient, $\frac{BTU}{sec - in^2 - {}^oR}$
I_{sp}	Specific Impulse, $\frac{LB\ f}{LB_m - sec}$
K_b	Thermal Conductivity of Bellows $\frac{BTU}{sec - in - R}$
K_s	Thermal Conductivity of Belleville Spring, $\frac{BTU}{sec - in - {}^oR}$
L	Bellows Stroke, in
L_b	Bellows Conduction Path, in
L_s	Belleville Spring Conduction Path, in
M_b	Mass of Bellows Corrugations, lb
M_s	Mass of Belleville Spring, lb
P_b	Bellows Charge Pressure, psia
P_c	Thrust Chamber Pressure, psia
P_i	Inlet Pressure, psia
P_o	Control Pressure, psia
R	Specific Gas Constant $\frac{Ft - LB_f}{LB_m\ {}^oR}$
T_b	Temperature of Bellows, ^oR
T_{bo}	Temperature of Bellows, ^oR
T_g	Temperature of Propellant, ^oR
T_s	Temperature of Belleville Spring, ^oR

DEFINITIONS OF SYMBOLS (continued)

T	Temperature, ^{o} R
t	Time, secs
V	Volume, in^3
w	Flow Rate, lb/sec
x	Percent error in oxygen flow rate
y	Percent error in hydrogen flow rate
Z	Compressibility Factor, dimensionless

3.0 BASIC DESIGN CONCEPT

In the all mechanical approach a fixed flow restriction is combined with a temperature biased absolute pressure regulator, hereinafter referred to as the Mass Flow Controller (MFC). In a rocket engine the injector together with the ducting connecting the injector and the MFC constitute the fixed flow restriction. At the beginning of the program this flow restriction was assumed to result in a 60 psi pressure drop when passing rated flow at 100°F to a combustion chamber at 300 psia. The chamber pressure varies somewhat with the temperature of the entering propellant in accordance with Figure 2.

Figure 2 was obtained from the expression

$$\frac{Pc(T)}{Pc(560} = \frac{I\ sp\ (T)}{I\ sp\ (560)} \quad . . . . (2)$$

which is valid for constant mass flow of the rocket engine.

The variation of specific impulse with temperature was obtained from Figure 3. Figure 3 was prepared from data from NASA Houston for a rocket engine with a O/F ratio of 4, **expansion** ratio of 40 and a thrust chamber pressure of 300 psia. This curve is valid for O/F ratio from 3.8 to 4.2.

Figure 4 includes two curves, one for oxygen gas and one for hydrogen gas, showing the required variation in control pressure with temperature for constant mass flow. The curves were prepared using the equation

$$\omega = \frac{CA\ P_c\ M}{Z\ \ T} \quad . . . . (3)$$

Which is a more exact equation than (1) for the flow through a fixed restriction.

Figure 5 is a schematic drawing of the Mass Flow Controller. It incorporates a shutoff poppet, which is controlled by a two-position, three-way solenoid pilot valve for the off-on function. Downstream of the shutoff poppet is the pressure balanced throttling element, consisting of a stationary cylinder and a rotating cage. The cage is normally positioned by the belleville spring so that its slots are aligned with the slots in the cylinder. When the pressure at the outlet, Po, rises to the set value, the bellows, which connects with the cage through a linkage, rotates the cage toward a more restrictive position. The amount of cage rotation is that required to maintain the outlet pressure at its correct value for the temperature of the propellant. When the propellant temperature increases, the internal pressure in the bellows increases and causes the MFC to control the outlet pressure to a higher value.

In order for the MFC to vary the outlet pressure with temperature in accordance with one of the curves of Figure 4, the slope must be correct and the pressure level must be correct. The slope of the curve is determined primarily by the bellows charge pressure: the greater the charge pressure, the steeper the slope (larger pressure change for a given change in propellant temperature). The pressure level of the MFC is determined by the pressure charge and the belleville spring load.

3.1 Tolerance

The all mechanical MFC is basically a temperature biased absolute pressure regulator. It uses a helium charged bellows to sense both the pressure and the temperature of the flowing gas. Because the MFC is a pressure operated device its precision is best expressed in terms of a tolerance in the control pressure, e.g. ±3 psi at 0°F temperature. It is of interest however to relate pressure tolerance to tolerance in mass flow, mixture ratio and thrust when two controllers (an oxygen MFC and a hydrogen MFC) are used to supply a rocket engine.

When one MFC delivers its propellant at a higher or lower pressure than the correct value, it causes a proportional error in the flow rate of its propellant. This error in flow rate results in a deviation in the chamber pressure of the rocket engine. The change in chamber pressure represents a change in the outlet pressure of the fixed flow restriction of the other propellant; consequently it causes an error in the mass flow rate of the other propellant even when the MFC for that propellant is controlling without a pressure error.

An analytical method was developed for relating these tolerances. It consists of assuming a percentage error in flow rate of each propellant and calculating the resulting mixture ratio, chamber pressure, and control pressure for each propellant. Figures 6 and 7 were constructed from the results of several such computations. Details of the method are described below.

An error of +x% error in oxygen flow rate and +y% error in hydrogen flow rate results in the following O/F mixture ratio

$$O/F = \frac{4\left(1 + \frac{x}{100}\right)}{1 + \frac{y}{100}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

and a change in flow rate through the engine of

$$\frac{\Delta\omega}{\omega} = \frac{4\,\frac{x}{100} + \frac{y}{100}}{5} \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

A new chamber pressure was calculated using the chamber pressure from Figure 2 and modifying it by the new mass flow

$$Pc = 1 + \frac{\Delta\omega}{\omega} \quad x \quad Pc \text{ (from curve)}$$

Equation (1) was then used to calculate a new outlet pressure, Po, for each propellant. These two pressures were used to establish a point on one curve of Figure 6 or Figure 7.

For an oxidizer-fuel ratio of four, the hardware required for an oxygen MFC should be the same size as a hydrogen MFC. This follows since for equal pressure drop the flow passages should be approximately the same for both propellants. It is therefore logical to expect equal pressure errors of the MFC for each propellant. Figures 6 and 7 show that for equal pressure errors the hydrogen MFC will suffer approximately twice the mass flow percentage error of the oxygen MFC.

Figure 8 is a plot of the allowable pressure band over the entire temperature range band on a mass flow error of 2-1/2 percent and 5 percent for the oxygen and hydrogen units respectively. This figure shows that the allowable pressure error decreases as the temperature of the propellants decreases.

The allowable pressure control band can be increased without increasing the mass flow error by designing the system for a greater pressure drop through the fixed flow restriction. (See paragraph 6.3)

3.2 Bellows Charge

The bellows is charged with helium gas and subsequently sealed. The charge required to cause the MFC to control the outlet pressure in accordance with Figure 3 may be calculated from a force balance. The force balance, in its simplest form, consists of the

1) spring force, F: belleville spring load plus the installed load in the bellows (the bellow is assembled so that it is in compression throughout its stroke). The spring force acts to hold the throttling element in its open position. This force is a function of temperature, decreasing approximately 2% per 100°F increase.

2) gas charge, P_b, acting over the effective areas of the bellows, A_b, pushes the throttling element toward the open position. This force varies directly with absolute temperature.

3) outlet pressure, Po, acting over the effective area of the bellows, A_b, opposes the other two forces and balances them when the outlet pressure reaches the correct pressure value.

The force equation in its simplest form is

$$\frac{F}{A_b} + P_b = P_o \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (6)$$

If the terms $\frac{F}{A_b}$ and P_b represent their magnitude at 100°F temperature, their magnitude at any lower temperature T

$$\frac{F}{A_b}\,(T) = \left[1 + .02(560-T)\right] \times \frac{F}{A_b} \quad \ldots \ldots \ldots \ldots \ldots \ldots (7)$$

$$P_{b(T)} = \frac{T}{560} \times P_b \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (8)$$

The above three equations and the values of Po taken from Figure 3 can be used to calculate P_b and $\frac{F}{A_b}$. These calculations for the oxygen unit give

P_b = 112 psia at 100°F

$\frac{F}{A_b}$ = 248 psi at 100°F

During testing of the prototype MFC it was discovered that the above force balance requires modification in order to account for a temperature dependent closing force. This force results from the pressure drop between the throttling element and the MFC outlet. The pressure drop creates a difference in pressure across the belleville spring, resulting in an additional closing force on the throttling device. Additionally, the pressure drop results in a greater pressure surrounding the bellows than is indicated by the outlet pressure. These two effects are temperature dependent since pressure drop, at constant flow, is temperature dependent.

The effect of the additional closing force was determined empirically. It results in the revised charge pressures and spring loads as follows:

For the oxygen MFC

P_b = 148.7 psia at 100°F

F/A_b = 246.3 psi

For the hydrogen MFC

P_b = 133.6 psia at 100°F

F/A_b = 261.4 psi at 100°F

3.3 Thermal Response

The thermal response of the MFC is determined by the rate at which the belleville spring and the helium charge inside the bellows respond to a temperature change of the propellant gas. The most rapid change of propellant temperature occurs when the MFC, stabilized at its maximum temperature (100°F), is opened with a gas supply at its minimum temperature (-210°F for an oxygen MFC, -260°F for a hydrogen MFC). In this circumstance the MFC will regulate to a pressure higher than it should until the bellows and belleville cool to near the temperature of the propellant gas. Slower thermal response occurs when oxygen is the propellant as its thermal conductivity is less than that of hydrogen.

Bellows - The bellows thermal response was calculated by assuming that the mass of the bellows is concentrated in the center of the bellows wall and that the length of the conduction path is one-half the wall thickness. The heat transferred from the center of the wall to its outer surface is derived from cooling the bellows mass; i.e.

$$M_b C_b \frac{dT_b}{dt} = \frac{K_b A_b}{L_b} (T_b - T_{bo}) \quad \ldots\ldots\ldots\ldots (9)$$

where the expression on the left side of the equation is the cooling rate of the bellows and the expression on the right the rate of conduction to the outer wall of the bellows.

The energy conducted to the outer wall of the bellows is transferred to the propellant by convection.

$$\frac{K_b A_b}{L_b} (T_b - T_{bo}) = hA_b (T_{bo} - T_g) \quad \ldots\ldots\ldots\ldots (10)$$

Equation 10 can be solved for T_{bo} and the result substituted in equation 9. The resulting expression may be written

$$dt = \frac{1 + \frac{Kb}{hLb}}{\frac{KbAb}{LbMbCb}} \quad \frac{dTb}{Tb - Tg}$$

an expression which can be integrated if Tb and t are considered as the only variables. Actually, conductivity, specific heat, and the film coefficient vary with temperature, but not sufficiently to invalidate the result. Integration gives

$$t = \frac{1 + \frac{K_b}{h L_b}}{\frac{K_b A_b}{Lb\,Mb\,Cb}} \quad \ln \frac{(Tb - Tg)t = o}{(Tb - Tg)t = t} \quad \ldots \ldots \ldots \ldots (11)$$

Figure 10 is a plot of Tb vs t obtained from equation 11 for the oxygen MFC. Values used for the constants are listed below.

$$Kb = 1.16 \times 10^{-4} \ \frac{BTU}{Sec - in - {}^\circ F}$$

$$Lb = 7.85 \times 10^{-3} \ In$$

$$Cb = .076 \ \frac{BTU}{lb - {}^\circ F}$$

$Ab = 38.2 \ In^2$ (Bellows area and mass were calculated neglecting the end fittings)

$Mb = .174$ lbs

$$h = .34 \times 10^{-3} \ \frac{BTU}{Sec - in^2 - {}^\circ F}$$

Belleville Spring - An analogous expression to equation 11 for the relationship between belleville spring temperature Ts and time t is as follows:

$$t = \frac{1 + \frac{Ks}{hLs}}{\frac{Ks\ As}{Ls\ MsCs}} \ln \frac{(Ts - Tg)\ t = o}{(Ts - Tg)\ t = t} \qquad (12)$$

The equation was derived in the same manner as the equation for the bellows. The spring was considered symmetrical to a plane passing through its center (perpendicular to its axis) with the length of heat transfer equal to 1/4 its thickness and a heat transfer area equal to its surface area, or

$L_s \doteq .0188$

$A_s = 18\ in^2$

$M_s = .196\ in^2$

Film coefficient, conductivity and specific heat was assumed to be the same as for the bellows.

Figure 9 includes a plot of the belleville spring temperature vs. time obtained from Equation 12.

The temperature of the bellows and the belleville spring at any time t was used to calculate a regulated outlet pressure for that same time. The technique used was to calculate (1) the amount that the helium gas charge pressure decreases (assuming that the helium gas temperature closely follows the bellows wall temperature) as a result of its temperature decrease from its initial temperature to its temperature at time t and (2) the amount that the belleville spring force increases ΔF_s ; as a result of its temperature decrease from its initial temperature to its temperature at time t. The regulated pressure at time t was taken to be its initial regulated pressure (360 psia) plus the belleville spring effect ($\Delta F_s / A_B$) less the pressure change of the helium charge. (This calculation did not include a term for the pressure drop through the unit. It did use a bellows charge pressure, 112 psia at 100 degrees F, which is correct for a MFC without the pressure drop effect (See paragraph 3.2). Results of the calculation are plotted in Figure 10. It shows that the MFC, when subjected to a step temperature change of 310 degrees F, regulates within three psi of the correct pressure setting for the new propellant temperature within approximately two seconds. It is interesting to note from Figure 11 that after 2 seconds time the temperature of both the bellows (-162 degrees F) and the belleville spring (-67 degrees F) are considerably greater than the propellant temperature (-210 degrees F) and yet the regulation pressure is within 3 psi of the correct regulation pressure. This apparent paradox is explained by noting that the effect of a bellows temperature error is opposite from the effect of a belleville spring temperature error; i.e. a bellows temperature higher than the propellant causes a high regulation pressure whereas a high belleville spring temperature causes a low regulation pressure.

4.0 DESIGN

The Mass Flow Controller design is shown in Figures 11 and 12. Its primary elements are a shutoff valve incorporating a housing, a shutoff valve, a pressure balanced throttling device, consisting of a stationary cylinder and a rotating cage, a hermetically sealed bellows assembly containing a helium gas charge, and a negative rate belleville spring. These elements are pictured in Drawing 5716187 and Drawing 5716068, reduced size copies of which are included as Figures 11 and 12. These elements are discussed in some detail below.

4.1 Housing

The MFC is designed for an operating pressure of 2000 psia inlet and 360 psia outlet (at 100 degrees F). Proof pressures are 3000 psia and 540 psia respectively. The housing is structurally sound for outlet pressures up to 2000 psig but such pressures would damage the bellows. Safety factors at the flanges for inlet and outlet pressures of 3000 and 2000 psig respectively are shown on Figure 13.

4.2 Shutoff Valve

The shutoff valve is a piston operated type controlled by a separate solenoid pilot valve. The poppet, which is clamped to the piston at its inner periphery, has some self-alignment capability at its seating surface, which projects beyond the skirt of the piston and seats on a raised, flat-lapped annulus on the cylinder. In the closed position the poppet is pressure loaded in contact with the seat.

The piston is normally spring loaded to the closed position. Pressure at the inlet communicates with the piston chamber via the solenoid pilot valve. When the solenoid pilot valve is energized, the piston chamber is connected to the outlet port of the MFC. This causes the piston chamber to bleed down until the inlet pressure opens the piston. The piston is prevented from slamming opening by the built-in snubber action as the piston approaches its open position stop.

The piston is guided by a CRESstem which moves in a filled Teflon bearing. Its peripheral seal consists of two step-cut piston rings of a filled Teflon material backed up by a CRES expander ring.

4.3 Cylinder and Cage

The throttling element consists of a stationary cylinder and a rotating cage, each with six peripheral slots. Throttling occurs as the slots in the cage rotate out of alignment with those in the cylinder.

4.3 (continued)

There are six slots in the cylinder and six matching slots in the cage. Four of the slots are 1/8-inch wide and two are 1/4-inch wide. The orientation is such that the four narrow slots close simultaneously when the two wide slots are in their mid position. There is .0025 radial clearance (nominal) between the two parts when installed. Twenty-three degrees rotation from the closed position is required to fully open all slots. The flow area versus rotation is shown on Figure 14.

4.4 Bellows Assembly

The bellows used in the MFC was an off-the-shelf item. It has 7-1/2 active convolutions and was obtained by machining an existing 14 convolution bellows obtained from Robertshaw Controls Company, Knoxville, Tennessee. This bellows, Robertshaw P/N A2000A08, is a single-ply, hydrostatically formed, seamless, 18-8 CRES bellows with the following specifications:

OD: 2.00
ID: 1.34 inches
Wall thickness: .0157 in.
Length per active corrugation: .110 in.
Spring rate per active corrugation: 4000 lb/in
Maximum stroke per action corrugation: .023 in.
Effective area: 2.22 in.^{2}
Maximum pressure rating: 395 psi differential

Bellows Spring Rate

The spring rate of the bellows is made up of a mechanical portion, or that due to the spring rate of the 7-1/2 active convolutions, and a pneumatic portion. The pneumatic spring rate results from the fact that the bellows cannot be deflected without compressing or expanding the internal charge. If the internal charge follows an isothermal process during deflection, the pneumatic spring rate may be calculated as follows:

Differentiating the perfect gas equation for an isothermal process (pV = constant),

$$P_b \frac{dV}{dL} + V \frac{dP_b}{dL} = 0$$

Since $dV = A_B \, dL$ and $dP = \frac{dF}{A_B}$

$$\frac{dF}{dL} = - A_B^2 \frac{P}{V} \qquad (13)$$

The mechanical spring rate is approximately 535 lb/inch at room temperature and decreases with increasing temperature at a rate of approximately 2% (10.7 lbs/inch) per hundred degree change. The pneumatic rate is directly proportional to the internal pressure and consequently increases with increasing temperature. The bellows assemblies were charged with helium to 148.7 psia (bellows assembly at midstroke, 100 degree F temperature) for the oxygen MFC and 133.6 psia for the hydrogen MFC. (See Paragraph 3.2) The spring rate variation with temperature is shown below for the bellows used in the oxygen MFC.

Temperature Degrees F	Mechanical Spring Rate lb/inch	Pneumatic Spring Rate lb/inch	Assembly Spring Rate lb/inch
100	532	490	1022
-210	565	219	784

4.5 Belleville Spring

The spring loads, as described in the preceding paragraph, were found to be :

F = 246.3 x 2.22 = 546 lbs. for the oxygen unit and
F = 261.4 x 2.22 = 580 lbs. for the hydrogen unit

Approximately 20 lbs of each of the above loads is obtained from the compression of the bellows. The remainder is the calculated load of the belleville at its mid-stroke position.

The belleville spring operates in the negative spring rate regime throughout the operating stroke (.036 inches) of the linkage. The spring rate of the belleville spring was designed to be near the spring rate of the bellows assembly. If the two were equal (but of opposite sign) the net spring rate would be zero. A zero spring rate system would permit the throttling device to take whatever restrictive position required by changing pressure and/or temperature of the propellant without change of outlet pressure. For stability reasons, however, it is desirable that the net spring rate remain positive.

4.6 Solenoid Pilot Valve

The Solenoid Pilot Valve is a two-position, three-way direct operating valve purchased from Circle Seal Corporation, Part No. SV 30 A 32 P 4 T, cleaned for oxygen service.

5.0 TEST PROGRAM

The test program was originally planned to include component tests, prototype tests, Acceptance Tests and Design Verification Tests. It was necessary to expand this to include additional tests, termed "Pre Production Tests" because of unanticipated problems requiring (1) redesign of the cage and cylinder and (2) modifying the bellows charge.

5.1 Component Testing

At the beginning of the program, certain components were recognized as being critical to the success of the all-mechanical Mass Flow Controller. These were (1) the cage and cylinder assembly (2) the charged bellows and (3) the belleville spring. Development tests were planned for these components to verify their performance as components before assembly into a complete MFC.

5.1.1 Cage and Cylinder Assembly

A prototype case and cylinder were machined from 17-4 barstock in accordance with Parker Drawings 5716069 and 5716070, both to Revision A. These components were assembled and tested in a test fixture.

When pressure was applied, a high separating force was developed. This was determined to be caused by inadequate venting of the space between the cage and cylinder. The venting area was increased by slotting the end plate of the cage and chamfering its forward end. This eliminated the high separating force.

Torque testing of the cylinder and cage was conducted at various pressures with an orifice in the outlet line downstream of the fixture of a size which will pass rated flow at approximately 300 psi in the test fixture. Torque readings were obtained using hand held torque wrench and also using an electrically driven torque meter. Results of the test using the torque meter are included as Figure 15. The torques obtained indicate an opening torque on the cage, that is, the fluid tends to align the slot in the cage with the slot in the cylinder.

An effort was made to eliminate or reduce the magnitude of the torque by the following three methods.

(1) Shaping of the leading edge of the slot in the cage.

(2) Attaching a fence to the cage at two of the slots which protruded into the slot of the cylinder. The arrangement is shown in Figure 16. The fences produce an unbalanced pressure area which result in a closing torque when the slot in the cage is in the near closed position.

(3) Attaching a shroud to the cage which directs the flow from the slots in a longitudinal direction. The shroud is pictured in Figure 17. Various positions of the shroud were tried relative to the slots in the cage.

The various devices tried in an effort to reduce the torque altered the shape of the torque-displacement curve but none showed a consistent improvement of the total torque range over the working angle of the assembly.

When parts became available to complete the assembly of a MFC, the prototype cylinder and cage in its unmodified form was used in the assembly. The assembly was tested over an inlet pressure range of 400-1000 psig and performed without any problem traceable to a torque on the cage. Further torque tests of the cylinder and cage were discontinued.

5.1.2 Prototype Bellows

A prototype bellows assembly was fabricated and filled with helium to a pressure of 112 psia at midstroke and 100 degrees F temperature. (The pressure was calculated to be the required charge pressure for an oxygen MFC without a flow sensitivity correction). The bellows was stroked using a spring tester and a force deflection-curve obtained both for increasing load and for decreasing load. From this curve the following data was obtained.

Force at midstroke: 225 lbs.
Spring rate of filled bellows, 75 degrees F = 835
Hysteresis: negligible

The prototype bellows was used in the prototype MFC assembly. The performance of this unit is shown in Figure 19.

5.2 Prototype MFC Testing

The first MFC was assembled using the prototype cage and cylinder, the prototype bellows assembly and the prototype belleville spring. It was tested in the test setup shown in Figure 19.

Pressure regulation performance of this unit is shown in Figure 19. Analysis of this data resulted in the following conclusions:

(1) Scatter of data at a particular flow rate is approximately 12 psi ($\pm$ 6 psi).

(2) Decreasing the flow rate by changing the downstream orifice from .687 diameter to .624 diameter causes an upward shift in control pressure of approximately 20 psi at 0 degrees F.

(3) The slope of the pressure vs. temperature curve at constant flow rate is less steep than the target curve. The target curve shown is obtained from the oxygen curve of Figure 3 less (a) 14.7 psi to convert it to a sea level gage pressure reading) and (b) the velocity head in psi for rated flow in the outlet line where outlet pressure is measured.

The prototype MFC was cycled 1000 times at room temperatures using a solenoid pilot valve. Inlet pressure was 400 psia. Following the cycle test the unit was disassembled and inspected. No damage was detected as a result of the cycle test.

5.3 Pre Production Testing

Analysis of the results of testing the prototype components and the prototype MFC assembly led to certain design changes. The bellows assembly charge pressure was increased to increase the slope of the pressure regulation curve and the cage and cylinder were altered for increased strength and improved performance.

The cage wall thickness was increased to strengthen it where the prototype cage had proved weak. The journal of the bearing was increased in section to reduce the deflection resulting from the linkage loads.

The radial clearance between the cage and cylinder was decreased and the length of the slots were decreased to reduce the fluid torque effects and consequently improve precision. The cage and cylinder were made in a four-slot and six-slot version. Comparative tests showed the six slot version markedly superior. All testing of the four-slot version was discontinued and six-slot cages were ordered for all production units.

At this time it was decided that remaining performance testing would be conducted over a 500-700 psi inlet pressure range rather than 400-2000 psi design range. The limited inlet pressure range avoids the inlet pressures which cause a still unexplained rise in outlet pressure of approximately 20 psi. The inlet pressure range of 500 to 700 psig is consistent with use of a roughing regulator upstream of the MFC.

The body which had been used on the prototype MFC was modified by adding a second outlet port. This was accomplished by drilling a hole in the body downstream of the cylinder and cage assembly, tapping a 1-inch pipe thread and installing an AN816-16 nipple. The body was used in a complete assembly using a six slot cage and cylinder configuration. The original outlet port was capped and the unit placed in the test setup with the downstream system, including the orifice, connected to the new outlet port. In this configuration the flow passes from the cylinder and cage to the outlet, bypassing the belleville spring and bellows. Outlet pressure was modified at the port in the original outlet flange which opens to the region of the bellows. The bellows assembly used was charged to 135 psia at 100 degrees F, midstroke position.

The modified assembly was tested with orifices of .687 diameter and .562 diameter installed in the outlet. The resulting pressure regulator curves are shown in Figure 20. The curve for the .687 diameter orifice shows the outlet pressure to be approximately 42 psi higher at O° F than when tested in the conventional manner. This increase results from (1) elimination of the closing force on the belleville spring and (2) measurement of the pressure at a location which is at the same pressure level as the bellows. The tests also show an upward shift in outlet pressure of approximately 9 psi (at 0° F) when the orifice in the outlet is changed from .687 to .562 diameter. This is a smaller shift than occurs when testing the unit in the conventional manner but is greater than anticipated.

Analysis of the test data resulted in the revised bellows charge levels described in paragraph 3.2. A bellows charged to the new level was assembled in a MFC using an unmodified body. The pressure regulation curves resulting are shown in Figure 21 for an orifice size of .687 and .624 diameter. A point on the rated flow performance curve is obtained where the test points taken for a .687 diameter orifice cross the rated flow line for that orifice. A second point on the rated flow performance curve is obtained where the test points for the .624 diameter orifice cross the rated flow line for that orifice. A line joining these two points is the rated flow performance curve. This curve shows the correct slope for an oxygen MFC and the correct pressure level.

The best transient temperature test occurred during test of this unit. The inlet temperature was suddenly lowered by approximately 300°F. The recorder trace obtained is reproduced as Figure 22. It shows inlet temperature, outlet temperature and outlet pressure vs. time. The test was conducted with a .624 diameter orifice in the outlet line and an inlet pressure of approximately 600 psig. The trace shows the inlet temperature changing more rapidly than the temperature measured at the bellows which is to be expected since there is some warming of the gas as it passes through the MFC. The outlet pressure responds more rapidly than either temperature which indicates that the charged bellows responds more rapidly than the thermocouples used in the test.

The data from Figure 22 is reproduced on a larger scale in Figure 23. Plotted also in Figure 23 is the transient curve prepared from calculations for a step temperature change. (See paragraph 3.3 and Figure 10.)

The test curve covers a greater pressure range since it is a test with a .624 diameter orifice in the outlet line (hence the flow rate increases as the temperature decreases) rather than with constant rated flow throughout the temperature range. The test curve shows the outlet pressure to change more slowly than the calculated curve. Part of the difference is explained by the fact that (1) a true step temperature change was not obtained in the test and (2) some warming of the flow occurs between the inlet and the bellows which was not accounted for in the calculations.

An interesting recorder trace obtained with the preproduction unit by amplifying the outlet pressure signal. This trace is reproduced as Figure 24. It shows very clearly the variation in outlet pressure as the temperature varies. It also shows the outlet pressure responds more rapidly than does the thermocouple used to measure the temperature.

5.4 Acceptance Tests

Four MFC units were assembled in accordance with the Manufacturing Operations Routing for Part No. 5716068, a copy of which is included in the appendix. For each bellows assembly and each belleville spring used, a load deflection curve was obtained by use of a spring tester. These curves are included in the appendix. The curves show a belleville negative spring rate somewhat greater in magnitude than the bellows assembly positive spring rate. This results in a slightly negative spring rate of the MFC which is undesirable for stability. Instability did not prove to be a problem however during testing at limited inlet pressures (500-700 psig).

All production MFC units, adaptors and solenoid pilot valves were tested in accordance with PTS5716068. Copies of these documents are included in the appendix. Results of these tests are summarized below. Copies of actual data sheets are included in the appendix.

5.4.1 Leakage

Leakages recorded for the four production units are summarized in Table 1. External leakage occurred at the joint when the cap attaches to the body which sees inlet pressure, and at the joint where the housing attaches to the body, which sees outlet pressure. The seals used consist of a single piece Teflon jacket with an internal CRES expander spring and are standard parts obtained from Raco. Surfaces in contact with the seals have finishes and dimensions in accordance with the seal manufacturer's recommendations. Total external leakage at the limited inlet pressure is less than 10 sccm.

Internal leakage occurred at the poppet seat (which may have been augmented by leakage past two Raco seals which are potential parallel leakage within two light bands and with a finish of four micro inch, except for one oxygen MFC, S/N 02. This unit leaked excessively.

Another leakage recorded on the data sheets but not listed in Table 1 is the piston leakage. This is the leakage past the piston ring and occurs only when the MFC unit is open. This leakage passes through the solenoid pilot valve and into the MFC outlet, bypassing the throttling device. It produces no detectable effect on the performance of the MFC.

5.4.2 Pressure Response

A recorder trace obtained during a pressure response test is shown as Figure 25. Four inputs were monitored:

(a) Solenoid voltage
(b) Inlet pressure
(c) Outlet pressure
(d) Pressure in the shutoff piston chamber

5.4.2.1 Opening Response

When the solenoid pilot valve is energized it shuts off the fluid communication path from the MFC inlet to the shutoff valve piston chamber and opens a communication path from the piston chamber to the MFC outlet. The pressure in the chamber then blows down until the shutoff piston begins to move. Once the piston begins to move, the downstream face of the piston, unpressurized when closed, becomes pressurized. The increased area exposed to pressure produces sufficient force on the piston to open it fully without further flow of gas from the piston chamber.

The opening time can be considered to consist of four intervals:

(1) Solenoid Response Time - the time required for the two-position solenoid pilot valve to shift position after energization. (60 milliseconds)

(2) Blowdown Time - the time required to depressurize the piston chamber to the pressure at which the piston can begin to move. (60 milliseconds)

(3) Piston Travel Time - the time required for the piston to travel sufficiently to pass rated flow. (20 milliseconds)

(4) Controller Reaction Time - the time for the throttling element, which is initially fully open, to overshoot, recover, and achieve regulation. (20 milliseconds)

The times shown in parentheses are the times taken from the recorder traces of Figure 25.

5.4.2.2 Closing Response

When the solenoid pilot valve is de-energized it shuts off the fluid communication path between the piston chamber and the MFC outlet port and opens a path from the MFC inlet to the piston chamber. The pressure in the piston chamber then rises to near inlet pressure and is closed by the piston return spring. When the piston approaches the seat the pressure drop across the piston produces an additional closing force.

The closing time can be considered to consist of 4 intervals.

(1) Solenoid Response Time: the time required for the two-position solenoid pilot valve to shift position after de-energization. (5 milliseconds)

(2) Pressurization Time: the time required for the chamber to pressurize to the point when the spring can initiate closing. (25 milliseconds)

(3) Spring Closure Time: the time required for the spring to return the piston from its fully open position to the point when the pressure drop across the piston aids closure. (115 milliseconds)

(4) Pressure Assisted Closure Time: the time required for the piston to move the final distance under the influence of the pressure drop across the piston and, to a lesser extent, the spring force. (10 milliseconds)

These times shown in parentheses are the times taken from the recorder traces of Figure 25.

5.4.3 Control Pressure with Varying Inlet Pressure

Pressure regulation performance was obtained over an inlet pressure range up to 1000 psig with the temperature essentially constant. A typical trace obtained from one of the four units (an oxygen MFC, Serial No. 02) is included as Figure 26. This curve shows that the MFC controls outlet pressure high by as much as 20 psi when the inlet pressure is between 400 and 500 psig for both increasing and decreasing inlet pressure. The reason for this pressure rise was not established conclusively but is suspected to be associated with torqueon the cage. The outlet pressure is low also during increasing inlet pressure between 700 and 900 psig and during decreasing inlet pressure between 950 and 700 psig although the effect is not so great as at the low inlet pressures.

5.4.4 Control Pressure with Varying Temperature

Pressure regulation performance was obtained throughout the temperature range with the inlet pressure in the 500-700 psig range. Each unit was tested without thermal conditioning using a .687 diameter orifice in the outlet. An orifice of .624 inch diameter was substituted prior to the test runs in which thermal conditioning was accomplished. A curve plotted for one of the four units (an oxygen MFC, Serial No. 02) is shown on Figure 27. Similar curves for the remaining three units are included in the appendix. The curves show that the units were not adjusted as precisely as was the preproduction unit. (See Figure 21.) The slope of the constant flow curve does not match the target slope as well as did the preproduction unit.

5.4.5 Thermal Response

Thermal response was conducted on each unit and the results tabulated in Table 2. This shows the magnitude of the inlet temperature change resulting from a sudden opening of the liquid nitrogen supply and the time required for the outlet pressure to reach the new equilibrium pressure.

5.5 Design Verification Testing

One of the four units (a hydrogen MFC, Serial No. 01) was subjected to Design Verification Testing in accordance with DVT5716068, a copy of which is included in the appendix. Test results are summarized in Table 3. Copies of actual data sheets are included in the appendix.

5.5.1 Endurance Test

The unit was cycled with the solenoid pilot valve at an inlet pressure of 400 psig. A sufficiently small orifice was installed in the outlet to cause the throttling element to reach its fully restricted position each time the solenoid valve opened. Ten thousand cycles were imposed. Poppet leakage following the cycle test was approximately the same as before the test. The piston leakage increased but not sufficient to affect performance

5.5.2 Pressure Drop Test

The pressure drop test was conducted at an outlet pressure well below the set pressure to assure that the throttling element was in its fully open position. At 100 ° F (outlet pressure of 360 psia) the test data indicates a pressure drop of 60 psi which exceeds the 40 psi design point. The excess pressure drop resulted from the changes to the cage and cylinder following the prototype tests, which decreased the open flow area. The pressure drop of the unit is adequate for the revised inlet pressure range (500 - 700 psig), which requires a pressure drop less than 155 psi at full flow.

5.6 Helium Test

One of the two hydrogen units (Serial No. 02) was tested for stability using helium as the flowing medium. The test setup was identical to that shown on Figure 18 except that a "six pack" of helium bottles manifolded together was connected to the MFC inlet in place of the gaseous nitrogen supply. No thermal conditioning was employed but the spherical pressure vessel was utilized (by opening ball valve B2) to lengthen the time of the test run. This was necessary since the opening from the manifolded six pack was too small to meet the flow demand of the MFC. An orifice of .687 inch diameter was installed in the outlet for this test. The inlet pressure was approximately 600 psig. No audible instability was detected with helium as the test medium nor did the outlet pressure as monitored by the recorder indicate an instability. The length of the test run obtainable by this test method is too limited to establish conclusively that the MFC is stable with helium flowing.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 The all mechanical mass flow controller can control outlet pressure within ± 1 percent over the entire temperature range (- 250 ° F to + 100 °F) provided the inlet pressure range is limited to 500-700 psig. Further development is recommended to increase the inlet pressure range without adversely affecting the control pressure band. The element in the MFC which requires improvement is the throttling device (the cylinder and cage).

6.2 The errors in mass flow control and mixture ratio resulting from a pressure control error of ± 1 percent were determined by analytical techniques. It is recommended that these errors be determined also during test firing of a rocket engine with the propellants supplied through two all mechanical MFC units.

6.3 The error in mass flow and mixture ratio resulting from an error in control pressure of ± 1% is shown over the entire temperature range in Figure 28 . The curve was calculated on the basis of a pressure drop through the fixed restriction of 60 psi (at 100 °F). For a pressure drop of 120 psi the errors in mass flow and mixture ratios are less. These are plotted in Figure 29 . It is recommended that the pressure drop allowable through the fixed restriction be reviewed to ascertain whether it can be increased and how much.

6.4 The design which was tested is flow sensitive. Its control pressure changes when the flow rate changes. This characteristic is undesirable in an application when one MFC unit supplies a cluster of rocket engines. The flow sensitivity can be considerably reduced, by redesigning so that the flow does not pass through the belleville spring. Additional improvement can be achieved by reducing the pressure drop between the throttling element and the outlet port. It is recommended that further work be performed to determine how much improvement is feasible.

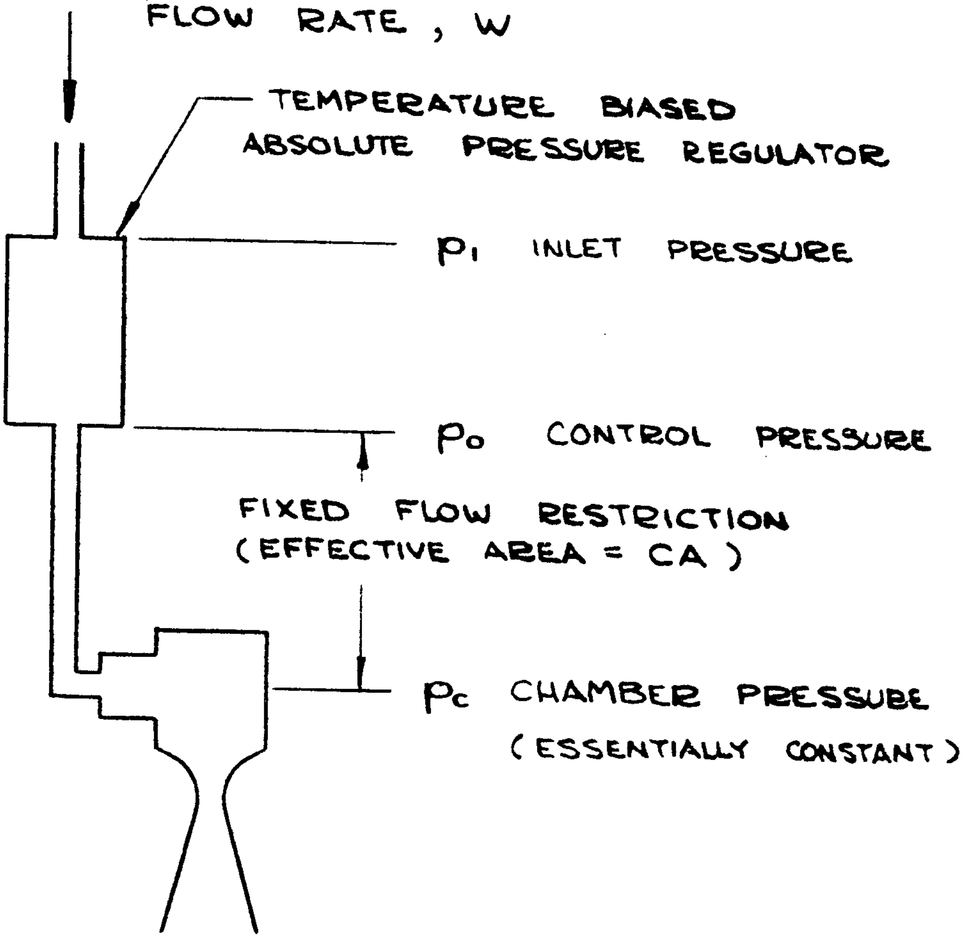


FIGURE 1 PRINCIPLE OF ALL MECHANICAL MASS FLOW CONTROLLER

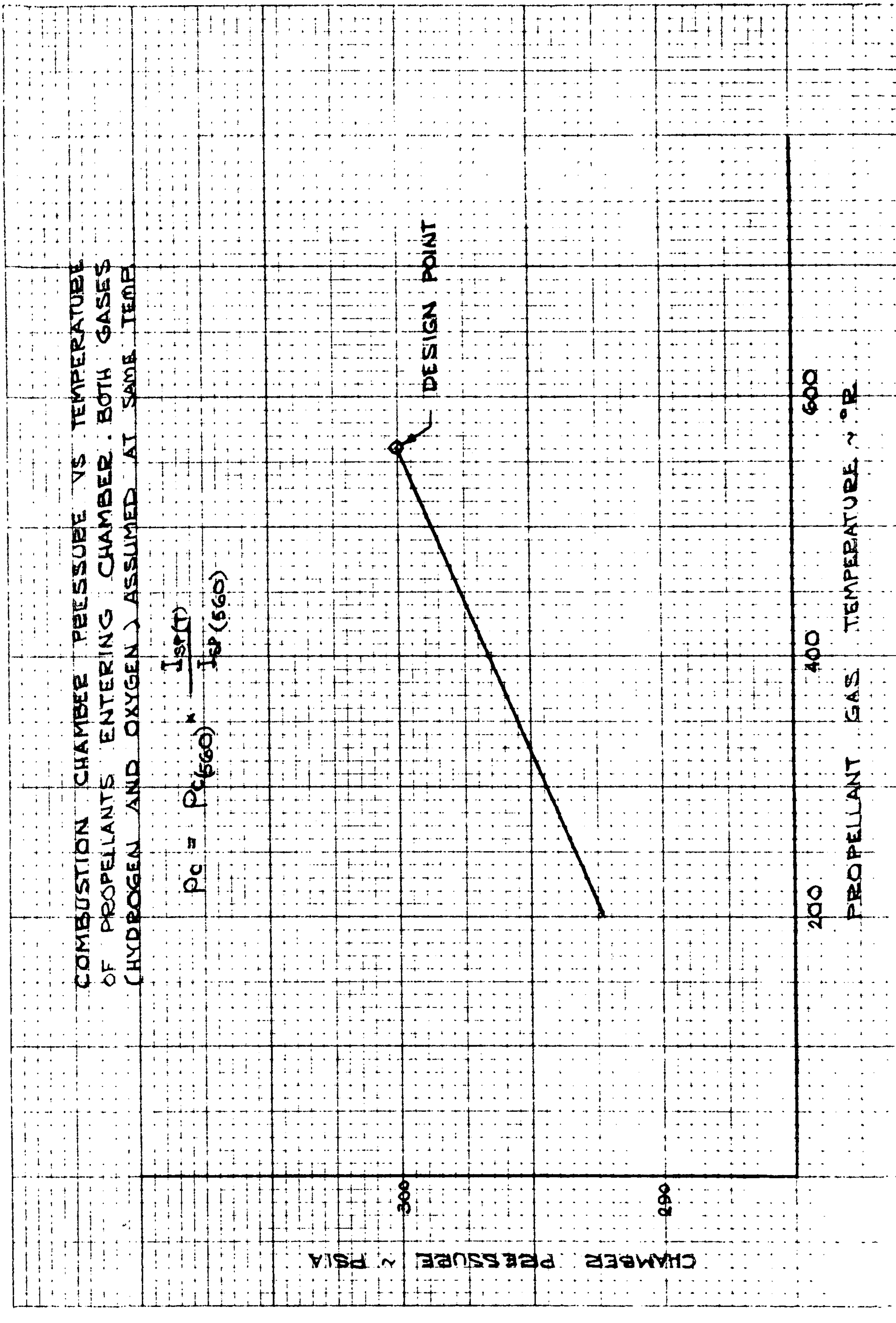


FIGURE 2 COMBUSTION CHAMBER VARIATION WITH TEMPERATURE

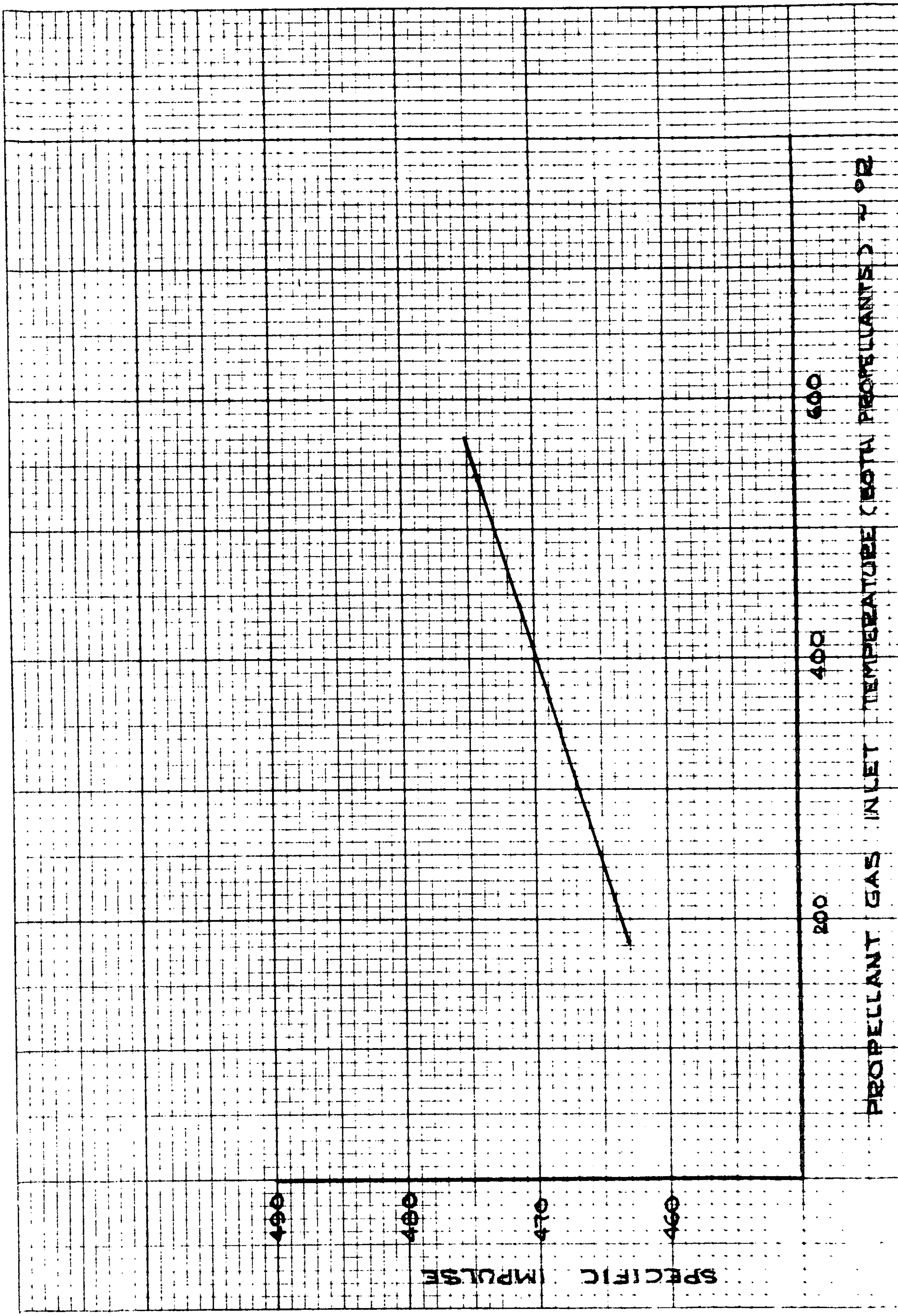


FIGURE 3 SPECIFIC IMPULSE VARIATION WITH TEMPERATURE

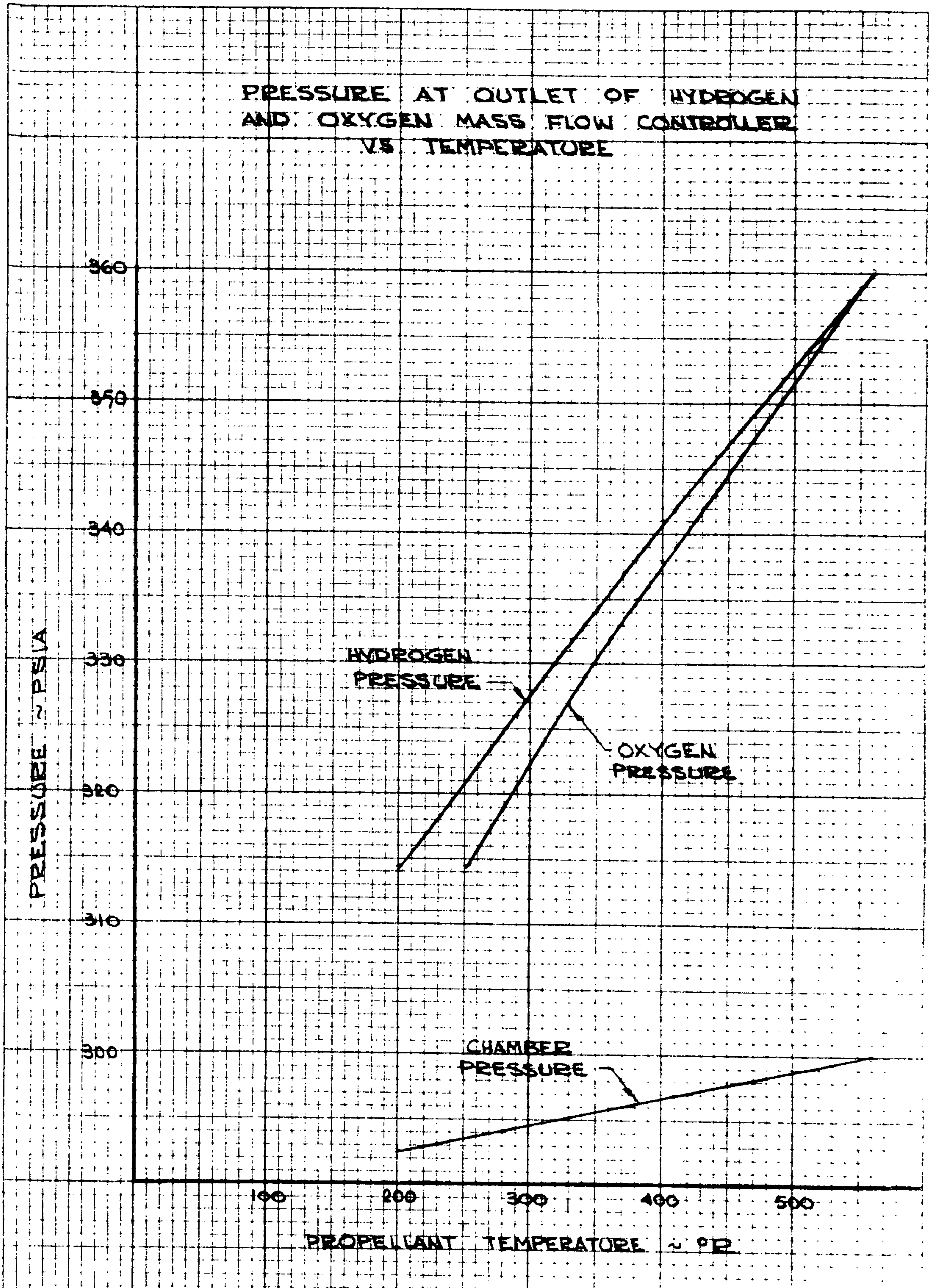


FIGURE 4 CONTROL PRESSURE VS TEMPERATURE

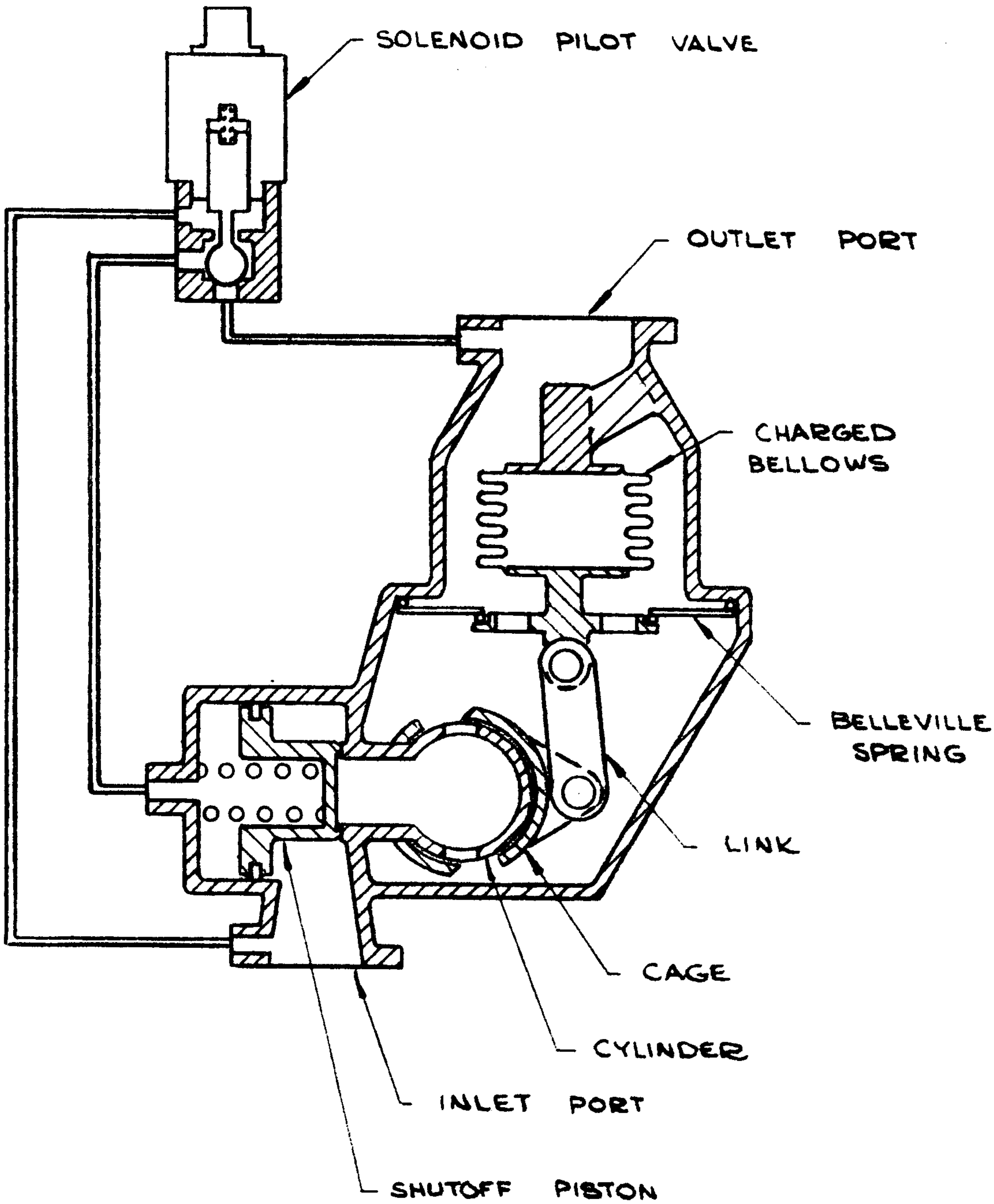


FIGURE 5 SCHEMATIC DRAWING OF MASS FLOW CONTROLLER

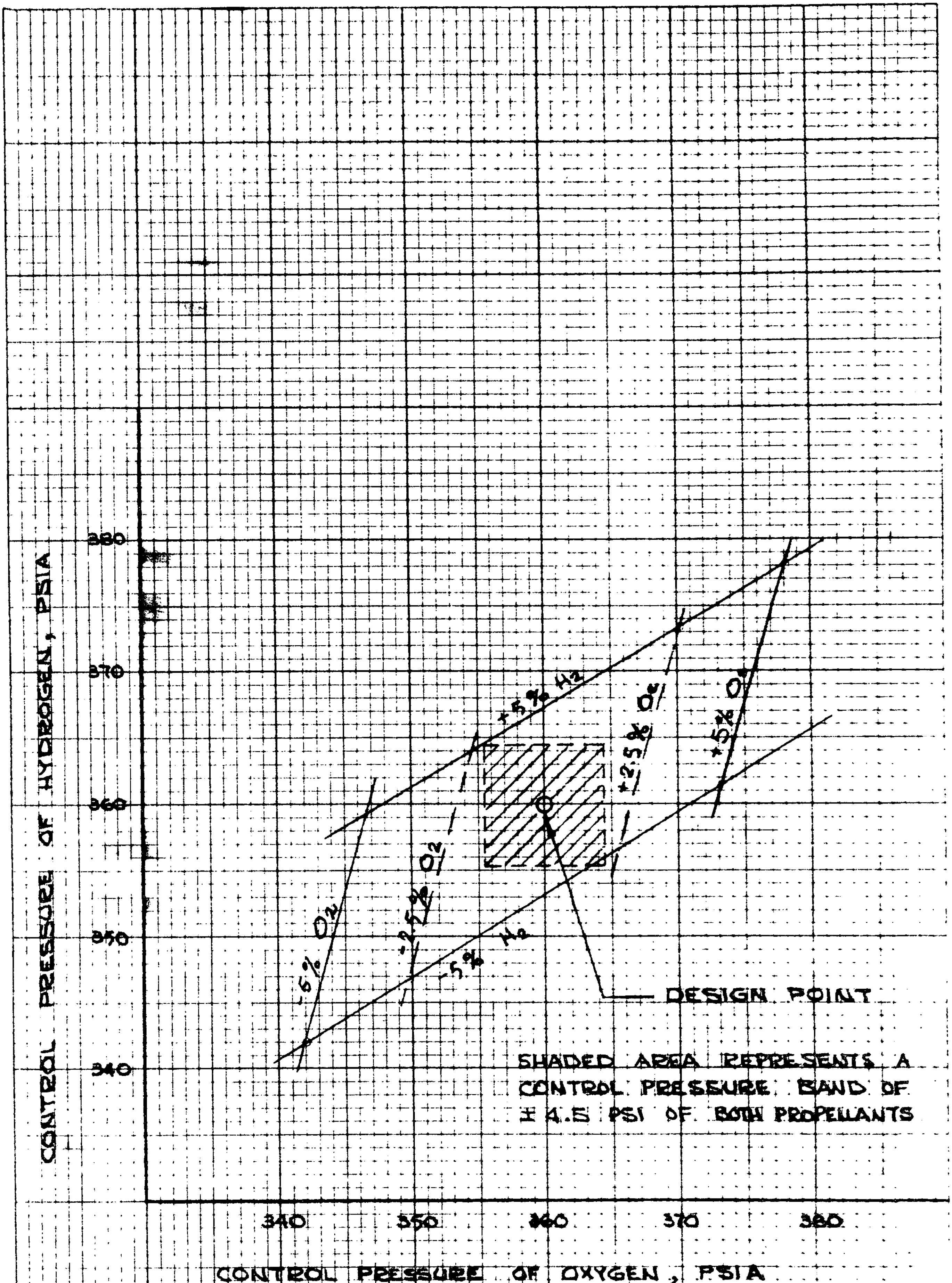


FIGURE 6 TOLERANCE OF CONTROL PRESSURE AT 100°F

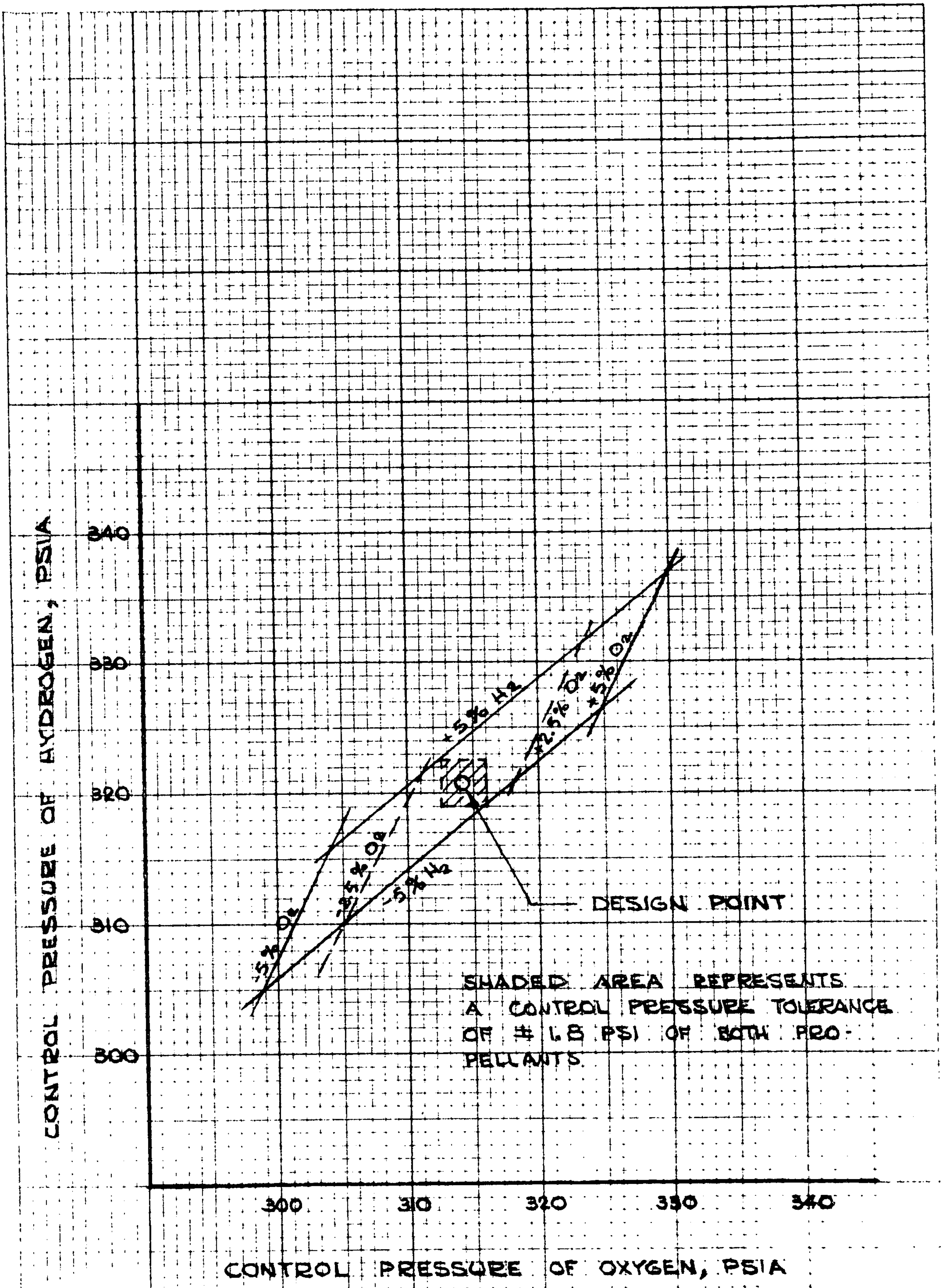


FIGURE 17 TOLERANCE OF CONTROL PRESSURE AT -210°F

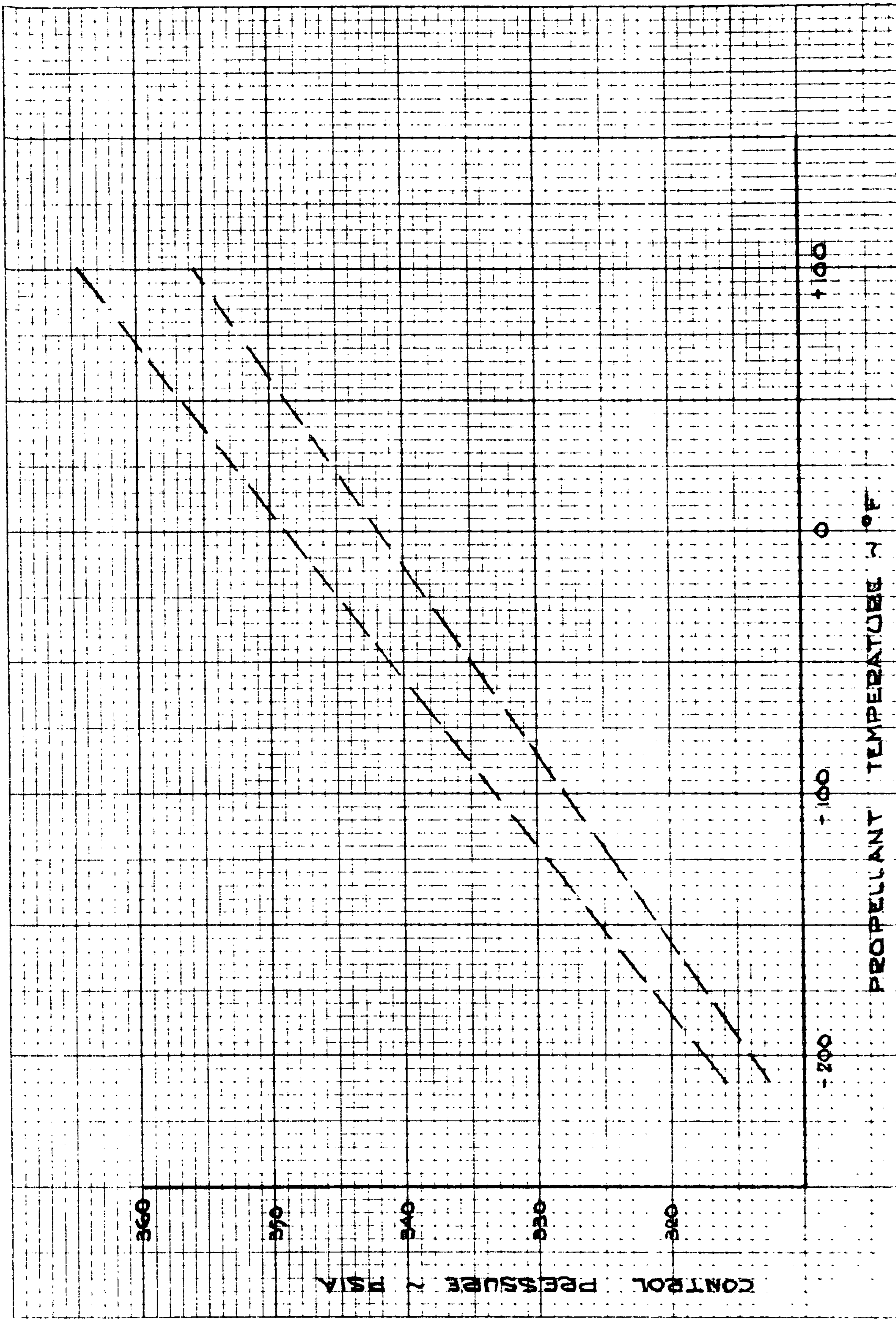


FIGURE 8 ALLOWABLE TOLERANCE BAND FOR MASS FLOW TOLERANCE OF ± 2½ % OXYGEN AND ± 5% HYDROGEN PRESSURE SLOPE SHOWN IS FOR OXYGEN MFC

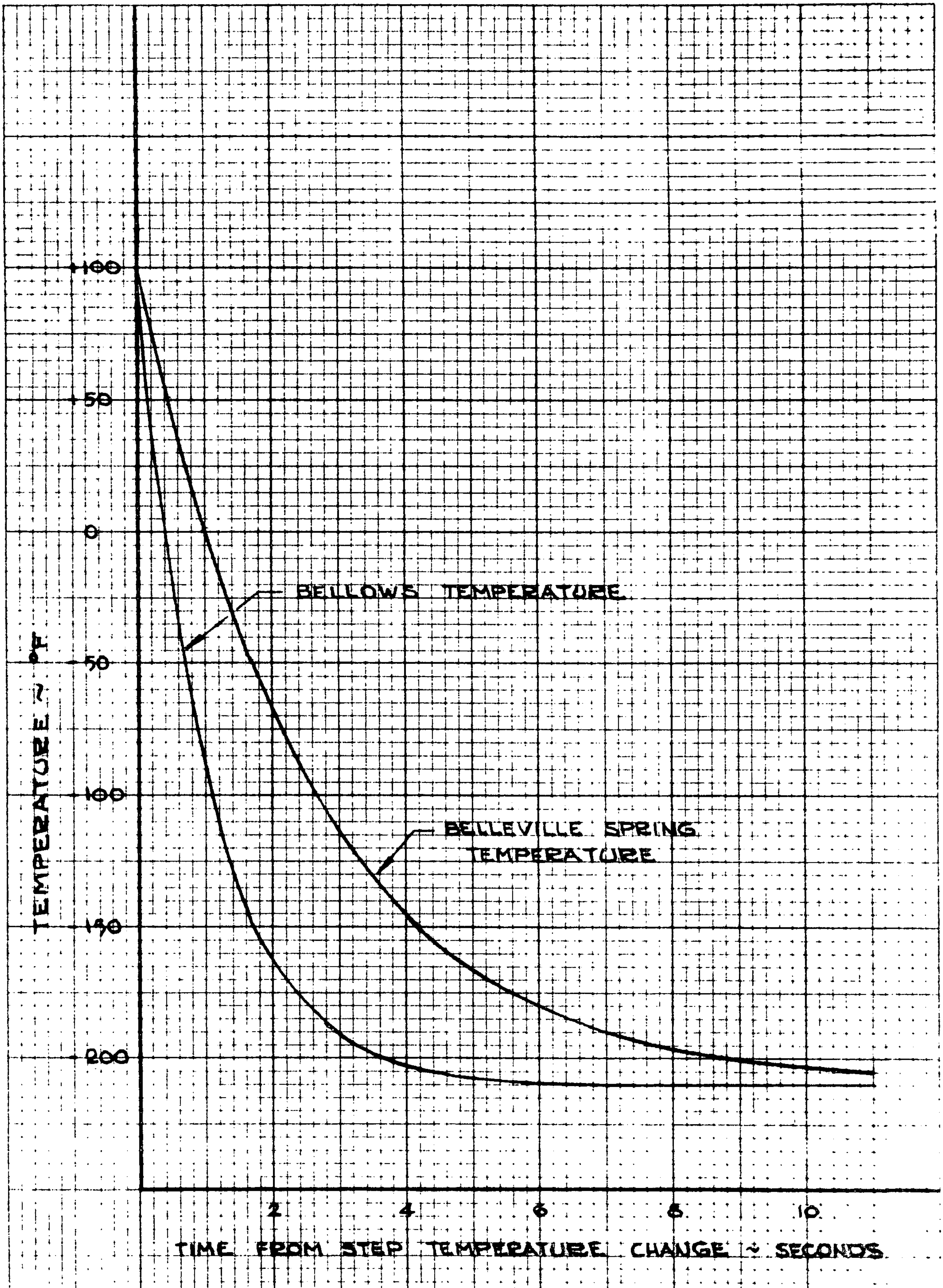


FIGURE 9 CALCULATED TEMPERATURES DURING TRANSIENT

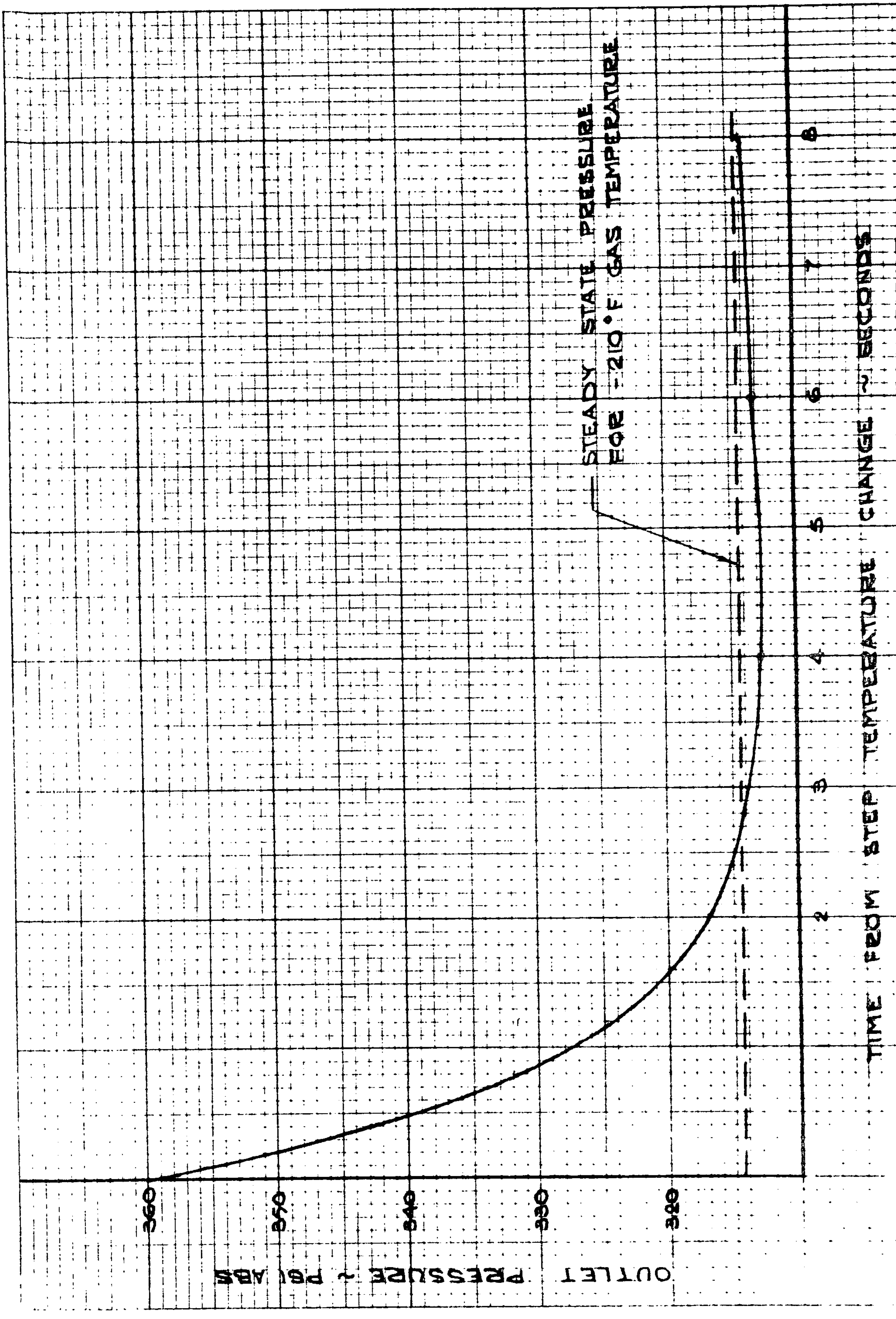
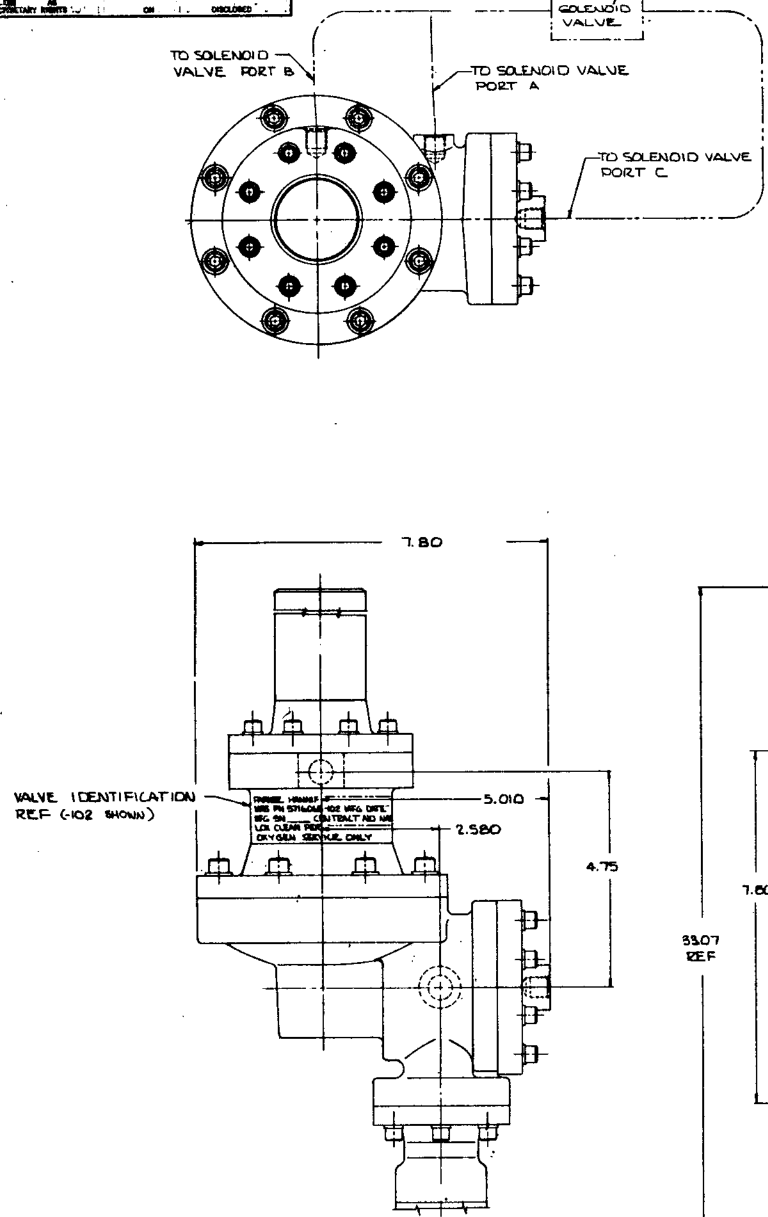
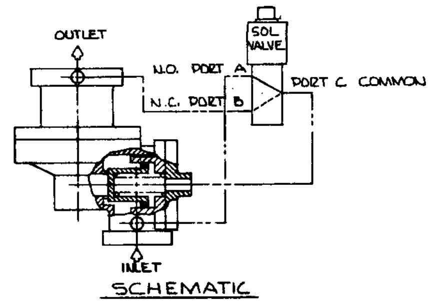
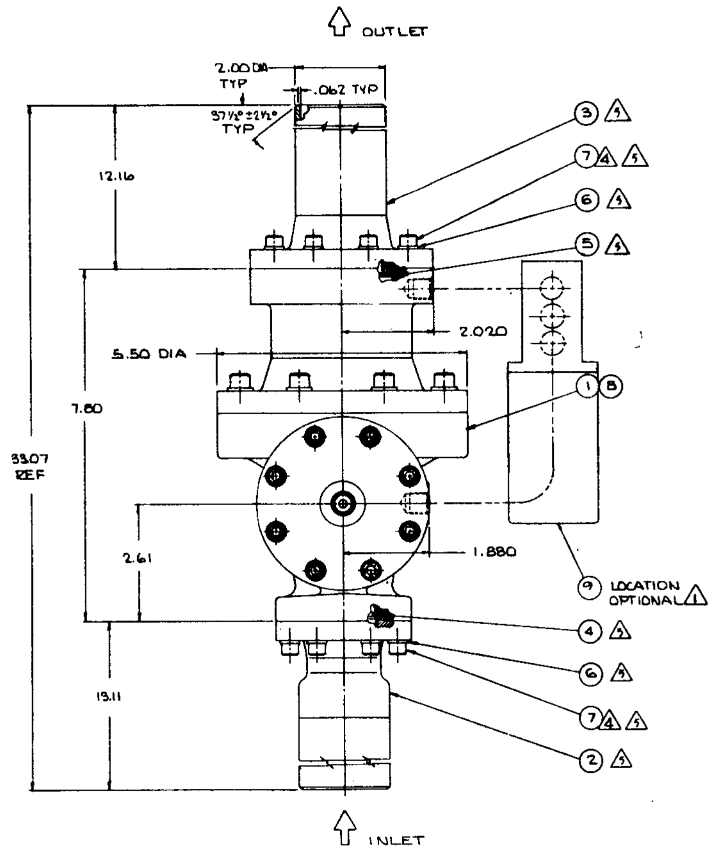


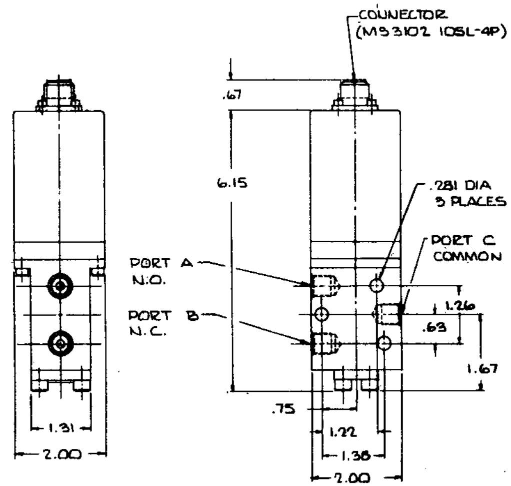
FIGURE 10 CALCULATED CONTROL PRESSURE DURING TRANSIENT

LTR	ZONE	NO	DESCRIPTION	DATE	APPROVED
-1	-	NC	RELEASE FOR SPL PROJ		
-2	-	A	CORRECTED ERROR IN IDENTIFICATION ... PARTS LIST		









DETAIL ITEM 9
PORTS PER MS 33649-4
28 VDC (1.0 AMP @ 24VDC @ 70°F)

CFG -102	CFG -101	QTY REQD	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	CODE IDENT		DWG SIZE	ITEM NO.
1	1	—	SV30A32P4T	SOL VALVE, 3WAY 2POS	27409	VICTOR CONTROLS		9
1	—	—	5716068-102	CONTROL ASSY				8
14	14	—	NAS1351C4-12	SOC HD CAP SCR				7
14	14	—	NAS 620C416	WASHER				6
1	1	—	1160-2.625	SEAL, OUTLET		RACO		5
1	1	—	1160-1.875	SEAL, INLET		RACO		4
1	1	—	5716155	OUTLET ADAPTER			C	3
1	1	—	5716154	INLET ADAPTER			C	2
—	1	—	5716068-101	CONTROL ASSY			E	1
102	101	—	—	ASSEMBLY	—	—	—	—

PARTS LIST

5 THESE PARTS TO BE ASSEMBLED BY CUSTOMER
4 TORQUE : 90 TO 100 IN.LB.
3. CLEAN PER ES5-15, LEVEL VI (REF NASA MSFC 164)
2. PORTS IN CONTROLLER BODY PER MS33649-4.
1 FITTINGS AND HARDWARE TO BE CUSTOMER SUPPLIED
NOTES UNLESS OTHERWISE SPECIFIED

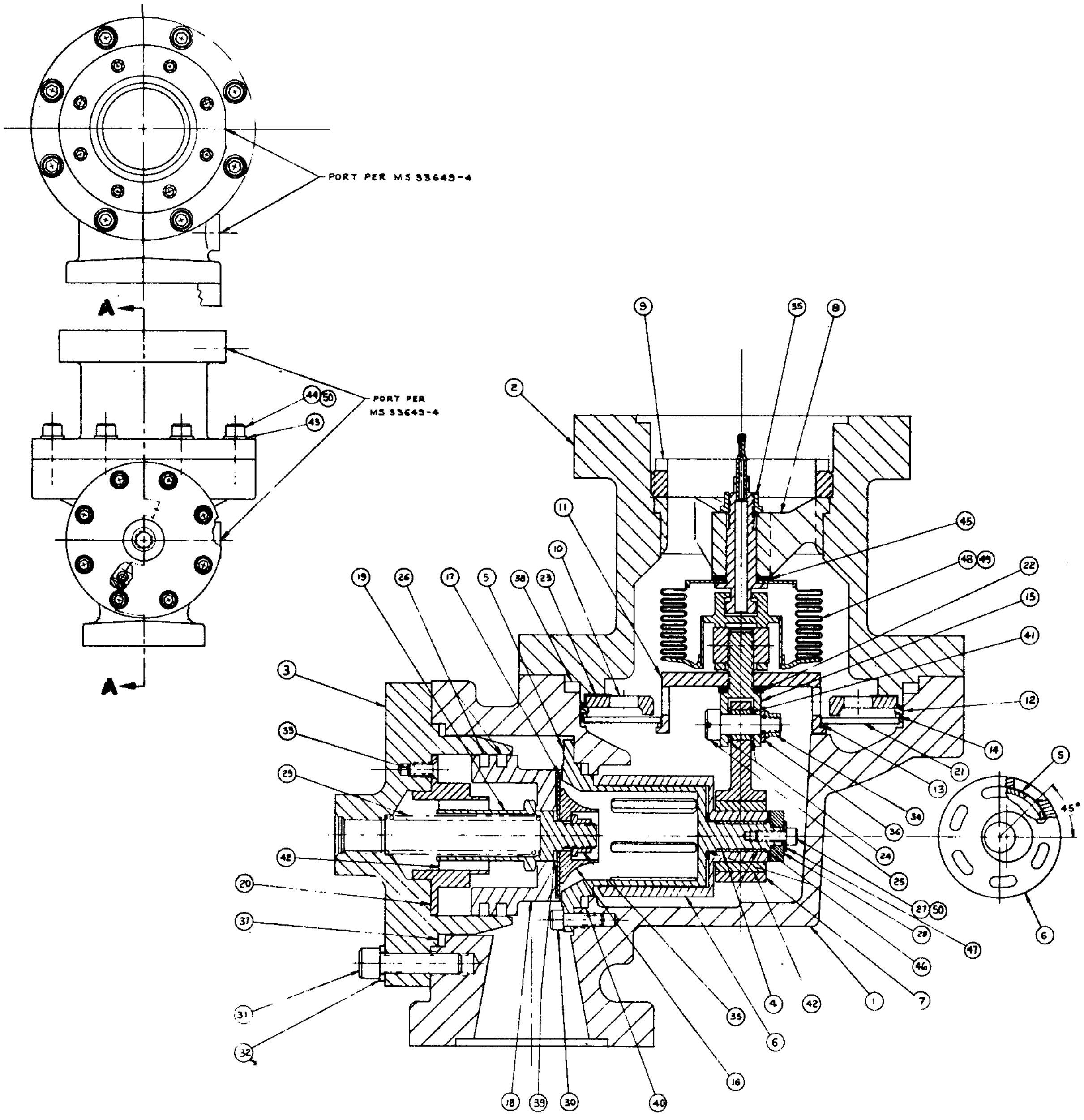
DO NOT SCALE DRAWING
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
MATERIAL
FINISH
HEAT TREAT
NEXT ASSY | USED ON
APPLICATION
CONTRACT NO.
PREP R. Burns
CHK
DSGN
PROJ
APVD
156

PARKER HANNIFIN IRVINE, CALIFORNIA
MASS FLOW CONTROLLER
DIRECT OPERATING (O_2+He)
SIZE E | CODE IDENT NO. 92003 | DWG NO. 5716187
SCALE 1/1 | UNIT WT | SHEET 1 OF 1

5716187

FIGURE 11

E.C.O. NO.	ZONE	LTR	REVISIONS DESCRIPTION	DATE	APPROVED
-2		A	REDRAWN REL FOR SPL PROJECT	6-28-71	[illegible]
3	-	B	REVISED ITEMS 4,24,27,28 & 46 ADDED ITEMS 46 THRU 50 ADDED CFG NO. -102	8-13-71	[illegible]



SECTION A-A SCALE 2/1

QTY REQD -102	QTY REQD -101	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	CODE IDENT		DWG SIZE	ITEM NO.
AR	AR	MS20995C	LOCKWIRE			-	50
1		5716161	CHARGED BELLOWS				49
	1	5716160	CHARGED BELLOWS				48
1	1	AN960C6	WASHER			-	47
2	2	5716158	WASHER			C	46
AR	AR	5716124-2-3-4	SHIM, SPIDER			B	45
8	8	NAS1351C5H18	SCREW			-	44
8	8	AN960PD516	WASHER			-	43
2	2	DBS-10-030	BUSHING		SOUTHWEST PROD CO	-	42
3	3	DBS-4-030	BUSHING		SOUTHWEST PROD CO	-	41
1	1	1161-01.500	SEAL		RACO	-	40
1	1	1151-00.375	SEAL		RACO	-	39
1	1	1170-04.375	SEAL		RACO	-	38
1	1	1160-02.750	SEAL		RACO	-	37
1	1	MS15795-808	WASHER			-	36
2	2	MS21043-5	NUT			-	35
1	1	MS21043-3	NUT			-	34
2	2	MS24693C26	SCREW			-	33
8	8	NAS620A416	WASHER			-	32
8	8	NAS1351C4H16	SCREW			-	31
6	6	NAS1352C08-08	SCREW			-	30
1	1	LC-063G-12	SPRING, COMP		LEE CO.	-	29
1	1	5716156	SPACER			C	28
1	1	NAS1352C06H6	SCREW			-	27
2	2	5716105	SEAL ASSY, PISTON			C	26
1	1	5716107	BOLT, CLEVIS			C	25
2	2	5716106	WASHER, TEFLON			B	24
AR	AR	5716103-2,-3,-4	SHIM, BELLEVILLE			C	23
AR	AR	5716104-2,-3,-4	SHIM, CLEVIS			B	22
1	1	5716102	SPRING, BELLEVILLE			C	21
1	1	5716101	RETAINER, BUSH			C	20
1	1	5716086	GUIDE, POPPET			C	19
1	1	5716084	PISTON			D	18
1	1	5716085	POPPET			C	17
1	1	5716099	GUIDE, FLOW			C	16
1	1	5716077	CLEVIS			C	15
1	1	5716098	RING, OUTER			B	14
1	1	5716096	RING, INNER			B	13
1	1	5716097	GUIDE, OUTER			C	12
1	1	5716095	GUIDE, INNER			C	11
1	1	5716094	STOP BELLEVILLE			C	10
1	1	5716092	NUT, SPIDER			C	9
1	1	5716091	SPIDER			C	8
1	1	5716071	LINK			D	7
1	1	5716069	CAGE			D	6
1	1	5716070	CYLINDER			D	5
1	1	5716157	BUSHING			C	4
1	1	5716083	CAP ASSY			D	3
1	1	5716090	HOUSING ASSY			D	2
1	1	5716082	BODY ASSY			E	1
-102	-101						-

PARTS LIST

DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

CONTRACT NO. 156

PREP RON BURR 5-14-71

DSGN W. TAYLOR 5-17-71

PARKER HANNIFIN IRVINE, CALIFORNIA

MASS FLOW CONTROLLER DIRECT OPERATING TYPE

SIZE E CODE IDENT NO. 92003 DWG NO. 5716068

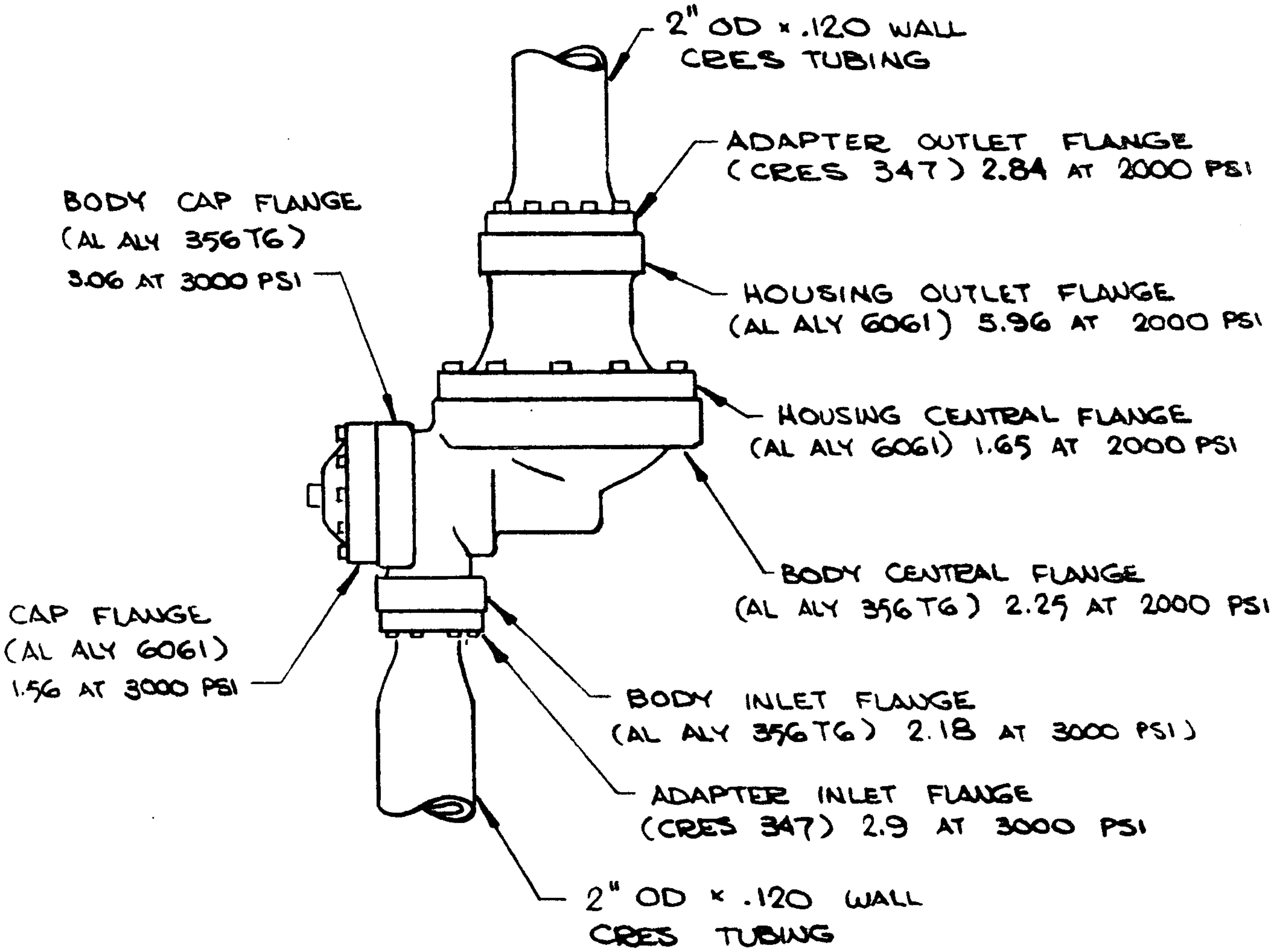
SCALE 1/1 SHEET 1 OF 1

NEXT ASSY | USED ON | APPLICATION

NOTES (UNLESS OTHERWISE SPECIFIED)

5716068

FIGURE 12



1. SAFETY FACTORS BASED ON ULTIMATE STRENGTHS OF MATERIALS AT PRESSURES INDICATED
   - CRES 347: 75000 PSI ULTIMATE
   - AL ALY 6061: 45000 PSI ULTIMATE
   - AL ALY 356T6: 33000 PSI ULTIMATE
2. STRESSES CALCULATED PER ASME CODE

FIGURE 13 SAFETY FACTORS FOR FLANGES OF MFC

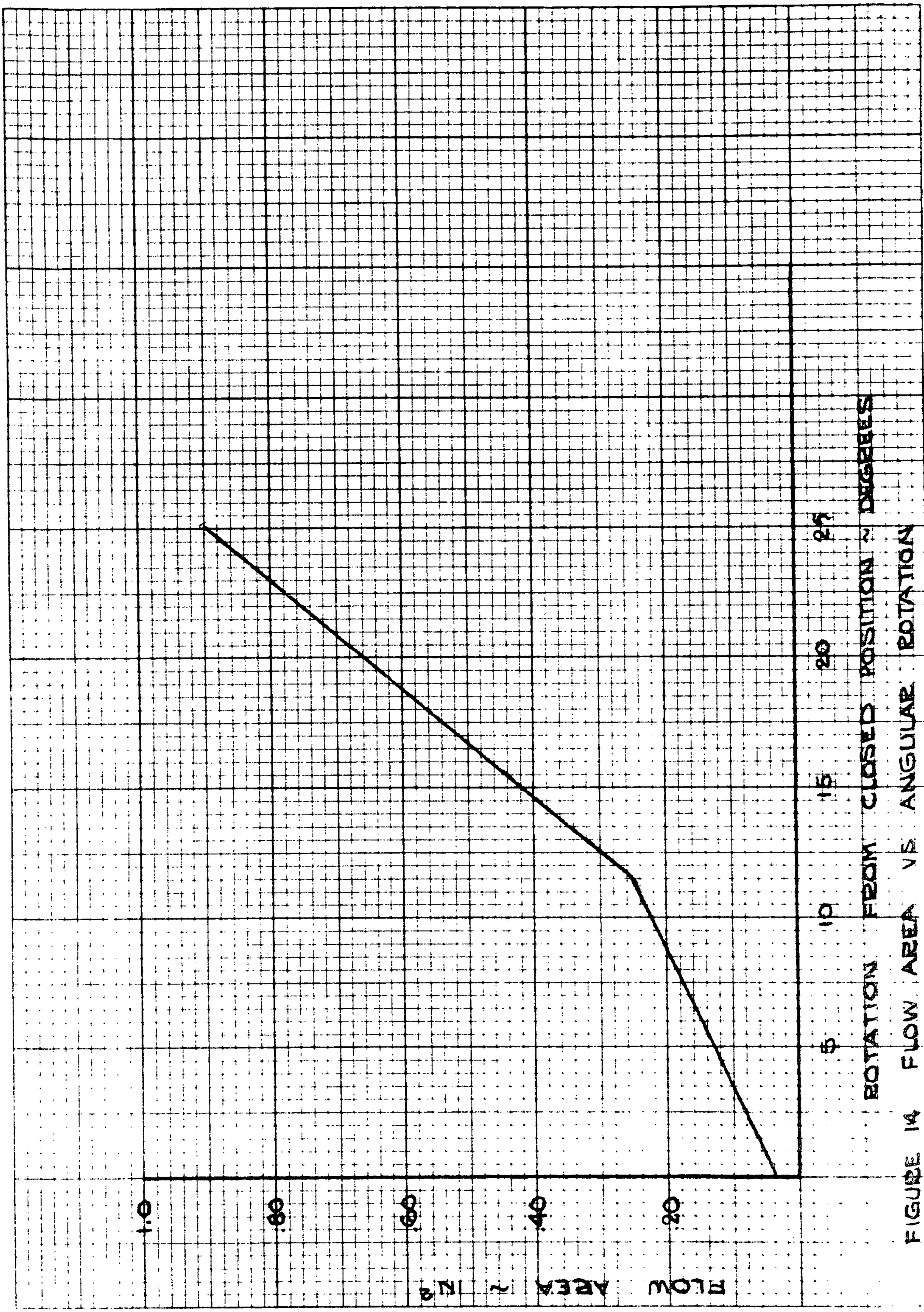


FIGURE 14 FLOW AREA VS ANGULAR ROTATION

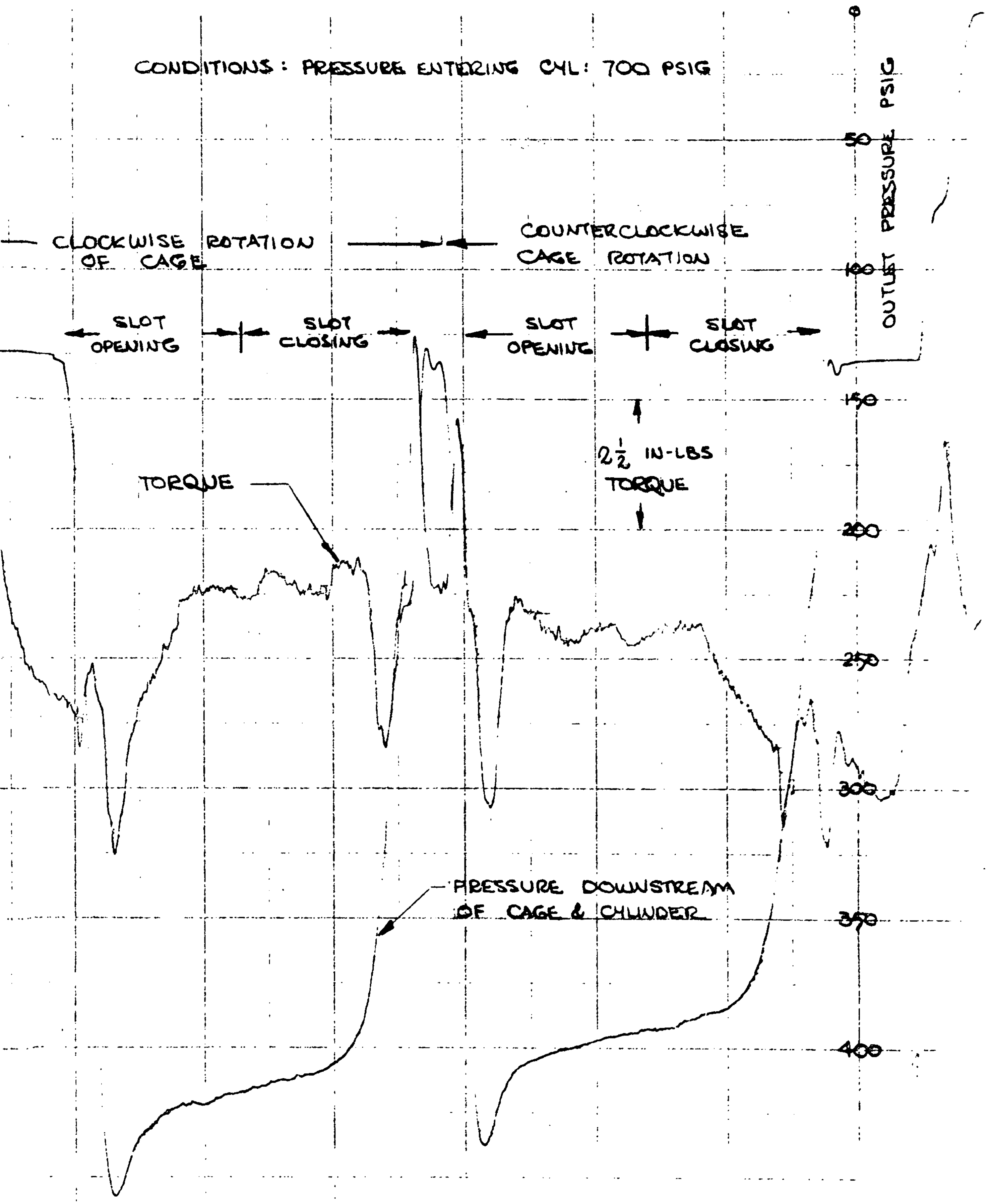


FIGURE 15 TORQUE ON PROTOTYPE CAGE DURING ROTATION

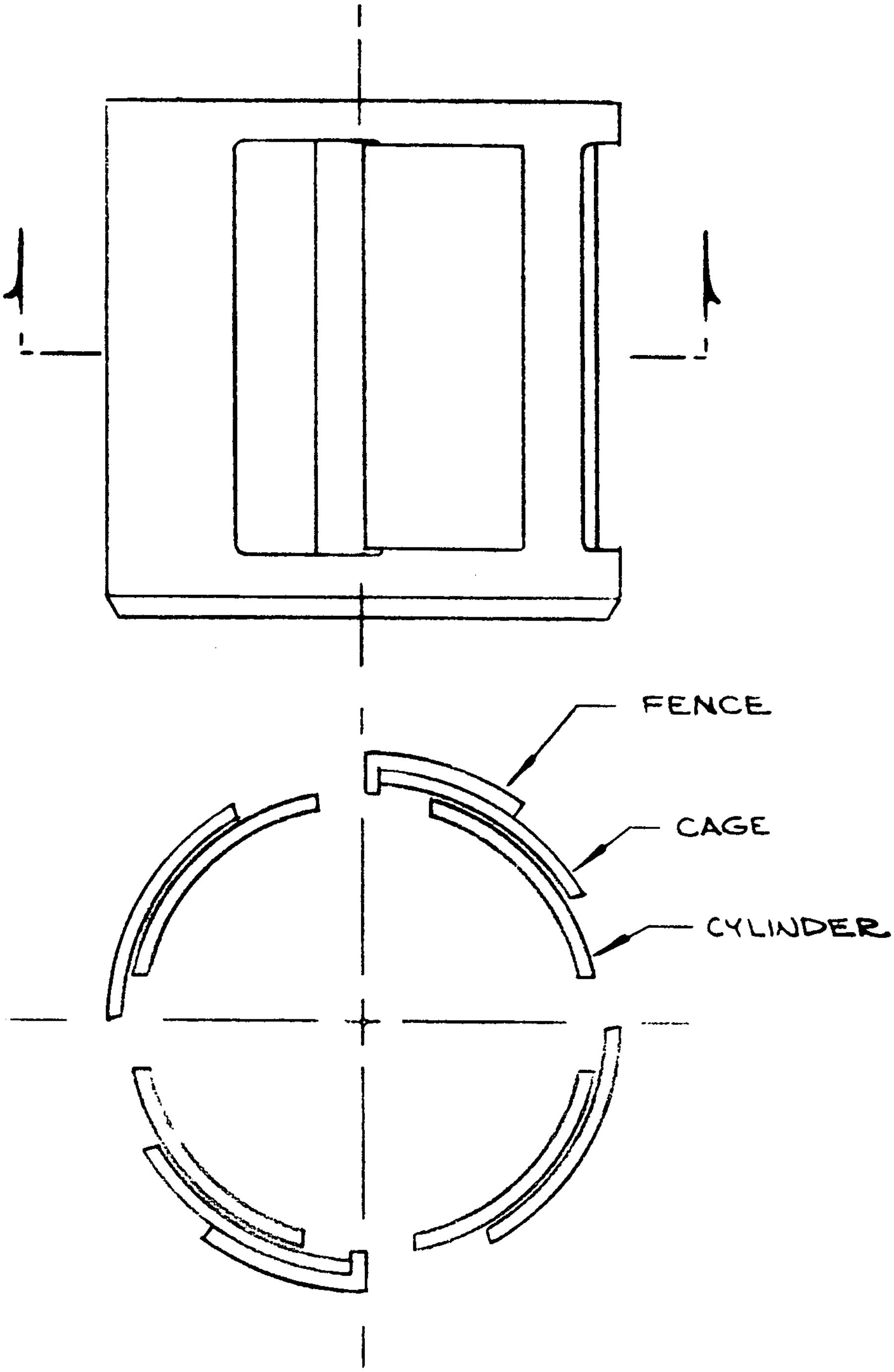


FIGURE 16 PROTOTYPE CAGE AND CYLINDER WITH FENCE

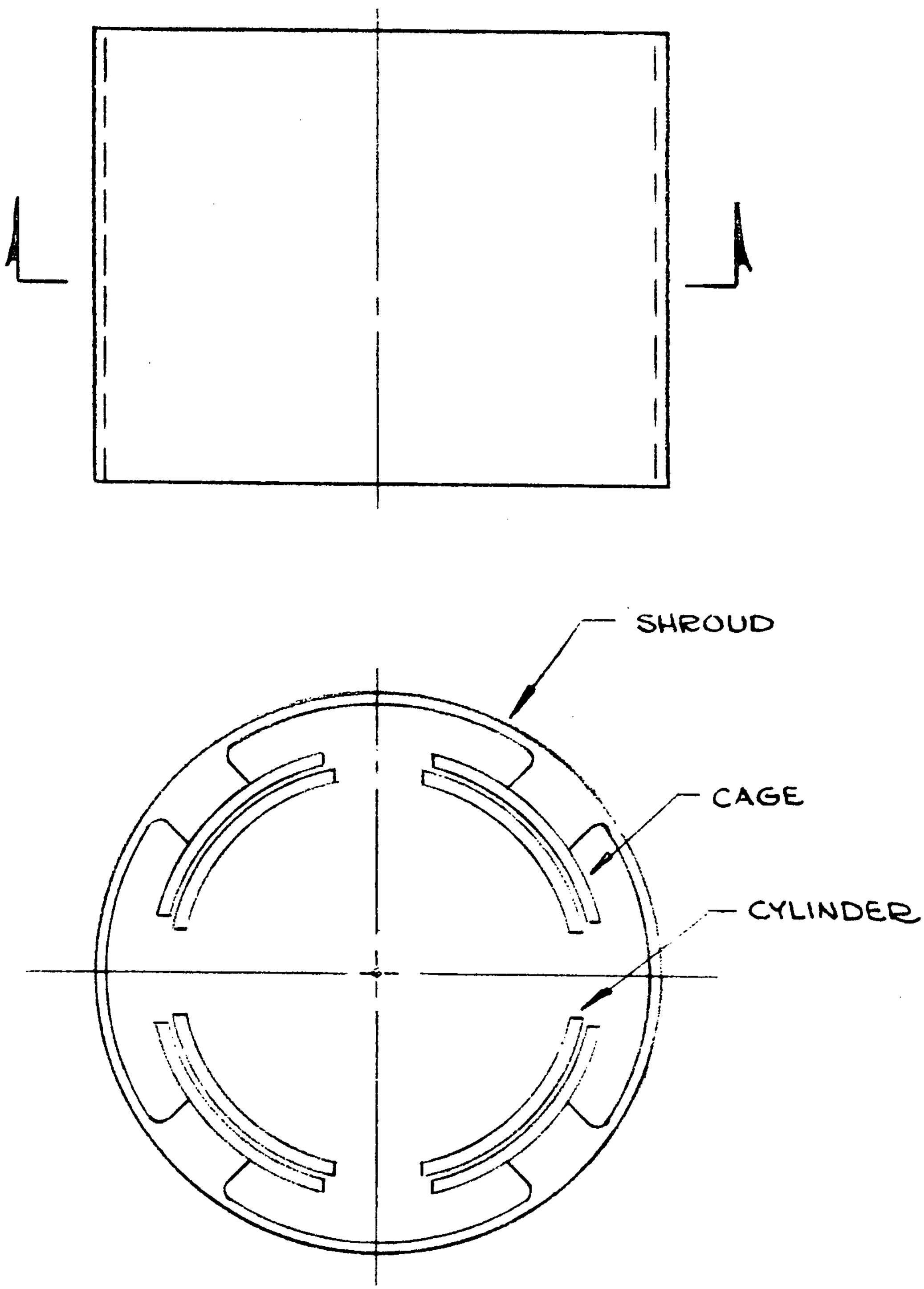


FIGURE 17 PROTOTYPE CAGE AND CYLINDER WITH SHROUD

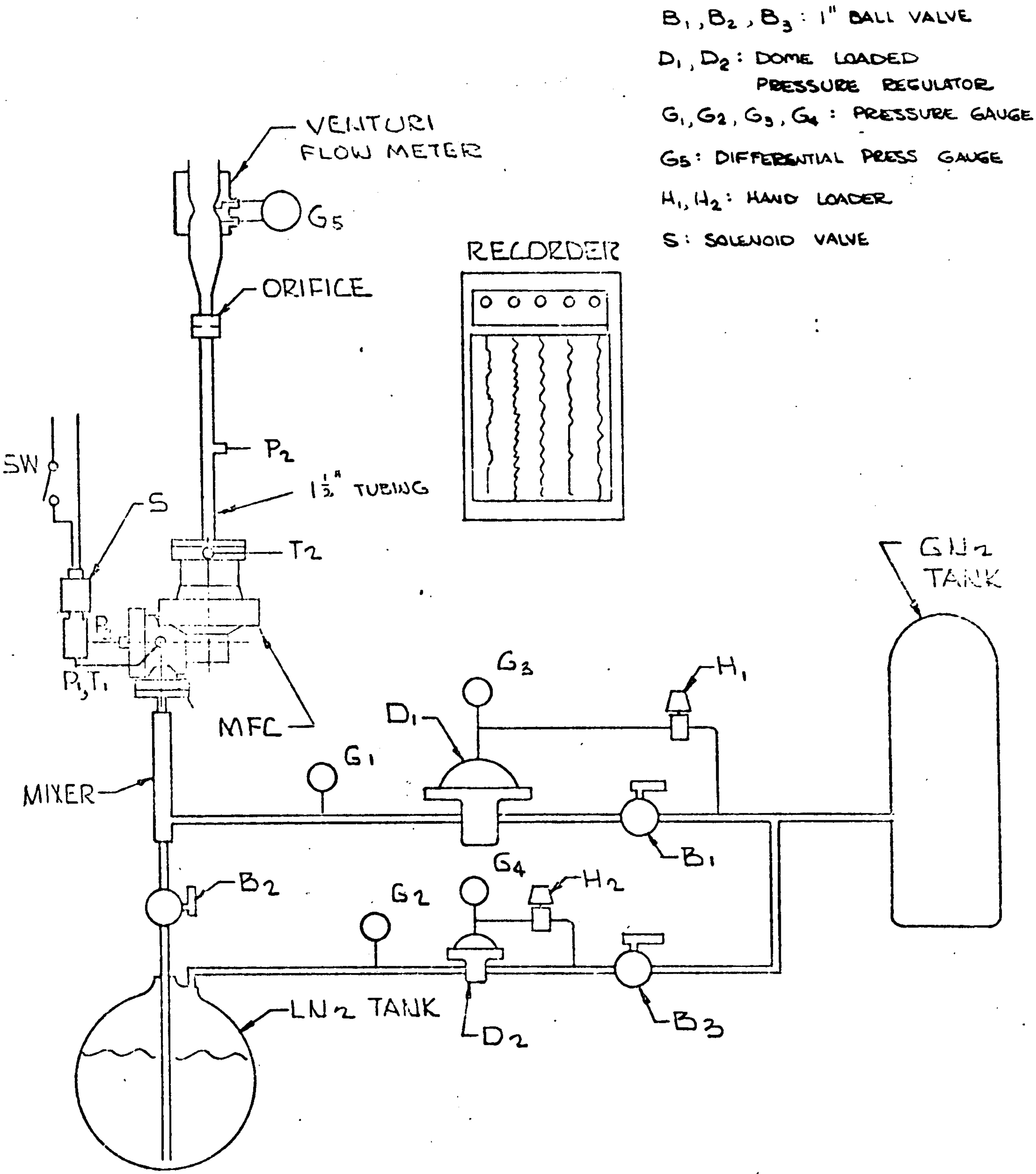


FIGURE 18 SETUP FOR MFC TESTS

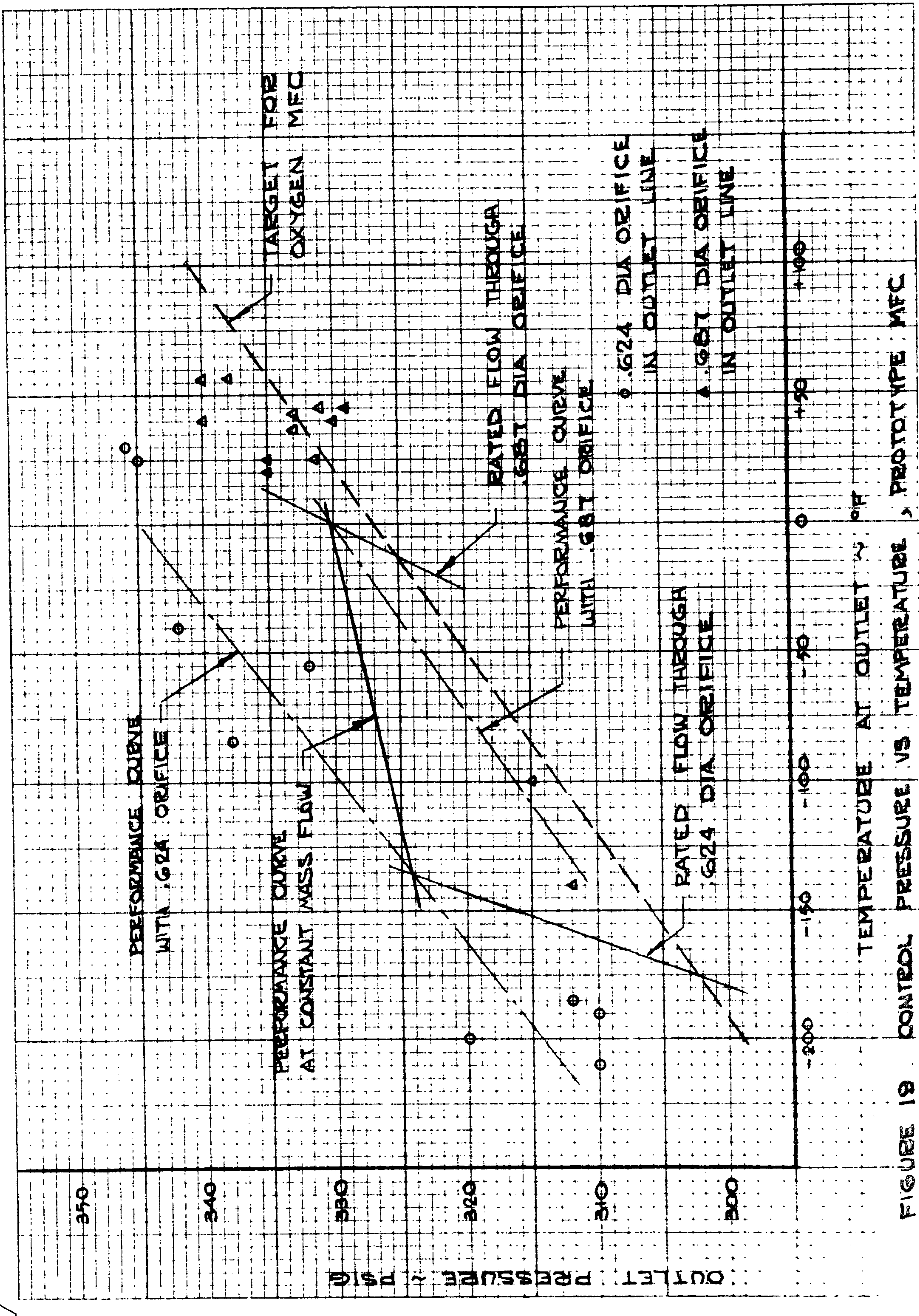


FIGURE 19 CONTROL PRESSURE VS TEMPERATURE, PROTOTYPE MFC

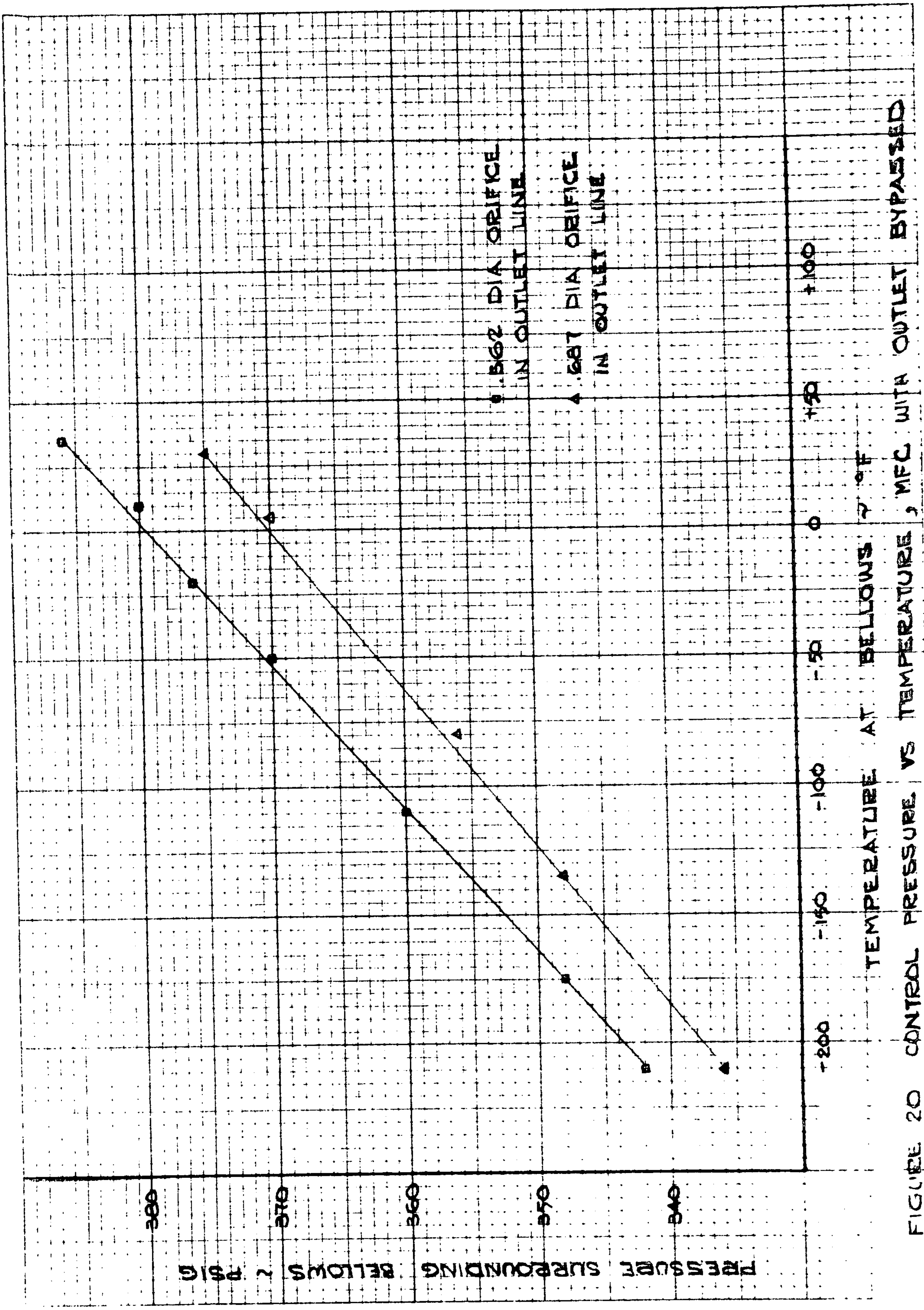


FIGURE 20 CONTROL PRESSURE VS TEMPERATURE, MFC WITH OUTLET BYPASSED

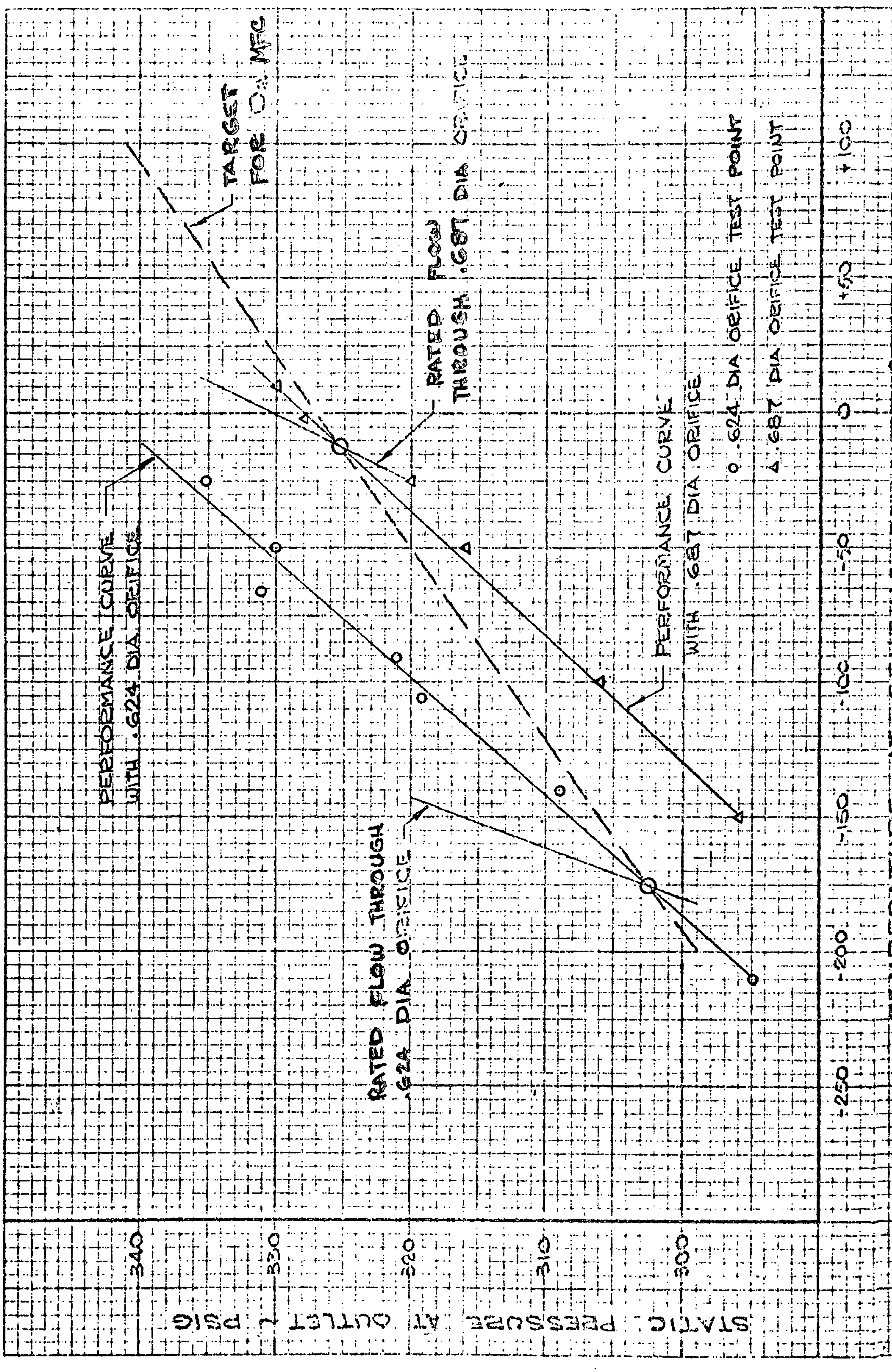


FIGURE 21 CONTROL PRESSURE VS TEMPERATURE, PREPRODUCTION MFC

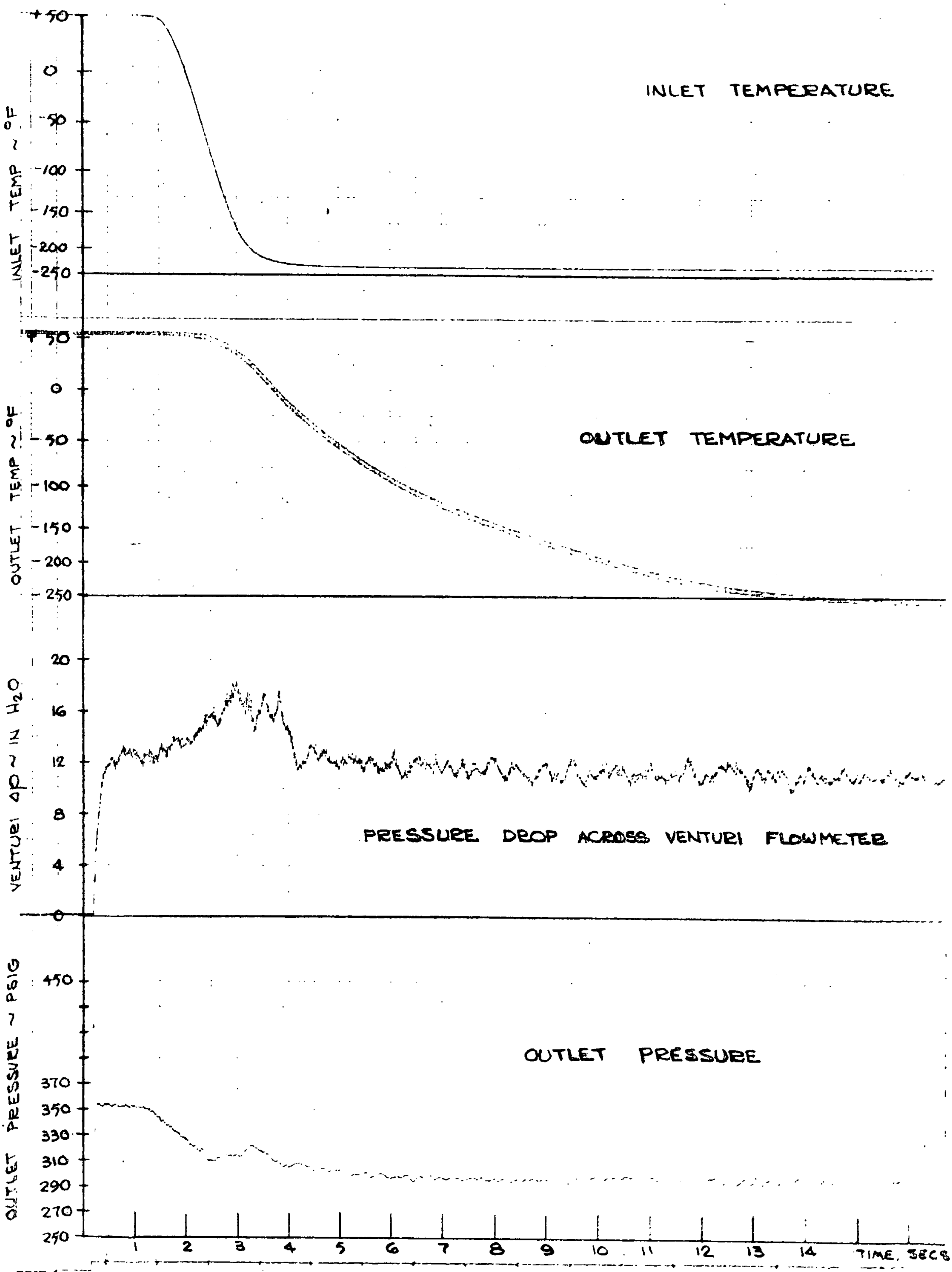


FIGURE 22 RECORDER TRACE OF TRANSIENT, PREPRODUCTION MFC

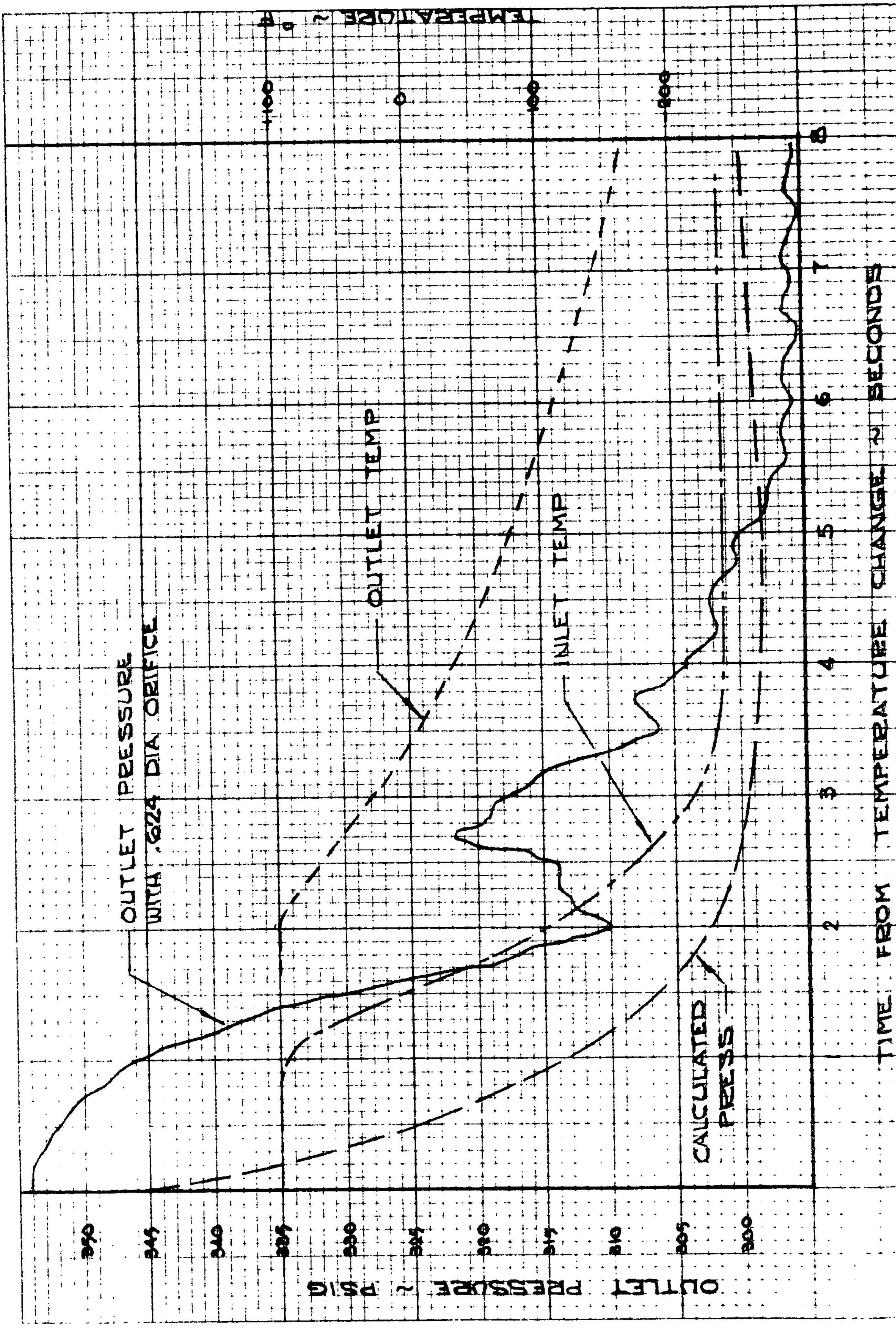


FIGURE 23 COMPARISON OF TEST TRACE WITH CALCULATED CURVE

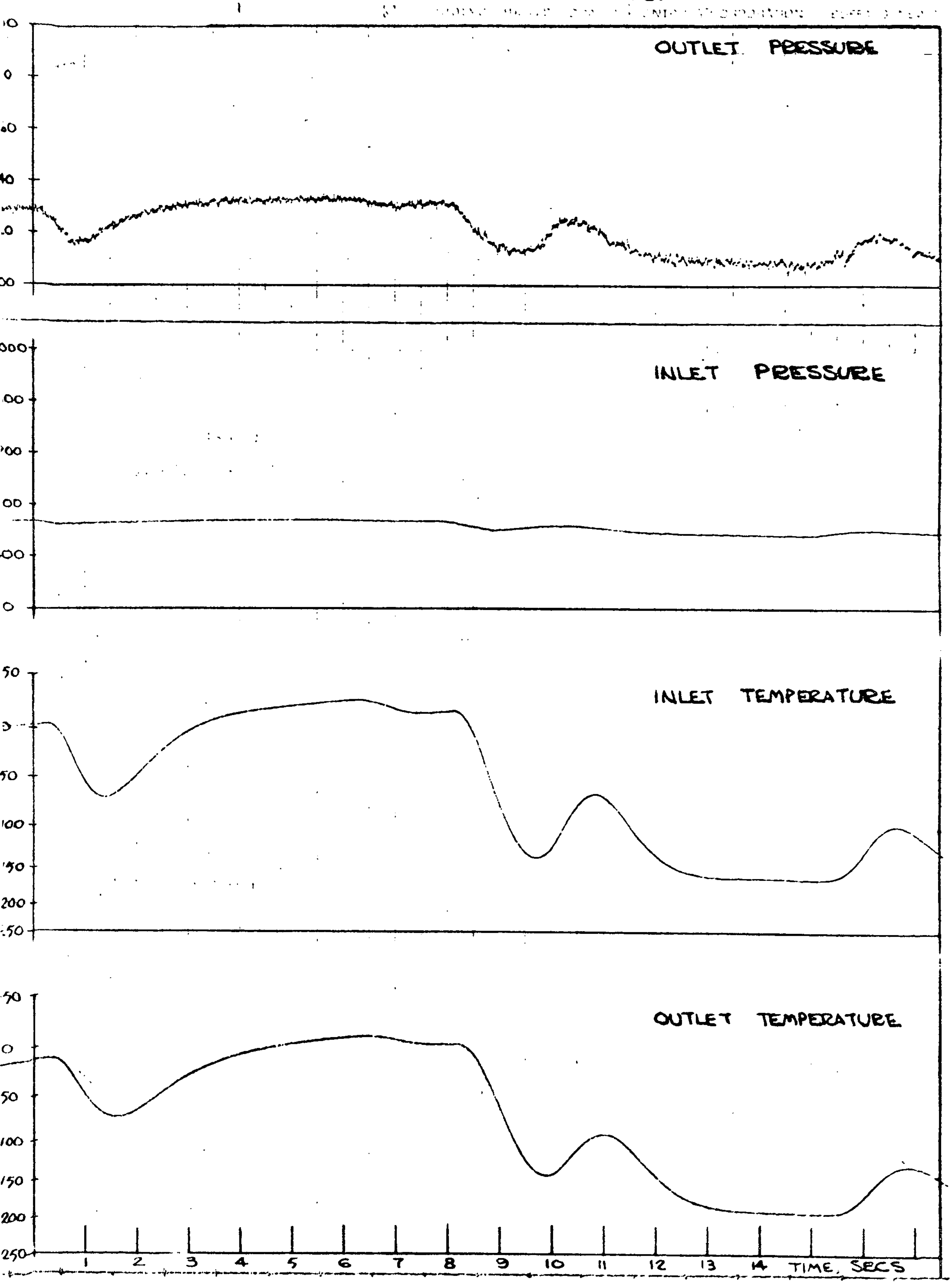


FIGURE 24 RECORDER TRACE FROM TEST OF PREPRODUCTION MFC

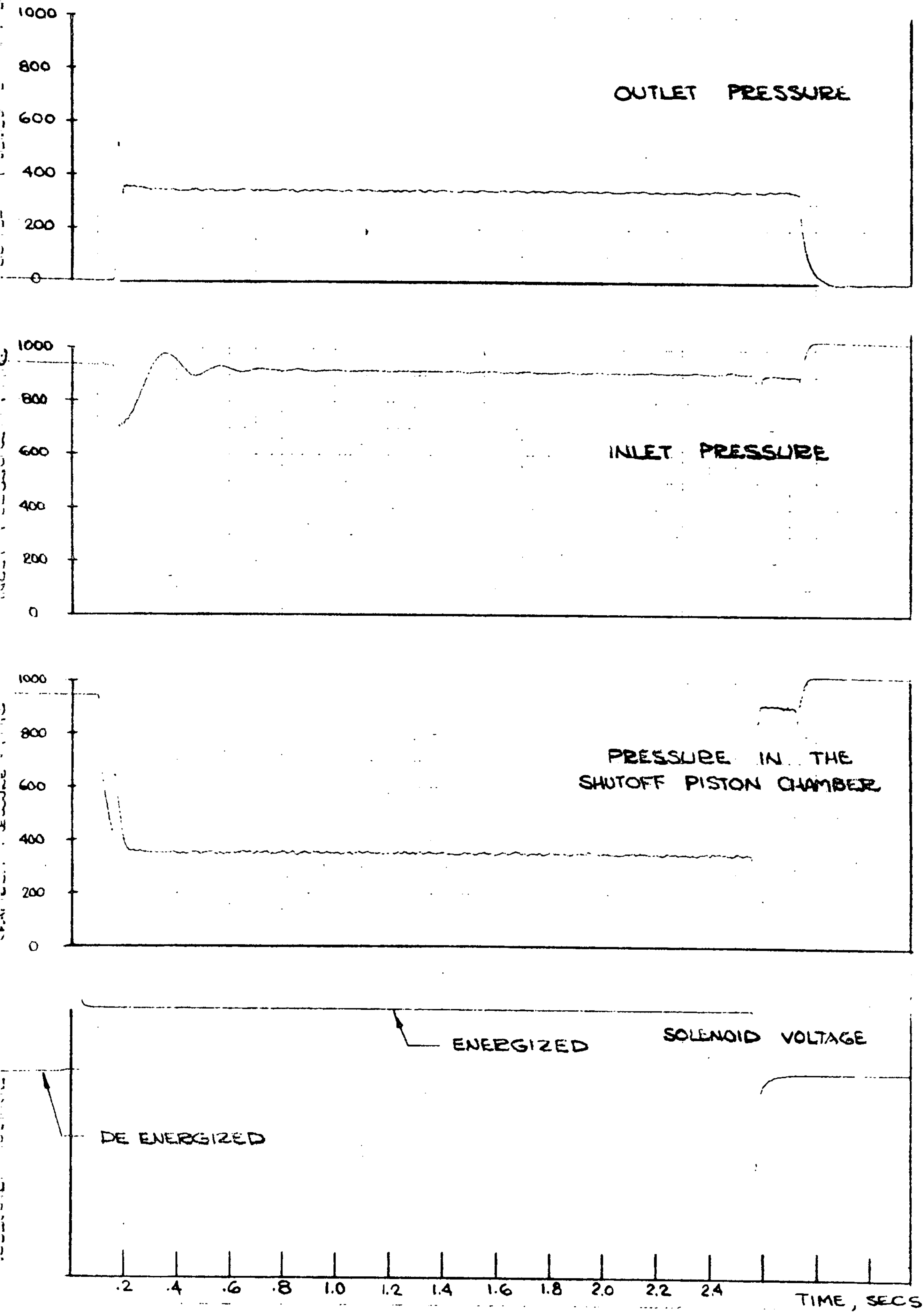


FIGURE 25 PRESSURE RESPONSE H₂ MFC, S/N 01

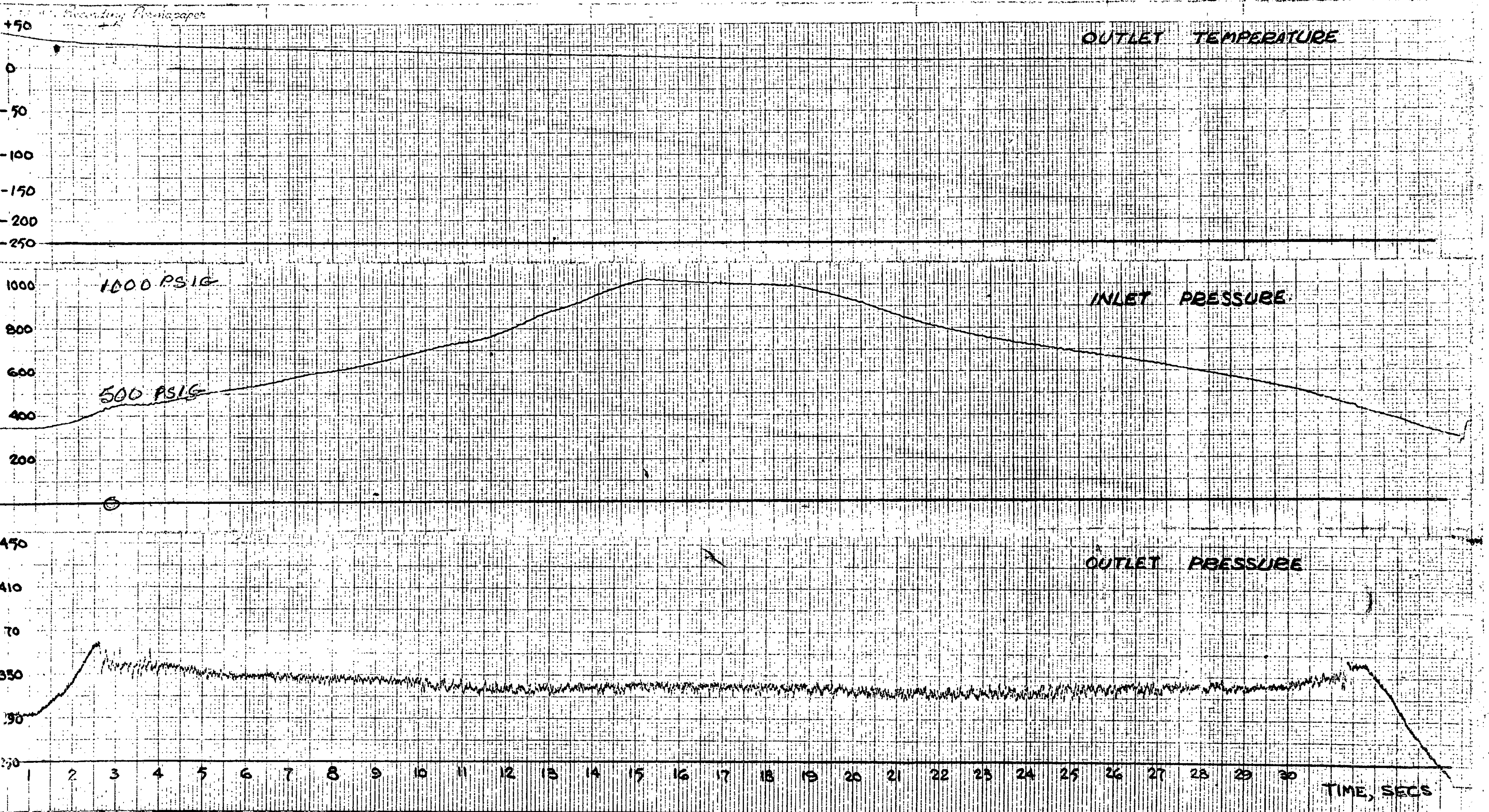


FIG 26 OUTLET PRESSURE WITH VARYING INLET PRESSURE O_2 MFC, S/N 02

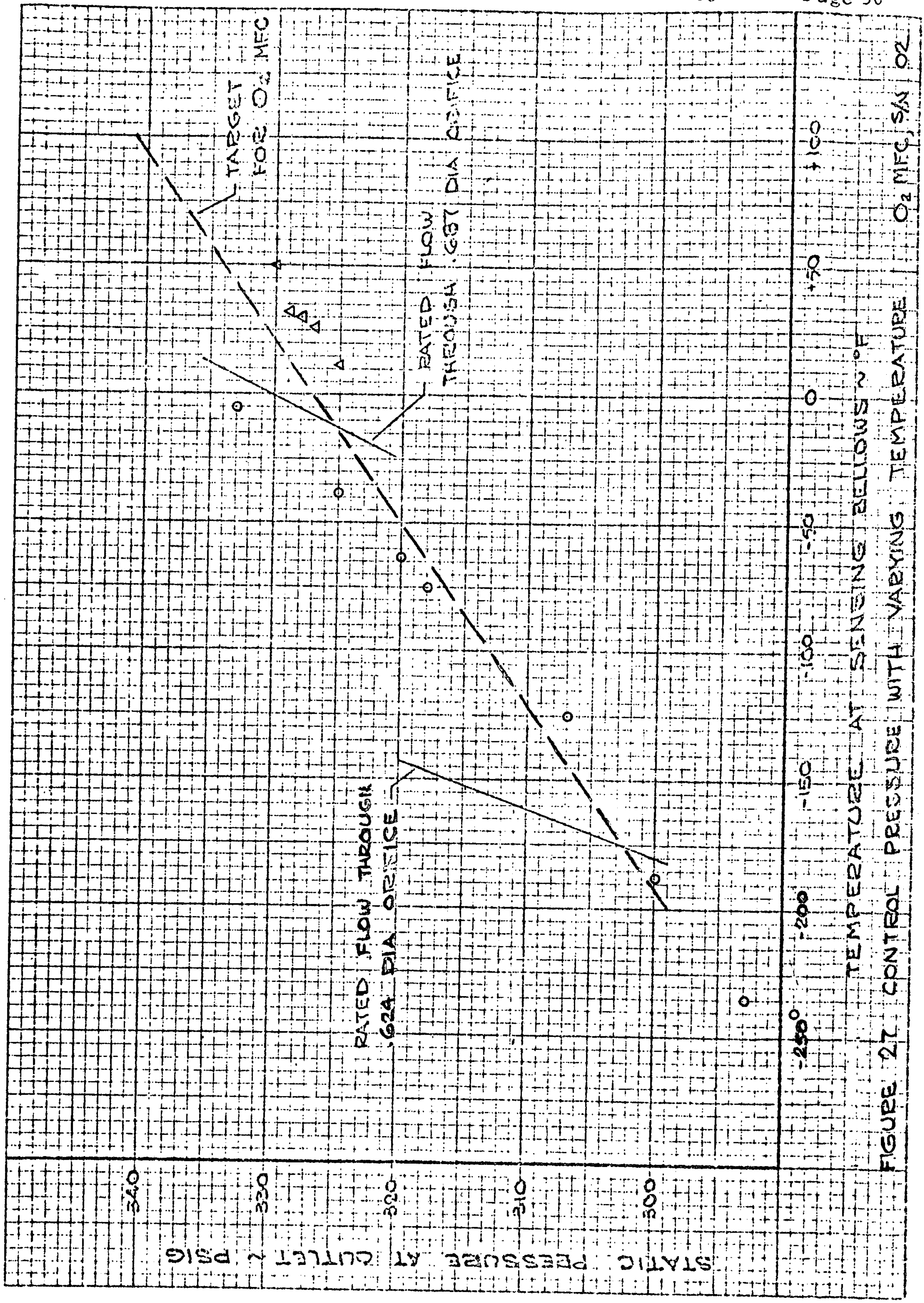


FIGURE 27 CONTROL PRESSURE WITH VARYING TEMPERATURE O_2 MFC, S/N O2

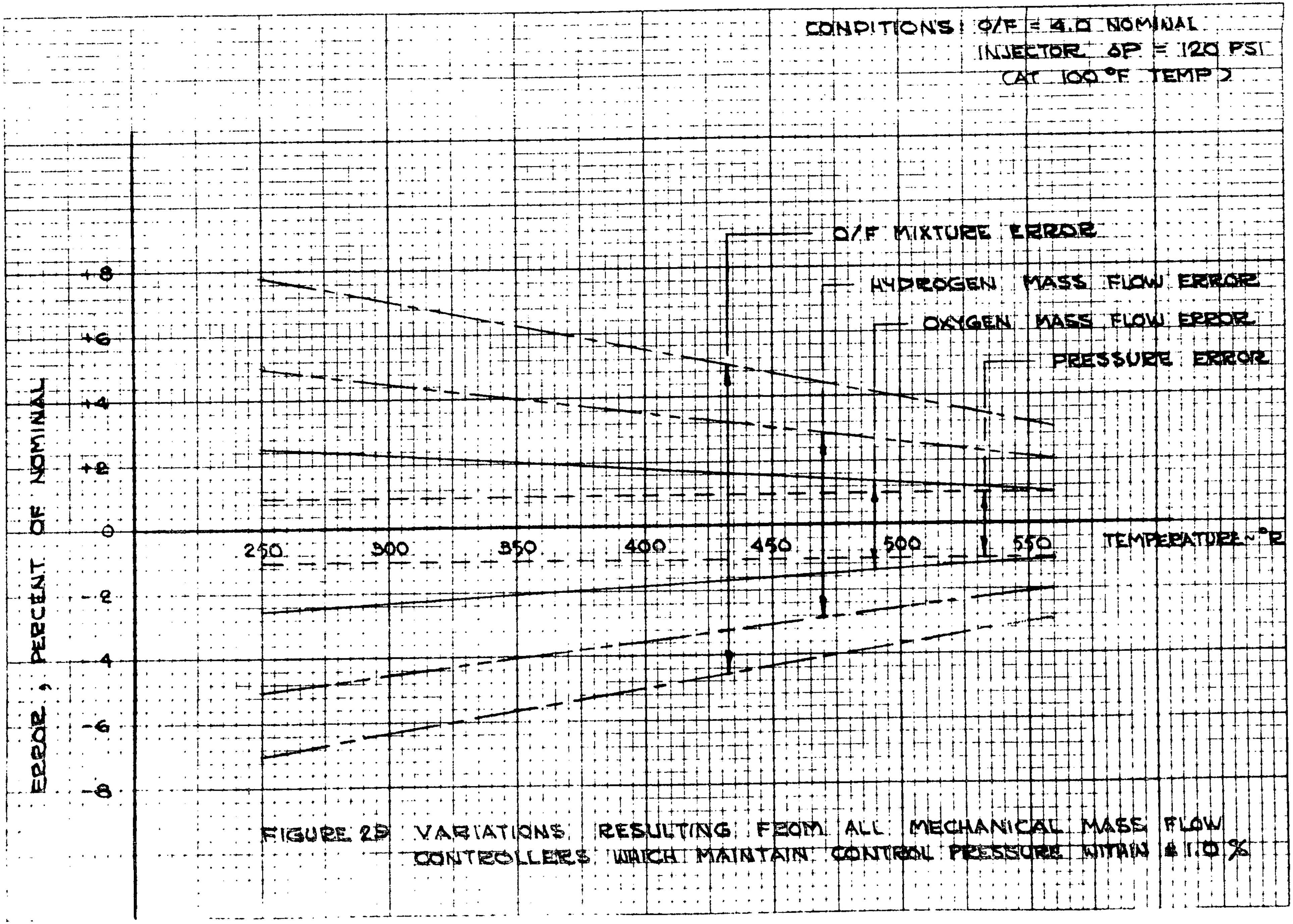


FIGURE 25 VARIATIONS RESULTING FROM ALL MECHANICAL MASS FLOW CONTROLLERS WHICH MAINTAIN CONTROL PRESSURE WITHIN ± 1.0 %

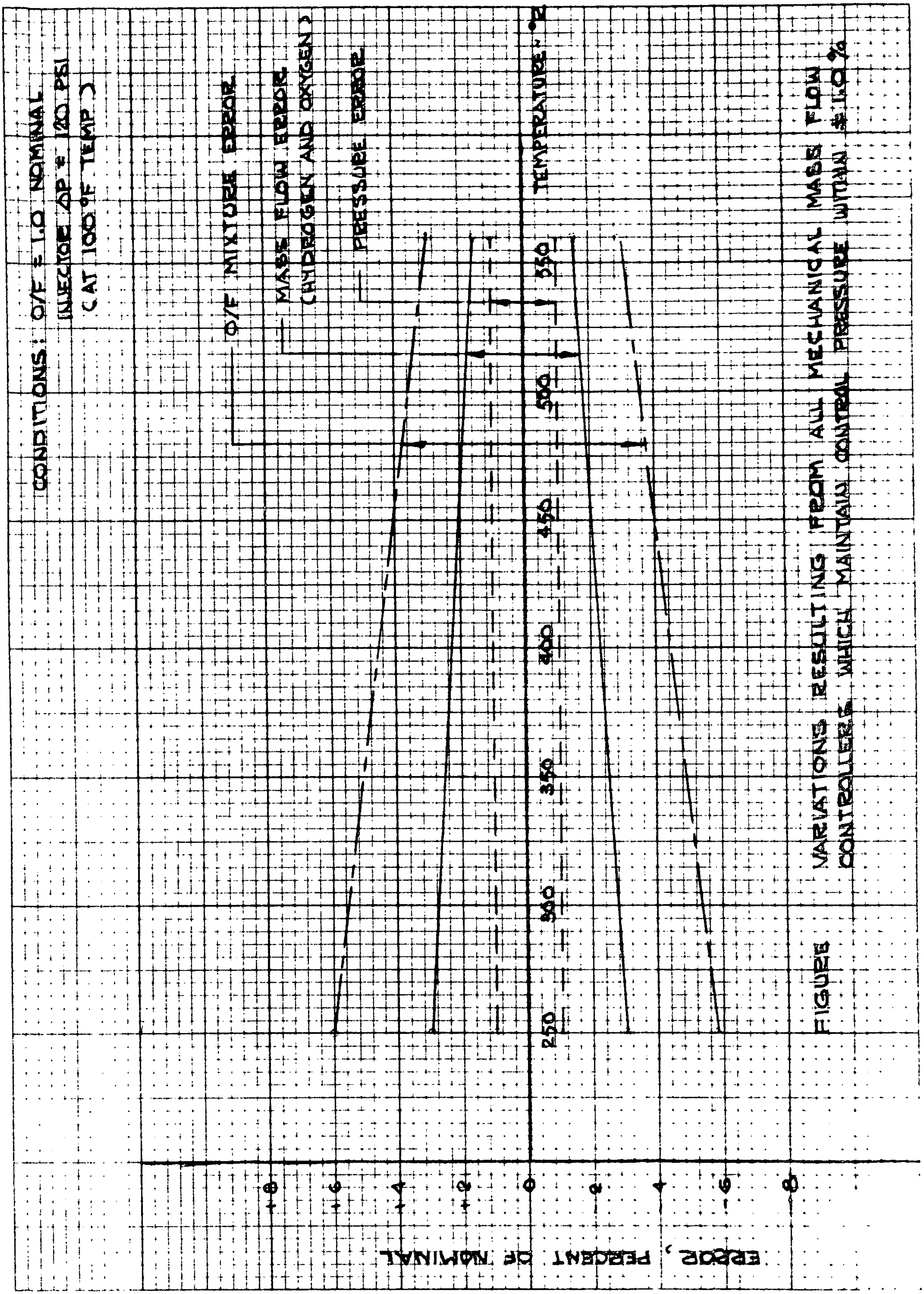


FIGURE VARIATIONS RESULTING FROM ALL MECHANICAL MASS FLOW CONTROLLERS WHICH MAINTAIN CONTROL PRESSURE WITHIN ±1.0%

	PRESSURE PSIG	LEAKAGE, SCCM (TEST MEDIUM: GN_2)			
		HYDROGEN MFC P/N 5716068-101		OXYGEN MFC P/N 5716068-102	
		S/N 01	S/N 02	S/N 01	S/N 02
EXTERNAL LEAKAGE					
CAP FLANGE	1000	10	5	8	8
	2000	232	13	15	56
HOUSING FLANGE	400	<1	0	2	0
SOLENOID VALVE	3000	0	0	0	0
INTERNAL LEAKAGE					
POPPET	400	50	34	365	9000
	1000	330	420	1140	24000
	2000	1375	1520	2315	40 000
SOLENOID VALVE					
ENERGIZED	3000	0	0	0	0
DEENERGIZED	3000	0	0	0	0

TABLE I RESULTS OF LEAKAGE TESTS OF MASS FLOW CONTROLLERS

INTERNAL (POPPET) LEAKAGE, SCCM GN_2

INLET PRESSURE PSIG	BEFORE CYCLES	AFTER 10000 CYCLES
400	50	45
1000	330	500
2000	1375	1300

PRESSURE DROP THROUGH FULLY OPEN MFC

$\sigma \Delta p$ = 1400 PSI AT RATED FLOW

$$\sigma = \frac{\text{DENSITY OF } GN_2 \text{ AT MFC OUTLET}}{\text{DENSITY OF } GN_2 \text{ AT 1 ATMOSPHERE, } 70°F}$$

TABLE 2 SUMMARY OF DVT TEST RESULTS

	TEMPERATURE CHANGE, °F	CONTROL PRESSURE CHANGE, PSI	TIME REQ'D, SECS
HYDROGEN MFC 5716068 - 101			
S/N 01	-170	-23	0.8
S/N 02	-242	-25	1.3
OXYGEN MFC 5716068 - 102			
S/N 01	-132	-20	0.6
S/N 02	-125	-12	0.8

TABLE 3 RESULTS OF THERMAL RESPONSE TESTS OF MASS FLOW CONTROLLERS

APPENDIX A

MANUFACTURING OPERATION ROUTING

for P/N 5716068

MFG OPERATION ROUTING - SYSTEMS DIVISION

Part No. 5716068-102 Rev B

Prepared By	Date	Appd By	Date	Appd By	Date	Planner	Part Name
EMERY	7/9/71					WIRTZ	MASS FLOW CONTROL DIRECT OPERATING TYPE

Next Assy	No. Req	Start Date	Due Date	Project	Task	C. E	Control Number
				156	A	1	

End Item

Material and Specification: PER ASSY PARTS LIST

Stock Required

REV	DATE	REVISIONS	Rev By	Appd By
N/C	7/9/71	RELEASED	EEE	
B	10/4/71	REV. TO ENG. CHG 'B'	EEE	

REV	DATE	REVISIONS	Rev By	Appd By

CONTROL NUMBER ______ SHEET ______ OF ______

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
10	30			ISSUE ALL ITEMS PER PARTS LIST					
				& ALL TOOLING LISTED BELOW:					
				S80-0-905-1 & -2 BUSHING INSTALL. TOOLS					
				S65-0-1793 SET UP FIXTURE					
				S66-0-130 GAGE RING					
				S66-0-131 GAGE PLATE					
				S80-0-906 TORQUE ADAPTER					
20	110		A-	BAG OR PLACE IN PROTECTIVE PKG ONLY					
				THOSE PARTS WITH CRITICAL SURFACE					
				FINISHES, ALSO VERY SMALL PARTS					
				I.E. SCREWS, BOLTS, SEALS THAT					
				COULD EASILY BECOME LOST.					
			B-	KEEP PARTS IN THEIR RESPECTIVE					
				GROUP & PASS THRU TO CLEAN					
				ROOM					

CONTROL NUMBER ________ SHEET ___ OF ___

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept/ No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
20	(CONTINUED)		C-	ALL TOOLING USED IN CLEAN ROOM					
				ASSY SHALL BE CLEANED IN					
				ACCORDANCE WITH CATEGORIES					
				IN OP. 30.					
			D-	ALL PARTS IN ALL CATEGORIES SHALL					
				BE BLACK LITE INSPECTED AFTER CLEANING.					
			E-	REMOVE ANY DYE FROM BOLTS WITH					
				ACETONE & CLEAN WITH GROUP "C"					
				IN OPER. 30.					
			F-	DO NOT SCRUB ALUMINUM PARTS					
				WITH S.S. BRUSHES					
			G-	DO NOT REMOVE TAGS ON					
				BELLEVILLE SPRINGS OR BELLOWS ASSY					

CONTROL NUMBER ______ SHEET 4 OF [illegible]

MFG OPERATION ROUTING – OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	Machine and Operation Description	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
25	110			CLEAN VALVE PARTS AS FOLLOWS:					
				GROUP 'A' - NON METALLIC PARTS					
				ALL NON METALLIC PARTS SUCH AS 'O' RINGS,					
				SEALS, ETC., SHALL BE CLEANED IN					
				TURCO 4215 WITH SOFT NYLON BRUSH					
				& RINSED IN D.I. WATER. FINAL					
				RINSE IN FREON & AIR DRY.					
				GROUP 'B' - MICROSEALED PARTS					
				ALL MICROSEALED PARTS SHALL BE					
				VAPOR DEGREASED IN FREON. BRUSH					
				LIGHTLY TO REMOVE LOOSE PARTICLES.					
				GROUP 'C' - STAINLESS STL. & ALUM. PARTS					
				TRICHLORETHYLENE VAPOR DEGREASE					
				ALL ST. STL. & ALUM. PARTS. SCRUB					
				IN TURCO 3878 & RINSE IN D.I. WATER.					
				DO NOT SCRUB ALUM. PARTS WITH ST. STL.					
				BRUSHES. SCRUB IN TURCO 4215 &					
				RINSE IN D.I. WATER. BRUSH HOLES					
				WITH NYLON BRUSH. OVEN DRY FOR					
				(1) HR. @ 150°F.					
				BLACK LIGHT INSPECT ALL PARTS IN ALL GROUPS.					

CONTROL NUMBER ______ SHEET [illegible] OF [illegible]

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
30	120		A-	SONIC CLEAN IN FREON GROUPS					
				'A' & 'C' ONLY. CLEAN GROUP 'B'					
				(MICROSEALED PARTS) WITH FREON					
				SPRAY RINSE. IF NECESSARY,					
				GROUP 'B' PARTS MAY BE SONIC					
				CLEANED IN FREON FOR 30 SECONDS					
				MAX.					
			B-	RINSE EACH GROUP WITH FREON &					
				COLLECT 1000 ML SAMPLE TOTAL.					
				VERIFY PER ES5-15 LEVEL VI.					
				RECORD BELOW.					
				PARTICLE SIZE / REQ'D / ACTUAL					
				175 - 700 / 10 /					
				700 - 2500 / 2 /					
				2500 & UP / 0 /					
				APPROX. SURFACE: 2 SQ. FT.					
				NVR TEST PER ES5-15 PARA. 5.2 - 2 Mg PERMISS.					
			C-	DRY ALL PARTS IN VACUUM OVEN 110°F					
				TO 120°F WITH 28.5" VACUUM, FOR (1) HR.					
				(REF: ES5-14 PARA. 5.5)					

MFG 0013-25-071

CONTROL NUMBER ______ SHEET ______ OF ______

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
35	120			PACKAGE ALL PARTS IN POLY BAG &					
				PLACE ON TRAYS FOR ASSEMBLY					
				AT OP. 130.					
40	130			CAGE-CYLINDER BUSHING ASSY.					
			A-	INSTALL BUSHING, ITEM 4, ON CYLINDER,					
				ITEM 5, INSTALL WASHER ITEM 46.					
				WRAP BUSHING WITH ELASTIC BAND OR					
				EQUIVELANT, TO COMPRESS ON CYLINDER					
				SHAFT. SUBMERGE CYLINDER WITH					
				BUSHING IN LIQUID NITROGEN.					
				REMOVE FROM LN_2 & BREAK AWAY					
				THE ELASTIC BAND. QUICKLY & CAREFULLY					
				PRESS THE CAGE ONTO THE CYLINDER					
				& BUSHING.					
			B.	WORK THE CYLINDER & CAGE BACK					
				& FORTH SEVERAL TIMES. IF PARTS					
				DO NOT BECOME FREE - HEAT THE					
				ASSEMBLY TO 500-550°F FOR					
				30 MINUTES. REMOVE FROM OVEN					
				& WORK THE PARTS SEVERAL TIMES					
				WHILE STILL HOT.					

CONTROL NUMBER ______ SHEET ______ OF 6

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
40	(CONTINUED)			COOL TO ROOM TEMP., PARTS SHOULD					
				NOW BE FREE. REMOVE THE CAGE					
				FROM THE CYLINDER & CLEAN UP					
				ANY EXCESS BUSHING OR MICROSEAL					
				PARTICLES.					
			C-	REASSEMBLE THE CAGE TO THE CYLINDER,					
				INSTALL WASHER ITEM 51, SPACER					
				ITEM 28, WASHER ITEM 47 &					
				SCREW ITEM 27. TORQUE SCREW					
				TO 20-25 INCH LBS. & SAFETY WIRE.					
45	130			ASSEMBLE LINKAGE					
			A	ASSEMBLE:					
				BUSHING DBS-10.030 ITEM 42, TO	5800-0.9054 & -2				
				LINK 5716071 ITEM 7. ASSEM.	INSTALLATION TOOLS				
				CLEVIS BOLT 5716107 ITEM 25 &					
				CAGE 5716069 ITEM 6 TO					
				DETERMINE IF FIT ALLOWS					
				SMOOTH OPERATION. WORK BACK					
				& FORTH UNTIL FREE.					

CONTROL NUMBER ______ SHEET __ OF __

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

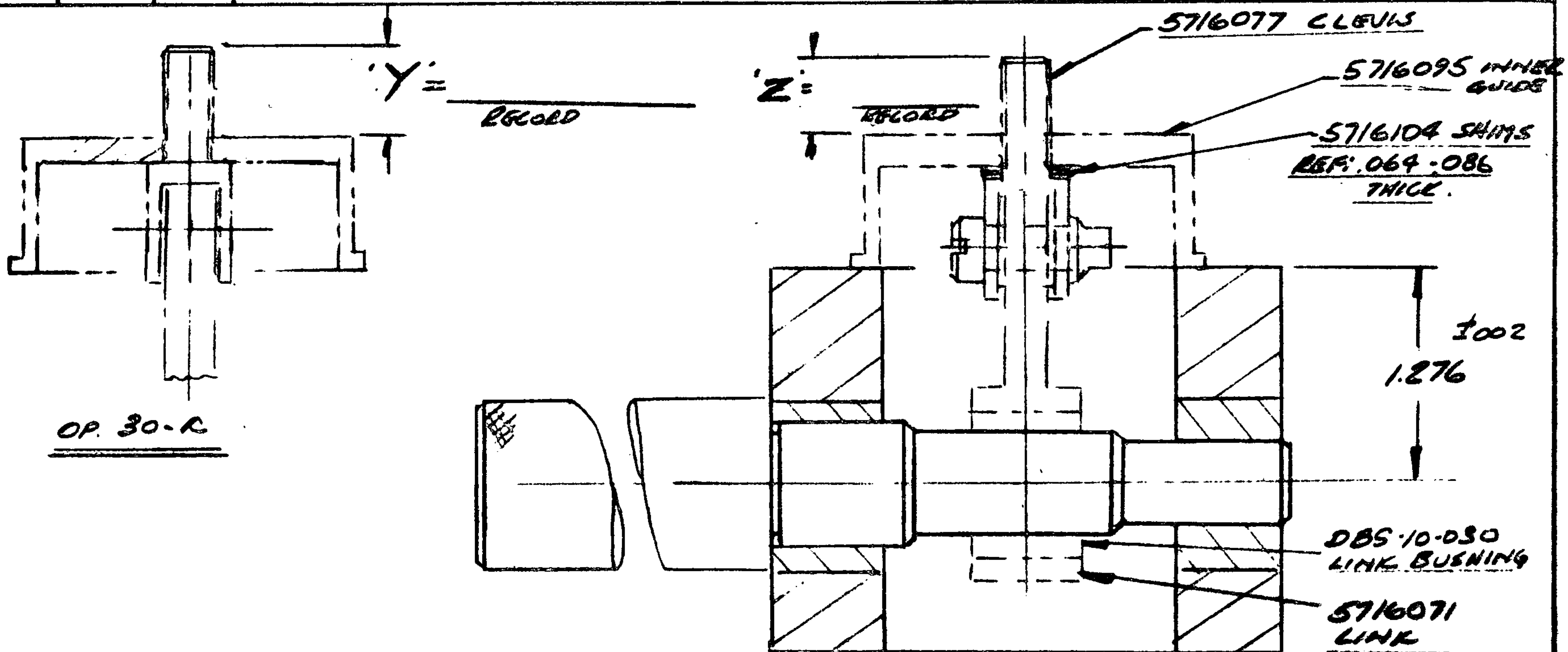
Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
45	(CONTINUED)		B-	ASSEM. CLEVIS 5716077, ITEM 15,					
				TEFLON WASHERS 5716106, ITEM 24,					
				CLEVIS BOLT 5716107, ITEM 25,					
				WASHER MS15795-808, ITEM 36 &					
				NUT MS21043-3, ITEM 34 PER B/P.					
				WORK THE ASSEMBLY UNTIL PARTS					
				ARE FREE. TORQUE TO 20-25 INCH LBS.					
			C-	PER SKETCH SHEET 9					
				ASSEMBLE INNER GUIDE 5716095,					
				ITEM 11, TO THREAD ON CLEVIS &					
				TURN UNTIL INNER GUIDE BOTTOMS					
				ON CLEVIS SHOULDER. MEASURE					
				& RECORD 'Y' DIM. PER SKETCH					
				SHEET 9.					
			D-	UNTHREAD INNER GUIDE APPR. 1/4 INCH	S650-1793 SET UP FIXT.				
				PLACE SUB ASSY IN FIXTURE WITH PLUG					
				THRU LINK BUSHING PER SKETCH SHEET 9.					
				THREAD INNER GUIDE UNTIL IT BOTTOMS					
				ON FIXTURE. MEASURE & RECORD 'Z' DIM.					
			C-	SUBTRACT 'Z' DIM. FROM 'Y' DIM.					
				& RECORD ACTUAL 'S' DIM. (NUMBER					
				OF SHIMS REQ'D)					

CONTROL NUMBER ______ SHEET ___ OF ___

MFG OPERATION ROUTING - SKETCH SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
45	(CONT'D)		f.	ASSEM. PROPER NUMBER OF SHIMS	S65-0-1793 SET UP FIXT.				
				5716104 TO EQUAL 'S' DIM.					
				HAND TIGHTEN INNER GUIDE &					
				CLEVIS.					



OP. 30-c

OP. 30-e

$$\frac{\begin{array}{r} Z \\ -Y \end{array}}{S}$$

S = THICKNESS OF 5716104 SHIMS. RECORD - ______

S65-0-1793

SET-UP FIXTURE

OP. 30-d

CONTROL NUMBER ______ SHEET ______ OF ______

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
50	130		A-	INSTALL SEAL, ITEM 40, ON CYLINDER					
				& INSERT CYLINDER & CAGE INTO					
				BODY ASSY. & ALIGN CYLINDER					
				SO THAT THE TWO LARGER SLOTS					
				APPEAR AT 11:00 O'CLOCK &					
				5:00 O'CLOCK POSITIONS WHEN					
				VIEWING INTO THE PISTON PORT					
				WITH THE VALVE OUTLET PORT IN					
				VERTICAL POSITION.					
			B-	BEFORE INSTALLING SCREWS NAS1352CD8-08,					
				ITEM 30, WITHDRAW CAGE & CYLINDER					
				& SLIP LINKAGE ON CAGE ECCENTRIC.					
			C-	INSERT SCREWS, ITEM 30 & TORQUE					
				TO 20-25 INCH LBS ABOVE RUNNING					
				TORQUE.					
60	130			BELLEVILLE SHIMMING					
			A.	ROTATE CAGE SUCH THAT THE LARGE					
				SLOTS IN THE CAGE MATCH THOSE					
				IN THE CYLINDER & SO THAT THE					
				CAGE ECCENTRIC IS AS SHOWN ON B/P.					

CONTROL NUMBER ______ SHEET 11 OF 22

MFG OPERATION ROUTING – OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
60	(CONTINUED)		B-	INSTALL SHIMS, ITEM 22, (AS DETERMINED					
				IN OPER. 45) ON CLEVIS, ITEM 15 &					
				SCREW ON INNER GUIDE, ITEM 11,					
				UNTIL HAND TIGHT.					
			C-	WITH THE INNER GUIDE HAND					
				TIGHT ON THE SHIM PACK &					
				RESTING ON THE BODY STOP,					
				THE LARGE SLOTS IN THE CYLINDER					
				& CAGE SHOULD BE FULLY OPENED.					
			D-	PLACE INNER RING, ITEM 13, ON					
				INNER GUIDE, ITEM 11. MOUNT	S66-0.130 GAGE RING				
				GAGE RING ON TOP OF BODY PER					
				SKETCH & MEASURE TO FIND					
				DIM 'A' - SEE SKETCH SHEET 12.					
			E-	PER SKETCH SHEET 13 - PERFORM					
				OPER. 60-D & RECORD 'E' DIM.					
				ON SKETCH SHEET.					
			F-	PER SKETCH SHEET 13 - PERFORM					
				OPER. 60-F & RECORD 'S' DIM.					
				(SHIM THICKNESS REQD.)					

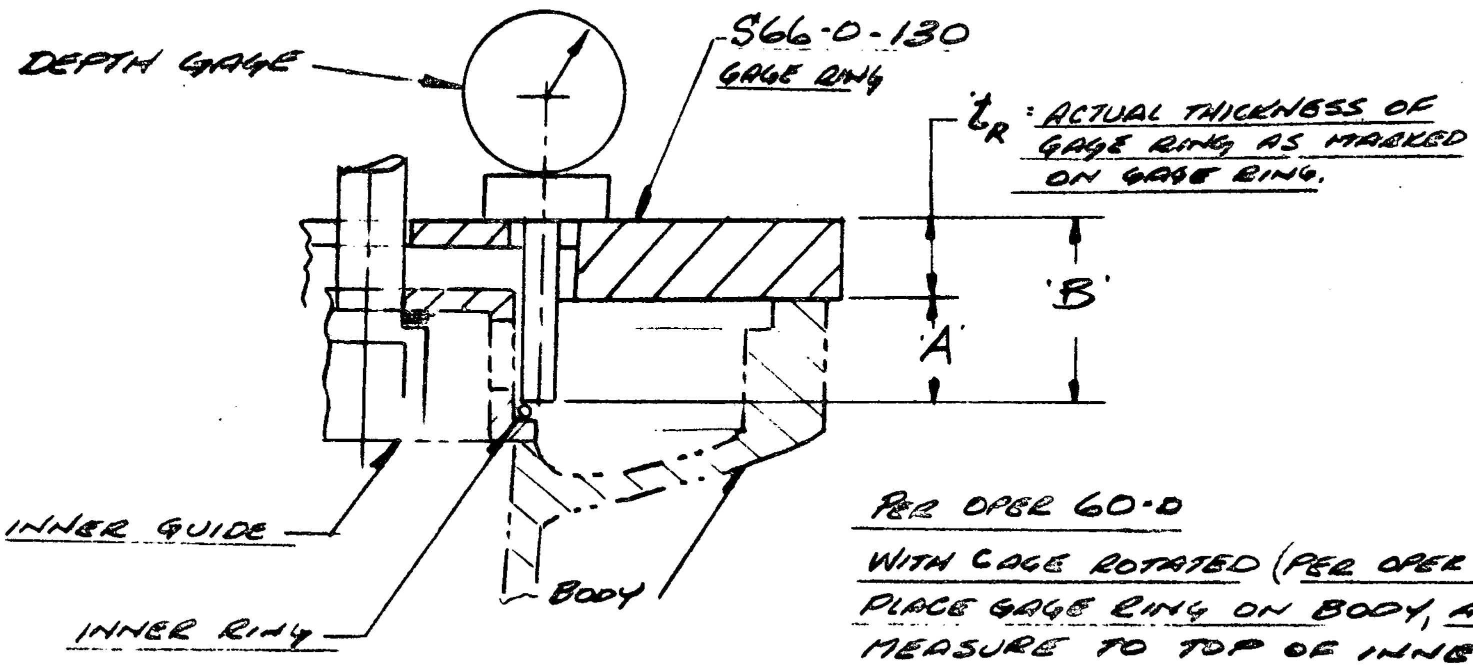
RE-20 (3-63-69)

CONTROL NUMBER ______ T ____ OF ____

MFG OPERATION ROUTING - SKETCH SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
60	(CONTINUED)			WITH CAGE ROTATED PER OPER. 60					
				PERFORM OPER.					



PER OPER 60-D

WITH CAGE ROTATED (PER OPER 60-C)
PLACE GAGE RING ON BODY, AS SHOWN.
MEASURE TO TOP OF INNER RING TO
OBTAIN 'B' DIM.
SUBTRACT GAGE RING THICKNESS 't_R'
& RECORD RESULT AS 'A' DIM. ______

$(B - t_R = 'A')$

FA1880 03 10-60 071

CONTROL NUMBER ______ OF ______

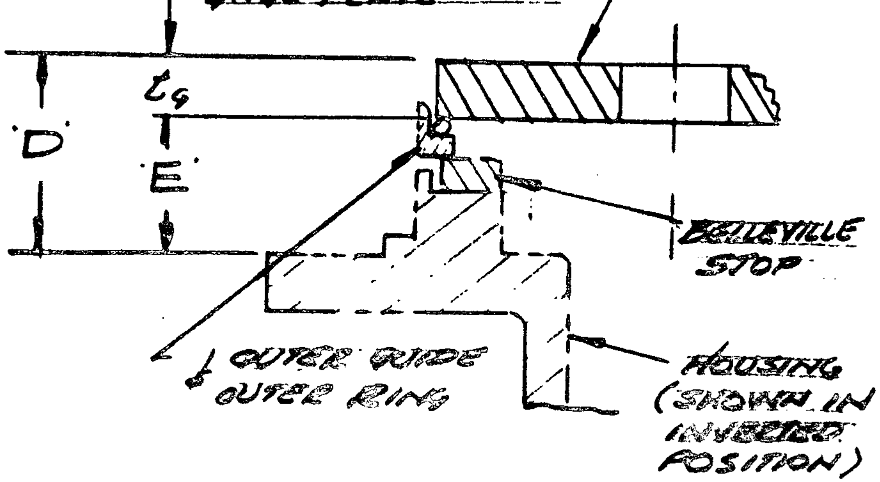
MFG OPERATION ROUTING - SKETCH SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
60	(CONTINUED)			SEE SKETCH BELOW	S66-0-131 GAGE PLATE				

OPER. 60-E INVERT HOUSING & ASSEMBLE BELLEVILLE STOP, OUTER GUIDE & OUTER RING. MOUNT GAGE PLATE ON HOUSING & FIND 'D' DIM. WITH DEPTH GAGE. SUBTRACT GAGE PLATE ACTUAL THICKNESS DIM. t_G & RECORD AS 'E' DIM.

$D - t_G = E$ ________



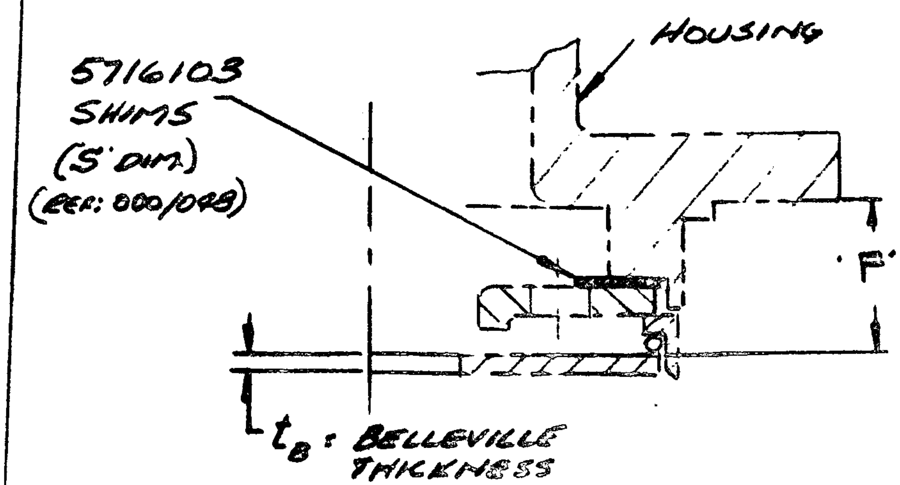
OPER. 60-F.

A - E = AVAILABLE SPACE FOR BELLEVILLE = 'F'

FULL OPEN PRELOAD STROKE = .090
BELLEVILLE THICKNESS = .078
TOTAL = .168

THEREFORE: SHIMS 'S' = F - .168

S = ______

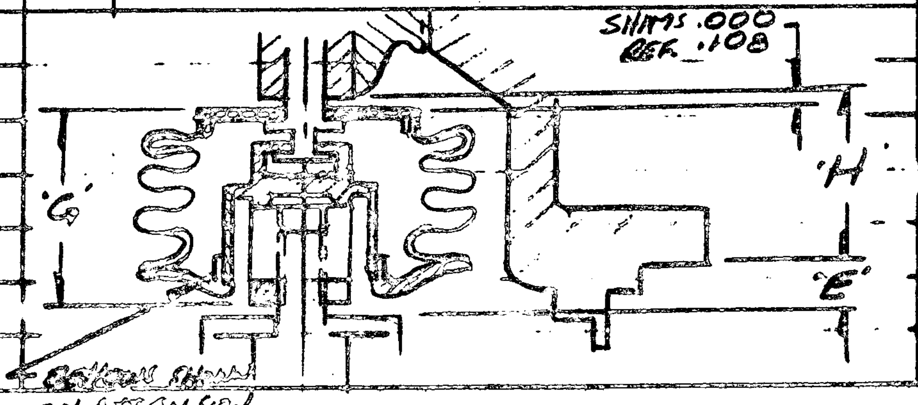


CONTROL NUMBER ______ SHEET ___ OF 2

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
60	(CONTINUED)		G-	INSTALL BELLEVILLE SPRING, ITEM 21 TO RING WIRE ITEM 13,					
				WITH CONCAVE SIDE UP. INSTALL RING-WIRE					
				ITEM 14 & OUTER SUPPORT, ITEM 18 THEN					
				SPACER, ITEM 10 & FINALLY SHIM STACK 'S'					
				ITEM 23.					
70	130			BELLOWS SHIMMING - MAKE MEASUREMENTS					
			A-	MAKE MEASUREMENTS AS SHOWN ON					
				SKETCH BELOW. 'G' =					
				'H' =					
			B-	MEASURE DIM. 'J' FROM TOP OF INNER GUIDE					
				TO OUTSIDE BODY FLANGE. IF INNER GUIDE					
				IS ABOVE THE BODY FLANGE, MAKE DIM. 'E'					
				NEGATIVE, POSITIVE IF IT IS BELOW.					
				J='A' - .609 ('A' AT OPER. 60)					



(CONT'D ON SHEET 13)

CONTROL NUMBER ______ SHEET ___ OF ___

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
70	(CONTINUED)		C.	BELLOWS SHIMS, ITEM 22,					
				'K' IS AS FOLLOWS:					
				'K' = H - G - J					
80	130			BELLOWS ASSEMBLY ADJUSTMENT					
			A.	ASSEMBLE THE SPIDER, ITEM 8 & NUT,					
				ITEM 9 TO HOUSING ASSY, ITEM 2.					
				TORQUE NUT TO 50-100 INCH-LBS.					
			B.	SCREW BELLOWS ASSY, ITEM 48 OR 49					
				TO CLEVIS, ITEM 15. AFTER BELLOWS ASSY					
				HAS FULLY BOTTOMED ON THE INNER					
				GUIDE, BACK OFF ONE FULL TURN.					
				MODIFY THE ONE FULL TURN ADJUSTMENT					
				TO SET THE CENTER LINE OF THE TRUNION					
				IN THE BELLOWS ASSY PERPENDICULAR					
				TO THE CENTER LINE OF THE CLEVIS BOLT.					
			C.	INSTALL SHIM STACK, ITEM 45 DETERMINED					
				IN OPER. 70 ON BELLOWS SHAFT.					
			D.	INSTALL SEAL, ITEM 38 TO BODY FLANGE,					
				CENTER SPACER, ITEM 10 & SHIM STACK,					
				ITEM 23 ON BELLEVILLE OUTER					
				SUPPORT, ITEM 12.					

CONTROL NUMBER ______ SHEET 14 OF 23

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
80	(CONTINUED)		E.	CAREFULLY ASSEM. BUSHING ASSY OVER					
				BELLOWS ASSY ONTO THE BODY FLANGE.					
				BE SURE THE HOUSING DOES NOT HANG					
				UP ON THE BELLEVILLE SPACER &					
				SHIM STACK.					
			F.	FOR EASE OF ASSEMBLING BOLTS,					
				ITEM 44 & WASHERS, ITEM 43,					
				COMPRESS THE HOUSING TO THE					
				BODY BY USING AN ARBOR PRESS.					
				TORQUE BOLTS TO 100-140 INCH LBS.					
			G-	ASSEMBLE NUT, ITEM 35, TO BELLOWS					
				SHAFT & TORQUE TO 50-70 INCH LBS.					
				CONT'D - NEXT SHEET					

CONTROL NUMBER ______ SHEET ____ Of ____

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
90	130			SHUTOFF VALVE					
			a.	PRESS DBS-10-030 BUSHING INTO	880-0-905-1 INSTALL. TOOL				
				5716101 BUSHING RETAINER &					
				ASSEMBLE BUSHING RETAINER TO					
				CAP ASSY. (USE ARBOR PRESS - IF NEC)					
				ASSEM. MS24693C26 SCREWS					
				& TORQUE TO 10-12 INCH/LBS.					
			b.	ASSEMBLE POPPET GUIDE 5716086,					
				SEAL 1151-00.375, POPPET 5716085, .005 SHIM, ITEM 95					
				GUIDE, FLOW 5716099, NUT MS21043-5.					
				TORQUE NUT TO 200-220 INCH/LBS.					
				INSTALL SUB-ASSEMBLY INTO					
				GUIDE BUSHING (PREVIOUSLY INSTALLED					
				IN CAP ASSY) & VERIFY THAT PISTON					
				WILL MOVE THRU ITS COMPLETE					
				STROKE WITHOUT METAL-TO-METAL					
				CONTACT. REMOVE PISTON SUB-					
				ASSY & INSTALL PISTON RING SEALS,					
				ITEM 26. (NOTE: LIGHT PRESS FIT					
				MAY BE REQUIRED TO INSERT					
				POPPET GUIDE INTO PISTON)					

CONTROL NUMBER ______ SHEET [illegible] OF [illegible]

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

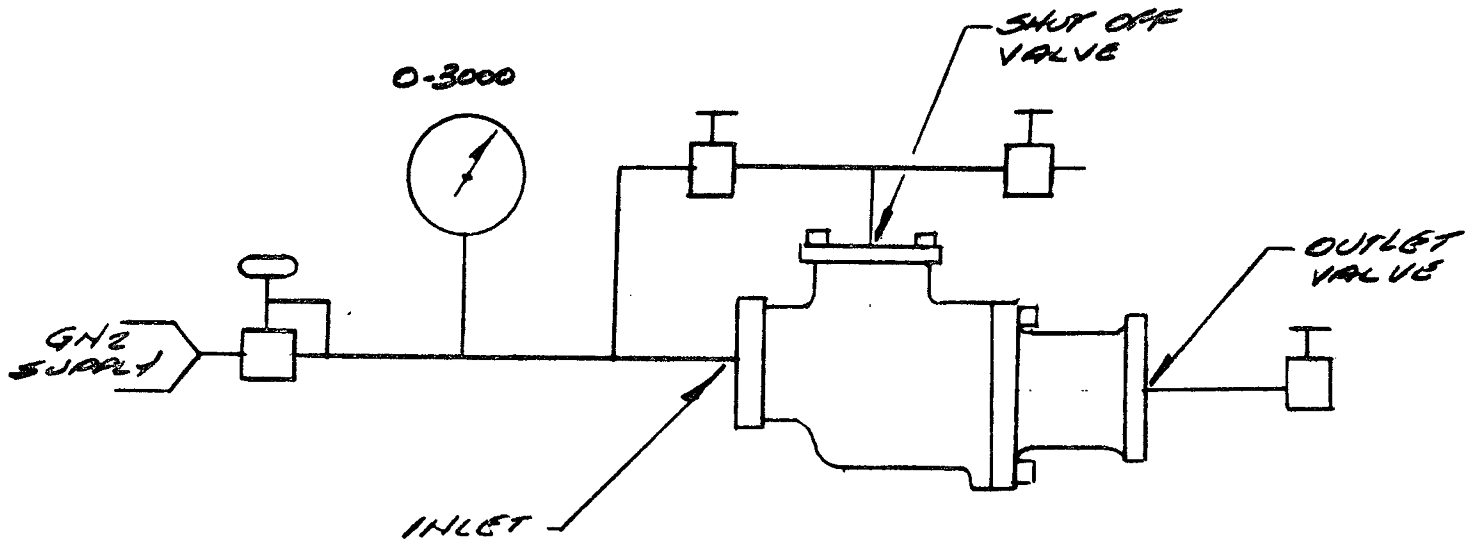
Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
90	(CONTINUED)		C-	INSTALL SPRING LC-0636-12. COMPRESS					
				SEALS ONTO PISTON & INSERT PISTON					
				INTO CAP ASSEMBLY, ITEM 3. A VACUUM					
				APPLIED TO THE PORT IN THE CAP ASSY					
				WILL ASSIST IN INSERTING THE PISTON					
				& INSTALLING THE ASSY ONTO THE					
				VALVE BODY.					
			D-	INSERT SEAL, ITEM 37 TO BODY FLANGE.					
				ATTACH CAP ASSY TO BODY USING SCREW,					
				ITEM 31 & WASHER, ITEM 32.					
				TORQUE TO 50-70 INCH LBS.					
100	130			PRE TEST & CALIBRATION VERIFICATION					
				INSTALL INLET & OUTLET TEST FLANGE	S65-0-1799				
				USE 'O' RINGS 2-131 & 2-132	S65-0-1800				
				OR EQUIV. (REF. MS29513-131 or 143)					
			A-	PROOF TEST - SETUP AS SHOWN ON					
				SKETCH SHEET 20. WITH OUTLET PORT VENTED,					
				APPLY 3000 PSIG OF GN_2 TO THE INLET &					
				SHUT OFF VALVE SIMULTANEOUSLY. HOLD					
				PRESSURE 5 MINUTES. REDUCE PRESSURE					
				TO ZERO.					

CONTROL NUMBER ______ SHEET ___ OF ___

MFG OPERATION ROUTING - SKETCH SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
100	(CONTINUED)			VENT SHUT OFF VALVE PORT. CAP					
				OUTLET PORT & APPLY 500 $^{+25}_{-0}$ PSIG TO					
				INLET PORT & HOLD FOR 5 MINUTES.					
				REDUCE PRESSURE TO 2500.					



PROOF TEST SETUP

CONTROL NUMBER ______ SHEET [illegible] OF [illegible]

MFG OPERATION ROUTING - OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
100	(CONTINUED)		B-	EXTERNAL LEAKAGE TESTS					
				SET UP AS SHOWN ON SKETCH					
				SHEET 23. WITH THE OUTLET PORT					
				VENTED, APPLY 2000 PSIG TO THE INLET &					
				SHUT OFF PORTS SIMULTANEOUSLY.					
				OBSERVE ANY INDICATION OF EXTERNAL					
				LEAKAGE FROM FLANGE SEALS.					
				MONITOR LEAKAGE FOR ONE MINUTE.					
				REDUCE PRESSURE TO ZERO. VENT THE					
				SHUTOFF VALVE PORT. CAP THE					
				OUTLET PORT & APPLY 300 PSIG TO					
				THE INLET. OBSERVE ANY INDICATION					
				OF EXTERNAL LEAKAGE FROM FLANGE					
				SEALS. MONITOR LEAKAGE FOR ONE					
				MINUTE MINIMUM. REDUCE ALL					
				PRESSURE TO ZERO.					
			C-	INTERNAL LEAKAGE TESTS					
				SET UP AS SHOWN IN SKETCH SHEET 23					
				THE UNIT NEED NOT BE SUBMERGED					
				IN FLUID. MEASURE THE LEAKAGE					
				FROM THE OUTLET PORT WHEN THE INLET					
				& SHUT OFF VALVE PORTS PRESSURE IS					
				400, 1000, 1500 & 2000 PSIG GN_2.					

(SEE NEXT SHEET)

CONTROL NUMBER ________ SHEET ___ OF 2

MFG OPERATION ROUTING – OPERATION SEQUENCE SHEET

Part No. 5716068-102

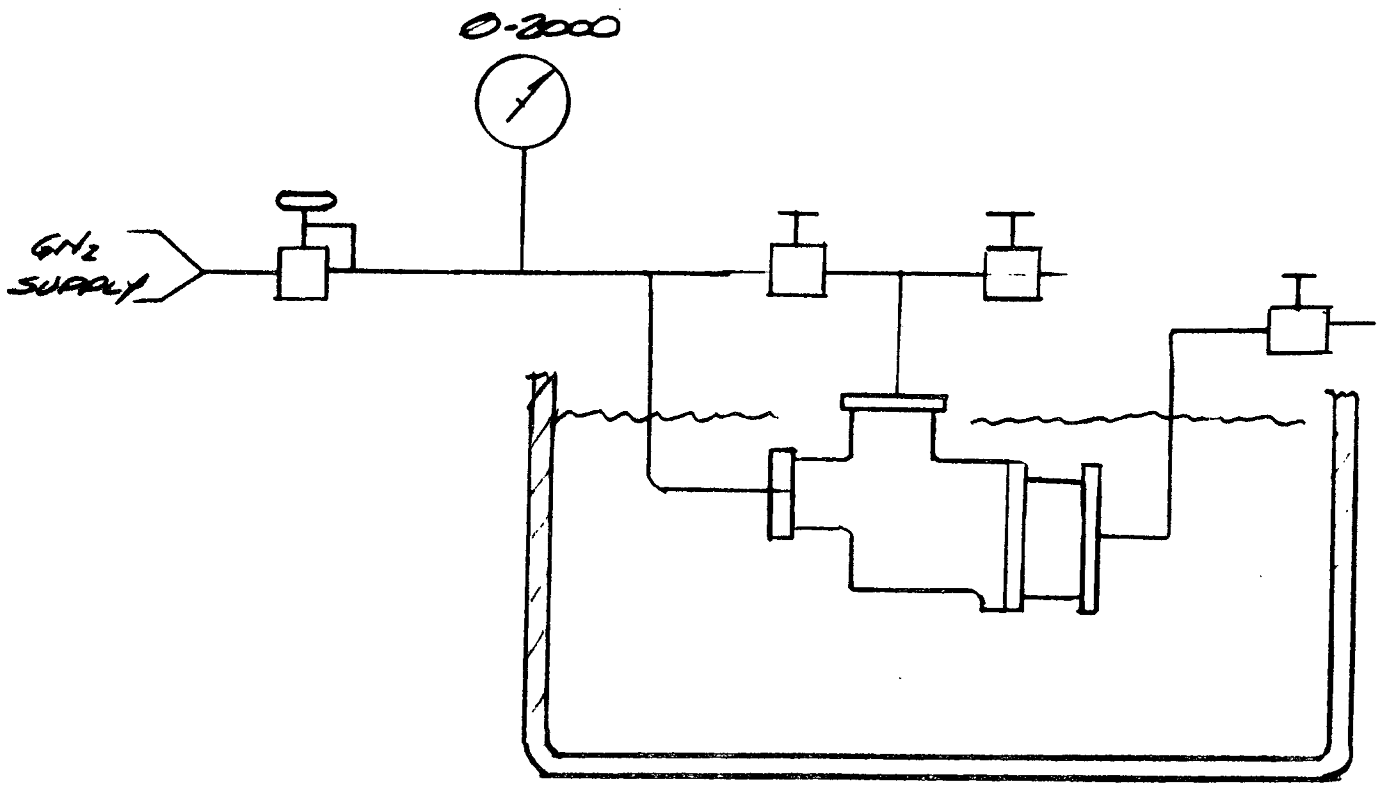
Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
100	(CONTINUED)			THE LEAKAGE SHALL BE 10 SCIM					
				MAXIMUM. RECORD BELOW.					
				400 PSIG =					
				1000 PSIG =					
				1500 PSIG =					
				2000 PSIG =					
				MEASURE THE LEAKAGE FROM THE					
				SHUTOFF VALVE PORT WHEN					
				THE OUTLET PORT IS CAPPED &					
				THE INLET PORT IS PRESSURIZED					
				TO 400 PSIG GN_2. THE LEAKAGE					
				SHALL BE 200 SCIM MAXIMUM.					
				RECORD LEAKAGE @ 400 PSIG	SCIM				

CONTROL NUMBER ________ SHEET ___ OF ___

MFG OPERATION ROUTING - SKETCH SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
100	(CONTINUED)								



LEAKAGE TEST SET UP

CONTROL NUMBER ______ SHEET ___ OF ___

MFG OPERATION ROUTING – OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
100	(CONTINUED)		C-	FLOW TEST - SET UP ASSEMBLY					
				FOR HIGH FLOW TEST.					
				PARAMETERS					
				INLET PRESSURE 0-2000 PSIG (RECORDER)					
				OUTLET PRESSURE 0-500 PSIG (RECORDER)					
				DOWN STREAM ORIFICE 0.687 DIA.					
				INLET & OUTLET TEMP +50 TO -200°F (RECORDER)					
				CAUTION - DO NOT, AT ANY TIME,					
				ALLOW THE DOWN STREAM PRESSURE					
				TO EXCEED 450 PSIG					
				INSTALL THE SOLENOID OPERATED SHUTOFF					
				VALVE WITH THE N.O PORTS CONNECTED					
				TO THE SHUT OFF VALVE PORT & THE					
				SUPPLY PORT CONNECTED TO THE INLET					
				PORT. CONNECT THE SOLENOID VENT					
				PORT TO THE OUTLET PORTS.					
				WITH THE SOLENOID VALVE DE ENERGIZED					
				APPLY 400 PSIG INLET PRESSURE.					
				ENERGIZE THE SOLENOID VALVE, ADJUST					
				THE INLET PRESSURE TO 400 TO 450 PSIG					

CONTROL NUMBER ____ SHEET 2 OF ____

MFG OPERATION ROUTING – OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
100	CONTINUED			AND NOTE THE OUTLET PRESSURE.					
				IF THE OUTLET PRESSURE IS BETWEEN					
				300 & 375 PSIG, INCREASE THE					
				INLET PRESSURE TO 1000 PSIG &					
				THEN REDUCE TO ZERO. OTHERWISE					
				TERMINATE TEST.					
				EXAMINE THE OUTLET PRESSURE					
				TRACE & DETERMINE THE OUTLET					
				PRESSURE BAND. THE REQM'NT					
				IS 340 ± 2 PSIG @ +25°F WITH					
				500 PSIG INLET PRESSURE					
				RESHIM THE BELLOWS PRE-LOAD TO					
				ACHIEVE THE DESIRED PRESSURE					
				LEVEL. INCREASING SHIMS WILL					
				INCREASE THE PRESSURE LEVEL.					
				.010 SHIM CHANGE WILL RESULT					
				IN 12 TO 16 PSI PRESSURE CHANGE.					
				AFTER FINAL SHIM CHANGES HAVE					
				BEEN MADE, RERUN FLOW TEST					
				FROM 400 TO 2000 TO 400 PSIG.					

CONTROL NUMBER ______ SHEET ______ OF ______

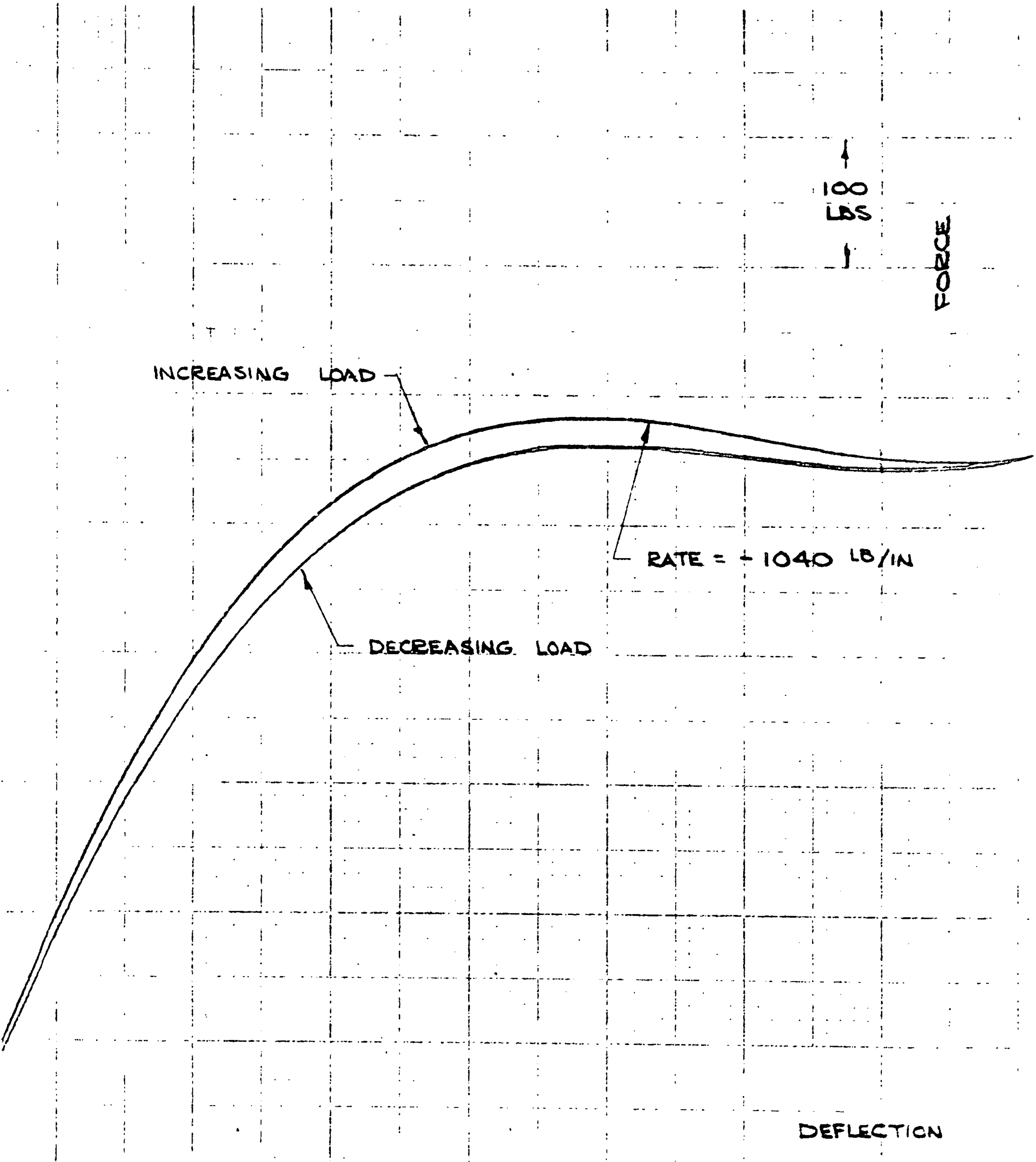
MFG OPERATION ROUTING – OPERATION SEQUENCE SHEET

Part No. 5716068-102

Oper No.	Dept No.	Setup	Run	MACHINE AND OPERATION DESCRIPTION	Tools, Gages and Remarks	Oper and Insp Stamp	Date	Qty Comp	Qty Rej
110	130			LOCKWIRE PER B/P 5716068					
120	130			TEST PER PTS 5716187					
130	110			IDENTIFY PER B/P 5716068					
				PKG IN POLY					
140	20			VERIFY IDENT.					
				STOCK					

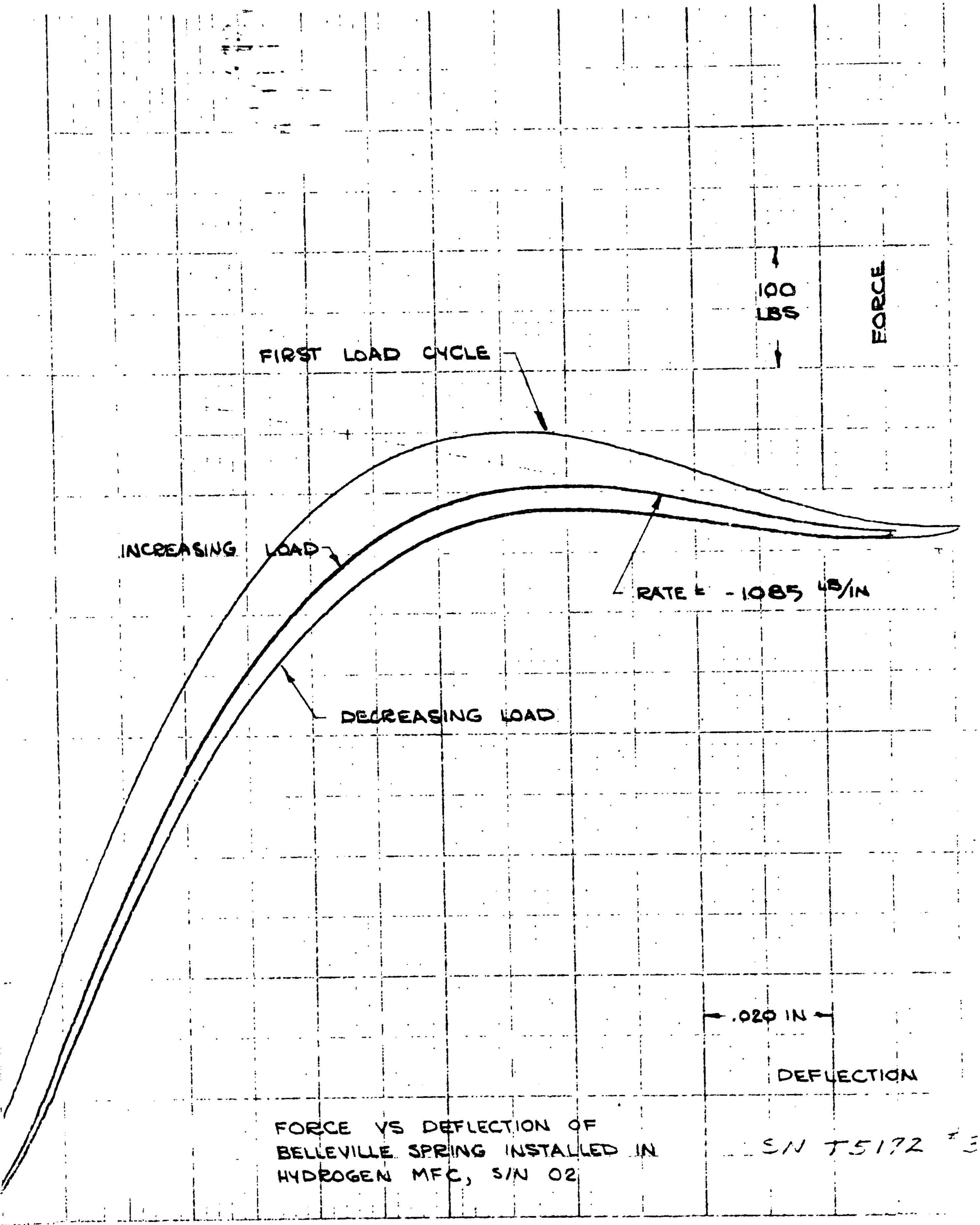
APPENDIX B

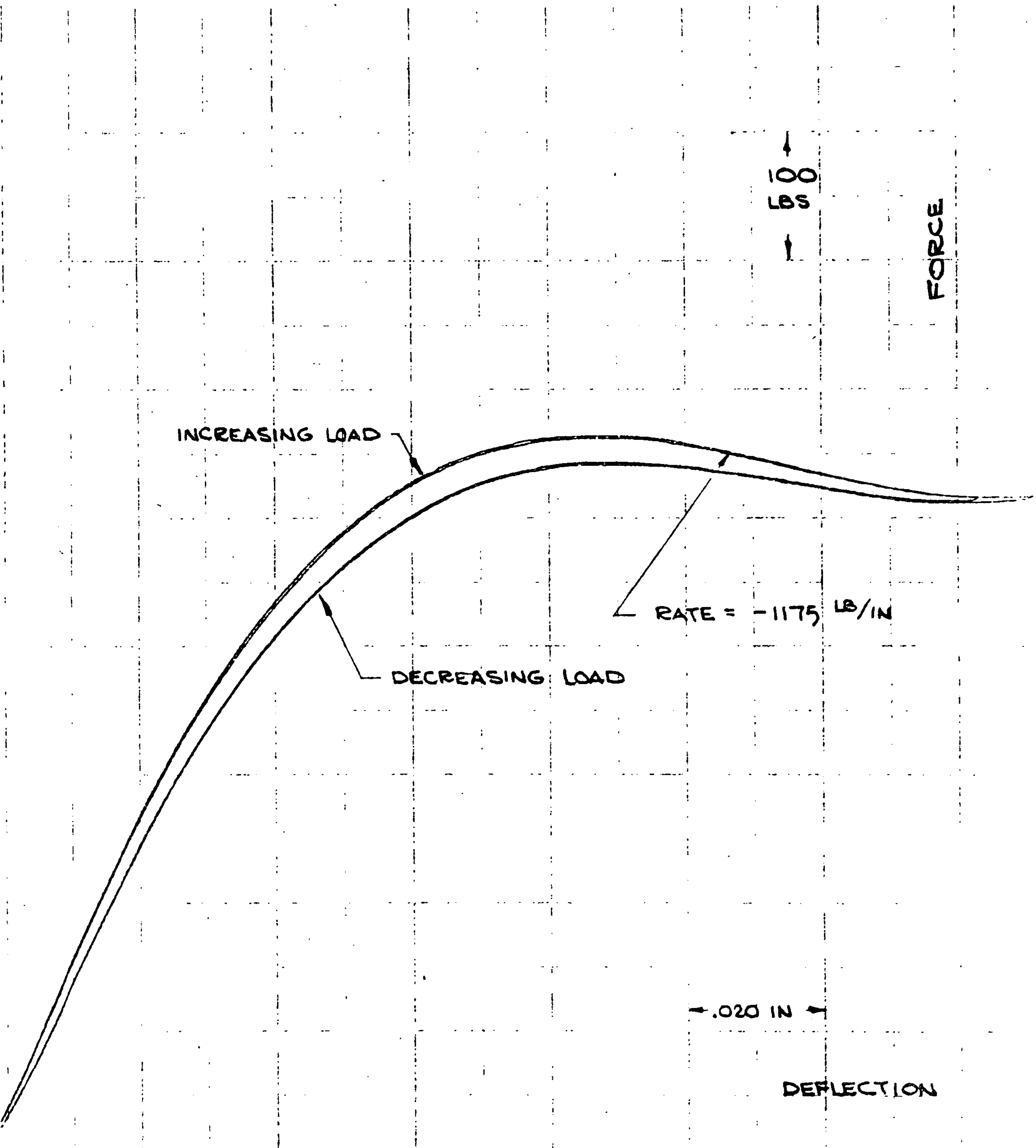
BELLEVILLE SPRING FORCE - DEFLECTION CURVE



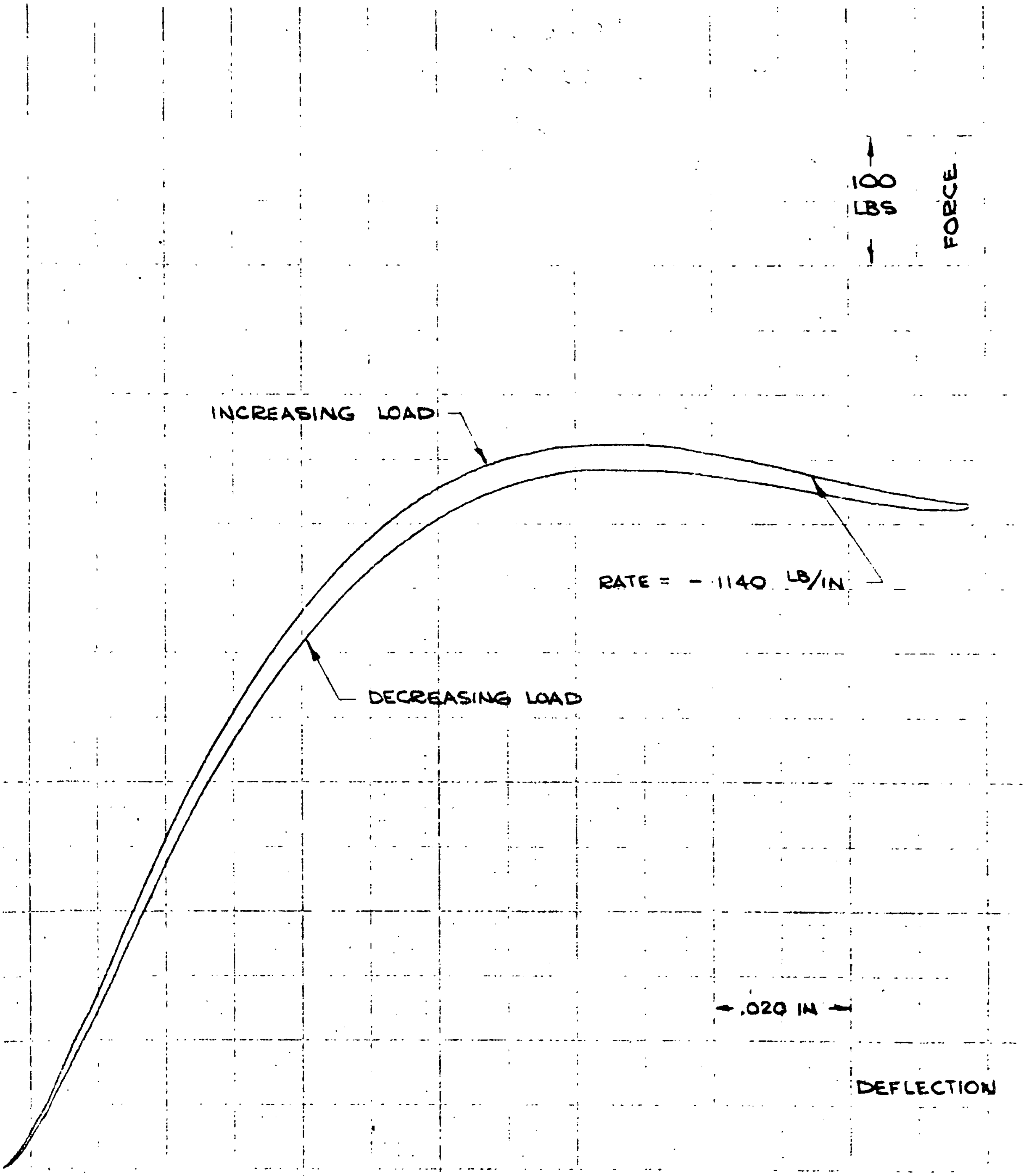
FORCE VS DEFLECTION OF
BELLEVILLE SPRING INSTALLED
IN HYDROGEN MFC, S/N 01

SN T5036 #2


100 LBS
FORCE
FIRST LOAD CYCLE
INCREASING LOAD
RATE = -1085 LB/IN
DECREASING LOAD
.020 IN
DEFLECTION
FORCE VS DEFLECTION OF
BELLEVILLE SPRING INSTALLED IN
HYDROGEN MFC, S/N 02
SN T5172



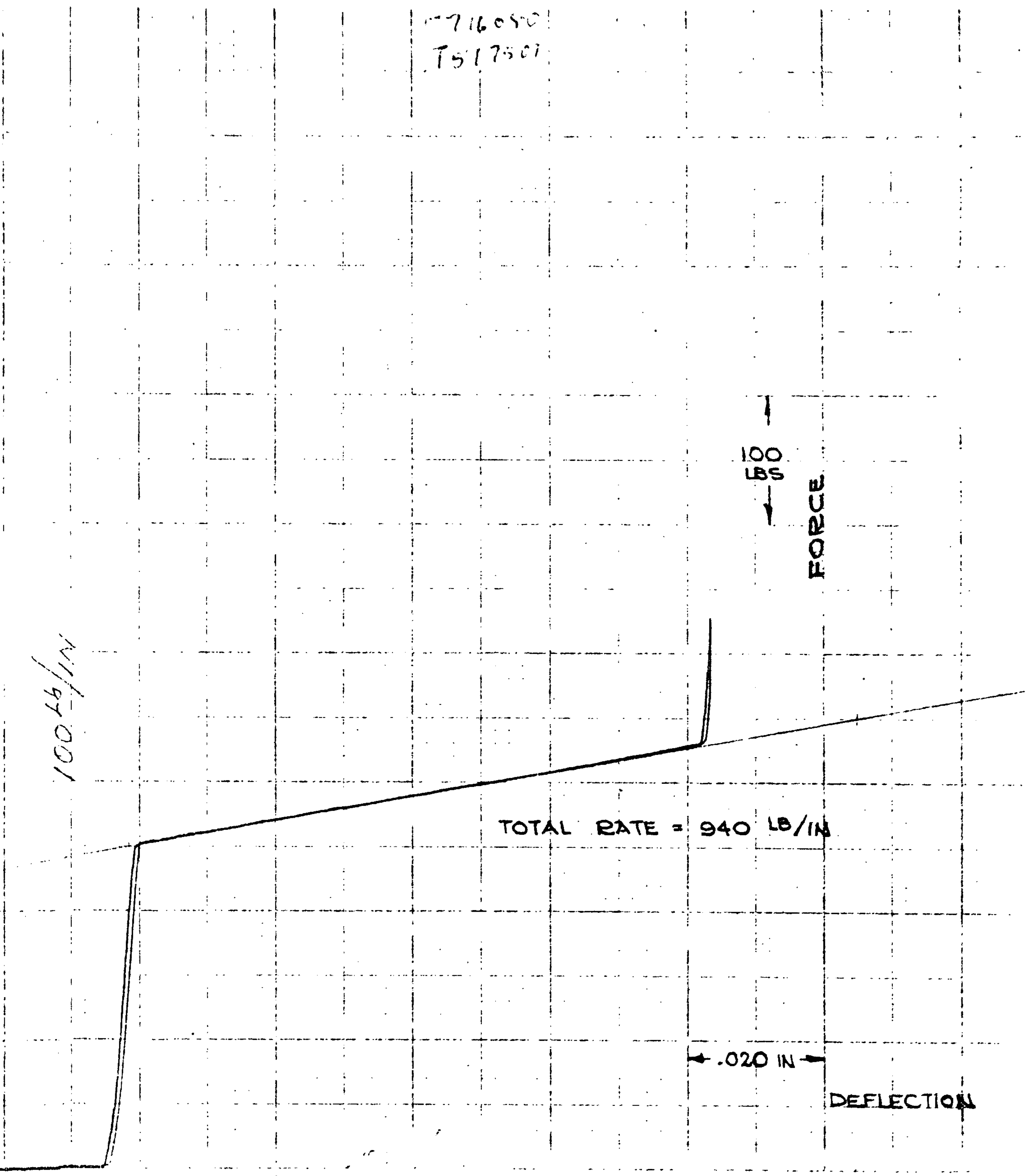
FORCE VS DEFLECTION OF BELLEVILLE SPRING INSTALLED IN OXYGEN MFC S/N 01



FORCE VS DEFLECTION OF BELLEVILLE SPRING INSTALLED IN OXYGEN MFC S/N 02

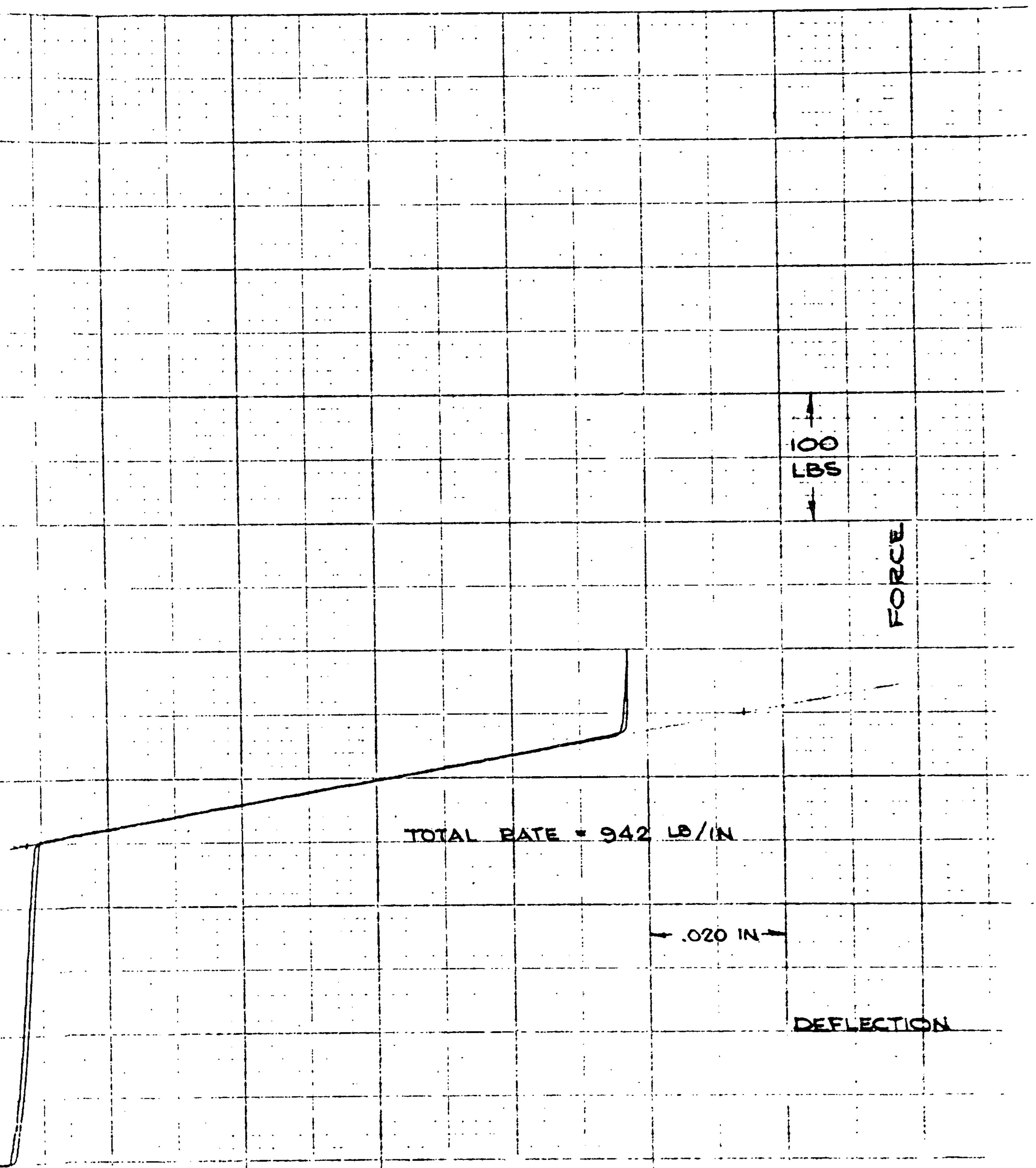
APPENDIX C

CHARGED BELLOWS- FORCE DEFLECTION CURVE



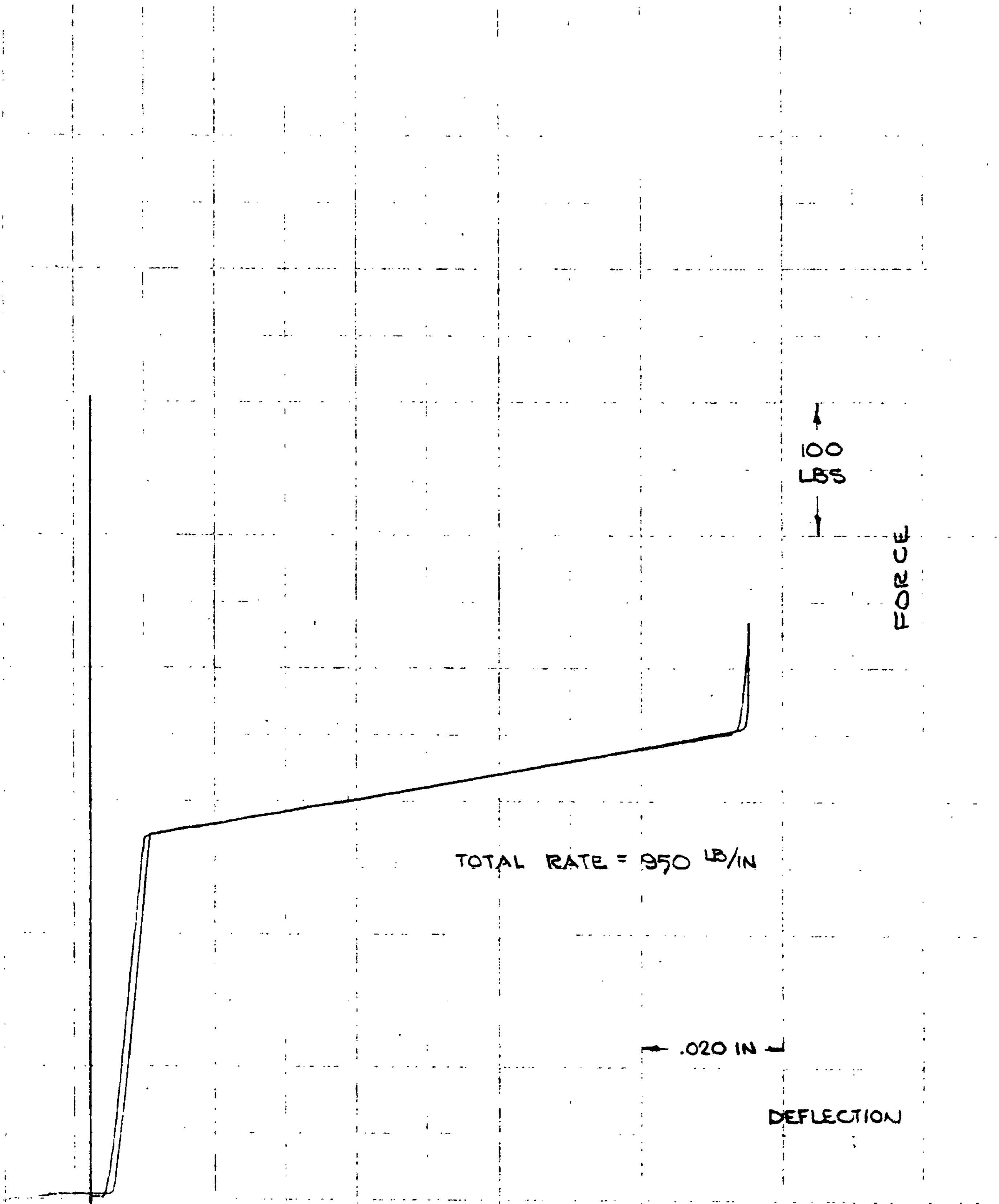
FORCE VS DEFLECTION OF HELIUM CHARGED BELLOWS INSTALLED IN HYDROGEN MFC, S/N 01

S/N TS17501



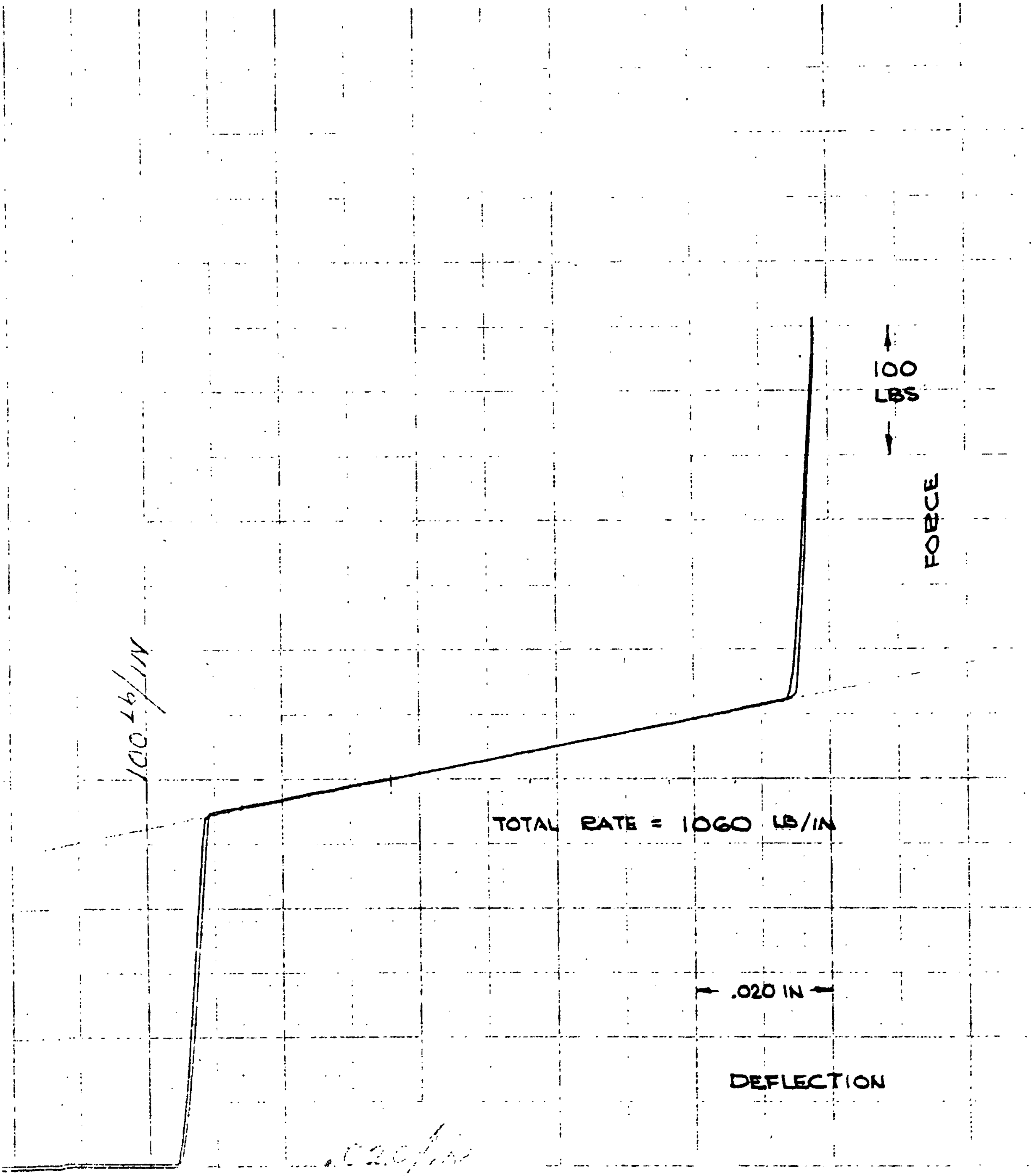
FORCE VS DEFLECTION OF HELIUM CHARGED BELLOWS INSTALLED IN HYDROGEN MFC, S/N 02

SN T517505



FORCE VS DEFLECTION OF
HELIUM CHARGED BELLOWS
INSTALLED IN OXYGEN MFC
S/N 01

SN T517504



FORCE VS DEFLECTION OF
HELIUM CHARGED BELLOWS
INSTALLED IN OXYGEN MFC
S/N 02

SN T57563

C2

APPENDIX D

PTS 5716187

SYSTEMS DIVISION

PARKER HANNIFIN ■ 18321 JAMBOREE BOULEVARD ■ IRVINE, CALIFORNIA 92664

CONTROLLED DOCUMENT

NUMBER: PTS5716187

TITLE: Acceptance Test Procedure for Mass Flow Controller Assy PN 5716187

RELEASE HISTORY							
DATE	REVISION	E.O. NO.	MICROFILM	DATE	REVISION	E.O. NO.	MICROFILM
18-Oct-71	NC	01					

REFERENCE:
1. Parker Program S156
2. NASA P.O. # NAS9-11750

PREPARED BY: W. Taylor, Sr. Project Engr.

APPROVED BY: J. Ulanovsky, Mgr., Design Engr.

LIST OF EFFECTIVE PAGES

This document consists of 6 pages as follows:

SYSTEMS DIVISION
PARKER HANNIFIN

NO. PTS5716187		BY WT		PAGE ii	
REV LTR	NC				
DATE	10-18-71				

CONTENTS

1.0 SCOPE

This document specifies the test procedure for the Mass Flow Controller (MFC) Solenoid Pilot Valve and Adapters supplied to NASA Houston for controlling the flow of gaseous hydrogen and gaseous oxygen propellants, PN 5716187.

2.0 TEST REQUIREMENTS

2.1 Test Facilities - All testing shall be conducted at the Systems Division, Parker Hannifin Corporation, Irvine California Facility.

2.2 Test Results - Complete test results data shall be recorded for each acceptance test.

2.3 Environmental - Unless otherwise specified all testing shall be conducted within the following environmental conditions:

a. Temperature: 75° ± 20°F
b. Relative Humidity: 90 percent or less
c. Barometric Pressure: Local Atmosphere

2.4 Test Media - The test media used for acceptance testing shall be nitorgen in accordance with MIL-P-27401.

2.5 Tolerances - Unless otherwise specified, the following tolerances apply to the application of test requirements and the recording of data:

a. Temperature: ± 3°F
b. Barometric Pressure: ± 5 percent
c. Pressure: ± 1 percent
d. Flow Rate: ± 2 percent
e. Leakage Rate: ± 3 percent

3.0 DETAILED TEST PROCEDURES

3.1 Solenoid Valve

3.1.1 Proof Pressure

3.1.1.1 Setup - Connect pressure source to Ports A, B and C to permit pressurizing all three ports simultaneously.

3.1.1.2 Procedure - Apply 3000 psig for 5 minutes.

3.1.2 External Leakage

3.1.2.1 Setup - Same as proof pressure test.

3.1.2.2 Procedure - Apply 2000 psi to ports and immerse valve in freon or alcohol past the flange where solenoid mounts. Observe for bubbles. There shall be no bubbles during 2 - minute test.

3.1.3 Internal Leakage

3.1.3.1 Setup - Connect pressure source to NO Port A and connect tube to Port B. Cap Port C. Immerse tube in liquid.

3.1.3.2 Procedure - Apply 2000 psi to Port A and observe for bubbles. Record number of bubbles during 2 minute test.

Remove tube from liquid and energize valve with 28 volts DC. Immerse tube and observe for bubbles. Record number of bubbles during 2 minute test.

3.1.4 Actuation

3.1.4.1 Setup - Connect pressure source to NO Port A and connect gauge to Port C. Leave Port B open.

3.1.4.2 Procedure - Apply 2000 psi to Port A and energize solenoid with 28 volts DC. De-energize solenoid. Repeat 5 times observing gauge. Valve must open and close promptly as signified by pressure at the gauge.

3.2 5716154 Inlet Adapter Proof Test

3.2.1 Setup - Install Inlet Adapter in Fixture No. S65-0-1802.

3.2.2 Procedure - Apply 3000 psi for 5 minutes.

3.3 5716155 Outlet Adapter Proof Test

3.3.1 Setup - Install Outlet Adapter in Fixture No. S65-0-1802.

3.3.2 Procedure - Apply 2000 psig for 5 minutes.

3.4 5716068-101 and -102 Mass Flow Controller Assy

Test per PTS5716068 Acceptance Test Procedure.

APPENDIX E

PTS 5716068

SYSTEMS DIVISION
PARKER HANNIFIN ▪ 18321 JAMBOREE BOULEVARD ▪ IRVINE, CALIFORNIA 92664

CONTROLLED DOCUMENT

NUMBER: PTS5716068

TITLE: Acceptance Test Procedure for Mass Flow Controller Assys; PN's 5716068-101 and 5716068-102

RELEASE HISTORY							
DATE	REVISION	E.O. NO.	MICROFILM	DATE	REVISION	E.O. NO.	MICROFILM
18-Oct-71	NC	01					

REFERENCE: 1. Parker Program S156
2. NASA P.O. # NAS9-11750

PREPARED BY: W. Taylor
W. Taylor
Sr. ~~Project~~ Engr.

APPROVED BY: J. Ulanovsky
J. Ulanovsky
Mgr., Design Engr.

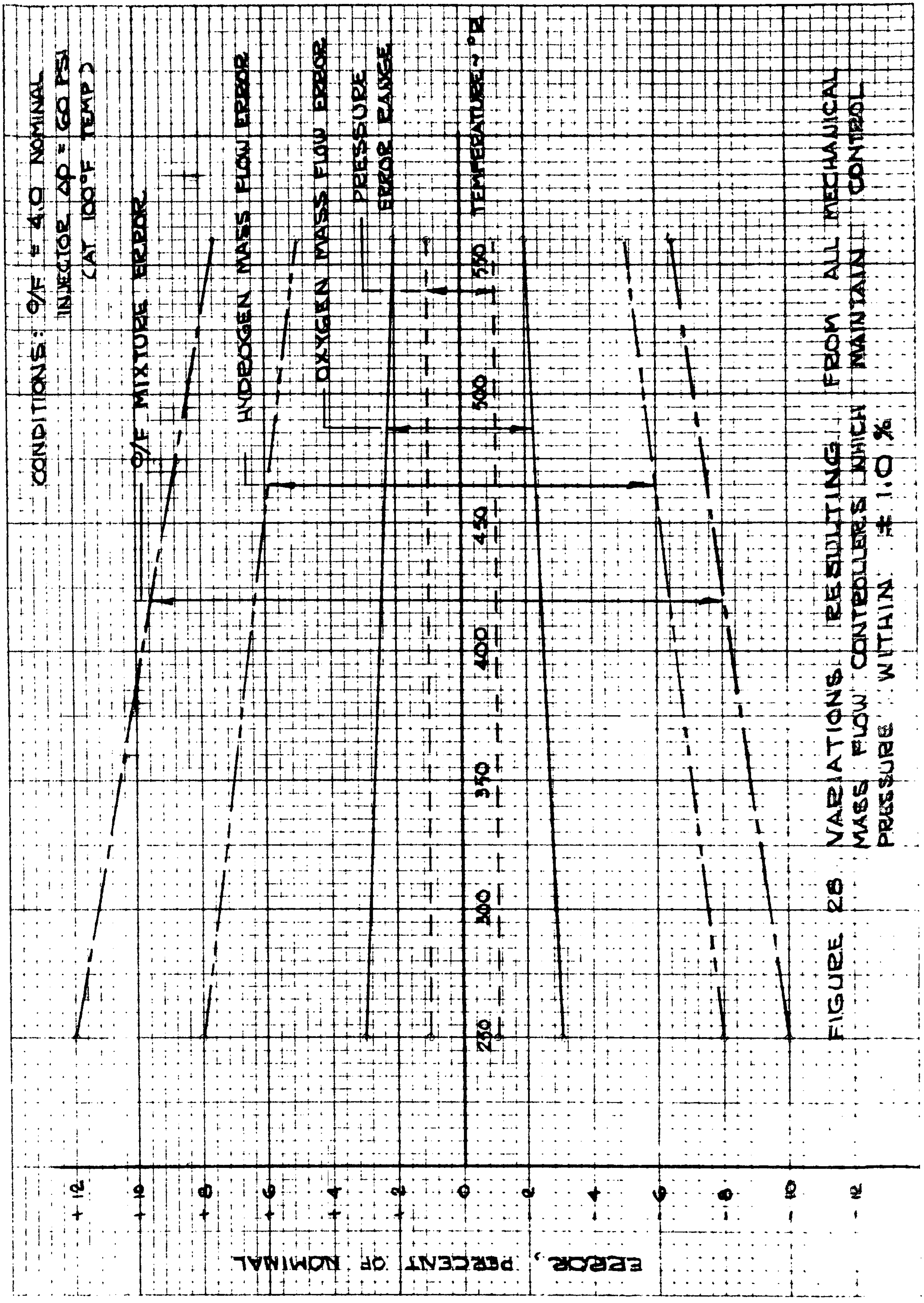


FIGURE 28 VARIATIONS RESULTING FROM ALL MECHANICAL MASS FLOW CONTROLLERS WHICH MAINTAIN PRESSURE WITHIN ± 1.0 %

LIST OF EFFECTIVE PAGES

This document consists of 9 pages as follows:

Page	Rev Ltr
Cover	NC
i and ii	NC
1 through 6	NC

CONTENTS

1.0 SCOPE

This document specifies the test procedure for the Mass Flow Controller (MFC) supplied to NASA Houston for controlling the flow of gaseous hydrogen and gaseous oxygen propellants,

PN 5716068-101 Hydrogen Mass Flow Controller
5716068-102 Oxygen Mass Flow Controller

2.0 TEST REQUIREMENTS

2.1 Test Facilities - All testing shall be conducted at the Systems Division, Parker Hannifin Corporation, Irvine California Facility.

2.2 Test Results - Complete test results data shall be recorded for each acceptance test.

2.3 Environmental - Unless otherwise specified all testing shall be conducted within the following environmental conditions:

a. Temperature: 75° ± 20°F
b. Relative Humidity: 90 percent or less
c. Barometric Pressure: Local Atmosphere

2.4 Test Media - The test media used for acceptance testing shall be nitrogen in accordance with MIL-P-27401.

2.5 Tolerances - Unless otherwise specified, the following tolerances apply to the application of test requirements and the recording of data:

a. Temperature: ± 3°F
b. Barometric Pressure: ± 5 percent
c. Pressure: ± 1 percent
d. Flow Rate: ± 2 percent
e. Leakage Rate: ± 3 percent

2.6 Equipment (Shown on Figure 2)

B_1, B_2, B_3	Jamesbury 1" Ball Valve
D_1	Grove Model M-13958-D Dome Loaded Pressure Regulator
D_2	APCO 112900-23 Dome Loaded Pressure Regulator
G_1, G_2, G_3, G_4	Pressure Gauge, psi
G_5	Differential Pressure Gauge, inches H_2O
H_1	Marotta Hand Loader
H_2	Benbow Hand Loader
Mixer	Parker S65-0-1795
Recorder	7 Channel
S	Victor Solenoid Valve SV 30A32P4T
Venturi Flow Meter	Barco BR 31615-68-61

3.0 DETAILED TEST PROCEDURES

3.1 Proof Pressure and External Leakage

3.1.1 Setup - The test setup shall be as shown in Figure 1.

3.1.2 Procedure

Inlet - Open shutoff valves V_1 and V_3 and close V_2. Immerse unit and apply 3000 psig with regulator valve for two minutes. Reduce pressure to 2000 psig and observe for bubbles. There shall be no bubbles in a two minute test.

Outlet - Close shutoff valve V_1 and V_3 and open valve V_2. Apply 525 psig to inlet port for two minutes. Reduce pressure to 400 psig and observe for bubbles. There shall be no bubbles in a two minute test.

3.2 Internal Leakage

3.2.1 Setup - Use setup shown in Figure 1 except attach flow meters to outlet of shutoff valves V_2 and V_3 suitable for measuring internal leakage.

B

3.2.2 Procedure

Poppet - Open shutoff valves V_1 and V_3 and close V_2. Using regulator valve apply pressure to inlet port of 400, 1000 and 2000 psig. Record leakage from V_3.

Piston Seal - Close shutoff valves V_1 and V_3 and open V_2. Using regulator valve apply pressure to inlet port of 50, 100, 200 and 400 psig. Record leakage from V_2.

3.3 Response & Regulation

3.3.1 Setup - Use setup shown in Figure 2. For tests conducted without adding LN_2, use orifice diameter of .687 inch. For tests conducted with LN_2 use orifice diameter of .624 inch. Record p_1, p_2, p_3, T_1, T_2, and voltage at solenoid.

3.3.2 Ambient Temperature Tests (.687 inch orifice)

3.3.2.1 Using dome loader D_1, establish the pressure which results in 550 ± 50 psig at P_1 when the MFC is open and flowing. Open MFC shutoff poppet by closing switch. Use a recorder speed sufficient to obtain response of unit. Close MFC by opening switch.

3.3.2.2 Open MFC by closing switch with inlet pressure of 350 ± 50 psig. Increase inlet pressure to 1000 psig and lower to 350 psig, obtaining a trace of outlet pressure as inlet pressure varies.

3.3.2.3 Repeat 3.3.2.1 with inlet pressure set for 1000 ± 50 psig.

3.3.3 Cold Test (.624 inch orifice)

3.3.3.1 Using dome loader D_1 establish the pressure which results in 550 ± 50 psig when the MFC is open and with LN_2 injected in quantity sufficient to produce an outlet temperature of -210°F or lower. Using dome loader D_2, establish a pressure on the LN_2 container required to flow LN_2 at the required rate when ball valve B_2 is opened.

3.3.3.2 Close switch and open ball valve B_2 simultaneously. Obtain a trace of outlet pressure as the temperature drops to -210°F.

3.3.3.3 Close B_2 (and increase pressure of dome loader D_1 if required to maintain inlet pressure to MFC) and obtain trace of outlet pressure as temperature warms to ambient.

3.3.3.4 Repeat 3.3.3.1 - 3.3.3.3 with inlet pressure of 1000 ± 50 psig.

3.3.4 During response and regulation test

a. Note any region of instability.
b. Observe for evidence of external leakage when MFC is cold.

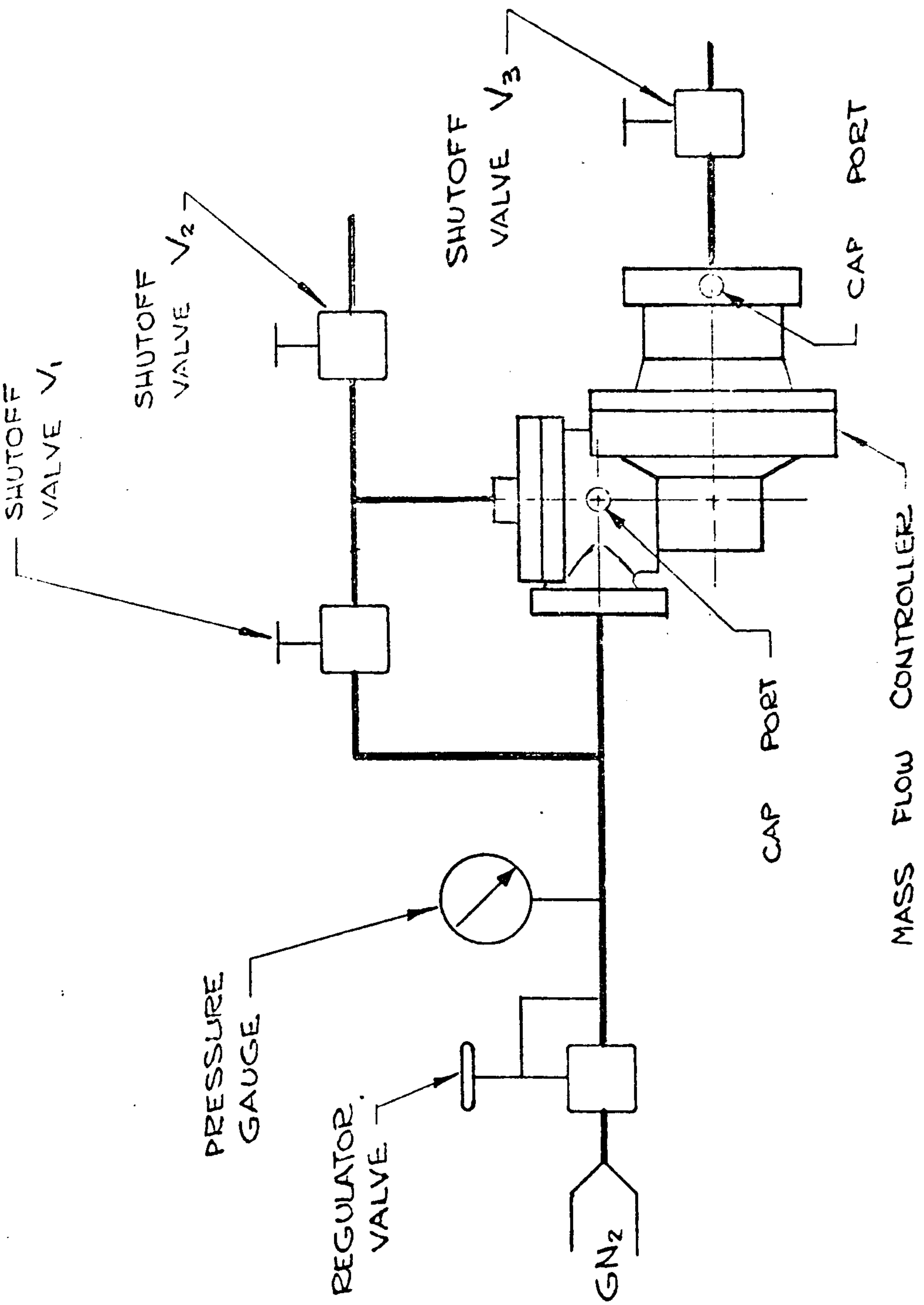

SHUTOFF VALVE V_1
SHUTOFF VALVE V_2
SHUTOFF VALVE V_3
CAP PORT
CAP PORT
MASS FLOW CONTROLLER
PRESSURE GAUGE
REGULATOR VALVE
GN_2

FIGURE 1

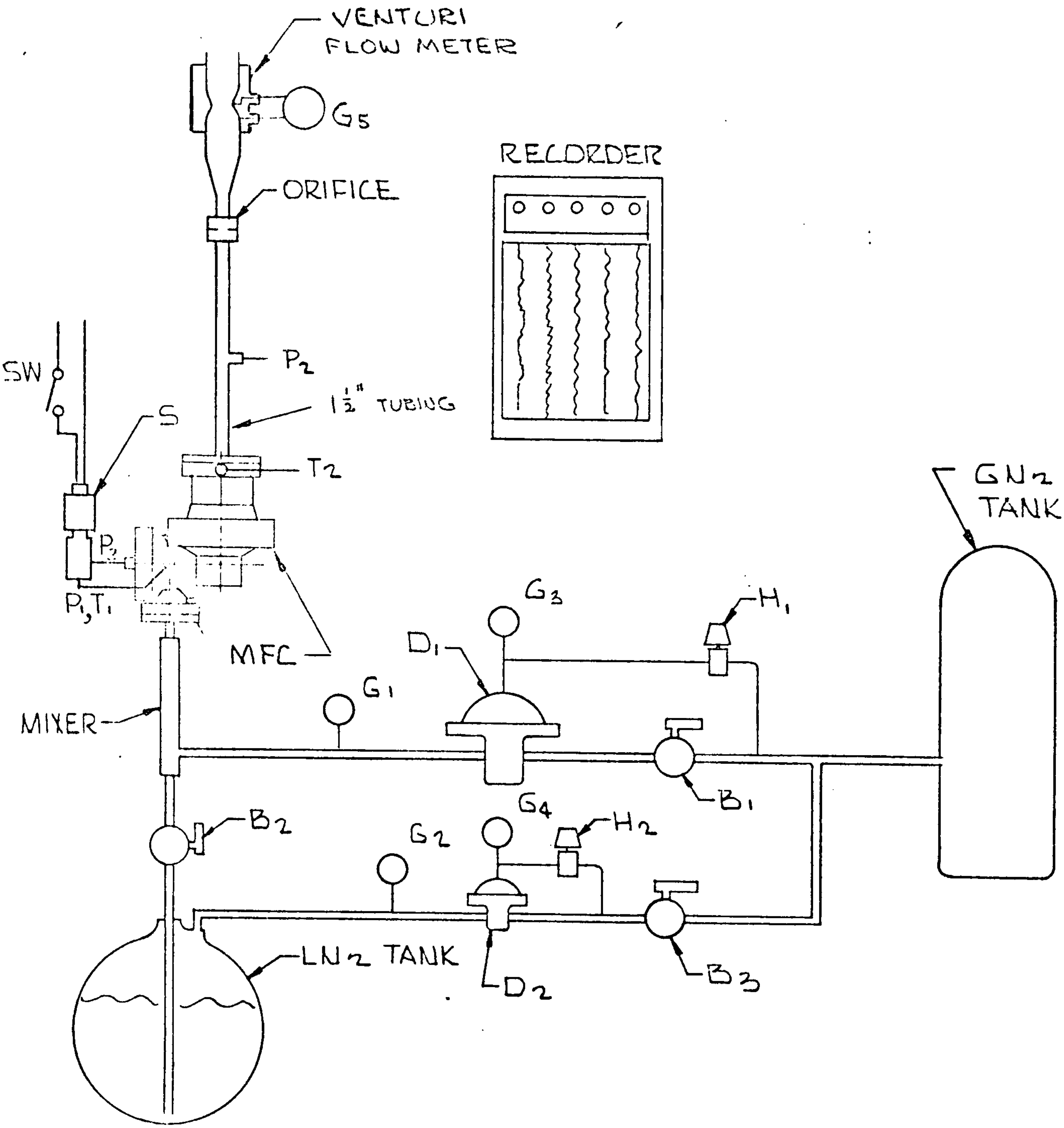

VENTURI FLOW METER
G5
RECORDER
ORIFICE
P2
$1\frac{1}{2}$" TUBING
SW
S
T2
GN2 TANK
P2
P1,T1
G3
H1
MFC
D1
G1
MIXER
B1
G4
B2
G2
H2
LN2 TANK
D2
B3

TABLE 2

APPENDIX F

ACCEPTANCE TEST DATA SHEETS

PARKER HANNIFIN

REPORT NO. EER5716068 PAGE E-2
REV. LTR. NC BY WT DATE 1-9-72
DATA BY: OSHIRO DATE 11-12-71 APPR.

TEST: PROOF PRESSURE & EXTERNAL LKG

SAMPLE No. T515201

BAROM. PRESS. IN. Hg

PART NO. & NAME: 5716068 - 101 MASS FLOW CONTROLLER

TEST MEDIUM: GN_2

WET BULB TEMP. °F.

MEDIUM TEMP. °F.

DRY BULB TEMP. °F.

PTS 5716068	INLET PRESSURE		OUTLET PRESSURE		TIME		EXTERNAL LEAKAGE		
	REQ.	ACTUAL	REQ.	ACTUAL	REQ	ACTUAL	REQ	ACTUAL	
PARA No.	PSIG	PSIG	PSIG	PSIG	MIN	MIN		SCCM	
3.1.2	3000	3000	—	—	2	2	—	—	
	2000	2000	—	—	2	1		232	
	1000	1000	—	—	2	1		10	
	525	525	525	525	2	2	—	—	
	400	400	400	400	2	2		<1	

SETUP PER H_2 MFC S/N 01

N. REF. SPEC. DATA SHEET NO.

A 1P6 (4-69)

PARKER HANNIFIN

REPORT NO. EER5716068 PAGE F-3
REV. LTR. NC BY WT DATE 1-9-72
DATA BY: OSHIRO DATE 11-12-71 APPR.

TEST: INTERNAL LEAKAGE

SAMPLE No. T515201 | BAROM. PRESS. IN. Hg

PART NO. & NAME: 5716068 - 101 MASS FLOW CONTROLLER

TEST MEDIUM: GN_2 | WET BULB TEMP. °F

MEDIUM TEMP. 75 °F | DRY BULB TEMP. °F

PTS5716068 PARA. NO.	INLET PRESSURE REQ PSIG	INLET PRESSURE ACTUAL PSIG	OUTLET PRESSURE REQ PSIG	OUTLET PRESSURE ACTUAL PSIG	TIME REQ SEC	TIME ACTUAL SEC	LEAKAGE REQ —	LEAKAGE ACTUAL SCCM
3.2.2 POPPET LKG.	400	400	—	—	—	*	—	50
	1000	1000	—	—	—	*	—	330
	2000	2000	—	—	—	*	—	1375
PISTON SEAL LKG	50	50	—	—	—	*	—	700
	100	100	—	—	—	*	—	900
	200	200	—	—	—	*	—	1180
	400	400	—	—	—	*	—	1890

* USED FLOWMETER PARKER STOCK NO 3625
RANGE 5.0 TO 23,000 SCCM GN_2

SETUP PER H_2 MFC S/N 01

J. H. ______ REF. SPEC. ______ DATA SHEET NO. ______

PHLA 1P6 (4-69)

PARKER HANNIFIN

REPORT NO. EER5716068 PAGE F-4

REV. LTR. NC BY WT DATE 1-9-72

DATA BY: OSHIRO DATE 11-19-71 APPR.

TEST: PROOF PRESSURE & EXTERNAL LKG

SAMPLE NO. T515202

BAROM. PRESS. IN. HG

PART NO. & NAME 5716068-101 MASS FLOW CONTROLLER

TEST MEDIUM GN_2

WET BULB TEMP. °F.

MEDIUM TEMP. °F.

DRY BULB TEMP. °F.

PTS 5716068	INLET PRESSURE		OUTLET PRESSURE		TIME		EXTERNAL LEAKAGE	
	REQ.	ACTUAL	REQ.	ACTUAL	REQ	ACTUAL	REQ	ACTUAL
PARA NO.	PSIG	PSIG	PSIG	PSIG	MIN	MIN		SCCM
3.1.2	3000	3000	—	—	2	2	—	—
	2000	2000	—	—	2			13.0
	1000	1000	—	—				5.0
	525	525	525	525	2	2	—	—
	400	400	400	400	2	2		0

SETUP PER H_2 MFC S/N 02

J. N. REF. SPEC. DATA SHEET NO.

PHLA 1P6 (4-69)

PARKER HANNIFIN

REPORT NO. EER5716068 PAGE F-5

REV. LTR. NC BY WT DATE 1-9-72

DATA BY: [illegible] DATE 11-19-71 APPR.

TEST: INTERNAL LEAKAGE

SAMPLE NO. 7515202

BAROM. PRESS. IN. HG

PART NO. & NAME 5716068-101 MASS FLOW CONTROLLER

TEST MEDIUM GN_2

WET BULB TEMP. °F.

MEDIUM TEMP. °F.

DRY BULB TEMP. °F.

PTS 5716068 PARA NO.	INLET PRESSURE REQ PSIG	INLET PRESSURE ACTUAL PSIG	OUTLET PRESSURE REQ PSIG	OUTLET PRESSURE ACTUAL PSIG	TIME REQ SEC	TIME ACTUAL SEC	LEAKAGE REQ —	LEAKAGE ACTUAL SCCM
3.2.2 POPPET LKG.	400	400	—	—	—	*	—	34
	1000	1000	—	—	—	*	—	420
	2000	2000	—	—	—	*	—	1520
PISTON SEAL LKG	50	50	—	—	—	*	—	260
	100	100	—	—	—	*	—	610
	200	200	—	—	—	*	—	900
	400	400	—	—	—	*	—	1300

* FLOWMETER

STOCK NO 3625

RANGE 5.0 TO 24000 SCCM GN_2

SETUP PER H_2 MFC S/N 02

J. N. REF. SPEC. DATA SHEET NO.

PHLA 1P6 (4-69)

PARKER HANNIFIN

REPORT NO. EER 5716068 PAGE F-6
REV. LTR. NC BY WT DATE 1-9-72
DATA BY: OSHIRO DATE 11-18-71 APPR.

TEST: PROOF PRESSURE + EXTERNAL LKG.

SAMPLE No. TS18101
BAROM. PRESS. IN. Hg
TEST MEDIUM GN_2
WET BULB TEMP. °F.
MEDIUM TEMP. 75 °F.
DRY BULB TEMP. °F.

PART NO. & NAME
5716068-102 MASS FLOW CONTROLLER

PTS 5716068	INLET PRESSURE		OUTLET PRESSURE		TIME		EXTERNAL LEAKAGE	
	REQ.	ACTUAL	REQ.	ACTUAL	REQ	ACTUAL	REQ	ACTUAL
PARA No.	PSIG	PSIG	PSIG	PSIG	MIN	MIN		SCCM
3.1.2	3000	3000	—	—	2	2	—	—
	2000	2000	—	—	2	2		15
	1000	1000	—	—	2	2		8
	525	525	525	525	2	2	—	—
	400	400	400	400	2	2		2

SETUP PER O_2 MFC S/N '01'

J. H. REF. SPEC. DATA SHEET NO.

PHLA 1P6 (4-69)

PARKER HANNIFIN

REPORT NO. EER5716068	PAGE F-7
REV. LTR. NC	BY WT	DATE 1-9-72
DATA BY: OSHIRO	DATE 11-12-71	APPR.

TEST: INTERNAL LEAKAGE

PART NO. & NAME: 5716068-102 MASS FLOW CONTROLLER

SAMPLE NO. T518101

TEST MEDIUM: GN_2

MEDIUM TEMP. 75 °F.

BAROM. PRESS. IN. HG

WET BULB TEMP. °F.

DRY BULB TEMP. °F.

PTS 5716068	INLET PRESSURE		OUTLET PRESSURE		TIME		LEAKAGE	
	REQ	ACTUAL	REQ	ACTUAL	REQ	ACTUAL	REQ	ACTUAL
PARA NO.	PSIG	PSIG	PSIG	PSIG	SEC	SEC	—	SCCM
3.2.2	400	400	—	—	—		—	365
POPPET LKG.								
	1000	1000	—	—	—		—	1140
	2000	2000	—	—	—		—	2315
PISTON SEAL LKG	50	50	—	—	—		—	1140
	100	100	—	—	—		—	2220
	200	200	—	—	—		—	3800
	400	400	—	—	—		—	7000

SETUP PER O_2 MFC S/N 01

J. H. REF. SPEC. DATA SHEET NO.

PHILA 1P6 (4-69)

PARKER HANNIFIN

REPORT NO. EER5716068 PAGE F-8
REV. LTR. NC BY WT DATE 1-9-72
DATA BY: [illegible] DATE [illegible] APPR.

TEST: PROOF PRESSURE & EXTERNAL LKG

SAMPLE No. TS18202 | BAROM. PRESS. IN. HG
TEST MEDIUM GN2 | WET BULB TEMP. °F.
MEDIUM TEMP. °F. | DRY BULB TEMP. °F.

PART NO. & NAME 5716068-102 MASS FLOW CONTROLLER

PTS 5716068	INLET PRESSURE		OUTLET PRESSURE		TIME		EXTERNAL LEAKAGE	
	REQ.	ACTUAL	REQ.	ACTUAL	REQ	ACTUAL	REQ	ACTUAL
PARA No.	PSIG	PSIG	PSIG	PSIG	MIN	MIN		SCCM
3.1.2	3000	3000	—	—	2	2	—	—
	2000	2000	—	—	2			56.0
	1000	1000	—	—				8.0
	525	525	525	525	2	2	—	—
	400	400	400	400	2	2		0

SETUP PER O2 MFC S/N 02

J. H. REF. SPEC. DATA SHEET NO.

PHLA 1F6 (4-69)

PARKER HANNIFIN

REPORT NO. EER5716068 PAGE F-9

REV. LTR. NC BY WT DATE 1-9-72

DATA BY: OSHIRO DATE 11-23-71 APPR.

TEST: INTERNAL LEAKAGE

SAMPLE No. TS18202

BAROM. PRESS. IN. Hg

PART NO. & NAME: 5716068 - 102 MASS FLOW CONTROLLER

TEST MEDIUM: GN_2

WET BULB TEMP. °F.

MEDIUM TEMP. °F.

DRY BULB TEMP. °F.

PTS5716068 PARA NO.	INLET PRESSURE REQ PSIG	INLET PRESSURE ACTUAL PSIG	OUTLET PRESSURE REQ PSIG	OUTLET PRESSURE ACTUAL PSIG	TIME REQ SEC	TIME ACTUAL SEC	LEAKAGE REQ —	LEAKAGE ACTUAL SCCM
3.2.2 POPPET LKG.	400		—	—	—	*	—	9000
	1000		—	—	—	*	—	24,000
	2000		—	—	—	**	—	40,000
PISTON SEAL LKG	50	50	—	—	—	*	—	3000
	100	100	—	—	—	*	—	5500
	200	200	—	—	—	*	—	7000
	400	400	—	—	—	*	—	4250

* MEASURED ON FLOWMETER # 3625
RANGE 5.0 TO 24000 SCCM

** MEASURED ON FLOWMETER # 4605
RANGE 0.2 TO 1.8 SCFM GN_2

SETUP PER On MFC S/N 02

J. H. REF. SPEC. DATA SHEET NO.

PHLA 1P6 (4-69)

PARKER HANNIFIN

REPORT NO. EER5716068	PAGE F-10
REV. LTR. NC BY WT	DATE 1-9-72
DATA BY: OSHIRO DATE 11-26-71	APPR.

TEST: PROOF, LEAKAGE AND ACTUATION	SAMPLE No. NOTED	BAROM. PRESS. IN. Hg
PART NO. & NAME SV30A32P4T SOLENOID VALVE	TEST MEDIUM GN_2	WET BULB TEMP. °F.
	MEDIUM TEMP. °F.	DRY BULB TEMP. °F.

PTS5716187 PARA NO.	SOLENOID VALVE SERIAL NUMBER 109248	109246	109247	109249
3.1.1 PROOF PRESS	3000 PSIG	3000 PSIG	3000 PSIG	3000 PSIG
3.1.2 EXT LKG	NO BUBBLES	NO BUBBLES	NO BUBBLES	NO BUBBLES
3.1.3 INT LKG				
DE ENERGIZED	ZERO	ZERO	ZERO	ZERO
ENERGIZED	ZERO	ZERO	ZERO	ZERO
3.1.4 ACTUATION	OK	OK	OK	OK

SETUP PER

J. H. REF. SPEC. DATA SHEET NO.

PHI A 1P6 (' 69)

PARKER HANNIFIN

REPORT NO. EER5716068 PAGE F-11

REV. LTR. NC BY WT DATE 1-9-72

DATA BY: OSHIRO DATE 11-26-71 APPR.

TEST: PROOF TEST

SAMPLE No. T5130

BAROM. PRESS. IN. Hg

TEST MEDIUM GN_2

WET BULB TEMP. °F.

PART NO. & NAME 5716155 OUTLET ADAPTOR

MEDIUM TEMP. °F.

DRY BULB TEMP. °F.

TOOL NO. S65-0-1802

PTS 5716187

PARA NO	QTY	PRESSURE PSIG	TIME MIN						
3.3	4	2000	5	17					

SETUP PER

J. H. REF. SPEC. DATA SHEET NO.

PARKER HANNIFIN

REPORT NO. EER5716068 PAGE F-12

REV. LTR. NC BY WT DATE 1-9-72

DATA BY: OSHIRO DATE 11-24-71 APPR.

TEST: PROOF TEST

SAMPLE NO. T5127

BAROM. PRESS. IN. HG

TEST MEDIUM GN2

WET BULB TEMP. °F

PART NO. & NAME 571615 4 INLET ADAPTOR

MEDIUM TEMP. °F

DRY BULB TEMP. °F

Tool NO 565-0-1802

PTS5716187

PARA NO	QTY	PRESSURE PSIG	TIME MIN						
3.2.1	4	3000	5						

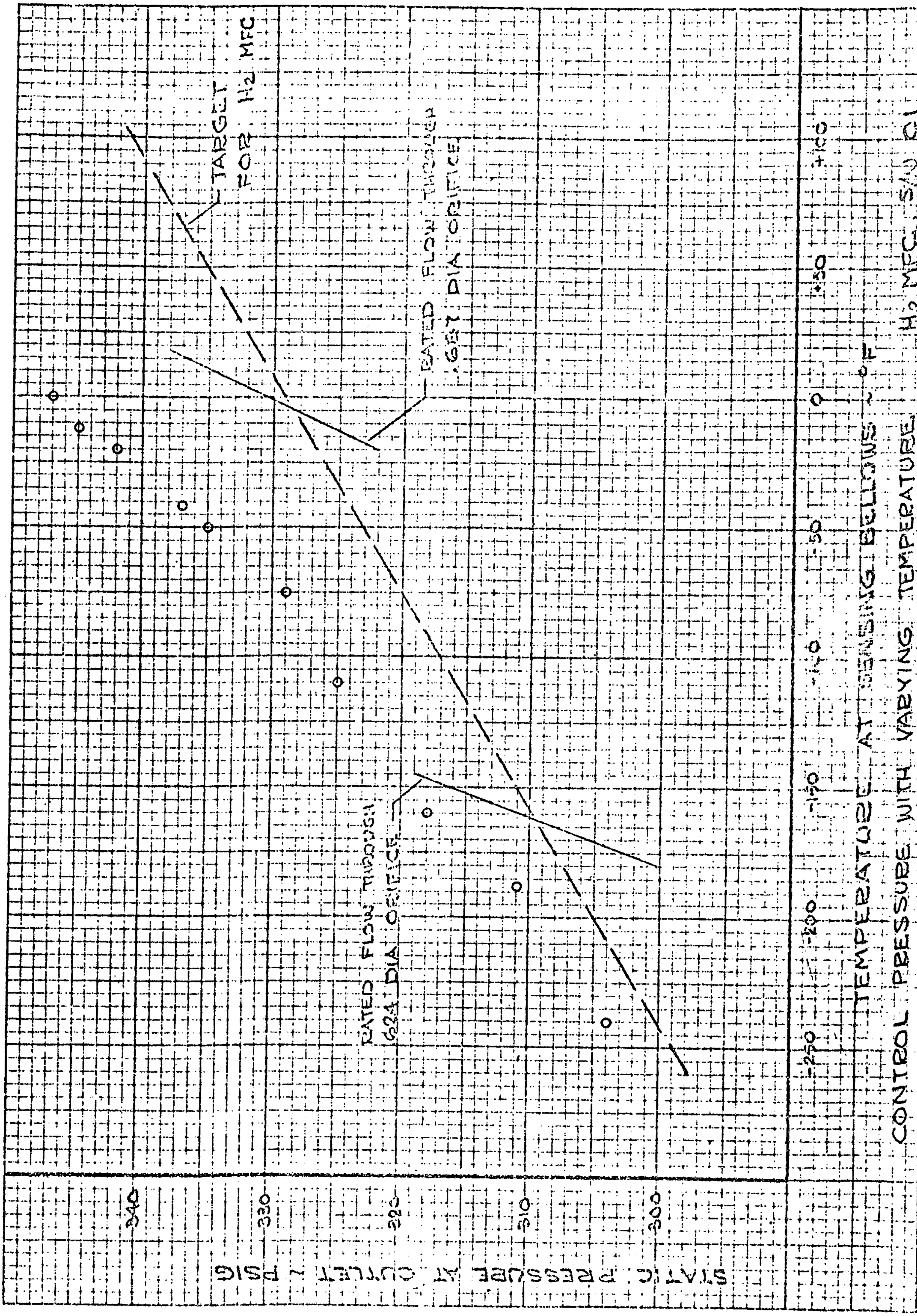
SETUP PER

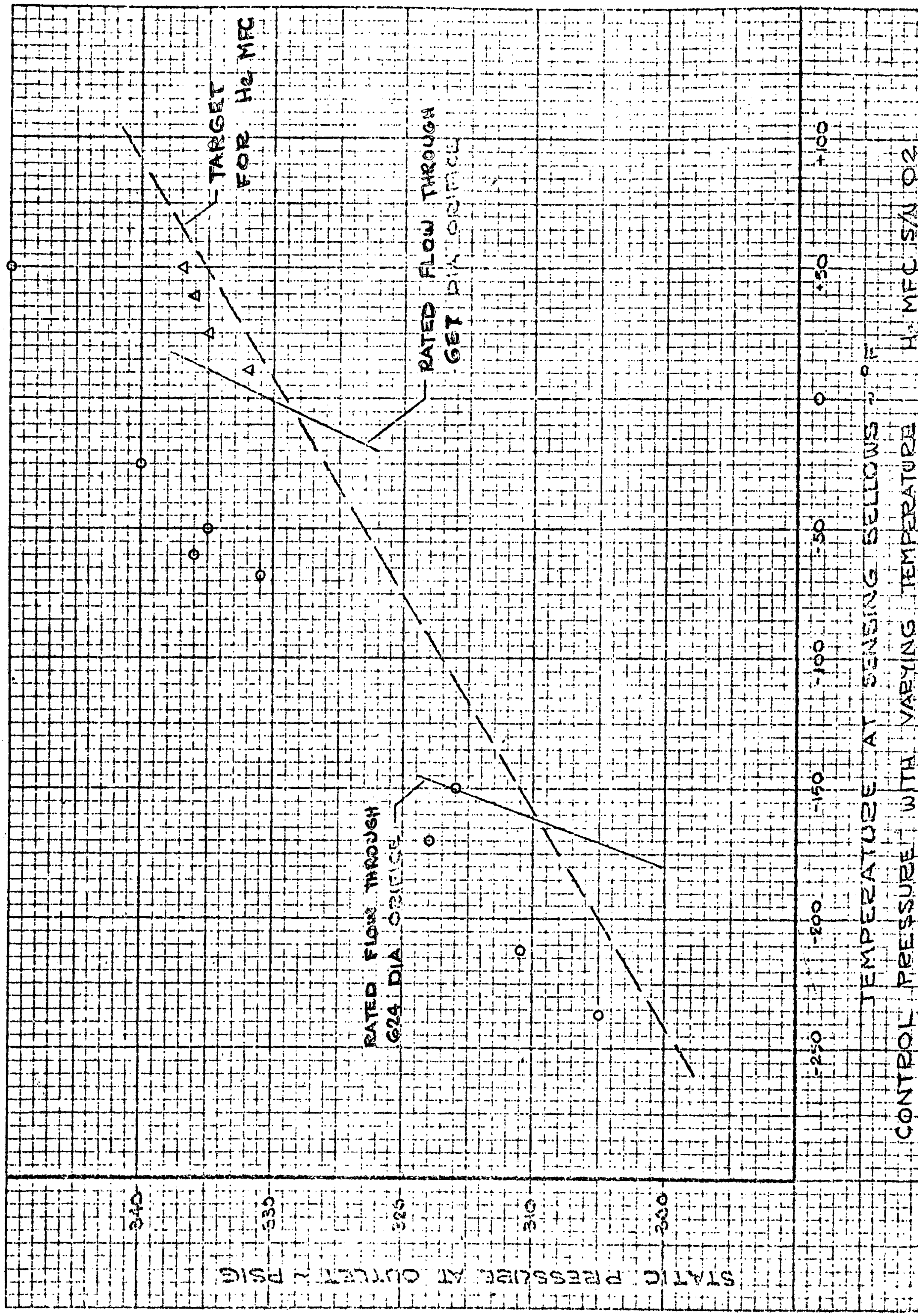
J. H. REF. SPEC. DATA SHEET NO.

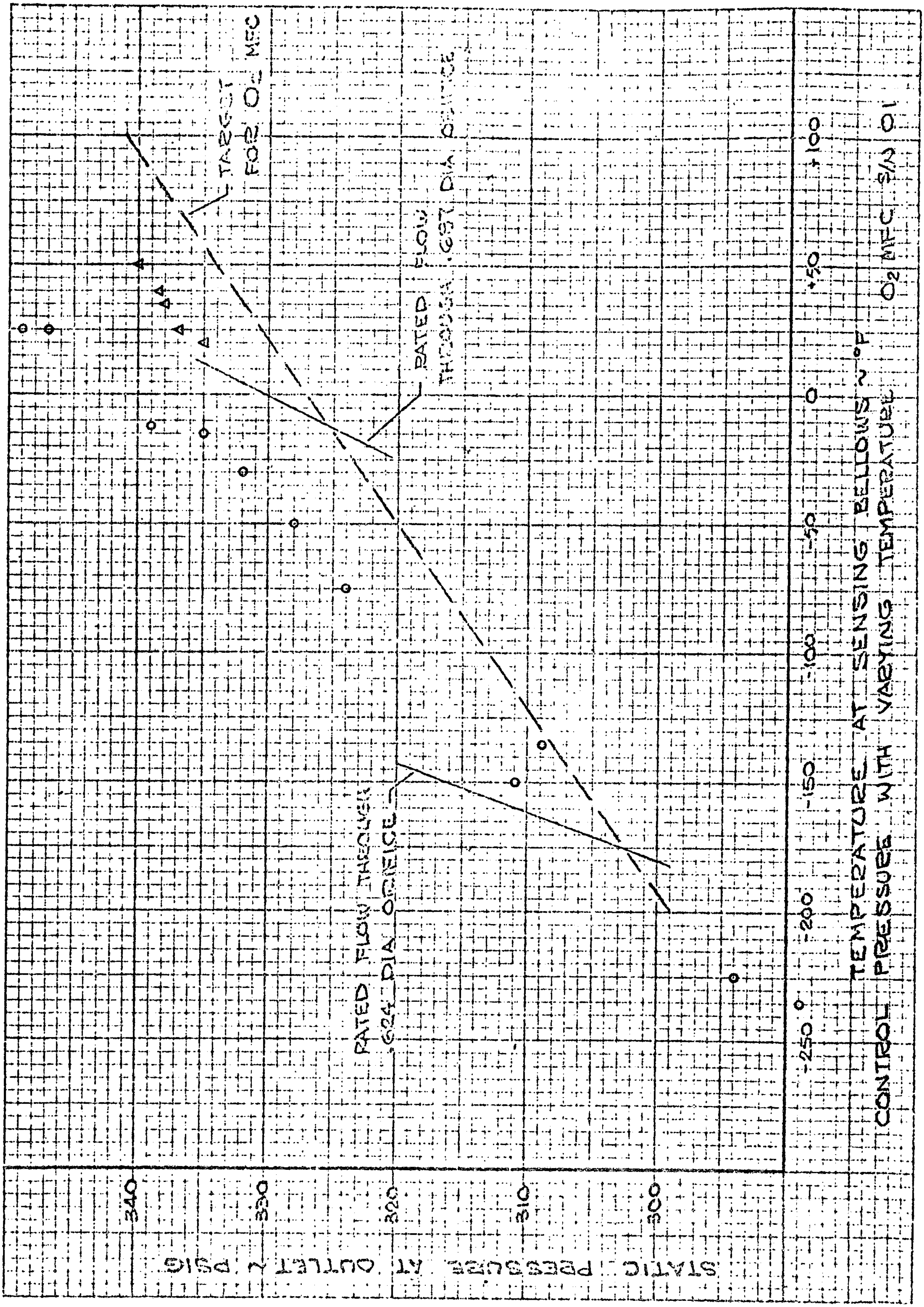
PH 1P6 (-69)

APPENDIX G

PRESSURE CONTROL VS. PROPELLANT TEMPERATURE


TARGET FOR H_2 MFC
RATED FLOW THROUGH
DIA ORIFICE
RATED FLOW THROUGH
.624 DIA ORIFICE
-250
-200
-150
-100
-50
0
+50
+100
TEMPERATURE AT SENSING BELLOWS ~ °F
340
330
320
310
300
STATIC PRESSURE AT OUTLET ~ PSIG
CONTROL PRESSURE WITH VARYING TEMPERATURE, H_2 MFC, S/N C1


TARGET FOR He MFC
RATED FLOW THROUGH
RATED FLOW THROUGH .624 DIA ORIFICE
+100
+50
-50
-100
-150
-200
-250
TEMPERATURE AT SENSING BELLOWS ~ °F
CONTROL PRESSURE WITH VARYING TEMPERATURE He MFC S/N 02
340
335
STATIC PRESSURE AT OUTLET ~ PSIG


TARGET FOR O2 MFC
RATED FLOW
RATED FLOW THROUGH .624 DIA ORIFICE
340
330
320
310
300
STATIC PRESSURE AT OUTLET ~ PSIG
-250
-200
-150
-100
-50
0
+50
+100
TEMPERATURE AT SENSING BELLOWS ~ °F
CONTROL PRESSURE WITH VARYING TEMPERATURE O2 MFC S/N 01

APPENDIX H

DVT 5716068

SYSTEMS DIVISION

PARKER HANNIFIN ■ 18321 JAMBOREE BOULEVARD ■ IRVINE, CALIFORNIA 92664

CONTROLLED DOCUMENT

NUMBER: DVT5716068

TITLE: Design Verification Test Procedure for Mass Flow Controller Assy: PN's 5716068-101 and 5716068-102

RELEASE HISTORY							
DATE	REVISION	E.O. NO.	MICROFILM	DATE	REVISION	E.O. NO.	MICROFILM
18-Oct-71	NC	01					

REFERENCE:
1. Parker Program S156
2. NASA P.O. # NAS9-11750

PREPARED BY: W. Taylor
W. Taylor
Sr. Project Engr.

APPROVED BY: J. Ulanovsky
J. Ulanovsky
Mgr., Design Engr.

LIST OF EFFECTIVE PAGES

This document consists of 5 pages as follows:

Page	Rev Ltr
Cover	NC
i and ii	NC
1 through 2	NC

CONTENTS

1.0 SCOPE

This document specifies the test procedure to be followed for design verification testing of two mass flow controller assemblies,

PN 5716068-101 Hydrogen Mass Flow Controller
5716068-102 Oxygen Mass Flow Controller

2.0 TEST REQUIREMENTS

2.1 Test Facilities - All testing shall be conducted at the Systems Division, Parker Hannifin Corporation, Irvine California Facility.

2.2 Test Results - Complete test results data shall be recorded for each design verification test.

2.3 Environmental - Unless otherwise specified, all testing shall be conducted within the following environmental conditions:

a. Temperature: 75° ± 20°F
b. Relative Humidity: 90 percent or less
c. Barometric Pressure: Local Atmosphere

2.4 Test Media - The test media used for design verification testing shall be nitrogen in accordance with MIL-P-27401.

2.5 Tolerances - Unless otherwise specified, the following tolerances apply to the application of the test requirements and the recording of data.

a. Temperature: ± 3°F
b. Barometric Pressure: ± 5 percent
c. Pressure: ± 1 percent
d. Flow Rate: ± 2 percent
e. Leakage Rate: ± 3 percent

3.0 DETAILED TEST PROCEDURES

3.1 Internal Leakage - Conduct internal leakage test per paragraph 3.2 of PTS5716068.

3.2 Response & Regulation - Conduct response and regulation test per paragraph 3.3 of PTS5716068.

3.3 Pressure Drop

3.3.1 Setup - Use setup shown in Figure 2 of PTS5716068. Use .718 dia orifice in outlet line.

3.3.2 Procedure - Using D1, set inlet pressure of 300 psig. Close switch, initiating flow through MFC. Increase inlet pressure from 300 to 400 psig in 10 psi increments. Record inlet pressure, outlet pressure, outlet temperature, Δp at venturi flowmeter.

3.4 Endurance

3.4.1 Setup - Use setup shown in Figure 2 of PTS5716068. Install .160 dia orifice in outlet line.

3.4.2 Procedure - Using D_1 establish a pressure of 550 ± 50 psig at inlet of MFC. Cycle unit 10,000 times by closing and opening switch. At conclusion of test perform ambient temperature tests and internal leakage test (paragraph 3.2 and 3.3.2 of PTS5716068).

APPENDIX J

DESIGN VERIFICATION TEST DATA SHEETS

PARKER HANNIFIN

REPORT NO. EER5716068 PAGE J-2

REV. LTR. NC BY WT DATE 1-9-72

DATA BY: OCH RJ DATE 11-26-71 APPR.

TEST: INTERNAL LEAKAGE (AFTER 10000 CYCLES)

SAMPLE No. T515201

BAROM. PRESS. In.

TEST MEDIUM GN_2

WET BULB TEMP.

PART NO. & NAME 5716068-101 MASS FLOW CONTROLLER

MEDIUM TEMP. °F.

DRY BULB TEMP.

PTS5716068 PARA NO.	INLET PRESSURE REQ PSIG	INLET PRESSURE ACTUAL PSIG	OUTLET PRESSURE REQ PSIG	OUTLET PRESSURE ACTUAL PSIG	TIME REQ SEC	TIME ACTUAL SEC	LEAKAGE REQ —	LEAKAGE ACTUAL SCCM
3.2.2 POPPET LKG.	400	400	—	—	—	*	—	45
	1000	1000	—	—	—	*	—	500
	2000	2000	—	—	—	*	—	1300
PISTON SEAL LKG.	50	50	—	—	—	*	—	3200
	100	100	—	—	—	*	—	7500
	200	200	—	—	—	*	—	12500
	400	400	—	—	—	*	—	20000

* FLOW METER #3625
RANGE 5.0 TO 24000 SCCM

SETUP PER H_2 MFC S/N 01

J. N. REF. SPEC. DATA SHEET NO.

PHLA 1P6 (4-69)

PARKER HANNIFIN

REPORT NO. EER5716068 PAGE J-3

REV. LTR. NC BY WT DATE 1-9-72

DATA BY: OSHIRO DATE 11-24-71 APPR.

T: PRESSURE DROP (GN_2)

SAMPLE No. T515201

BAROM. PRESS. IN. HG

TEST MEDIUM GN_2

WET BULB TEMP. °F.

T NO. & NAME

5716068 -101 MASS FLOW CONTROLLER

MEDIUM TEMP. °F.

DRY BULB TEMP. °F.

INLET PRESS PSIG		OUTLET PRESS PSIG		VENTURI ΔP IN H_2O	VENTURI TEMP °F		CORRECTED FLOW LB/SEC
321		—		18	+32		2.77
344		265		21	+14		3.03
372		286		25	+4		3.35
385		299		27	-4		3.50
408		320		31	-12		3.77
327		255		19	-8		2.97
349		270		22	-12		3.20

UP PER H_2 MFC S/N 01

N. REF. SPEC. DATA SHEET No.