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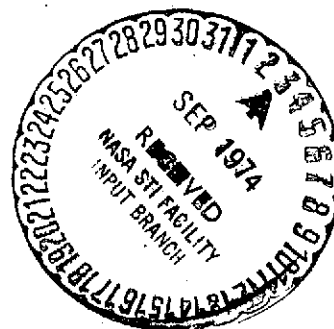
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ON-LINE CALIBRATION OF HIGH-RESPONSE PRESSURE TRANSDUCERS DURING JET-ENGINE TESTING

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ABSTRACT

Current jet engine testing is concerned with the effect of inlet pressure and temperature distortions on engine performance and involves the use of numerous miniature pressure transducers. Despite recent improvements in the manufacture of miniature pressure transducers, they still exhibit sensitivity change and zero-shift with temperature and time. To obtain meaningful data, a calibration system is needed to determine these changes. A system has been developed which provides for computer selection of appropriate reference pressures selected from nine different sources to provide a two- or three-point calibration. Calibrations are made on command, before and sometimes after each data point. A unique "no leak" Matrix Valve design is used in the reference pressure system. Zero-shift corrections are measured and the values are automatically inserted into the data reduction program.

INTRODUCTION

The high response, miniature pressure transducers currently in use for dynamic studies of air flow in turbofan and turbojet engines exhibit the faults shared by most force transducers; that is, the relationship between apparent strain, gage resistance, and gage factor which varies with temperature. This dependence shows up mainly in the form of thermal zero shifts and sensitivity changes. Recent innovations have greatly improved the performance characteristics of miniature pressure transducers. Non-linearity and hysteresis effects are almost non-existent. Over-pressure limits have been extended for pressures applied to both the front and back sides of the transducer diaphragm by improved bonding and sealing technology. Despite the improvements, on-line calibrations to determine zero shift and changes in sensitivity are considered necessary until confidence can be established in transducer stability.

It is standard procedure in the Propulsion Systems Laboratory facilities at Lewis Research Center to calibrate each transducer for both zero and sensitivity shift prior to each high-response or transient data scan. This is done by balancing the pressure across the transducer to obtain an electrical output at zero differential pressure and then applying two or more known pressures to the reference side of the transducer to establish the sensitivity.

In a recent inlet distortion test on a TF-30-P-9 engine, a standard configuration of 40 miniature, hi-response transducers was installed at the engine inlet. Over a test time of 2 hours and 27 minutes, 10 data scans were taken. Figures 1 and 2 show the range of zero and sensitivity values of the 40 transducers for the 10 calibration points, as well as the specific

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values for the first and last data scans. This variation emphasizes the need for a calibration prior to each data scan.

This paper provides a description of the mechanisms and method used to obtain such calibrations.

DESCRIPTION OF SYSTEM

The basic purpose of the calibration system is to obtain a value for the zero offset and the sensitivity for each transducer for each data scan. The offset value is obtained by creating zero pressure differential across the transducer and measuring the output signal. The sensitivity is determined by placing known pressures on the back (reference) side of the transducer diaphragm. It is not necessary to know what pressure is on the front face of the transducer, only that it stays constant for the different reference pressure readings. The ratio of the difference between their respective electrical output signals is the slope or sensitivity of the transducer. The basic purpose has thus resolved itself into providing known pressures to the reference side of the transducers and to record the appropriate output signals.

It is not practical nor economically feasible to provide an unlimited number of pressure levels for use as references for each transducer. A review of previous and present jet engine test programs showed that the test article could be divided into a maximum of five zones, (e. g. engine inlet, fan, low compressor, high compressor). By doing this, the full-scale range of the transducers in a zone can be kept as low as possible to improve accuracy. All of the transducers in any one zone would be connected to the same line manifold and would be subjected to the same set of reference pressures.

The calibration system provides for a two point calibration of each transducer, therefore nine different pressure levels were made available to provide adequate range for calibration of the transducers connected to the five line manifolds. The pressure selection for each manifold is made by the computer. After the calibration data is recorded, a reference pressure is placed on the transducers for operation during testing. Any variation in this pressure, within set limits, during testing alarms the system.

The reference and calibrate system consists of four basic sections shown in figure 3:

      I. PRESSURE SOURCES

      II. "NO-LEAK", MATRIX VALVE

      III. CONTROL MODULES

      IV. COMPUTER CONTROLS

The following paragraphs describe each of these sections:

I. PRESSURE SOURCES - There are nine (9) different pressure levels available for the reference system. The magnitude of eight of these is designated by the research engineer prior to the start of the testing. Six of these pressures are above atmospheric pressure; four of the six are in the range of 0 to 100 psig and the remaining two in the range of 10 to 300 psig. One of the remaining pressures is atmospheric and the other two are pressures less than atmospheric. The pressure levels selected by the research engineer are based on:

1. Range of the transducers used with each of the five manifolds.

2. Range of pressures that will be encountered during testing, and

3. Back pressures desired for operation.

The six higher pressures are supplied by dead weight pneumatic regulators that are commonly used as secondary lab standards, figure 4. They have an error range of .025 percent of reading, with a repeatability of .005 percent of reading. Nitrogen gas is supplied to each regulator at a pressure at least 50 percent higher than the desired output pressure. A small leakage keeps the weights floating and slowly spinning after the pressure and the weights are stabilized.

The two vacuum pressure levels are provided by two regulators supplied by a common vacuum source. The vacuum levels are measured by stable, individual transducers which are periodically calibrated.

The nine pressures are each connected to a source manifold in the Matrix Valve. Control valving determines which pressure source is used, which fill manifold it is used in, and in what sequence.

II. "NO-LEAK" MATRIX VALVE ₋ The "no-leak" matrix valve is the heart of the system and is the device that makes this reference system reliable. Reference and calibrate systems used prior to this design produced questionable results because of undetected leaks in the plumbing of the reference pressures. The Matrix Valve replaces numerous solenoid valves which were the chief cause of the undetected leaks.

The two body parts of the valve assembly are shown in figure 5. This valve assembly contains 55 valves. The opening and closing of each valve is independently controlled by air pressure or vacuum acting on a flexible diaphragm which covers or uncovers two manifold ports. A section view of one valve is shown in figure 6. The control pressure acts on the flexible valve diaphragm. lifting it to allow flow between the two ducts connecting the fill and source manifolds, or closing off the ports to stop flow. Fig-

ure 7 shows the internal passages of a portion of the valve. Each of the nine source pressures has five valves for connection between the input source manifold and the five fill manifolds. At each end of each fill manifold is another valve, one for venting and one to "fill" or allow the selected pressure to flow to the miniature pressure transducers connected to that line.

Figures 8(a) and (b) show the Matrix Valve installed with control tubing connected.

The 55 valves are divided equally for control of the 5 different pressure ranges of transducers to be calibrated. Each of these five divisions has 1 vent valve, 1 fill valve and 9 source-pressure valves.

There is a wide range of material available that is suitable for the diaphragm. The diaphragm material must be non-porous, withstand repeated flexing, have the strength to withstand the shear forces involved at the valve ports and have some degree of elasticity such that the control pressure required will not be excessive.

Tests were run using several thicknesses of different materials. Most of the materials used were satisfactory, the only difference being the amount of overpressure that was required for a control pressure to seal the valve. The material finally selected was a .032" thick neoprene material which requires a pressure of approximately 10 psi, greater than the source pressure to seal the valves. As a safety factor, the control pressure is set to 25 psi over the maximum source pressure to be used. The criterion chosen for acceptable sealing was that no bubbles should appear over a two minute time span for the most extreme pressure differential that would be experienced.

III. CONTROL MODULE - Five control modules are used in the system,

one module being required for each fill manifold. Each module as shown in figure 9, consists of 12 solenoid valves and associated relays to control the operation of the Matrix Valve and provide an indication of operating sequence to the user. Each module also contains a differential pressure switch which is one of the safety features incorporated to protect against overpressuring the reference side of the miniature transducers. The solenoid valves are three-way valves: the common port is connected to a valve on the Matrix Valve and the other inlet ports are connected to a control vacuum source and a control pressure source, (ref. fig. 3). Nitrogen gas is used for the control pressure source because of greater system reliability. The solenoids are connected in a fail-safe mode such that loss of electrical power applies gas pressure to the Matrix Valves to keep the system in a shut-off position and the miniature transducers in a "zero" differential pressure state.

The control-pressure system is isolated from the reference pressure system to eliminate any leakage of control air pressure into the reference pressure system. Any leak into the reference pressure system can lead to erroneous calibrations that can create more severe errors than if no calibration were made at all. Small leaks in the control portion of the system are not as detrimental and can be tolerated. Particular attention was exercised in the selection of the tubing and pneumatic connectors used. Welded joints were used in place of pneumatic tube fittings wherever possible. Numerous and careful leak checks of the system are a necessity.

IV. COMPUTER CONTROL - The local computer controls the operation of the reference and calibrate system. It controls the sequencing of events, timing, logic and recording of calibration points. The computer program

also employs a system of tagging specified steps in the program. This tagging consists of a voltage output or marker, the level of which identifies the different portions of the calibration sequence. These marders are used in the data reduction program to find the appropriate segment of data to use for the mathematical calculation of transducer sensitivity and zero offset. Four control buttons are provided to start automatic computer sequencing which provides the following conditions (ref. fig. 3):

1.   <u>ΔP Calibrate</u> - This control button starts the sequencing for calibration of all transducers designated and connected to the system. The sequence is as follows:

A.   The recording systems are started and after they are up to speed the "static" transducer conditions are recorded and identified with a marker level of 10 percent.

B.   For each of the five sections of the Matrix Valve the highest source level pressure is allowed to fill the "no-leak" valve fill manifold. If the fill manifold pressure is greater than the pressure on the front side of the pressure transducers connected to that sections' line manifold by more than 20 psi, this source pressure is rejected as a calibration reference pressure and vented. This condition is measured by a differential pressure switch connected to the manifold on one side and to a pressure on the other which is selected as being representative of the lowest pressure in that zone on the engine. There is a pressure switch for each fill manifold.

C.   If source pressure P-1 is rejected, pressure P-2 is allowed to fill the fill manifold and another check made through the pressure switch as to its suitability as a reference pressure. Sequentually stepping down

through decreasing pressure levels, the system finally arrives at a suitable pressure. A suitable pressure is defined as the first pressure found that is within 20 psi of the lowest zone pressure.

D. The suitable pressure is allowed to flow to the back side of all the pressure transducers connected to that line manifold through the fill valve. After a stabilization time, the marker level is set to 50 percent and calibration point "A" is recorded.

E. The first calibrate pressure is vented and the second calibrate pressure, which has been previously designated in the program, is admitted. This second pressure is the next lower source pressure from that used for point "A". The program has built-in options that may be exercised such that instead of using the next lowest pressure, a pressure two steps lower, or three steps lower may be used. This option must be stated for each manifold or the system defaults to the lowest pressure, P-9, which is a vacuum level.

F. The second calibrate pressure is allowed to flow to the back side of the transducers in the same manner as the first. The marker level is set at 65 percent and calibration point "B" is recorded.

G. The second calibrate pressure is then vented and the back-pressure that is to be used during the test point is placed on the transducers. This pressure is selected in the program as being one or two steps higher than that pressure used for point "B". It cannot be higher than the pressure used to obtain point "A", and if the step is not specified in the program, then the default pressure is the same as that used to obtain point "B".

H. After the back-pressure has been selected and stabilized, the marker level is set to 80 percent and the "READY" light on the operator's console is energized to verify that calibrations have been completed and research data may be taken. This condition will hold until the "STOP CALIBRATE" or "STATIC" control buttons are energized.

2. Static - This control insures a zero pressure differential condition. The vent valve in the Matrix Valve is opened, all the source pressure valves are closed and the shunt valves (see fig. 3) are energized. The shunt valves route the pressure that is present on the face of the transducer to the reference side of the transducer to create a zero differential pressure across the transducer diaphragm. A 35 percent marker level is established to identify the static condition. This control does not affect the status of any peripheral recording equipment.

3. Back pressure - This control is used to pressurize or fill a manifold with a pre-selected source pressure without first obtaining a zero and a two point calibration of the transducers. Within the Matrix Valve the pre-selected source pressure valve is opened, "vent" valve is closed and "fill" valve is opened. Shunt valves are energized, recorders are started, a marker indication is placed on the recorder showing what condition is present and a "READY" signal is given to the operator.

4. Stop calibrate - Activation of this control button turns off all recording equipment, removes the "READY" light and holds the existing back-pressure if one exists. It will not change the reference pressure in the system.

Different computer programs can provide modifications to the basic sequencing as listed under ΔP Calibrate. As an example, instead of letting

the computer search for the reference pressure to be used, the source pressure may be designated for each fill manifold for each calibration point. A time sequence for this method is shown in figure 10.

Because of a recent improvement in miniature transducer fabrication, hi-range transducers (greater than 25 psid) can now withstand reverse differential pressures across the diaphragm equal to the value of the normal differential pressure. For low range transducers the reverse differential is 50 psi. This permits the transducers to be calibrated in the third quadrant which increases the range between the two calibration points, and thus, improves the reliability of the calibration. For example, using the normal search method (quadrant I) and applying the highest pressure possible to the back side of the transducer will result in a low calibration point (point A). The millivolt reading for this point, called MV_A' is equivalent to the engine pressure (PE) on the face minus the reference pressure used $(PSMAN)_A$.

$$KMV_A = (PE) - (PSMAN)_A \qquad (1)$$

where K = slope in PSI/MV

The back pressure applied cannot be more than 20 psi greater than the face pressure on the transduer. Depending on the pressure levels set on the source pressure pneumatic regulators, this reference back pressure could be considerably less than the face pressure, such that the low reference point would be a positive number as shown by A' in figure 11.

Applying a low reference pressure or vacuum will result in a maximum reading for point "B" where:

$$KMV_B = (PE) - (PSMAN)_B \qquad (2)$$

Subtracting to calculate the slope:

$$K(MV_A - MV_B) = (PE - PSMAN)_A - (PE - PSMAN)_B \qquad (3)$$

$$K(MV_B - MV_A) = (PSMAN)_B - (PSMAN)_A \qquad (4)$$

$$K \Delta MV = \Delta MANIFOLD\ PRESSURES \qquad (5)$$

For hi-range transducers, the quadrant I method will yield the greatest spread between calibration points; for low-range units the quadrant III method, obtained by applying hi-level back pressures, is better.

TIME RESPONSE

It is desirable to keep the time required for calibration of the miniature pressure transducers to a minimum. Sufficient time is required, however, to allow the calibration pressures to stabilize. This time is a function of the time constants of the numerous tubing sections of the system.

Particular attention was given to minimizing the systems pneumatic volume. It was determined, however, that the main factor affecting the system's time constant was not the tubing used but the pneumatic pressure regulators. The four low-range pneumatic regulators have a flow rate considerably greater than the hi-range units, therefore settling-out times are shorter for low pressures supplied by the low-range regulators. The flow rate is a function of the back pressure or differential between the pressure and the desired output pressure as set with the weights. A typical curve is shown in figure 12 for the flow rates of the two types of regulators as a function of time for an output pressure of 60 psig.

Typical times to sense and fill the manifolds with calibration pressures are shown in figure 13. An additional buffer time was added for assurance of balanced conditions, and these times, as used by the computer, are as follows:

1. Time to fill the "no-leak" valve fill manifold for supplying -

    Vacuum sources   - 4 seconds

    Low-range regulators - 10 seconds

    Hi-range regulators   - 20 seconds

2. Time to fill the transducer line manifold and stabilize the

    back pressure -

    Vacuum sources   - 12 seconds

    Low-range regulators - 60 seconds

    Hi-range regulators   - 110 seconds

3. Time to vent -

    "No-leak" valve - 1 second

    System   - 3 seconds

Overall time to perform a two-point calibration is between 170 and 300 seconds.

ACCURACY

By definition, accuracy is the ratio of error to full-scale output or the ratio of error to output. The accuracy that we are concerned with in this report is that of the calibration system - not the transducers being calibrated. The error involved is the pressure delivered to the reference port of the transducers relative to the value of the weights placed on the pneumatic pressure regulators.

To test the system, various ranges of pressure transducers were connected to sense the pressure that would normally be delivered to the reference side of the miniature pressure transducers. The pressure transducers were calibrated frequently during the test and were selected because of their excellent lab calibration data. The system verification tests showed accura-

cies within approximately 0. 1 percent over the entire range, which is within the measurement accuracy of the miniature pressure transducers being calibrated.

SUMMARY

The reference and calibration system used to provide calibration updating of miniature pressure transducers during jet engine testing at Lewis Research Center is described and its operation explained. The inclusion of a Matrix Valve operating in conjunction with secondary-standard pneumatic pressure regulators provides a system with an overall accuracy of 0. 1 percent.
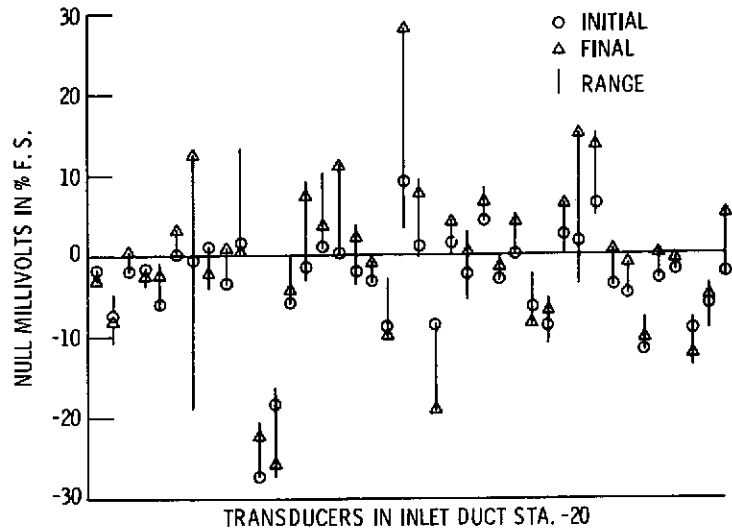
Figure 1. - Variation of null output of inlet transducers in
TF-30-P-9 engine.
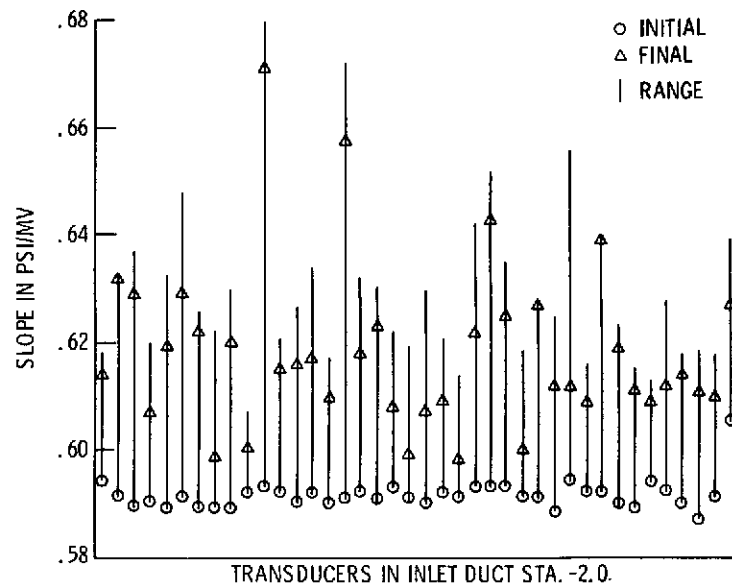
Figure 2. - Variation in sensitivity of inlet transducers in
TF-30-P-9 engine.
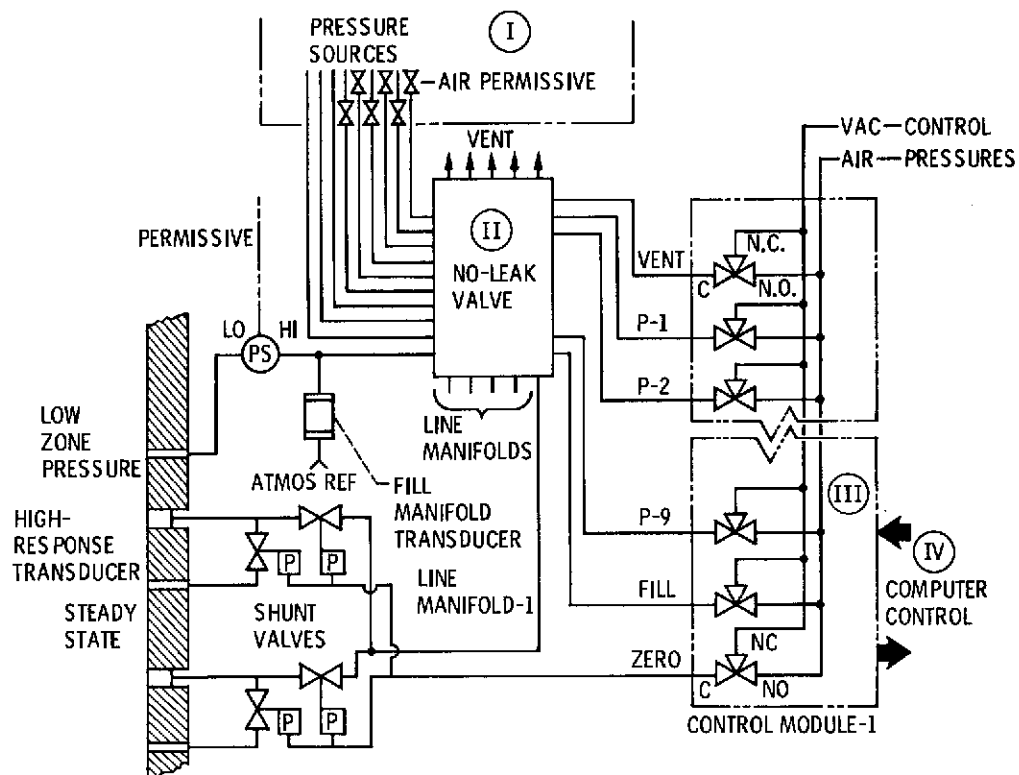
Figure 3. – Reference and calibrate system schematic.
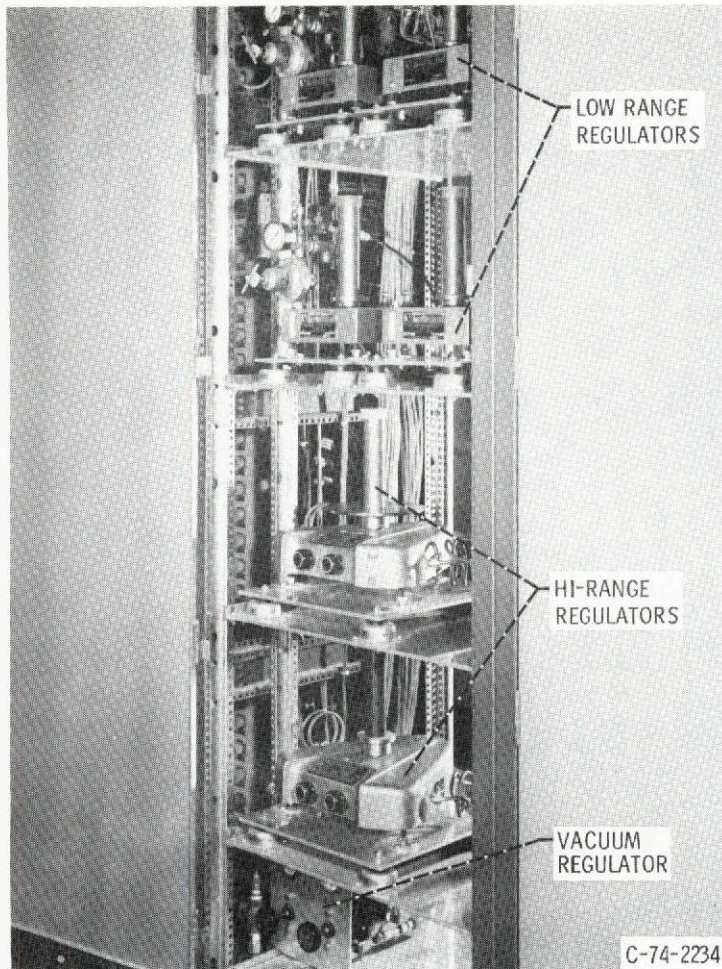
Figure 4. - Pneumatic regulators.
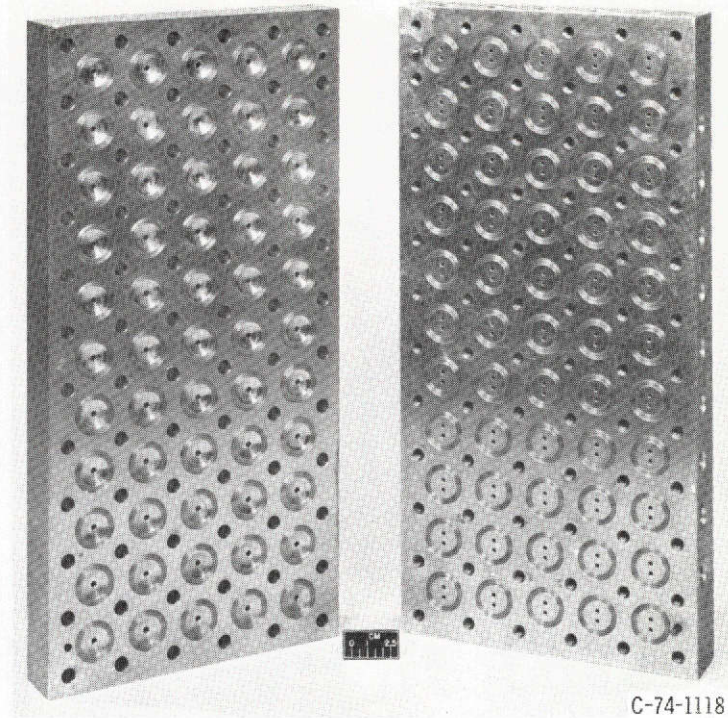
Figure 5. - No-leak valve body.

PRESSURE

VACUUM

CONTROL PRESSURE

DIAPHRAGM

CLOSED

OPEN
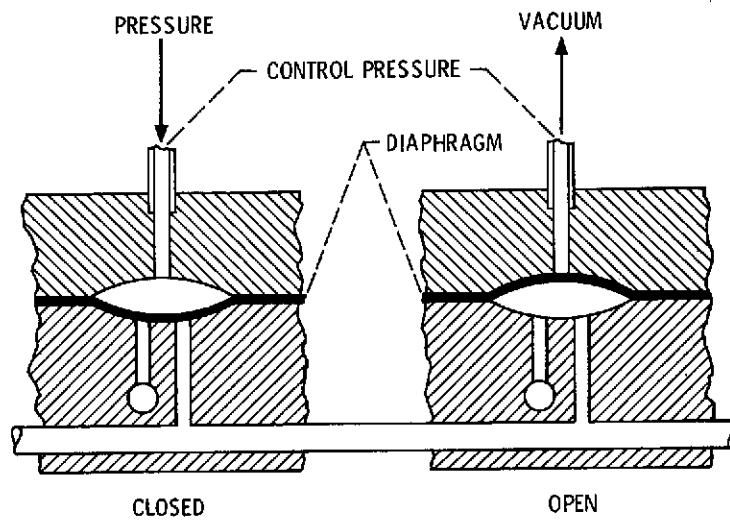
Figure 6. - Valve section of no-leak valve.

SOURCE REF. PRESSURES 2 OF 9 SHOWN

VENT

VENT VALVE

CONTROL PRESSURE

VALVE DIAPHRAGM

FILL MANIFOLDS 2 OF 5 SHOWN

SOURCE MANIFOLD

FILL VALVE

P.S.

FILL MANIFOLD

LINE MANIFOLD 1 OF 5 SHOWN
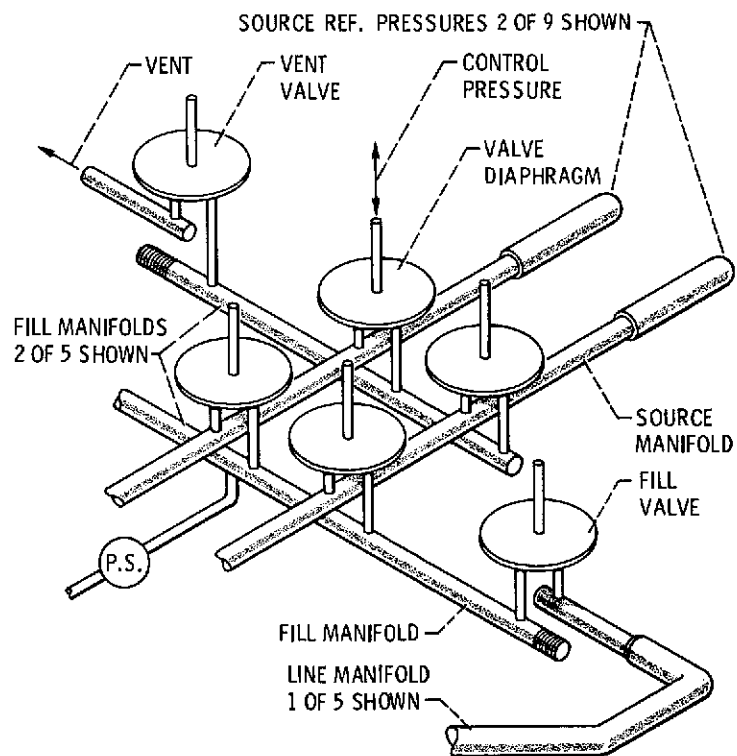
Figure 7. - No-leak valve functional section.

C-74-2235
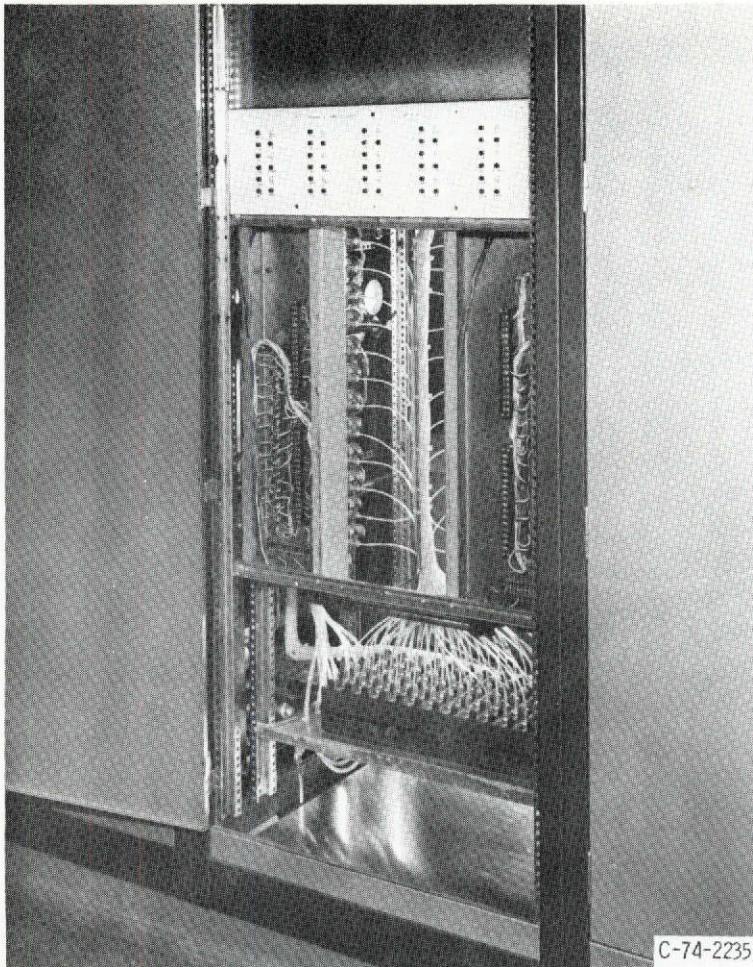
(a) FRONT VIEW.

Figure 8. - No-leak valve installation.

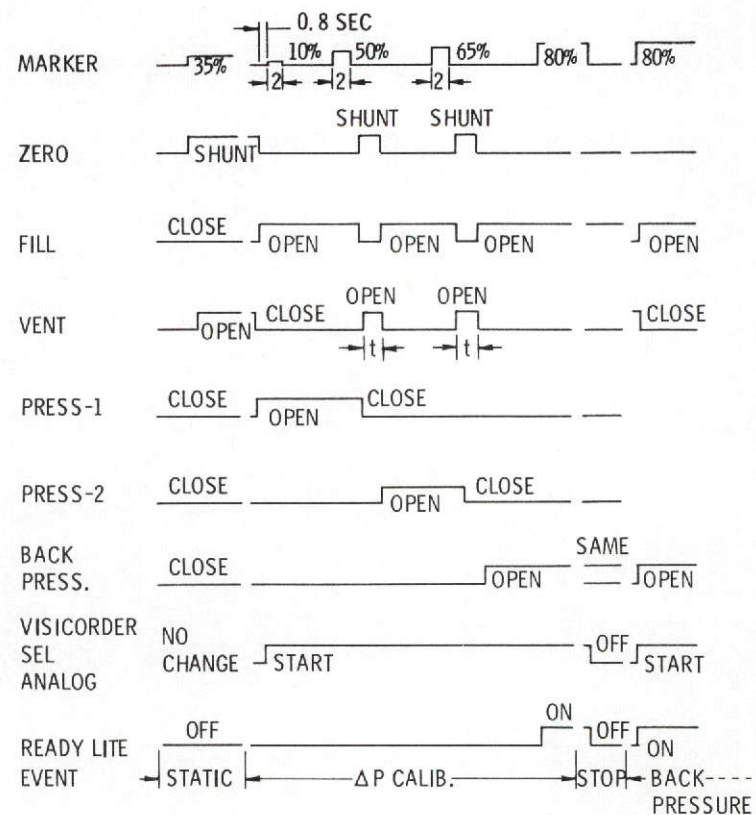C-74-2233
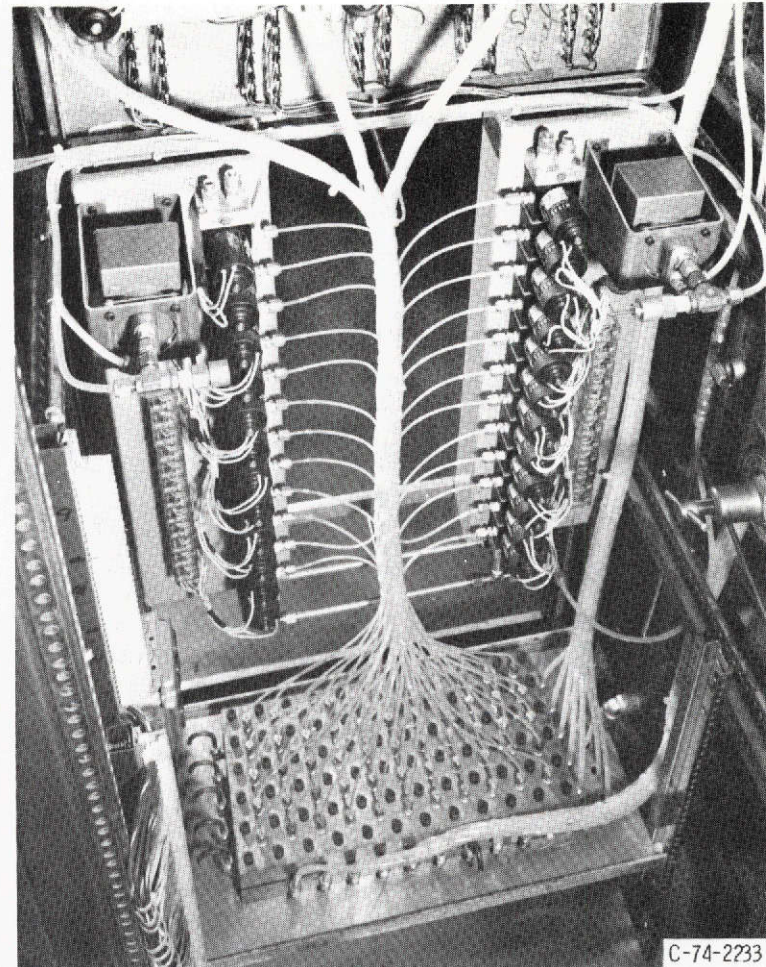
(b) REAR VIEW.

Figure 8. - Concluded.
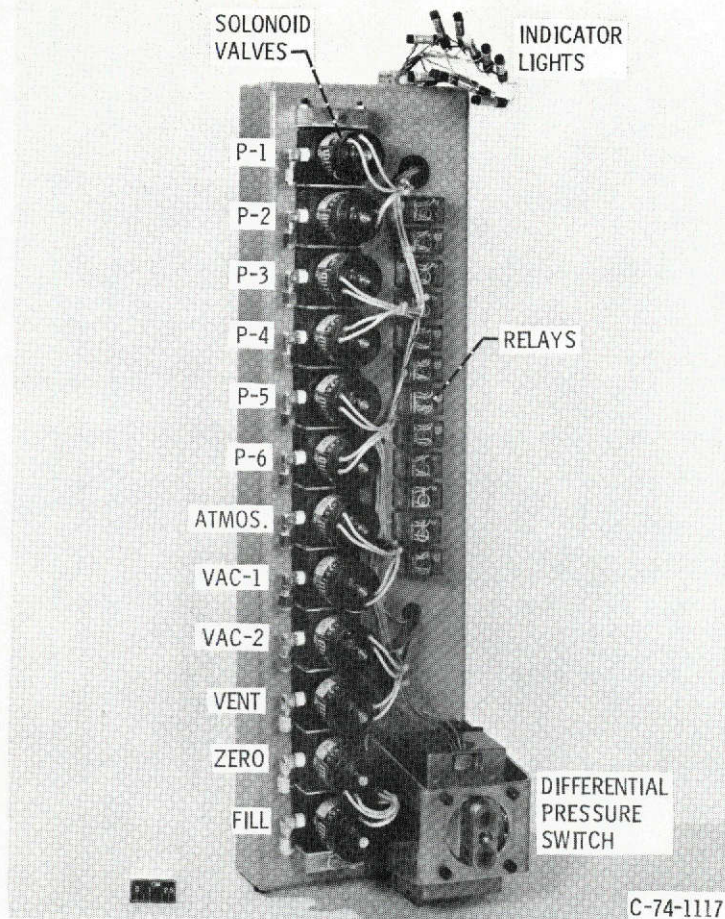
Figure 9. – Control module.

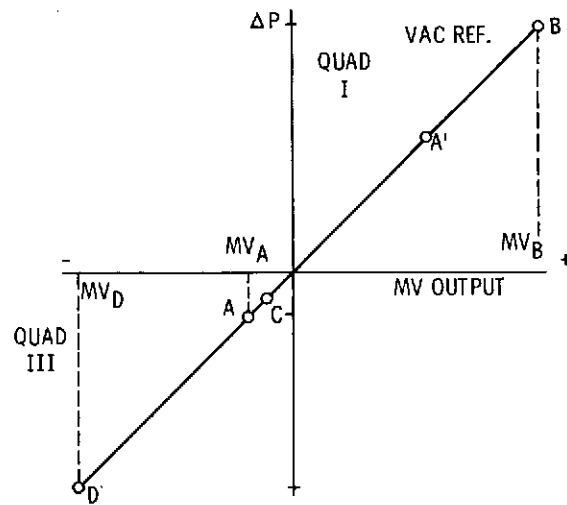Figure 10. – Reference and calibrate system time sequence.
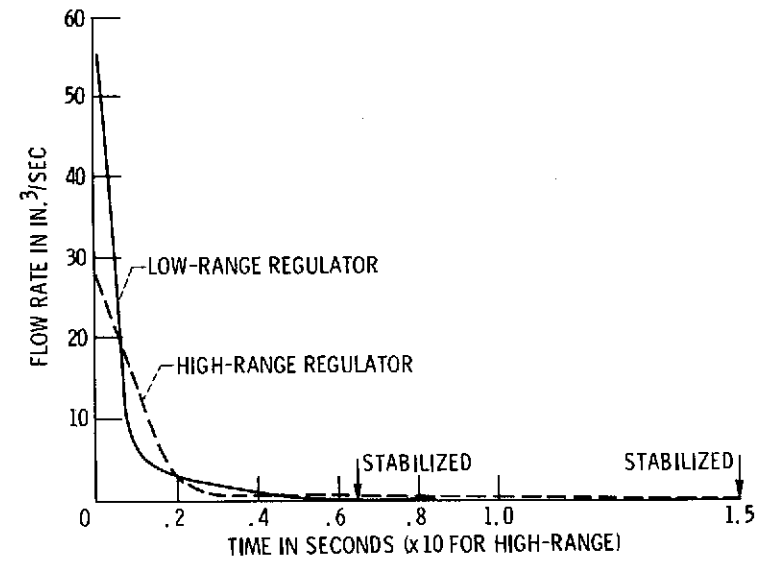
Figure 11. – Transducer calibration curve.

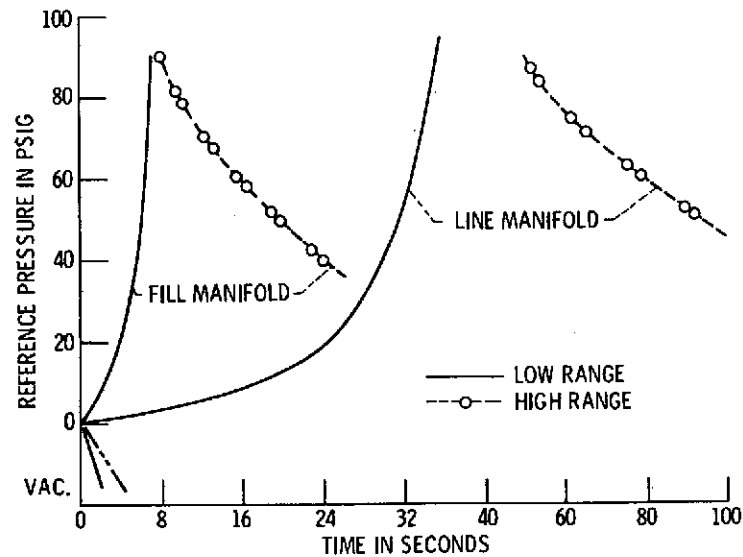Figure 12. – Flow rates of regulators. 60 psi pressure differential.

Figure 13. – Fill times of fill manifold and line manifold for pneumatic regulators.