# THE DEVELOPMENT OF AN INSTRUMENT TO CONTROL THE OXYGEN CONCENTRATION AND FLOW RATE OF AN AIR-OXYGEN MIXTURE

by

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# 1. INTRODUCTION

There are many applications for an air-oxygen mixture in the medical field with the capability of variable oxygen concentration for a given flow rate. Some examples of these are: input to a blood oxygenator, input to a respirator, and a supply for an oxygen tent.

The present equipment used for these applications is expensive (about $1500). Due to the lack of equipment, in many cases pure oxygen or air is administered when a mixture would be the most beneficial. The purpose of this study is to develop a device which could be produced less expensive (about $300) and have similar accuracy.

This thesis describes the development of a device which allows the oxygen concentration of a gas flow to vary from 100% air (approximately 22% oxygen) to 100% oxygen for any flow rate from about 4500 $cm^3$/min (4 1/2 ℓ/min)[*] to 1500 $cm^3$/min (15 ℓ/min). The inputs to this device are a constant 340 ± 21 kPa gage (50 ± 3 psig) for both air and oxygen which is standard for medical facilities.

The device (hereafter refered to as the mixing valve) basically consists of two valves: one valve to control the flow of air and the other to control the flow of pure oxygen. The uniqueness of these valves is that the flow rate is linearly proportional[**] to the stem position. This establishes the freedom to vary the relative flow rates

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[*] Liters per minute is the standard measurement for gas flow in the medical industry.

[**] Linearly proportional means a specific change in stem position develops a specific change in flow rate which is equal over the entire range of flow rates.

thus oxygen concentration without changing the total flow rate through the mixing valve. Additionally, since the two valves must work in unison, a mechanical linkage and read-out is required.

The key to the operation of the mixing valve is the flow characteristics of the two valves. The design of these valves however, is very simple. The gas flow is controlled by varying the size of a rectangular slot which is the flow area. The slot is of constant width 0.038 mm (0.0015 in.) and the length is variable up to 13 mm (0.5 in.). These valves are designed to operate in choked flow meaning the gas velocity at the flow area is sonic. When the flow velocity is sonic, the mass flow rate is directly proportional to the flow area establishing the linear flow characteristics of the valves.

An added benefit to operating in choked flow, is the fact that the pressure downstream of the mixing valve has no effect on the operation of the mixing valve as long as the pressure is below the critical pressure (about 140 kPa gauge (20 psig)). That is, at any driving pressure below 140 kPa gauge (20 psig), the settings on the mixing valve are correct.

# 2. EQUIPMENT DEVELOPMENT AND DESIGN

## 2.1 Preliminary Considerations

### 2.1.1 Basic Concepts

There are two basic approaches when attacking the problem of mixing two fluids and controlling the relative concentration of the mixture. They are "quantity" method and "rate" method.

Quantity method is the passing of isolated quantities of each fluid in succession by alternately filling and emptying a known amount. In this case, assume that the desired concentration is 41.5% oxygen or 75% air and 25% oxygen. For every three quantities of air passed there is one quantity of oxygen passed.

Rate method is the passing of a continuous stream of fluid, metered by its interaction with some element such as a valve orifice. In the hypothetical case, the concentration is controlled by adjusting a valve controlling air flow rate to three times as great as the oxygen flow rate. Again this generates an oxygen concentration of 41.5%.

### 2.1.2 Design Concepts

Designing around the quantity method requires a moving mechanical linkage such as two vane type air motors with a variable ratio drive between them to control the concentration or possibly two pneumatic cylinders with a linkage which in some way varies the stroke of each to control the concentration. Problems arise in these types of arrangements from several sources. First, some type of working power is needed whether it be derived electrically or from the fluid being metered. Second, the accuracy of oxygen concentration is related to the capacity of the entrapped fluid. If the capacity were smaller then the accuracy would be greater, but there are problems of motion and speed in the proportioning mechanical elements.

A rate method design is viewed simply as two valves adjusted properly to give the proper concentration. The problem in this design is accurately adjusting these valves to provide the desired concentration. The flow rate through the valves would have to be accurately predicted every time the total flow or concentration is changed. However, the mechanical arrangement is simpler than that of the quantity method. Once the proper valve positions are set, there would be no moving linkages or drives to increase the possibility of mechanical slip.

From the analysis comparing the quantity method to the rate method, the rate method is superior for this application.

## 2.2 Tapered Tube Design

### 2.2.1 Design Concepts

Initially, because of the anticipated varied use of the mixing valve, the design specifications are very broad. They are: to develop a device which will deliver up to 100,000 $cm^3$/min (100 ℓ/min) of an air-oxygen mixture with the output oxygen concentration controllable to within 1% up to 280 kPa gage (40 psig).

The first decision is related to the high pressure requirement relative to 340 kPa gage (50 psig) input. It is simpler to design around a constant pressure drop across a metering element because the flow through a metering element such as an orifice is related to the pressure drop. Therefore, the downstream pressure is maintained at a constant 280 kPa gage (40 psig).

The type of metering element needed is one which has linear flow characteristics at a constant pressure drop, is controllable to close tolerance, and is easily and cheaply fabricated. By observation, a rotameter* appears to have the needed linear characteristics. Many are accurate to within the necessary 1% and the device is easily fabricated. Since the operation of a rotameter is actually a balance of forces on the metering element (float), then control of flow rate is a force balance. Instead of balancing just the weight of the element, a force is imposed which will have some relationship to the flow rate. Varying this force is accomplished using a pressure regulator with a cylinder and piston.

### 2.2.2 Schematic and Operation

Figure 1 shows schematically the design arrangement. F1 and F2 are pressure regulators, PG1 and PG2 are pressure gauges, C1 and

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*"A rotameter is a very commonly used flow measurement device... The flow enters the bottom of the tapered vertical tube and causes the bob or 'float' to move upward. The bob will rise to a point in the tube that the drag forces are just balanced by the weight and buoyancy forces."[1]

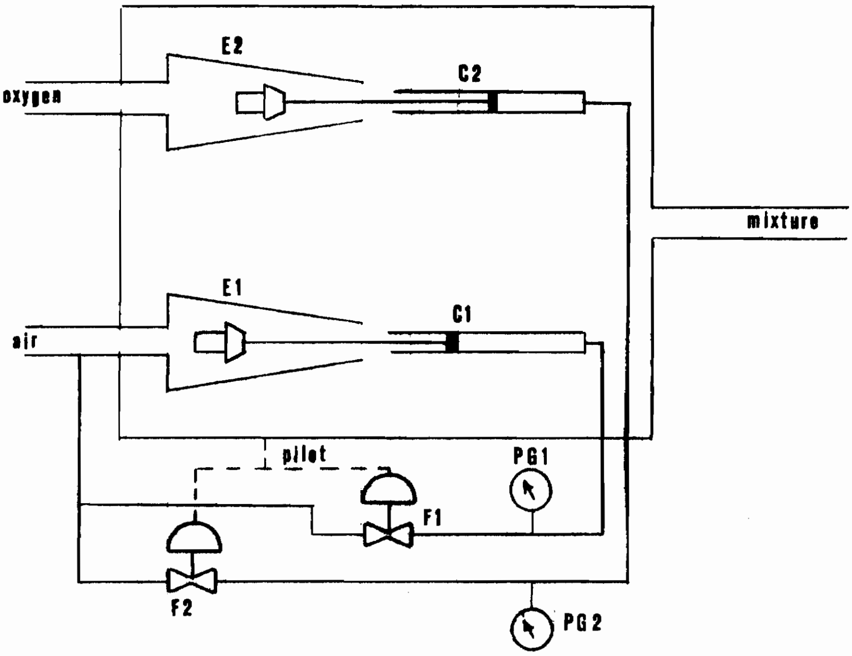


FIGURE 1. Schematic of Tapered Tube Design

C2 are cylinders and pistons, and E1 and E2 are metering elements (floats). The taper of the tubes is opposite that of a conventional rotameter: the smaller end is downstream of the metering element. This is necessary so that the greater force establishes the greater flow.

The operation of the system is as follows. The following gas (air or oxygen) imposes a drag force on the metering element which is linearly proportional to the mass flow rate for the particular gas. To balance this force, pressure is applied to the cylinder which is proportional to the drag force. Thus, the imposed pressure on the cylinder is proportional to the mass flow rate through the tube. The greater the pressure is, the greater the flow rate becomes.

The pressure applied to the cylinders is controllable by the pressure regulators and can be read by the pressure gages. The total flow (through both the air and oxygen tubes) is a function of readings on PG1 and PG2. The oxygen concentration is a function of the ratio PG2/(PG1 + PG2). Thus, once the system is calibrated, it is a simple mathematical operation to determine the total flow rate and the oxygen concentration.

The big advantage to this system is the stability of oxygen concentration when the flow rate is varying, since the pressure regulators maintain the downstream chamber at 280 kPa gage (40 psig) and are sensitive to change in flow. If the flow increases, the pressure in the chamber drops slightly. This causes the pressure regulators to increase the pressure to the cylinders and thus increasing the total flow rate. Thus, once the proper ratio of pressure is set, the oxygen concentration is maintained for any flow rate. The chamber is viewed as a tank of air-oxygen mixture with the capability of changing the oxygen concentration.

### 2.2.3 Analysis

The analysis of this system is the determination of the numerical relationship between the imposed force by the cylinders and the flow rate through the tube for a given tube and float size. Because it is assumed that the characteristics are the same for both air and oxygen so air is used as the representative fluid.

The assumptions in this analysis are as follows:

1. Reversible isentropic flow
2. Tube taper is not so great to influence flow (i.e., the tube is considered without taper)
3. Gases are ideal

Figure 2 is generated from calculations shown in detail in Appendix B. These results are for a float diameter of 5 mm (0.2 in.) which is as small as practical considering available resources.

### 2.2.4 Evaluation

The tapered tube design is impractical because the forces are too small to work with easily and the flow range is limited.

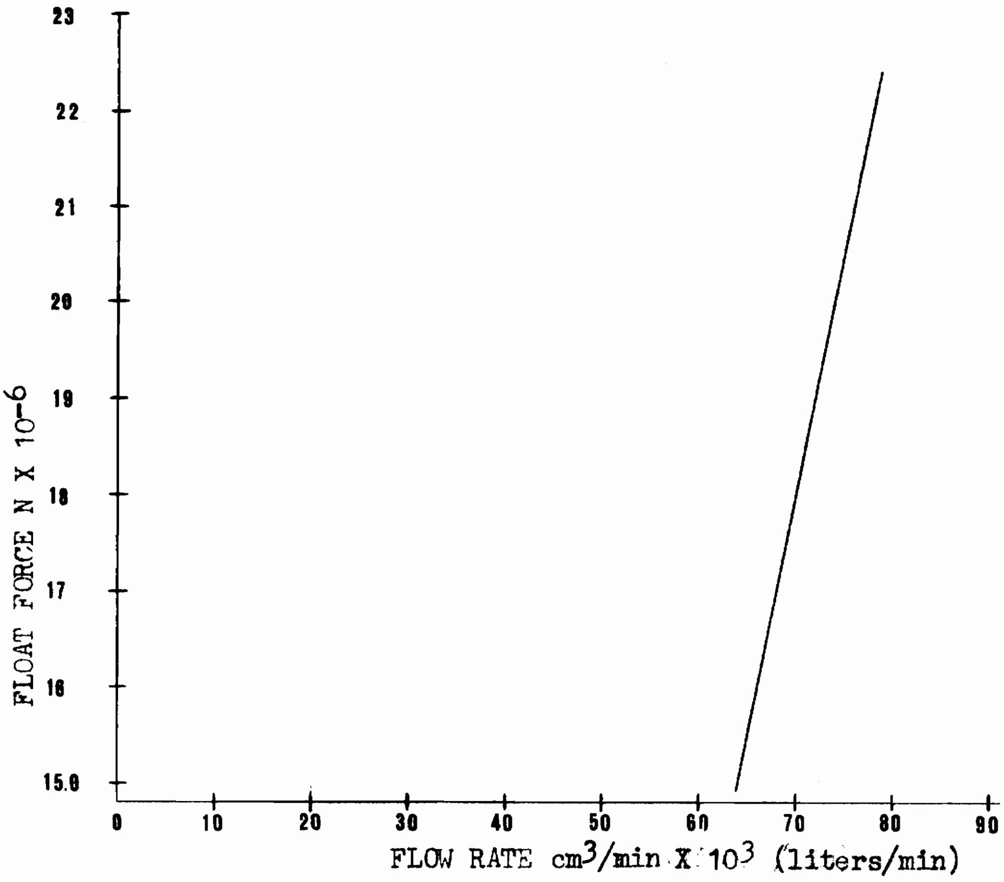


FIGURE 2. Flow Rate vs Float Force for Tapered Tube Design

As a result of discussion with Dr. L. J. Arp, it was decided that the lower flows (below the 15,000 $cm^3$/min (15 ℓ/min)) at lower pressures (up to 100 kPa gage (15 psig)) have a more important end use than the higher flows at higher pressures. Therefore, the tapered tube design was abandoned and the design specifications for the mixing valve were changed to eliminate the use for high flow, high pressure applications.

## 2.3 Choked Flow Design

### 2.3.1 Design Concepts

The design specifications are to develop a device which controls the oxygen concentration of an air-oxygen mixture up to 15,000 $cm^3$/min (15 ℓ/min) at pressures up to 100 kPa gage (15 psig).

Because the output pressure is low relative to the input pressure, a different flow condition is used for flow control, choked flow. Choked flow refers to the condition when the fluid velocity at the control element is sonic. In this condition, with no other change, an increase in the upstream pressure or a decrease in the downstream pressure has no effect on the mass flow rate through the control element. This condition exists whenever the downsteam pressure is below the critical pressure. There are important advantages relative to the subject application which are described below.

First, when the flow is choked, ideally the mass flow rate is directly proportional to the flow area (cross-sectional area where fluid velocity is sonic). Therefore, if the flow area changes linearly with some parameter, then the mass flow rate changes linearly with the same parameter.

Second, because the downstream pressure has no effect on the flow rate, equipment downstream of the mixing valve has no effect on the flow rate as long as the downstream pressure remains below the critical pressure and the supply pressure is unchanged. This means the user of the mixing valve need not be greatly concerned with the flow resistance of the driven equipment. The settings of the mixing valve are constant whether at no load or 100 kPa gage (15 psig).

### 2.3.2 Schematic and Operation

Figure 3 shows schematically the design arrangement. A1 and A2 are the flow areas and P2 is the downstream pressure. The flow rate is directly proportional to the flow areas. Thus, the total flow rate is a function of A1 plus A2 and the oxygen concentration is a function of the ratio A2/(A1+A2). The flow areas are variable such as in a valve stem and seat but the areas are linearly proportional to some controllable parameter. The total flow rate is set by knowing the total flow areas of both orifices and the oxygen concentration is set by the above ratio.

### 2.3.3 Analysis

The analysis covers:

1. The verification of the linearity between mass flow rate and the flow area.

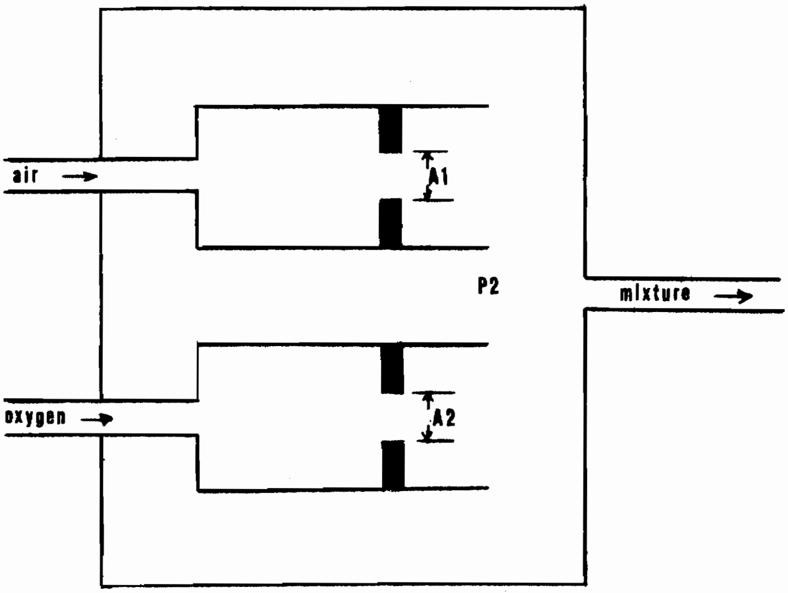


FIGURE 3. Schematic of Choked Flow Design

2. The verification that the flow area changes linearly with a controllable parameter.
3. Calculation of the critical pressure.
4. The comparison of the similarity of the flow parameters between air and oxygen.

From Streeter and Wylie[1], their equation for a ratio of specific heats equal to 1.40 as applied to a perfect gas for one-dimensional, frictionless flow is shown below.

$$\dot{m}_{max} = 0.686\ A^{*}\ Po/\sqrt{RTo} \qquad (1)$$

where $A^{*}$ = critical area

$\dot{m}_{max}$ = maximum air flow rate

Po = upstream pressure

R = gas constant

To = total temperature

Referring to the above equation, Streeter and Wylie state "that the mass flow rate varies linearly as $A^{*}$ and Po and varies inversely as the square root of the absolute temperature."[2] Po in this application is constant and To is relatively constant.

Choosing the flow area to be rectangular and the controllable parameter to be position makes the flow area change linearly. The change in position is in effect "collapsing" one side of the rectangle. When the side is halved then the flow area is halved.

The critical pressure ratio is the maximum pressure ratio between the inlet and the outlet of the flow element and have choked flow. The equation from Streeter and Wylie[3] which describes this ratio is given below:

$$P^*/Po = (2/(k+1))^{k/k-1} \tag{2}$$

where $P^*$ = critical pressure

$k$ = ratio of specific heats

$Po$ = inlet pressure

For oxygen, $k = 1.395$ and for air $k = 1.401$, thus a value of $k = 1.40$ is assumed for both air and oxygen. Therefore, $P^*/Po = 0.528$. Thus, the critical pressure for this application using 340 kPa gauge (50 psig) input is 130 kPa gage (19.5 psig).

Referring back to equation 1, the only difference between air and oxygen is the gas constant "R". For air this constant is 287 m • N/Kg • K (53.3 ft • $lb/lb_m$ • R) and 260 m • N/Kg • K(48.3 ft • $lb/lb_m$ • R) for oxygen. If one assumes identical metering elements, this is a difference in mass flow rate of about 5% which is accounted for in calibration.

### 2.3.4 Evaluation

The flow characteristics are well suited for this application plus the equipment is simple and easily machined. From an operational standpoint, this design is good because the positions of the flow elements are easily adjusted with a screw and nut.

## 2.4 Design of Mixing Valve

### 2.4.1 Design of the Metering Element

The first step in the design of the metering element is to determine the maximum flow area. Equation 1 is rewritten as shown below:

$$A^* = \dot{m}_{max} \sqrt{RTo} \ / \ 0.686\ Po$$

For a mass flow rate of 1.18 g/min ($2.60 \times 10^{-3}$ lbm/min), $A^*$ equals $0.516 \times 10^{-6}$ $m^2$ ($0.800 \times 10^{-3}$ $in^2$). This is the area required for maximum flow rate. Since a rectangle is chosen as the shape of the flow area, the length times the width of the rectangle equals the flow area. Therefore, the narrower the width, the longer the length becomes making the positioning more accurate. A very narrow "slot" is used to control the flow because the area is so small. As shown by Figure 4, this is fabricated by laminating two pieces of brass stock with brass shim stock between them. The brass shim stock is cut to provide for the slot. The thinnest shim stock available was 0.038 mm (0.0015 in.). The mating parts are hand-lapped for flatness. A small cavity is cut to shorten the distance of gas flow along the slot. This is done to insure choked flow and to best stagnate the flow ahead of the slot.

To control the length of the slot and thus the flow area, a part of the slot is covered. This is done (shown by Figure 5) with a spring loaded piece with a rubber insert. The spring provides a

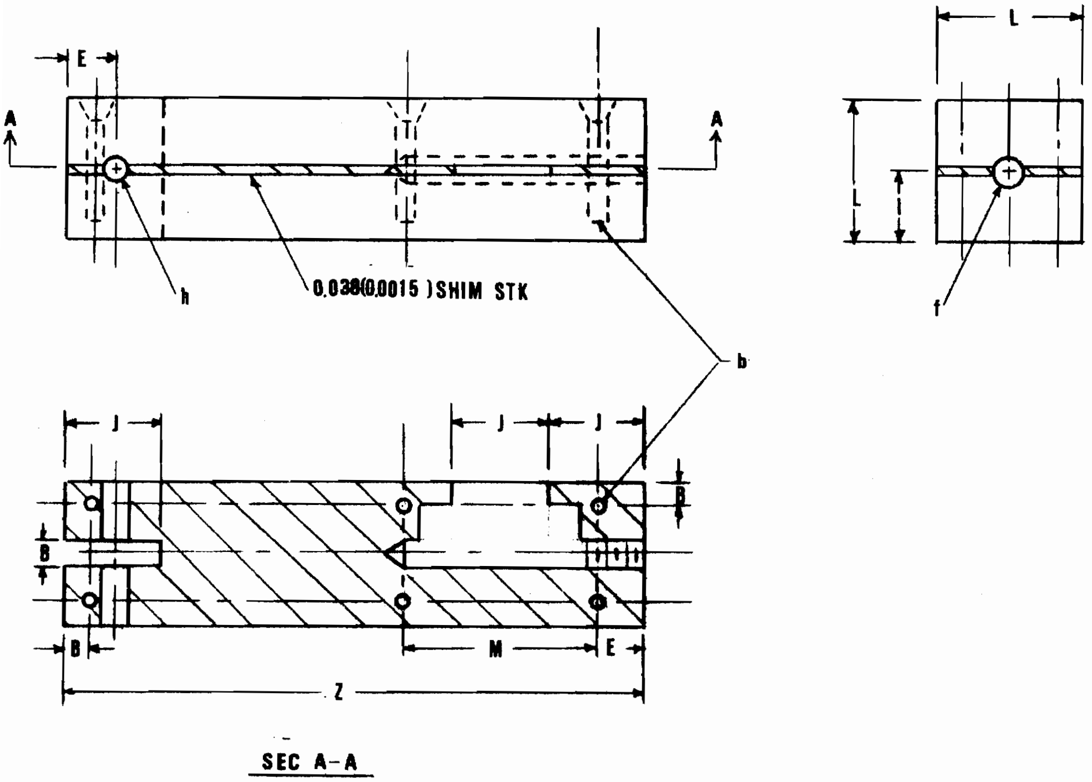


FIGURE 4. Metering Element Assembly
Assembly-1
Scale: 1=1

Note: All material in this and subsequent figures is brass unless otherwise noted

Letters refer to dimensions in Tables 19 and 20 of Appendix A

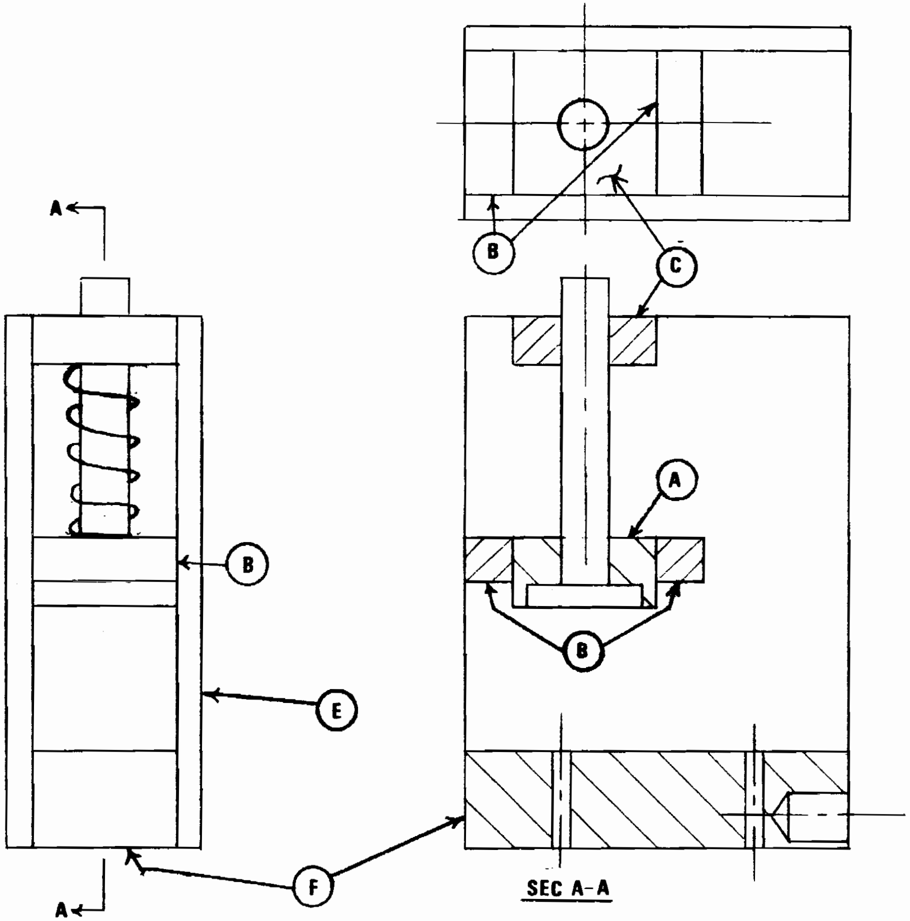
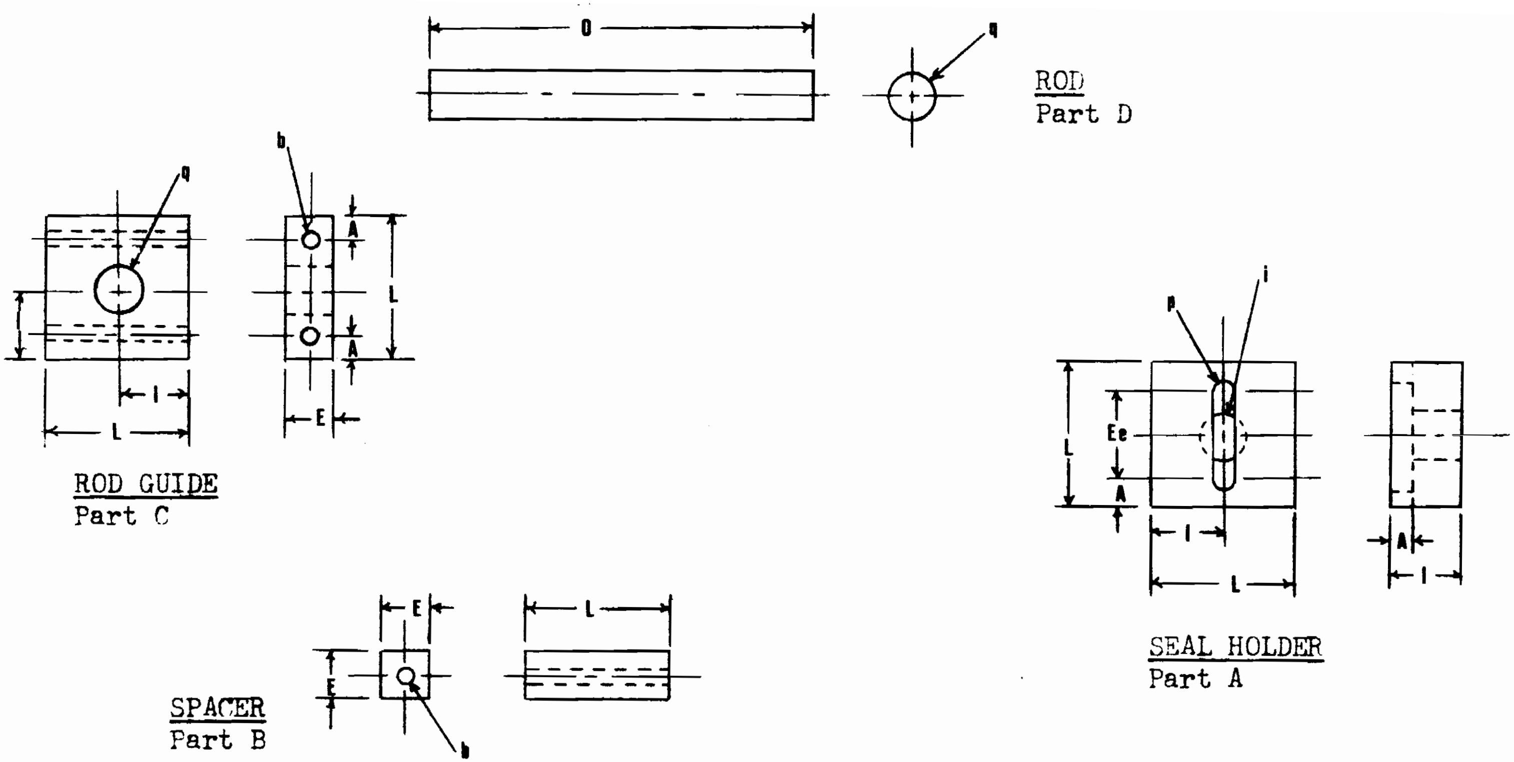


FIGURE 5. Metering Element Seal Assembly
Assembly-2
Scale: 1=1
(See FIG.6&7 for Details)

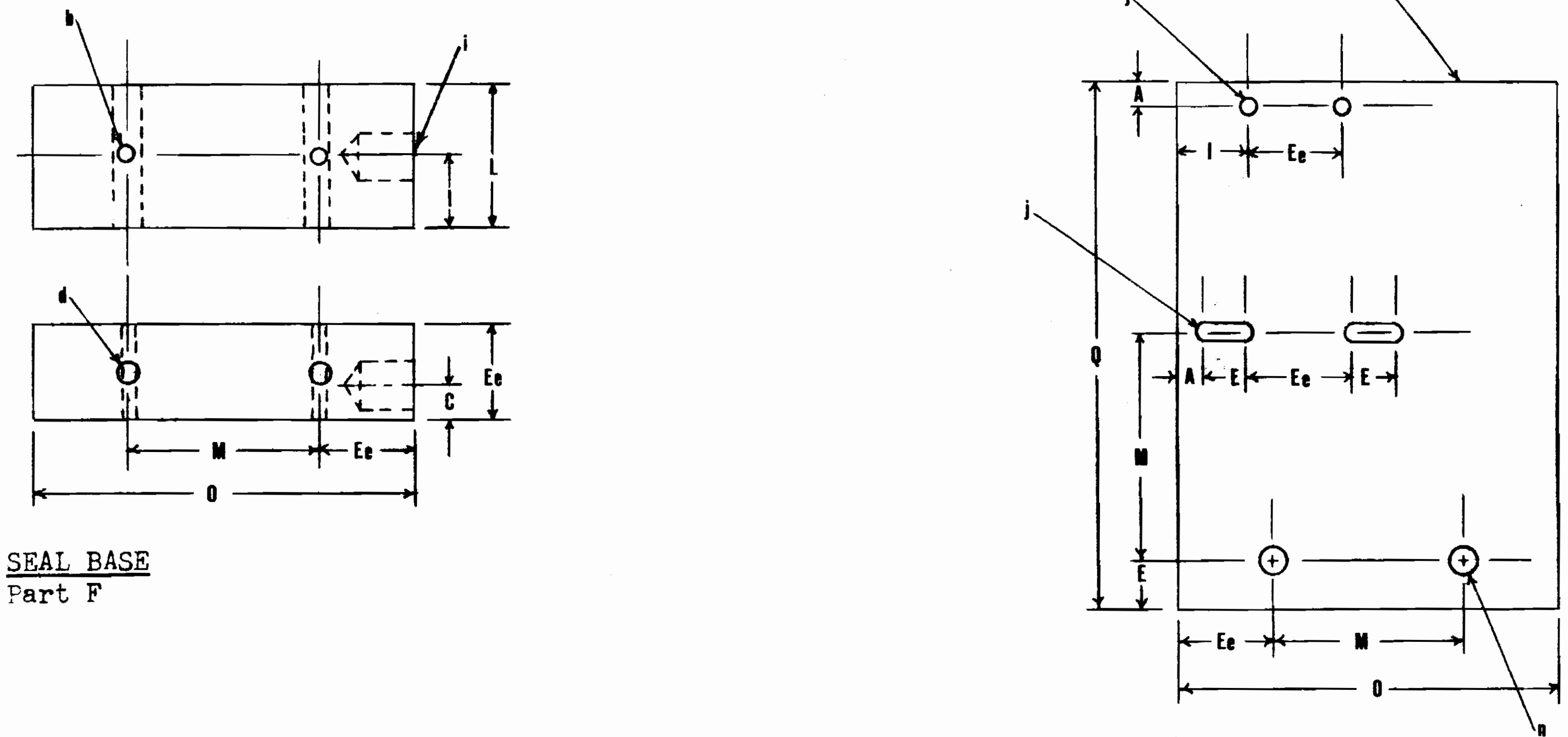

ROD
Part D

ROD GUIDE
Part C

SEAL HOLDER
Part A

SPACER
Part B

FIGURE 6. Details of Metering Element Seal Assembly
Scale: 1=1



SEAL BASE
Part F

SEAL SIDE
Part E

FIGURE 7. Details of Metering Element Seal Assembly
Scale: 1=1

constant force and is capable of adjusting for wear. Rubber is needed as a seal over the covered portion of the slot. The durometer* of the rubber is not known but estimated to be 80.

### 2.4.2 Design of Linkage

The linkage is the mechanism which positions the metering elements. The linkage ties together the position of both the air metering element and the oxygen metering element. This is done so that after the total flow rate is chosen, the rate remains constant as the concentration is varied.

Figure 8 shows the operation schematically. The position of point "B" sets the total flow. Points "A" and "C" pivot about point "B" setting the oxygen concentration. Mechanically, point "B" is moved relative to a base with a screw and nut (refered to as the total flow screw) while point "C" is moved relative to point "B" again with a screw and nut (refered to as the concentration screw).

### 2.4.3 Read Out Design

The read out is designed to indicate total flow rate and oxygen concentration. These two parameters are not directly related to the revolutions of the controlling screws. The revolutions of the total flow screw are proportional to the total flow rate, but the oxygen concentration is related to both the revolutions of the total flow screw and the revolutions of the oxygen concentration screw.

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*Durometer is used to describe the resiliency of rubber.

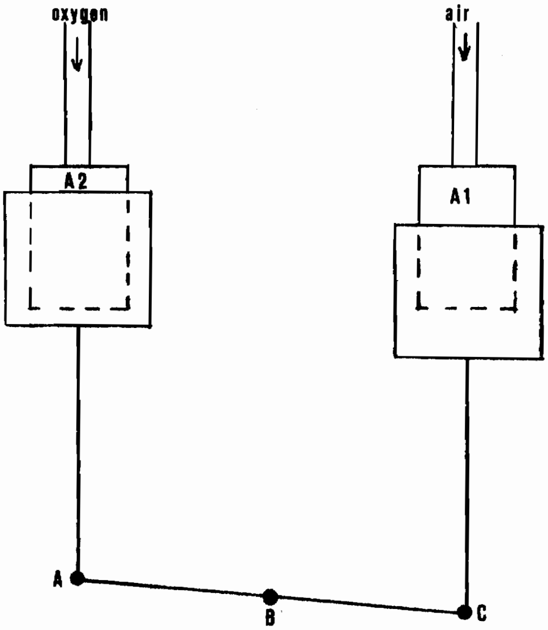


FIGURE 8. Schematic of Mechanical Linkage

As an example, if the revolutions of the total flow screw from zero flow is 5 then 40% oxygen is 1 1/4 revolutions of the concentration screw from 60% concentration. However, if the revolutions of the total flow screw is 7, then 40% oxygen is 1 3/4 revolutions of the concentration screw. To further complicate this, air is about 22% oxygen which also must be taken into account. Mathematically this is shown by the equations below:

$$Q_t = N_f \cdot K$$

where $Q_t$ = total flow rate

$K$ = calibration constant

$N_f$ = revolutions of total flow screw from zero flow rate

$$C_o = 0.39\ N_c/N_f + 0.22$$

where $C_o$ = oxygen concentration

$N_c$ = revolutions of concentration screw

The read out mechanically simulates the above equations. It consists of a pivot and lever type arrangement moving a calibrated scale.

Figure 9 shows schematically how this works. The lever pivots about point "A". The scale is read at the pointer which is positioned by the lever. The positioning of the lever is controlled by the two wires. Wire "F" moves horizontally proportional to the flow rate positioning wire "C" to the proper point along the lever. Wire "C" moves vertically proportional to the concentration screw positioning the lever to the proper angle. The concentration is then read on

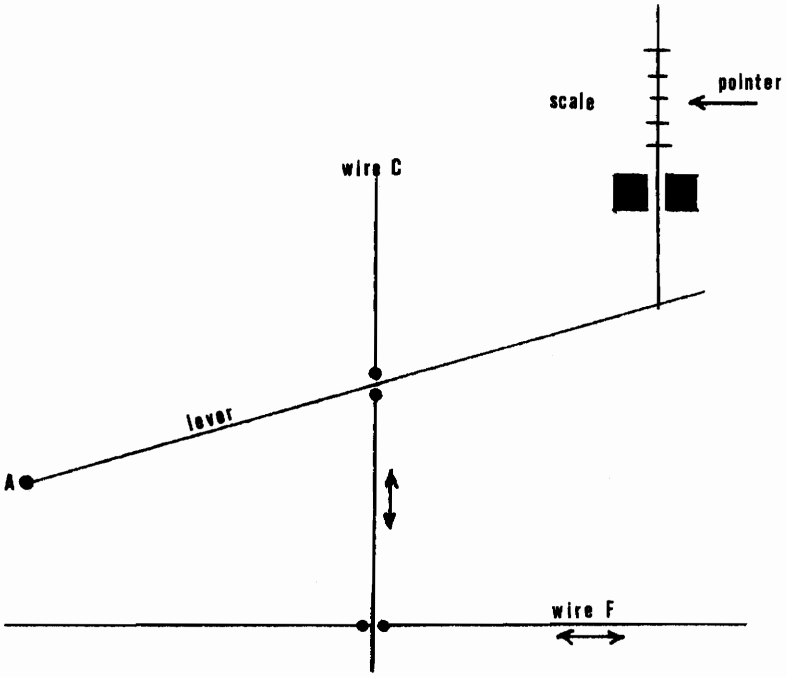


FIGURE 9. Schematic of the Read-Out

the scale.

The hardware is similar to a radio dial. Figure 10 illustrates the equipment.

### 2.4.4 Overall Design

This section covers the design of the enclosure, the elimination of hystersis, and miscellaneous information. Figure 12 is the assembly of the mixing valve.

The enclosure serves as the mixing chamber for the air and oxygen, is strong enough to contain the maximum pressure of 100 kPa gauge (15 psig) and has a plexiglass top to observe the operation of the mechanism. The important aspect is to be "air-tight" to prevent significant leakage. "O" rings are used as a seal around the screw shafts. Silicon rubber is used to seal joints. Figure 13 shows the design of the "O" ring plates and Figures 14, 14A show the design of the enclosure.

Hystersis is generated in the mechanism from screws running in and out and from pins working on either side. To eliminate this on the air side of the mechanism, spring "A" is installed (see Figure 12). This removes the hysteresis in the concentration screw and the connecting pins. The flow screw hysteresis is removed by spring "F".

Silicon grease is used for all lubrication. Petroleum lubricants vaporize and are a serious fire danger when used around high oxygen concentrations.

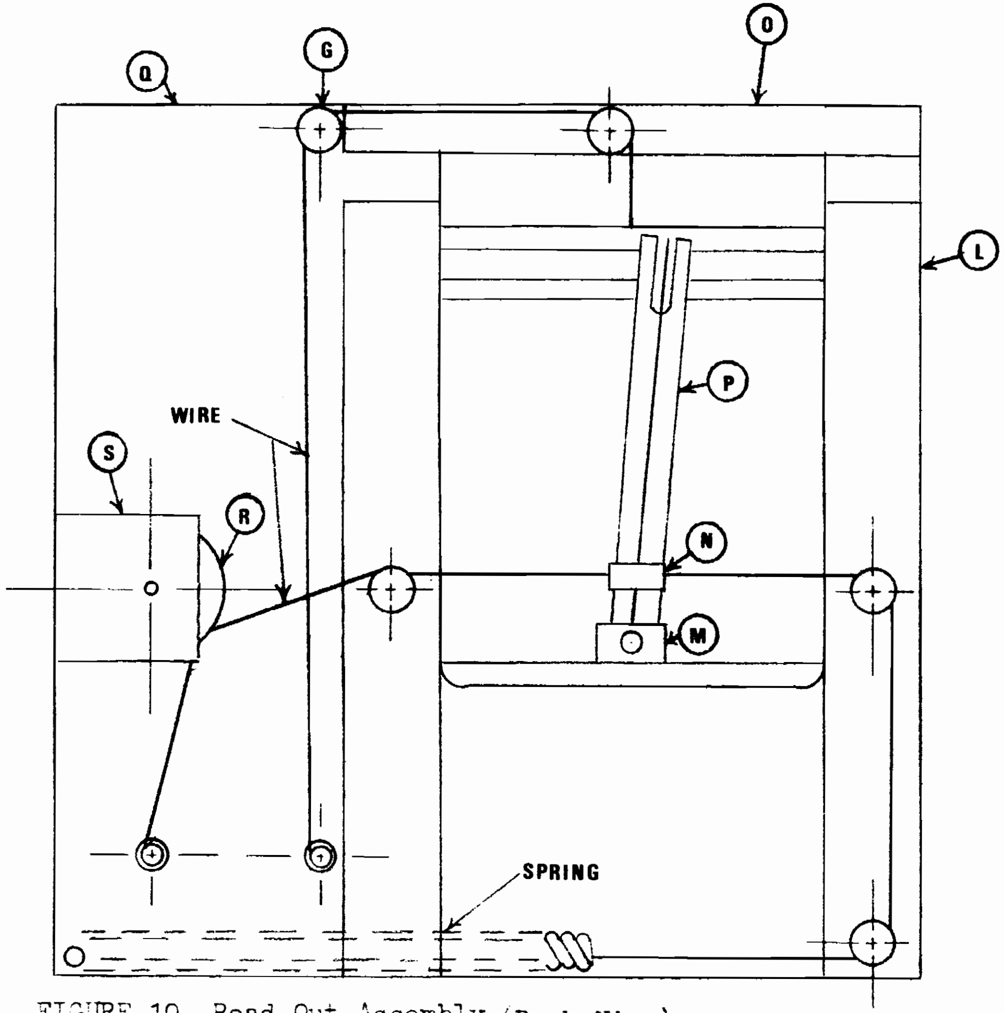


FIGURE 10. Read-Out Assembly (Back View)
Assembly-3
(See FIG.11-11E for Details)

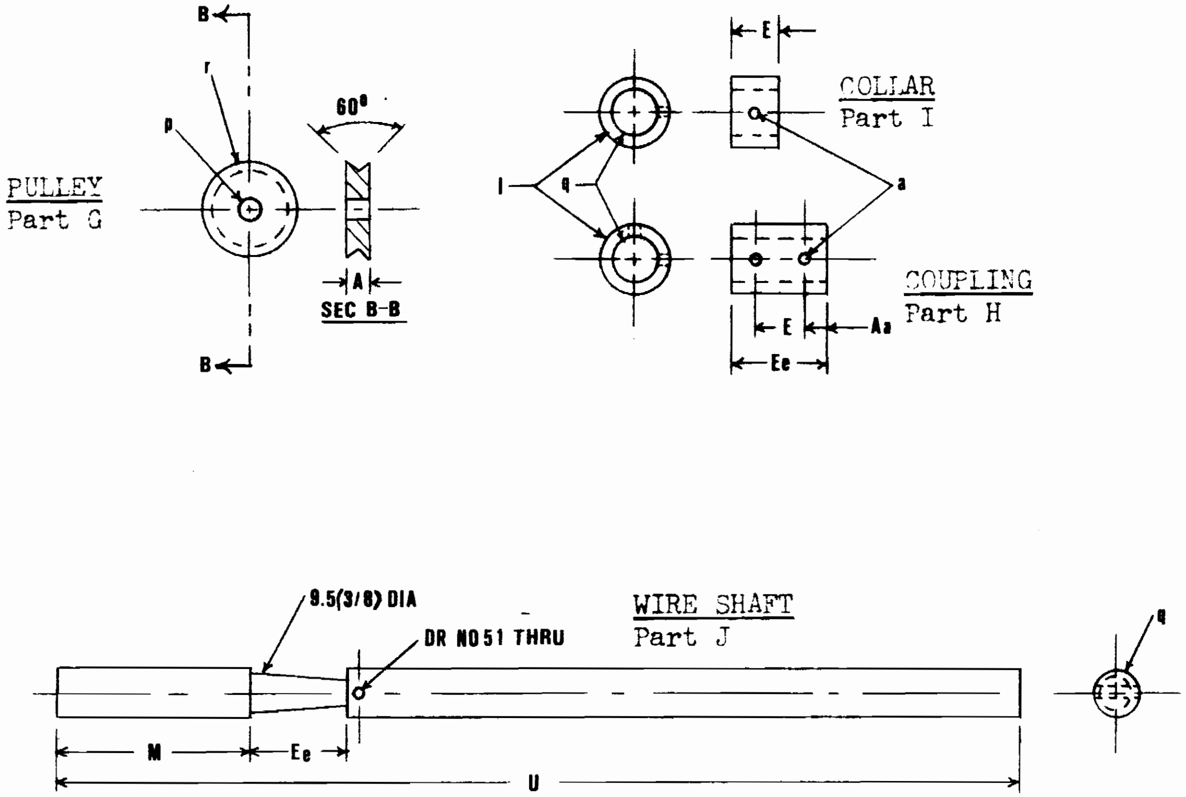
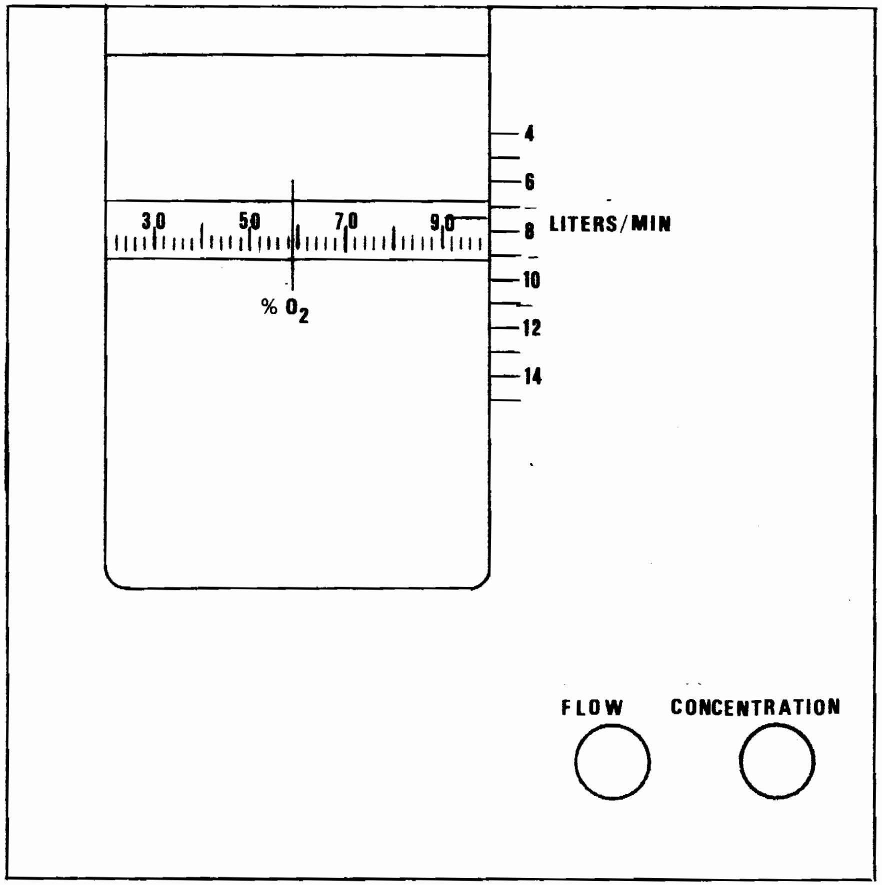
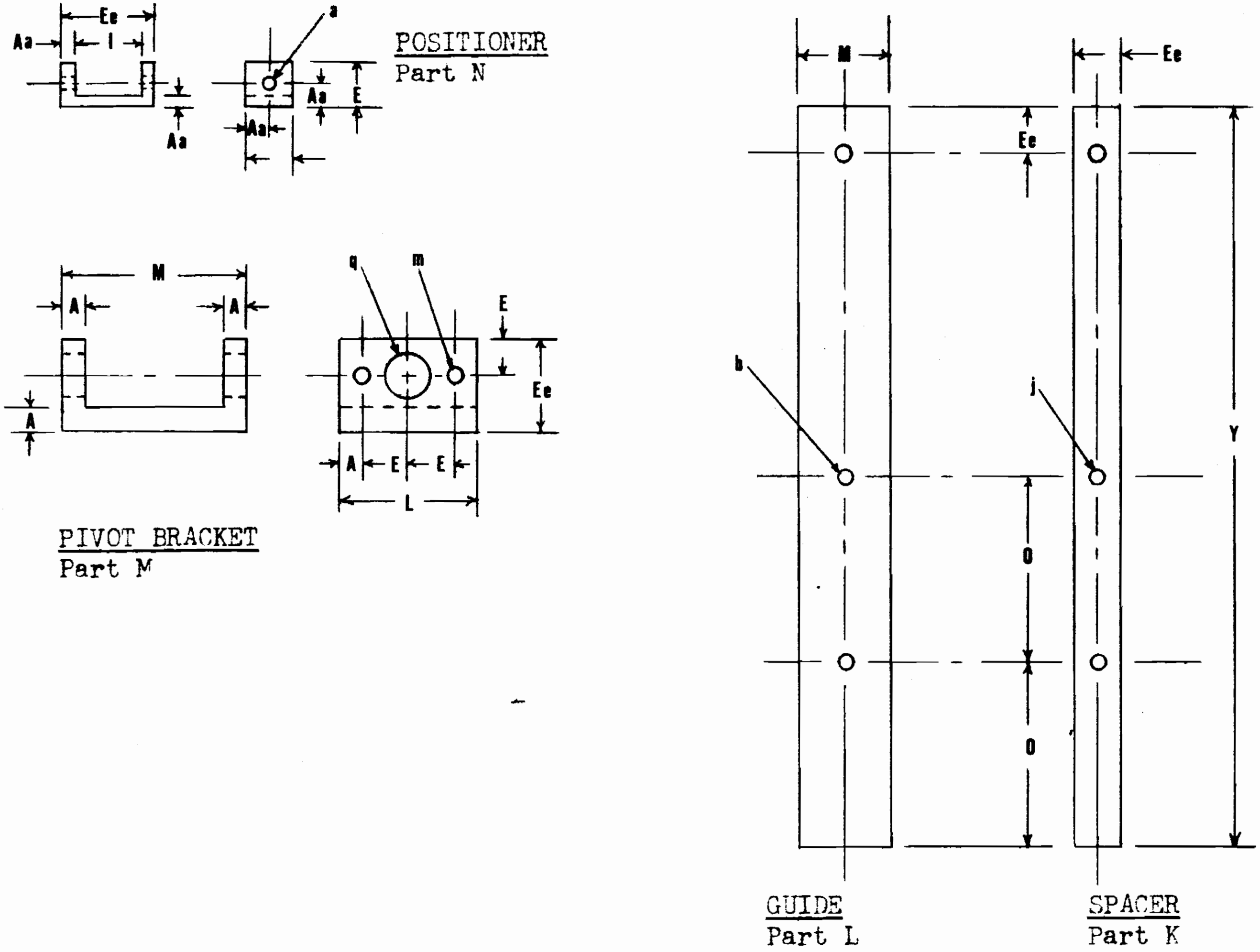


FIGURE 11. Details of Read-Out Design
Scale: 1=1



FRONT PANEL LAYOUT

FIGURE 11A. Details of Read-Out
Scale: 1=1



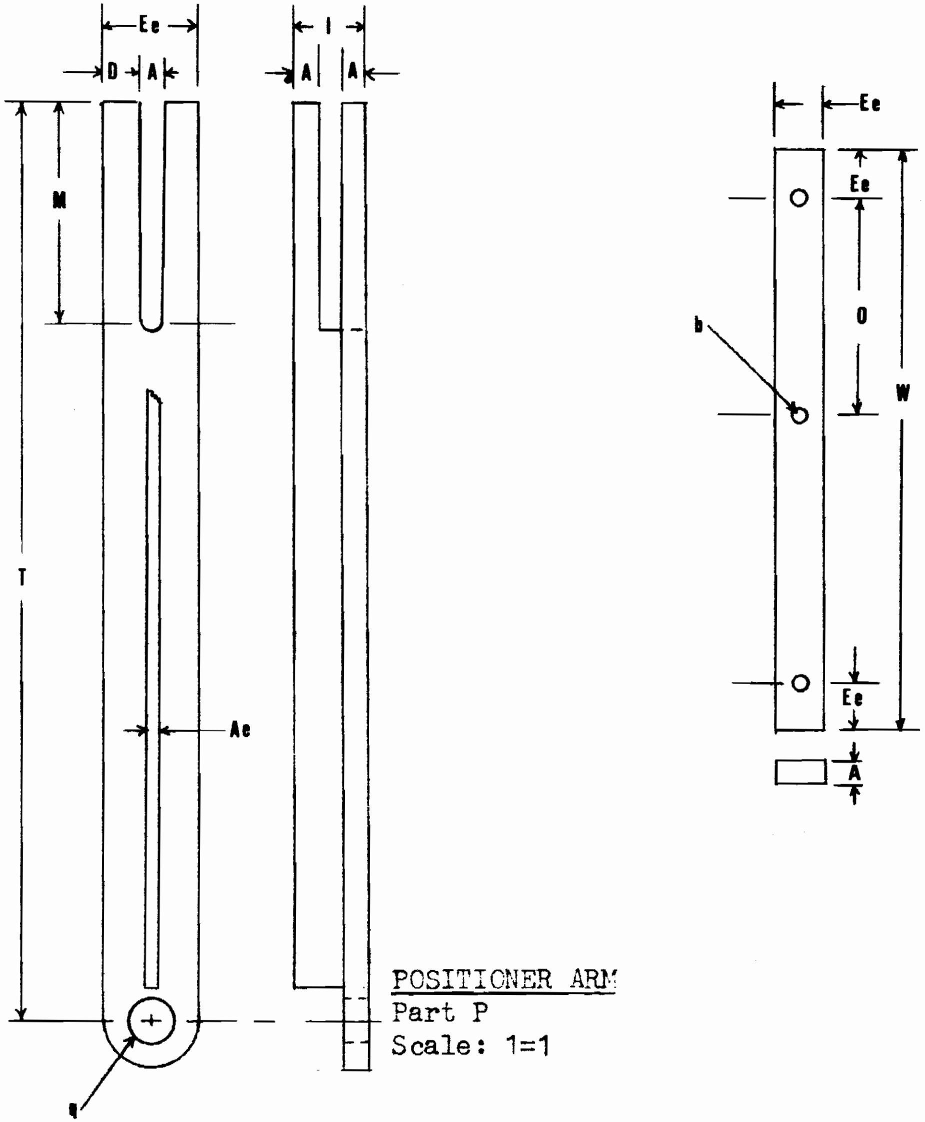
POSITIONER
Part N

PIVOT BRACKET
Part M

GUIDE
Part L

SPACER
Part K

FIGURE 11B. Details of Read-Cut
Scale: 1=1
Mat'l: Al



POSITIONER ARM
Part P
Scale: 1=1

CROSS SUPPORT
Part O
Scale: 1=2

FIGURE 11C. Details of Read-Out
Mat'l: Al

**FACE**
Part Q

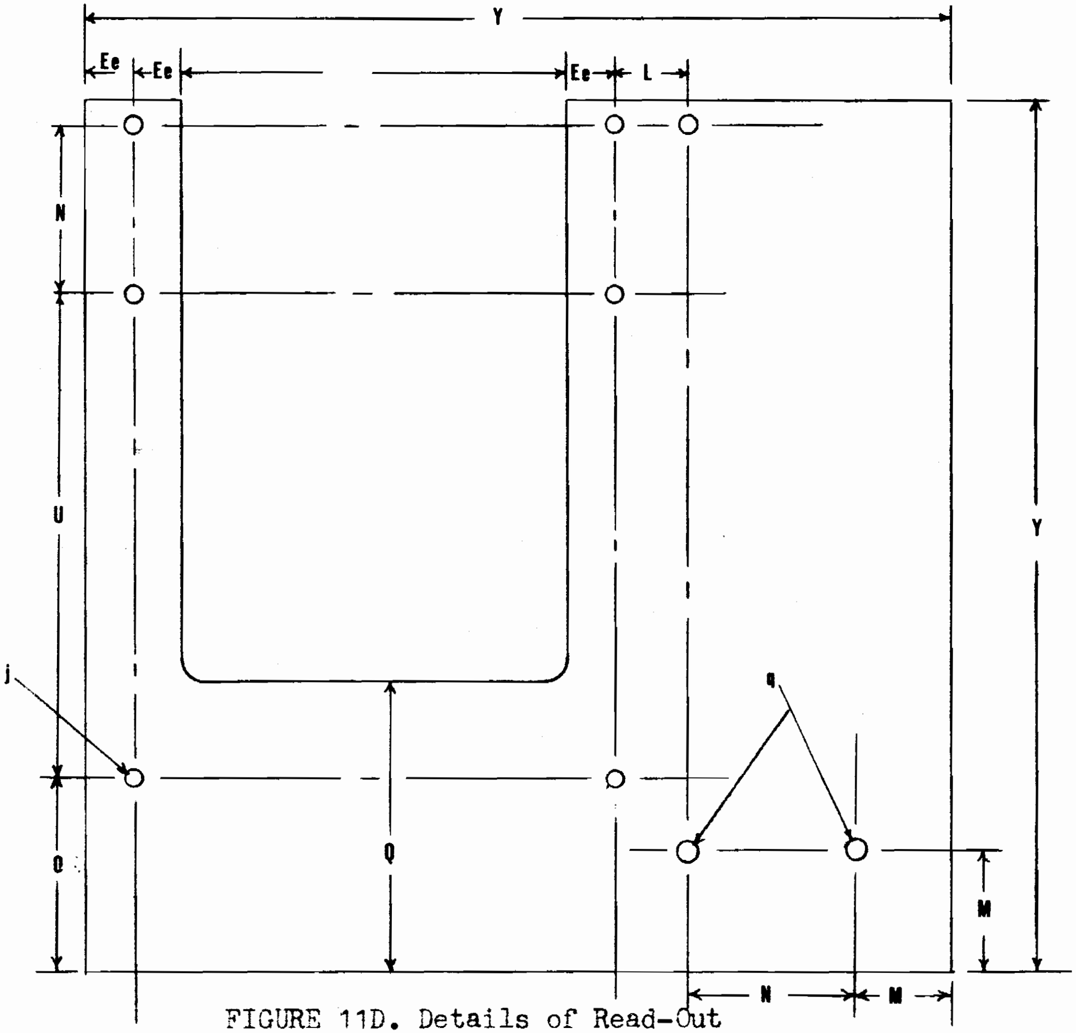


FIGURE 11D. Details of Read-Out
Scale: 1=2
Mat'l: Al

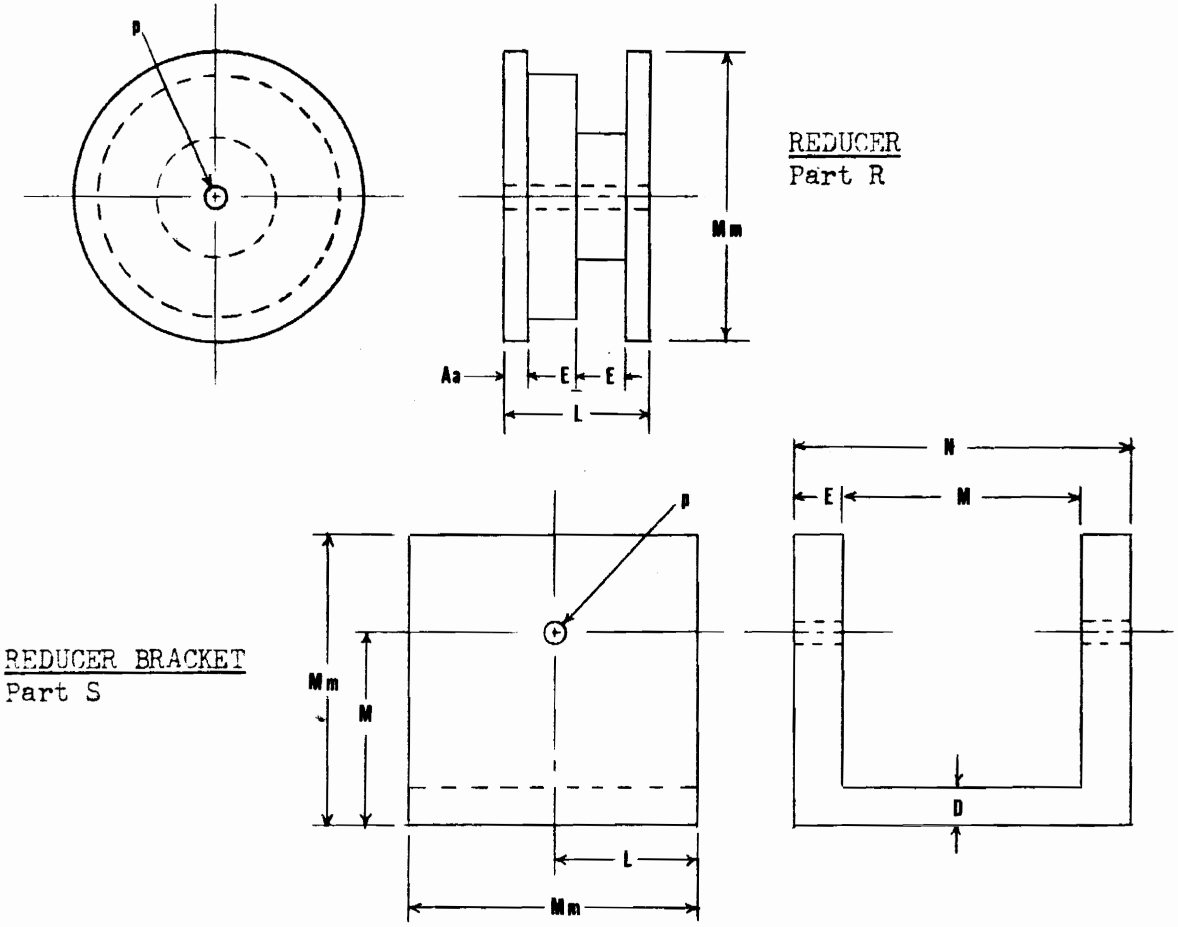


FIGURE11E. Details of Read-Out
Scale: 1=1
Mat'l:Al

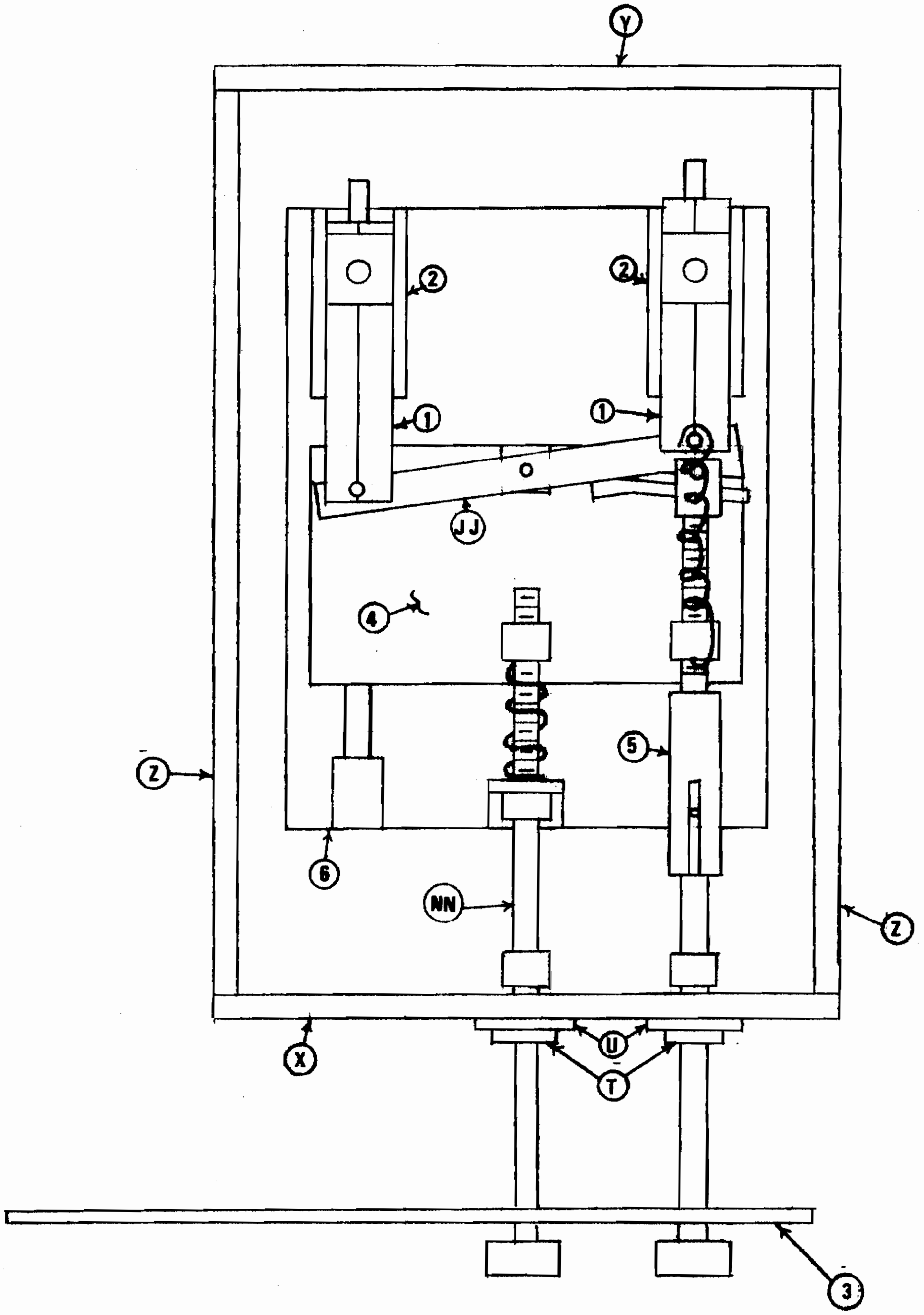
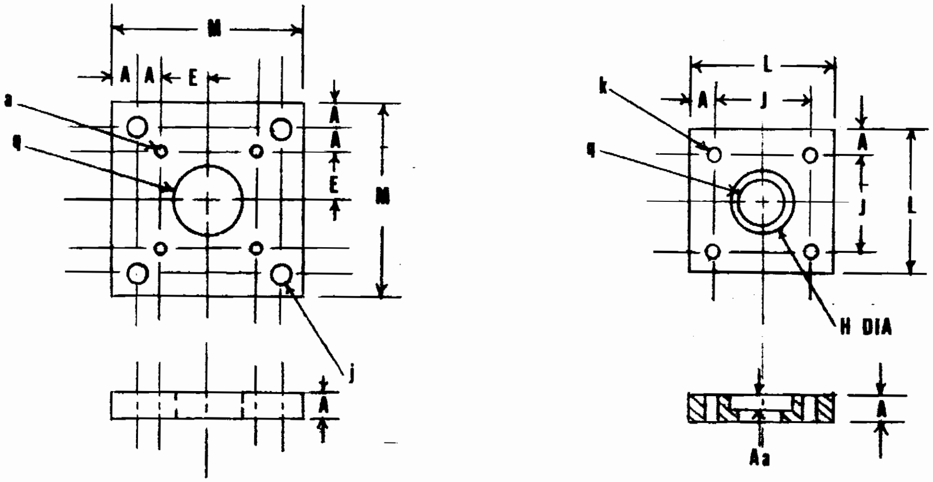


FIGURE 12. Overall Assembly

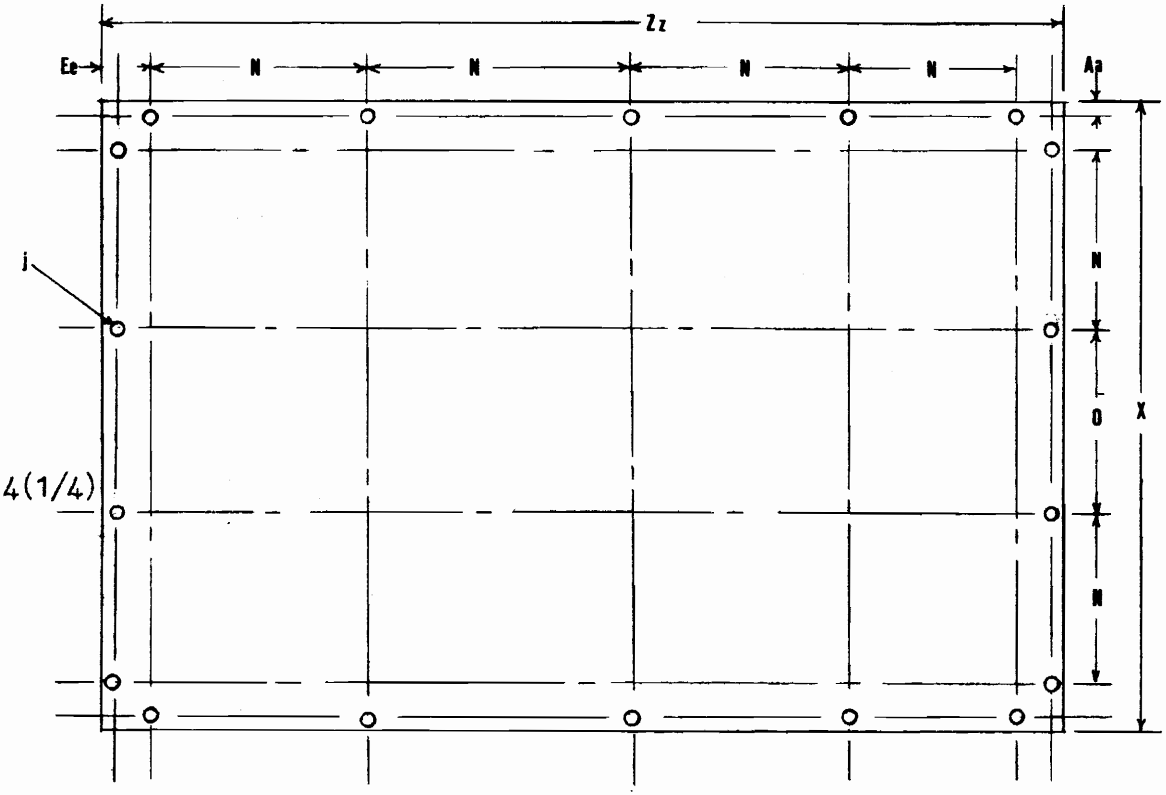


BASE PLATE
Part T

RING PLATE
Part U

Note: For No. 5 ring

FIGURE 13. Details of "O" Ring Plates
Scale: 1=1



<u>BOTTOM</u>
Part W
Mat'l: 6.4(1/4)
Al

<u>TOP</u>
Part V
Mat'l: 19(3/4)
Plexiglass

FIGURE 14. Details of Enclosure
Scale: 1=2

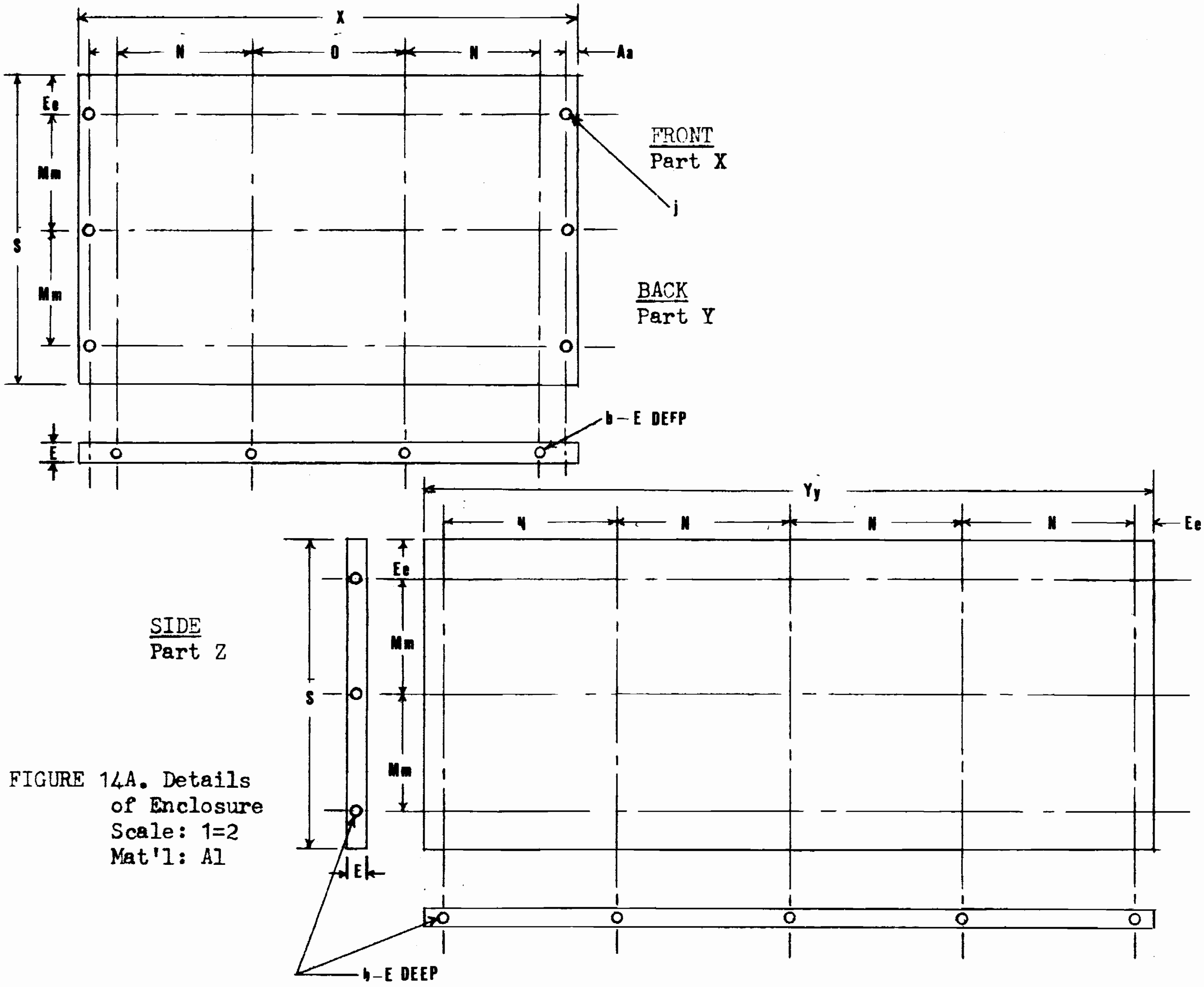


FIGURE 14A. Details
of Enclosure
Scale: 1=2
Mat'l: Al

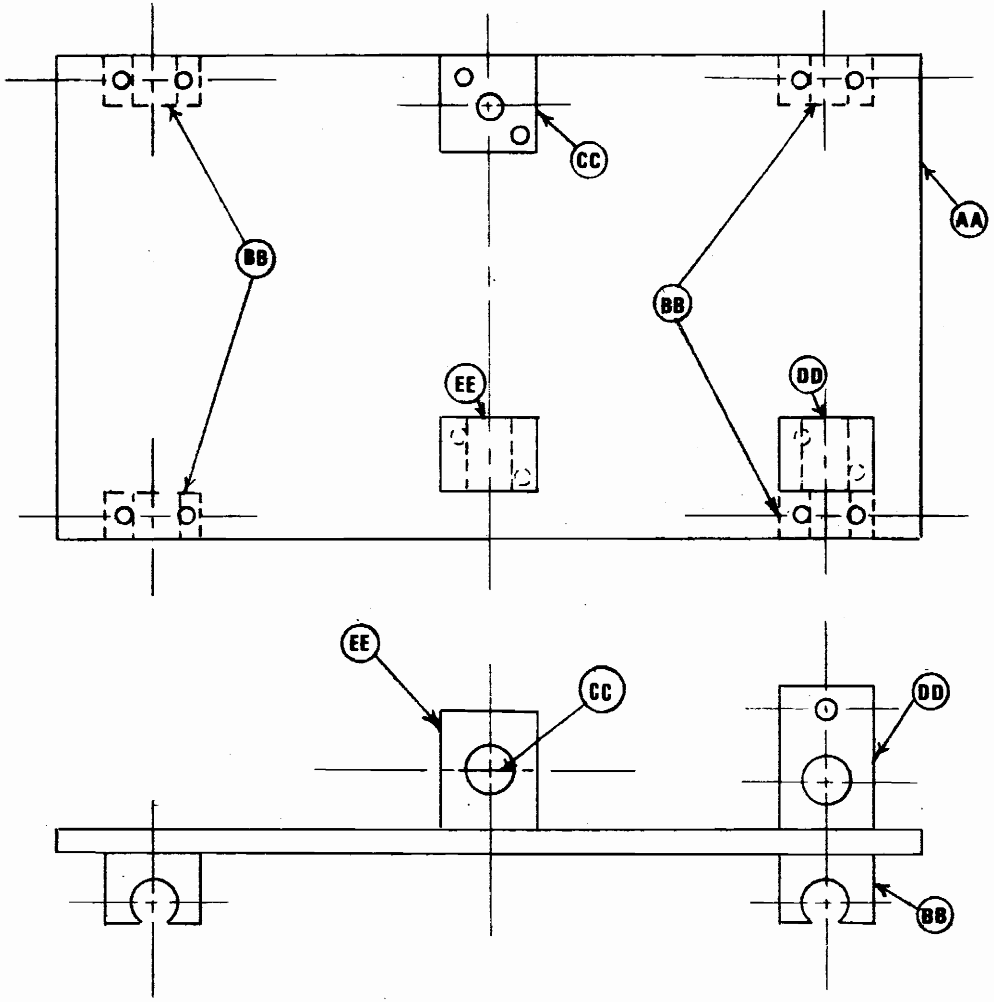


FIGURE 15. Sliding Base Assembly
Assembly-4
Scale: 1=1
(See FIG. 15A for Details)

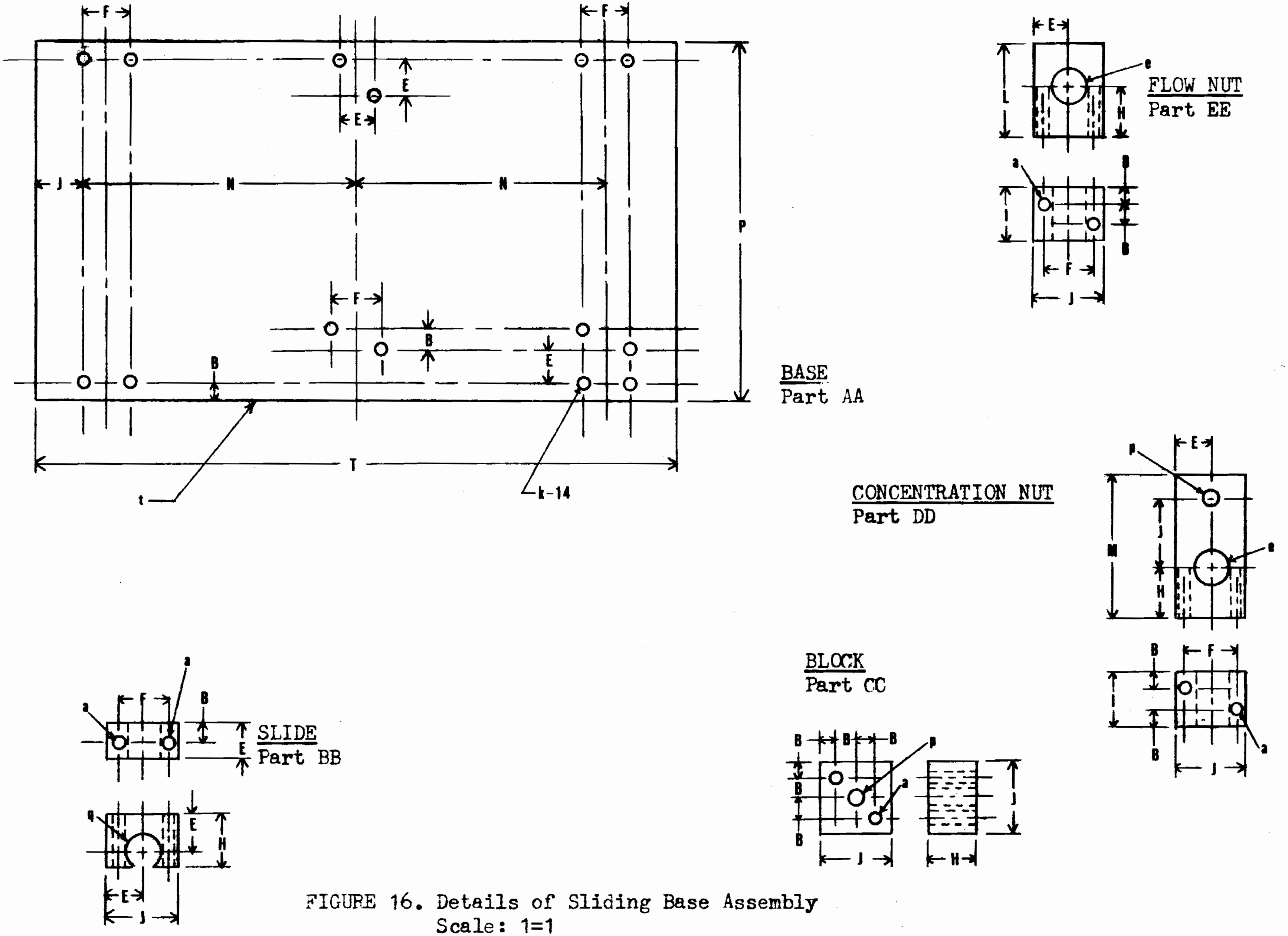


FIGURE 16. Details of Sliding Base Assembly
Scale: 1=1

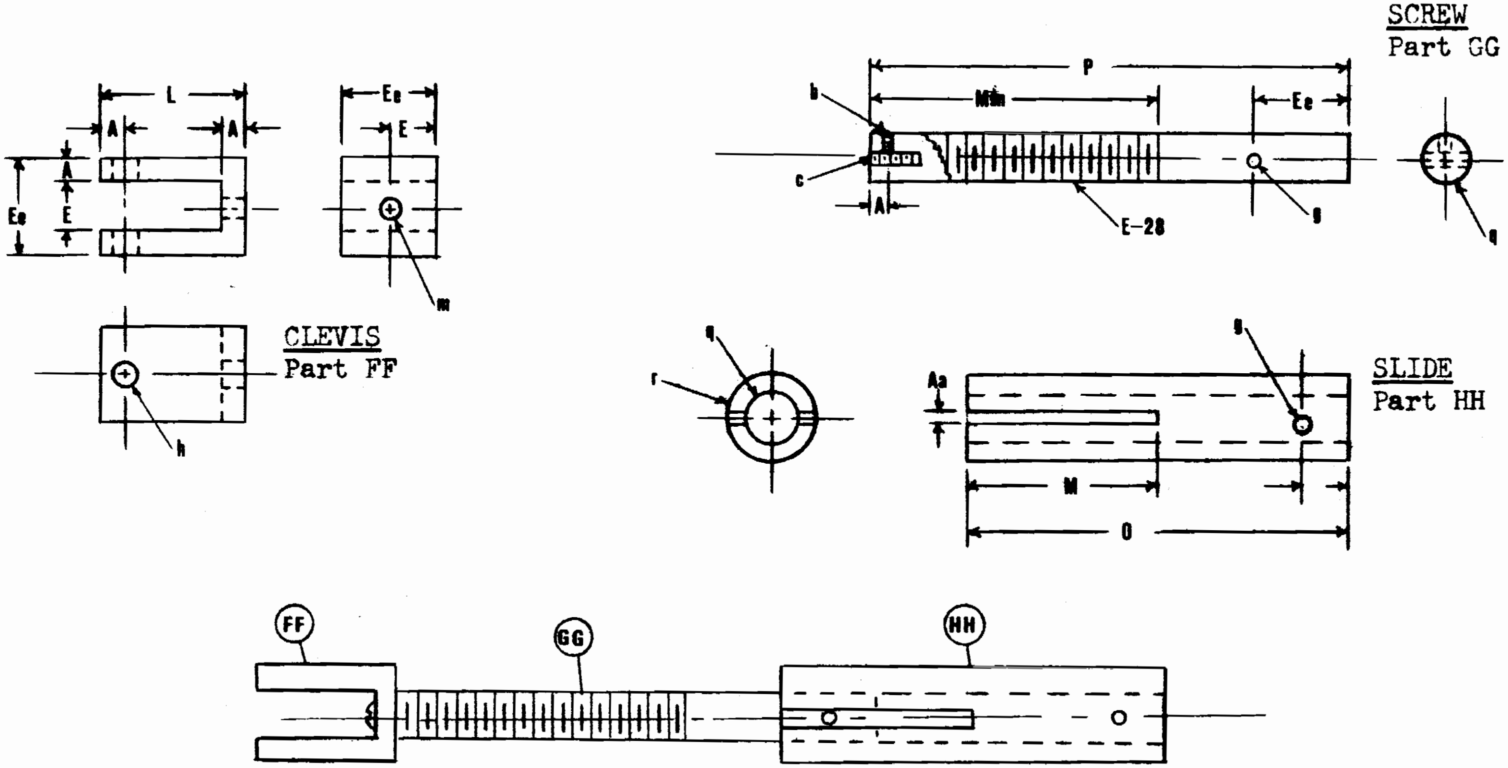


FIGURE 17. Concentration Screw Assembly and Details
Assembly-5
Scale: 1=1

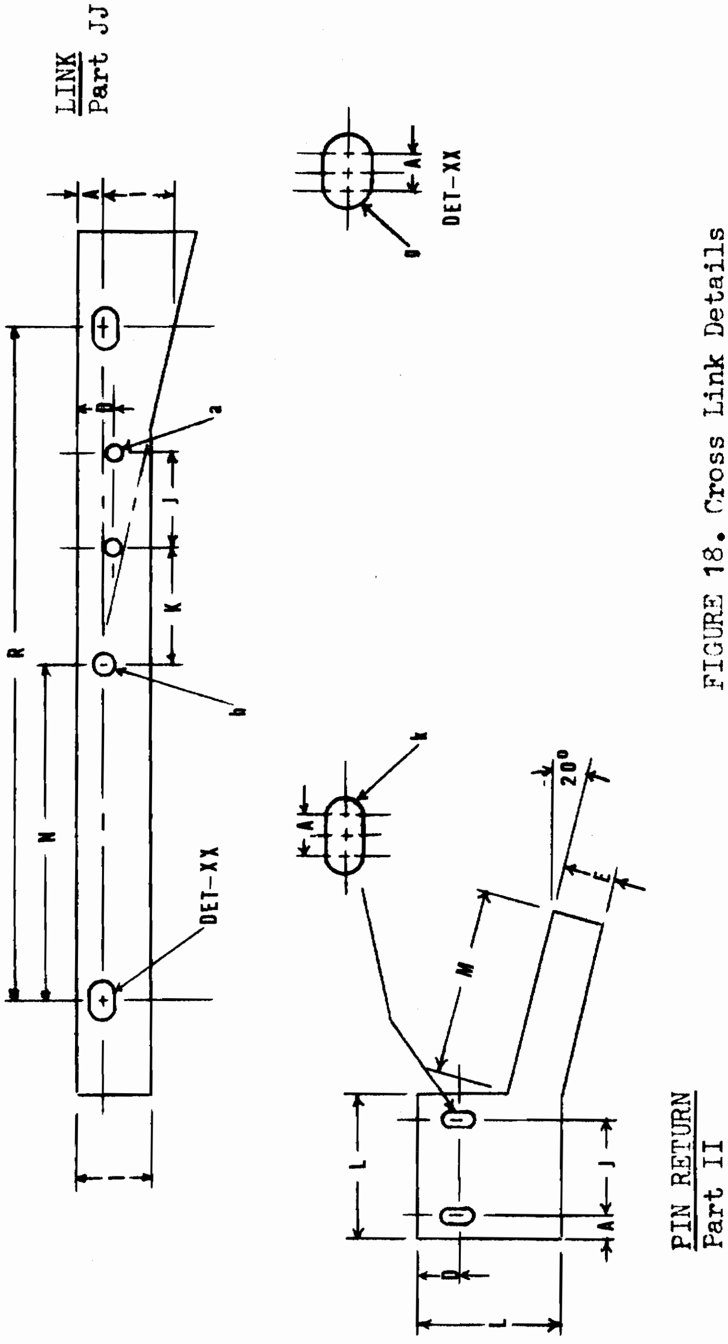


FIGURE 18. Cross Link Details
Scale: 1=1

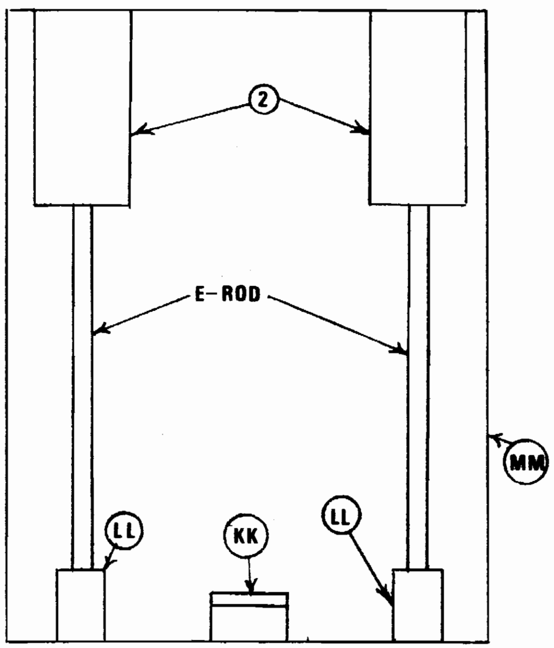
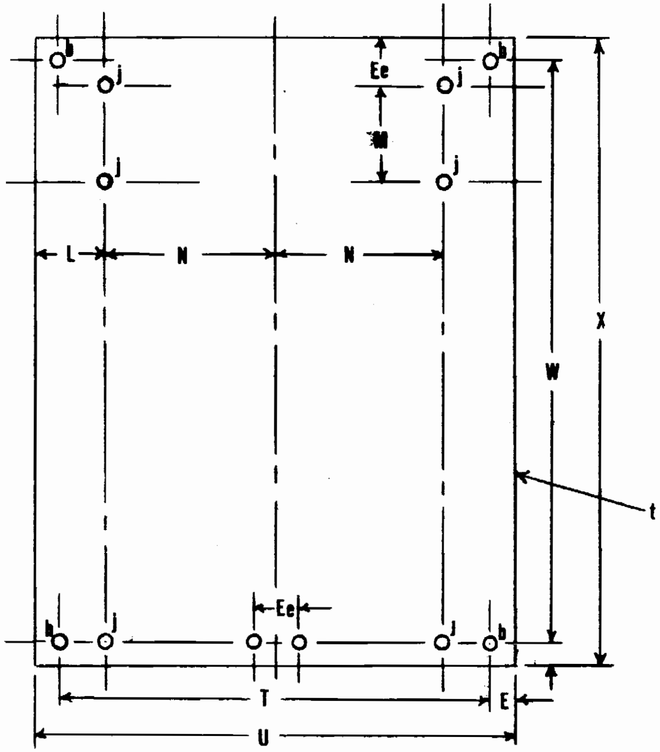
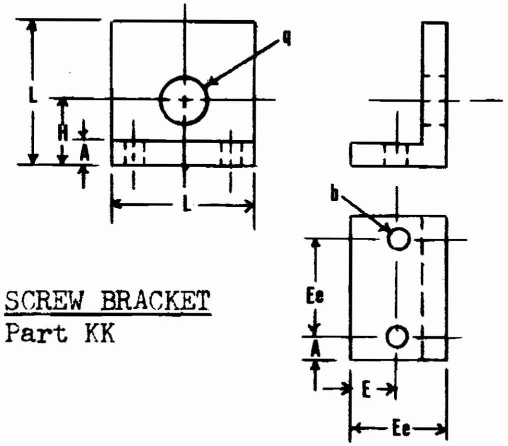


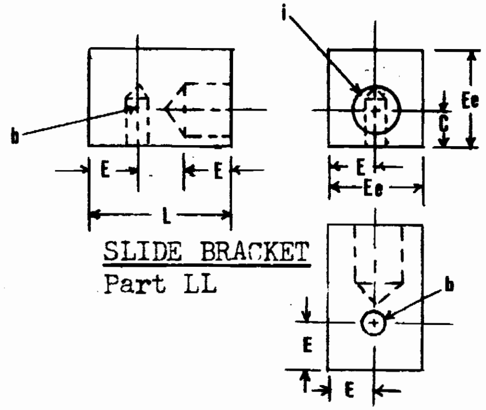
FIGURE 19. Base Assembly
Assembly-6
Scale: 1=1



BASE
Part MM
Scale: 1=2



SCREW BRACKET
Part KK



SLIDE BRACKET
Part LL

FIGURE 19A. Base Assembly Details
Scale: 1=1

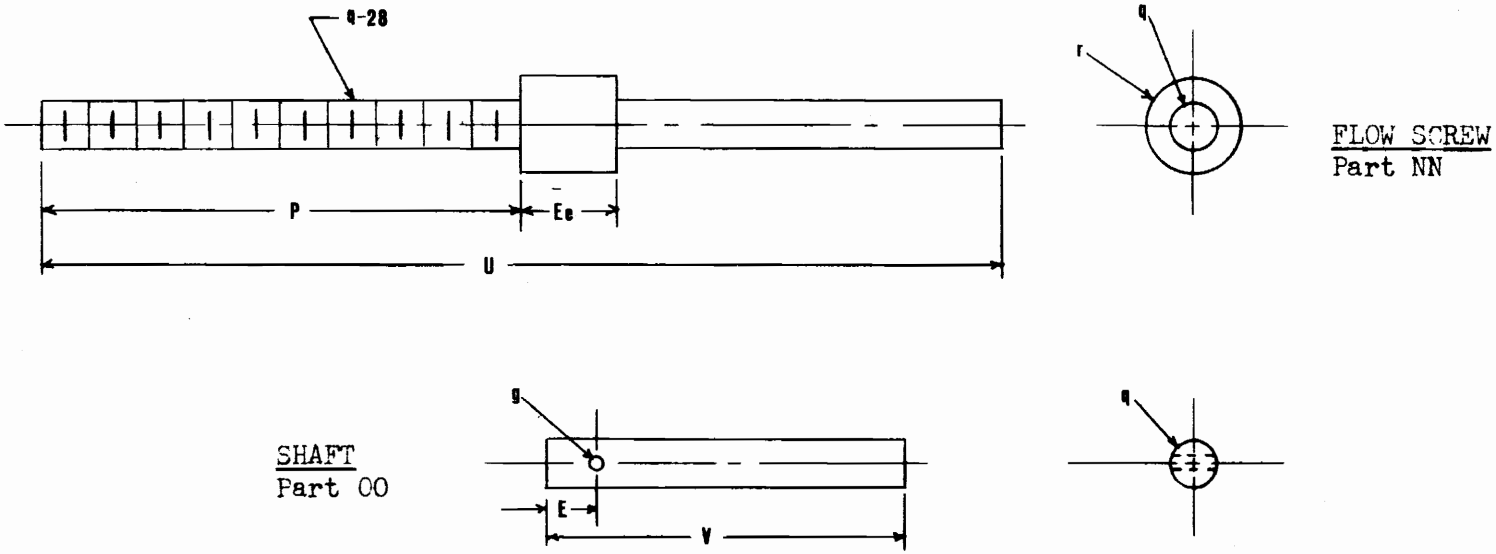


FIGURE 20. Flow Screw Details
Scale: 1=1

# 3. EXPERIMENTAL

## 3.1 Concentration Test

### 3.1.1 Concentration Test Apparatus

A schematic test set-up is shown in Figure 21, and Table 1 is a list of experimental equipment. The rotameters are used to get an approximate idea of the total flow rate by adding the values of both. These rotameters are identical, both calibrated for oxygen. The error in using one for air is small; a comparison showed the difference to be within needed accuracy. The output pressure from the mixing valve is measured with the pressure gauge and controllable with the downstream valve. The flask is used to catch the output so the oxygen concentration can be measured by the oxygen meter.

The size of the mixing valve chamber requires a period of five minutes for the concentration value to stabilize. Also, the oxygen concentration meter is re-calibrated* every 30 minutes.

### 3.1.2 Procedure and Results to Determine System Hysteresis

The procedure is shown below. There is a spring to eliminate backlash on the air side of the linkage as shown by the previous figures but there is no spring on the oxygen side.

---

*The meter is calibrated by exposing the probe first to air and then to pure oxygen. Adjustments are made to these reference points.

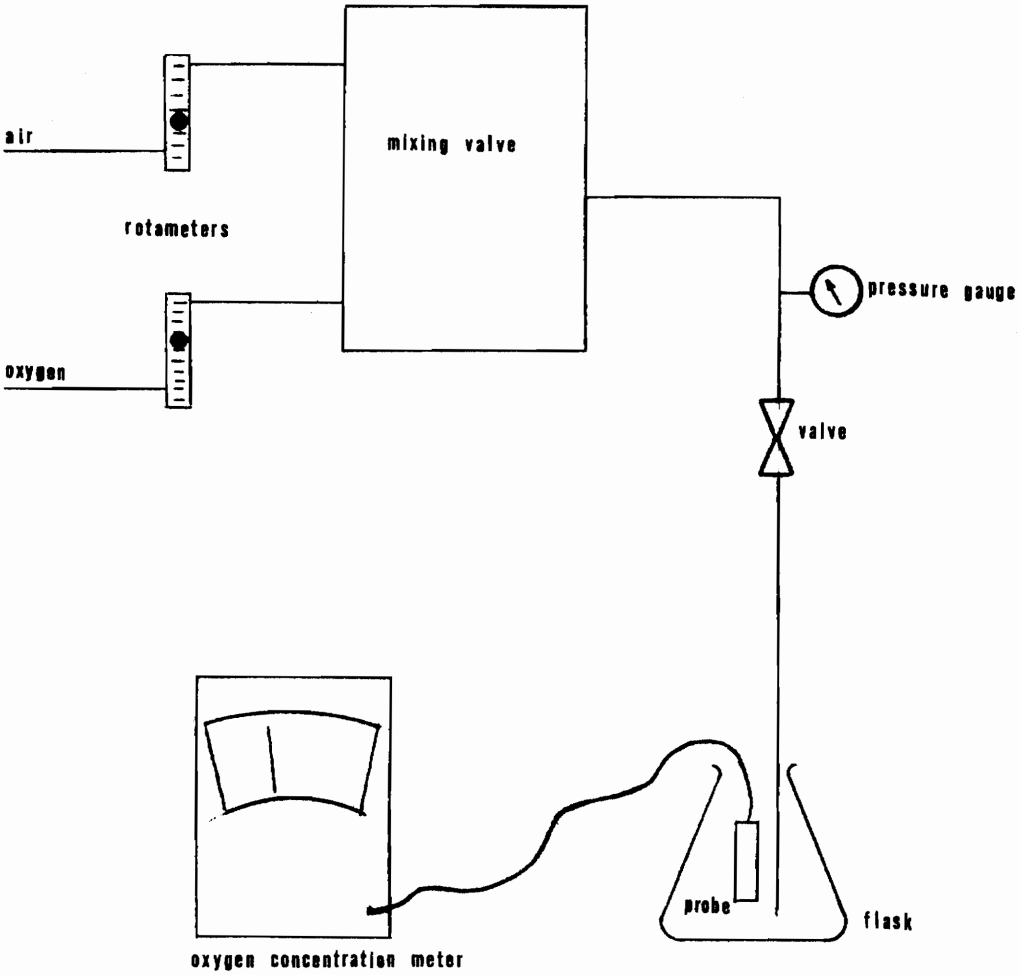


FIGURE 21. Schematic of Test Set-Up for Measuring Oxygen Concentration

# Table 1

## Table of Experimental Equipment for Oxygen Concentration Test

1. Oxygen Meter

   IMI Division of Becton Dickinson Company

   Model No. 3600

   Serial No. 554

   Accurate to 2% full range

2. Rotameters

   Puritan

   Pressure Compensated

   Series B

   Calibrated @ 50 psig internal pressure for

   liters of oxygen per min @ 70 F and 760 mm of Hg

1. Set flow rate.
2. Set the oxygen concentration by increasing values.
3. Record oxygen concentration on meter.
4. Change oxygen concentration.
5. Set the same oxygen concentration by decreasing values.
6. Repeat steps 2 through 5.

The results follow in Tables 2 through 7.

### 3.1.3 Procedure and Results to Determine the Effect of Output Pressure on Concentration

The procedure follows:

1. Set flow rate.
2. Set oxygen concentration.*
3. Set pressure.
4. Record oxygen concentration on meter.
5. Re-set pressure.
6. Record oxygen concentration on meter.
7. Repeat 5, 6.

The results follow in Tables 8 through 10.

---

*Based on the previous data, hysteresis does exist so all remaining data is taken on increasing oxygen concentration values.

### Table 2

### Concentration Set on <u>Increasing Values</u> at Constant Flow Rate of 4500 $cm^3$/min (4 1/2 ℓ/min) and 0 kPa gage (0 psig)

| Valve Setting (% $O_2$) | Test Run (% $O_2$) 1 | 2 | 3 |
|---|---|---|---|
| 30 | 24 | 24 | 24 |
| 45 | 42 | 43 | 43 |
| 60 | 60 | 61 | 62 |
| 75 | 74 | 75 | 75 |
| 90 | 90 | 91 | 91 |

Table 3

Concentration Set on Increasing Values at

Constant Flow Rate of 4500 $cm^3$/min

(4 1/2 ℓ/min) and 0 kPa gage (0 psig)

| Valve Setting (% $O_2$) | Test Run (% $O_2$) 1 | 2 | 3 |
|---|---|---|---|
| 30 | 28 | 30 | 30 |
| 45 | 50 | 51 | 50 |
| 60 | 67 | 65 | 65 |
| 75 | 78 | 79 | 79 |
| 90 | 98 | 98 | 98 |

Table 4

Concentration Set on Increasing Values

at Constant Flow Rate of 8000 $cm^3$/min

(8 ℓ/min) and 0 kPa gage (0 psig)

| Valve Setting (% $O_2$) | Test Run (% $O_2$) 1 | 2 | 3 |
|---|---|---|---|
| 30 | 24 | 24 | 24 |
| 45 | 46 | 45 | 46 |
| 60 | 62 | 62 | 62 |
| 75 | 76 | 75 | 76 |
| 90 | 89 | 91 | 90 |

## Table 5

Concentration Set on <u>Decreasing Values</u>
at Constant Flow Rate of 8000 $cm^3$/min
(8 ℓ/min) and 0 kPa gage (0 psig)

| Valve Setting (% $O_2$) | 1 | 2 | 3 |
|---|---|---|---|
| 30 | 38 | 38 | 38 |
| 45 | 53 | 50 | 52 |
| 60 | 66 | 64 | 66 |
| 75 | 79 | 80 | 80 |
| 90 | 93 | 95 | 95 |

Table 6

Concentration Set on Increasing Values

at Constant Flow Rate of 15000 $cm^3$/min

(15 ℓ/min) and 0 kPa gage (0 psig)

| Valve Setting (% $O_2$) | Test Run (% $O_2$) 1 | 2 | 3 |
|---|---|---|---|
| 30 | 28 | 29 | 28 |
| 45 | 45 | 46 | 46 |
| 60 | 62 | 63 | 63 |
| 75 | 76 | 76 | 76 |
| 90 | 91 | 92 | 92 |

## Table 7

## Concentration Set on Decreasing Values at Constant Flow Rate of 15000 $cm^3$/min (15 ℓ/min) and 0 kPa gage (0 psig)

| Valve Setting (% $O_2$) | Test Run (% $O_2$) 1 | 2 | 3 |
|---|---|---|---|
| 30 | 36 | 35 | 36 |
| 45 | 50 | 48 | 49 |
| 60 | 62 | 63 | 63 |
| 75 | 77 | 77 | 77 |
| 90 | 90 | 92 | 92 |

# Table 8

## Variable Pressure at Constant Concentration Setting and Constant Flow Rate of 4500 $cm^3$/min (4 1/2 ℓ/min)

| Valve Setting (% $O_2$) | Pressure kPa gage (psig) ± 7(1)<br>0(0) | 33(5) | 66(10) | 100(15) |
|---|---|---|---|---|
| 24 | 22 | 22 | 22 | 22 |
| 30 | 24 | 24 | 24 | 24 |
| 40 | 34 | 34 | 34 | 34 |
| 50 | 48 | 47 | 47 | 47 |
| 60 | 61 | 61 | 61 | 61 |
| 70 | 70 | 70 | 70 | 70 |
| 80 | 81 | 82 | 81 | 81 |
| 90 | 92 | 92 | 92 | 92 |
| 96 | 97 | 97 | 97 | 97 |
| 100 | 100 | 100 | 100 | 100 |

## Table 9

## Variable Pressure at Constant Concentration Setting and Constant Flow Rate of 8000 $cm^3$/min (8 ℓ/min)

| Valve Setting (% $O_2$) | Pressure kPa gage (psig) ± 7(1)<br>0(0) | 33(5) | 66(10) | 100(15) |
|---|---|---|---|---|
| 24 | 23 | 23 | 23 | 23 |
| 30 | 24 | 24 | 24 | 24 |
| 40 | 38 | 38 | 38 | 38 |
| 50 | 50 | 50 | 50 | 50 |
| 60 | 62 | 62 | 62 | 62 |
| 70 | 72 | 72 | 72 | 72 |
| 80 | 81 | 81 | 81 | 81 |
| 90 | 92 | 92 | 92 | 92 |
| 96 | 97 | 98 | 98 | 98 |
| 100 | 100 | 100 | 100 | 100 |

## Table 10

## Variable Pressure at Constant Concentration Setting and Constant Flow Rate of 15000 $cm^3$/min (15 ℓ/min)

| Valve Setting ($\% O_2$) | | Pressure kPa gage (psig) ± 7(1) | | |
|---|---|---|---|---|
| | 0(0) | 33(5) | 66(10) | 100(15) |
| 24 | 22 | 22 | 22 | 22 |
| 30 | 28 | 28 | 28 | 28 |
| 40 | 40 | 40 | 40 | 40 |
| 50 | 50 | 50 | 50 | 50 |
| 60 | 61 | 61 | 61 | 61 |
| 70 | 71 | 71 | 71 | 71 |
| 80 | 81 | 81 | 81 | 81 |
| 90 | 91 | 91 | 91 | 91 |
| 96 | 97 | 97 | 97 | 97 |
| 100 | 100 | 100 | 100 | 100 |

### 3.1.4 Procedure and Results to Determine the Precision in Setting Oxygen Concentration

The procedure is shown below. The output pressure for all values is 0 kPa gage (0 psig). The oxygen meter is calibrated at every data point.

1. Set flow rate.
2. Set oxygen concentration.
3. Record oxygen concentration on meter.
4. Change oxygen concentration.
5. Set oxygen concentration to same value as above.
6. Record oxygen concentration on meter.
7. Repeat 2 through 6.

Results follow in Tables 11 through 13.

### 3.1.5 Procedure and Results to Determine the Accuracy of Setting Oxygen Concentration

The procedure follows:

1. Set flow rate.
2. Set oxygen concentration.
3. Record oxygen concentration on meter.
4. Set new oxygen concentration.
5. Record oxygen concentration on meter.
6. Repeat 4 and 5.

## Table 11

## Precision Test Data

| Valve Setting (% $O_2$) | Flow Rate $cm^3$/min (ℓ/min) | Test Run (% $O_2$) 1 | 2 | 3 |
|---|---|---|---|---|
| 30 | 4500 (4 1/2) | 26 | 26 | 26 |
| | 8000 (8) | 24 | 24 | 24 |
| | 15000 (15) | 28 | 28 | 28 |
| 60 | 4500 (4 1/2) | 61 | 61 | 61 |
| | 8000 (8) | 62 | 62 | 62 |
| | 15000 (15) | 61 | 61 | 61 |
| 90 | 4500 (4 1/2) | 94 | 94 | 94 |
| | 8000 (8) | 93 | 93 | 93 |
| | 15000 (15) | 91 | 91 | 91 |

The results follow the sample calculation for the mean (see Tables 14, 15, and 16).

$$\text{mean} = (\sum C_o)/N$$

where $C_o$ = oxygen concentration

$N$ = number of test runs

## 3.2 Flow Rate Test

### 3.2.1 Flow Rate Test Apparatus

A schematic test set-up is shown by Figure 25. The three-way valve is used to divert the output flow from the mixing valve. The flask is a known volume. The valve controls the output pressure from the mixing valve and is read on the pressure gauge. A stop watch is also needed for timing the filling of the flask.

### 3.2.2 Procedure and Results for Determination of the Effect of Pressure on Total Flow Rate*

The procedure is as follows:

1. Set flow rate

---

*Flow rate is the volumetric flow rate when the gas is expanded to atmospheric pressure.

Table 12

Accuracy Test Data at Flow Rate of 4500 $cm^3$/min

(4 1/2 ℓ/min)

| Valve Setting (% $O_2$) | Test Run (% $O_2$) 1 | 2 | 3 | 4 | 5 | mean |
|---|---|---|---|---|---|---|
| 24 | 22 | 22 | 22 | 22 | 22 | 22 |
| 30 | 25 | 24 | 24 | 24 | 24 | 24.2 |
| 40 | 36 | 34 | 34 | 35 | 34 | 34.6 |
| 50 | 49 | 46 | 46 | 46 | 48 | 47.0 |
| 60 | 62 | 60 | 59 | 60 | 61 | 60.4 |
| 70 | 71 | 70 | 69 | 71 | 70 | 70.2 |
| 80 | 81 | 81 | 80 | 82 | 81 | 81.0 |
| 90 | 92 | 92 | 90 | 93 | 92 | 91.8 |
| 96 | 97 | 97 | 96 | 97 | 97 | 97.0 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 |

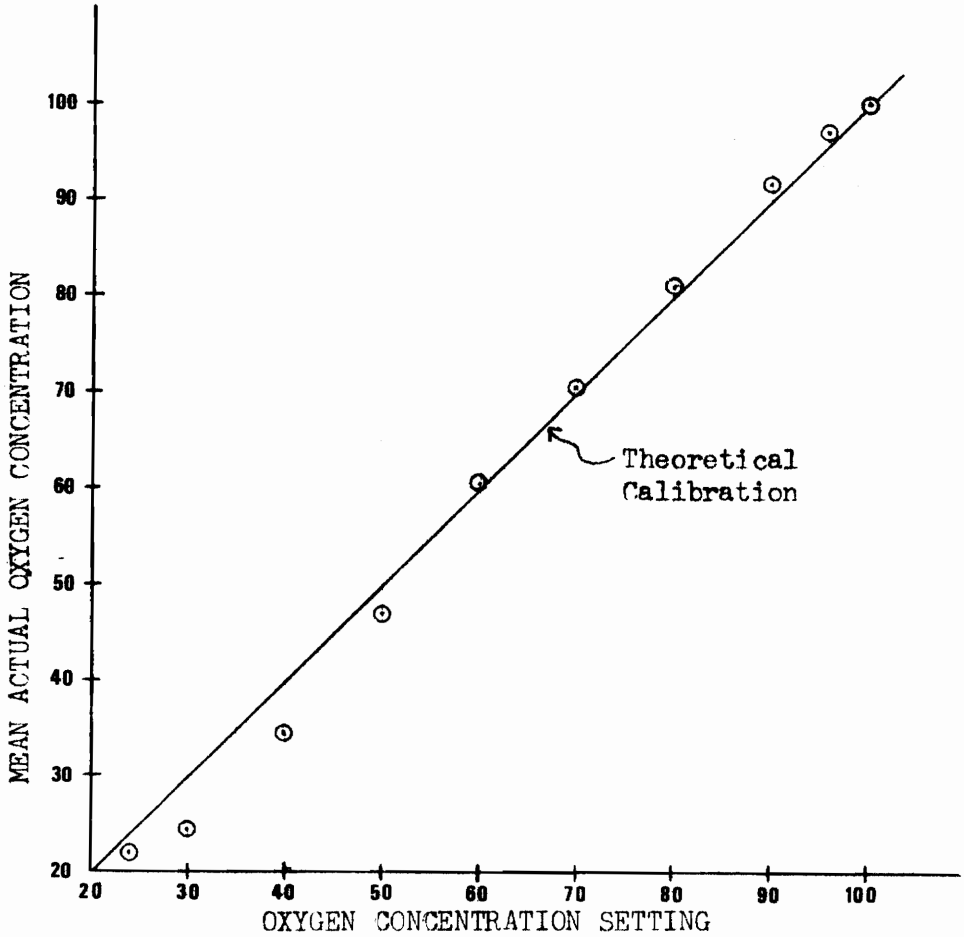


FIGURE 22. Plot of Indicated Oxygen Concentration versus Mean Actual Oxygen Concentration at 4500 $cm^3$/min ($4\frac{1}{2}$ litres/min)

## Table 13

## Accuracy Test Data at Flow Rate of 8000 $cm^3$/min

## (8 ℓ/min)

| Valve Setting (% $O_2$) | Test Run (% $O_2$) 1 | 2 | 3 | 4 | 5 | mean |
|---|---|---|---|---|---|---|
| 24 | 23 | 23 | 23 | 23 | 23 | 23.0 |
| 30 | 24 | 24 | 24 | 24 | 24 | 24.0 |
| 40 | 40 | 37 | 37 | 36 | 38 | 37.6 |
| 50 | 50 | 50 | 50 | 48 | 50 | 49.6 |
| 60 | 62 | 61 | 61 | 60 | 62 | 61.2 |
| 70 | 72 | 72 | 72 | 72 | 72 | 72 |
| 80 | 80 | 82 | 82 | 81 | 81 | 81.2 |
| 90 | 91 | 93 | 93 | 92 | 92 | 92.2 |
| 96 | 97 | 98 | 98 | 98 | 97 | 97.6 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 |

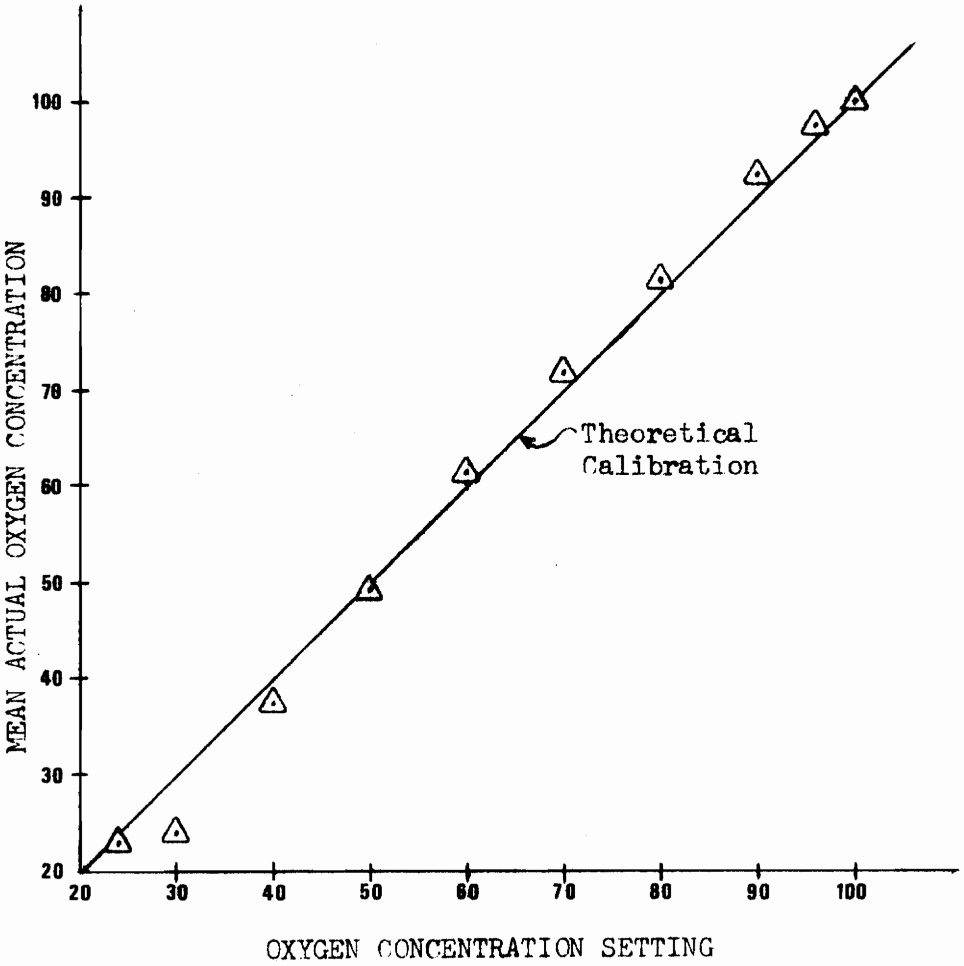


FIGURE 23. Plot of Indicated Oxygen Concentration versus Mean Actual Oxygen Concentration at 8000 $cm^3$/min (8 liters/min)

## Table 14

### Accuracy Test Data at Flow Rate of 15000 $cm^3$/min

### (15 ℓ/min)

| Valve Setting (% $O_2$) | Test Run (% $O_2$) 1 | 2 | 3 | 4 | 5 | mean |
|---|---|---|---|---|---|---|
| 24 | 22 | 22 | 22 | 22 | 22 | 22.0 |
| 30 | 28 | 28 | 28 | 28 | 28 | 28.0 |
| 40 | 41 | 41 | 41 | 40 | 40 | 40.6 |
| 50 | 52 | 52 | 52 | 50 | 50 | 51.2 |
| 60 | 62 | 63 | 63 | 62 | 61 | 62.2 |
| 70 | 72 | 72 | 74 | 72 | 71 | 72.2 |
| 80 | 82 | 81 | 82 | 80 | 81 | 81.2 |
| 90 | 91 | 90 | 92 | 90 | 91 | 90.8 |
| 96 | 97 | 97 | 97 | 96 | 97 | 96.8 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 |

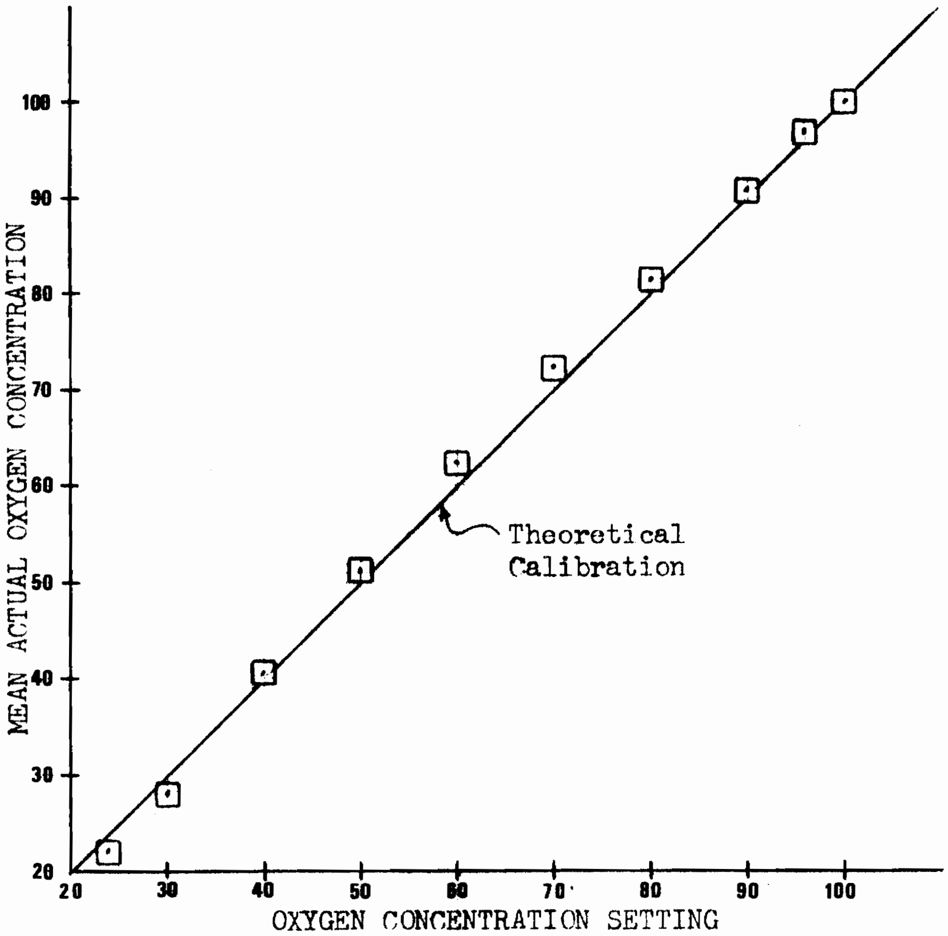


FIGURE 24. Plot of Indicated Oxygen Concentration versus Mean Actual Oxygen Concentration at 15000 $cm^3$/min (15 liters/min)

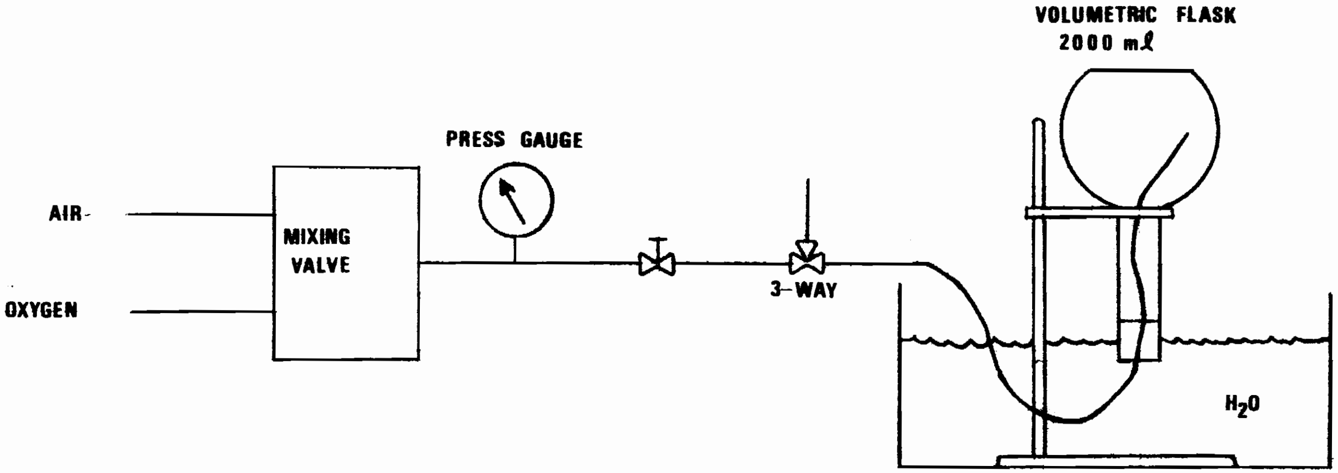


FIGURE 25. Schematic of Test Set-Up for Measuring Flow Rate

2) Set oxygen concentration to 60%
3) Set pressure
4) Measure the time (sec) to displace water in 2000 mℓ flask
5) Repeat

The results follow the equation for calculation of flow per unit time.

$$\text{Flow rate } (\text{cm}^3/\text{min} \times 10^3 (\ell/\text{min})) = 240/(T_1 + T_2)$$

where $T_1$ and $T_2$ = filling time (sec) for two readings at the same flow rate setting.

## Table 15

### Flow Data at Constant Flow Setting and Variable Pressure

| Valve Setting ($cm^3$/min x $10^{-6}$) (ℓ/min) | Pressure kPa (psig) ± 7(1) 0(0) time (sec) | Calculated Value | 53(8) time (sec) | Calculated Value | 100(15) time (sec) | Calculated Value |
|---|---|---|---|---|---|---|
| 2 | 48.0 | 2.5 | 47.5 | 2.5 | 52.2 | 2.3 |
| 2 | 47.7 | | 47.3 | | 51.9 | |
| 4 | 28.5 | 4.2 | 28.1 | 4.2 | 31.5 | 3.9 |
| 4 | 28.6 | | 28.3 | | 30.6 | |
| 6 | 19.8 | 6.0 | 19.8 | 6.0 | 20.1 | 5.9 |
| 6 | 20.0 | | 19.6 | | 20.3 | |
| 8 | 14.2 | 8.4 | 14.7 | 8.2 | 14.7 | 8.2 |
| 8 | 14.5 | | 14.5 | | 14.8 | |
| 10 | 11.4 | 10.4 | 11.4 | 10.4 | 11.5 | 10.3 |
| 10 | 11.7 | | 11.6 | | 11.7 | |
| 12 | 9.8 | 12.1 | 9.8 | 12.2 | 9.7 | 12.2 |
| 12 | 10.0 | | 9.9 | | 9.9 | |
| 14 | 8.8 | 13.6 | 8.6 | 13.8 | 8.7 | 13.6 |
| 14 | 8.7 | | 8.8 | | 8.9 | |

### 3.2.3 Procedure and Results for Determination of the Effect of Oxygen Concentration Setting on Total Flow Rate at 0 kPa gage (0 psig)

The procedure is as follows:

1) Set flow rate
2) Set oxygen concentration
3) Measure the time (sec) to displace water in 2000 mℓ flask
4) Repeat

The results follow.

## Table 16

### Flow Data at Constant Flow Setting and Variable Oxygen Concentration Setting at 0 kPa gage (0 psig)

| Valve Setting ($cm^3$/min x $10^{-6}$) (ℓ/min) | Concentration (% $O_2$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 30 | | 45 | | 60 | | 90 | |
| | time (sec) | Calculated Value | time (sec) | Calculated Value | time (sec) | Calculated Value | time (sec) | Calculated Value |
| 2 | 42.6 | 2.8 | 51.8 | 2.3 | 48.0 | 2.5 | 45.4 | 2.6 |
| 2 | 42.8 | | 52.0 | | 47.7 | | 45.0 | |
| 4 | 30.0 | 4.0 | 29.1 | 4.1 | 28.5 | 4.2 | 26.5 | 4.5 |
| 4 | 29.8 | | 28.8 | | 28.6 | | 26.7 | |
| 6 | 23.5 | 5.1 | 20.3 | 5.9 | 19.8 | 6.0 | 19.9 | 6.0 |
| 6 | 23.5 | | 20.5 | | 20.0 | | 19.9 | |
| 8 | 16.8 | 7.1 | 15.8 | 7.6 | 14.2 | 8.4 | 14.6 | 8.3 |
| 8 | 17.0 | | 15.7 | | 14.5 | | 14.4 | |
| 10 | 13.1 | 9.0 | 12.2 | 9.8 | 11.4 | 10.4 | 11.6 | 10.3 |
| 10 | 13.3 | | 12.3 | | 11.7 | | 11.6 | |
| 12 | 11.3 | 10.6 | 10.3 | 11.6 | 9.8 | 12.1 | 9.8 | 12.2 |
| 12 | 11.3 | | 10.3 | | 10.0 | | 9.8 | |
| 14 | 9.2 | 13.0 | 8.9 | 13.5 | 8.8 | 13.6 | 8.9 | 13.6 |
| 14 | 9.5 | | 9.0 | | 8.7 | | 8.6 | |

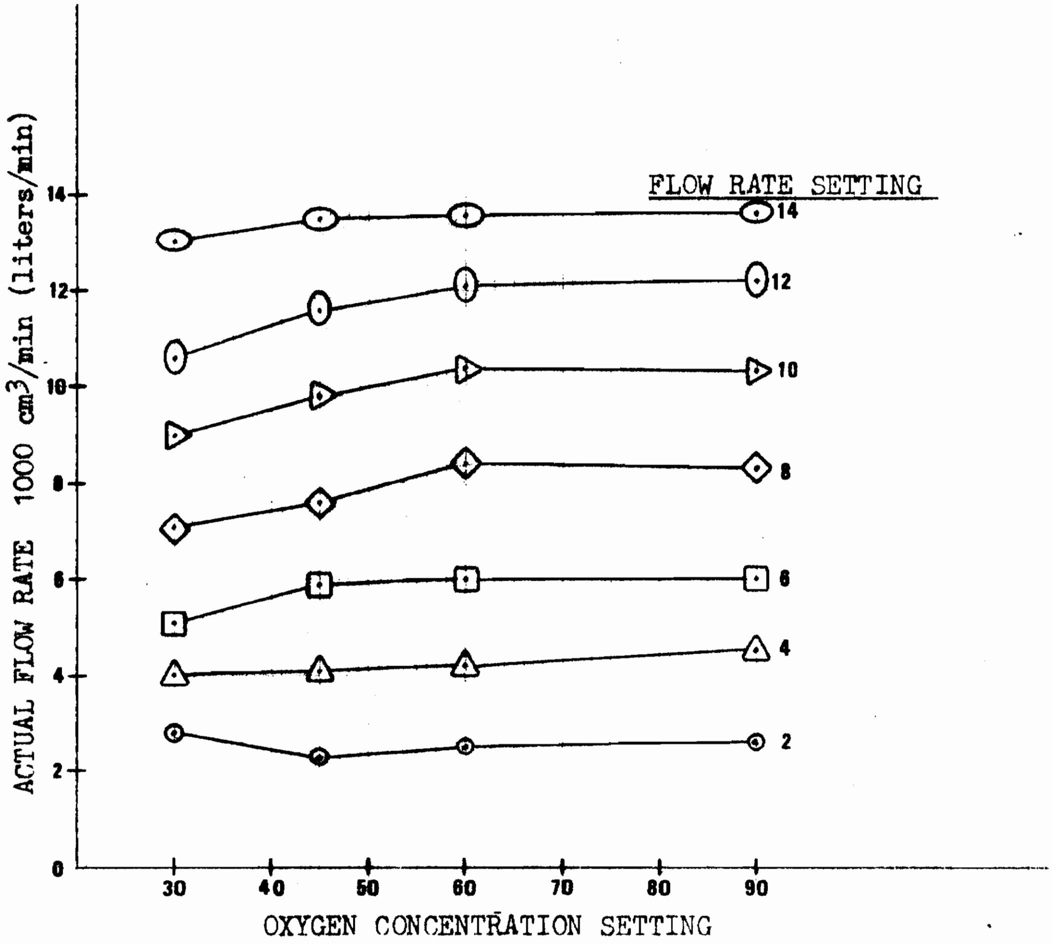


FIGURE 26. Plot of **Actual** Flow **Rate versus** Oxygen Concentration Setting **at Specified** Set Flow Rates

## 3.3 Analysis of Experimental Error

The experimental error in measuring oxygen concentration is primarily due to the accuracy of the oxygen concentration meter. Barring error from misreading the scale or a gross calibration error, all oxygen concentration readings are within ± 2%. The only exception is in the measurement of mixing valve precision. In this case, the precision of the mixing valve was compared to the precision of the oxygen concentration meter. The precision of the oxygen concentration meter is exact within readable accuracy. This precision was found by comparing five readings of a constant oxygen concentration.

The experimental error in measuring flow rate is primarily due to human error in starting and stopping the stop watch. Other factors involved in the measurement but remaining constant are: flask volume, temperature and pressure of the gas, and mixing valve setting.

The error in measuring flow rate is determined by first considering the flow rate data. (Tables 15 and 16). The maximum difference between any two filling time readings at the same flow rate is 0.8 sec. This time is taken to be the maximum possible absolute error in filling time and is used in the equations below to calculate the per cent error and absolute error in the flow rate.

$$\%e = \left( \frac{FR}{120 + 9.8\ FR} \right) 100$$

where FR = flow rate as set on the mixing valve, $cm^3/min \times 10^3$ (ℓ/min)

%e = per cent error

$$Ae = \frac{(\%e)\ FR}{100} = \frac{FR^2}{120 + 0.8\ FR}$$

where Ae = absolute error in flow rate, $cm^3/min \times 10^3$ (ℓ/min)

Table 17 shows the calculated values of %e and Ae for various flow rates. It is noted that both %e and Ae are a function of flow rate such that the lower the flow rate is the lower the error.

## Table 17

## Table of Experiment Error in Flow Rate Measurement

| Flow Rate $cm^3/min \times 10^3$ (ℓ/min) | %e | Ae $cm^3/min \times 10^3$ (ℓ/min) |
|---|---|---|
| 2 | 1.6 | 0.033 |
| 4 | 3.2 | 0.13 |
| 6 | 4.8 | 0.29 |
| 8 | 6.3 | 0.51 |
| 10 | 7.8 | 0.78 |
| 12 | 9.3 | 1.1 |
| 14 | 10.7 | 1.5 |

## 4. CONCLUSIONS

The equipment as designed and constructed is a workable solution to the problem of mixing air and oxygen at selectable oxygen concentrations and flow rates. Control of the flow of the individual gases is adequate with the metering elements as designed. The laminated brass stock and shim stock is easily fabricated and works well. The mechanical linkage is the weakest link in the design. The hysteresis in setting concentration and the inaccuracies in setting concentration are primarily related to poor design in the linkage. Ways to possibly improve the linkage are discussed in the Recommendation section of this thesis. The only problem with the read-out design is at low flow rates, i. e. less than 5000 $cm^3$/min (5 ℓ(min)) the scale sticks at times.

Hysteresis does exist in the system and there is no adjustment in the design to eliminate this. Tables 2 through 7 show specifically the amount of backlash in adjusting concentration on increasing and decreasing values. This problem is less severe at the higher flow rates as seen by Tables 6 and 7 because a slight misadjustment has, by per cent, less effect on flow rate. This problem hampers the operation of the mixing valve and cannot be tolerated in a marketable product.

The output pressure from the mixing valve has no effect on the oxygen concentration. There are only a few isolated data points at low flows (see Table 8) which change, however these are within experimental error (see Table 17). This is a good point in this design because the resistance of the driven equipment, as long as it is not so great as to increase the pressure above 100 kPa (15 psig), has no effect on oxygen concentration.

The precision in setting oxygen concentration is excellent. As seen by Table 11 values are repeatable. This is a good point of this design because if a calibration curve were plotted for a specific flow rate, then the oxygen concentration could be controlled very accurately and repeatable. It is noted that hysteresis was eliminated in taking this data by setting the oxygen concentration on increasing values.

The accuracy of setting oxygen concentration is about 2% above 50% oxygen concentration (as shown by Tables 12, 13, and 14). Below 50% oxygen concentration, the accuracy is progressively worse with lower flow rates and lower oxygen concentrations. The reason for the better accuracy at higher concentrations is because the read-out was calibrated for accuracy at those concentrations. The accuracy could be improved at the lower concentrations if a fine adjustment were designed into the linkage. This adjustment would "fine tune" the relative position of the oxygen metering element to the cross-link (see Figures 12, and 16). With this adjustment, the oxygen flow rate could be increased relative to the air flow rate thus improving the oxygen concentration accuracy below 50%.

The output pressure from the mixing valve has little effect on flow rate. The variance of calculated values (see Table 15) in the upper flow rates (above 6 $cm^3/min \times 10^3$ (6 ℓ(min)) is due to experimental error (see Table 17). Pressure does seem to have an effect on flow rates below 6 $cm^3/min \times 10^3$ (6 ℓ/min) and high pressure (100 kPa (15 psig)). Apparently this is due to the geometry of the metering elements. The end effects of the flow area (slot) are added flow resistance so the flow is not choked. The effect of pressure is less significant the higher the flow, again this indicates geometric causes.

Table 16 shows that there is an effect on flow rate due to oxygen concentration setting on the valve. This is not due to a change in the properties of the gas but due to the mixing valve. Figure 26 is a graph of Table 16 which shows that the flow rate is constant at oxygen concentrations above 60% but decreases progressively below 60% at upper flow rates and increases at 2 $cm^3/m \times 10^3$ (2 ℓ/min).

The reason for this problem is as stated earlier, the oxygen flow rate needs to be greater relative to the air flow rate at lower oxygen concentrations.

## 5. RECOMMENDATIONS

The major recommendation is to re-design the mechanical linkage. Although the linkage does a fair job as is, it is the source of the major problems in the system. A possible solution would be to put the metering elements in line (see Figure 27). To control flow, the distance between seals is increased for increasing flow and decreased for decreasing flow by using a shaft which is threaded with both left hand and right hand threads. The concentration is set by the position of one metering element (with two metering ports) between the seals. A read-out similar to the existing would be necessary for the display. This design would be simpler and the metering elements positioned more accurately.

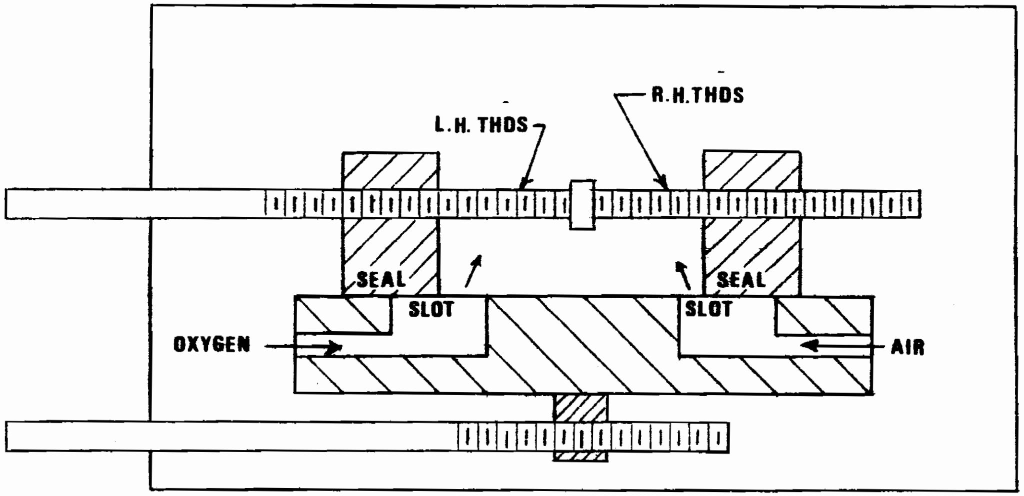


FIGURE 27. Schematic of Recommended Linkage Design

## 6. LITERATURE REVIEWED

1. Holman, J. P., Experimental Methods for Engineers, McGraw-Hill Book Company, p. 203, 1971.

2. Streeter, V. L. and Wylie, E. B., Fluid Mechanics, McGraw-Hill Book Company, p. 247, 1975.

3. Ibid, p. 346.

4. Head, V. P., "Coefficient of Float-Type Variable-Area Flow-Meters," Trans. ASME, Vol. 76, p. 851, Aug. 1954.

5. Bean, H. S., Fluid Meters, ASME, p. 88, 1971.

6. Beard, C. S., Final Control Elements, Rimbach Publications Division, Chilton Co., Philadelphia, Pa., 1969.

# 7. APPENDICES

## Appendix A

Table 18

Table of Dimensions

| Symbol | SI (mm) | English (in.) |
|---|---|---|
| Aa | 1.6 | 1/16 |
| A or B | 3.2 | 1/8 |
| C | 3.8 | 0.15 |
| D | 4.8 | 3/16 |
| E | 6.4 | 1/4 |
| F | 7.9 | 0.31 |
| G | 8.4 | 0.33 |
| H | 8.9 | 0.35 |
| I | 9.5 | 3/8 |
| Ee or J | 13 | 1/2 |
| K | 16 | 5/8 |
| L | 19 | 3/4 |
| M | 25 | 1 |
| Mm | 38 | 1 1/2 |
| N | 44 | 1 3/4 |
| O | 51 | 2 |
| P | 63 | 2 1/2 |
| Q | 73 | 2 7/8 |
| R | 89 | 3 1/2 |
| S | 102 | 4 |
| T | 114 | 4 1/2 |
| U | 127 | 5 |
| V | 48 | 1 7/8 |
| W | 152 | 6 |
| X | 165 | 6 1/2 |
| Y | 229 | 9 |
| Z | 76 | 3 |
| Zz | 250 | 10 |
| Yy | 240 | 9 1/2 |

Table 19

Table of Notes

| Symbol | Note |
|---|---|
| a | Drill No. 51 and Tap 2-56 |
| b | Drill No. 43 and Tap 4-40 |
| c | Drill No. 36 and Tap 6-32 |
| d | Drill No. 29 and Tap 8-32 |
| e | Drill No. 3 and Tap 1/4-28 |
| f | Drill No. 21 and Tap 10-32 |
| g | Drill to press 1.6 (1/16) pin |
| h | Drill to press 3.2 (1/8) pin |
| i | Drill to press 6.4 (1/4) pin |
| k | Drill No. 43 through unless specified |
| j | Drill No. 33 " " " |
| m | Drill No. 28 " " " |
| n | Drill No. 19 " " " |
| p | 3.2 (1/8) dia |
| q | 6.4 (1/4) dia |
| r | 13 (1/2) dia |
| t | 3.2 (1/8) stock |

# Appendix B

## Detailed Analysis of Taper Tube Design

This appendix describes the equations and the method used to calculate the force on the flow element (float) and relate it to the volumetric flow rate for a single tube and float. The calculations are to determine the practicality of the **proposed design** by finding order of magnitude numbers. Figure 28 is the schematic of the tube and float. The steps for the calculation are as follows:

1. Choose a float diameter (DF).* This fixes the size of the system.
2. Choose the ratio of major to minor diameters of the variable annular metering area (a).

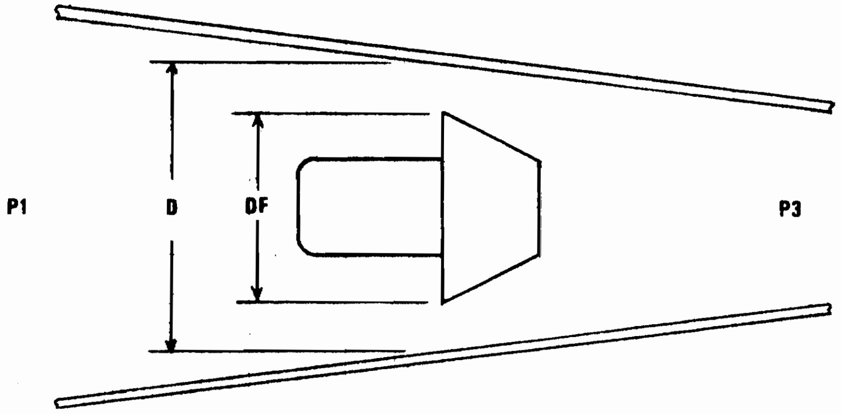
   "a" ranges from 1.06 to 1.40
3. Calculate the contraction coefficient (cc). In V. P. Head[4], the contraction coefficient is calculated using Von Mises' procedure for a float shown in Figure 29. The graph of the results are re-drawn from that literature as shown by Figure 29. To simplify the **calculations the** curve is assumed linear and approximated by the equation below:

   $$cc = 0.605 + 0.15 \quad (a - 1)$$
4. Calculation of flow coefficient (K). From V. P. Head the equation is below:

   $$K = cc/(a^2 - cc(a^2 - 1))$$

---

*The symbol for each factor follows in parentheses.



a = D/DF

FIGURE 28. Schematic of Tube and Float of Tapered Tube Design

5. Calculation of the pressure ratio (r). This is the ratio of the pressure outlet of the metering annular area to the inlet to the tapered tube.

$r = P3/P1$ $P3$ = pressure at outlet

$P1$ = pressure at inlet

6. Calculation of the float force (F). From Fluid Meters[5] the equations are shown below:

Let $A = (\pi/4)(aDF)^2$ (area of tube where float is read)

Let $Aa = a^2/((a^2-1)r^{1/k})$ K = ratio of specific heats

Let $B = (k-1)/k$

Let $Y = (1/(a^2-1))\{1/[(Aa-1)[(Aa+1)(B)((1-r)/(1-r)^B]]\}^{1/2}$

$F = AP1(1-r)[1/(1+2Y^2(a^2-1)^2(Aa-1))]$

7. Calculation of volumetric flow rate (Q). From Fluid Meters the equation is below:

$Q = (1.883/R3)(a^2-1)\ KY\sqrt{AFR1}$

Where: $R3$ = outlet density

$R1$ = inlet density

Note: Q is calculated in English standard in cubic feet per minute at P1 and inlet temperature. To be consistent, area is expressed in square inches, density in pounds per cubic foot and pressures in pounds per square inch. The conversion to SI units is from the value of Q. Also, Q is converted to atmospheric pressure and temperature.

For DF of 5 mm (0.2 in.) Table 20 is generated.

## Table 20

### Table of Computed Values of Force and Flow Rate for Tapered Tube Design

| Force (N x $10^{-6}$) | Flow Rate ($cm^3$/min x $10^3$) or (ℓ/min) |
|---|---|
| 149 | 64.2 |
| 152 | 64.9 |
| 155 | 65.6 |
| 159 | 66.3 |
| 162 | 67.0 |
| 164 | 67.6 |
| 167 | 68.3 |
| 171 | 69.0 |
| 174 | 69.7 |
| 177 | 70.3 |
| 180 | 71.0 |
| 184 | 71.7 |
| 187 | 72.3 |
| 190 | 73.0 |
| 193 | 73.6 |
| 197 | 74.2 |
| 200 | 74.9 |
| 203 | 75.5 |
| 207 | 76.2 |
| 210 | 76.8 |
| 213 | 77.4 |
| 215 | 78.0 |
| 219 | 78.7 |
| 224 | 79.3 |

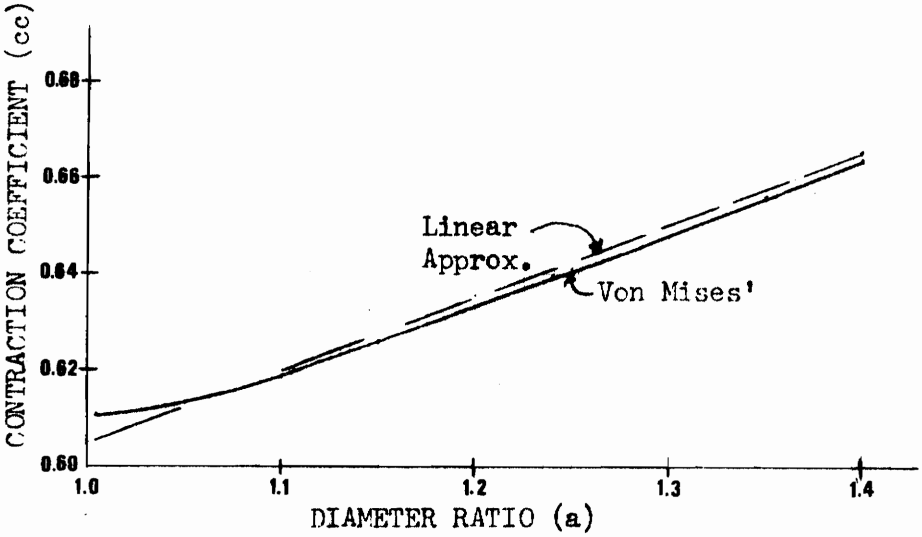


FIGURE 29. Plot of Von Mises' Calculation of the Contraction Coefficient Compared to a Linear Approximation

## 8. VITA

The author was born in Newport News, Virginia on September 17, 1951. He attended schools in Newport News and was graduated from H. L. Ferguson High School in 1969.

He began college at Virginia Polytechnic Institute in 1969 and completed degree requirements for a Bachelor of Science in Mechanical Engineering in June, 1973.

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# THE DEVELOPMENT OF AN INSTRUMENT TO CONTROL THE OXYGEN CONCENTRATION AND FLOW RATE OF AN AIR-OXYGEN MIXTURE

by

J. Robert Fletcher

## (ABSTRACT)

An instrument is described which controls the oxygen concentration and flow rate of an air-oxygen mixture. Flow metering elements (valves), mechanical linkage, and a read-out was developed to accomplish this. The key to this design is the characteristics of the metering elements. These characteristics are established by controlling the length of a 0.0381 mm (0.0015 in.) wide slot which is the metering area. By means of a mechanical linkage the metering elements are positioned to give the proper oxygen concentration and flow rate. The read-out displays the variables on linear scales by means of sliding scales and a pivoted-lever arrangement for proportioning. A complete design and description is presented along with data obtained from the operation of the instrument.