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DEVELOPMENT OF A FLUIDIC OXYGEN REGULATOR

Honeywell Inc.
2600 Ridgway Parkway
Minneapolis, Minnesota 55413

January 1977

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Final Report for Period February 1975 to July 1976

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NOTICE

This technical report has been reviewed and is approved for publication.

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The object of this study was to build and test a breadboard of an automatic oxygen regulator using fluidic techniques. Goals set for the regulator were that it should have oxygen economy, be rugged, simple, and self-powered. Feasibility of controlling the oxygen enrichment following a specified cabin pressure schedule was demonstrated. Features of the mixture control circuit were a fluidic function generator, a fluidic pulse duration modulator and an ejector pump. Feasibility of controlling the output

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pressure for normal breathing and pressure breathing as a function of cabin pressure was demonstrated. Major components in the closed pressure control loop were a fluidic function generator, a fluidic comparator amplifier, and a fluidically driven mechanical shutoff valve.

The goal of low oxygen waste (0.02 lpm) was not met in the tests but achievement methods were recommended. No implementation was made during this phase.

Present operating problems are in the pressure control loop. The first problem is a small oxygen waste through the vent of the fluidic comparator amplifier. A recommended mechanical solution is to drive a diaphragm comparator with a mechanical link from the function generator. Output of the comparator would open and close the shutoff valve. An all fluidic solution is to drive a diaphragm comparator with a mechanical link from the function generator. The second problem is unacceptable short duration pressure spikes in the output during pressure breathing. Preliminary tests with acoustic filters demonstrated considerable attenuation of the spikes; thus, the recommended solution is to design special filters for future models.

A miniature high density package version of the fluidic pulse duration modulator was designed and built to a size compatible with the specified package size for an aircraft installation. It operated successfully in the breadboard mixture control circuit.

FOREWORD

This is the final report for the work done by Honeywell, Inc. for the United States Air Force, Air Force Systems Command, Wright Patterson Air Force Base, Ohio in accordance with the requirements defined by contract number F33615-75-C3004, project number 6146, "Advanced Oxygen Regulator Concepts." The monitoring laboratory was Air Force Flight Dynamics Laboratory. Mr. David Gieger and Captain Gene Puhl, Environmental Control Branch/FEE, were the technical monitors. The work was done between February 1975 and July 1976 at the Systems and Research Center of Honeywell in Minneapolis, Minnesota. Principal Investigator was Mr. Frederick Moynihan of the Sensor Technology Section, and Dr. George Webber, Section Chief, acted as Program Manager.

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SECTION I

INTRODUCTION

BACKGROUND

Recently the oxygen regulation systems on aircraft have tention for their excessive use of oxygen. This high oxygen use means that mis n dura must be curtailed and/or that larger oxygen supply systems are needed for dern bombers such as the B1. Past development of regulators by industry have not addressed the oxygen economy problem, and improvements have been modifications to existing designs rather than an exploration of new basic concepts. In addition, other improvements to existing regulators are needed such as better reliability, ruggedness, reduced size and weight, and simplified maintenance.

Fluidic technology offers a fresh approach to the oxygen regulator problems. It brings its reputation for ruggedness and reliability, its ability to be self-powered by oxygen supply, and a promise to prevent waste through a tight control of the amount of oxygen supplied during the dilution mode.

OBJECTIVE

The purpose of this project was to evaluate a fluidic concept for an aviator's oxygen regulation which would provide significant improvement of oxygen conservation over current designs for an automatic pressure breathing, dilution demand type. The regulator had to mix air and oxygen for breathing in proportions which are a function of cabin pressure and had to follow closely the schedule dictated by physiological requirements.

The performance of the regulator breadboard was to determine feasibility in terms of the specified goals.

SECTION II

SUMMARY AND RESULTS

The objective of the program was to build and evaluate a breadboard model of an aviator's oxygen regulator using fluidic techniques but with off-the-shelf hardware. Goals set for the regulator were that it have oxygen economy, reliability, ruggedness, and simplicity.

The regulator design provides an air-oxygen mixture using a pulse duration modulator. This modulator follows a function generator driven by a cabin pressure sensor. The output pressure is a closed loop control with a reference pressure that is set by a second function generator driven by the cabin pressure sensor.

Problems with poor performance of off-the-shelf diaphragm valves, which were in the original design, delayed development of the complete circuit. Spool valves were found to be the best off-the-shelf replacement. Major components such as the Pulse Duration Modulator (PDM), the function generators, and the ejector, which are not off-the-shelf, were built and successfully demonstrated.

Briefly, the present status is that the breadboard performs the major functions of the mixture control and the pressure control. Test results of the mixture versus altitude, while not complete, show that no major problems are expected in this circuit. The pressure control loop operates successfully at cabin pressure but has problems during pressure breathing in the form of short duration pressure spikes which would be unacceptable to the user. Preliminary tests with acoustic filters showed sizeable attenuation of the pressure spikes. It is expected that the spikes could be successfully attenuated. Subsystems such as the pressure mode switches, mixture mode switches, and the flow indicator have been designed but not actually implemented in the breadboard. These subsystems are not expected to be problems.

Highlights of the accomplishments and problems are the following:

- A mixture control system was developed which demonstrated that it could follow the design modulation schedule.
- A means for designing a fluidic function generator for pressure and mixture versus cabin altitude was developed, computerized, and verified experimentally.

- An ejector was designed and, when dynamically tested, had an efficiency (mass flow ratio) of 5 to 6 over the whole modulation range compared to an efficiency of 9 demonstrated by steady state tests. The mixture function generator needs to be redesigned to account for the reduced efficiency, and/or the ejector needs to be redesigned to increase its dynamic efficiency.
- A fluidic PDM was miniaturized to a size compatable with the final package volume, and it demonstrated acceptable performance.
- Diaphragm valves, in general, were found to be too slow for use in the system which resulted in overpressurization in the plenum.
- The fluidic amplifier necessary for a speedy comparator amplifier in the breadboarded control loop was the only necessary vent of 0_2 in the regulator. The amount of vented 0_2 was too large for the goal of small waste so an alternative comparator must be used in the future. Waste is a higher priority than elimination of a second source of power; therefore a recommended fluidic solution is to power the pressure control loop with a small amount of compressed air from an external source.
- The pressure control loop controlled the plenum pressure within less than 1 inch H_2O during simulated breathing at cabin pressure. During pressure breathing, short duration pressure spikes (acoustic like) of about 10 inches H_2O were present. Acoustic filters made of orifices and volumes were shown to be a feasible means to reduce the pressure spikes.
- The components in the breadboard show feasibility to fit into the package size for a panel mount (Figure 1).

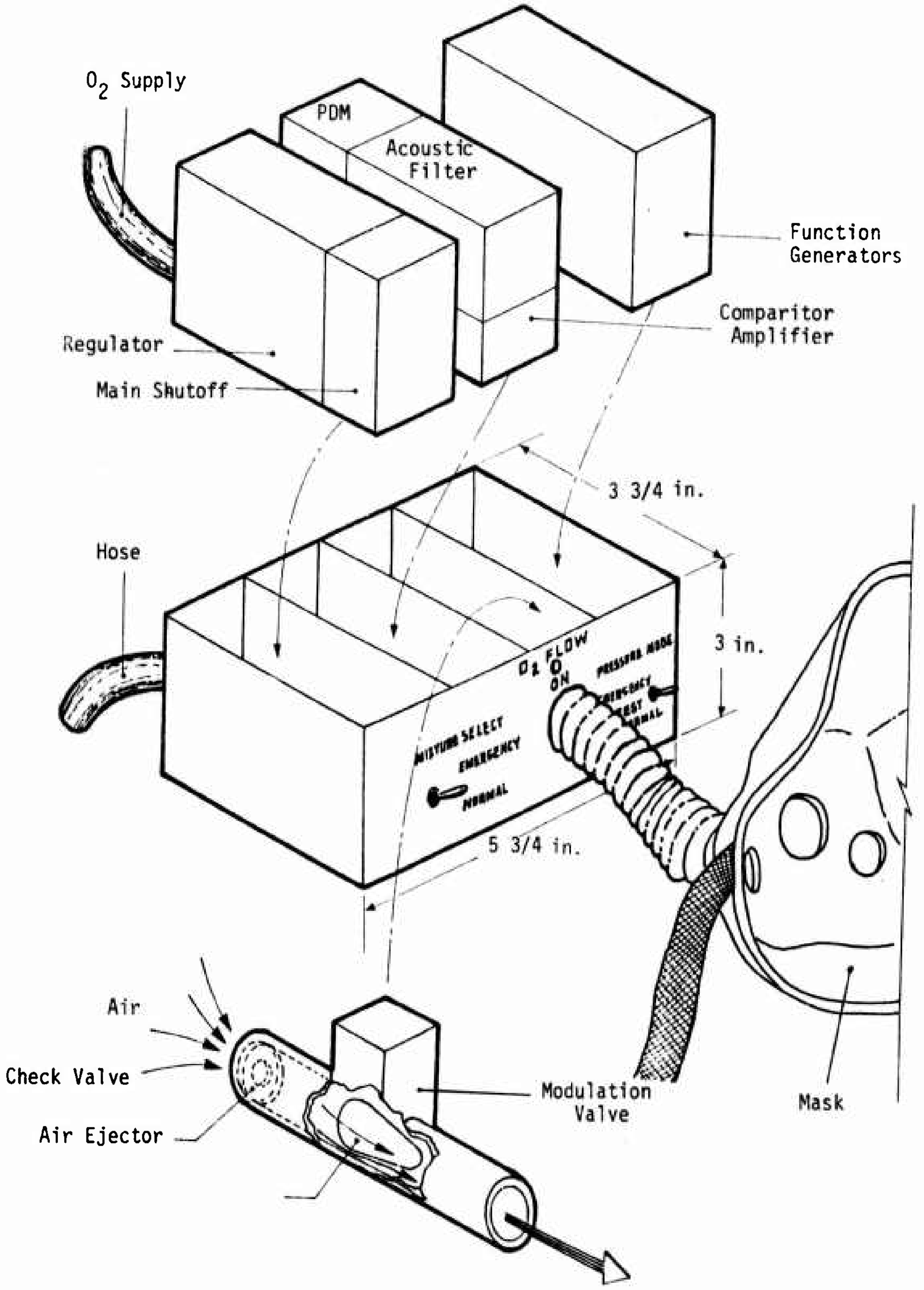


Figure 1. Panel Mount Package for the O_2 Regulator

SECTION III

RECOMMENDATIONS

Briefly, the recommendation is to follow the present work with a Phase II brass board which would include the following major tasks:

1. Reduce existing breadboard performance problems to an acceptable level:
   - Attenuate the plenum pressure spikes with acoustic filters,
   - Eliminate O_2 waste in the plenum pressure control loop by using a mechanical comparator or a fluidic comparator with compressed air supply,
   - Increase ejector efficiency by adding a converging diverging section.

2. Build a brass board model that closely resembles the size of the prototype elements. The major features would be:
   - A small ejector housing,
   - Smaller size function generator needles and chambers,
   - Miniature PDM in a small tank for collecting vented O_2 from PDM and reinsertion into circuit.

3. During simulated breathing, evaluate:
   - Pressure control as a function of simulated pressure altitude,
   - Mixture control as a function of simulated pressure altitude.

4. Develop a bellows mechanism to drive the function generator needles.

SECTION IV

TECHNICAL DISCUSSION

DESIGN GROUND RULES

The ground rules for the regulator require the use of fluidic type devices wherever possible to perform the control functions as outlined in Appendix C. System performance, as described in Appendix C, was to be judged as a set of goals rather than as a set of concrete specifications to be met. Primary construction was a breadboard with secondary considerations of size and weight when future miniaturization seemed reasonable. In order to simplify development testing, compressed air rather than compressed O_2 was used. No significant different performance of fluidic devices was expected because of their similarity. Portions of the circuit were to be developed separately to simplify isolation and correction of the problems prior to operation of the complete system.

Details of the performance such as mixture schedule, mask pressure schedule and permissible O_2 wastage rates are listed in Appendix C which is taken from the work statement.

FUNCTIONAL DESCRIPTION

Functional description of the O_2 regulator is best followed using the block diagram in Figure 2. Fundamentally, there are only two controls. The first is for mixture and the second is for pressure in the pilot's mask; therefore it is convenient to discuss them separately.

Mixture Control

The mixture of air and added O_2 to the plenum follows a designed schedule with cabin pressure. Cabin pressure (altitude) is sensed and mechanically drives a mixture function generator which supplies a fluidic signal to the Pulse Duration Modulator according to altitude. Output of the PDM drives the mixture modulation valve. This valve diverts the O_2 flow either straight to the plenum or to the primary flow of an ejector pump. The ejector pump sucks open the check valve and draws air into the plenum. Mixture in the plenum depends on the percentage of time spent supplying O_2 straight to the plenum. Actually the flow from the ejector is not all cabin air because it includes the O_2 needed to drive the pump. The extra O_2 through the ejector is accounted for in the design of the mixture function generator to provide the desired O_2 enrichment.

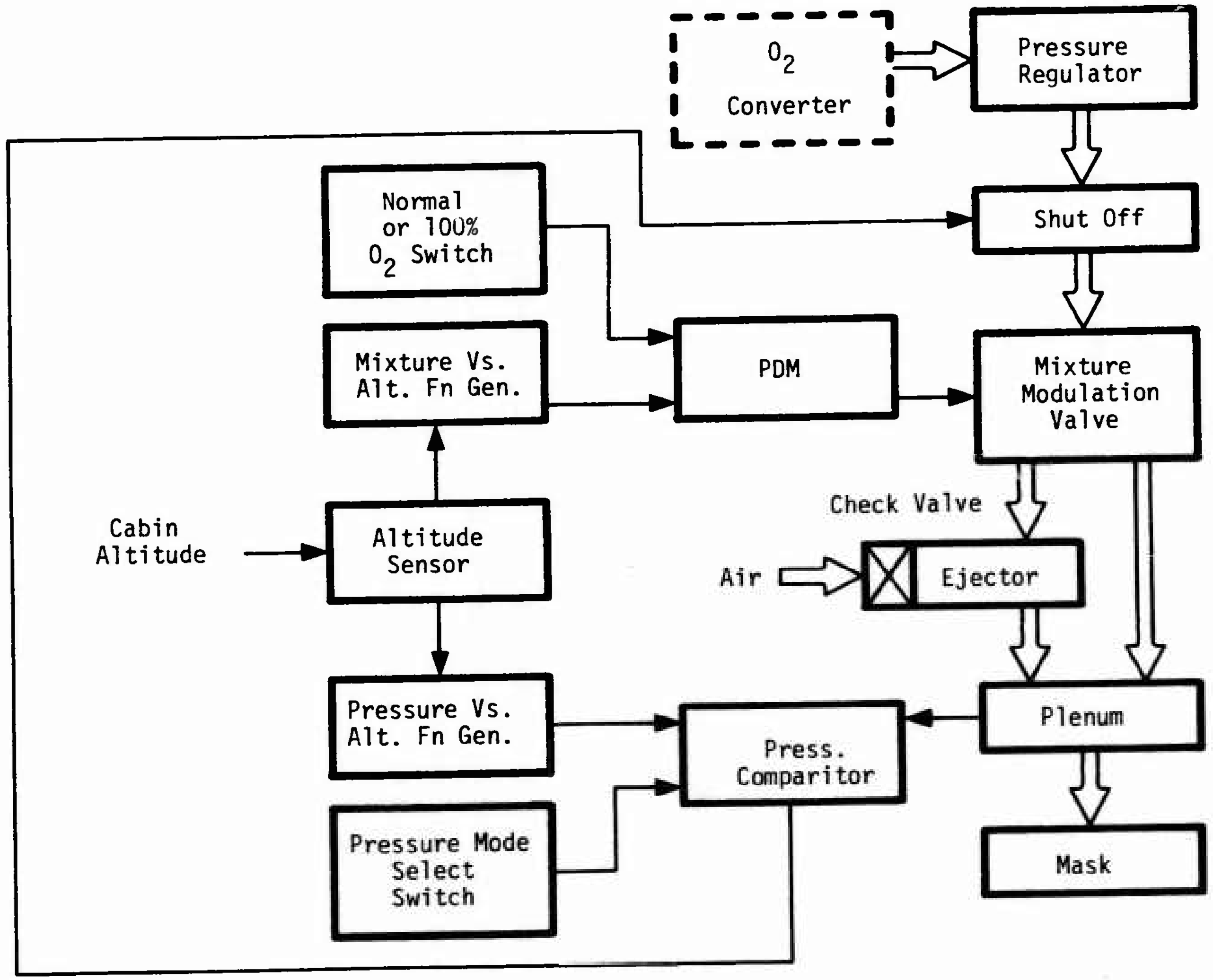


Figure 2. Block Diagram of O_2 Regulator

Pressure Control

The pressure control maintains the desired mask plenum pressure as a function of the cabin pressure (i.e., pressure altitude) in a closed loop. The actual plenum pressure is sensed and compared with the desired pressure from the pressure function generator. Output of the comparator turns the O_2 on or off at the shutoff according to a low or high plenum pressure. Cabin pressure is sensed, and its output positions the mask pressure versus cabin pressure function generator which supplies the desired pressure to the comparator. Supply pressure to the shutoff valve is maintained by a conventional pressure regulator at a gage pressure sufficient to supply the maximum O_2 flow to the mask.

Normally the mask pressure is ambient ($\pm$ 0.5 inch H_2O) and higher pressures are needed for pressure breathing above cabin pressure altitudes of 27,000 feet.

Provision is made to select an emergency pressure breathing mode or a test mode in addition to the normal operation. These signals are initiated by a manual switch which provides a bias to the pressure comparator.

CIRCUIT DEVELOPMENT

The original circuit utilized diaphragm logic type valves for everything except the PDM which was made of fluidic bistable and proportional amplifiers. Diaphragm valves large enough for passing the required maximum O_2 flow of 135 lpm proved to be too slow. Thus spool valves were substituted for the modulation valve in the mixture control and the shutoff valve in the pressure control loop.

Overpressurization of the plenum was a problem so it was decided to supply the mixture modulation valve with a scheduled flow nearer to that demanded by the pilot. A flow control circuit was added to provide this function. The first version of the flow control loop, Figure 3, used a vortex valve to throttle the O_2 supply according to a low pressure sensed in the plenum. This proved inadequate because the vortex valve did not have enough turndown, either singly or in cascade of two and three. A spool valve was substituted for the vortex valve but the circuit performance was still inadequate because of overpressurization.

The overpressurization problem was improved by redesigning the comparator and amplifier in the pressure control loop to speed up its operation. This was done by replacing the two diaphragm logic valves with a single fluidic proportional amplifier which did both the

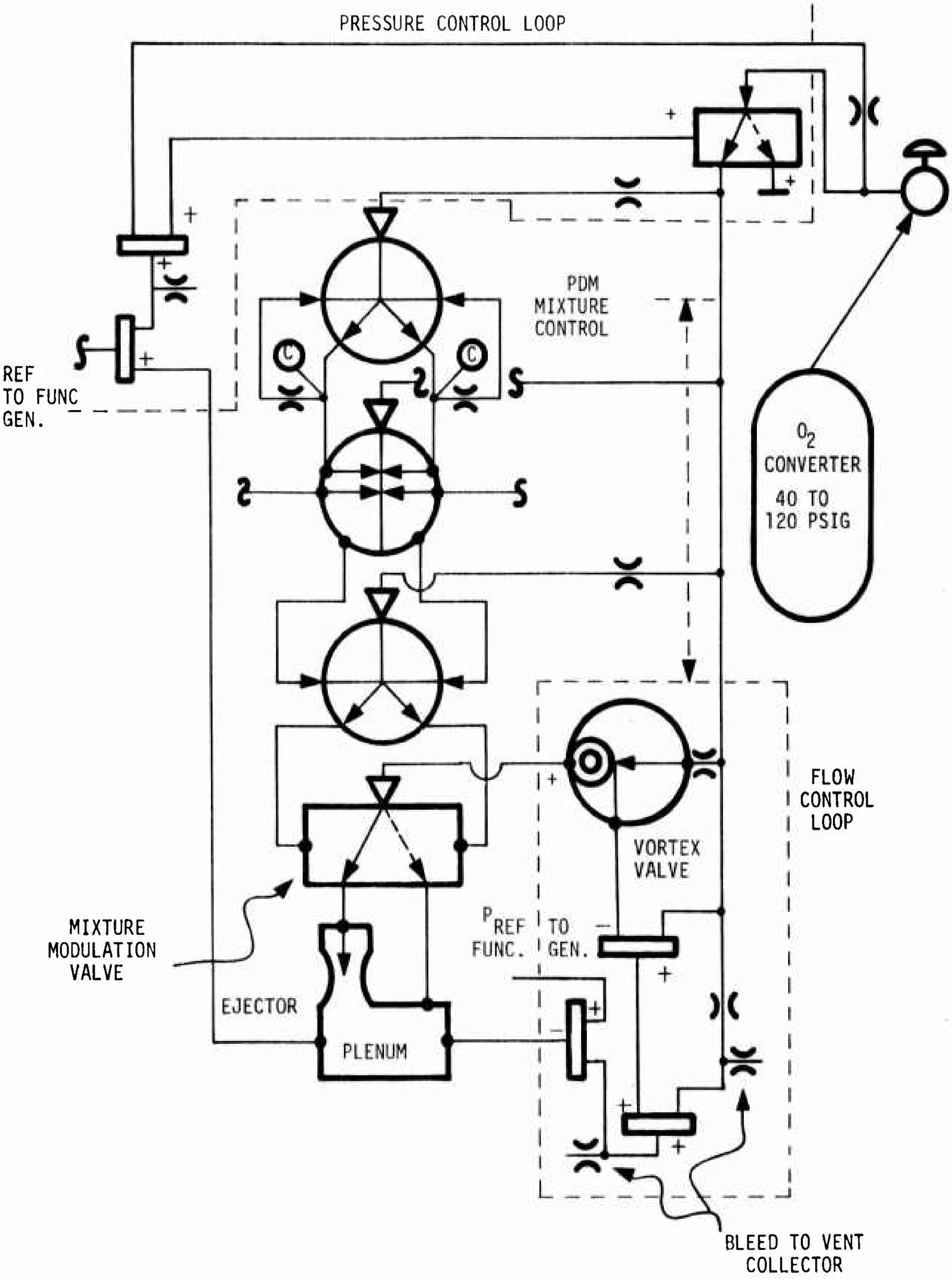


Figure 3. Preliminary Circuit Diagram of the O_2 Regulator

comparison and amplification functions. With this improvement it was possible to get good operation of the pressure control loop for normal breathing pressures even without the flow control loop. Thus, the flow control loop was eliminated. Figure 4 shows the latest version of the circuit.

The remaining problem with the pressure control loop is short duration pressure spikes (acoustic type) in the plenum during pressure breathing caused by the spool valves. Feasibility experiments with acoustic type filters have shown promise for reducing the spike amplitude.

COMPONENT DESCRIPTION AND PERFORMANCE

The breadboard circuit, Figure 4, was developed from the individual design and evaluation of the components. Consequently it is appropriate to discuss the components separately. A photograph of the breadboard is shown in Figure 5.

Mixture Control Loop

Function Generator--The function generator uses an evacuated bellows to sense the cabin pressure and provide movement to a needle valve which controls the control flow to a proportional fluid amplifier. Output of the amplifier is applied to opposing input ports of the summing amplifier in the PDM. The bellows and the fluidic proportional amplifiers are available state-of-the-art devices, but design technique of the needle to meet a specified function was developed especially for this project (see Appendix D). Micrometers were substituted for a bellows movement for the breadboard.

Movement of the needle is continuous with cabin pressure so the problem is to make it effective in the PDM over a certain portion of the range of movement when the mixture must be varied with cabin altitude. In order to design the breadboard needle, it was necessary to assume performance of the bellows, the ejector, modulation of the PDM, performance of the fluid amplifier, and a mixture schedule. By using an annular restrictor formed by a conical needle and conical orifice, it was possible to calculate the geometry that would meet the desired function. A breadboard of the needle was built and tested and the results verified the needle design procedure (Figure 6).

Features of the design are predominantly laminar flow losses for the linear portions of the operating curve and the use of entrance losses in the duct for curved portions of the function. Success of this breadboard function generator gives confidence that other

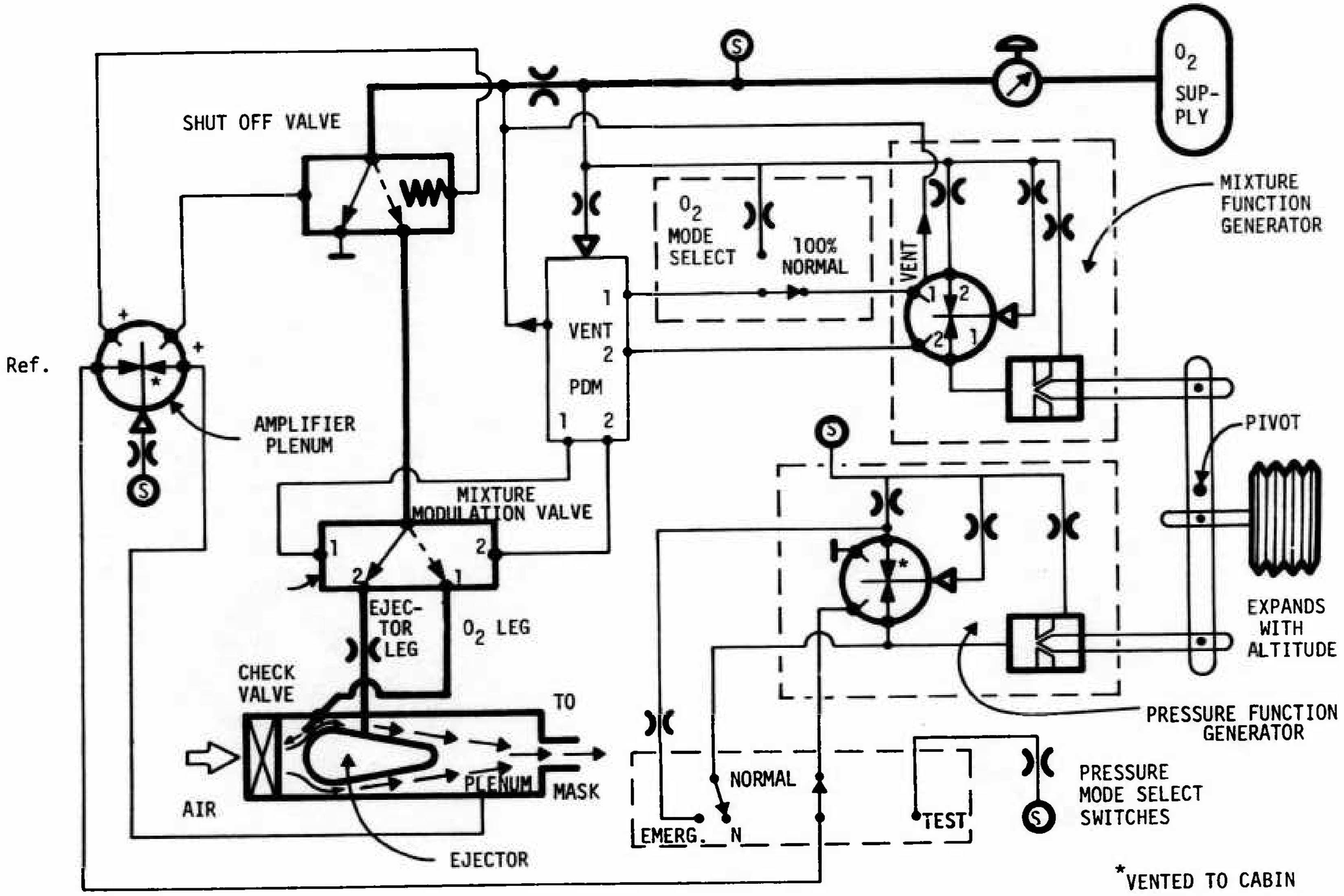


Figure 4. Circuit Diagram of Oxygen Regulator

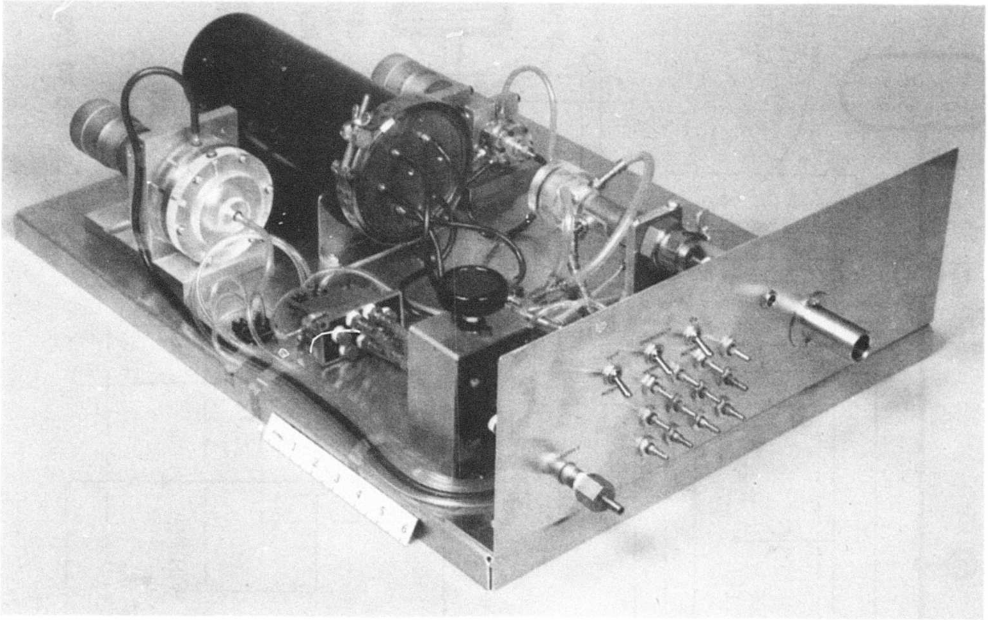


Figure 5a. Breadboard of O_2 Regulator

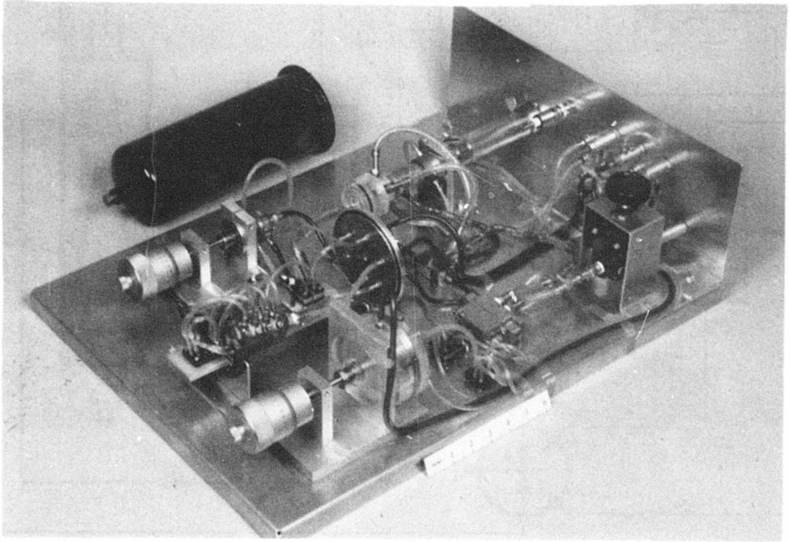


Figure 5b. Breadboard of O_2 Regulator (second view)

functions can be generated as needed when matching the actual performance of all the other components whose characteristics were assumed for this feasibility test. Details of the design are discussed in Appendix A.

The proportional fluidic amplifier which amplifies the output of the needle and feeds the PDM is a GE model MG11 three-stage cascade with a nominal gain of 100. The size is nominally 75 in^3 and effective nozzle size is 0.020" square. Physically it is located with the PDM in a pressure tight container to collect the vent flow. Supply pressure is 10 psi above the tank pressure.

Pulse Duration Modulator -- The PDM mixture controller function is done fluidically with a saw tooth oscillator, a summing amplifier, a bistable amplifier, and a mixture modulator (Figure 7).

The oscillator consists of a bistable amplifier (GE model DF34) with negative feedback. A delay, which sets the frequency at about 10 Hz, is furnished by a capacitance (volume) of approximately 1 in^3.

Output of the oscillator is added to the output of the mixture function generator in the summing amplifier. Provision is made for the mixture mode selector to override the function generator signal by driving the summing amplifier to a 100 percent modulation (i.e., 100 percent O_2) regardless of the oscillator output. Input to the summing amplifier supplies a DC bias to the saw tooth waveform. The summing amplifier used is a GE model MS11 which is approximately 1 in^3 and has an effective nozzle size of 0.020" square.

The bistable amplifier which sequentially follows the summing amplifier is a thresholding device which defines the pulse duration times. Output of the amplifier drives the mixture modulation valve which directs the O_2 flow either to the ejector or directly to the plenum. The bistable amplifier is actually a three-stage cascade consisting of a proportional amplifier (GE model AW32) followed by two flip flops (GE model 34 and a Honeywell AB19-3). The model 34 is approximately 0.25 in^3 and has an effective nozzle size of 0.020" square. The AB19-3 amplifier has an effective nozzle size of 0.010" x 0.020". The modulation valve is a free floating spool valve (Numatrol LM5-0110) which has a flow capacity of $C_v = 0.25$.

The spool valve has a frequency limit of about 50 Hz while the PDM is capable of more than 100 Hz if needed. O_2 modulation is related to the frequency of the PDM and the modulation valve according to

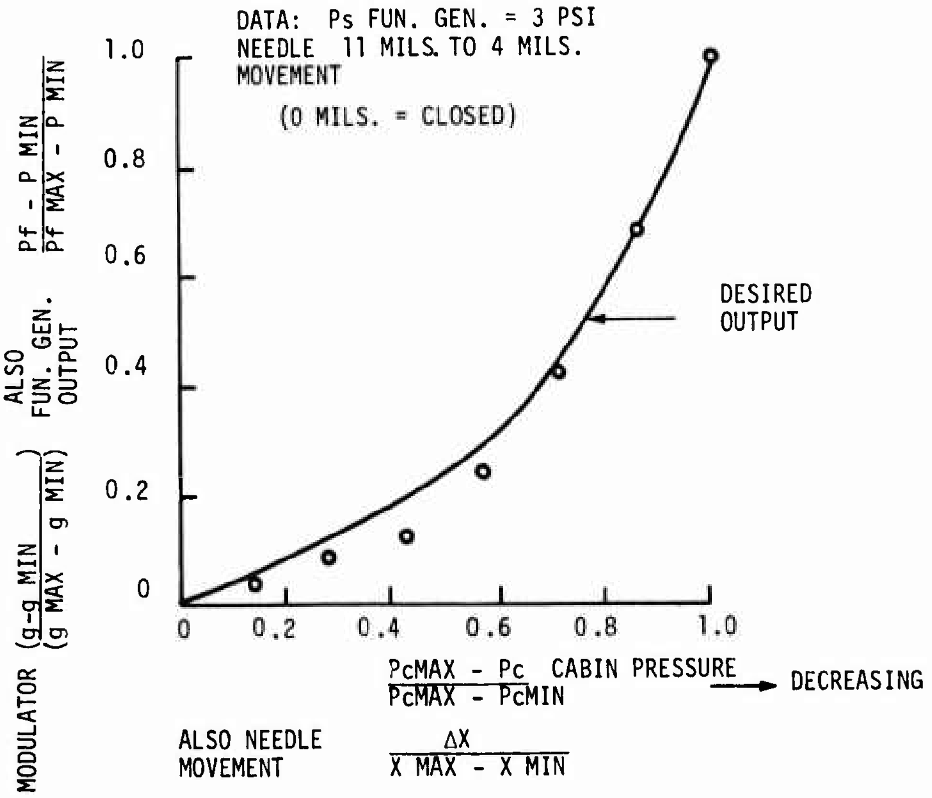


Figure 6. Mixture Function Generator Test Results

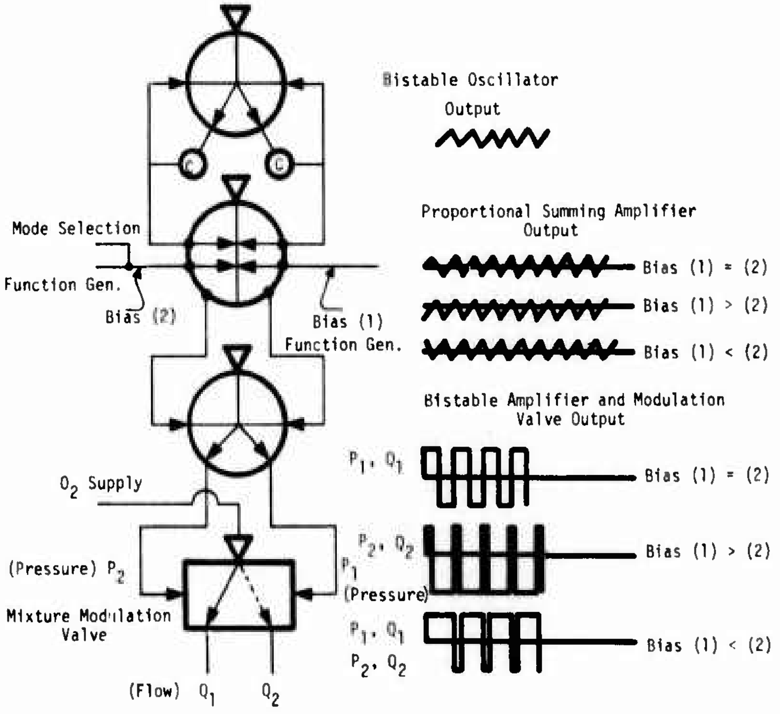


Figure 7. Pulse Duration Modulator Circuit

$$\frac{\text{PDM frequency}}{\text{valve frequency}} = \frac{g}{2}$$

where

$$g = \frac{\text{time delivery to } O_2}{\text{time delivery to } O_2 + \text{time delivery to ejector}}$$

This expresses the trade-off between maximum modulation of the PDM frequency. Thus, if the valve is capable of 50 Hz, the PDM must be operated at about 8 Hz in order to modulate between $g \approx 0.3$ to 0.7.

Clearly the maximum frequency of the spool valve limits the desire to go to higher PDM frequencies for good mixing and still have a reasonable modulation range. There are spool valves that will go to higher frequencies but they are small and will not handle the maximum flow of 135 lpm. Other types of off-the-shelf valves such as diaphragm valves were tried, but they either were too small to handle the maximum flow and/or had frequency response less than 50 Hz. If it is necessary to improve the accuracy of the O_2 and air mixture in the plenum by increasing the PDM frequency, then a faster modulation valve needs to be developed. Accuracy of the mixture is connected to the breathing flow rate and the plenum volume (i.e., enough cycles have to be completed to assure proper mixture before the plenum is emptied).

The PDM amplifiers all need to vent flow to ambient. In order to eliminate waste, the vented flow is collected by locating the whole PDM fluidic circuit in a pressure tight container and reinserting the collected vent flow into the supply to the modulation valve which is located outside the tank. This requires that the supply pressure to the fluid amplifiers and the signal pressures to the summing amplifier be elevated above the tank ambient by the same amount used during room pressure development tests. Input from the mixture function generator is from a fluidic proportional amplifier which also requires a vent. Thus it is also located inside the tank so that its vent flow is not wasted. After initial development sans vent flow collection the circuits were installed in the container and successfully operated at elevated pressures.

When the PDM was included with the mixture function generator and the modulation valve, its performance was satisfactory. The results indicated that modulation was possible from 10 to 90 percent which implies that the PDM frequency was slightly less than 8 Hz and/or that the modulation valve was responding to frequencies above 50 Hz.

Supply pressure to the PDM was 10 psig, where the reference pressure is the tank pressure.

Ejector Design -- The ejector uses a center body to diffuse the driving flow which provides the entrainment of the secondary flow. Primary flow exits through a narrow annular slit at the upstream end of the ejector, attaches to the outer surface of the center body, and turns 90 degrees. It then diffuses and entrains the secondary air flow (Figure 8). The breadboard model was scaled down from a previous model which had an efficiency of 14 where efficiency is the ratio of secondary flow to primary flow. Assuming a similar efficiency, the breadboard model was sized to deliver the 135 lpm at an ejector primary pressure of 2 psi.

Ejector Steady State Performance -- When the scale model was first tested, the efficiency at 2 psi supply pressure was of the order of 10 when discharging to room pressure. When discharging to a back pressure of 0.5 inch H_2O, the efficiency dropped to near zero. Sensitivity to back pressure was reduced by decreasing the internal diameter (ID) of the outer tube to 0.55 inch and increasing the primary flow supply pressure to 20 psi. The trade-off is a reduction of efficiency to 9 at zero back pressure which decreases to 6 at a back pressure of 1 inch H_2O.

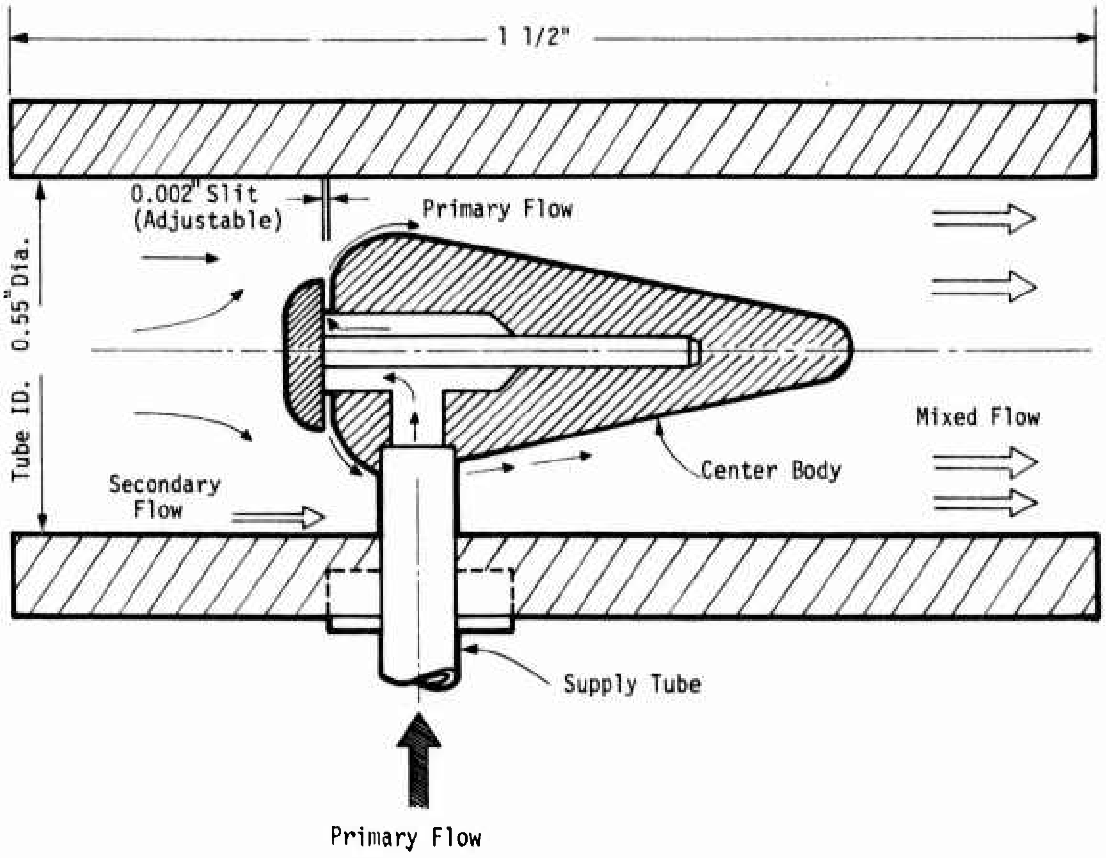


Figure 8. Ejector Pump

During these tests the air intake was open to the room and the ejector did not have to suck open a check valve to allow air to enter. We concluded that the sensitivity to back pressure was because the low velocity of the mixed flow was at the downstream end of the ejector center body. In fact the dynamic pressure was less than the back pressure and some reverse flow was detected. A reasonable solution to this is to provide a converging - diverging duct downstream of the ejector to isolate the mixing from the effects of small changes in the back pressure.

Detailed results of the static tests are listed in Appendix B.

Ejector Dynamic Performance -- The ejector dynamic performance was measured while being modulated with the mixture function generator. Ejector primary flow was measured with a pressure transducer across a calibrated orifice, and the mixture (i.e., air flow + ejector O_2) was measured simultaneously with a laminar flow meter located downstream of the plenum. The results, Figures 9 through 11, show that the ejector efficiency is relatively consistent at 5 over the whole modulation range. During this test the ejector is required to suck open the check valve as well as operate against a slight back pressure. These requirements could account for the decrease in efficiency from 8 under unloaded static conditions to 5 under the loaded dynamic conditions. Our conclusion is that the ejector's dynamic performance is consistent and could be used in the present O_2 system for further evaluation of the rest of the circuit. A further conclusion is that its efficiency could be increased, if needed, to about 10 with further development.

Ejector Check Valve -- A check valve upstream of the ejector is required to shut off the air when the ejector is off and O_2 is being supplied directly to the plenum. It must open with a ΔP of a fraction of an inch of water and must pass 135 lpm with an even smaller pressure drop. Such a valve was built using a design similar to that of a check valve in a skin diver's face mask. A silicone rubber diaphragm (approximately 1 inch diameter) with a center stem was obtained from such a mask. A special mount for the diaphragm was made which also adapts to the shroud of the ejector. Tests showed that a ΔP of about 0.35 inch H_2O was required to open the valve. To insure a quick shutoff and seal of the valve, the O_2 inlet to the plenum was arranged as four jets which impinge on the inner surface of the diaphragm.

Performance of the Mixture Control -- The mixture control was evaluated while holding the plenum pressure at zero gage which is the normal operating condition. Larger plenum pressures (i.e., pressure breathing) are required when 100 percent O_2 is required,

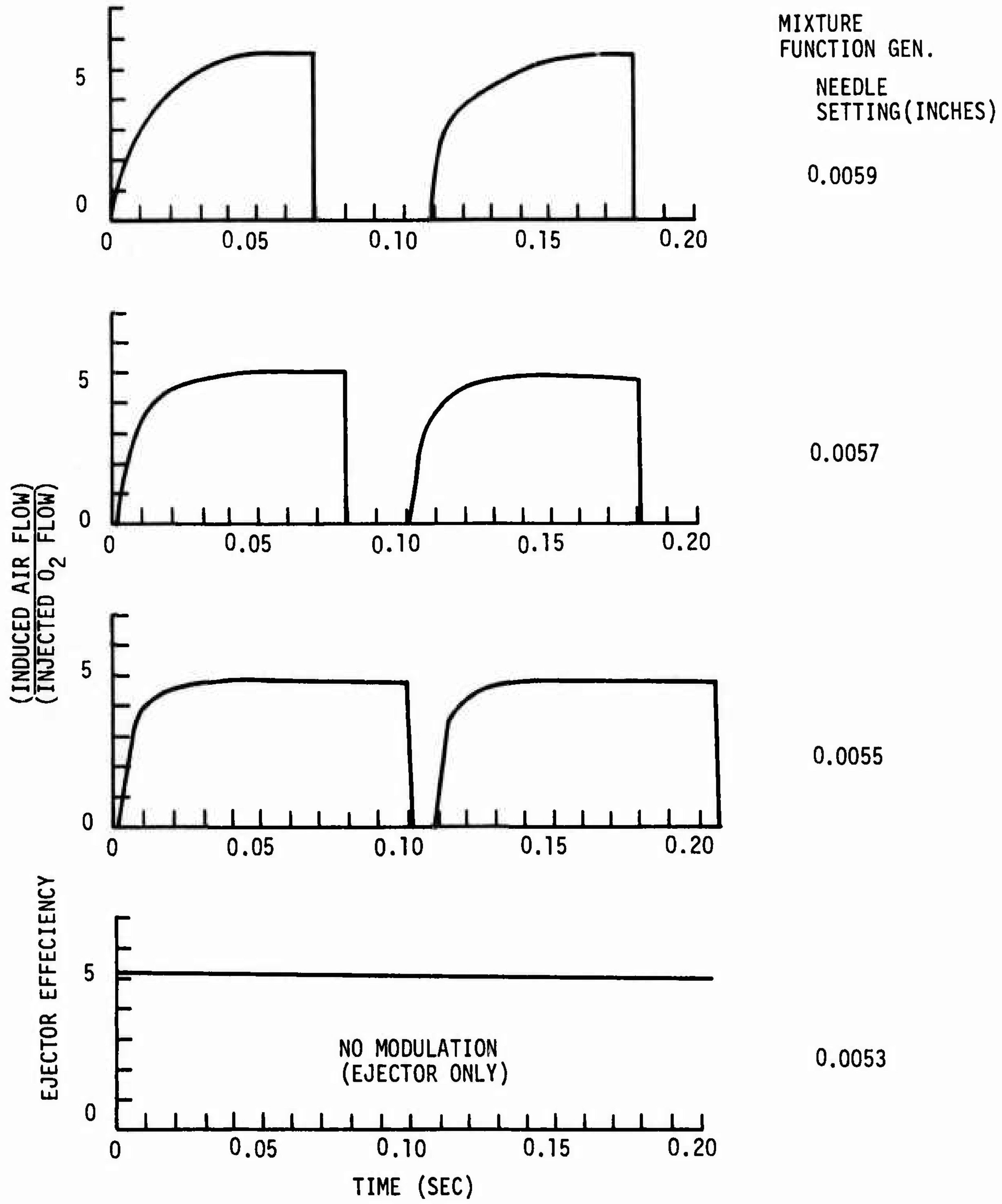


Figure 9. Ejector Dynamic Performance at Low Modulation

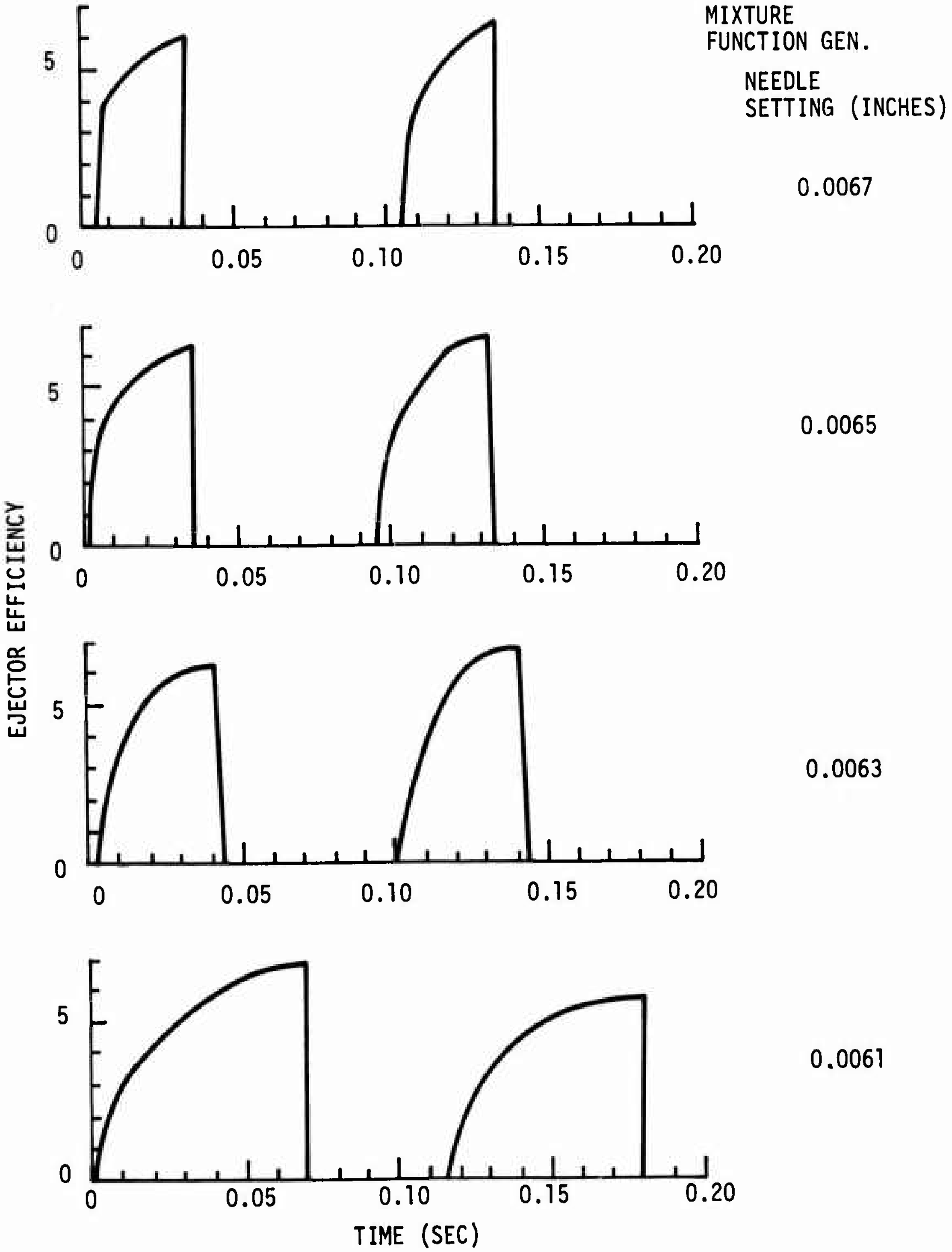


Figure 10. Ejector Dynamic Performance at Medium Modulation

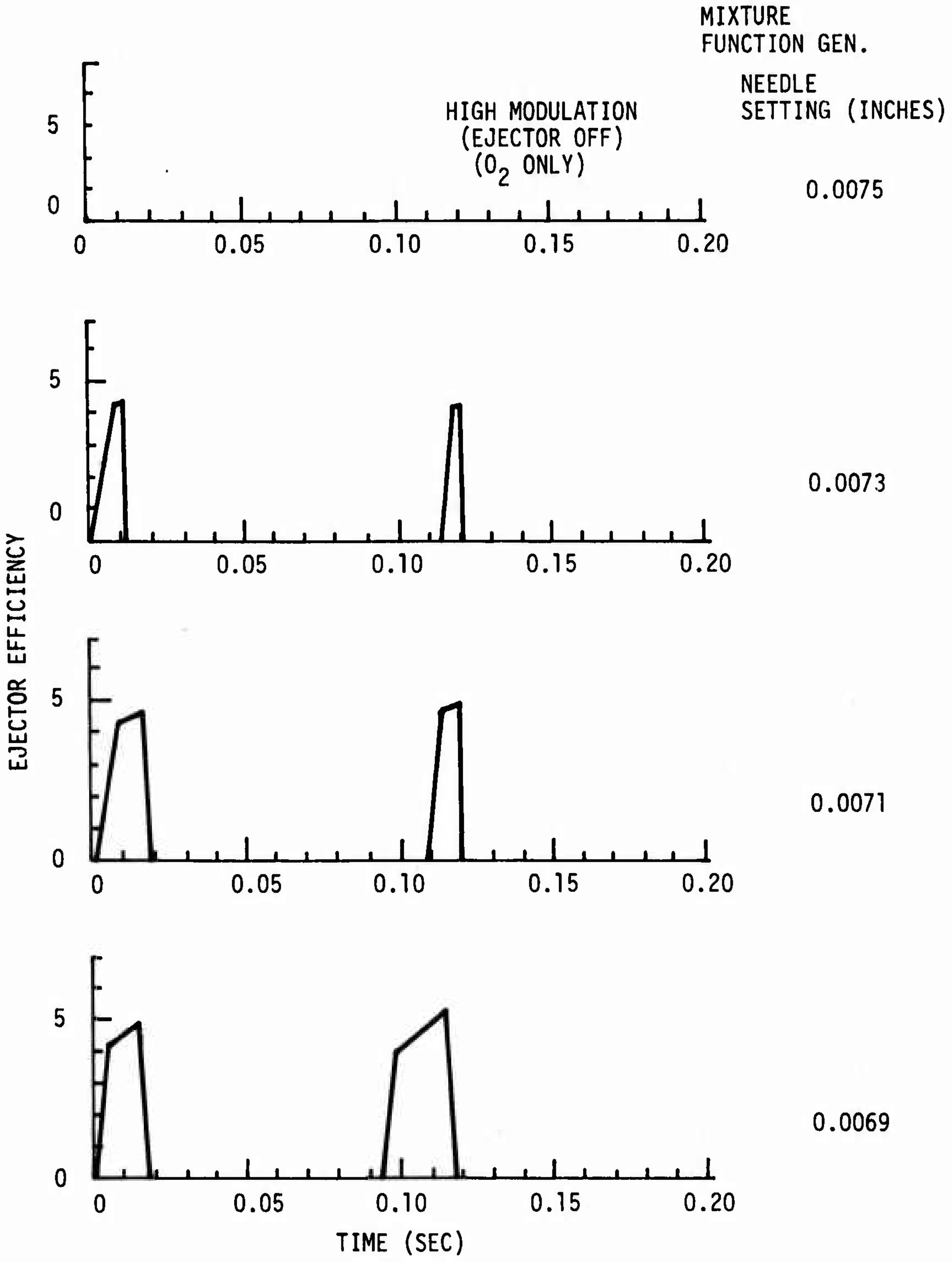


Figure 11. Ejector Dynamic Performance at High Modulation

which means there is no modulation of O_2 and air by the PDM and mixture modulation valve during pressure breathing. The desired output of the function generator for this particular performance evaluation was changed to that shown in Figure 12 because the operating characteristics of the other components in the mixture control are different than used in the original design. Because this version is essentially linear, it was possible, through the use of a different portion of the existing needle travel, to generate the proper function.

Evaluation of the mixture by measuring the O_2 flow and the air flow in the plenum was not completed. However, measurements of the time spent by the mixture modulation valve delivering O_2 directly or driving the ejector were made versus needle movement. The shape of the experimental operation curve, Figure 13, is similar to the desired function, Figure 12. Our conclusion is that the complete mixture modulation control works and is versatile enough to alter the operating function, within limits, with the same needle shape.

Pressure Control Loop

Regulator -- The pressure regulator is a conventional off-the-shelf, diaphragm-operated device, specifically a Fairchild Model 30, which is compatable with the breadboard but too large for eventual prototype use. Its control range is 1 to 60 psi from a supply of 250 psi maximum. Maximum flow of 850 lpm is larger than the required 135 lpm. Thus it is reasonable to expect that the overall size of 2 1/2 inches x 1 3/4 inches x 3 1/2 inches can be reduced later with state-of-the-art redesign to fit within the alloted final regulator package. For example, Fairchild also makes a regulator 7/8 inch diameter by 1.8 inch that has a maximum flow of 70 lpm. While this flow is below the O_2 regulator requirements, it illustrates that miniaturization is feasible.

The diaphragm material for the Model 30 is Buna N and nylon which have reasonable but limited life with O_2. Other diaphragm materials more compatable with pure O_2 were not available for this particular model. Inert materials such as dacron and teflon are available on other regulators so it is reasonable to assume that these materials will also be available for a redesigned regulator for the final package.

Our conclusion is that the breadboard regulator is adequate, but a miniature version must be made for the final package. This redesign is within present state-of-the-art.

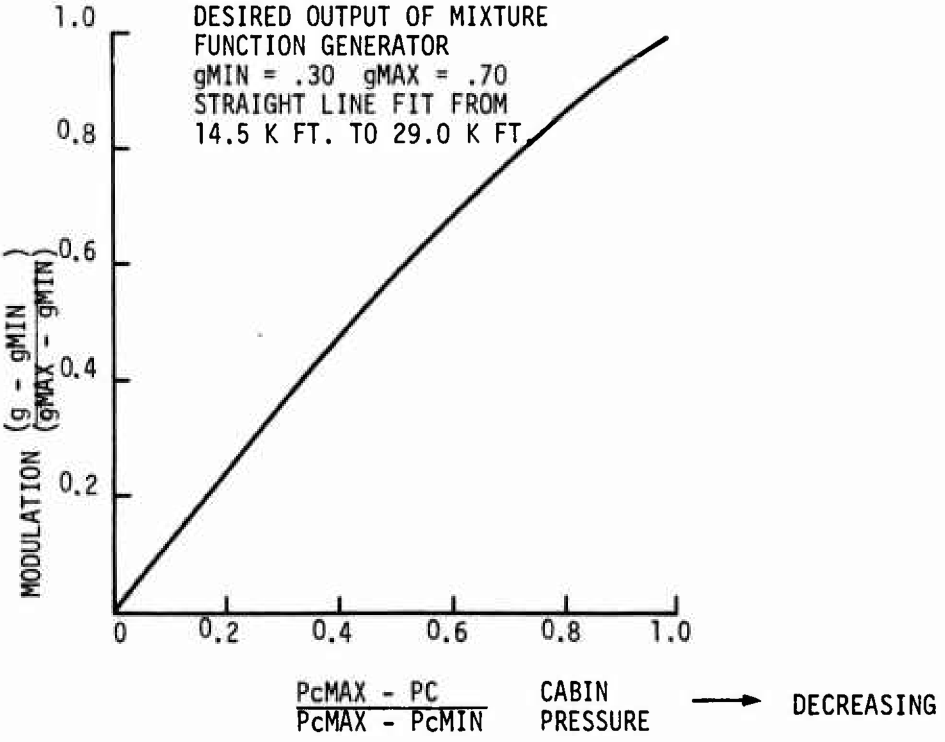


Figure 12. Desired Output of Mixture Function Generator

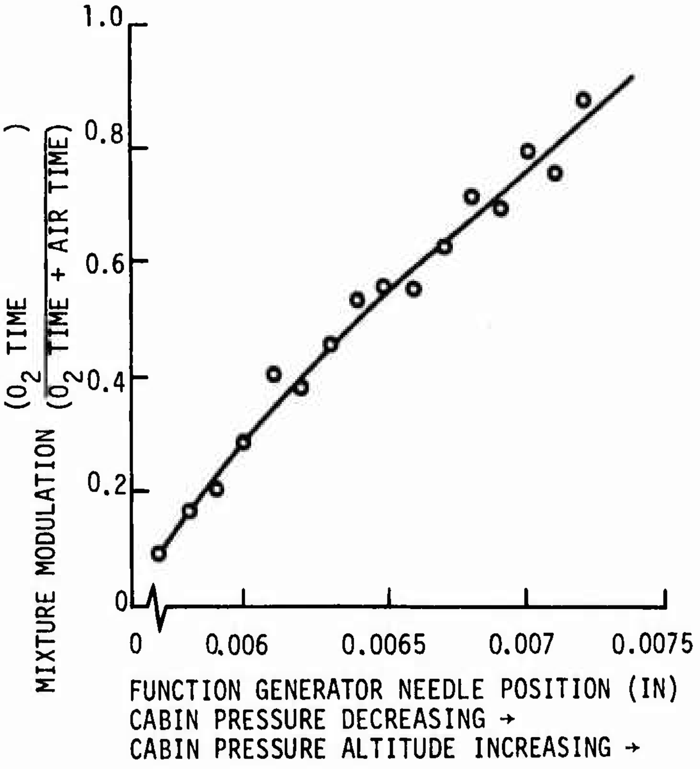


Figure 13. Measured Mixture Modulation versus Function Generator Position

Shutoff Valve -- The shutoff valve in the pressure control loop shuts off the O_2 to the plenum by shutting off the supply to the mixture modulation valve. The shutoff valve also shuts down the mixture function generator and the PDM because the pressure vessel ambient will increase and equal supply pressure. A spool valve was chosen for the shutoff valv because it offered faster operation than diaphragm valves (60 Hz versus 30 Hz), low operating pressures (2 psi), no signal flow (no O_2 waste), and flow capacities compatible with the 135 lpm requirement. The valve used is spring biased to the shut position. It is a Numatrol RA7-0101 modified by using a soft spring to reduce the pilot pressure difference to approximately 1 psi to hold the valve open. It has a flow capacity of $C_v = 0.44$.

A disadvantage of the spool valve is that it acts as a rapid on-off (bang bang) device which creates acoustic type overpressurization pulses to the plenum as it alternately turns on and off the high supply pressure necessary for the maximum flow of 135 lpm. These short duration pressure spikes are best eliminated at the source, which means a shutoff valve capable of proportional operation. Proportional operation is feasible because the output of the comparator, that drives the shutoff valve, is a proportional signal that is an amplified error signal of the plenum and the pressure function generator. Experimentation with and without springs of various stiffness and pilot pressure levels were made to get proportional type operation from the spool valve. Results were that limited proportional operation was possible by carefully adjusting the pilot pressure Δ P. This is done by adjusting the supply pressure to the comparator amplifier. The proportional action did reduce the plenum pressure spikes. However, the reduction was only when pressure breathing was not called for and hence was unsatisfactory for overall operation. Our conclusion is that the spool type shutoff valve does operate in the system but an improved version should be developed for the future.

Suggested developments to the spool type valve would include:

- Modification of the lands by chamfering the square edges so that the valve area versus time is altered during closing. This modification is intended to reduce the pressure spikes.
- Reduction of the mass of the shuttle to increase its operating frequency.
- Preventing bounce of the shuttle, in order to reduce pressure spikes whe it opens or shuts, by providing either a mechanical and/or fluidic detent action to act as a latch.

Function Generator -- The heart of the plenum pressure versus pressure altitude function generator is a conical plug closing a conical hole (similar to a needle valve) as the cabin pressure altitude increases. As the cabin pressure decreases, a bellows expands and mechanically closes the opening. Output of the needle function generator reduces the control flow to a biased proportional amplifier whose output is fed to the comparator amplifier.

The purpose of the function generator amplifier originally was to both amplify the pressure level and change the sign of the pressure output (i.e., increase the output reference pressure as the needle closes). In the present circuit design, the function generator amplifier does not amplify but just changes the sign. This amplifier is a potential waste of O_2 in its present location because it vents to the cabin.

The amplifier cannot be located in the pressure chamber with the PDM because, unlike the PDM, the pressure function generator must run continuously. Elimination of the wasted O_2 (i.e., elimination of the proportional amplifier) requires a redesign of the function generator so that the output can be fed directly to the comparator. This could be done with a needle shaped so that, when the bellows expands, the output pressure of the needle will increase. This redesign is possible but could not be done within the scope of the present project.

The design of the function generator was aided with a computer program for the math model that was developed for matching the pressure flow characteristics of the needle valve with the required schedule, labeled "Design Curve" in Figures 14 and 15. Key dimensions of the needle are shown in Figure 16. Test data of the needle operation verify the predicted performance (Figure 15).

We concluded that the pressure versus altitude function generator design technique works. The proportional fluid amplifier wastes O_2. Elimination of this amplifier is possible by redesigning the needle and then feeding the needle output directly to the comparator.

Comparator-- The comparator must sense the difference between the plenum pressure and the reference pressure within something less than 0.1 inch H_2O and provide an output of at least $\Delta P = 1$ psi to the two pilot ports of the spool shutoff valve. Thus, amplification is required in addition to the performance of a comparison. A circuit of diaphragm valves could perform the comparison but off-the-shelf diaphragm valves could not provide either sufficient amplification or fast enough action. Thus a fluidic proportional amplifier cascade was chosen.

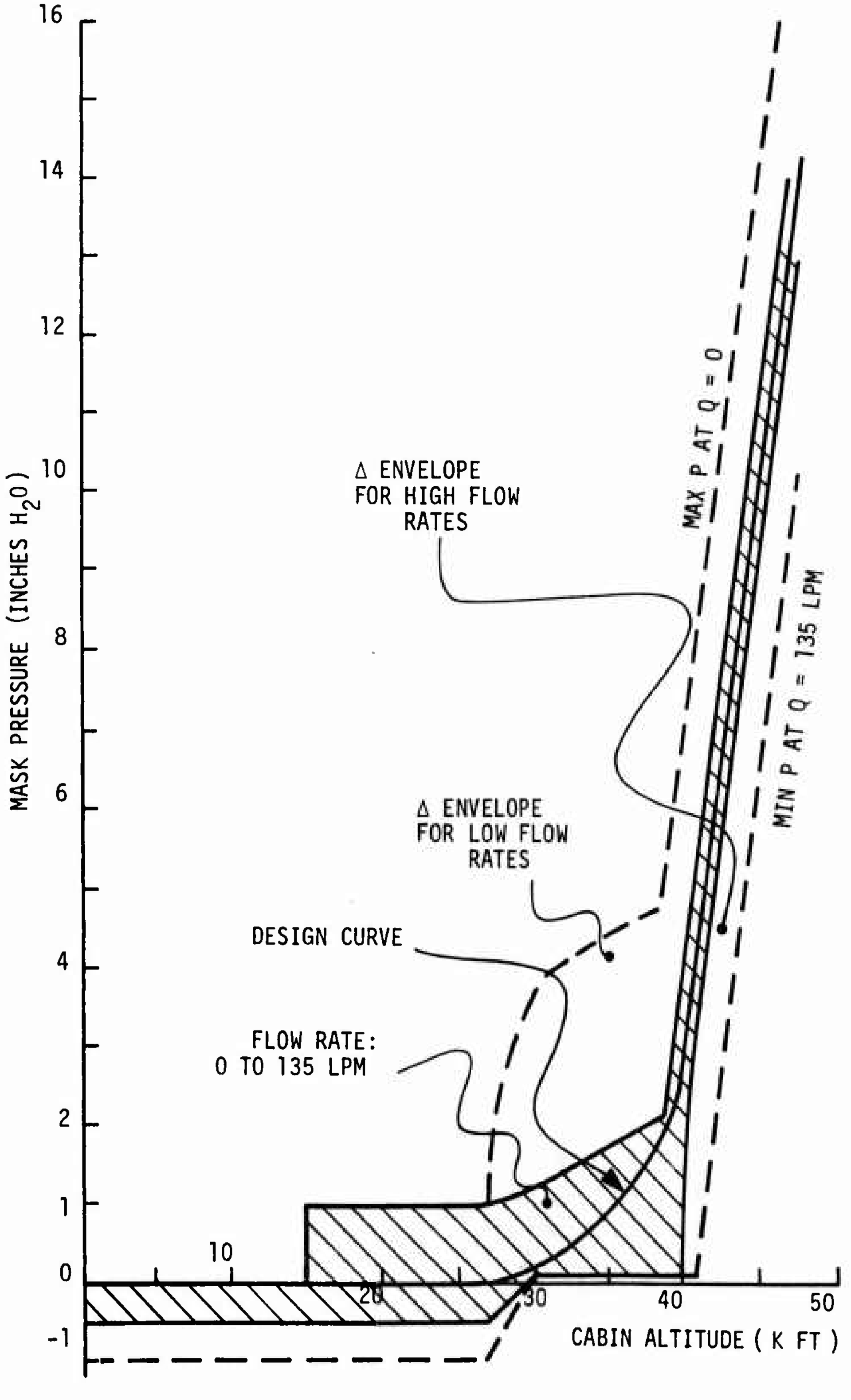


Figure 14. Mask Pressure versus Cabin Altitude Schedule

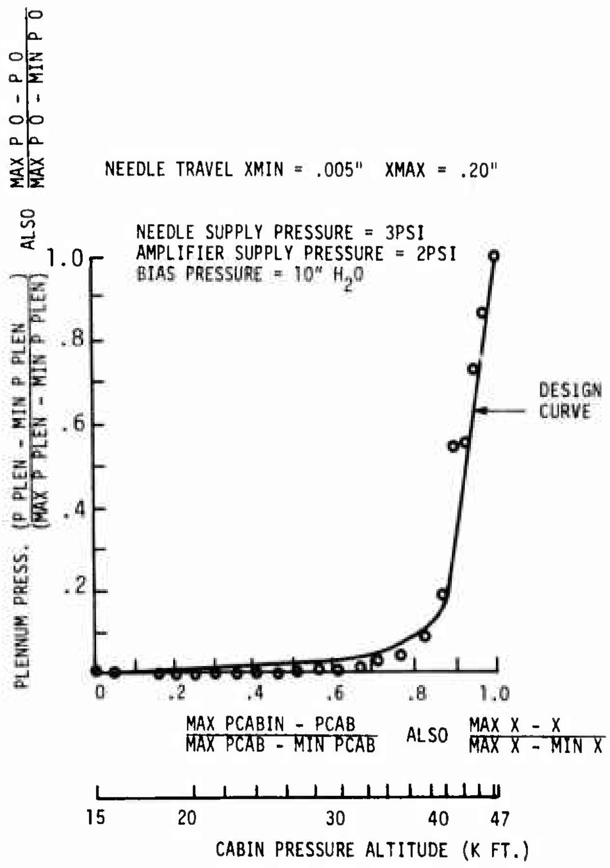
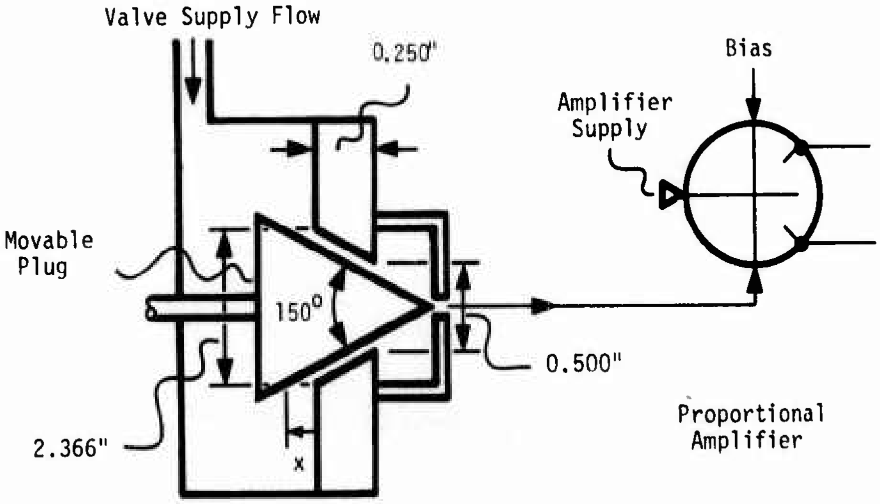


Figure 15. Output of Plenum Pressure Function Generator



x varies linearly with cabin pressure altitude

Bellows movement simulated by a micrometer

x decreases with altitude.

Figure 16. Schematic of Pressure Function Generator

The fluidic amplifier will amplify pressure differences by a factor of 300, is easily sensitive to input ΔP of 0.1 inch H_2O, and has a frequency response in excess of 100 Hz. These advantages have allowed the development of the breadboard O_2 regulator pressure control loop when diaphragm valves were not adequate. However, a disadvantage to be considered is venting the amplifier to the ambient. In the case of the comparator, it must vent to a pressure level similar to that of the plenum for proper operation. Further, the comparator must operate continuously. These two factors make it very difficult to inject collected vent flow back into the plenum.

The amount of vented O_2 is equal to the supply flow plus the control flow. Total flow was measured as follows:

Supply Pressure	Control Pressure	Total Flow
5 psi	0.5 psi	6.4 lpm
10 psi	1.0 psi	9.9 lpm

This means that something between 6 to 10 lpm would be vented to the cabin through the comparator amplifier used in the breadboard, which is a GE model MG11. It is reasonable to expect that the channels could be made half as large in a miniature version of the amplifier. This would reduce the total flow by a factor of 4 or a vented flow of something between 1.5 and 2.5 lpm which is still large compared to the goal of about one one-hundredth of this.

Thus, the fluidic amplifier performs satisfactorily in the pressure control loop as a comparator and amplifier but is subject to O_2 waste of the order of 2 lpm. If this is unacceptable, other devices must be developed to perform this function.

A possible candidate is a mechanical linkage from the present function generator to a diaphragm comparator whose output controls a pneumatic valve which opens and closes the spool valve. The pressure level in the lines leading to the spool valve would be above the plenum so that the required intermittent venting could be fed to the plenum and would not be wasted.

A fluidic solution to the O_2 venting problem is to use compressed air to drive the fluidic comparator amplifier. At this point there are two alternatives for connecting the plenum to the comparator.

The first alternative is to connect the plenum to one control port of the fluid amplifier which is a flow of about 0.01 to 0.02 lpm of the plenum mixture. Wasted O_2 would be equal to or less than this depending on the enrichment. This is within the specified goals for O_2 leakage.

The second alternative is to use a diaphragm valve as a comparator which would eliminate O_2 waste completely (Figure 17). This assumes that the diaphragm valve was fast enough which is a reasonable assumption since the valve is not required to also provide amplification.

Mode Select Switches -- The pressure mode select switches are three conventional on-off toggle valves. Position of the valves is shown in the "normal" position in the circuit diagram.

For "emergency" pressure, the emergency valve is turned on which short-circuits the output of the needle to the opposite side of the function generator amplifier. This gives the comparator amplifier a larger reference pressure from the function generator which then results in increased plenum pressure.

The "test" condition is established by shutting off the normal switch and turning on the test switch.

Pressure Control Loop Performance -- Tests show that the pressure control loop regulates the pressure in the 250 cc plenum within a fraction of an inch of H_2O with short duration pressure spikes of approximately 1.5 inch H_2O when the reference pressure is zero (i.e., pressure breathing is not required). This is illustrated in Figure 18 where the pressure control loop is maintaining the plenum pressure at zero reference during simulated breathing of 100 percent O_2 (i.e., modulation valve is not oscillating). The main shutoff valve is shutting on and off in order to maintain this plenum pressure. If the shutoff valve remained open, the plenum pressure would quickly rise because the supply pressure is large enough to maintain a steady flow of 135 lpm while the pilot is using only 30 lpm rms at 16 breaths per minute. The pressure spikes were shown to correspond to the movement of the spool in the shutoff valve.

Adding 50 percent modulation while controlling the plenum pressure to zero reference caused short duration pressure spikes of approximately 15 inches H_2O in the plenum (Figure 19). Frequency of these spikes corresponds with PDM frequency so it is reasonable

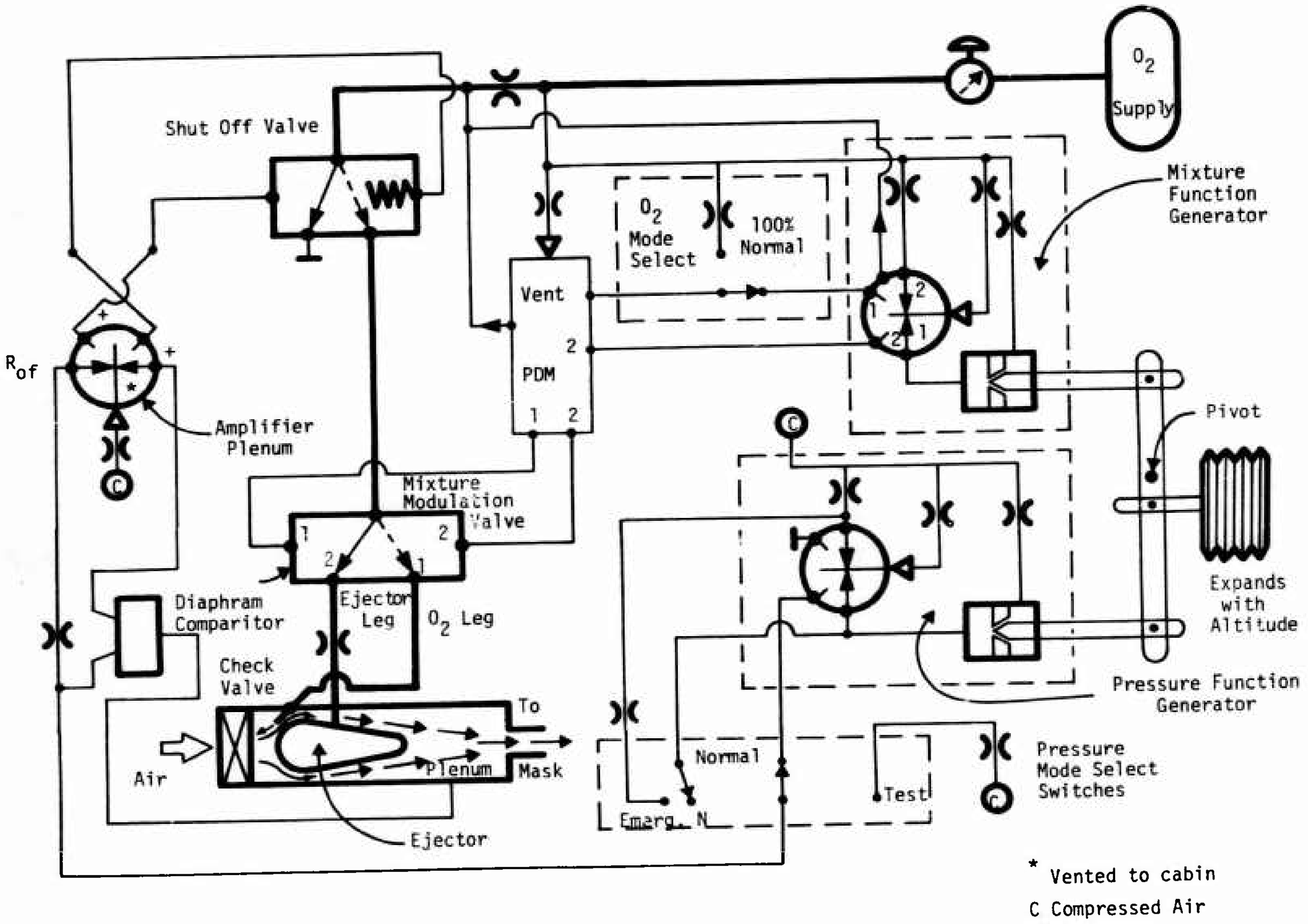


Figure 17. Circuit Diagram of Oxygen Regulator with Proposed Modification for Elimination of O_2 Venting

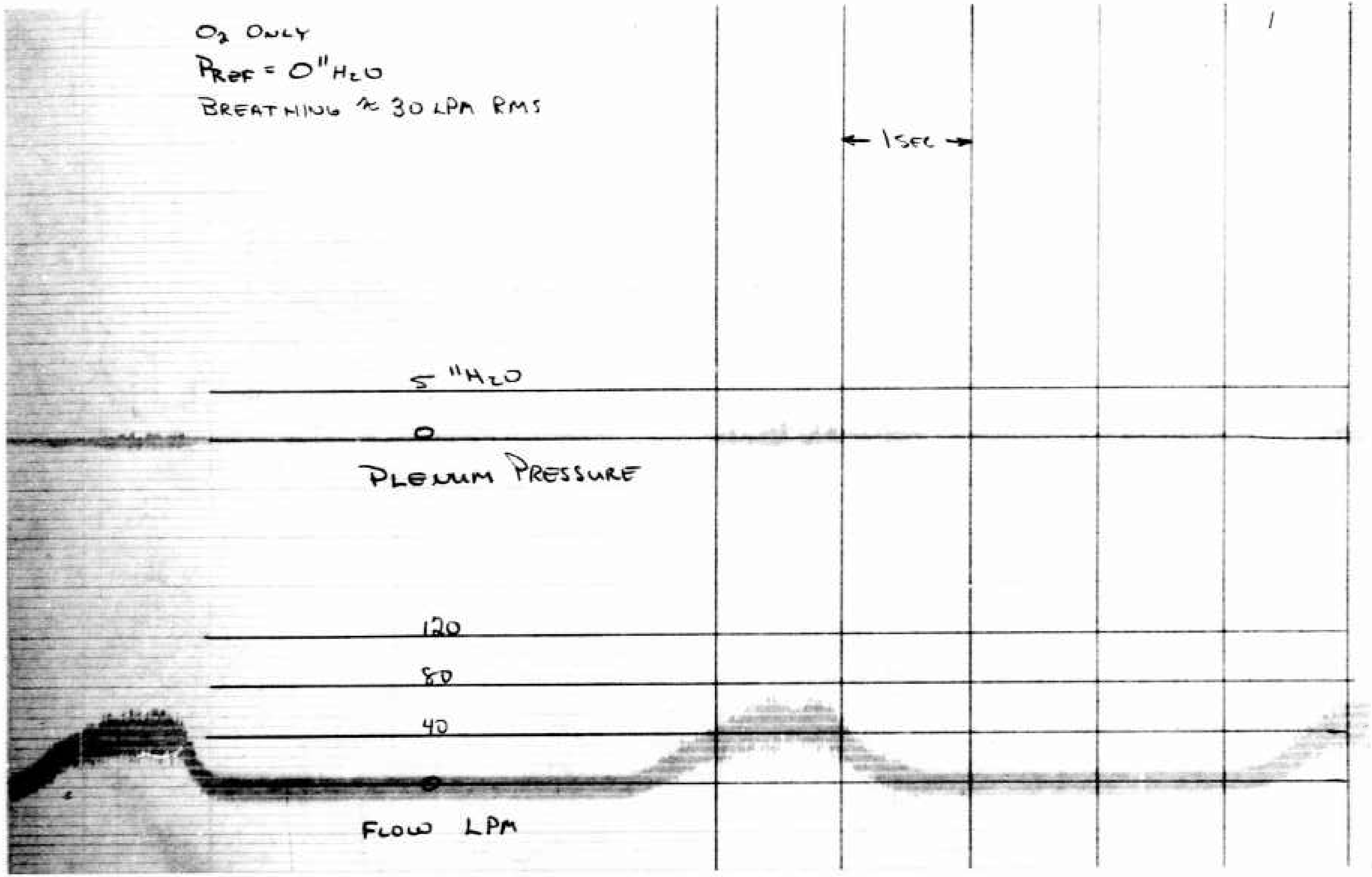


Figure 18. Plenum Pressure during Simulated Breathing with No Modulation

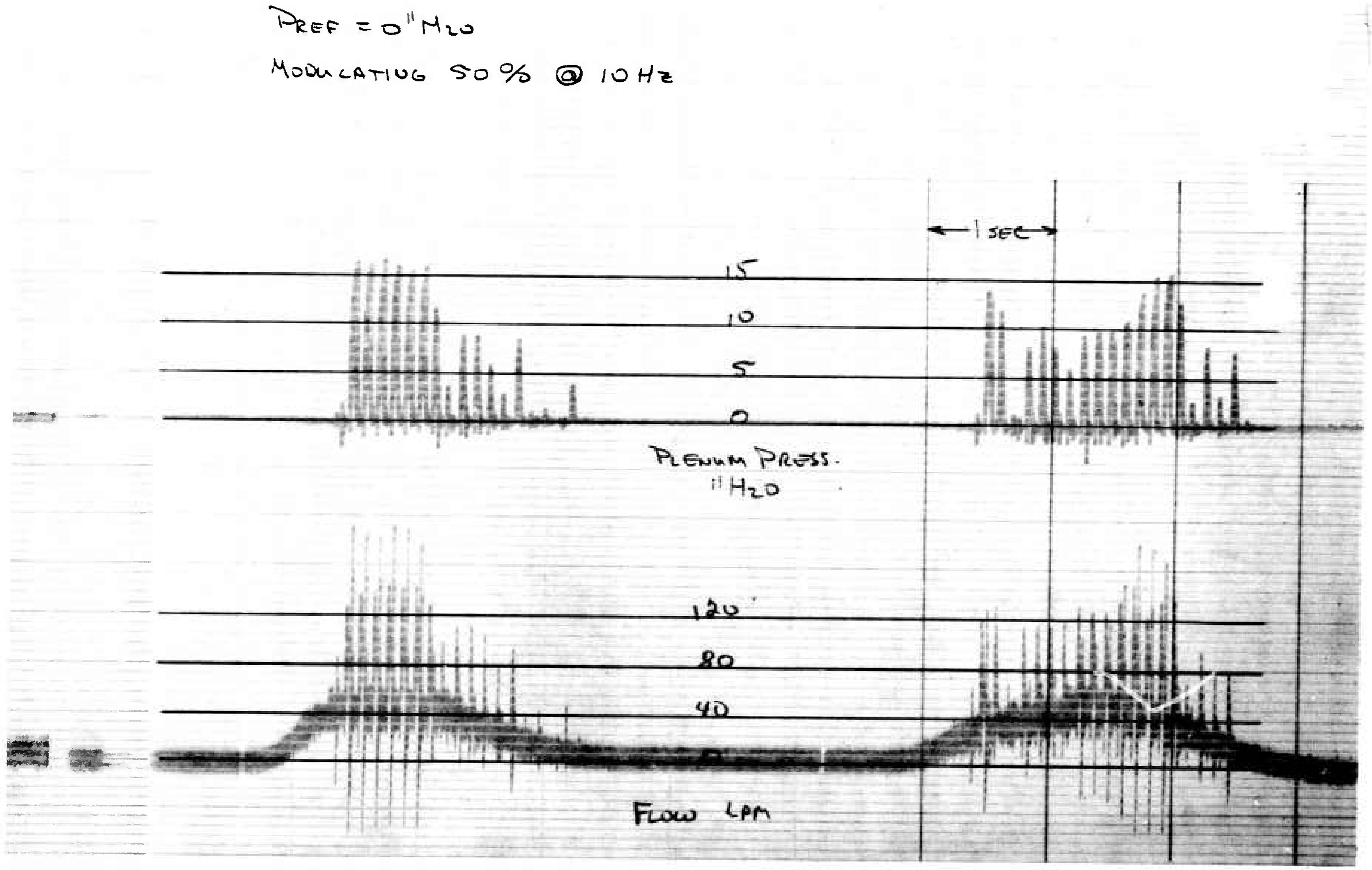


Figure 19. Plenum Pressure during Simulated Breathing with Modulation

to conclude that the spikes are from the modulation valve. Note that the similar pressure spikes are seen in the flow meter trace which is the output of a pressure transducer across laminar flow meter. It is unlikely that the flow is following such a drastic change at such a high frequency. Therefore it is safe to conclude that the pressure spikes are acoustic and are originating from the switching of the modulation valve.

Operation of the pressure control loop during simulated pressure breathing at 30 lpm rms at 16 breaths/minute of 100 percent O_2 was tested at reference pressures of 5 inches H_2O, 10 inches H_2O, and 15 inches H_2O. The results (Figures 20, 21, and 22) show short duration pressure spikes corresponding to the movement of the spool in the shutoff valve. Amplitude of those spikes is about 20 inches H_2O. Again the spikes also appear in the flow meter pressure transducer, indicating that they are acoustic in nature. Presence of the pressure spikes hide details, but it is possible to see in the figures that during inhalation (when the flow goes from 0 to 42 lpm and back to zero) the plenum pressure is being controlled to the reference pressures of 5, 10, and 15 inches H_2O, respectively. However, during the exhalation (when there is no flow in the plenum), the plenum pressure is rising to something like 5 to 10 inches H_2O above the reference pressure.

Subsequent to these data, feasibility experiments were made to reduce the pressure spikes by installing acoustic fillers in the line between the shutoff valve and the modulation valve. Using available volumes, the spike amplitude was reduced to 12 inches H_2O using a 12 cubic inch capacitor as a branch type filter, and a further reduction to 8 inches H_2O amplitude was achieved with a 3 cubic inch in-line filter. Feasibility was shown, and presumably further reduction of the pressure spikes is possible with proper design.

The best solution to the pressure spike problem is to eliminate it at the source which was found to be the spool valve which turns the 135 lpm O_2 flow on and off. Proportional action (i.e., throttling of the flow) with demand rather than bang-bang action would eliminate the pulses. Proportional valves that operate from fluidic type inputs are not available. Alternatives such as modification to a spool type valve which can reduce pressure spikes should be considered. This particular alternative was discussed in the section on the shutoff valve.

PDM MINIATURE PACKAGE DEVELOPMENT

The goal of this task was to demonstrate the feasibility of making a low volume, high density package of the fluidic components of the breadboard counter parts for an advanced

O2 ONLY
BREATHING ≈ 30LPM RMS
PREF = 5 "H2O

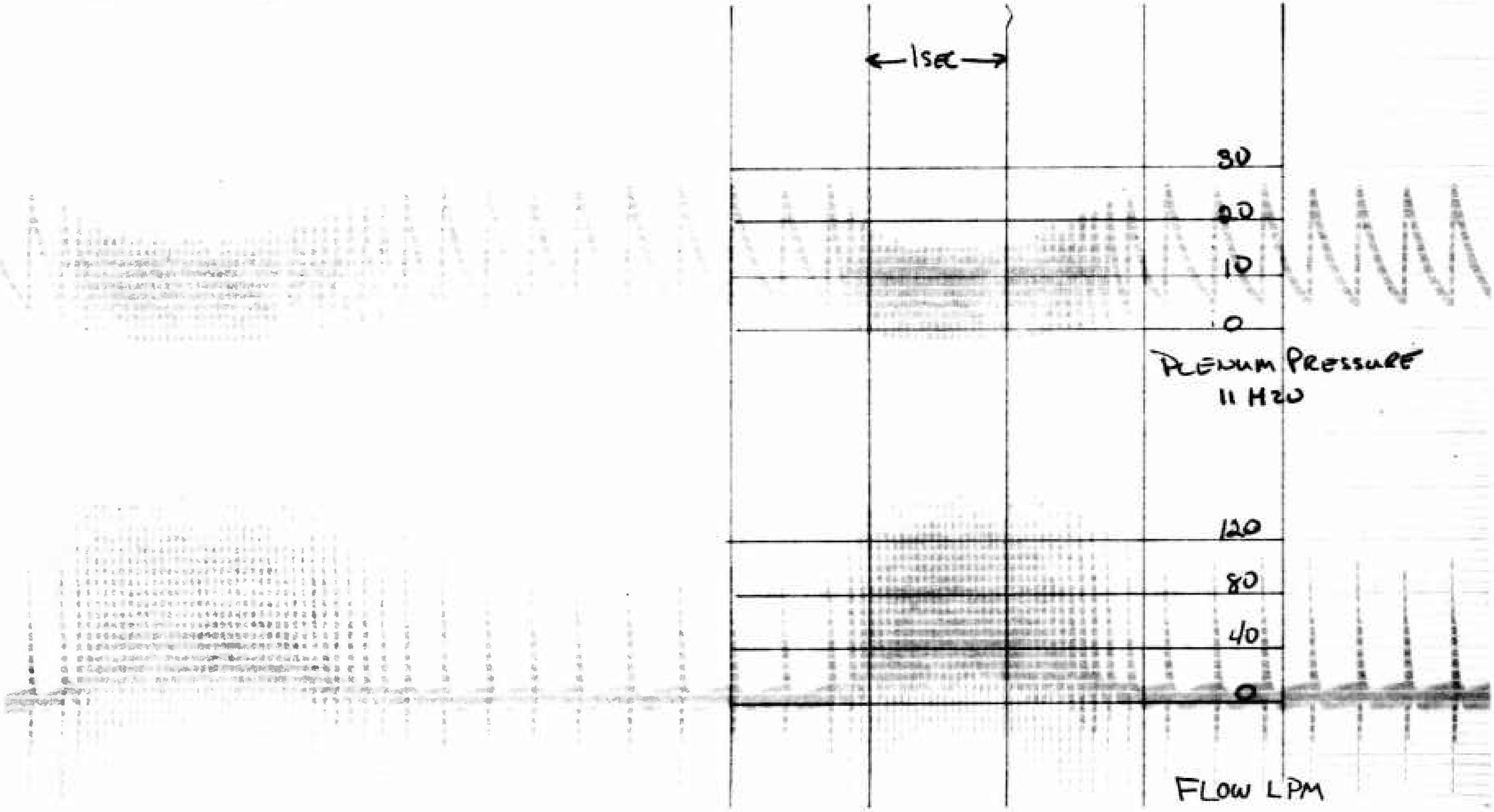


Figure 20. Plenum Pressure during Simulated Pressure Breathing 5 Inches H_2O

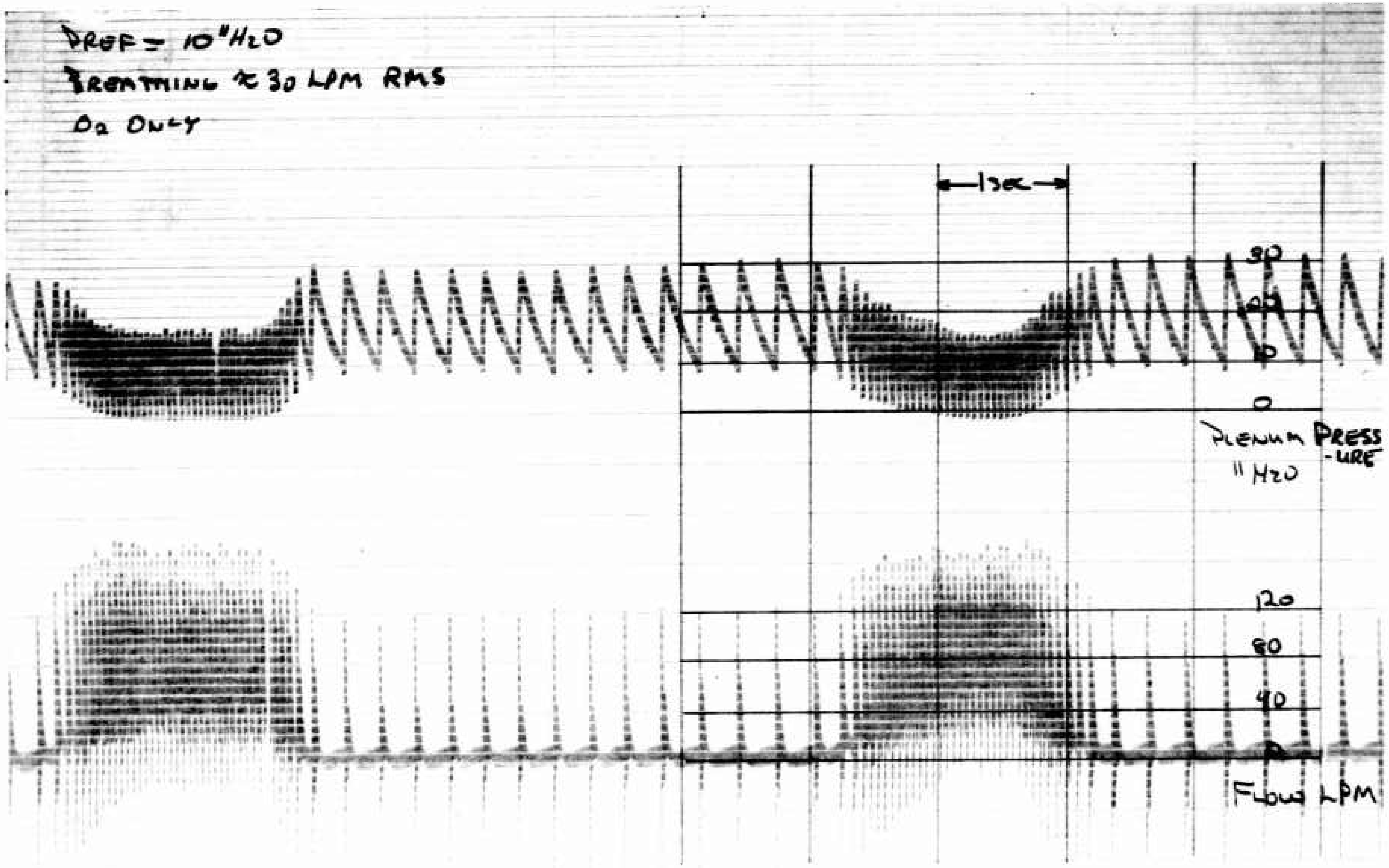


Figure 21. Plenum Pressure during Simulated Pressure Breathing 10 Inches H_2O

O_2 ONLY
PREF = 15" H_2O
BREATHING ≈ 30 LPM RMS

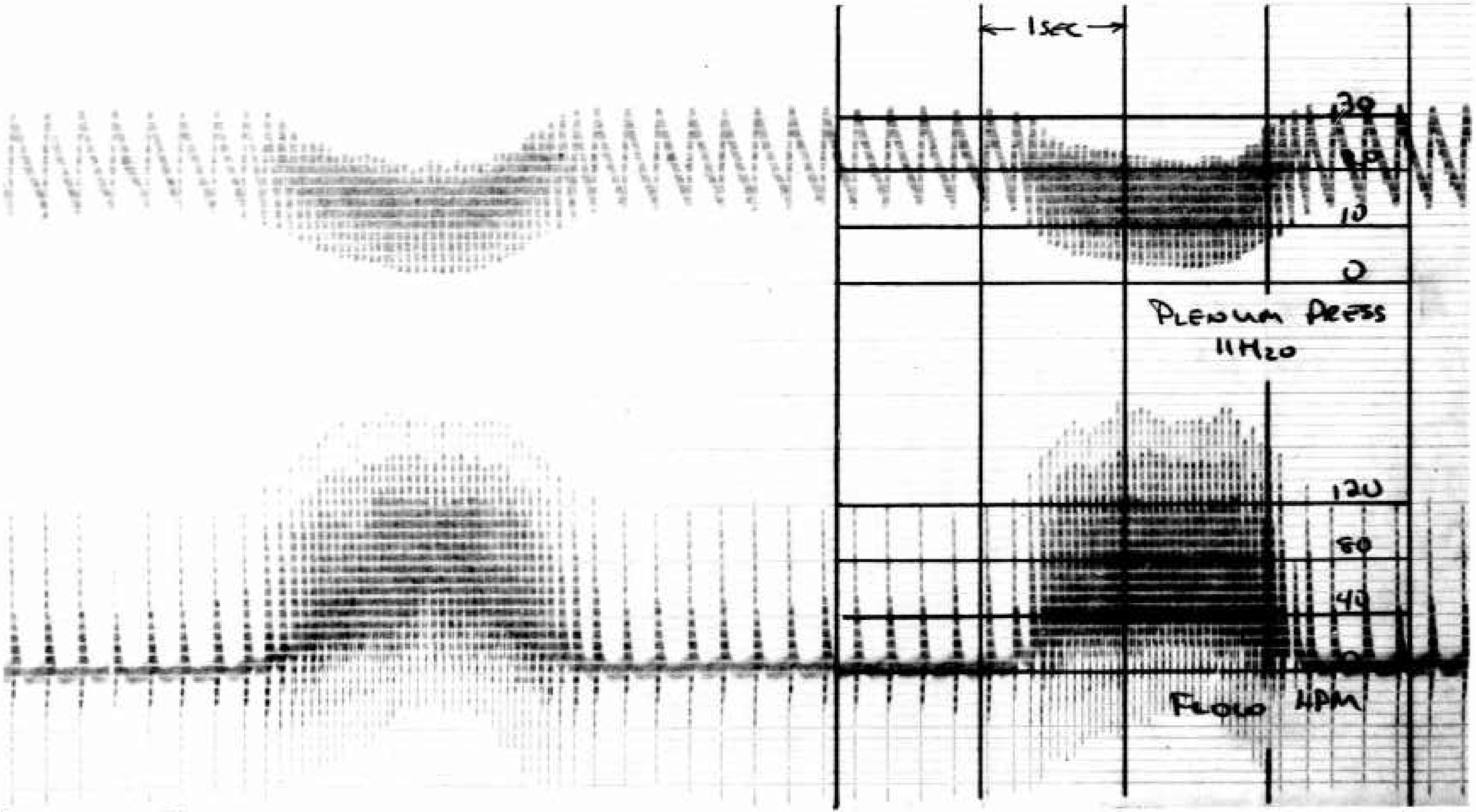


Figure 22. Plenum Pressure during Simulated Pressure Breathing 15 Inches H_2O

oxygen regulator. The PDM was chosen because it is the largest fluidic subsystem of the O_2 regulator.

The breadboard consists of five fluidic amplifiers with plastic tubing interconnections (Figures 23 and 24). The circuit of the packaged version is modified in that the last three stages of the breadboard, which act as a digital amplifier, are replaced with an amplifier using laminated construction that already has three stages (Figure 25). The replacement is a modified GE, MF11 amplifier.

The PDM package consists of three basic units:

- Oscillator - a modified GE, DF34 and two capacitors of 1.2 in^3 each.
- Summing Amplifier - a modified GE, MS11, that consists of three stages.
- Digital Amplifier - a modified GE, MF11, that consists of three stages.

The units are arranged in a stack consisting of 122 laminates (Figure 26). In the stack are seven amplifiers, nine resistors, and appropriate interconnections. Capacitors, each of 1.2 cubic inches, are not included. For this package they are connected to two pairs of barbed fittings at the top of the stack. However, in a final design, the capacitors can be integral with the package and connect directly with the holes at the top of the stack. Further, the shape of the capacitors is immaterial so the final design can be delayed to fit in available space of the complete O_2 package.

Inputs to the package are the function generator and its bias at the bottom of the package. Outputs to the modulation valve are also at the bottom. Supply flow is at both the top and bottom. Both supplies are at the same pressure so they can be easily mainfolded later in a final package for the complete O_2 regulator.

The PDM package performance was measured by itself and when driving the mixture modulation valve. The output waveform was not a perfect square wave; thus it is necessary to define the switching point to determine modulation of just the PDM (see Figure 27). Results (Figure 28) show the modulation to be reasonably linear between 10 and 90 percent when it is not driving anything. Beyond this range the waveform degenerates to a saw tooth without sufficient amplitude to switch the output load (assumed to be 1 psi).

Increasing the supply pressure to 14 psi did not change the modulation range but did make the waveform more triangular than that observed for the 10 psi data of Figure 28. At lower supply pressure, $P_s = 8$ psi, the performance was also similar to that for $P_s = 10$ psi.

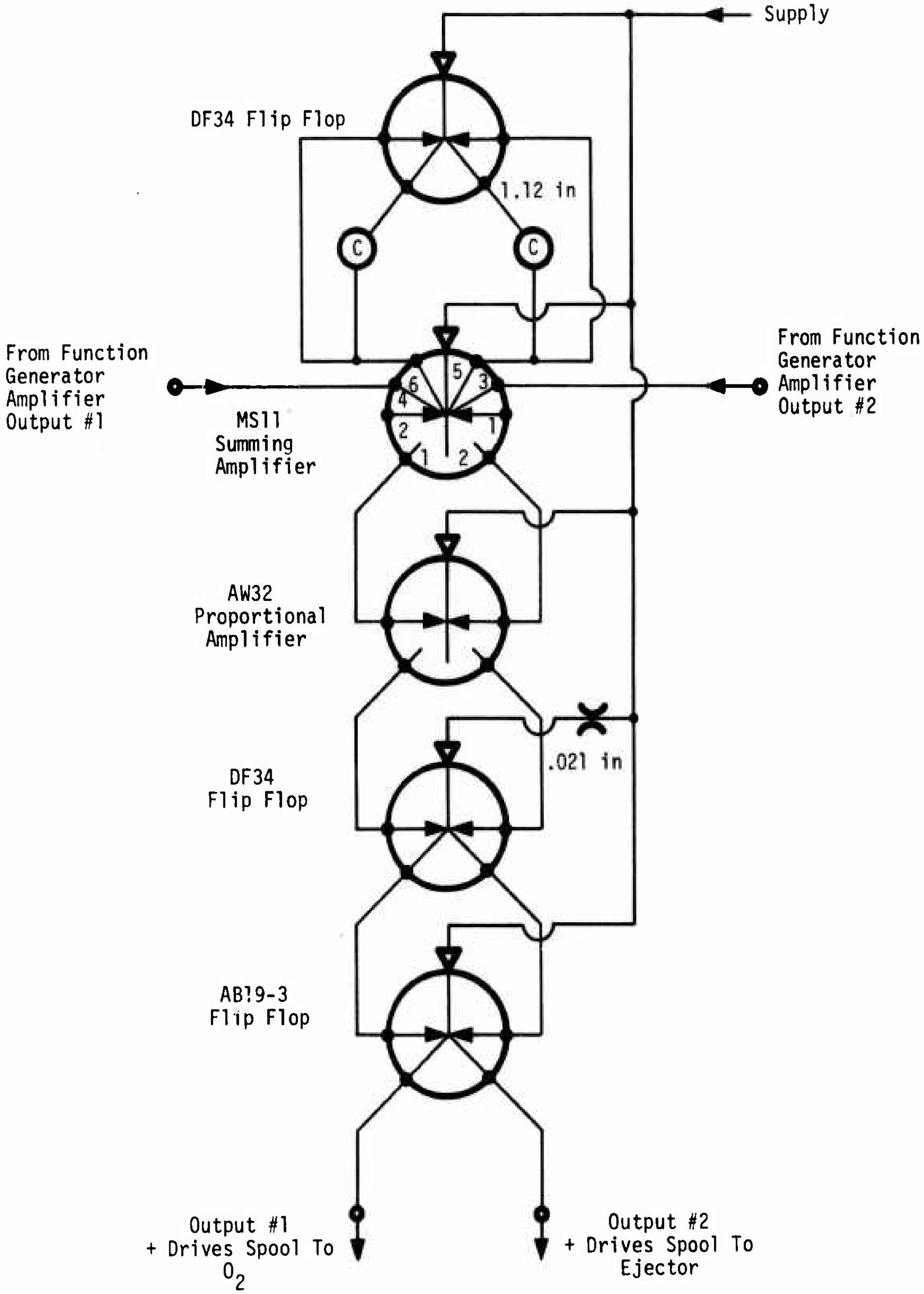


Figure 23. Breadboard PDM Circuit

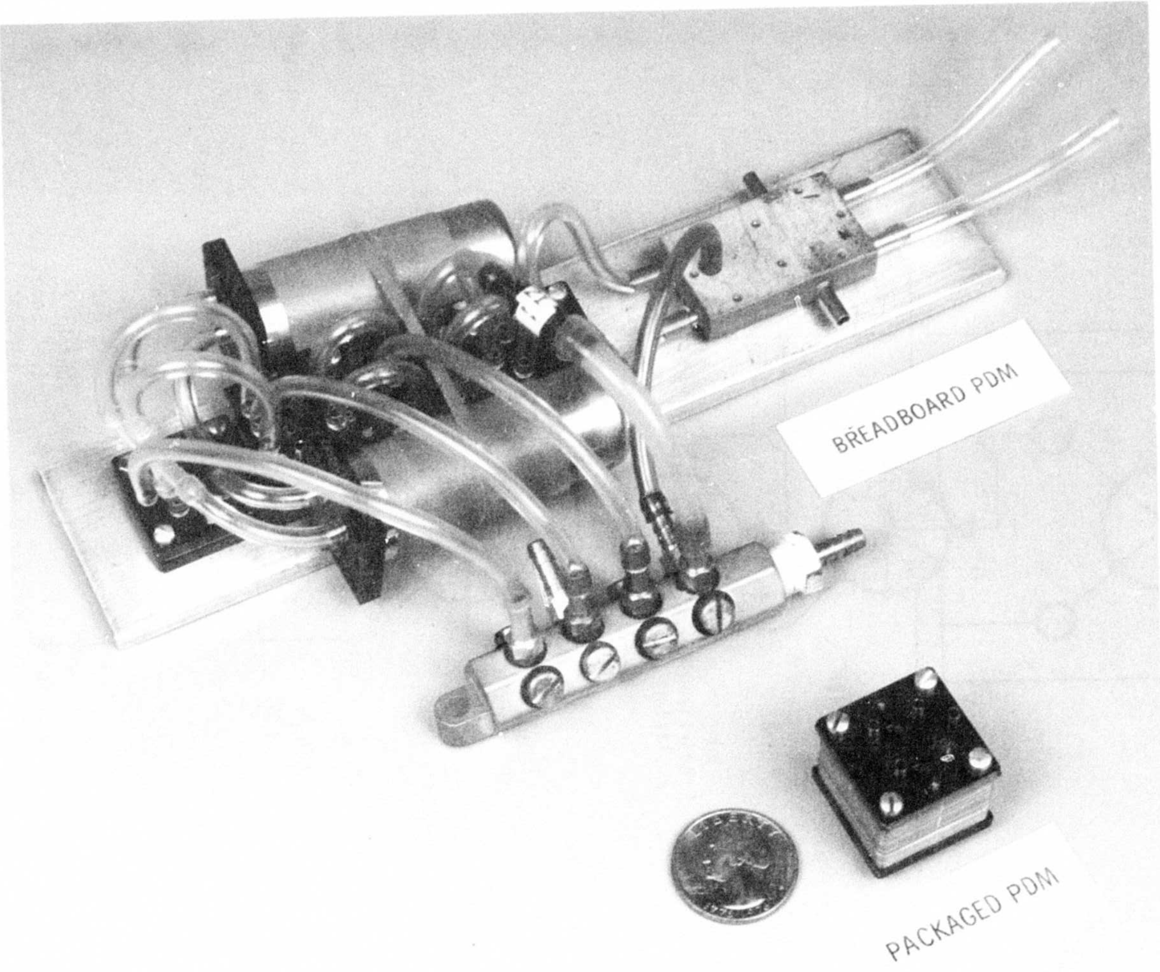
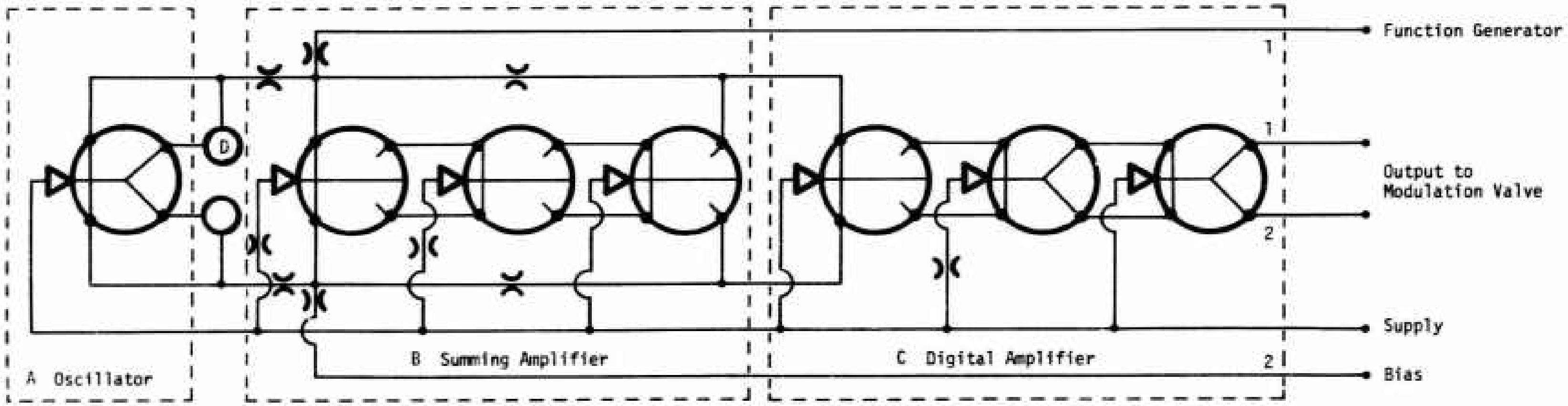


Figure 24. Comparison of Breadboard and Packaged PDM



Components are A Modified GE, DF34, Flip Flop
B Modified GE, MS11, 3 Input Summing Amplifier
C Modified GE, MF11, Digital Amplifier
D 1.2 cu. inch capacitors (not included in this package)

Port numbers (1,2) correspond to Figures 4 and 26.

Figure 25. Packaged PDM Circuit

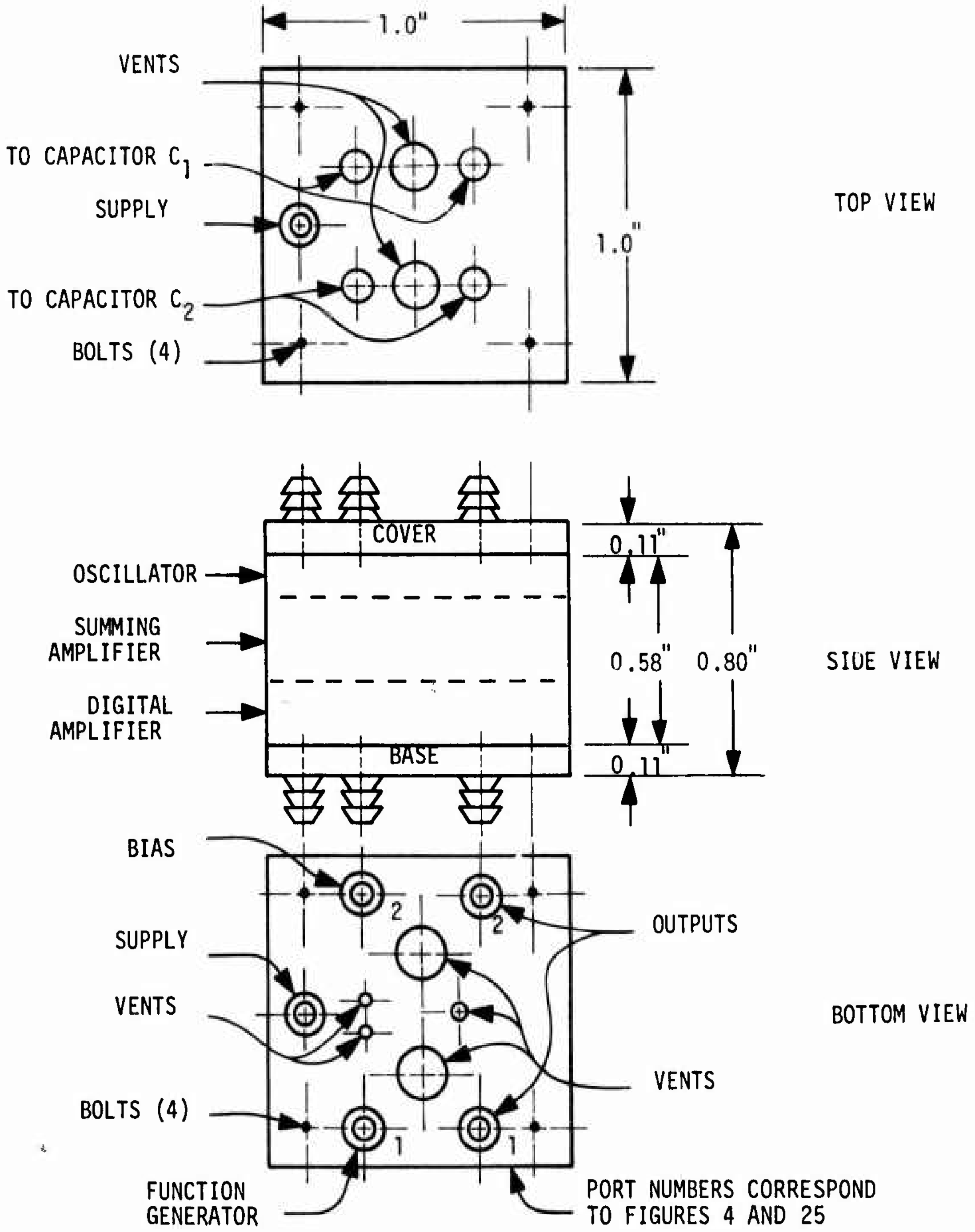


Figure 26. PDM Package

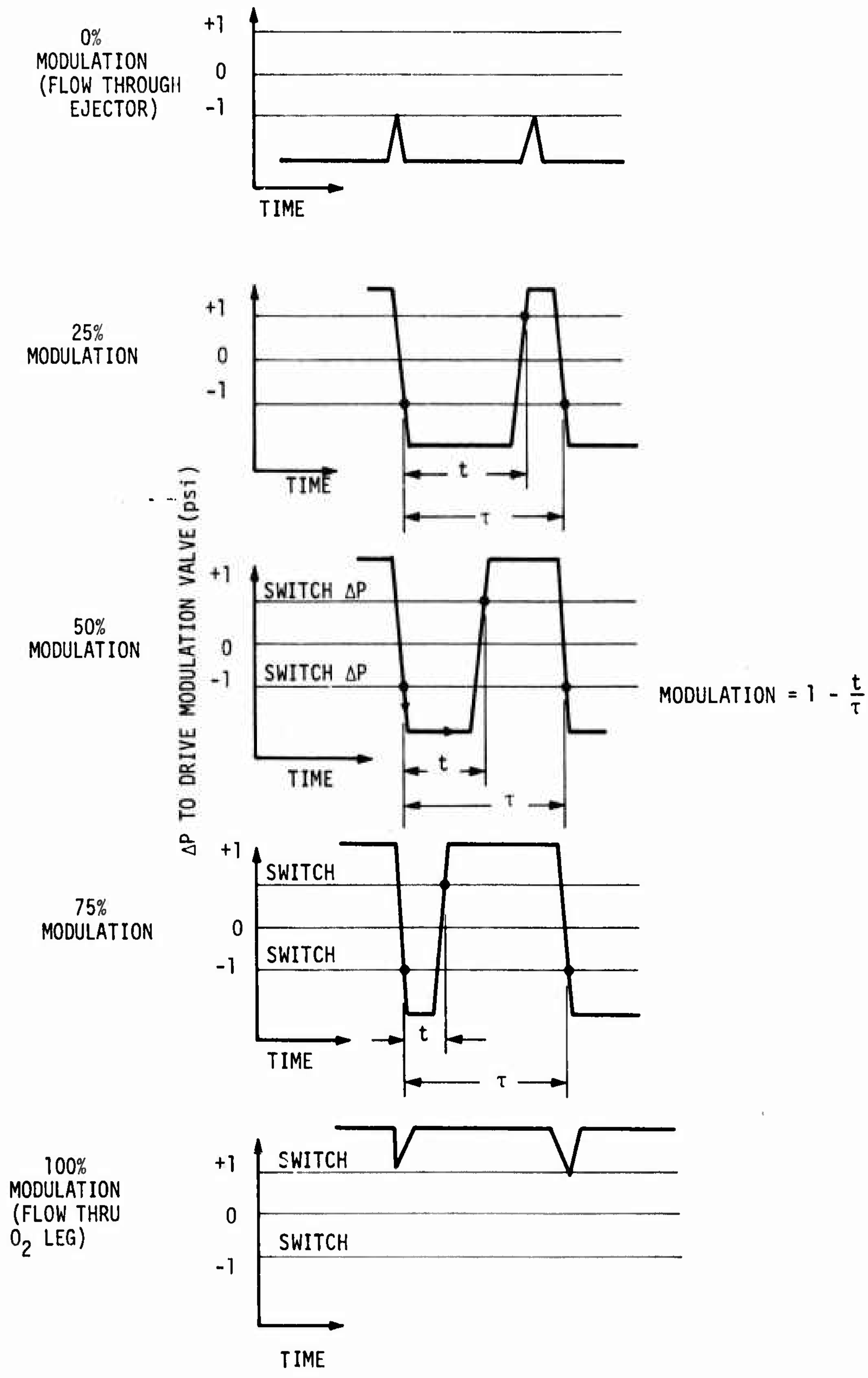


Figure 27. Modulation Definition (when Wave Is Not Square)

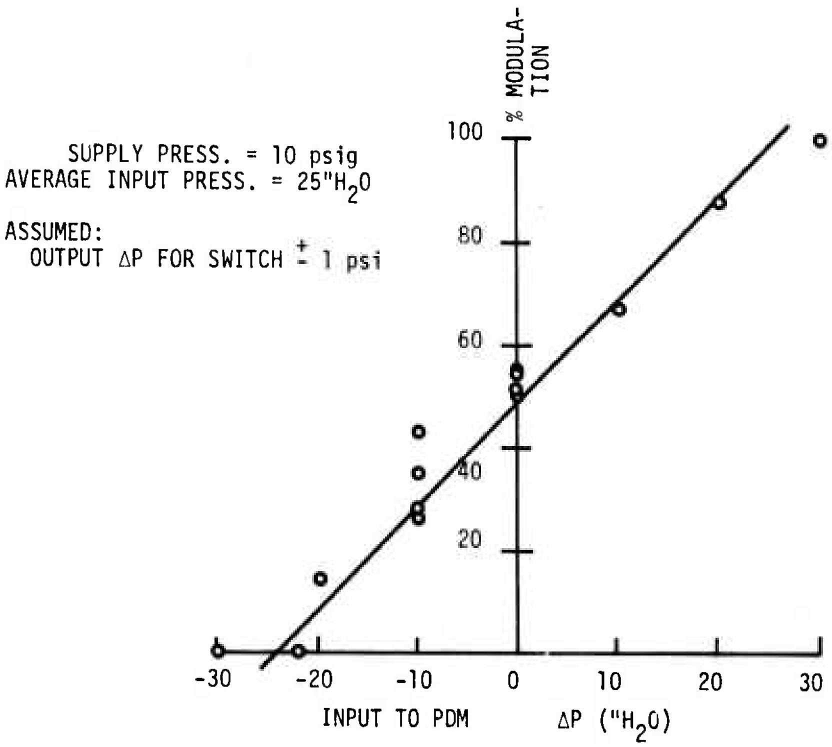


Figure 28. Performance of Packaged PDM

Output of the modulation valve when being driven by the PDM package (Figure 29) showed modulation from 30 to 70 percent compared to 10 to 90 percent for the breadboard PDM. Beyond this range the switching of the modulation was intermittent and unsatisfactory.

The present design needs a modulation range of 10 to 90 percent. If no changes were made the range of 30 to 70 percent would mean excess enrichment at low cabin pressure altitudes and low enrichment at the top end of the cabin altitude range. This can be corrected by either redesigning the schedule and/or improving the PDM to increase the modulation range. Improving the packaged PDM is best because excess O_2 is already a problem at low altitudes due to the ejector, which makes low altitude rescheduling difficult. The fact that the breadboard PDM did modulate at 10 to 90 percent adds confidence that the packaged PDM range can be extended by improving the output wave form to a better square wave.

A more complete comparison of the PDM package and the breadboard PDM is shown in Figure 30 where the output of the mixture control circuit is compared when using either of the two PDM's. The packaged PDM controls the circuit nearly as well as the breadboard but shifts the operating curve to a different range of needle settings. Correction for such a shift is merely a change of length in the mechanical linkage of the function generator and hence has no bearing on the feasibility of the PDM at this time.

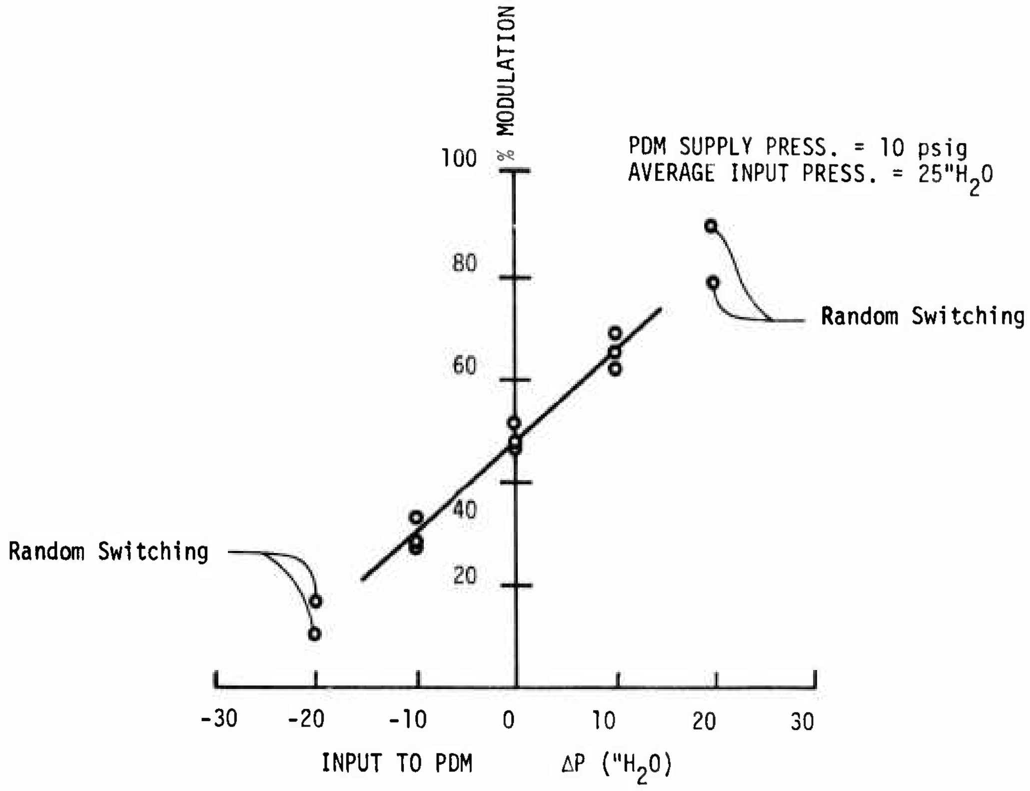


Figure 29. Performance of the Packaged DPM during the Mixture Modulation Valve

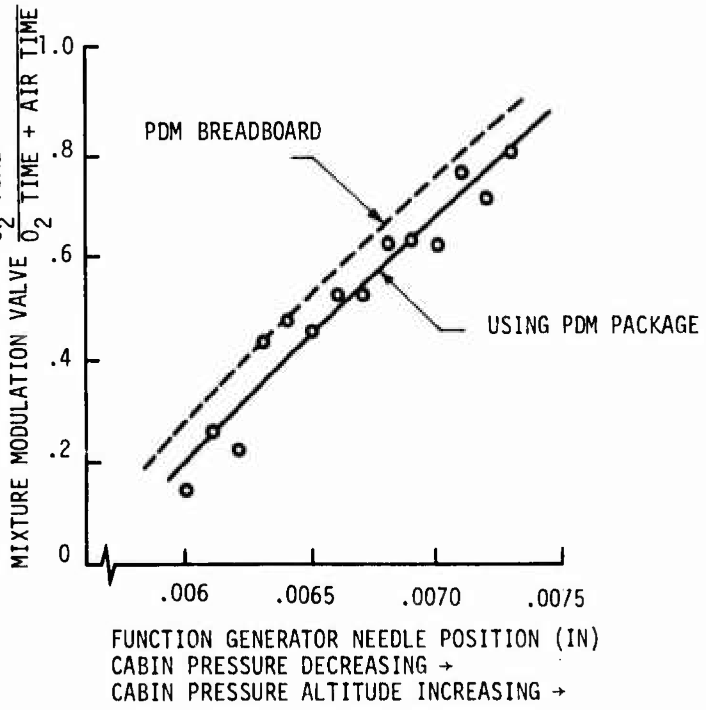


Figure 30. Mixture Modulation versus Function Generator Input when Using the Packaged PDM

Overall, the PDM package performance demonstrates feasibility for inclusion in a complete O_2 regulator circuit even though its performance is not quite as good as the breadboard. Improvement of the PDM output waveform to that of a better square wave would best be done by improving the last stage of the laminates to sharpen the switching characteristics. One possible method is to provide a smooth attachment wall for the power jet either by carefully honing the etched walls in assembly and/or adding a filler in the jet attachment region. Modifications such as these were beyond the scope of the present work. However, the present PDM package does operate in the circuit, and it is reasonable to expect even better operation with additional development.

APPENDIX A

MIXTURE MODULATION SCHEDULE AND ITS IMPLEMENTATION

When designing the mixture function generator, it was necessary to choose a mixture versus cabin pressure altitude and a set of components to implement it.

The specified function is midway between the upper and lower enrichment limits with variations determined by the operating limits of the system components (Figure 5). The schedule is described below with reference to Figure A-1.

- From 0 to 5000 feet (points 0 to 1), the system is off and air comes in through the air intake of the ejector. The reason is that if the ejector is on, the mixture to the plenum would exceed the upper enrichment limit below an altitude of 2500 feet. This results from the ejector ratio (air to O_2) of $R_{ej} = 8$.
- From 5000 feet to 13,000 feet (points 2 to 3), the regulator is turned on but O_2 flow from the mixture modulator is to the ejector only (i.e., $g = 0$). The reason is that the minimum modulation possible by the PDM is $g = 10$ percent, so if modulation began at a lower altitude, the upper enrichment limit would be exceeded.
- From 13,000 to 32,000 feet (points 4 to 6), the O_2 flow is modulated to provide a mixture midway between the upper and lower enrichment limits. In this range, the value of the O_2 flow ratio, R_o (defined in Figure 6), for 50 percent modulation is the trade-off. $R_o = 0.067$ is chosen so that the upper enrichment limit is not exceeded at high altitude when the modulation must go from the maximum of the PDM ($g = 90$ percent) to 100 percent by other means. The desired flow ratio, R_o, is obtained by adding resistance in the line between the modulation valve and the ejector.
- At 32,000 feet and above (points 6 and 7), the modulation valve is held such that flow to the plenum is only through the O_2 leg.

The mixture schedule of Figure A-1 is implemented into a modulation schedule (Figure A-2) and then into hardware shown schematically in Figure A-3. The significant points are circled and have corresponding numbers.

The bellows is assumed to expand continuously with cabin altitude and to supply a linear movement (with cabin pressure) of about 0.250 inch from sea level to 50,000 feet. A movement of the needle for the curved portion at the schedule (point 4 to 6) of about 0.010 is desirable. The problem then was to design an orifice and needle that would match the curve portion of the function. It was found that an annular restrictor formed by a conical needle should have a pressure versus needle movement that approximates this curve. Features of this analysis are laminar flow for the linear portion of the curve and entrance pressure losses to the annular duct for the curved portion of the function. The dimensions of the annular duct of D = 0.100, L = 0.189, and 0 = 35° and the needle movement, x, were determined from the analysis and incorporated into the test apparatus. Test results, Figure A-4, show that the curved function can be generated by the conical annular restrictor. The experimental points are taken for a range of needle movement of 0.007 inch.

The portions of the schedule for no modulation (g = 0 and g = 100 percent) will be done utilizing the flat saturation characteristics of the proportional fluid amplifier downstream of the needle valve. This can be seen by looking at the characteristics of the amplifier in Figure A-3. Below point 3 the output is independent of the control pressure from the needle valve. This saturates the summing amplifier in the PDM and provides an output to the modulation valve that holds it in the position for flow only to the ejector. Similarly, for control pressures above point 7, the amplifier will hold the mixture modulation valve so that all O_2 is directly into the plenum for g = 100 percent. In between the saturation conditions, the nonlinear pressure characteristics of the needle valve control the PDM summing amplifier to create the curved portion of the mixture versus altitude schedule.

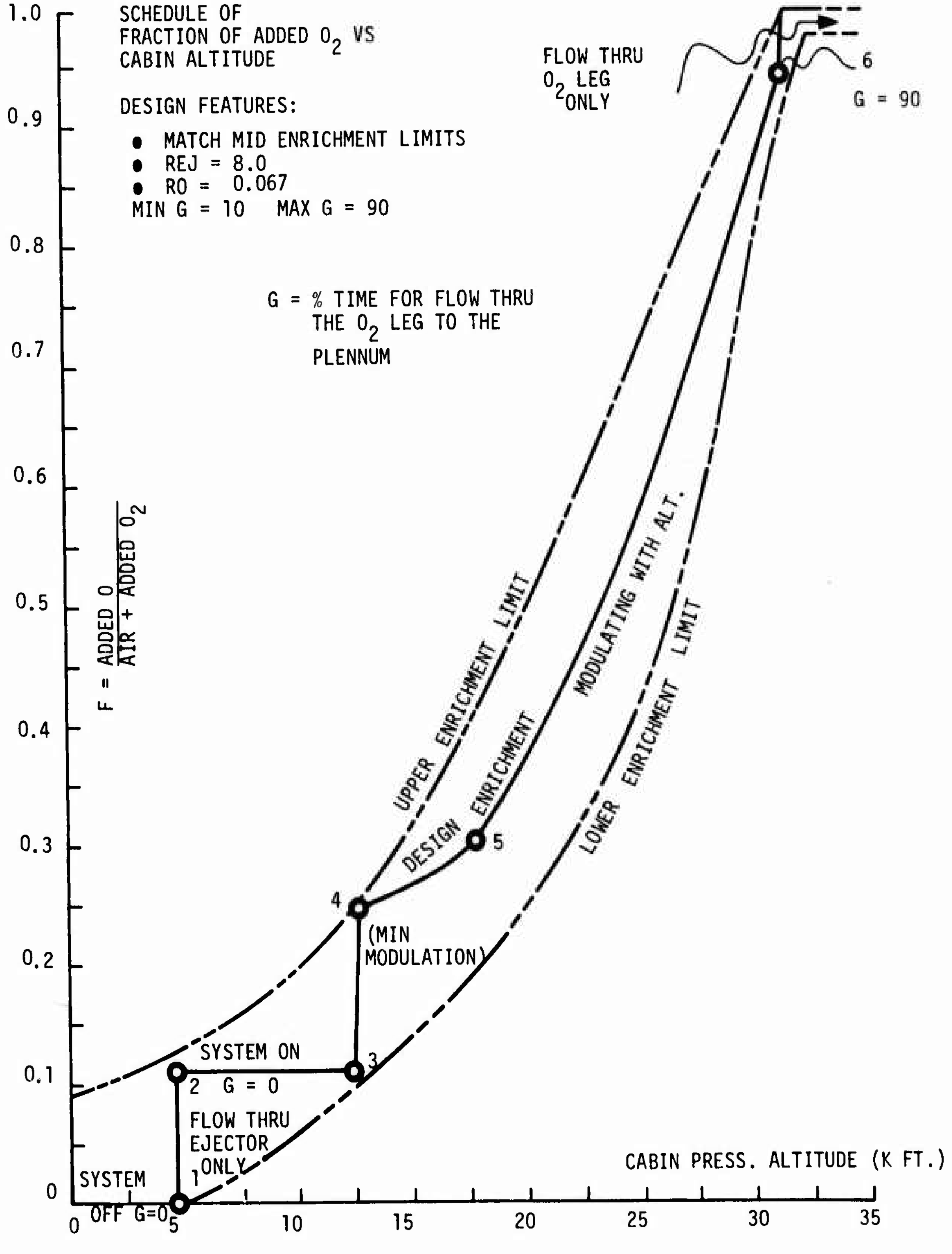


Figure A-1. Cabin Pressure Altitude

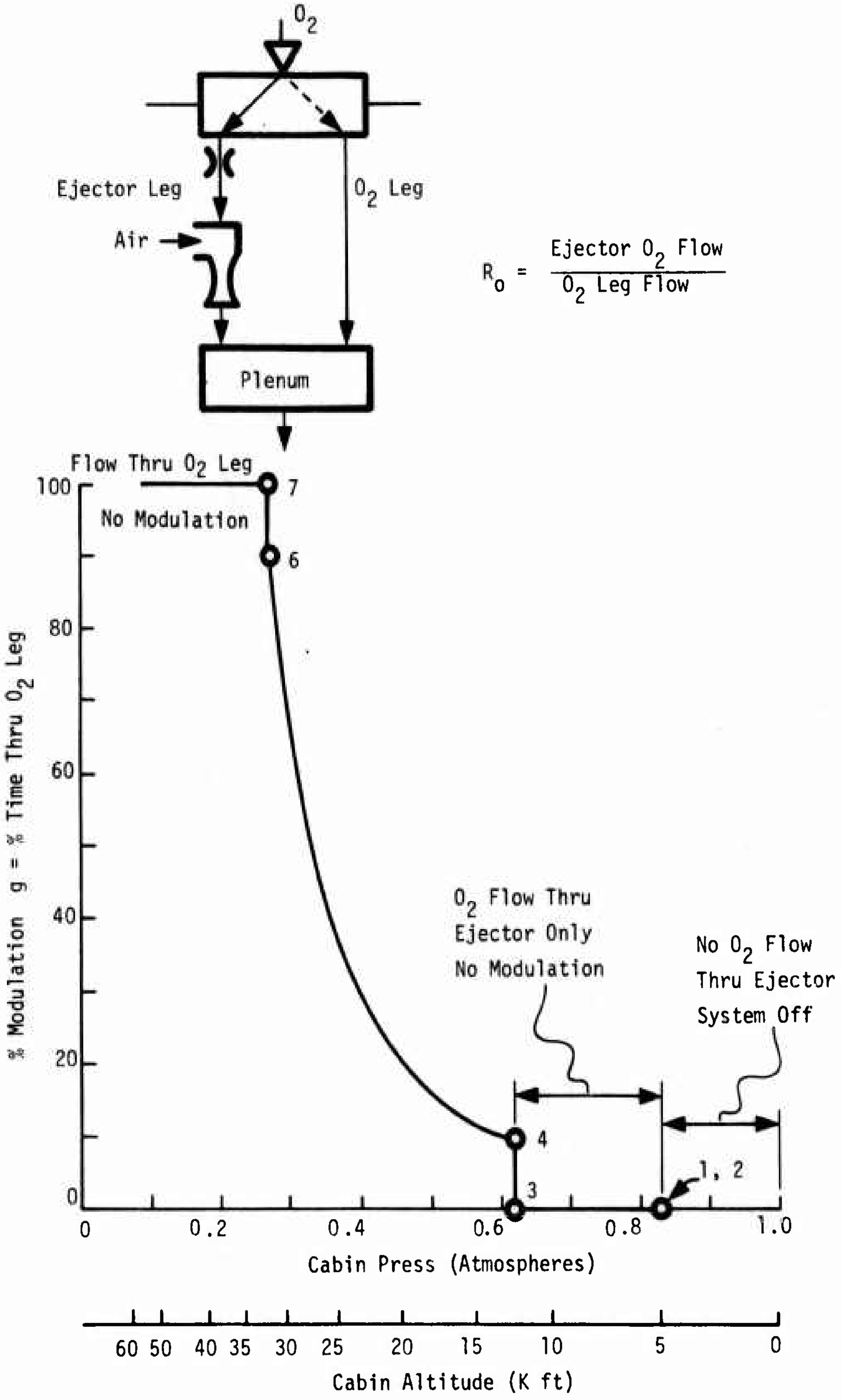


Figure A-2. Modulation Schedule

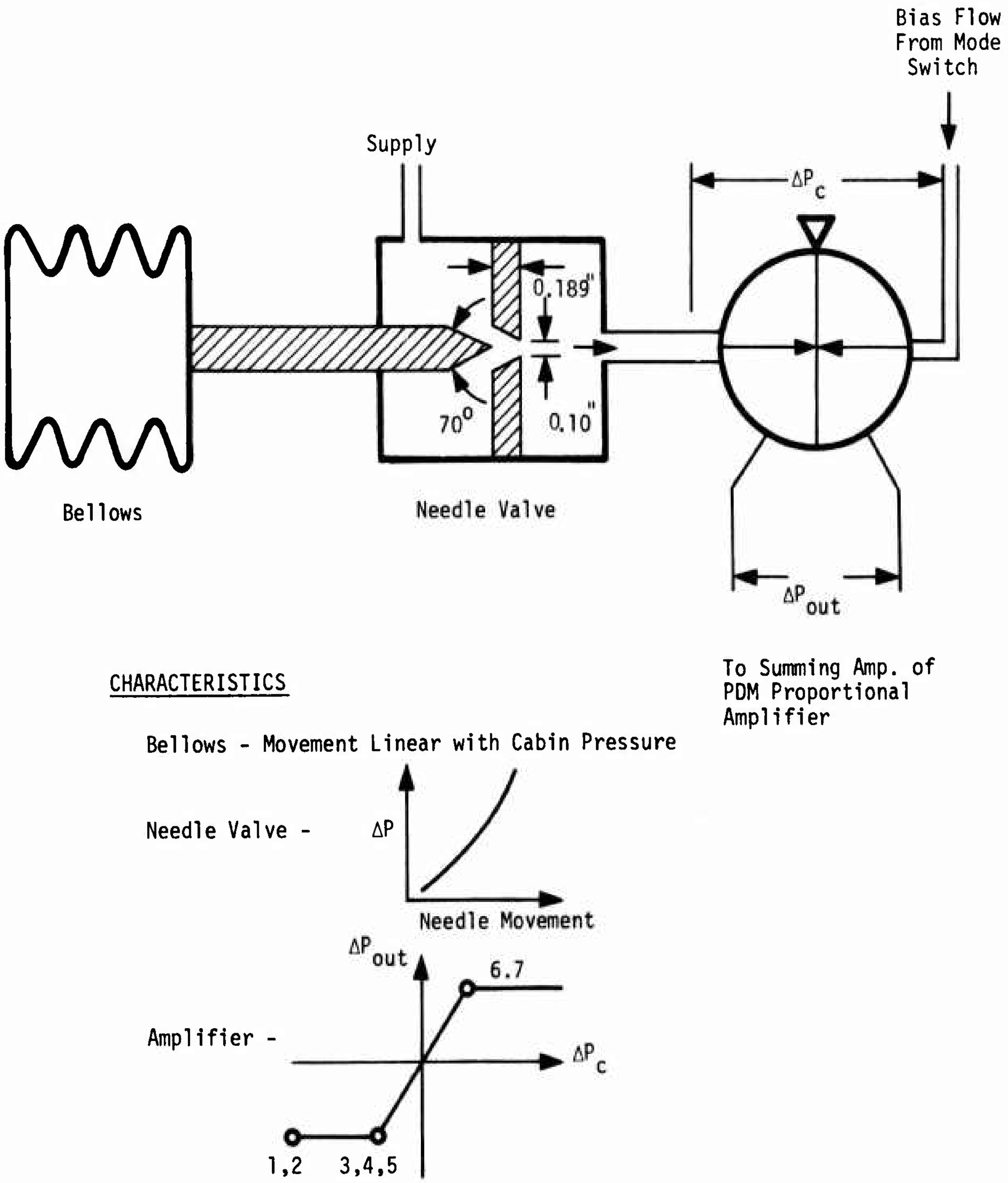


Figure A-3. Mixture Function Generator Schematic

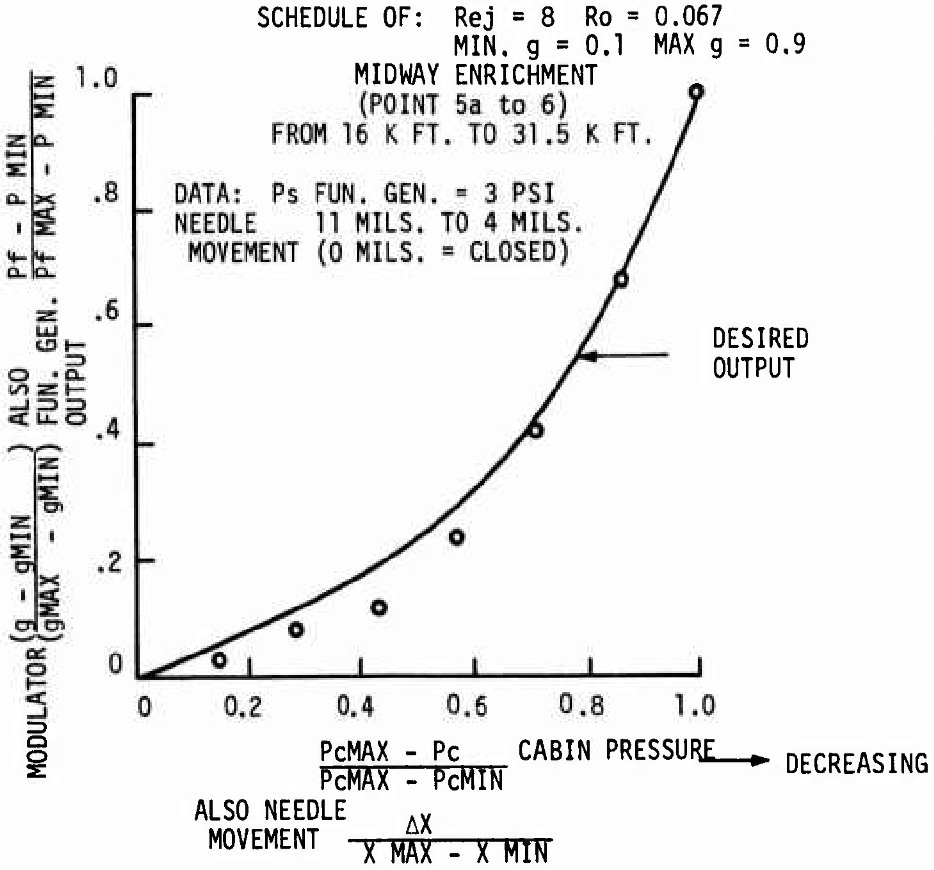


Figure A-4. Mixture Modulation versus Cabin Pressure

APPENDIX B

EJECTOR PUMP STATIC TEST RESULTS

The ejector pump test results are presented according to the tube internal diameter (ID) in Tables B-1 through B-4. Terms used in the tables are defined below:

Primary Pressure -- pressure supplied to the primary flow of the ejector (O_2).

Back Pressure -- pressure downstream of the ejector, nominally the plenum pressure.

Exit Flow -- flow of the mixture of primary (O_2) and secondary (air).

R_{ej} -- the ejector ratio. Ratio of secondary to primary (i.e., air/O_2).

Exit q -- dynamic pressure of the mixture as it leaves the ejector.

It is calculated using

$$q = \frac{1}{2} \rho \left(\frac{Q}{A}\right)^2$$

where ρ = mass density
Q = exit flow
A = tube cross section area

OBSERVATIONS

The ejector performance (i.e., R_{ej}) is sensitive to back pressure, more so with large diameter tubes than with the small one. It is apparent that, with a large tube and with high back pressure, the exit dynamic pressure (exit q) is overcome and the flow actually reverses. This is especially apparent in Table B-4 where the primary pressure must be 30 psi to avoid reverse flow when the back pressure is 1.0 inch H_2O.

A tube ID $\approx$ 0.55 inch (and a center body gap $\approx$ 0.002 inch) at a primary pressure of approximately 20 psig will supply the maximum flow rate (135 lpm) with R_{ej} variation (Table B-2). Increasing the primary flow at the same pressure by increasing the gap to 0.004 inch improves R_{ej} but results in larger than necessary exit flow.

CONCLUSIONS

A tube ID ≈ 0.55 inch with a gap of 0.004 inch at a supply pressure of 20 psig is a good candidate configuration and will be the baseline for matching other circuit components. If lower flows are required, this baseline configuration can be scaled down.

Table B-1. Ejector Performance
(Tube ID = 0.44 inch,
Nozzle Gap = 0.002 inch)

Primary Pressure (psig)	Back Pressure (inches H_2O)	Exit Flow (lpm)	R_{ej}	Exit q (inches H_2O)
5	0	45	4.2	0.14
5	0.5	31	2.9	0.07
5	1.0	0		
10	0	65	5.0	0.30
10	0.5	68	4.8	0.33
10	1.0	51	3.4	0.18
20	0	105	5.2	0.78
20	0.5	105	5.2	0.78
20	1.0	105	5.2	0.78
30	0	133	5.1	1.26
30	0.5	139	5.3	1.37
30	1.0	136	5.2	1.31

Table B-2. Ejector Performance
(Tube ID = 0.55 inch)

Nozzle Gap (inch)	Primary Pressure (psig)	Back Pressure (inches H_2O)	Exit Flow (lpm)	R_{ej}	Exit q (inches H_2O)
0.002	5	0	59	5.8	0.10
0.002	5	0.5	21	1.6	0.01
0.002	5	1.0	0		
0.002	10	0	99	7.9	0.28
0.002	10	0.5	76	5.7	0.17
0.002	10	1.0	42	2.7	0.05
0.002	20	0	164	8.9	0.78
0.002	20	0.5	144	7.3	0.60
0.002	20	1.0	119	6.0	0.41
0.002	30	0	238	10.3	1.65
0.002	30	0.5	201	8.1	1.17
0.002	30	1.0	184	7.4	0.98
0.004	5	0	82	4.2	0.20
0.004	5	0.5	57	2.7	0.09
0.004	5	1.0	0		
0.004	10	0	150	7.4	0.65
0.004	10	0.5	108	5.0	0.34
0.004	10	1.0	85	3.7	0.21
0.004	20	0	244	10.0	1.73
0.004	20	0.5	207	8.2	1.25
0.004	20	1.0	187	7.3	1.02
0.004	30	0	337	12.0	3.30
0.004	30	0.5	283	9.9	2.33
0.004	30	1.0	275	9.6	2.20

Table B-3. Ejector Performance

(Tube ID = 0.65 inch,
Nozzle Gap = 0.002 inch)

Primary Pressure (psig)	Back Pressure (inches H_2O)	Exit Flow (lpm)	R_{ej}	Exit q (inches H_2O)
5	0	76	7.5	0.09
5	0.5	0		
5	1.0	0		
10	0	133	10.9	0.26
10	0.5	65	4.7	0.06
10	1.0	0		
20	0	204	11.5	0.62
20	0.5	161	8.6	0.39
20	1.0	85	4.1	0.11
30	0	258	11.1	0.99
30	0.5	261	10.9	1.02
30	1.0	204	8.3	0.62

Table B-4. Ejector Performance

(Tube ID = 0.72 inch,
Nozzle Gap = 0.002 inch)

Primary Pressure (psig)	Back Pressure (inches H_2O)	Exit Flow (lpm)	R_{ej}	Exit q (inches H_2O)
5	0	102	10.1	0.10
5	0.5	0		
5	1.0	0		
10	0	190	15.9	0.36
10	0.5	42	2.6	0.02
10	1.0	0		
20	0	275	15.7	0.75
20	0.5	150	7.7	0.22
20	1.0	0		
30	0	348	15.2	1.20
30	0.5	232	9.7	0.53
30	1.0	164	6.6	0.27

APPENDIX C

DESIGN GOALS

The design goals and operation details presented here are taken from the original work statement. Tables I, III and IV from MIL-R-83178 (USAF) (referenced in the work statement) are reproduced here.

5.0 Design Goals

5.1 Primary Control functions - All selected concepts shall provide these control functions, although the performance tolerances indicated for each are considered to be only goals.

5.1.1 Manual Selectors - The final regulator design shall provide two manual selectors. One of these will allow manual selection of either "Normal Oxygen" (dilution) or "100% oxygen" (no dilution) modes. The second selector will provide manual selection of either "Normal" or "Emergency" pressure modes. These modes of operation are described below. The design should also consider the method by which the second selector could be eliminated and the "Emergency" pressure position added as a third position to the first selector. In this design, "Normal" pressure would be provided in both the "Normal Oxygen" and the "100% Oxygen" positions.

5.1.2 Dilution Operation - With the manual selector set for "Normal Oxygen" and an oxygen supply to the regulator within the range 40-120 psig, the oxygen/air mixing ratio delivered by the regulator shall follow the altitude schedule shown in Figure 1, herein (also see para. 5.3.4).

The dilution schedule shall apply at constant outlet flowrates of 5, 15, 50, 85, and 135 LPM total gas mixture delivery rate. In addition, and perhaps more importantly, the dilution fraction shall remain rather constant with total flow fluctuations and average within the specified limits for each breath of a simulated sinusoidal breathing pattern which has a 30 LPM RMS flow during the inhalation half-cycle. The tests shall be conducted over the range of 10-16 cycles (breathes) per minute.

5.1.3 "100% Oxygen" Operation - With the manual selector set for "100% oxygen," air dilution shall be limited to no more than 2% of the total flow at all altitudes and flow conditions.

5.1.4 "Normal" Pressure Operation at altitudes 27,000-47,000 feet - With the pressure mode selector set for "Normal," the diluter selector in both "Normal Oxygen" and "100% oxygen," the cabin altitude within the range 27,000-47,000 feet, and the oxygen supply to the regulator within 40-120 psig, the pressure versus flow shall be within limits shown by the altitude schedule of Table III, MIL-R-83178. Additionally, with the oxygen supply pressure to the regulator at 70 psig, the pressure mode selector in the "Normal" position, and the diluter selector set for "Normal Oxygen," the delivery pressure shall not be influenced by flowrate beyond the limitations imposed by Table A, herein.

5.1.5 Flow Suction Characteristics at sea level - 27,000 feet - With the pressure mode selector set for "Normal," the diluter selector in both "Normal Oxygen" and "100% Oxygen," the cabin altitude within the range sea level - 27,000 feet, and the oxygen supply to the regulator within 40-120 psig, to obtain the flows indicated in Table I, MIL-R-83178, the outlet suctions causing the flows shall not exceed the values specified in Table I, MIL-R-83178. Additionally, with the diluter selector in both "Normal Oxygen" and "100% Oxygen," at ground level, and with either increasing or decreasing flows, the suctions required to produce the flows listed in Table IV, MIL-R-83178 shall not exceed the values listed in Table IV, MIL-R-83178 when oxygen supply pressure to the regulator is as given in Table IV, MIL-R-83178 ("maximum specified" pressure is 120 psig). After the suction is reduced to zero, the flow shall not exceed 0.01 LPM.

5.1.6 "Emergency" Pressure Operation - With the diluter selector set for both "Normal oxygen" and "100% oxygen," the pressure mode selector at "Emergency," the oxygen supply pressure to the regulator within the range 40-120 psig, and the altitude at ground level to 25,000 feet, the pressure at the outlet shall be 0.1-1.5 inches of water above ambient for all flows 0-135 LPM. For the "Normal Oxygen" (dilution) mode, alteration of the dilution characteristics toward greater enrichment is acceptable but should be minimized.

5.1.7 Overpressure Relief - Provision shall be included to vent overboard any excess pressure occurring at the regulator outlet. This vent shall provide at least 50 LPM flow at not greater than 25 inches of water pressure. The relief shall not leak in excess of .01 LPM at 17 inches of water pressure.

5.1.8 Low Oxygen Warning and Antisuffocation - When there is no oxygen supply pressure to the regulator, the dilution port shall close for outlet suction in the range 0-4.5 inches of water below ambient. This abnormal breathing resistance warns the user of a depleted oxygen supply. When the suction increases to 5-6 inches of water below ambient, at least 50 LPM air flow shall be admitted to allow air breathing.

5.2 Secondary Functions - These functions apply only to panel-mounted regulators; whereas, the control functions identified in paragraph 5.1, apply to both panel-mounted and chest-mounted regulators.

5.2.1 Secondary functions requiring new devices - Although current devices perform these functions adequately, the potential for simplification exists. New concepts considered should suggest reduced cost, increased reliability, or increased flexibility and compatibility with conceptual designs for primary control functions.

5.2.1.I Oxygen Flow Indicator - This shall be a device which visually indicates white when oxygen flow is as follows: With the diluter control set for "100% oxygen" and with oxygen supply to the regulator at 40-120 psig, a full indication of flow shall be given for an outlet flow of 4 LPM at ground level and for an outlet flow of 8 LPM at 35,000 feet cabin altitude. With the diluter control set for "Normal oxygen" and with oxygen supply to the regulator at 40-120 psig, a full indication of flow shall be given for a total outlet flow of 18 LPM at all altitudes. With the diluter control in both the "Normal oxygen" and the "100% oxygen" positions, the flow indicator shall immediately register no flow when the outlet flow is reduced to zero, at any altitude. There shall be no flow indication unless there is a flow of oxygen.

5.2.1.2 "Test Mask" pressure - The pressure mode selector shall provide a third position, on panel-mounted regulators, which provides 11 ± 5 inches of water positive pressure at the regulator outlet, only while the selector is manually held in that position. The selector shall automatically revert to the "Normal" pressure mode upon release of the selector from the "Test Mask" position.

5.2.2 Secondary functions requiring no new devices - Current devices perform these functions satisfactorily. These functions are distinctly separate from all other functions, so the only likely problem of compatibility with primary control function devices would be in fitting them all into the allotted space envelope. The packaging of these conventional devices with the other functional devices, then, is the only required consideration of these devices under this program (reference para. 3.4.1, MIL-R-83178). These conventional devices are listed below:

a. Oxygen supply pressure gauge
b. Oxygen supply shutoff valve (ref. para. 3.6.10, MIL-R-83178)
c. Panel lighting (reference para. 4.6.31, MIL-R-83178)
d. Test ports (reference Figure 1 and paragraphs 3.6.14-15, MIL-R-83178)

5.3 Allowable Leakages - The following leakage limits and tests thereof are indicative of specifications for current regulator designs, except paragraph 5.3.4 refers strictly to new concepts which consume oxygen for control purposes.

5.3.1 Outward leakage - With the oxygen supply valve closed, the pressure selector at "Normal," and with 17 inches of water above ambient applied at the regulator outlet, leakage through the regulator shall not exceed 0.12 LPM (including the relief valve leakage which is allowed to be as much as .01 LPM at 17 inches of water pressure).

5.3.2 Outlet leakage - With oxygen supply to the regulator inlet at 40-120 psig, the leakage at the outlet shall not exceed 0.01 LPM.

5.3.3 Inward air leakage - With the diluter control set at "100% Oxygen," oxygen supply to the regulator off, ground level ambient pressure, and suction of 10 inches of water vacuum applied to the outlet, the air leakage through the regulator to the delivery port shall be less than 0.2 LPM.

5.3.4 Oxygen losses via control flow - Any concept which adds sources of oxygen waste (oxygen unavailable for inhalation by the regulator user) will be penalized according to the amount that oxygen losses (amount of vented control flow plus that measured per paragraph 5.3.2, above) exceed .01 LPM. Combined losses over .01 LPM shall cause modification to the oxygen enrichment specified by paragraph 5.1.2. In order to recoup this added oxygen waste, the upper limit of the "% added oxygen" curve of Figure 1 shall be lowered 1% for each incremental oxygen loss increase of 12 SCCM at sea level, 14 SCCM at 5000 feet, 16 SCCM at 10,000 feet, 21 SCCM at 15,000 feet, 27 SCCM at 20,000 feet, and 30 SCCM at 25,000 feet. In no case, however, shall the upper enrichment level fall below the curve identified as "sea level air equivalent" or the lower enrichment limit shown, whichever is higher. Since it is a secondary goal to eventually raise the lower limit to correspond to the "sea level air equivalent" curve, every effort should be made to limit oxygen losses so that some tolerance band can be maintained above the "sea level air equivalent" curve.

5.4 Design Environment

5.4.1 Operating temperatures - The entire regulator shall function within specifications when stabilized and operated within the temperature extremes of -65°F and +160°F.

5.4.2 Exposure temperatures - The entire regulator shall function within specifications when returned to standard room temperature following stabilization at the temperature extremes of -85°F and +160°F.

5.5 Dimensions - Designs for panel-mounted application shall not exceed 5 3/4" wide x 3" high x 3 3/4" deep (excluding small protruberances at the front allowed for selectors, lights, and test ports). Designs for chest-mounted application shall not exceed 3" x 3" x 2" (excluding small protruberances for selector(s) and the connector for the oxygen supply line to the regulator.

5.6 Weight - Designs for chest-mounted applications (exclude functions identified in paragraph 5.2) shall not exceed 8 ounces. Designs for panel-mounted applications (includes the secondary functions described in paragraph 5.2) shall not exceed 3 pounds.

TABLE A

SAFETY-PRESSURE AND PRESSURE-BREATHING CHARACTERISTICS

Outlet pressure for 10 liters per min flow (in. H_2O)	Altitude range for column 1 (1,000 feet)	Maximum outlet pressure increase for 0 liter per min (in. H_2O)	Maximum outlet pressure decrease for indicated flow (in. H_2O)
1.0	27 to 40	1.0	0.9 for 70 liters per min
2.0	29 to 41	1.3	1.3 for 135 liters per min
8.5	42 to 45	1.3	1.3 for 135 liters per min
15.0	47 to 50	1.3	1.3 for 135 liters per min

NOTE: The outlet pressure for the altitude range of 30,000 to 38,000 feet shall not fall below 0.01 in. H_2O for flow of 0 to 25 liters per minute. The outlet pressure for the altitude range of 34,000 to 40,000 feet shall not fall below 0.01 in. H_2O for flow of 0 to 135 liters per minute.

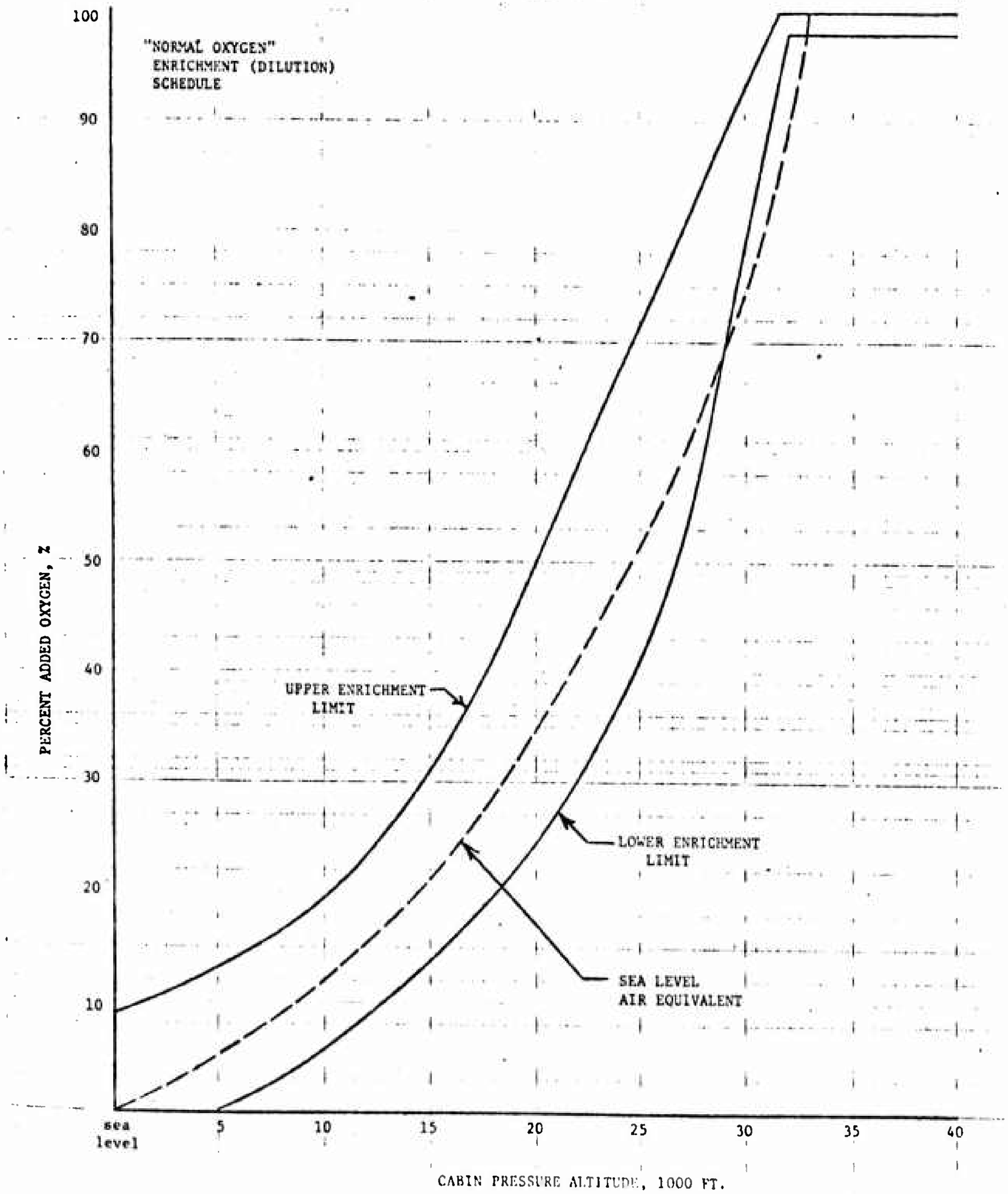

"NORMAL OXYGEN"
ENRICHMENT (DILUTION)
SCHEDULE
PERCENT ADDED OXYGEN, %
100
90
80
70
60
50
40
30
20
10
sea level
5
10
15
20
25
30
35
40
UPPER ENRICHMENT LIMIT
LOWER ENRICHMENT LIMIT
SEA LEVEL AIR EQUIVALENT
CABIN PRESSURE ALTITUDE, 1000 FT.

FIGURE 1

Reproduced from
MIL-R-83178 (USAF)

TABLE I. Flow Suction Characteristics

Supply Oxygen Pressure	Flow of Oxygen or Oxygen-Air Mixture (LPM)	Maximum Outlet Pressure (Inches of Water)	Altitude Range (1,000 Feet)
50 to maximum specified in applicable drawing	0 to 30	-0.45 to +1.0 1/	0 to 27
50 to maximum specified in applicable drawing	31 to 50	-0.7 to +1.0	0 to 27
50 to maximum specified in applicable drawing	51 to 85	-1.0 to +1.0	0 to 27
50 to maximum specified in applicable drawing	86 to 135	-1.0 to +1.0	10 to 27

1/ The positive pressure shall apply only from altitudes of 15,000 feet and above. Below 15,000 feet shall require a suction to induce any flow of oxygen in excess of 0.01 LPM.

Reproduced from
MIL-R-83178 (USAF)

TABLE III. Positive Pressure Loading at 10 LPM Ambient Flow

Positive Pressure (Inches of Water)		Altitude (1,000 Feet)
Minimum	Maximum	
-0.45	+1.0	27
+0.01	+2.5	30
+0.01	+2.8	32
+0.01	+3.0	34
+0.01	+3.2	36
+0.01	+3.4	38
+0.30	+3.5	39
+0.30	+5.6	40
+2.00	+7.2	41
+3.40	+8.6	42
+5.30	+10.2	43
+11.20	+15.3	47

Outlet pressure ranges in column 1 shall be allowed the tolerance specified in columns 2 and 3 for the indicated flows.

Column 1	Column 2	Column 3
Outlet Pressure in Range of (Inches of Water)	Pressure Decrease from 10 LPM for Indicated Flows (Inches of Water)	Pressure Increase from 10 LPM to Zero LPM (Inches of Water)
1.0 to 2.0	0.9 at 70 LPM	1.0
2.0 to 15.3	1.3 at 135 LPM	1.3

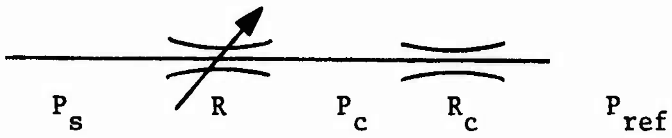
TABLE IV. Flow Suction Values

Supply Pressure (PSI)	Outlet Flows (LPM)	Outlet Suction (Inches of Water)
50	2	0.0 to -0.40
50	30	0.0 to -0.45
50	50	0.0 to -0.70
50	85	0.0 to -1.0
Maximum specified in applicable drawing	85	0.0 to -1.0

APPENDIX D

FUNCTION GENERATOR DESIGN

The function generator consists of a pressure sensor that provides motion to a variable restrictor which modulates the control pressure of a proportional amplifier. Schematically it is:



The equation relating the pressures and the resistances as the variable resistances change is:

$$\frac{P_c - P_{ref}}{P_s - P_{ref}} = \left[1 + \frac{R_B}{R_C}\,\frac{R}{R_B}\right]^{-1} \tag{1}$$

where

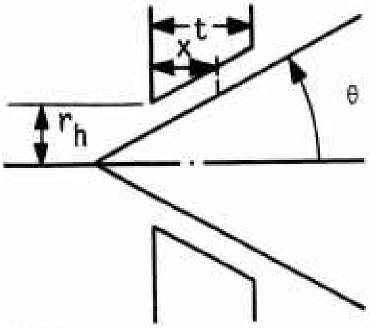
R_C = resistance of the amplifier control part (fixed)
R = resistance of variable resistor
R_B = resistance of the variable resistor at a base position

The resistances are assumed to be the constant of proportionality between flow and pressure drop. Further, it is assumed that the motion of the variable restrictor is linear with cabin pressure. The problem is to design a variable restrictor where R/R_B follows desired function versus cabin pressure.

Combining the equation for a Laminar restrictor and the geometry of a conical annular passage yields

$$R = \frac{1}{8\pi} \frac{t}{\sin\theta \tan^2\theta} \frac{\mu(\alpha + kR_{ey})}{x^3(2r_h - x\tan\theta)} \qquad (2)$$

where



μ = dynamic viscosity

α = $f \cdot R_{ey}$ (a function of cross section shape)

k = entrance pressure drop (a function of cross section shape)

R_{ey} = Reynolds No. = $\frac{Q}{A} D_H \frac{1}{\nu}$

f = friction factor

D_H = hydraulic diameter = $\frac{4A}{C}$

ν = kinematic viscosity

A = area (in^2)

C = perimeter (in)

The equation for the variable in equation (1) is

$$\frac{R}{R_B} = \left(\frac{x_B}{x}\right)^3 \frac{2r_h - x_B \tan\theta}{2r_h - x\tan\theta} \qquad (3)$$

The calculation procedure is as follows:

Knowing R_C, P_s and P_{ref} a geometry of θ, t, r_h is assumed. Then a value for x_B is chosen and using equations 3 and 1 the variation of the output pressure P_C versus cone position x is plotted and compared with the desired function. This procedure is repeated until a satisfactory fit is found.

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