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FLUID AMPLIFIER STATE OF THE ART

VOLUME I

RESEARCH AND DEVELOPMENT — FLUID AMPLIFIERS AND LOGIC

Prepared under Contract No. NAS 8-5408 *by*
GENERAL ELECTRIC COMPANY
Schenectady, N. Y.
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1964

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ABSTRACT

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The report surveys the current state-of-the-art of fluid amplifiers including both theoretical and practical aspects of devices having no mechanically moving parts.

It is based on a complete review of the published literature (with an extensive bibliography), information obtained from 20 organizations involved in fluid amplifier development, and work performed by the General Electric Company.

Specific areas covered are design techniques, both analytical and experimental; typical elements and assemblies; applications, both now in use and contemplated; fabrication techniques; and instrumentation.

The report concludes that, although simple applications are now being made, the fluid amplifier field is still in the early development stage. There continues to be a basis for optimism for space applications requiring extreme environmental tolerance, long life, or the elimination of fluid system interfaces. Specialized military, and commercial applications also look promising. Work now under way should provide a better understanding of the design of devices and increase the number of useful applications.

Author

EDITORS' NOTES

Several comments have been received in regard to Section 2.0 of the subject report. Some have felt that this section, "History of Fluid Amplifiers" might be elaborated upon to more suitably reflect the extent of the contribution made to the fluid amplifier technology by DOFL. Their work started in 1959 and was much broader in scope than is generally appreciated. It has also been reported to us that the Air Force cooperated with DOFL during this early development, an interest which has subsequently led to major R&D programs in industry under Air Force sponsorship. There can be little doubt that the progress to date in the field of no-moving-part fluid amplifiers received most of its initial stimulus from the DOFL work.

Additional clarification of a gain analysis by S. J. Pepperone and S. Katz* of HDL has been received and supersedes the discussion in the report (see pp. 4-31, 4th paragraph). Pepperone computes a pressure gain from total pressures at the receiver entrances and compares these computed gain values with values obtained from measurements. The analysis requires knowledge of the jet velocity profile for the receiver flow of interest. Since other velocity profile data were not available, the velocity profile of a submerged, undisturbed jet was used in the analysis. Tests then were carried out at maximum receiver flow conditions to provide the least jet velocity profile disturbance. Dynamic pressures at the receiver inlets were then computed from flow measurements and used as the basis for calculating the experimental pressure gain values. Gain values obtained in this manner represent limiting values since they do not include the performance of the output diffusers and do not have the proper jet velocity profiles, expecially for the blocked receiver case. These gain values, however, do provide a good means of evaluating the effects of internal amplifier parameters such as nozzle to receiver distance. Care should be taken in using gain values computed with this analysis for circuit design unless the characteristics of the diffuser and the proper jet velocity profiles are included.

*Goto, J.M., Katz, S., and Pepperone, S.J., "Gain Analysis of the Proportional Fluid Amplifier", Report No. TR-1073, October 1962, Harry Diamond Laboratories.

FOREWORD AND ACKNOWLEDGEMENTS

The survey was made for the Astrionics Laboratory of the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama, by the Advanced Technology Laboratories and the Light Military Electronics Department of the General Electric Company. It represents Phase 1 of NASA contract number NAS 8-5408.

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Prof. F.T. Brown of Massachusetts Institute of Technology, who contributed the general discussion of stability criteria, sections 4.6.1 and 4.6.2, including some yet unpublished work of his own; R. Muffley, J. Eige and H. Woodworth of Stanford Research Institute for helpful comments; and

All the laboratories and companies which provided information on their work (listed in Appendix B).

TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 Purpose of Report

A new class of logic and control devices possess potential for meeting many of the unusual environmental requirements faced by the National Aeronautics and Space Administration in advancing the nation's space effort. These devices are called "fluid amplifiers" and are unique in that they have no moving parts*. The absence of moving parts and associated wear promises extremely long life, and environmental tolerance determined primarily by the choice of structural materials.

In order to obtain an objective assessment of the value of these new devices for space applications, NASA authorized the General Electric Company, under Contract NAS 8-5408, to undertake the following three-phase program:

PHASE I - Assess the state of the art of fluid amplifier development by literature search, and visits to universities and laboratories engaged in the development.

PHASE II - Determine rewarding areas of application in the space mission where the new fluid devices result in a significant improvement in performance or reliability. Consultants from throughout General Electric having experience in space applications are contributing.

PHASE III - Comparing the results of Phase I and Phase II, determine areas of weakness or omission in the technology,make a preliminary investigation to determine feasibility of filling in these areas, and experimentally demonstrate feasibility of one or more applications mutually selected from Phase II.

This report documents the findings of Phase I; reports on Phase II and III will be issued during 1964.

The approach taken in this program is to determine the potential value of the fluid amplifiers by methodical and objective steps before committing critical programs or extensive funding to support their development. The purpose is to clearly define the capabilities of this new technology, the true status of development, and the areas where its exploitation will produce the greatest return in forwarding the exploration of space.

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*Recently developed logic and control devices with moving parts, also called fluid amplifiers, are not under consideration in this study.

While this program is directed specifically at the space problem, the report covers the entire field of no-moving-part fluid amplifiers and therefore, should be useful for consumer, industrial and military applications as well.

1.2 Organization of Report

The report is issued in four volumes, of which this document (Volume I) represents the major part. In Volume I, the state of the art is described from the standpoint of available techniques and hardware. It is based upon integration of all available information obtained from the literature and from those engaged in development. Volume II is a bibliography covering over 300 references, giving abstracts on over 200 of those which relate most specifically to fluid amplifiers.* Volumes III and IV contain the classified information omitted from Volumes I and II respectively.

Volume I is composed of ten sections, and to a large extent, each section is independent and covers one aspect of the technology. References and figures are given separately with each section. Where figures are obtained from a reference, the reference is indicated by number directly on the figure. Following is a brief summary of the content of Volume I by section:

Section I - Introduction - covers purpose of report and philosophy behind program, outlines program, describes organization of report and gives brief summary by sections, gives general conclusions of the state of the art study.

Section 2 - History - gives a brief history of fluid amplifiers and traces the key developments.

Section 3 - General Functional Description - describes fundamental operating principles, gives definitions, nomenclature and schematics. These definitions should be reviewed to avoid misinterpreting following material.

Section 4 - Design Procedures - discusses the analytical and empirical design techniques in use, including both steady state and dynamic considerations. Also includes cascading and staging techniques.

*Volume II - Bibliography NASA CR-102

Section 5 - Elements - a "tube manual" presentation of available data on fluid control elements in use on a production or prototype basis.

Section 6 - Assemblies, Sensor and Transducers - describes standard circuits and devices, their method of operation, and typical performance data.

Section 7 - Applications - describes 15 specific applications including diagrams and available data, and indicates several other applications in process.

Section 8 - Fabrication - discussion of techniques in use for fabricating elements. Includes tolerances possible, gives a comparative evaluation for development or production uses, and gives sources for some services.

Section 9 - Instrumentation - gives instrumentation requirements, ranges of available equipment, and illustrates some of the test methods.

Section 10 - Power Supplies - discusses the need for power supplies and what is available.

Volume II, the Bibliography, includes an alphabetical index of references by author, including cross reference for multiple authors, and a numerical cross reference by subject categories.

1.3 Conclusions

No-moving-part fluid amplifiers have advantages in extreme environmental tolerance and high potential reliability. They are in an early stage of development and in spite of the usual retarding influences are moving steadily toward military applications where the advantages outweigh the development costs. Industrial applications of very simple and specialized nature are also beginning to appear. Typical examples in these two fields are speed control of naval steam turbines, and controlling the flow of 700°F molten caustic soda in an industrial process plant. It appears almost certain, however, that future applications will combine both moving-part and no-moving-part fluid elements thus obtaining the better features of each.

At the first public release of these fluid amplifier devices in 1960, at the DOFL, hundreds of companies and laboratories were represented. The obvious advantages of the new devices struck an extremely high level of interest. Many people, however, did not fully appreciate the difficulties of designing them and forecasts of performance were overly optimistic. As a result some have become disappointed with results from their own programs. In spite of this Stanford Research Institute estimates that over 100 companies are now actively engaged in development and that by mid-1963 about 20 million dollars had been invested in development since the first public release. This level of activity has resulted in surprisingly few commercial applications on the market. This NASA study indicates that there are three very basic reasons for this situation.

The first reason is the technical problem in designing a specific element. While the fluid elements appear to be (and are) very simple devices mechanically, the selection of critical shapes and tolerances is complex. Tolerances of some of the internal parts are far more critical than expected. Analytical approaches are not sufficient to fully carry out a design. As a result, most designs are arrived at empirically using the analytical techniques as guides. It is not sufficient to consider only the steady state aspects of the design, but the dynamic response in the presence of interconnections and loads must also be considered. Some of the basic phenomena involved and their interactions are not clearly understood; some are nonlinear and only approximate techniques are available for handling them analytically.

The second reason for slow emergence of applications appears to be a slow rate of development due to limited interchange of information. The major source of development funds apparently has been individual corporation investments. This has resulted in many developments being held extremely proprietary with very little information released. The ASME and HDL have tried to improve the situation by sponsoring symposia to encourage an exchange of information. However, a review of the number of items of information in this report which were "not available" for proprietary reasons indicates that improvement can be made.

The third reason is that the inherent characteristics of the fluid amplifiers limit the places where they can be applied with significant advantages. The identification of these applications has been delayed as the progress of development undergoes continual assessment by industry. The major inherent limitations in these fluid devices are their low response speed compared to electronics, and their standby power consumption (they are constant flow devices). Response speeds can be improved by going to higher pressure; in some cases a compromise can be made between speed and power consumption. In general, however, response above 10,000 cps does not presently look practical.

1.3.1 Summary of Characteristics

Following are summaries of the major performance characteristics as revealed by the study:

Gain - Typical proportional and digital devices now in use have pressure and flow gains in the order of 5 to 20. Gains have been limited, by design, because of self generated noise and compromises required in obtaining reasonable maximum output amplitude. Performance of recent proprietary devices are claimed to have pressure gains as high as 200 with low noise and large output amplitude capabilities, and usable flow gains can approach infinity in certain operating regions.

Response - Typical speeds of fluid amplifier elements vary from 1 millisecond down to 0.3 millisecond. Responses of 0.1 milliseconds have been estimated using extrapolation methods. Typical circuit operating frequencies range from a few hundred cps up to 1000 cps. For the next few years it appears that circuit operating speeds will not exceed 2000 to 3000 cps.

Power Consumption - No-moving-part fluid amplifiers are constant flow devices. Power consumption can be minimized by using smaller sizes and lower pressures. Power consumption will vary depending on whether compressible or incompressible fluids are used. For example, an element with a 0.010 x 0.010 inch nozzle with a 0.1 psi drop is calculated to dissipate 0.05 milliwatts. The same size element operated on air has an equivalent power consumption of 2 milliwatts.

Typical operating pressures for logic and control systems are 0.5 to 15 psig although the use of lower pressures has been demonstrated for applications where power consumption is critical. Power applications have utilized supply pressures up to several hundred psi. Most work has been with air at subsonic velocities. Operation on water and hydraulic oil has been investigated.

Environmental Tolerance - Several types of fluid amplifiers have been tested at temperatures up to 1400°F with performance generally as predicted. The maximum operating temperature is believed limited only by the capabilities of the fabrication material. Tests have also shown that the fluid amplifier is immune to acceleration and vibration environments. Vibration levels of 5000 cps at 50g's have been achieved with no apparent effect on devices.

Size - Typically, the smaller fluid amplifiers in use today have power nozzle widths ranging from0.020" to 0.040". Several types have been operated with 0.010" nozzle widths. The smallest known operating device has a nozzle width of 0.002". Little work on nozzle sizes smaller than 0.010" is predicted for the next few years. Smaller elements do not provide much gain in packing density because of manifolding problems.

1.3.2 Technical Areas Requiring Emphasis

Areas where the fluid amplifier technology appear to require additional effort for anticipated NASA applications are:

1. Design Techniques - Design techniques for both elements and cascading of elements into systems are lacking. Analytical techniques are becoming available and will improve the situation. It is expected to be several years before they are adequate because of the relatively slow "cycle time" of research programs.

2. Transducer and Sensors - A variety of concepts are understood to be under development but for proprietary reasons, little information has been revealed.

3. Fluid Power Supplies - Many fluid amplifier applications will be considered because of an existing power source but other applications would be attractive if a highly reliable power source existed (for example, an orbital vehicle with solar energy available).

4. Reliability - Reliability work on fluid amplifiers must be carried out concurrently with the development of fluid amplifier systems. With the exception of the work by Fox* no work on fluid amplifier reliability is known.

5. Fabrication - Production fabrication methods must be developed for producing small, high tolerance devices in metals or ceramics if extreme environmental capabilities are required. Packaging studies of interconnection and manifolding considerations are needed.

Instrumentation such as a good pneumatic signal generator is now beginning to appear on the market. Special instrumentation techniques for inspection and checkout of completely assembled systems have not received much attention but will be needed when systems work becomes more predominant.

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* Fox, H. L., "A Comparison of the Reliability of Electronic Components and Pure Fluid Amplifiers", Fluid Amplification Symposium Proceedings DOFL, October 1962.

2.0 BRIEF HISTORY OF FLUID AMPLIFIERS

Fluid amplifiers such as jet pipe valves, spool valves and actuators using moving mechanical parts have been known for years and represent a relatively well developed field. In this report, however, fluid amplifiers are defined as devices which can perform logic and control functions without the use of moving parts. While fluid amplifiers with no moving parts are generally considered as a recent development, work was carried out several decades ago which undoubtedly has led to the present high interest in them. Brief historical reviews of the development of these devices have been included in several references (e.g., 2-1, 2-2, 2-3, 2-4*). The highlights of these and some additional information are presented below.

In 1916 Nikola Tesla[2-5] applied for a patent on a device which was probably the first fluid control element with no moving mechanical parts. Although he probably did not envision the use of it in a fluid amplifier system, the device performs the function of a fluid diode as shown in Figure 2.1. Henri Coanda, experimenting with flow around obstacles in about 1932, identified the attachment of a jet to a wall as shown in Figure 2.2. Metral[2-6] in 1938 reported on this Coanda effect and some inventions embodying the effect. This phenomena is the basis for the wall-attachment devices now receiving so much attention. References 2-1 and 2-2 provide additional background and detail. Also, during 1938, an American engineer, McMahon[2-7], described a "fluidynamic" control concept which could be used to control the flow of fluid through ducts or a fan housing without the use of moving parts. He described the phenomena in electron tube analogies as well as in fluid dynamic terms. Other inventions and developments about this time approached the fluid amplifier concept but utilized some moving parts. For example, in 1940, Braithwaite and Wilcox[2-8] received a British patent on a "mechanical relay of the fluid jet type". This device utilized an axial power nozzle and receiver and a perpendicular third nozzle, a control nozzle. The control nozzle provided a jet to intersect and divert the power stream from the receiver. This nozzle was mechanically actuated to vary the degree of deflection of the power stream. If, instead, a fixed control nozzle had been used and the power stream deflected by varying the control stream momentum, these inventors probably could have claimed the first fluid amplifier. In that same year, a British patent was issued to Todd[2-9] on a "mechanical relay of the fluid jet type" which fundamentally differed little from Braithwaite's device except for the addition of an actuator and feedback linkages. In 1958 Kline[2-10] presented some result on diffuser work which probably provided a valuable input leading to the invention of fluid logic devices. Kline described how, for a wide angle diffuser, the flow can separate from one wall and flow along the other. For even wider angles the flow will separate from both diffuser walls and stream down the center. Further, for a certain angle of the diffuser walls, a hysteresis zone exists where the flow can separate from one wall or both walls and is stable in any of these states

* References are listed at the end of each section.

(as shown in Figure 2.3). A fluid amplifier valve of an entirely different concept was investigated in the early fifties by Rhoades and Cain[2-11]. They successfully demonstrated that the pressure drop across a free vortex could be used to modulate the flow of fluid as reported by Dexter[2-12]. This device has not been applied until recently, perhaps because of a lack of associated fluid amplifier elements to build up a complete circuit. The free vortex is also used as the primary mechanism for a rate sensor. Until recently this concept has been classified (certain parts of the sensor are still classified and have patent secrecy restrictions), although the idea was revealed about 1960.

Development activity was rather low, however, until in March 1960 the Diamond Ordnance Fuze Laboratories made a public news release which identified the new field of fluid amplifiers and described some of the devices which had been successfully demonstrated. The news release described a concept for an analog amplifier[2-13], utilizing the interaction of streams and described a wall attachment digital amplifier. These concepts will be described in more detail in other sections of this report. That same year Greenwood and Ezekiel[2-14, 2-15] described a logic element which performs the half-adder function using momentum interaction principles. About this time MIT revealed that fundamental work on fluid amplifiers was being carried out in their laboratories. These announcements provided the impetus for many Government laboratories, universities and private industries to initiate development programs for various fluid amplifier concepts and systems. Russian researchers have been reported to be quite active in this field, but little work has been revealed that utilizes no moving parts for logic and control concepts. Arrangements which have been described are shown in the next section.

Today it is estimated that over 100 companies are active in the field and the activity seems to be still increasing. As an indication of the interest in the field, two symposiums which have been devoted entirely to fluid amplifier concepts, devices and systems were held in the Fall of 1962[2-16, 2-17] and more are planned**.

Practically all the effort to date has been applied toward basic and development work. There are no systems in production to the authors' knowledge, although one company uses a fluid element in a commercial product and also has a line of larger power valves available for commercial use. The latter are described in section 7 of this report.

**e.g., Harry Diamond Laboratories, May 26-28, 1964.

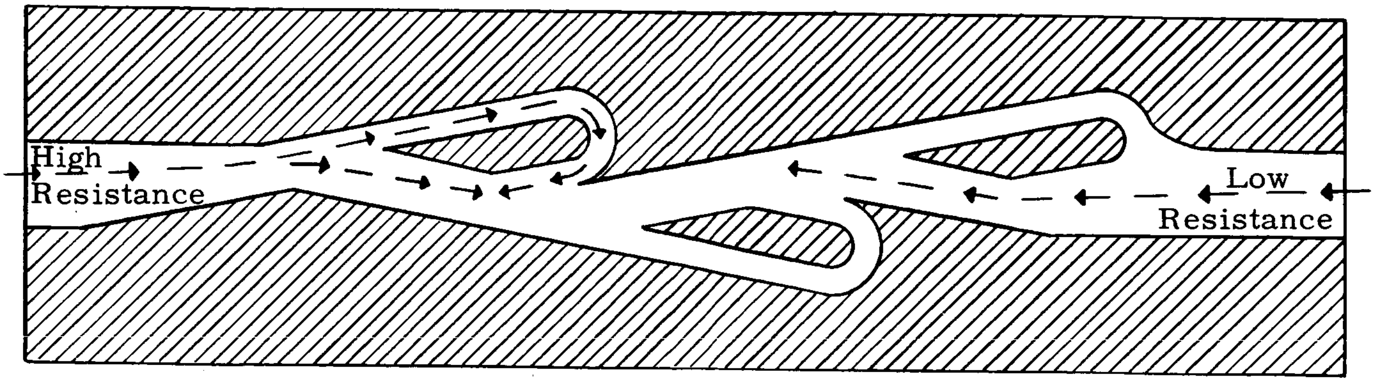


Figure 2.1. Tesla's Diode

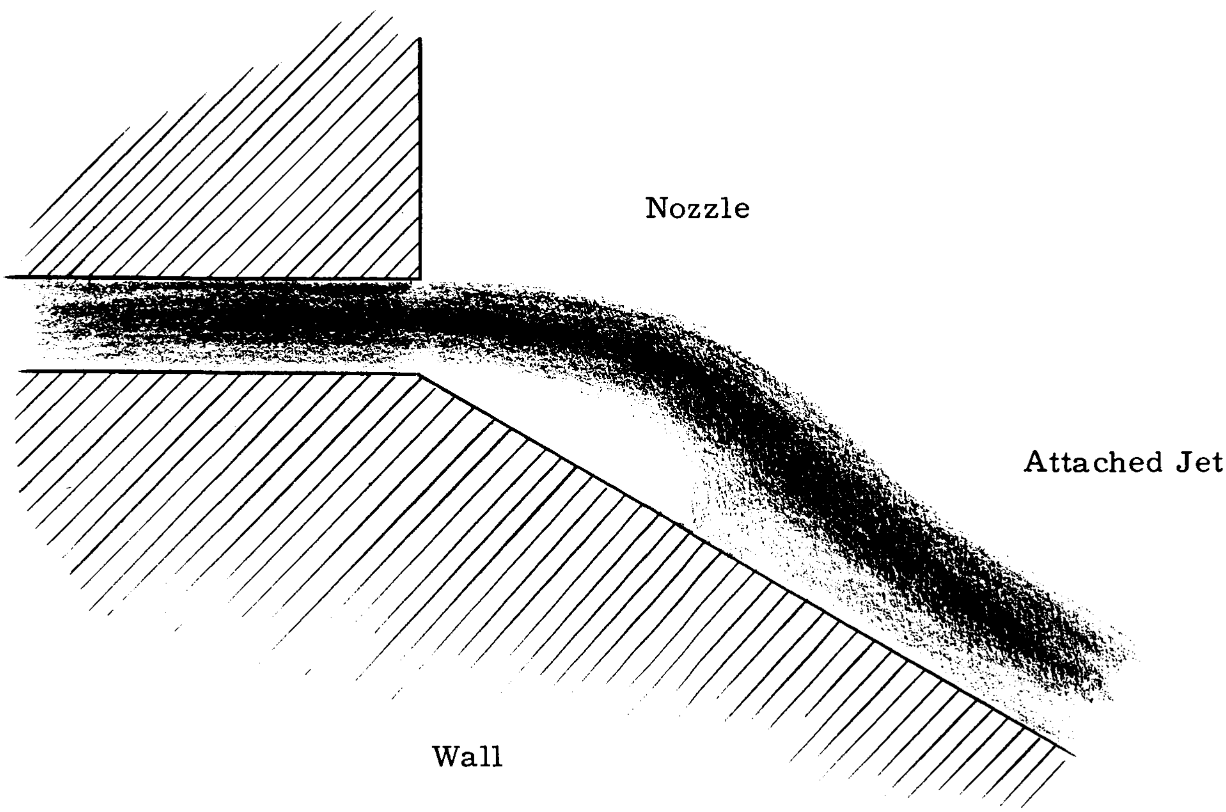
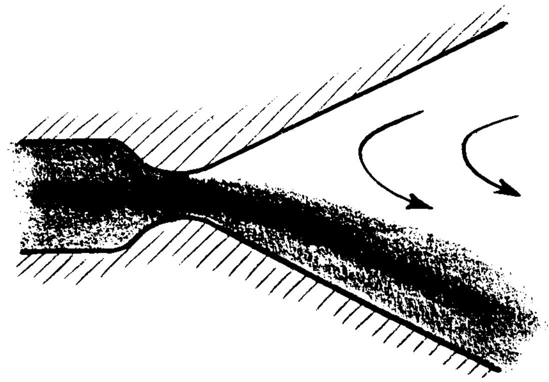
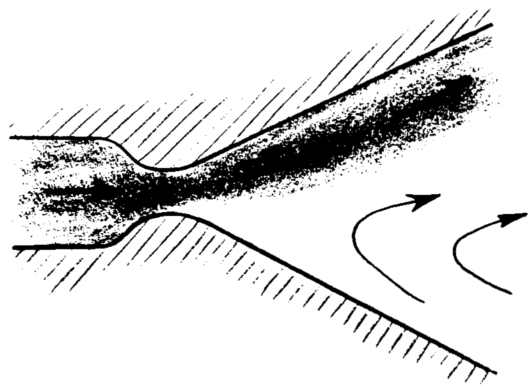


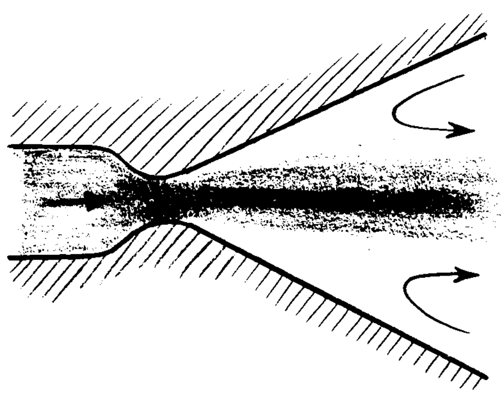
Figure 2.2. The Coanda Effect



Flow separates from upper wall.



Flow separates from lower wall.



Flow separates from both walls.

Figure 2.3. Wide Angle Diffuser Flow Patterns.

REFERENCES - SECTION 2

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2-2 Chang, P.K., "Survey on Coanda Flow" Fluid Amplification Symposium Proceedings, DOFL, October 1962.

2-3 Fox, H.L. and Wood, O.L., "A Survey of Fluid Devices and Automatic Control Systems," paper presented at 6th Region I.E.E.E. Technical Conference, April 26, 1963.

2-4 Bowles, R.E., "State of the Art of Pure Fluid Systems", Fluid Jet Control Devices, ASME Symposium Notes, November 28, 1962.

2-5 Tesla, N., "Valvular Conduit," U.S. Patent No. 1,329,559.

2-6 Metral, O.R., "L'effect Coanda," Proceedings, 5th International Congress of Applied Mechanics, 1938.

2-7 McMahan, K.D., "Fluidynamics Control of Fluid Flow," Proceedings, 5th International Congress of Applied Mechanics, 1938.

2-8 Braithwaite, R.C. and Wilcox, K., "Mechanical Relay of the Fluid Jet Type," U.S. Patent No. 2,408,603.

2-9 Todd, K.W., "Mechanical Relay of the Fluid Jet Type," U.S. Patent No. 2,408,705.

2-10 Kline, S.J. and Moore, C.A., "Some Effects of Vanes and Turbulence in Two Dimensional Wide Angle Subsonic Diffusers," NACA, TN4080, June 1958.

2-11 Information from the Advanced Technology Laboratories, General Electric Company, Schenectady, N.Y.

2-12 Dexter, E.M., "No Moving Parts - Feature of New Valves," SAE Journal, September 1961, Page 102.

2-13 Horton, B.M., "Amplification by Stream Interaction," Northeast Electronics Research and Engineering Meeting, IRE, Boston, November 1960.

2-14 Greenwood, J.R., "The Design and Development of a Fluid Logic Element," B.S. Thesis, M.I.T., Mechanical Engineering Department, May 1960.

2-15 Ezekiel, F.D. and Greenwood, J.R., "Hydraulics Half-Add Binary Numbers," Control Engineering, February 1961, Page 145.

2-16 Fluid Amplification Symposium, Diamond Ordnance Fuze Laboratory, October 1962.

2-17 Symposium on Fluid Jet Control Devices, ASME, November 28, 1962.

3.0 FUNCTIONAL DESCRIPTION, NOMENCLATURE AND SCHEMATICS

The general operating characteristics of fluid amplifiers are discussed briefly in this section in order that a reader unacquainted with the devices may obtain a general understanding before becoming involved with more specific and detailed discussions in later sections.

Two generic classes of fluid amplifier devices and systems are under development today. These have been defined as digital and proportional in this report. For clarity in discussions, further definitions have been made for the pieces that make up a system. Devices such as fluid switches, proportional amplifiers and OR-NOR gates are defined as "elements". When these sorts of devices are interconnected to perform standard functions such as counters, operational amplifiers or shift registers, the arrays of elements are defined as "assemblies". In this section, the operation of typical digital and proportional elements is described and schematics and nomenclature are included. Some typical assemblies are then discussed, based on this information.

3.1 Elements

3.1.1 Digital Elements

Three different operating principles have been demonstrated for digital fluid amplifiers: (1) the use of jet entrainment (wall attachment device), (2) momentum interaction, and (3) jet turbulence. The wall attachment device seems to be receiving, by far, the most attention.

3.1.1.1 Wall Attachment Devices

These devices are most easily understood by first considering simply a submerged or unbounded jet; i.e., a jet of air in ambient air or a jet of water in a water ambient. Because of the high shear at the edges of the jet, it entrains fluid from the ambient as illustrated in Figure 3.1a, a two-dimensional representation. (See reference 3-1 or 3-2 for additional information on submerged jets). Coanda demonstrated this characteristic in his early experiments with jets. If a wall is placed near the jet, it will tend to limit the amount of entrainment by the adjacent side of the jet and the local pressure will be lowered. As a result, the jet will be deflected towards the wall by the pressure gradient across the jet as shown in Fig. 3.1b. As the jet moves towards the wall, the pressure between the wall and jet will be even further lowered since the entrainment on that side is further reduced, and, with the proper geometry, the jet can attach to the wall. With two walls present and the proper geometry (Fig. 3.1c) the jet can be made to attach to either wall and is stable in either attached position. This flow characteristic is similar to a region described by Kline [3-3] for diffusers with large wall angles. He showed that the flow will separate from one wall and will flow along the other (See Fig. 2.3). The attached jet creates a closed region identified as a "bubble" (Fig. 3.2c). A low pressure exists in the bubble and ambient pressure exists along the opposite side of the jet providing the pressure gradient to hold the jet against the wall. Control channels into this bubble, as shown in Fig. 3.1d, can be used for switching the jet. If sufficient flow is admitted to the bubble region the pressure can be increased sufficiently to detach the jet and to deflect it to the other side. The geometry illustrated in Fig. 3.1d is fundamental to the wall attachment switch. Digital devices using this principle also have been called boundary layer fluid amplifiers.

An element which exhibits relatively large hysteresis in its input-output characteristic has "memory" or is bistable and is defined as a fluid "flip-flop". References 3-4 and 3-5 describe the operation of this element. Fig. 3-2 illustrates the characteristics of this element. Note that the geometry of this element differs little from that of Fig. 3.1d except that receivers have been added to collect the power jet flow. If the control ports are open to the ambient, the low pressure bubble (Fig. 3.1c) will aspirate flow into the control port on the jet attachment side. If under normal operating conditions the device does not have a significant hysteresis loop or is monostable with such a high gain that it is operated in saturation, it is defined as a switch. A switch, then, requires a continual control port flow to maintain stability and produces continual flow from an output port. The switch can be made to have flip-flop characteristics by restricting the aspiration flow with orifices in the control ports, or increasing the control port impedance in some other manner. The outline of the element, Fig. 3.2, is not to scale and is intended only for illustrating the operating principles. Actual geometries are shown in Section 5.

The single input flip-flop is a useful element in fluid systems just as it is in electrical systems for functions such as frequency dividing and binary counters. In this report, this element is defined as a "binary flip-flop". This element can be made up somewhat like the electronic counterpart using the two-input flip-flop described above with additional elements to provide single input operation. A more straightforward arrangement, however, is that illustrated in Figure 3.3 developed by Warren. [3-6] In this arrangement the control ports of a flip-flop are joined to a common input by means of flow channels which have a configuration of a flip-flop with the control ports eliminated. The input pulses are applied at the port which ordinarily would be for the power source. When no input signal is applied, the jet will be attached to one side, e.g., the right-hand side as illustrated in sketch (a) Figure 3.3. In this state, the control port C1 will be at a lower pressure than C2 because of aspiration by the jet and the proximity of the jet to C2. This pressure difference across the control ports will establish a counterclockwise circulation flow in the loop interconnecting the control ports. When an input signal is applied, this circulation flow supplies sufficient bias to make the jet at C attach to the right side of the loop and flow into C2 to switch the flip-flop as shown in sketch (b). When the input signal is relaxed, a circulation flow will be set up in the opposite direction as shown in sketch (c). The next incoming signal will then be forced to attach to the opposite side of the loop to switch the element back to its original state. Thus, for every two input pulses, the output is returned to its original state.

The OR-NOR element often is used as a fundamental building block to build up other logic functions such as flip-flops and half-adders. The configuration and operating characteristics of the wall attachment OR-NOR is shown in Figure 3.4. In this case, the element is biased with a bias port to prevent attachment to the "OR" side. Other biasing arrangements are shown in Section 5.0. Figure 3.4 illustrates a two-input element; three-input elements of this configuration have also been demonstrated.

An EXCLUSIVE/OR or HALF-ADDER [3-7] is illustrated in Figure 3.5. Flow in C1 or C2 exclusively produces an output at O2 while flow simultaneously in C1 and C2 produces an output at O1. Note that this element is passive while the elements previously discussed are active, i.e., they require a power source and can provide gain. This element is also identified as a half-adder since two of these elements can form a full binary adder stage. As can be seen from Figure 3.5, this logic element can also be used as a two-input AND element.

3.1.1.2 Momentun Devices

Logic elements can utilize momentum interaction for operation. An example, Figure 3.6, is the half-adder by Greenwood and Ezekiel.[3-8] As illustrated, a signal from either C1 or C2 exclusively will provide an output at O1. When inputs occur at C1 and C2 simultaneously, the resultant momentum is such that an output occurs at O2. OR-NOR elements of the momentum type can be made up in a straightforward fashion using jet interaction principles, and these can be interconnected in conventional circuitry to form a flip-flop or to perform other logic functions.

3.1.1.3 Other Concepts

Russian activity in "no-moving parts" fluid amplifiers according to published literature has been on air-foil concepts such as illustrated in Figure 3.7. Flow in the control port causes controlled separation of the power flow over the top of the air foil. Receivers are places to capture the flow. The devices can be designed to have digital or proportional characteristics.

The turbulence amplifier [3-9] uses an entirely different operating principle. At low Reynolds numbers a submerged jet (air in air, water in water, etc.) can remain laminar for a relatively long distance. A receiver placed in the jet (Figure 3.8a) will provide good pressure recovery if the jet remains laminar up to the receiver. On the other hand, the receiver pressure recovery is low when the jet becomes turbulent. The pressure at the power nozzle, therefore, is adjusted so that the jet becomes turbulent just after the receiver. With this situation small disturbances such as flow in the control nozzle (Figure 3.8b) will make the jet become turbulent before it reaches the receiver, thus drastically lowering the receiver pressure (See Figure 3.8c). With multiple control nozzles (up to 4 have been demonstrated) this element provides NOR logic and these elements can be combined to form other logic elements such as the flip-flop, AND, and half-adder.

3.1.2 Proportional Elements

The types of proportional amplifiers which have received the most attention have been the beam deflector and the vortex. Other types are being studied and are discussed in later sections of this report.

3.1.2.1 Beam-Deflector Amplifier

The concept and potential usefulness of the beam-deflector amplifier was perhaps first advanced by Horton [3-10, 3-11]. The basic principle of this amplifier is illustrated in Figure 3.9. The input signal is the difference in flows or pressures present at the two control ports, and the output signal is the difference in flows or pressures at the receiver ports. The geometry is not too dissimilar to the fluid flip-flop except that the sidewalls in the unbounded jet region are removed considerably from the jet to prevent attachment or interaction. The deflection of the jet to provide a difference in flow to the receivers is achieved by momentum and pressure of the control flow. Momentum difference between the two control flows predominates in Horton's proportional element. Brown, however, in his proportional amplifier work, emphasizes a "pressure control" concept in which the jet is deflected primarily by pressure force on the jet instead of momentum interaction. Curtiss and Zisfein [3-12] make use of controlled separation to deflect a power stream.

3.1.2.2 Vortex Devices

The vortex amplifier [3-13] utilizes a free vortex for modulation of fluid flow. The basic concept is illustrated in Figure 3-10. With no control flow present, the fluid streams from the power inlet across the vortex chamber to the outlet with little flow resistance. When control flow is introduced, its momentum induces rotation and a vortex is generated with a resultant high pressure drop from the outer circumference of the vortex chamber into the fluid outlet. The pressure drop across the vortex represents an increased back pressure on the supply port and thus reduces the power flow. The vortex amplifier therefore is a variable restrictor; it reduces power flow rather than diverting flow as is done with all the previously discussed elements. Its use, therefore, appears advantageous in power systems. Some configurations of the vortex amplifier have exhibited regions of negative resistance so that digital vortex amplifiers appear practical.

The vortex can be used to provide a diode characteristic. [3-14] The configuration shown in Figure 3.11 exhibits low resistance in the direction shown and high resistance in the reverse direction.

The vortex is also used as the operating principle of a rate sensor. The fluid inlet is at the outer circumference of the cylindrical vortex chamber which is fixed to the body which is sensed for angular rate. As the fluid accelerates from the outer circumference to the center outlet, its angular rate increases obeying free vortex relations. The angular rate of the body thus can be greatly magnified. A pick-off is required at the vortex center to convert the angular momentum of the fluid to a useable signal. This pick-off is one of the key items in this sensor and, as a result, some of the higher performance elements are classified and even under patent secrecy orders.

3.2 Schematics and Nomenclature

Schematic representations of fluid amplifiers and other circuit elements are desirable to illustrate circuits and their operation. Representations which have been found convenient by the authors are illustrated in Figures 3.12 through 3.21 and are used throughout this report.

The difference between the digital and proportional beam deflector amplifier is shown in Figure 3.12; the dashed line indicates a proportional element. This same delineation is used for the vortex amplifier schematic Figure 3.13. An element is identified as being either active or passive by the symbol shown in Figure 3.14. The schematics for flip-flops and switches are illustrated in Figure 3.15. In general an arrowhead is included on signal lines to indicate that continual signal flow is required for operation. Figure 3.16 through 3.19 are schematics for the binary flip-flop and logic elements. Figure 3.20 shows schematics for indicating biasing methods.

Figure 3.21 illustrates schematics for fluid impedances. Figure 3.21a is the general symbol for impedance. Figure 3.21b shows the representation for an orifice which would obey a square-law relationship if an incompressible fluid is used. Figure 3.21c represents a laminar restriction where pressure drop varies linearly with flow and where friction effects predominate over inertial effects. Figure 3.21d, in turn, shows fluid inductance where inertial effects predominate over friction, such as a short length of line. Figure 3.21e shows the symbol for a fluid capacitor which, in some instances, is analogous to an electrical capacitor. A fluid capacitor consists of a fixed volume if the fluid is compressible, or a hydraulic accumulator or equivalent for an incompressible fluid. In drawing an electrical analogy, where voltage and current are analogous to pressure and flow, respectively, a fluid capacitor such as the volume or accumulator can only be the equivalent to shunt capacitance from the point in question to ground; it is never the equivalent of a blocking capacitor. The equivalent of blocking capacitors must be obtained by using other devices such as a pulse generator or a diaphram (which is a moving part and outside our definition). Figure 3.21f is the symbol for a fluid delay line which has the characteristic of providing a nearly pure time delay in the transmitted signal, with a minimum of dispersion.

3.3 Assemblies

As previously pointed out, assemblies are defined as a group of interconnected elements which perform a standard function. Some of the more typical assemblies are described below to illustrate typical circuits. These and additional assemblies are discussed in more detail in Section 6.

3.3.1 Digital Assemblies

Standard assemblies can be made up from digital elements using standard logic and digital circuits. For example, a free running multivibrator is made from a flip-flop with negative feedback from the output ports to the control ports. Feedback around only one side results in a monostable or "one-shot" multivibrator. It is often used as a pulse generator. Binary counters are made up from binary flip-flops. An oscillator or multivibrator driving a counter obviously results in a timer. An adder circuit using half-adder elements (Figure 3.5) is illustrated in Figure 3.22. "A" represents one binary number, "B" another binary number, and the sum of "A" and "B" is produced at "S". An additional example is shown to illustrate the operation of the circuit. Another versatile digital circuit is the shift register. This circuit is used when information is to be stored and later read out. It is also used where the propagation of information is to be synchronized with machine movement such as conveyor lines. The shift register utilizes flip-flops for information storage and gates controlled by an external "clock" to shift the information. A typical circuit is shown in Figure 3.23. This circuit uses half-adders as gates. The orifices and capacitance volumes shown provide an RC delay between the registers or flip-flops. In order to prevent multiple shifts, the clock pulses must be shorter than the time constant of these delays.

3.3.2 Proportional Assemblies

Control of both high power and signal levels has been demonstrated using proportional devices. An example is the operational amplifier which uses staged or cascaded proportional amplifiers to provide the high gain. Feedback can then be used for achieving the desired computational functions. Feedback circuits have been developed to provide differentiation and integration as well as fixed gain (independent of frequency). Some of these circuits are discussed in Section 6. Another proportional assembly which has received considerable attention is the oscillator-type temperature sensor. This concept uses a proportional amplifier with negative acoustic feedback to make an oscillator. The feedback results from internal paths, or external lines. The oscillator frequency is proportional to the acoustic wave-velocity (phase velocity), which is usually (except when wall shear is particularly significant) proportional to the square root of the absolute temperature.

3.4 Definitions

The definitions that have been made throughout this report are summarized below. The definitions have been chosen to agree as much as possible with present general usage.

Fluid Amplifier: A fluid device (gas or liquid) which performs a logic, amplification, or control function without the use of moving parts. This report does not consider fluid amplifiers using moving parts such as balls or spool valves.

Element: The lowest level of assembly used in a fluid amplifier circuit which provides a control or logic function. For example, an OR-NOR logic element or a proportional amplifier stage is defined as an element. A restrictor is also considered an element.

Assembly: Groups of elements which are interconnected in a circuit which performs a standard function. Examples are a counter, a shift register, or an operational amplifier made up of staged amplifiers.

Flip-Flop: A digital amplifier which has a hysteresis loop in the input/output characteristic and thus exhibits "memory".

Switch: A digital amplifier which has little or no hysteresis (i.e., can be randomly switched by noise present in jet) and requires a continual control signal present to maintain a given state.

Gate: A digital element which can inhibit signal transmission with a second input signal, e.g., an OR-NOR element.

Proportional Amplifier: An amplifier which has a useful range of operation over which the output is the product of a gain value and an input signal.

Operational Amplifier: Cascaded proportional amplifiers with sufficient overall gain and signal input characteristics so that the feedback establishes the overall amplifier performance (i.e., integrators, differentiators).

Impedance: The relationship between pressure and flow, usually non-linear, for an element or element integral part (i.e., control port).

Diode: An element which has a significantly higher impedance in a reverse direction compared to the forward flow direction.

Capacitance: The compressibility effects of fluid which result in a characteristic such that the pressure exhibits a phase lag with respect to the flow (equivalent to shunt capacitance in an electrical circuit).

Inductance or Inertance: Inertial effects of a fluid in a line, particularly in a short line, such that flow has a phase lag with respect to pressure.

Restrictor: An element which has a significant pressure drop over the flow range under consideration.

3.5 Commentary

Development of fluid amplifiers and assemblies is proceeding very rapidly, but as would be expected, not all known operating phenomena are receiving equal attention. Hence it is too early to categorize certain devices as being more suitable than others for performing a given function. For example, there is not sufficient data or experience to conclude that a wall attachment digital amplifier is better than a turbulence digital amplifier for a low-level logic operation. Those who attempt to make such a recommendation at this time do so without complete data and primarily on the basis of personal preference or intuition.

One qualitative conclusion that does appear valid is that vortex amplifiers will be superior to the other known types of amplifiers for power amplification. This is because the vortex amplifier is a variable restrictor rather than a diverter. Much more data is necessary, however, to properly locate the transition point where the vortex amplifier takes over its preferred position.

Although the field of fluid amplifiers is relatively young, its rapid growth rate indicates that work on standardization should be given more emphasis than it now receives. Harry Diamond Labs (formerly DOFL) made an early attempt at standardizing nomenclature and schematics. The schematics of Section 2.2 of this report were presented in 1962 as another recommendation. Report Section 2.4 now suggests some generic definitions which were needed to preserve continuity in this report. Broad agreement on nomenclature, schematics and definitions would probably do much to speed acceptance of the technology by industry. Action by an organization such as ASME would seem appropriate.

There is one area of standardization which is badly needed to even assess the-state-of-the-art, that is, in the definitions for gain and response. Presently available data from various sources cannot be compared directly without better knowledge of what the values mean and how the tests were conducted.

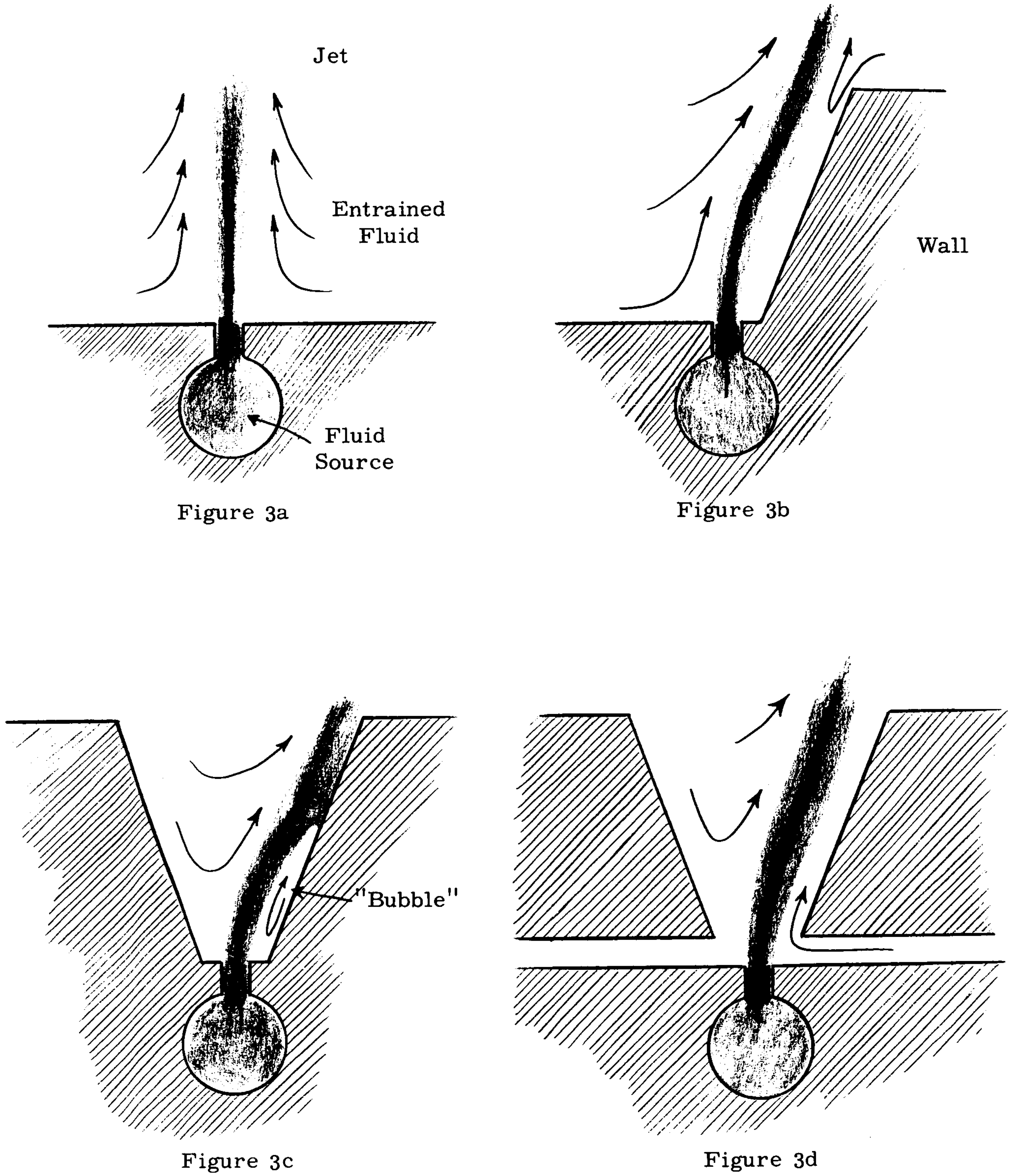


Figure 3. 1. Wall Attachment Principles.

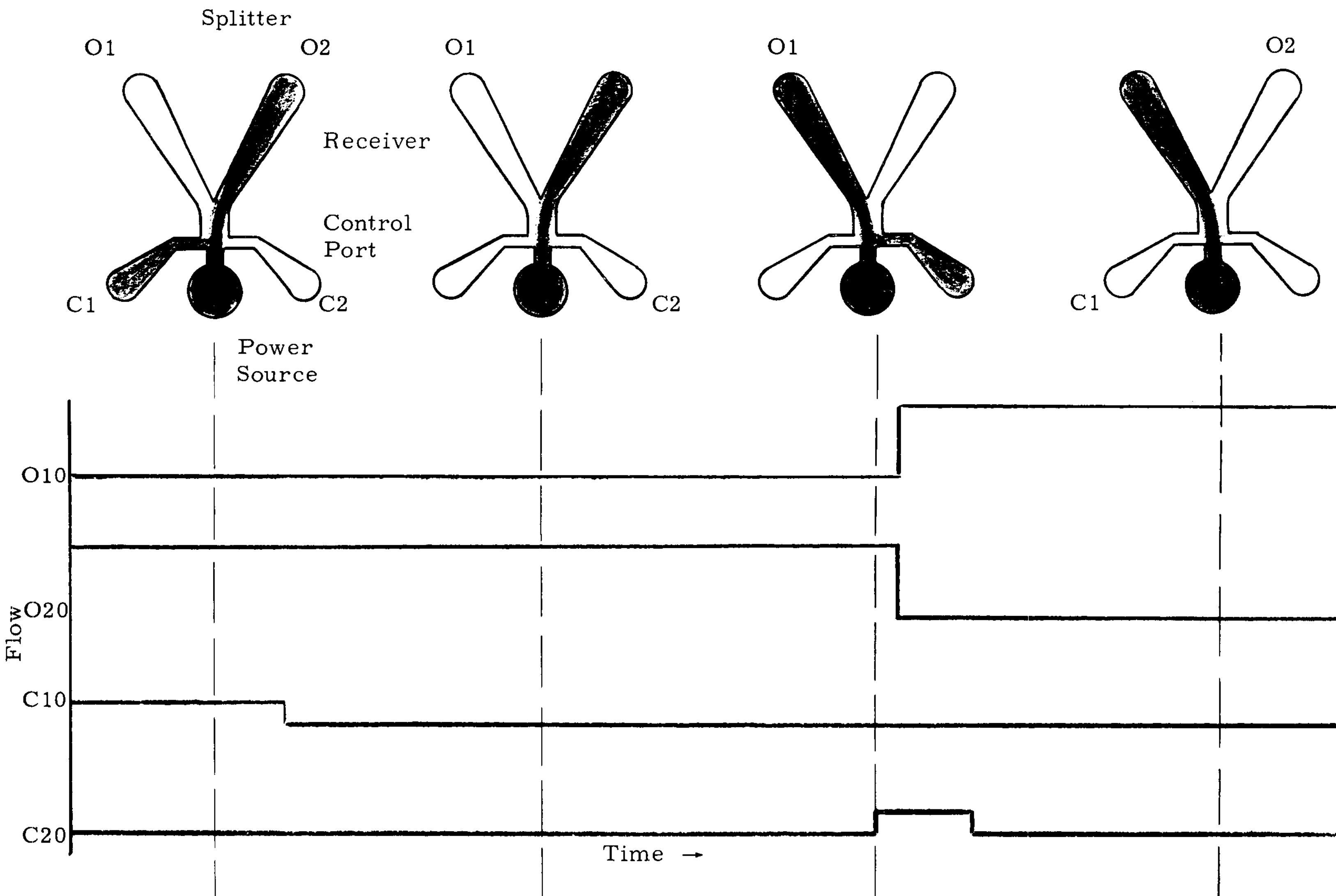


Figure 3.2. The Flip-Flop

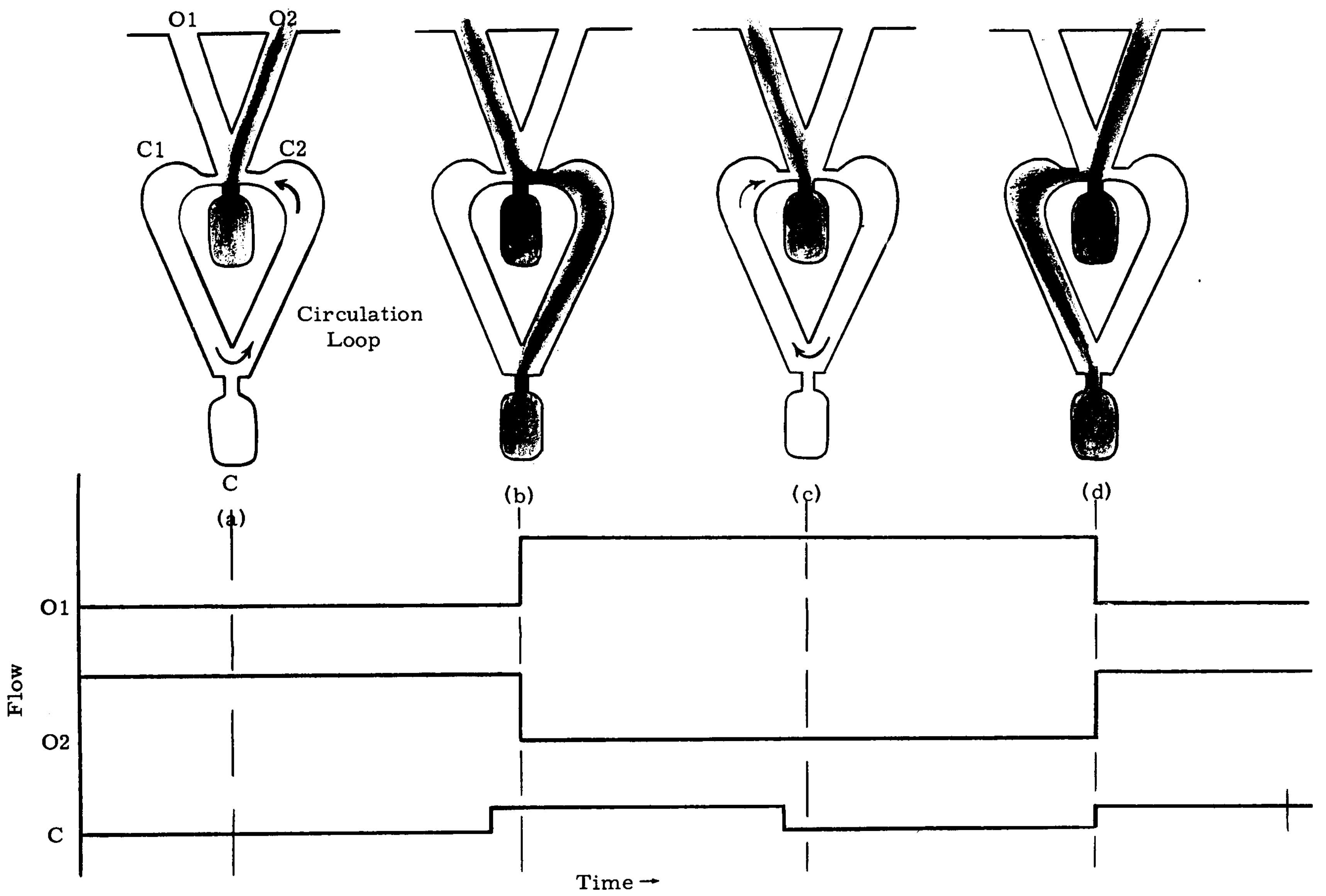


Figure 3. 3. The Binary Flip-Flop

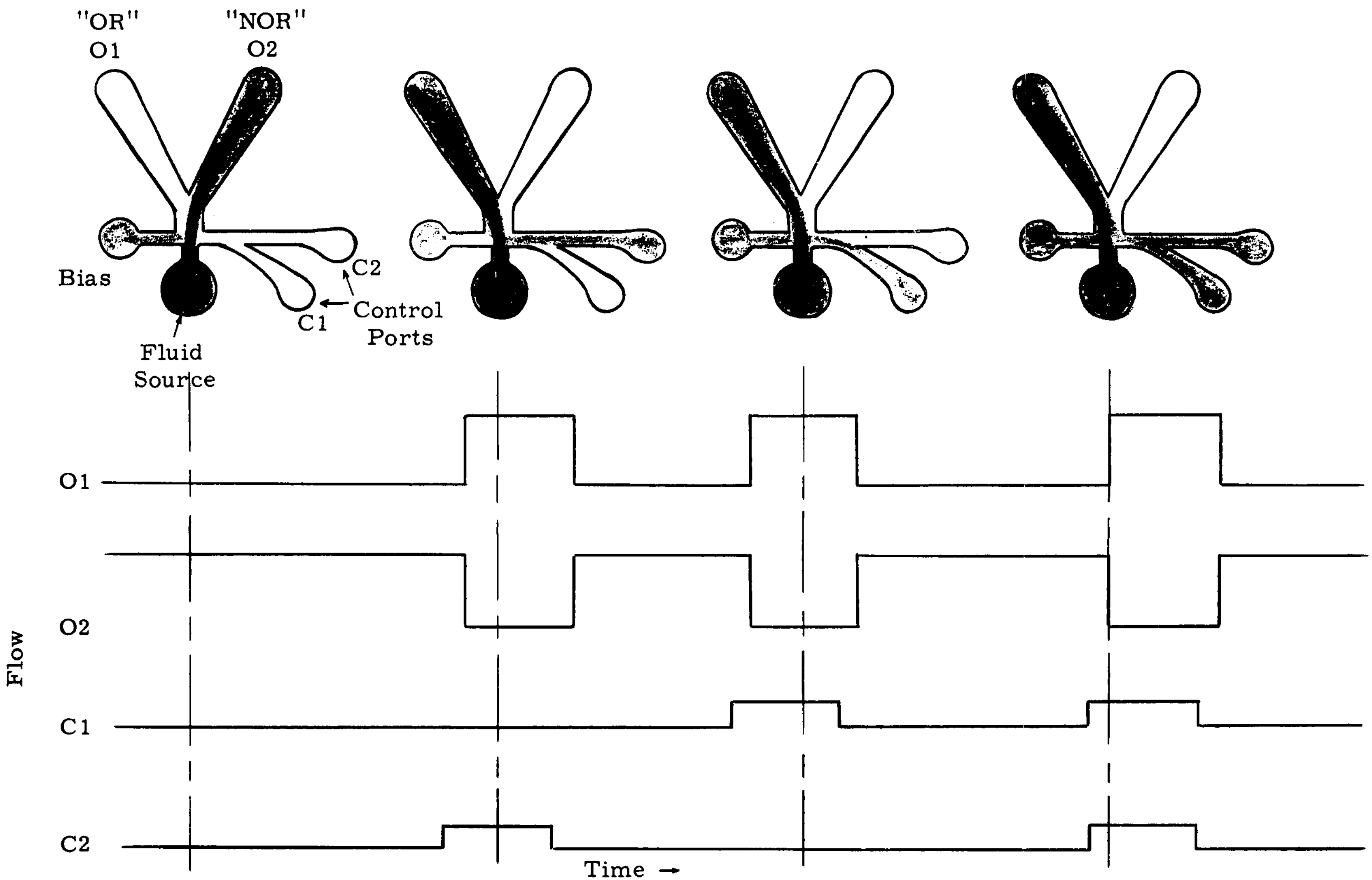


Figure 3.4. The Wall Attachment OR-NOR Element.

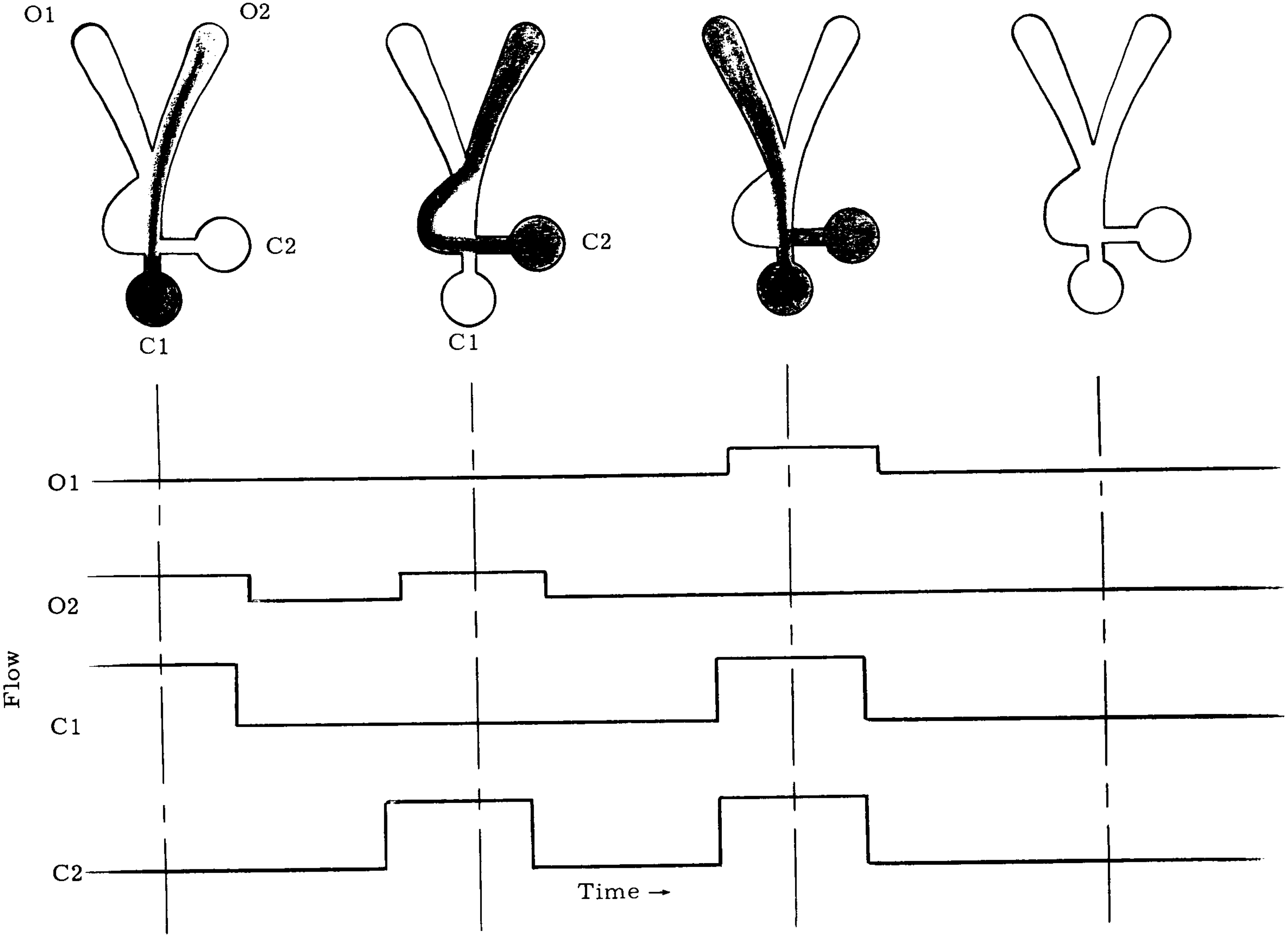


Figure 3. 5. The Wall Attachment Half Adder.

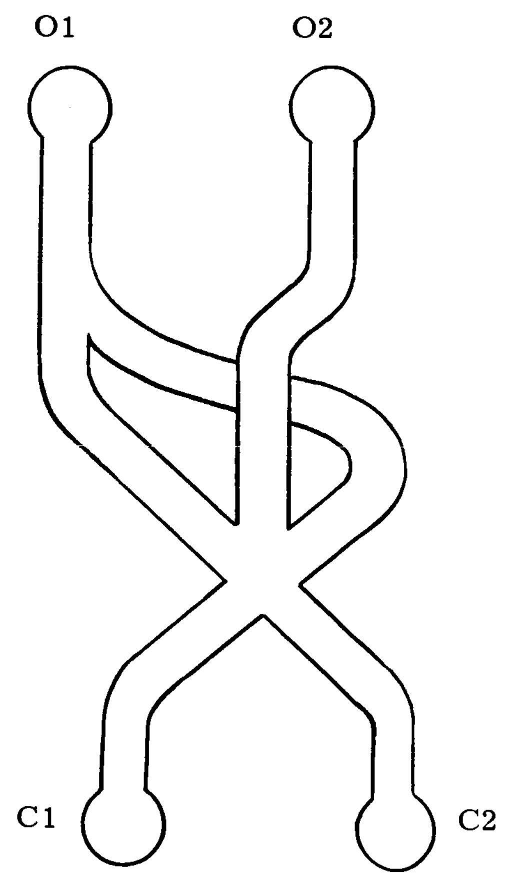


Figure 3. 6. The Momentum Half Adder.

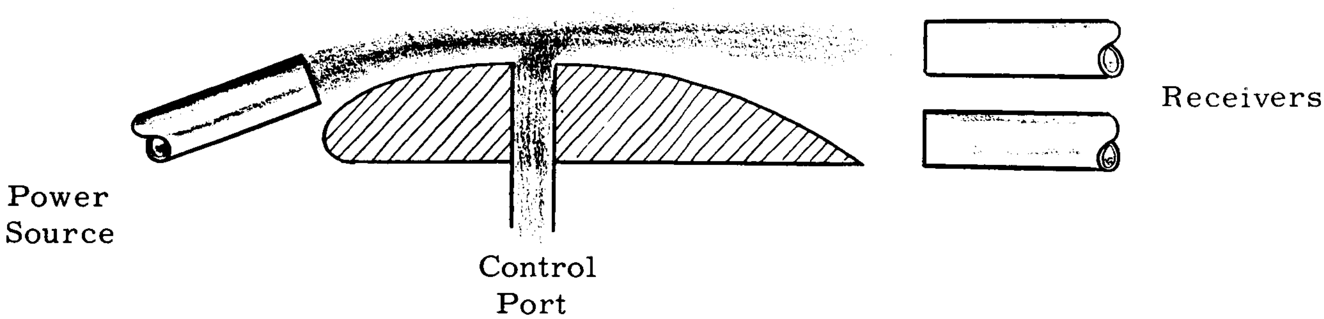
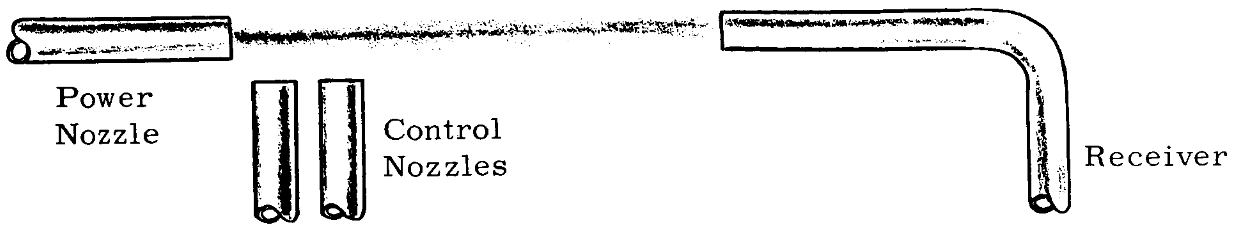
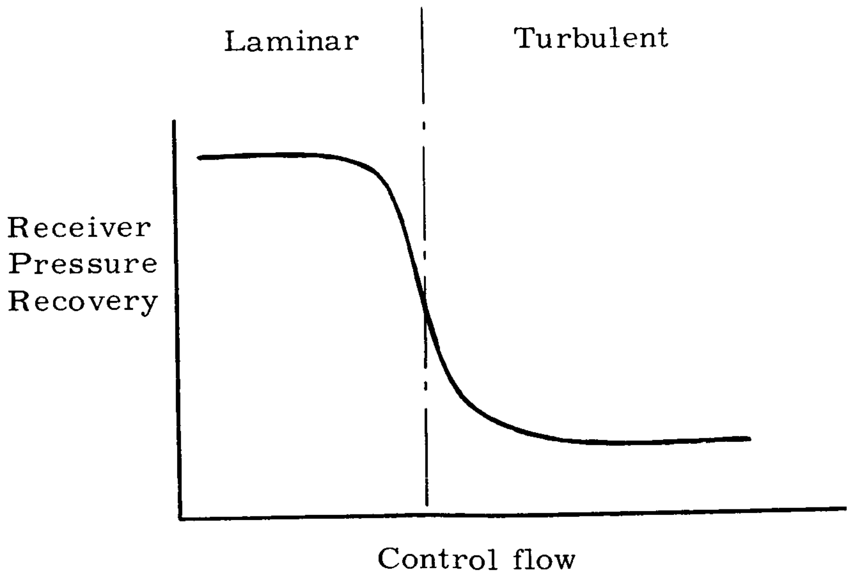


Figure 3. 7. Russian Fluid Amplifier Concept.



(a) Jet with Receiver and Control Nozzle.

(b) Jet with Control Flow.



(c) Recovery Characteristics

Figure 3. 8. The Turbulence Amplifier.

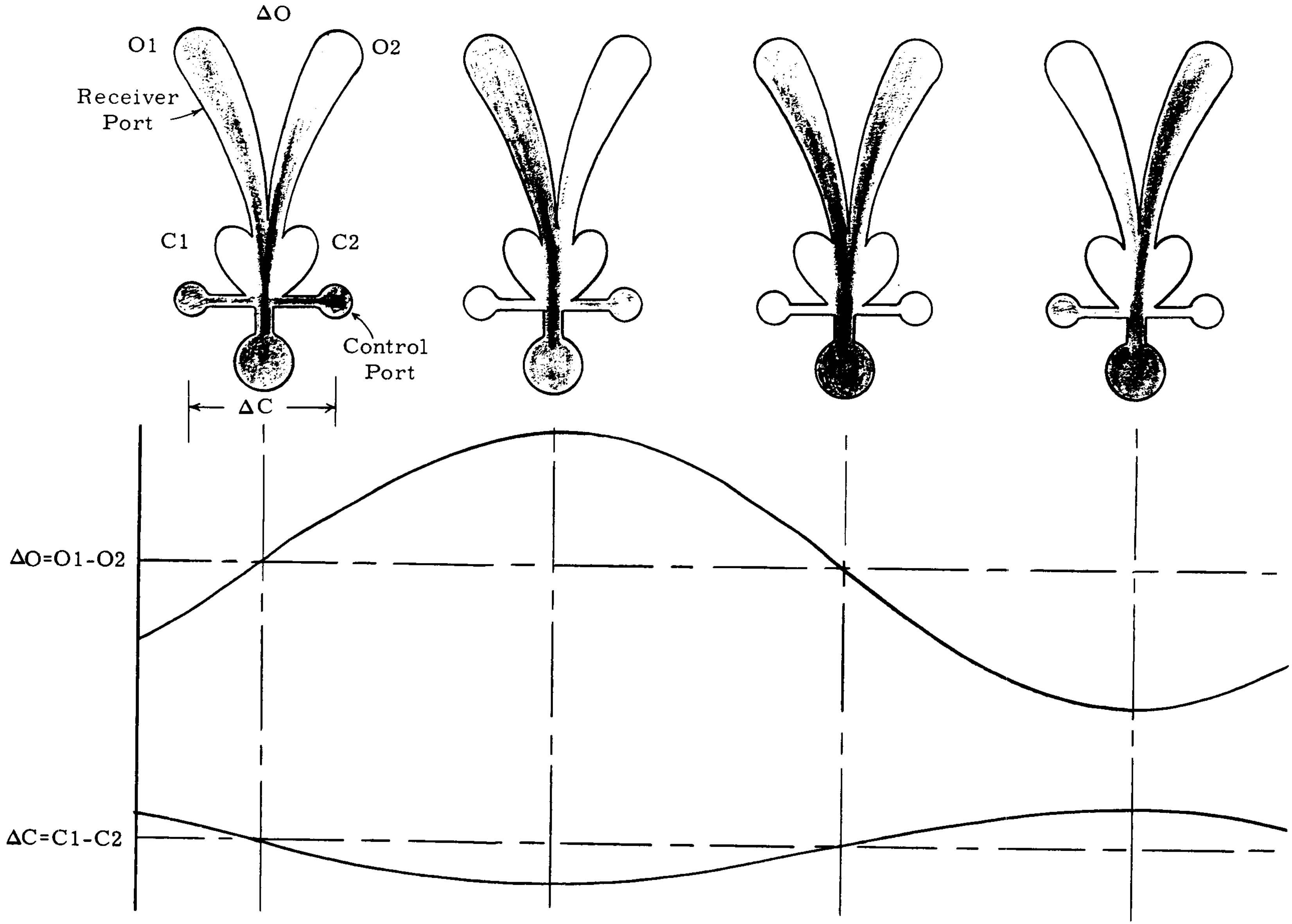


Figure 3.9. Proportional Amplifier, Beam Deflector Type.

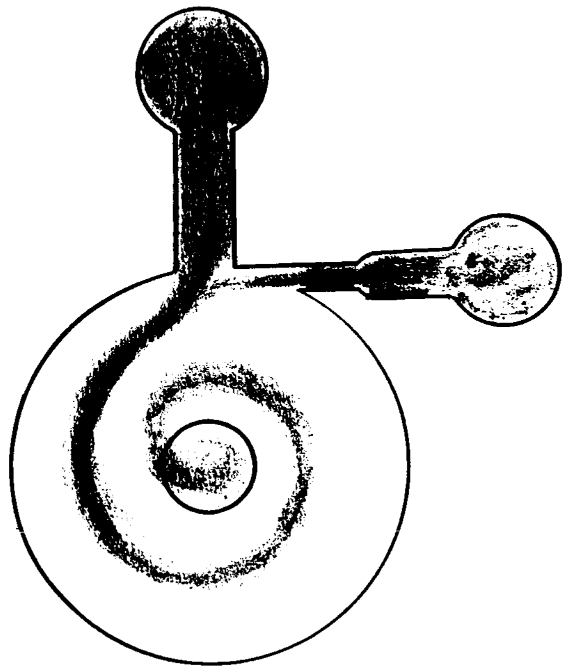


Figure 3. 10. Vortex Amplifier

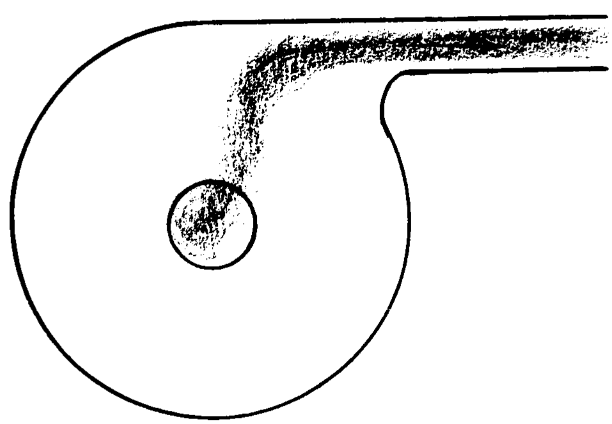
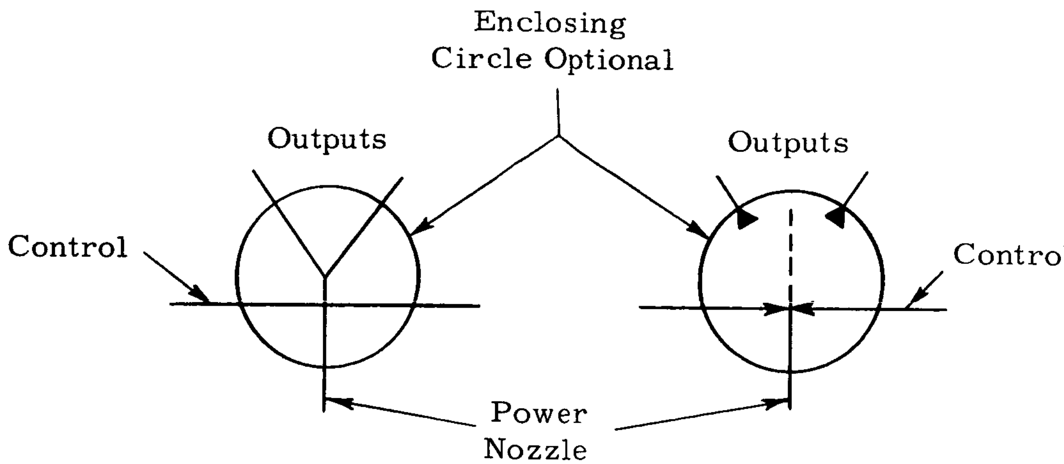


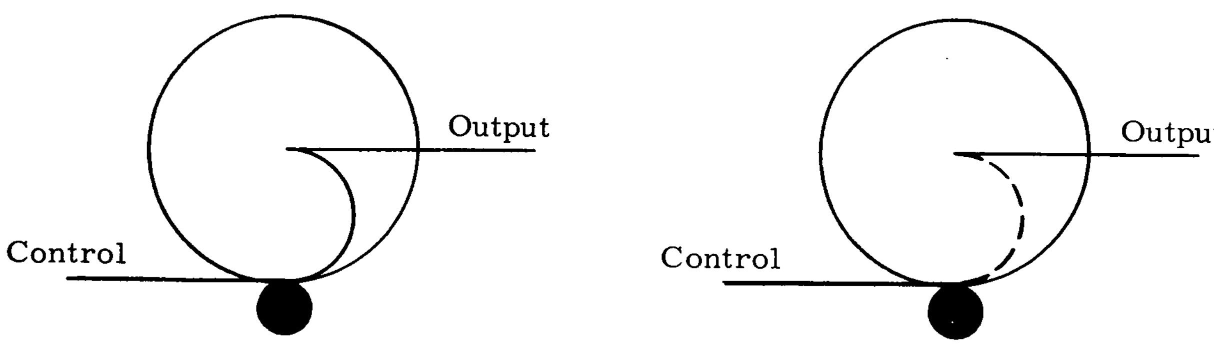
Figure 3. 11. The Vortex Diode



(a)
Digital Amplifier

(b)
Analog Amplifier

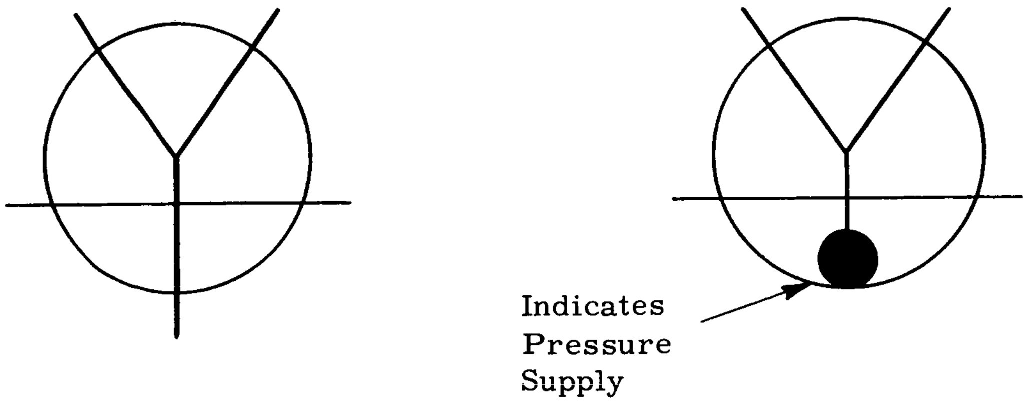
Figure 3. 12. Beam Deflector Amplifier Schematics.



(a)
Digital

(b)
Analog

Figure 3. 13. Vortex Amplifier Schematics.



(a)
Passive

(b)
Active

Figure 3. 14. Designation of Active vs. Passive Elements.

(a)
Flip-Flop (Memory)

(b)
Switch (No Memory)

Figure 3. 15. The Flip-Flop and Switch Schematics.

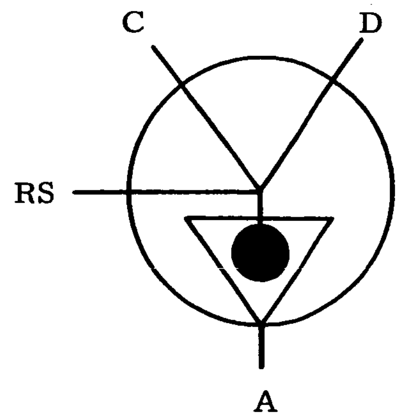


Figure 3. 16. Binary Flip-Flop Schematic.

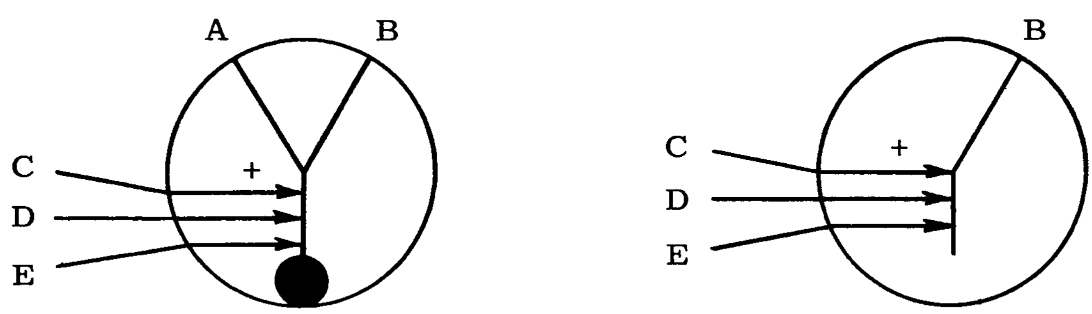
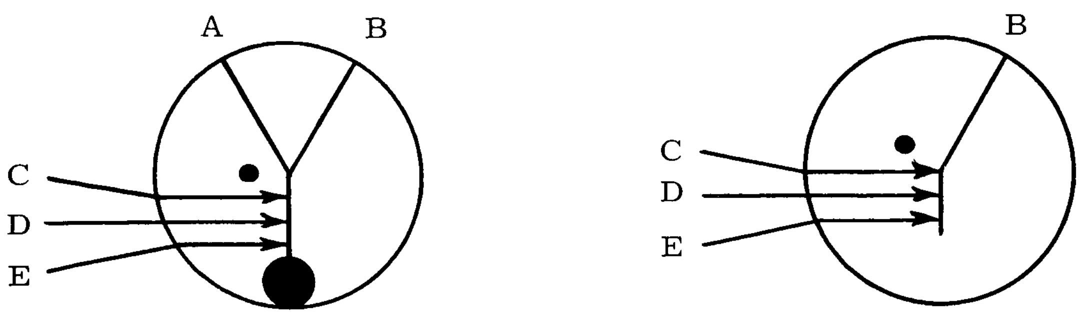


Figure 3. 17. "OR" Logic Element Schematics.



(a)
Active

(b)
Passive

Figure 3.18. "AND" Logic Element Schematics.

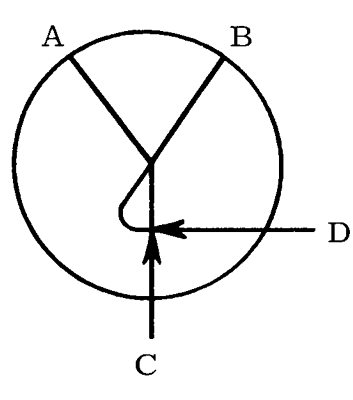
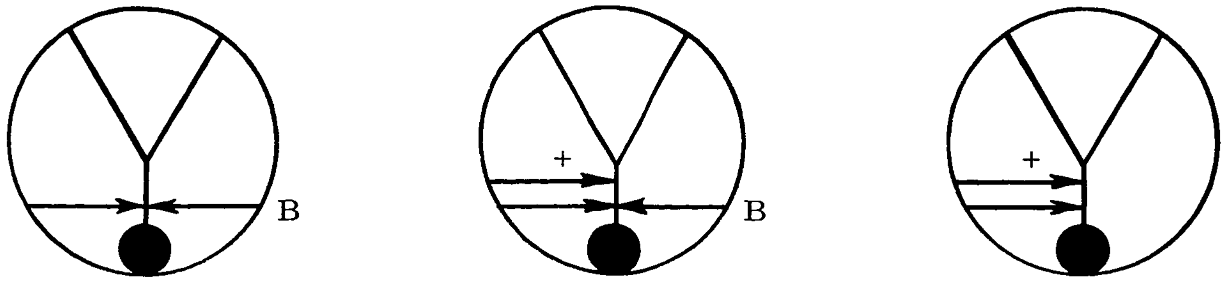


Figure 3.19. Half Adder, Exclusive OR Schematic.

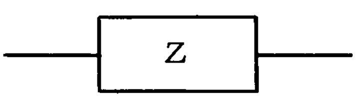


(a) Biased Flip-Flop

(b) "OR"-Signal Biased

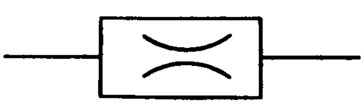
(c) "OR"-Geometrically Biased

Figure 3.20. Representation of Biasing Signals.



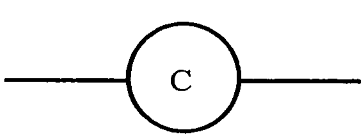
(a) General Impedance

(b) Orifice



(c) Capillary (Laminar) Restriction

(d) Inductance



(e) Volume or Accumulator

(f) Delay Line

Figure 3.21. Symbols for Impedances.

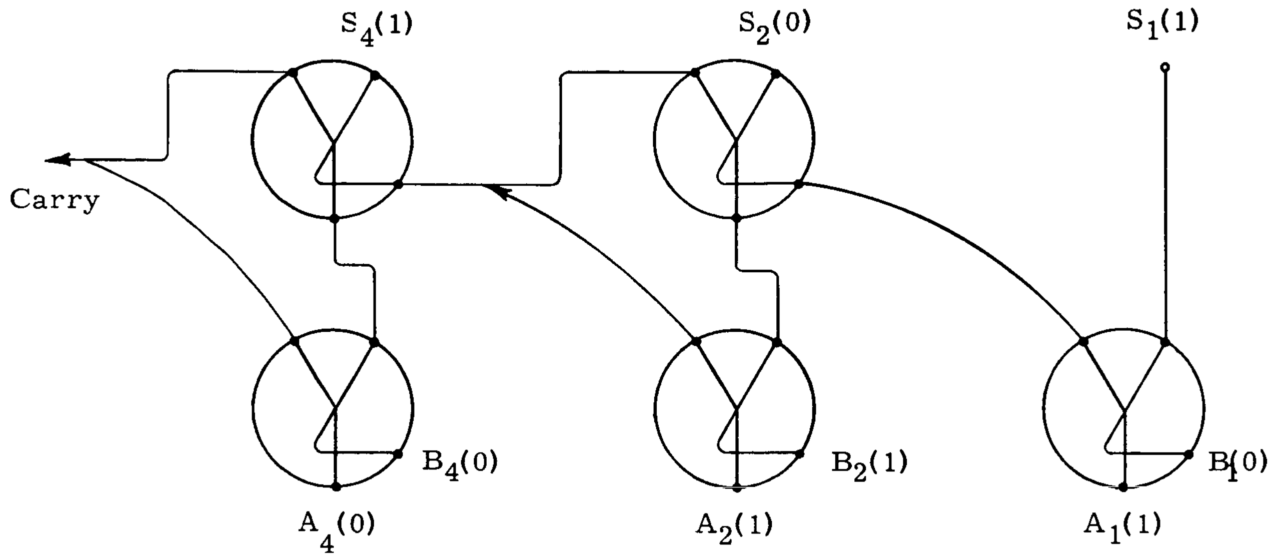


Figure 3.22. Adder Circuit

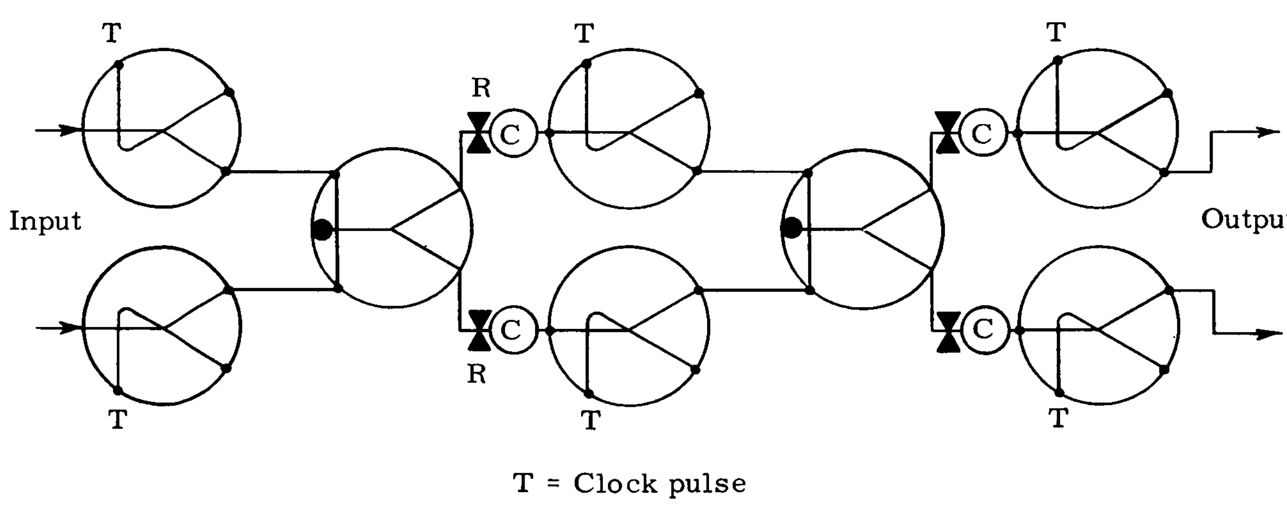


Figure 3.23. Shift Register

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4.0 DESIGN PROCEDURES

4.1 Nozzle and Submerged Jet Characteristics

4.1.1 Nozzle Flow

Axisymmetric convergent nozzles have long been adopted as a flow metering standard. Extensive experimental data of the flow coefficient as a function of Reynolds number is referenced or contained in references 4-1, 4-2, 4-7 and 4-8. Simmons[4-9] has applied laminar boundary layer theory to analytically predict nozzle flow coefficients up to transition Reynolds numbers of greater than 10^5. Hall[4-7] discusses the effects of transition on nozzle coefficients. A computer program for applying the boundary layer method of Bartz[4-3] and Coles[4-4] to supersonic axisymmetric nozzles is presented by Elliot[4-5], et al.

Data is generally unavailable for two-dimensional nozzles since the discharge coefficients would be sensitive to the aspect ratio and end wall fillet conditions. The general analytical treatments applied to the axisymmetric geometry could, with some modification, be applied to two-dimensional geometries as well.

4.1.2 Free Jet Flow

Jets have been one of the primary vehicles for studying turbulent flow phenomenon. As such, this geometry has been extensively investigated both theoretically and experimentally. For fluid amplifier applications, it is usually sufficient to consider the jet as being purely two-dimensional; we shall confine our discussion to this geometry.

Possibly the best starting point for free jet fundamentals is found in Schlichting[4-11] where most basic theories and historical developments are concisely covered. Except at the lowest velocities, a free jet flowing into stagnant fluid will turbulently mix with its surroundings. The exact Reynolds numbers at which the diffusion will be turbulent depends to a large extent on the previous history of the flow issuing from the jet-forming nozzle. It is, however, certain that jet diffusion is completely characterized by turbulence at a Reynolds number above 6000, while Schlichting states the jet will remain laminar at Reynolds numbers below 30. Crocco and Lees[4-12] further discuss the transition of separated flows. At intermediate Reynolds numbers the transition occurs slowly, with the growth of large vortices[4-13], and the possibility of serious edgetone effects[4-14].

The solution for incompressible laminar free jet diffusion of a line jet of axial momentum J has been given by Schlichting[4-11] as:

$$u = 0.454 \left(\frac{K^2}{\nu x}\right)^{1/3} (1 - \tanh^2 \xi) \qquad (1)$$

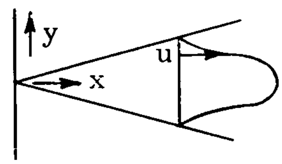
$$v = 0.550 \left(\frac{K\nu}{x^2}\right)^{1/3} \left[2\,\xi\,(1-\tanh^2\xi) - \tanh\xi \right] \tag{2}$$

where $\xi = 0.2752 \left(\frac{K}{\nu^2}\right)^{1/3} \frac{y}{x^{2/3}}$

and $K = J/\rho$

The volume flow at any section x is given by

$$Q = 3.302\,(K\nu x)^{1/3} \tag{3}$$



x = axial coordinate
y = coordinate normal to and measured from the jet axis
u = axial component of velocity
v = velocity in y direction
Q = volume flow
ν = kinematic viscosity

From the above solution, it can be seen that the jet profiles are similar, a consequence of the assumed line singularity. The jet width increases as the 2/3rd power of the axial distance x. Note also that the volume flow encompassed by the jet increases continuously with axial distance as more and more flow becomes entrained due to viscous action.

The solution of compressible laminar jets has been given by Krzywoblocki[4-15]

In most instances jet decay is due to turbulent mixing, which is much more intense than laminar mixing. As a consequence, the centerline velocity decays as $x^{-1/2}$ rather than as $x^{-1/3}$ for laminar jets, and the width increases linearly with x rather than as $x^{2/3}$. Unlike the laminar analysis the turbulent case cannot be solved completely, since some assumptions must be made for the variation of the turbulent shear stress. The simplest and most widely employed approach is based on a hypothesis due to Prandtl that the turbulent viscosity is proportional to the width of the mixing region and the maximum velocity difference across the mixing zone at each axial position. Thus,

$$\tau = \rho\epsilon \frac{\partial u}{\partial y} \tag{4}$$

$$\tau = \rho x b \frac{\partial U}{\partial y} \tag{5}$$

where U = center line velocity

ϵ = turbulent viscosity coefficient

K = turbulent exchange coefficient

ρ = density

τ = shear stress

b = jet width

u = axial component of velocity

The turbulent viscosity is assumed constant across the whole width of the jet at each x position. A solution due to Gortler for the incompressible slot-jet based on the above hypothesis is given in Schlichting[4-11] as

$$u = \frac{\sqrt{3}}{2}\sqrt{\frac{K\sigma}{x}}\,(1 - \tanh^2\eta) \tag{6}$$

$$v = \frac{\sqrt{3}}{4}\sqrt{\frac{K}{x\sigma}}\,\left[\,2(1 - \tanh^2\eta) - \tanh\eta\,\right] \tag{7}$$

where

$$\eta = \sigma\,\frac{y}{x}$$

$$K = J/\rho$$

$$\sigma = \frac{1}{2}\sqrt{\frac{x}{Kb}} = \text{constant}$$

The value of σ is obtained from experiments; Schlichting gives 7.67, but the actual value changes at low Reynolds numbers and, as we shall see, is very sensitive to Mach number.

This solution or minor variations of it have been utilized in many of the recent analyses of fluid amplifiers.

The solution is only for a line-slot jet, however. When considering jets emerging from nozzles of finite width, b, the above solution must be modified. The actual situation is shown approximately in Figure 4.1. Diffusion starts at the boundaries of the jet and proceeds inward to involve increasing quantities of jet flow. As shown in the figure, an internal wedge or potential core of undisturbed fluid extends down the jet axis. Kuethe's[4-16] analysis of mixing between two semi-infinite jet sheets can be applied to analyze the potential core region. However, possibly a more practical approach is based on experimental correlations as given by Kerr[4-17]. A summary of curves from that report are presented in Figures 4.1 through 4.6.

One customary method of representing a finite width jet with the line solution is to introduce a fictitious jet origin, "S_o":

$$S_o = \frac{\sigma b_o}{3} \tag{8}$$

and the axial coordinate x of equations (6) and (7) is replaced by $x + S_o$.

Olson[4-18] has extended Prandtl's constant-exchange-coefficient hypothesis to a treatment of compressible finite slot-jet flow. The static pressure and total temperature within the jet flow is assumed constant, and the density is thus a unique point function of velocity. Test data is given for jet Mach numbers from 0.66 to 2.0. At subsonic Mach numbers, the analysis agrees moderately well with the data if a different mixing coefficient is used in the core and fully developed regions. There is, however, increasing deviation at supersonic Mach numbers. The mixing intensity as experimentally determined increased with Mach number, which disagrees with other investigation results. Previous investigations by Warren[4-19] indicate that the mixing intensity of supersonic axisymmetric jets decreases with Mach number. Similarly, experiments on axisymmetric jets at Mach numbers 1.40 to 3.53 by Anderson and Johns[4-20] indicate that the length of the supersonic core of the jet increases rapidly with Mach number as shown in Figure 4.7, and the subsequent subsonic decay is nearly identical to the incompressible solution.

The tangential wall jet is analyzed by Olson[4-18] by matching the previous compressible jet solution with a boundary layer profile at the wall. Experimental data is given for fully expanded nozzles for Mach numbers from 0.66 to 2.0. The mixing coefficient throughout the core region corresponds approximately to that of a free jet. In the fully developed region the mixing intensity decreases with increasing Mach number, in contrast to his results (but not others') for free jets.

Weinstein[4-21] presented experimental data for incompressible wall jets.

Underexpanded supersonic wall jets are treated by Olson using the method of characteristics in the jet core, matched to a mixing analysis applied at the free boundary, and a boundary-layer analysis at the wall. The latter is taken from the uniform flow along a plate, and does not reflect the pressure changes due to shocks and expansion waves. The solution is applied well up to the point of boundary-layer separation due to shock pressure rise. A discussion of underexpanded free jets is also given by Frauenberger and Forbister[4-22].

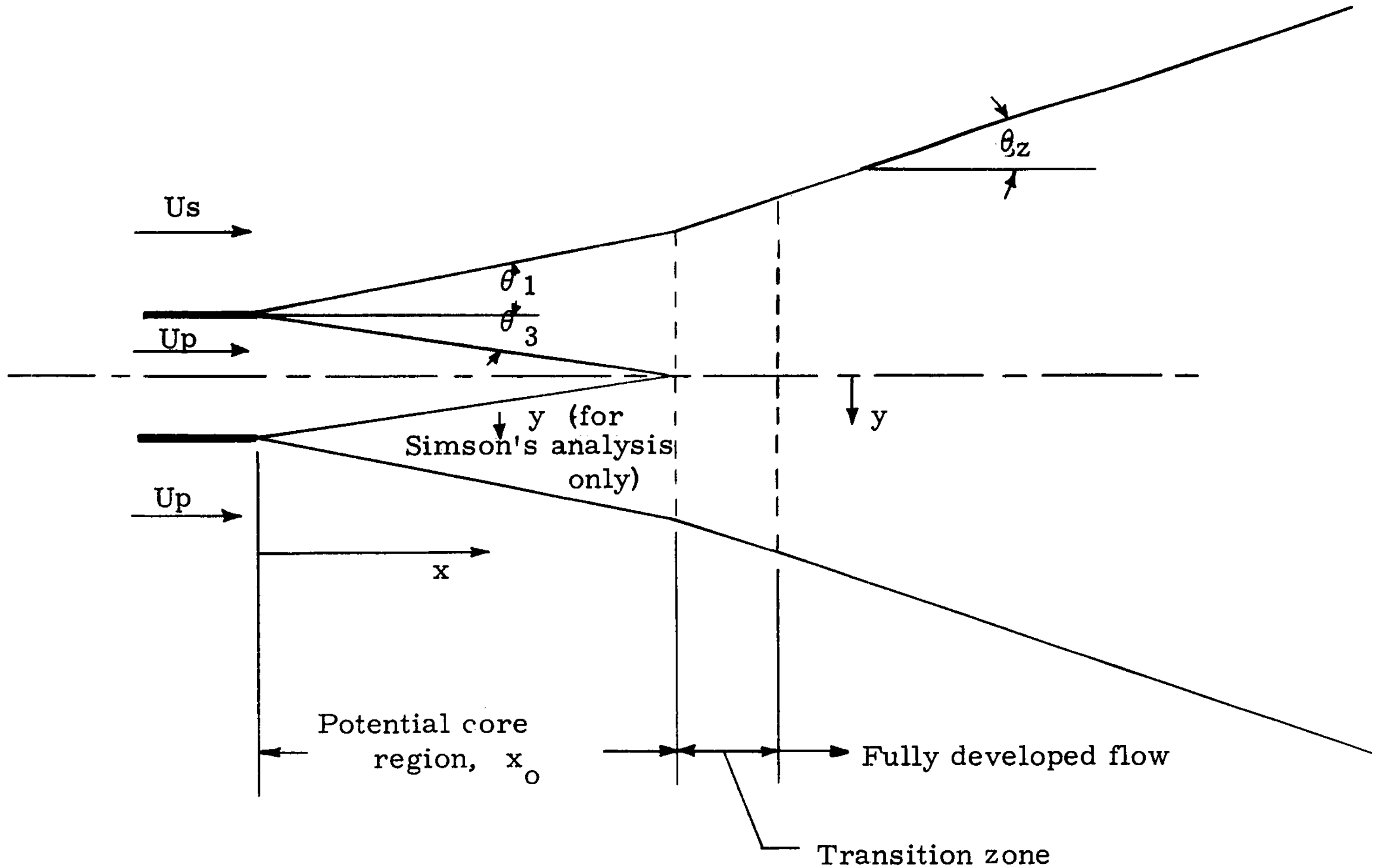
A superior way of representing a free jet is to use separate but matched expressions for the potential core region and the fully developed region. The two regions are customarily matched at the vertex of the potential-flow cone or wedge. Alberston, et al.,[4-23] propose such an analytic model, using exponential functions. The model has only one experimentally determined parameter; namely, the length of the potential-flow cone or wedge, x_o, but matches experimental data nicely everywhere, except for minor deviations in the transition zone of Figure 4.1, and toward the edges of the jet where excessive velocities are predicted. Since the edges of the jet are significant in the flow-entrainment process, Simson[4-24] sought a superior model for two-dimensional jets, which yet is quite simple.

In both regions of flow, Simson gives

$$u = U \left[1 - \left(\frac{y}{1.378 \frac{x}{x_o}} \right)^{7/4} \right]^2$$

in which y, x, and x_o are defined in Figure 4.1, and U is the centerline velocity of the jet, which for x greater than x_o is attenuated by the factor $\sqrt{x_o/x}$. The constant 1.378 is for a potential core length of 5.2 nozzle-widths, and can be changed.

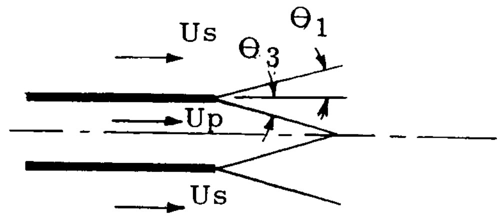
The core length, x_o, as the parameter σ, is not only a strong function of Mach number, but is a weak function of Reynolds number. The latter effect is shown by Baines in his discussion of the paper by Alberston, et al.



(from Refr. 4-17)

Figure 4.1 Nomenclature & Schematic - Two Dimensional Jet Flow into Moving Medium

Boundaries of Primary and Secondary Streams
in Mixing of Jets - Potential Core Region -



Legend:

——— Axially Symmetric
- - - - Two Dimensional Planar

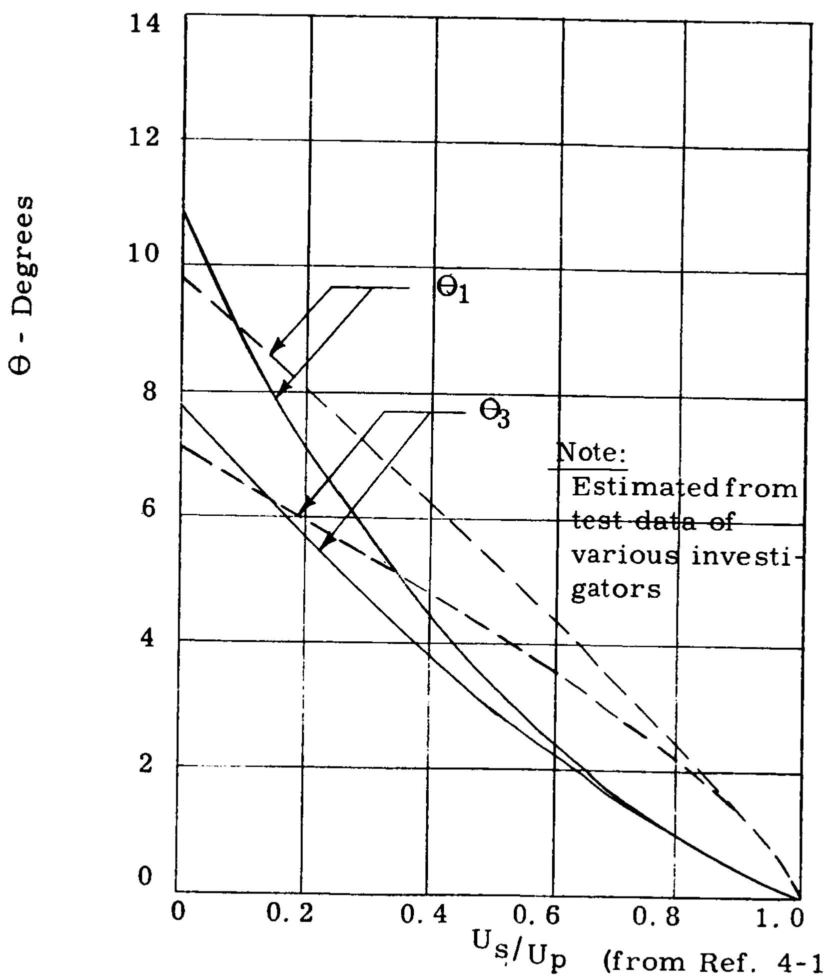


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Figure 4.2 Boundaries of Primary and Secondary Streams (Mixing of Jets)

Velocity Distribution Between Primary and
Secondary Streams in Potential Core Region
- Two Dimensional Planar -

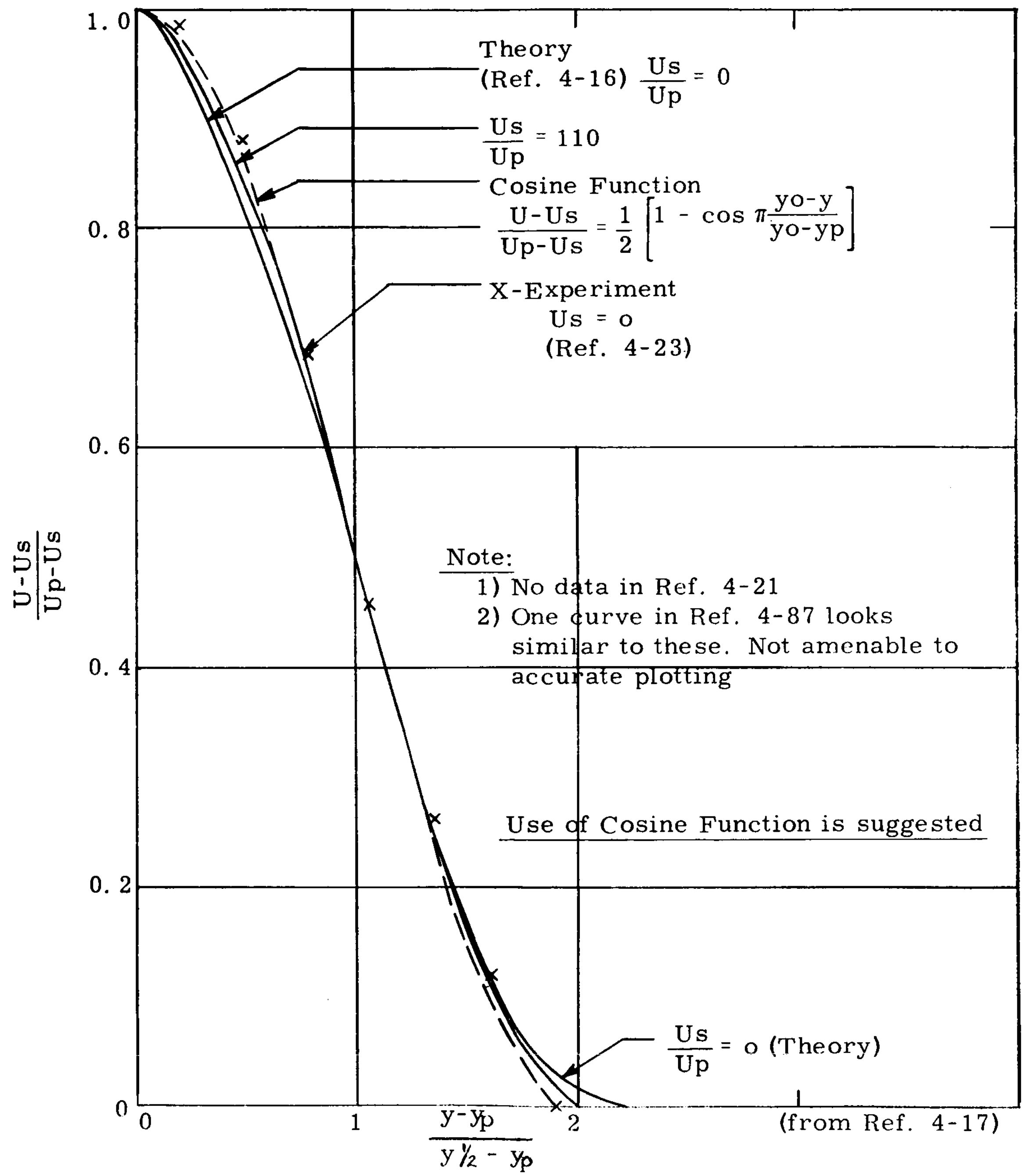
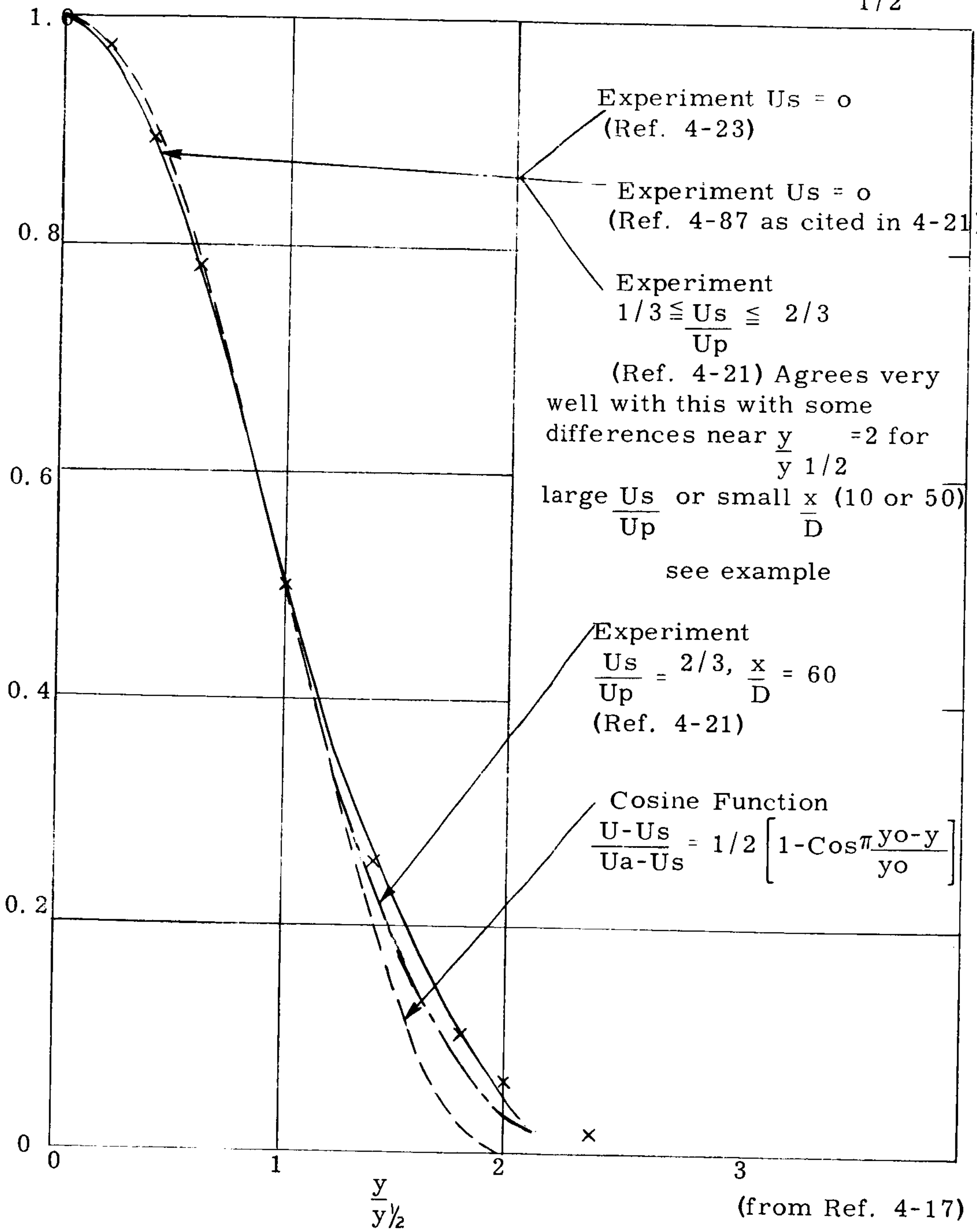


Figure 4. 3 Velocity Distribution

Transverse Velocity Distribution in Region of Fully Developed Flow - Two Dimensional Planar -

Recommend use of $\frac{U-Us}{Ua-Us} = e^{-\left(\frac{y}{y_{1/2}}\right)^2 \log_e 2}$

as shown by x points, and 'effective' jet boundary at $\frac{yo}{y_{1/2}} = 2.5$



(from Ref. 4-17)

Figure 4.4 Transverse Velocity Distribution

Centerline Velocity Variation in Region of
Fully Developed Flow - Two Dimensional Planar -

$$\frac{Ua - Us}{Up - Us} = \left[\frac{i_{p/D}}{x/_D} \right]^{1/2}$$

$$\text{For } \frac{x}{D} \geq 2 \frac{Lp'}{D}$$

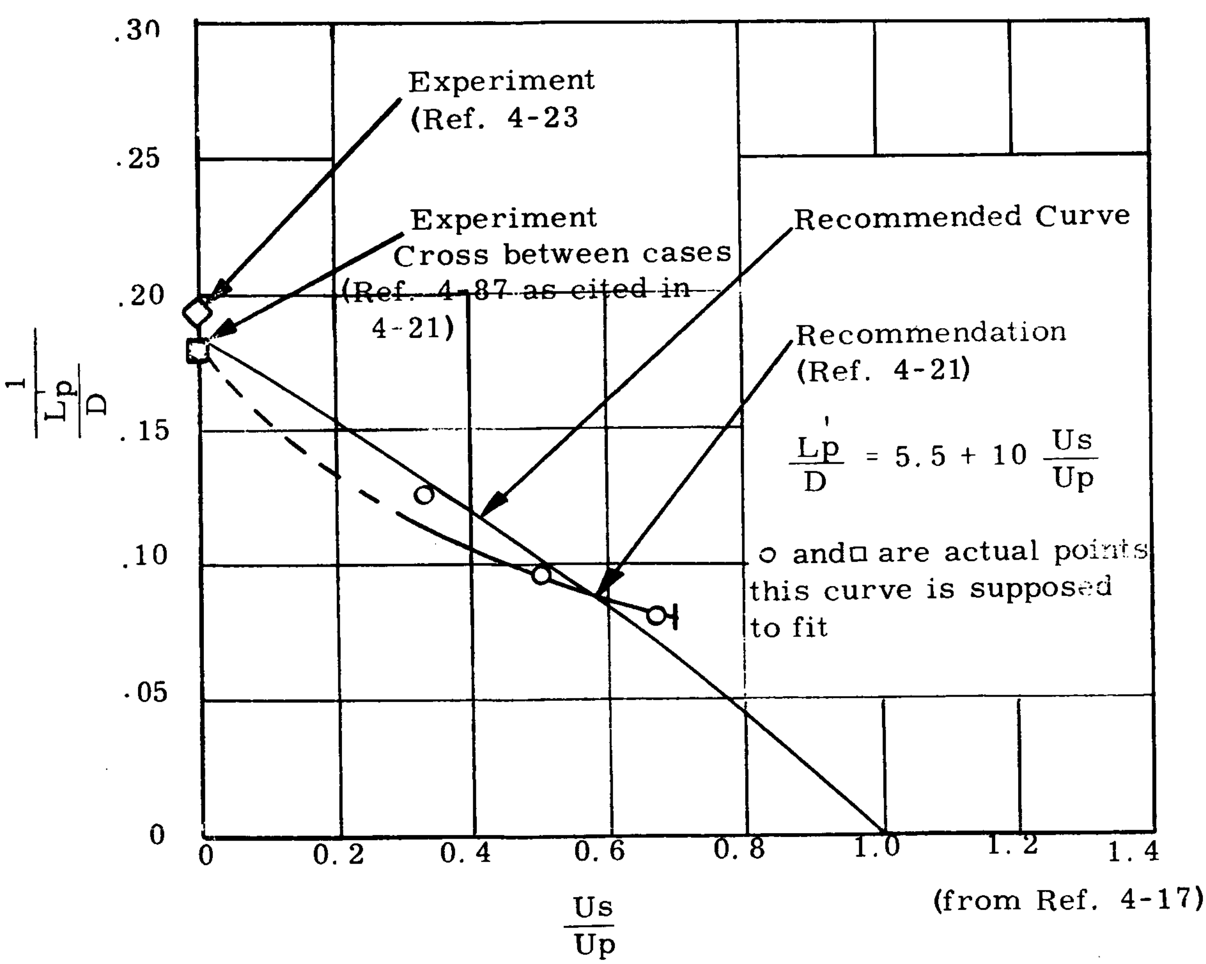
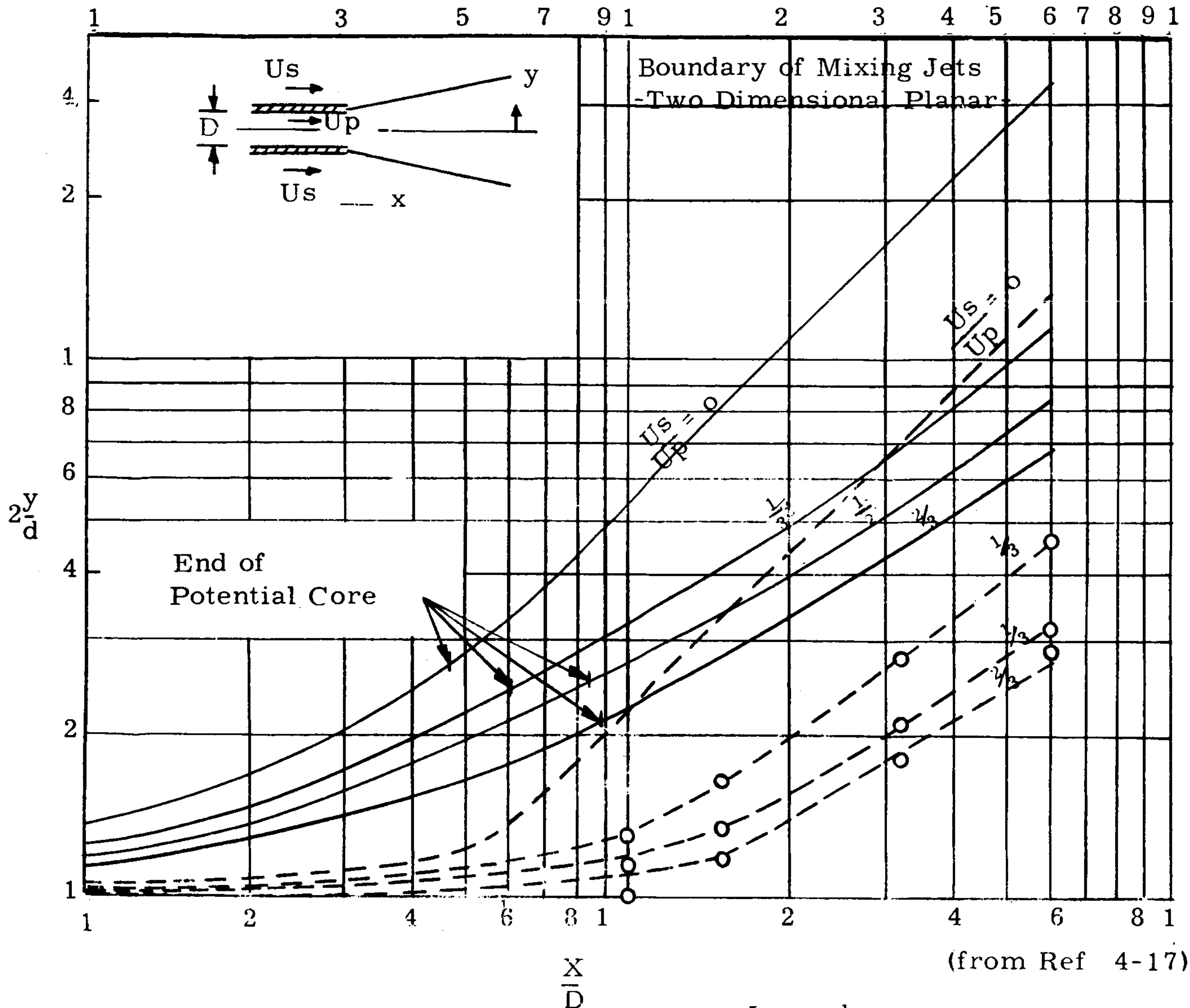


Figure 4.5 Centerline Velocity Variation



Legend:

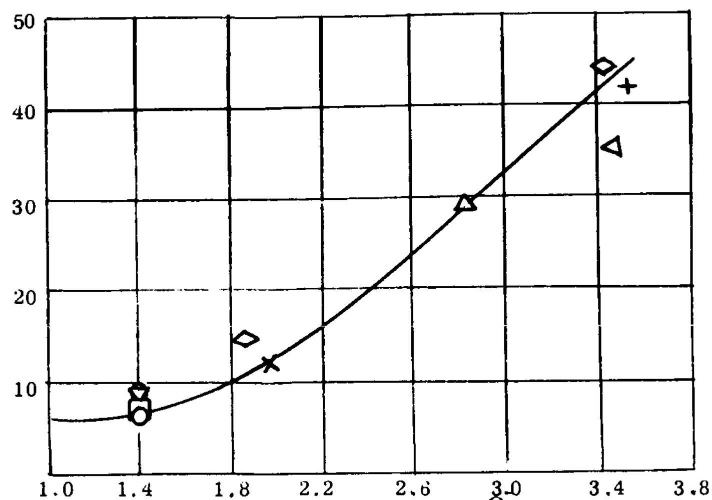
——— Jet Boundary

– – – Contour where velocity is arithmetic average of secondary and that on axis

o - Test data (Ref. 4-21)

D - Slot width

Figure 4.6 Boundary of Mixing Jets



○ M_e = 1.40, T = 740°F

□ M_e = 1.40, T = 1000°F

△ M_e = 1.40, T = 1500°F

▽ M_e = 1.40, T = 2200°F

◇ M_e = 1.84, T = 1500°F

× M_e = 1.96, T = 260°F (JHU)

▷ M_e = 2.84, Rocket 2

◁ M_e = 3.42, Rocket 3

◇ M_e = 3.42, T = Ambient (JHU)

\+ M_e = 3.53, Rocket 1

(from Refr. 4-20)

Figure 4.7 Length of Supersonic Flow Along Axis - Experimental (Axisymmetric Jet)

4.2 Wall Attachment Analysis and Measurements

4.2.1 Introduction and History

In many fluid jet devices, bounding surfaces are close enough to the jet to exert a pronounced deflection on the ensuing flow. For this reason, the phenomenon of a jet being attracted to an adjacent wall is of paramount importance in analyzing fluid jet devices. It accounts for the bistable deflection (memory) of most counters and flip-flop circuits and is related to the gain and stability in some analog amplifiers.

It was noted by the Hungarian inventor, H. Coanda, in the early 1930's, that a thin jet sheet (quasi-two dimensional) spewing into an unbounded region was deflected towards an adjacent wall. When such wall was reasonably close to the jet axis, the jet attached to and flowed along the wall.

The basic geometry is shown in Figure 4.8. It was found that attachment occurred even when the wall or plate was at a considerable angle to the jet axis, provided the wall was of sufficient length. If the angle of the wall was increased downstream of the initial attachment point in the form of a sharp bend followed by a straight segment, the jet deflection and reattachment phenomenon could be repeated thereby building up in successive steps a total jet deflection away from the initial axis of 90^{o} or more. The maximum angle at which reattachment will occur decreases and the required length of straight section increases with each successive segment.

Coanda applied this phenomenon to several inventions [4-25]. Bourque and Newman [4-26] and Chang [4-27] present summaries of the early Coanda jet experiments and applications. The comprehensive list of references given was largely extracted from a compilation by Dr. A.E. Mitchell of IBM, which appears in Dr. F.T. Brown's thesis [4-28] and the listing of Chang. [4-27]

Initially, it was supposed that a sharp angular discontinuity in the attachment surface was instrumental in causing the jet deflection. Von Glahn measured the forces on attachment walls with single [4-29] and successively [4-30] angled straight segments. His later experiments [4-30] included continuously curved walls which were found to be at least as effective in causing deflection as a series of straight segments. This has been followed by more complete investigations of curved wall deflection by Bailey [4-31] and Roderick. [4-32]

Bourque and Newman [4-26] have reported the maximum angular difference between the jet axis and a straight boundary coincident with one wall of a two-dimensional slot jet at which reattachment will occur as a function of the ratio of wall length to nozzle width. This data is reproduced in Figure 4.9. Two curves are shown: one indicates the maximum angle before detachment of an attached jet, and the other for spontaneous attachment of a free jet. Figure 4.10 is a plot of data on attachment distance versus angle for various jet Reynolds numbers and plate lengths.

The first attempts at explaining the jet deflection and reattachment were based on the potential flow analysis by Metral, [4-33] Lighthill, [4-34] and Yen [4-35] wherein the jet was assumed to fill the entire space to the adjacent wall while establishing a free constant pressure surface for its other boundary. A sharp angular discontinuity in the bounding surface away from the jet axis results in a local infinite velocity and infinitely negative pressure. Physically this type of boundary condition will cause separation of the jet as was indeed assumed for the opposing jet surface. This model does not represent the physically controlling phenomenon and has not been of significance to understanding the experimental data. Tu and Cohen [4-36] have recently analyzed a fluid-flow model which includes some aspects of the recirculatory flow in the reattachment region. However, their results do not represent a clarification of the problem.

The first, known successful treatment of the problem is due to Bourque and Newman [4-26] and is based on the following simple physical picture: Consider a two-dimensional jet issuing from a wall with an offset parallel plate some distance "D" from the jet centerline as shown in Figure 4.11. If flow is suddenly initiated, the jet at first will flow and expand along the nozzle axis. However, during the expansion process flow is continually entrained from the surroundings, entering the main jet flow stream with a velocity (and thus momentum) which is essentially normal to the jet axis. The entrainment flow on the wall side of the jet is confined to the jet boundary interspace and thus is at a slightly reduced pressure with respect to the opposed side of the jet. This pressure differential causes a jet curvature towards the wall. If the wall is sufficiently long and the flow is truly two-dimensional, the curved jet intersects the wall and thus reattaches. The jet now encapsulates a recirculating flow bubble which, from mass continuity considerations, is composed solely of flow entrained by the jet on the wall side from the point of jet nozzle discharge to reattachment. This situation is illustrated in Figure 4.11. After reattachment, it is quite likely that the entrainment flow from the free boundary is considerably larger than from within the recirculation bubble, adding a momentum differential force to the pressure force causing jet curvature. Caille [4-37] reports making use of the increased entrainment over a free jet to more effectively diffuse the flow. Pressure measurements within the separation bubble made by Bourque and Newman as shown in Figure 4.12 clearly establish this physical picture.

To simplify the problem, the following assumptions were made:

1. Flow is incompressible and two dimensional.
2. Pressure within the separation bubble is constant.
3. The centerline of the jet is a circular arc up to the point of reattachment.
4. Jet velocity distribution is similar to a free jet, and the jet entrains the same mass flow from each boundary up to the point of reattachment.
5. The shear force due to the wall is neglected.

Two theories are presented. The first considers the momentum balance of the flows in a direction parallel to the wall at the point of reattachment.

As shown in Figure 4.13, the initial jet momentum is identified as J, the momentum continuing down the wall as J_1 and the recirculating momentum as J_2. The basic equation is then written as:

$$J \cos \theta = J_1 - J_2 \qquad (9)$$

where J_1 and J_2 are evaluated for a free jet at a distance equal to the arc length up to the point of reattachment.

The free jet analysis used is that given by Gortler, namely:

$$u = \left[\frac{3J}{4} \frac{\sigma}{(S + S_o)} \right]^{1/2} \operatorname{sech}^2 \frac{\sigma y}{S + S_o} \qquad (10)$$

where $(S + S_o)$ is the axial distance from the point of efflux of an equivalent line source of flow. S_o is given approximately as $S_o = \frac{\sigma b_o}{3}$ as discussed in section 4.1.

The quantities in the above relations and in Figure 4.13 are defined as follows:

P_∞ = Free stream pressure

J = Momentum efflux from nozzle

X_R = reattachment distance from plane of jet

D = reattachment wall setback

S = axial distance from slot

y = perpendicular displacement from jet axis

b = jet slot width

ρ = gas density

σ = mixing or eddy viscosity constant. Assumed independent of position or momentum for any flow geometry; to be determined by test. Equal to 7.7 for a free turbulent jet.

The attachment position is given as:

$$\frac{X_R}{b} = \frac{\sigma\left(\frac{1}{t^2} - 1\right)\sin\theta}{3\theta} - \frac{\tanh^{-1} t}{3t^2 \sin\theta} \tag{11}$$

where t and θ are determined from equations (12) and (13):

$$\cos\theta = \frac{3}{2} t - \frac{1}{2} t^3 \tag{12}$$

$$\frac{D}{b} = \frac{\sigma\left(\frac{1}{t^2} - 1\right)(1 - \cos\theta)}{3\theta} - \frac{1}{2} \tag{13}$$

The analysis also predicts the mean bubble pressure as:

$$P_\infty - P_B = \frac{J}{b}\left[\frac{3\theta}{\sigma\left(\frac{1}{t^2} - 1\right)}\right] \tag{14}$$

The primary deficiency in this simplified model appears to be in the assumptions that J_1 and J_2 are given by the corresponding free jet values and the neglect of the bubble pressure in evaluating the momentum balance. Nevertheless, the experimentally determined reattachment point for incompressible flow is well represented by a value of $\sigma = 12$ for values of D/b of 4 to 48 where the Reynolds number* is above 2600 for D/b equal to 48, and at 6000 for D/b equal to 12.

The above methods were applied to an angled plate with zero offset wherein the analysis does not do as well. As might be expected, the correlation of mean bubble pressure with the assumed constant bubble pressure is less than perfect but the trends are well represented.

A second theory was proposed which neglects the momentum of the recirculatory flow but introduces the bubble pressure into the plate momentum balance. The correlations based on this model are not as satisfactory as the former.

This physical picture and basic analysis by Bourque and Newman forms the essentials of the more recent analytical and experimental investigations of jet reattachment.[4-38, 4-39, 4-40]

Levin and Manion[4-38] extended both theories of Bourque and Newman to the case of an offset inclined wall. In the original treatment it was assumed that $\theta = \alpha$ as shown in Figure 4.14. This restriction has since been removed. Experiments were performed with a Mach 0.5 air jet with offset distances of 0, 2, 4, and 10 nozzle widths and at angular deflections of 0 to 55 degrees. Free surface water table tests were run at offsets of 0, 2, and 4 nozzle widths and deflection angles from 0 to 40°. These experiments at present provide the most complete subsonic data available. A representative curve from reference 4-38 is shown in Figure 4.15. The data follows the theory at $\sigma = 15$ for offsets from 0 to 4 nozzle widths and up to deflection angles of 30°.

The data clearly shows, however, that a large value of σ is appropriate for jets which reattach quickly, and a low value, nearly the 7.67 measured for free jets, is appropriate for jets which reattach after they are considerably dispersed. This fact coincides with the gradual spreading of a jet near the nozzle, and the more rapid spreading downstream, as discussed in Section 4.1.2. Thus the σ- model (Gortler model) is inappropriate for cases of close reattachment which, unfortunately, are the cases of greatest interest. The Albertson, et. al., model or especially the Simson model (Section 4.1.2) should give markedly better results. Measurements by Mueller, Korstand Chow[4-41] for semi-infinite flow over a step, indicate mixing intensity is approximately equal

* Reynolds number defined in Figure 4.10.

to a free jet up to the point of reattachment, and gradually diminishes in intensity further downstream.

It is of interest that the water table results at a simulated Mach number of 0.5 agreed with the air data for wall angles of less than 20^{o}. There was increasing divergence of the data on the two media at larger angles. Similar free surface water tests by Byrd [4-42] of a parallel offset wall jet correlated well with air test at simulated Mach numbers of 0.64 and 0.74. In this latter case the wall angle was 6^{o}.

Brown [4-39] extended Bourque and Newman's momentum-balance analysis to include a control flow entering the separation bubble. Both the Gortler model of the jet (the one involving σ) and the Simson model (Section 4.1.2) were used; the latter should give better results when the attachment occurs only a few nozzle-widths from the nozzle, and little difference should exist otherwise. Results are compared with experiment for a Mach 2 air jet with parallel wall offsets of 1, 2 and 3 nozzle widths. Wall lengths with lengths of 5, 10, 15, and 20 nozzle widths were used. A comparison with the theory based on Simson's jet model is shown in Figure 4.16 for $(X_o/b_o) = 18$. Here ω'_c is the ratio of control to jet nozzle flows, r' is the radius of curvature of the jet normalized to the nozzle width, b_o, and b' is the ratio of the nozzle width to the setback of the parallel wall. Better correlations should result from flows at lower Mach number.

When the wall is slightly shorter than the predicted attachment distance, a strong tendency is evident for the jet curvature to increase so that attachment actually still can occur. This phenomena is easily understood in terms of the balance of control entrained, and recirculatory flow discussed by Brown. Bourque and Newman's [4-26] data of Figure 4.10 corroborates this observation.

Olson and Miller [4-40] have developed an analogous theory applicable to predicting attachment location to setback angled walls. The analysis is quasi-compressible in that the density is assumed to be proportional to the static temperature for a constant static pressure and constant total energy flow. The solution for jet mixing is similar to Bourque and Newman's except that the jet velocity profile is given by an error function rather than hyperbolic functions.

Their reattachment theory combines some aspects of both the momentum and pressure balance concepts of Bourque and Newman. [4-26] However, two experimentally determined coefficients are introduced in addition to the jet mixing parameter. Olson has found that for fully expanded jets from M = 0.20 to 2.0 the data of attachment parameters are only a function of Mach number and the other solely a function of setback. The jet mixing constant is also a function of Mach number. The range of variables is not clearly defined in this work, however, data is presented at angles of 6° and 10°, and setbacks from 0.5 to 1.6 nozzle widths. It is not certain that these conclusions are applicable beyond the data examples given.

Each of the analyses discussed assumed turbulent jet conditions. Bourque and Newman's [4-26] data indicate that there is no dependence on Reynolds numbers above the 2,000-6,000 range, i.e., turbulent mixing completely dominates the flow. For lower values laminar mixing will be significant and, as discussed by Mitchell, [4-43] will result in an order of magnitude increase in the extent of the recirculation cavity. The important characteristic of a jet is actually the turbulence level or "noise" level in the jet, [4-13, 4-14] which depends on much more than Reynolds number. Supersonic jets are frequently modeled as incompressible jets, except that the value of the spreading coefficient σ may need revision (See Section 4.1.2).

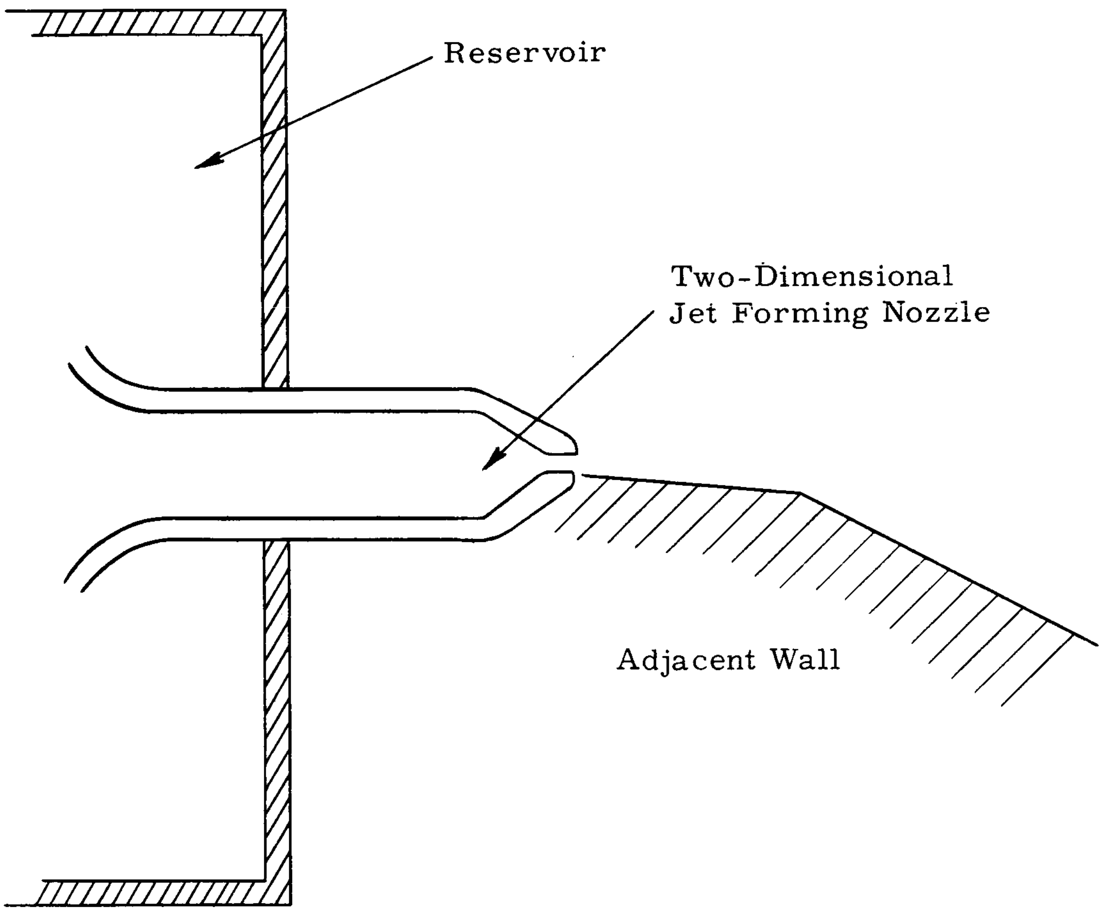
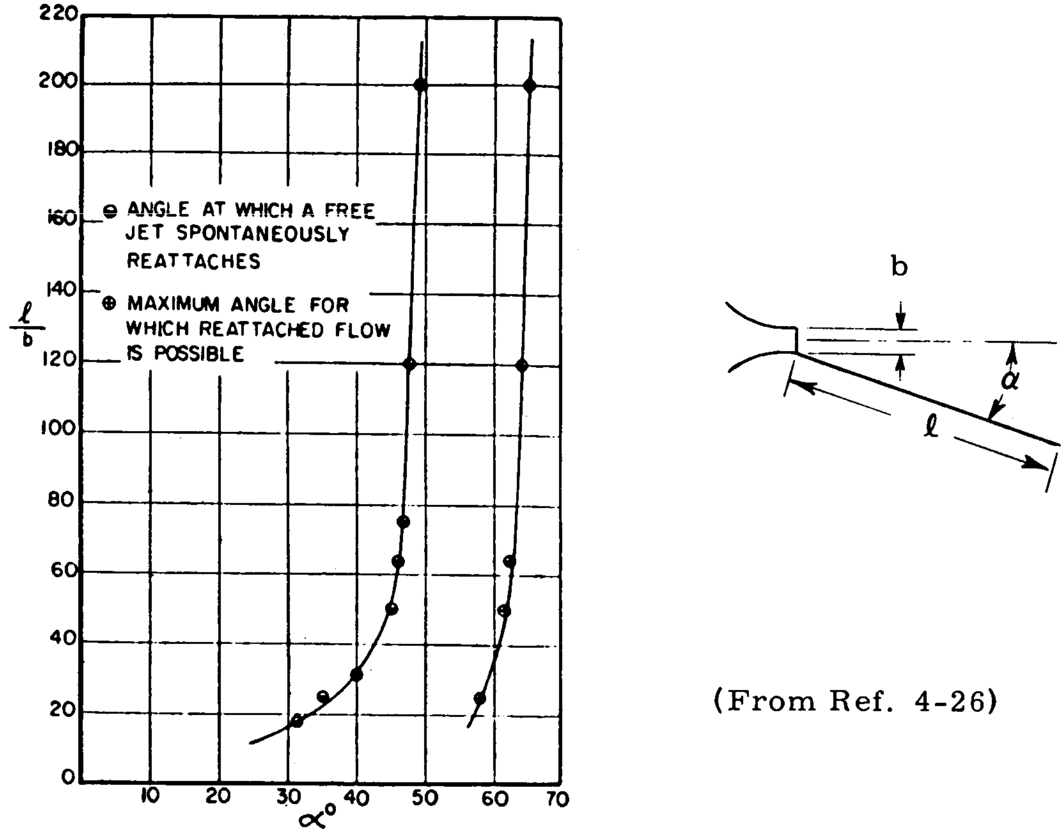
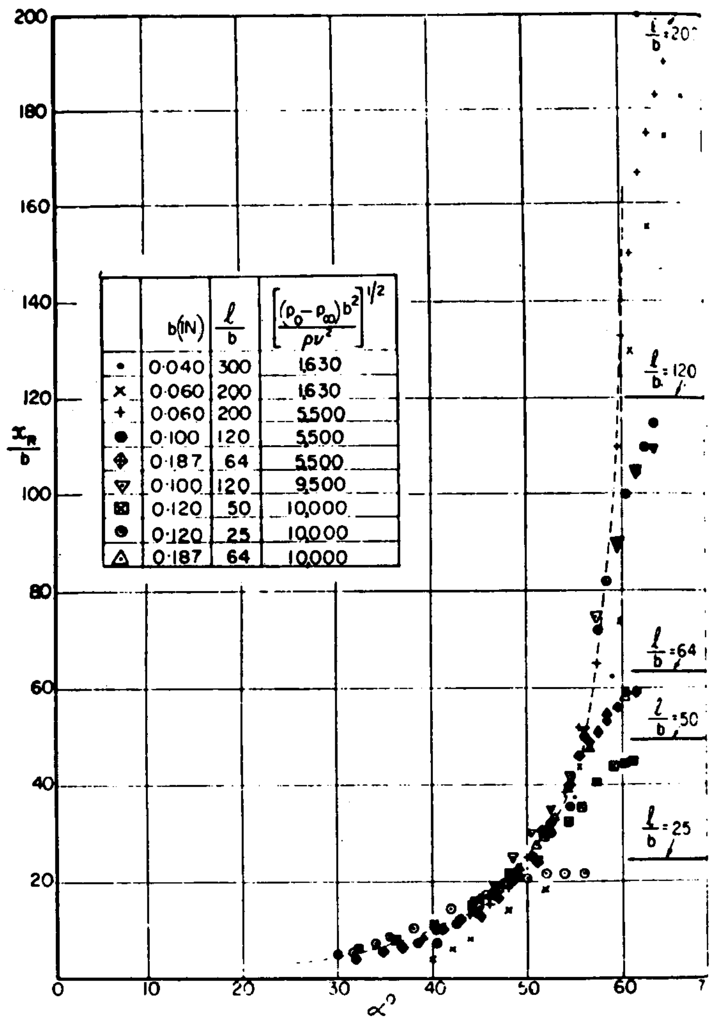


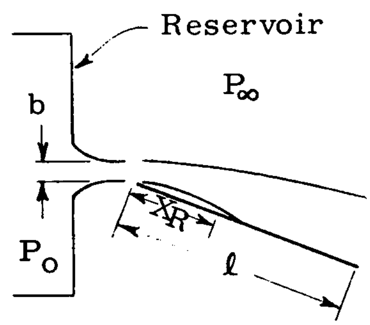
Figure 4.8. Jet Attachment to Segmented Angled Wall.



(From Ref. 4-26)

Figure 4.9. Limits of Coanda Jet Deflection at Reynolds Number $\gtrsim$ 6000.

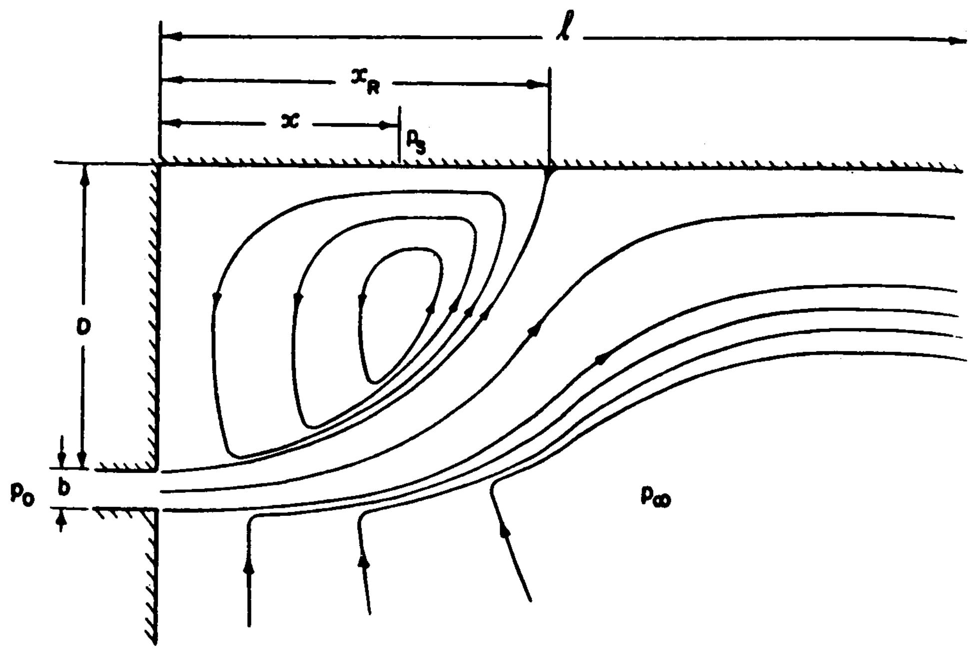




Reynolds Number = $\sqrt{\frac{(P_o - P_\infty)b^2}{\rho\nu^2}}$

(From Ref. 4-26)

Figure 4. 10. Reattachment Distance for a Straight Inclined Plate.



(from Refr. 4-26)

Figure 4.11 Two Dimensional Jet Reattaching to Offset Parallel Plate (Approximate mean-flow stream lines)

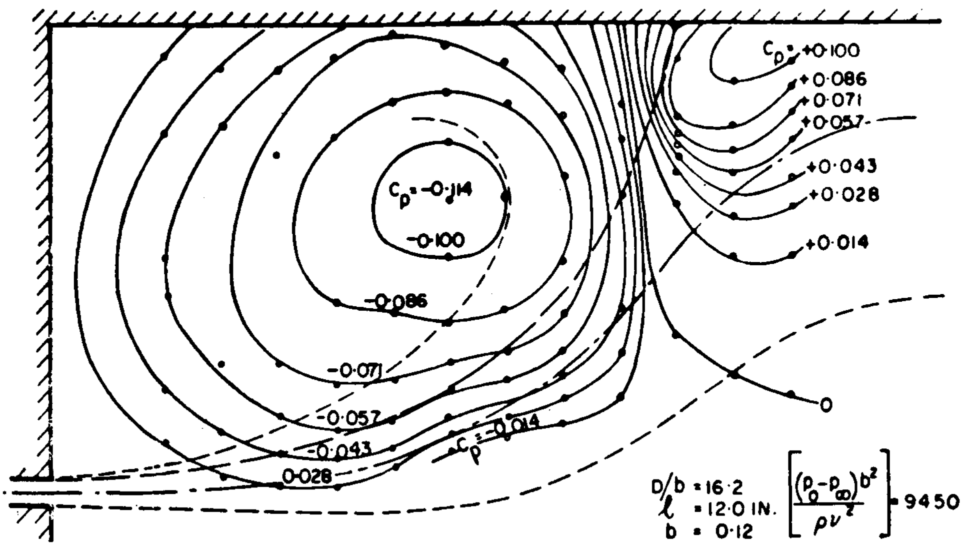


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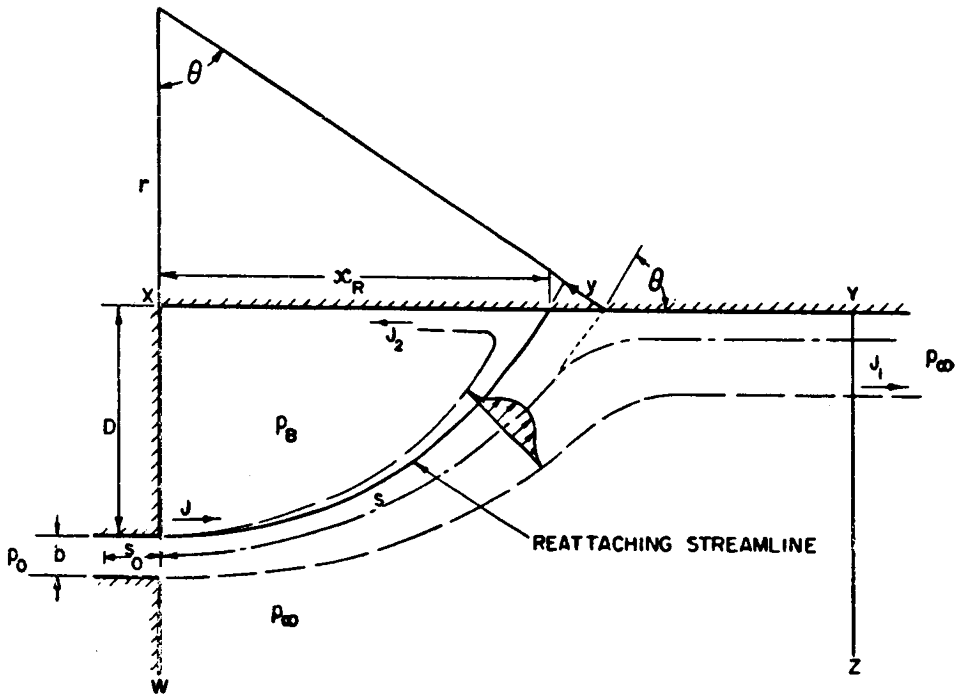
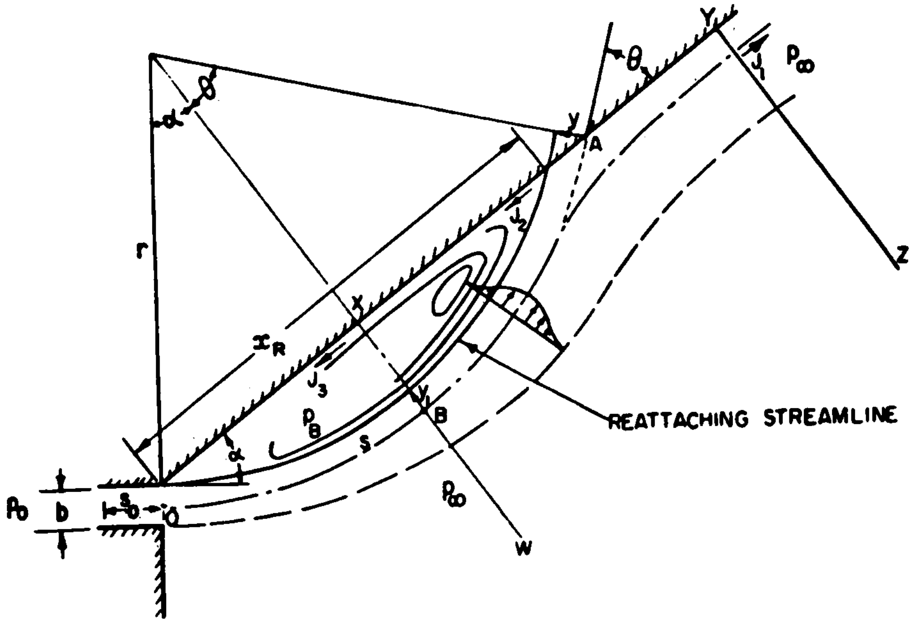
Figure 4.12 Jet Reattachment-Approximate Contours of Constant Pressure in Separation Bubble



(from Refr. 4-26)

Figure 4.13 Mathematical Model - Offset Parallel Plate



(from Refr. 4-26)

Figure 4.14 Mathematical Model - Reattachment to Angled Wall

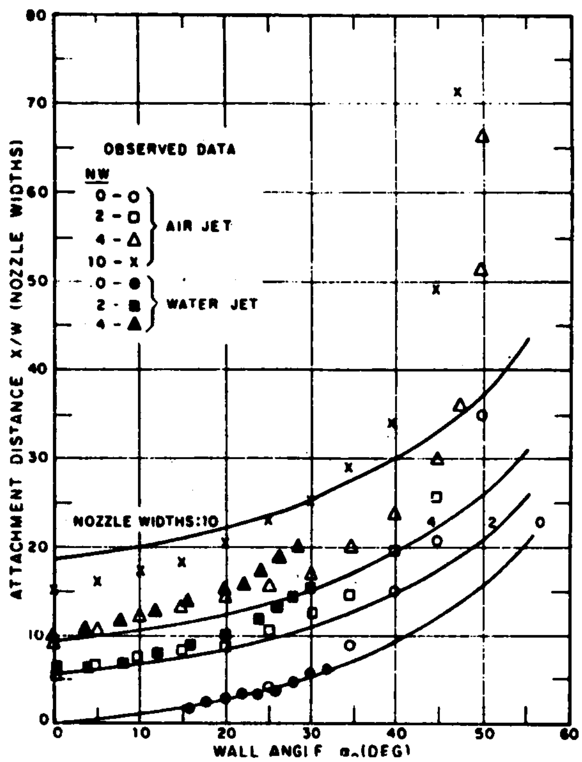


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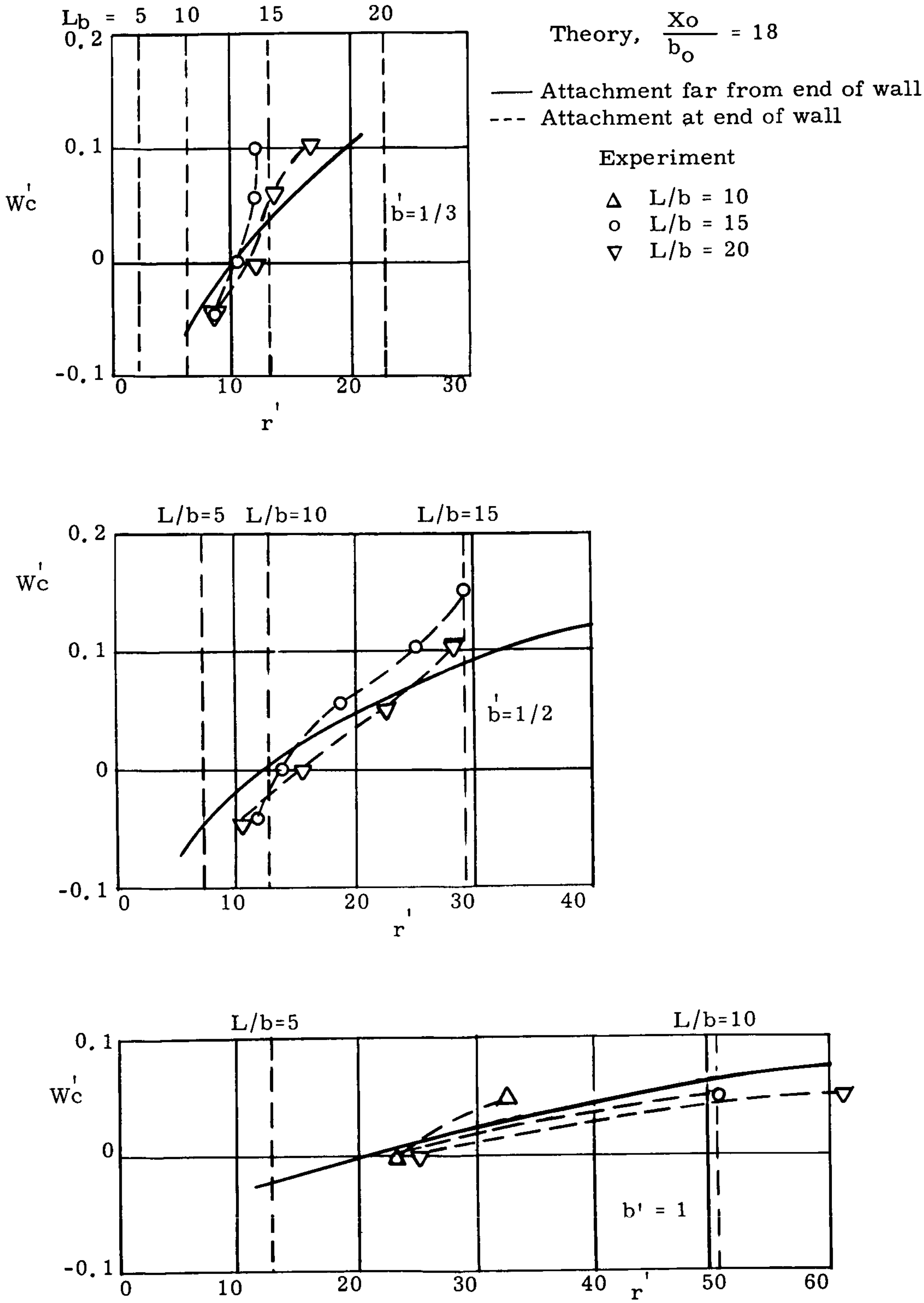
Figure 4.15 Attachment to an Offset Wall



(from Ref. 4-39)

Figure 4.16 Theory and Experiment for Attachment of Jet to Offset Parallel Wall

4.3 Vortex Analyses and Measurements

Vortex motion is of interest because of its use by several laboratories for amplifier and rate sensor concepts. Vorticity has been the subject of a number of basic fluid dynamic studies. A good description of the various types of vortex flow that can result is presented by Rouse[4-44] in his discussion and review of eddies. The general characteristic vortex flow of interest in this report is circulating flow with a source at the outer periphery and a fluid sink at the center. If the flow is irrotational, the tangential velocity varies inversely with radius, and a free or potential vortex is established. A small angular velocity at the outer periphery thus will be greatly magnified near the center of the vortex. The high velocity near the vortex center is accompanied with a correspondingly low static pressure, since the total head remains nearly constant (except often near the very center). A pickup is located near the center of the vortex to sense static pressure, which is the output signal of the vortex sensor indicating the magnitude of angular rate. A large outer-to-inner radius ratio is desirable for producing a high output signal or gain. Thus, quite high velocity magnification can be obtained if a large radius ratio, or a small inner radius, is used. A limit arises, however, when use of a small inner radius is attempted. A region of the center of the circulating flow will cease to be irrotational and will rotate as a solid body. Thus real vortex motion quite often consists of a free vortex and the solid body core, called Rankine's combined vortex. When sink flow is also considered, the problem becomes three-dimensional and therefore quite complicated to obtain an analytical solution. In one such study Lewellen[4-45] investigated a free vortex of a viscous incompressible fluid, with particular attention to the sink flow which exits axially inside a finite radius core. The fluid source for this study was considered to be tangential fluid flow at the outer periphery. The results are in a form of series solution. Lewellen in this reference also includes a good survey of classical vortex flow studies. Studies of vortex motion as applied to vortex amplifiers have been much less numerous than studies of beam deflector amplifiers, apparently because the latter are in more common usage.

The engineer who must design a vortex fluid amplifier has often found it more convenient to use simpler mathematical models and experimentation. For example, Cain[4-46] carried out optimization work on several vortex amplifier configurations and used simple mathematical models to gain insight to the problem. Dexter[4-47] reported on some of Cain's work and also included a revised simplified theory relating input control flow to pressure drop across the amplifier and compared this theory to test data. The theory and test data did not correlate well over a wide operating range, and it was concluded that the vortex induced by control flow was not a potential vortex and perhaps deviated significantly from being two-dimensional. Egli[4-48] has obtained a more refined representation of the vortex flow in fluid amplifier geometries by including wall effects. This work was carried out on a classified contract, and is reported in more detail in Volume II. Bendix Research Laboratories, in their work on vortex amplifiers, [4-49] conceived a theory of operation which allowed formulation of a simplified analytical model. Test results have indicated the analytical model is adequate for prediction of gross performance. The test results also showed scaling possible within certain limits and that performance was unaffected by temperature up to 1400°F except for expected changes from variation in gas density.

As is the case for beam deflector devices, simplified analytical models with some experimental work provides the most economical approach to the design of hardware.

4.4 Element Optimization

Proportional and digital amplifiers have been studied experimentally and analytically. A comparison of work and results is difficult because of a lack of standardized definitions of gain and amplification factor. Gains may be expressed as flow gain, pressure gain or power gain. Many different ways of defining each type of gain exist. All too often, the definition chosen happens to be the one which presents the best performance picture for the element under discussion. As a result, to intelligently evaluate claims as to gain or amplification factor, care should always be taken to determine how the gain is defined. Although gain is an important consideration, other parameters must also be considered when developing or choosing an amplifier. Often maximum output signal or flow gain must be sacrificed at the expense of higher gains. In actual circuit design, it is usually wiser to make use of parametric plots of the amplifier characteristics rather than to rely on numerical gain figures. Parametric plots and their use for both analog and digital devices are discussed by Katz and Dockery[4-50]. (See also Section 4.6)

4.4.1 Proportional Amplifiers

Gain information on proportional amplifiers is reported from a number of sources, (4-51, 4-52, 4-53, 4-54, 4-55, 4-56, 4-57, 4-58, 4-24).

Since these cover a wide range of devices including beam deflector amplifiers, elbow amplifiers, vortex amplifiers and proprietary concepts, generalizations as to gains are not possible.

Beam deflector amplifiers are generally categorized as either "momentum exchange" or "pressure control" devices, although these two types are actually ends of continuous spectrum. They are usually four terminal networks having two input ports and two output ports. Pressure gain is usually defined as the slope of the curve of differential output static pressure vs. differential input static pressure, with blocked load conditions. A typical curve is given in Figure 4.17 where results[4-57] are presented in normalized form. When the receiver ports are unblocked, the pressure gain decreases. Since no standard receiver-flow-for-gain definition is presently used (but see the "transfer admittances" in Section 4.6), values of pressure gain at other than blocked flow conditions become quite meaningless. One approach, used by Pepperone[4-58] defines gain as the change in differential total pressures at the output ports under "maximum" flow conditions, but this is either imprecise or arbitrary. Moreover, the total pressure at maximum output flow conditions (zero back pressure) will not correspond to that at zero or partial output flow conditions.

Flow gain for proportional amplifiers is usually expressed as the slope of a differential output flow vs. differential control flow curve taken for "wide open" conditions. The same problems as discussed above for pressure gain definition also exist for flow gain definition.

Power gain is the most difficult to define. Generally, power is defined as the product of flow and pressure, a definition that is not exact in the compressible case and is affected by pressure datum in both compressible and incompressible cases. Definitions range from simply the product of pressure and flow gains (as defined above) which is incorrect, to definitions where power is defined as instantaneous differential pressure times differential flow, a more exact definition where instantaneous changes in power are considered at each of the four terminals. The first case is clearly only a figure of merit, and has no real significance if pressure and flow gain are defined at different operating points. The usefulness of either of the latter two definitions depends on the application.

Analyses of beam deflector analog amplifier gains have been conducted by Pepperone,[4-58] Dexter,[4-54], Boothe,[4-59] and Simson[4-24] In general, they make use of the Gaussian velocity profile of the fully developed jet and combine this with the momentum balance defining the jet deflection. Dexter and Boothe arrive at a maximum theoretical pressure gain of 20 and 18.4 respectively for a simple momentum exchange valve using narrow receivers optimized for pressure recovery. Pepperone's analysis predicts simultaneous pressure and flow gains of approximately 10 and power gains of 100. Simson uses his own improved jet model for extensive analyses and optimizations of pressure-controlled proportional jet amplifiers.

Actual tests[4-54, 4-57, 4-58] show blocked load or equivalent pressure gains ranging from 8 to 9 for actual amplifiers of both the "momentum exchange" and "pressure control" type, although gains for the latter can be increased indefinitely, with noise and linearity the only limitation. Flow gains of 9.4 are reported in reference 4-58 for the momentum exchange amplifier and reference 4-60 indicates flow gain as high as 20 for the pressure control type.

Beam deflector amplifiers with boost arrangements offer higher gains. For instance, Minneapolis-Honeywell[4-56] reports simultaneous flow and pressure gains of 10 and 20 respectively.

Dosanjh and Sheeran carried out experimental studies of impinging jets to determine the effect of a "control" flow on a power jet. Pilot traverses were made to determine the angle of deflection and the velocity profile of the deflection jet. Shadowgraphs were taken to determine the shock structure of the supersonic power jet under the reference of control flow. The results provide background for the design of supersonic momentum exchange amplifiers.

The more exotic forms of analog amplifiers must be looked at individually to judge their gain capability. The Giannini single leg elbow amplifier (SLEA) has a single control port and two output ports. Flow gains as high as 220[4-52] have been reported, where gain is defined as the slope of a differential output flow vs. control flow curve. Corresponding power gains (definition not reported) are 10 to 25. Flow gains of 110 are indicated with the SLEA amplifier[4-53].

Vortex amplifiers can be high gain devices with a variety of configurations. Bowles[4-62] reports pressure gains of 7000, without details. The Marquardt Corporation reports[4-63] a pressure gain of 148 to 200 with their vortex amplifier (zero load flow). Figure 4.18 shows their test results, although information on their exact configuration was withheld.

Another proprietary amplifier is claimed by the Johnson Service Company to have a pressure gain of 220[4-55]. Marquardt[4-63] reports a two-dimensional device with a flow gain of 12.8 (Figure 4.19).

Receiver ports drastically disturb the jet profile, and experimental techniques must be used. Liebowitz[4-64] obtained data for a large scale axial jet receiver model, using water. The deterioration of the pressure recovery for large-angle diffusers was measured, and the use of a constant-diameter inlet to the diffuser improved the recovery somewhat. The improvement might be more marked for off-center jets, which were not tested.

Most experimental optimization work seems to have been carried out by varying the geometry of one part of an element at a time, on a parametric basis. For example, a comprehensive parametric study of the Harry Diamond Laboratory's design of proportional amplifier was made by Van Tilburg and Cochran[4-60]. In addition to studying the effects of normal tolerance variations of etched glass units, they made studies of nozzles, aspect ratio, receiver width, receiver location, control nozzle width, and others. For the range of parameters tested, no startling change in performance (pressure and flow gain) was observed, except for the effect of aspect ratio. For very high values of aspect ratio, the pressure gain decreased, contrary to expectations, as shown in Table 4.1.

TABLE 4.1

Aspect Ratio t/d	Pressure Gain
1	3 to 4.8
2	4.5 to 5.8
5	3.7 to 4.3
6	2.8

Dexter,[4-54] in optimizing the performance of a beam deflector proportional amplifier, resorted to experimental techniques to eliminate instabilities. He found the vent geometry and impedance quite important in designing of the element.

4.4.2 Digital Amplifiers

Since there are a wide variety of digital amplifier types as well as a large number of ways of operating a given element in a circuit, a generalized gain definition for the digital amplifier is difficult. For instance, the amplifier may be a flip-flop, an OR-NOR, or one of a variety of other logic elements, each requiring its own type or combination of inputs. The control input may be a pulse, or a step change or a ramp in pressure or flow, or perhaps even negative flow (suction). It may occur with or without a signal on other control inputs to the amplifier. The static and dynamic switching requirements vary considerably as discussed in Section 4.5.

In view of these facts, the use of "gains," as such, in actual circuit design is extremely limited. Katz and Dockery[4-50] report methods of using plots of amplifier characteristics in circuit design and others[4-65, 4-66] report methods of plotting characteristics. However, "gains" serve a usefulness as a figure of merit for comparing elements. Other factors to consider include pressure and flow recovery, efficiency or power recovery, load sensitivity, coupling between output ports, input impedance and impedance changes.

It should also be recognized that, with wall attachment digital amplifiers, "gain" and the stability of attachment of the jet to the sidewall are a compromise. The less stable the jet attachment, the lower the necessary switching signal. A high pressure recovery, flow recovery, or both, also result in higher gains.

Many references to digital amplifier gains exist in the literature(4-62, 4-67, 4-57, 4-68, 4-66, 4-65). In evaluating the "gains", the above cautions must be observed. However, they are presented to give a "feel" for orders of magnitude.

Bowles[4-62] reports pressure gains of 30, flow gains of 100, and power gains of 250, gain definitions and element types unknown. Bauer[4-67] presents characteristics of an OR-NOR element. Compagnuolo[4-68] reports on a three-stage digital amplifier having a flow gain of 3000 and a power gain of 9000. The elements are beam deflector type flip-flops and gain definitions are given. Warren[4-65] describes several forms of beam digital deflector elements including the type used in Compagnuolo's amplifier.

Boothe[4-66] describes a bistable flip-flop and gives performance characteristics of the device. Gains are defined in terms of the change in output variable (flow, pressure or power) divided by the level of the same variable in the appropriate control port at the instant of switching for several modes. The best gains reported were in the "Open Control" mode. A maximum pressure gain of 17.4, maximum flow gain of 25.7 and a power gain of 262 were reported. The latter paper also points out how control pressure often rises in a control port after switching. This is due to the change in amplifier input impedance when the jet is switched, and further demonstrates the difficulty of obtaining a meaningful definition of gain in digital elements. Should the input on which gain is based be that before or after switching? Both are important. Each is affected by the impedance of the element producing the input signal as well.

A parameter of fundamental interest for the wall attachment devices is the nozzle Reynolds number.* A minimum value of Reynolds number for wall attachment indicates a possible limitation on low supply pressure or minimum size for a given configuration. Test results of Comparin, et al.,[4-69] have shown values of minimum Reynolds numbers for wall attachment. The minimum Reynolds number was determined for a single sided geometry and double sided geometry. When an aspect ratio of 0.6 was used, the minimum attachment Reynolds number for a chosen geometry ranged from 1000 to 4000. An investigation of the effect of aspect ratio show that at t/d values of two to five, the minimum Reynolds number for attachment could be as low as 200, as shown in Figure 4.20. In another publication Comparin[4-70] also illustrates similar results for this effect of aspect ratio on the minimum Reynolds number for attachment. These publications also show the effect of offset a and discuss the effects of varying the splitter distance s, the wall angle (α), and the wall length l on the minimum Reynolds number for attachment (see Figure 4.22). These variables did not seem to be nearly as significant as the aspect ratio. As an indication of the low power nozzle velocities possible for wall attachment devices, Reilly[4-56] was able to confirm jet attachment with a jet supply pressure head of about one inch of propane. It seems difficult, therefore, to establish a minimum attachment Reynolds number, since it is so strongly influenced by geometry.

Comparin and other investigators (e.g. Johnston[4-51]) have made parametric studies of digital amplifiers and have shown the effects of some of the geometrical variables such as wall length and angle. These data provide an insight to the design of a complete element, but because of the interrelation of the large number of parameters, a design is usually optimized experimentally by a systematic variation of the parameters. Warren[4-65] has summarized qualitatively the significance of the more common parameters of a digital element in the form shown in Figure 4.21. Usually, a design is somewhat more complicated and involves additional parameters. For example, Boothe[4-66] has described an empirically designed bistable element which includes the additional refinements of vents and a cusp or vortex generator; Figure 4.23 illustrates the general configuration. The design resulted from the systematic variation of the parameters shown in Figure 4.22 and the dimensions and locations of the vents and the cusp. Design charts have not been developed because of the large number of variables. A counter configuration of Warrens[4-71] is being studied experimentally in a similar fashion by the Univac Corporation[4-72] to determine the significance of the parameters of this element.

*Reynolds number here is based on nozzle width.

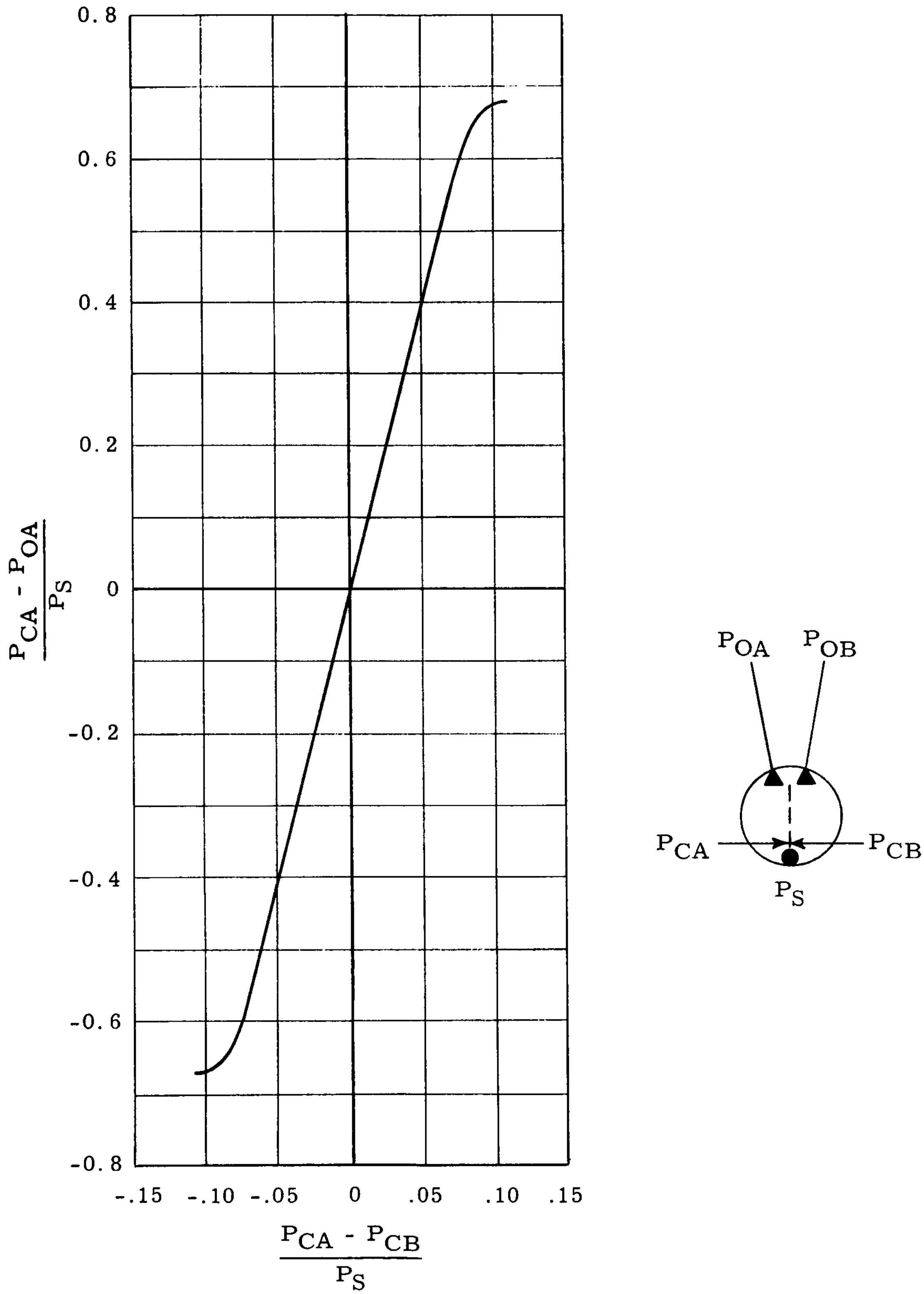


Figure 4.17. Input - Output Curve for Analog Amplifier (No Output Flow). (Reference 4-57)

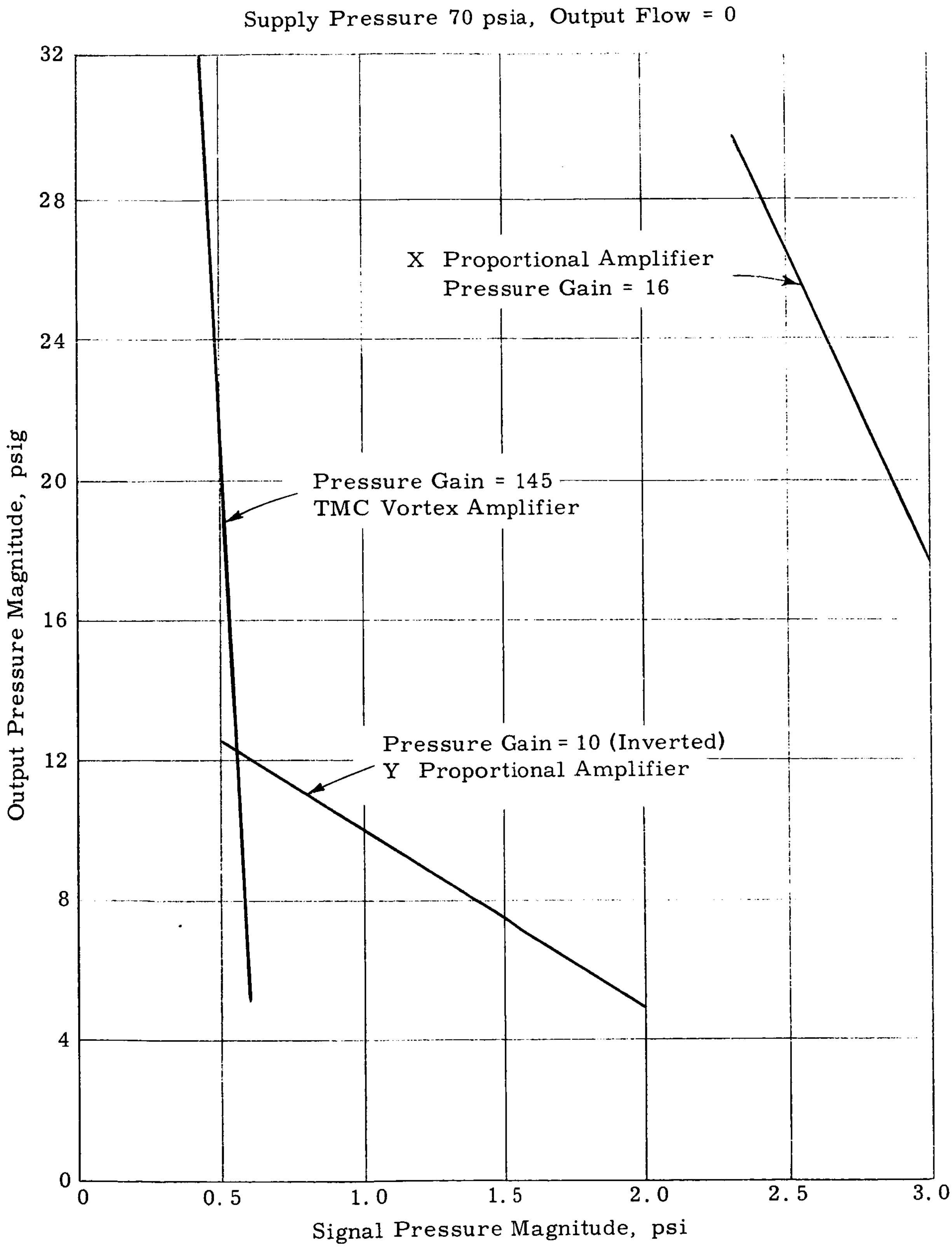


Figure 4.18. Pressure Gain Characteristics of Proportional Amplifiers (Reference 4-63).

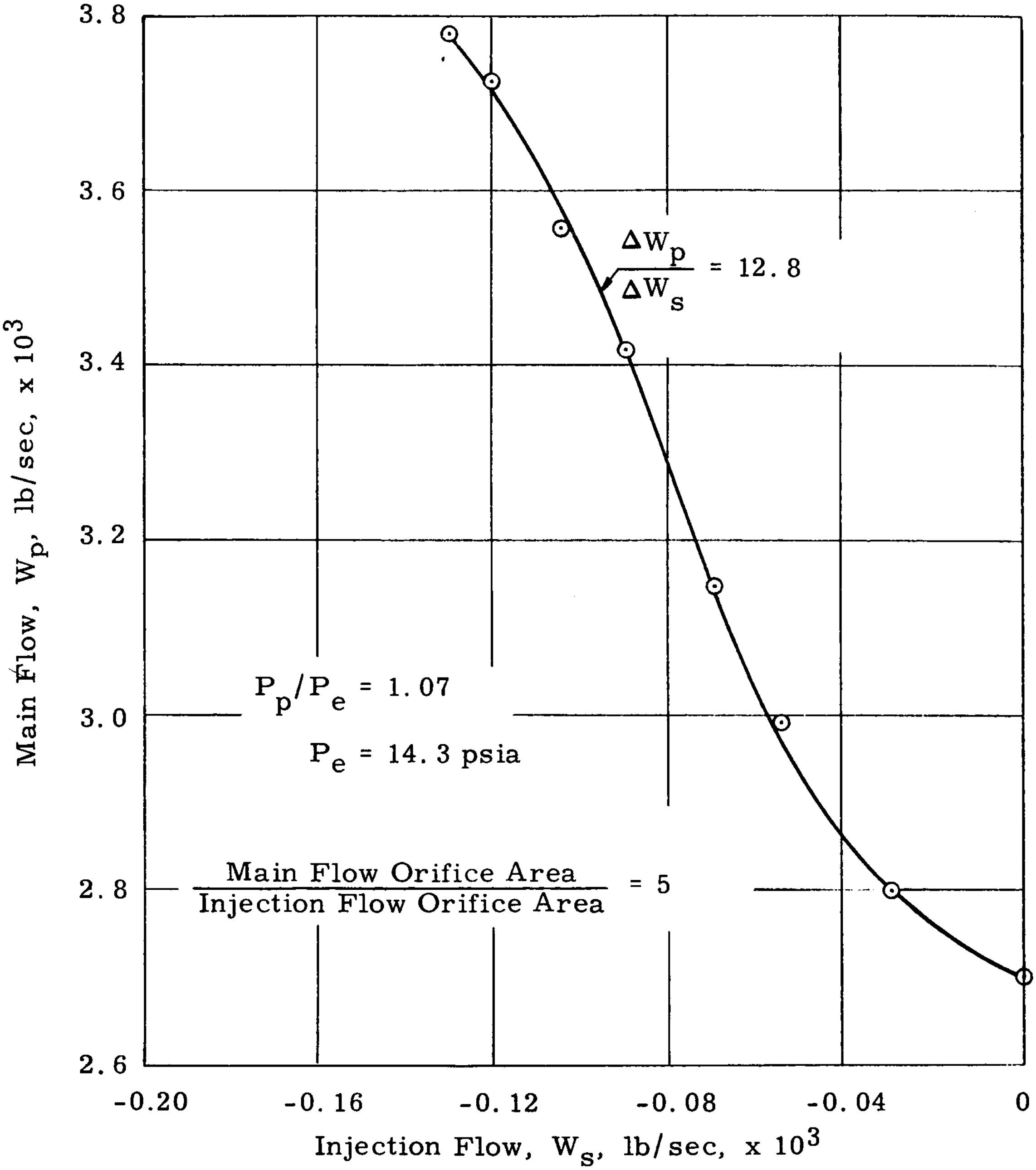


Figure 4.19. Flow Gain of Fluid Amplifier (Reference 4-63).

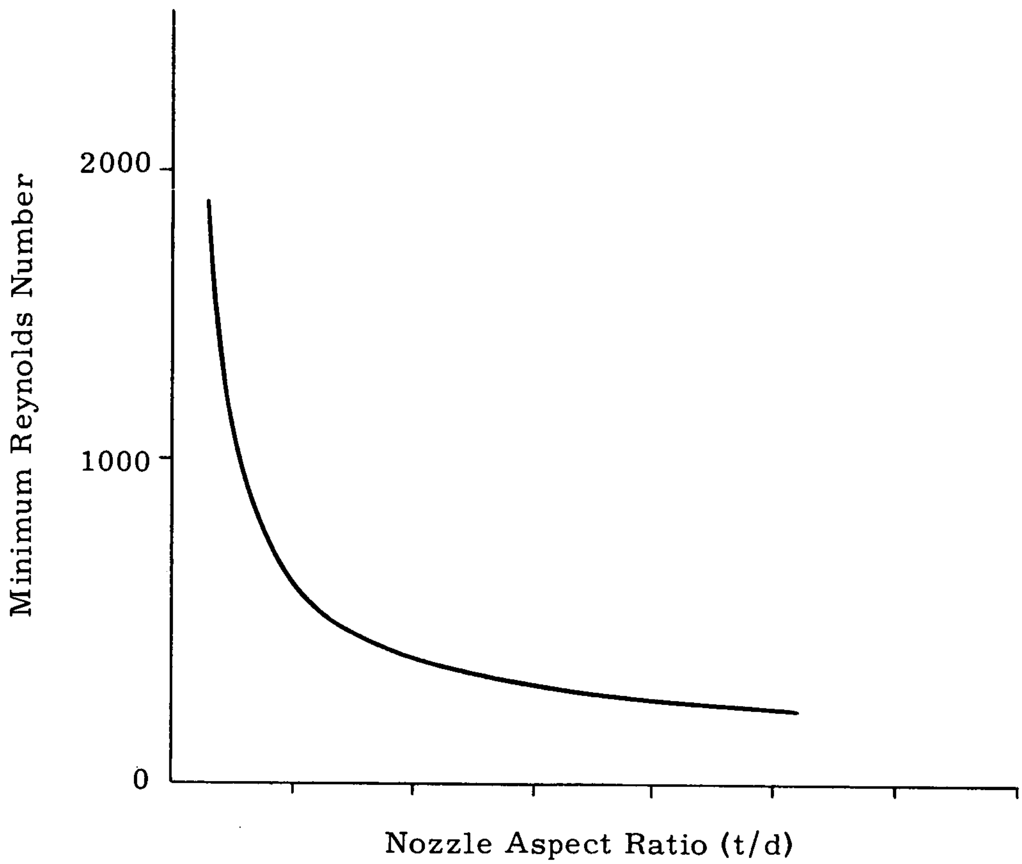
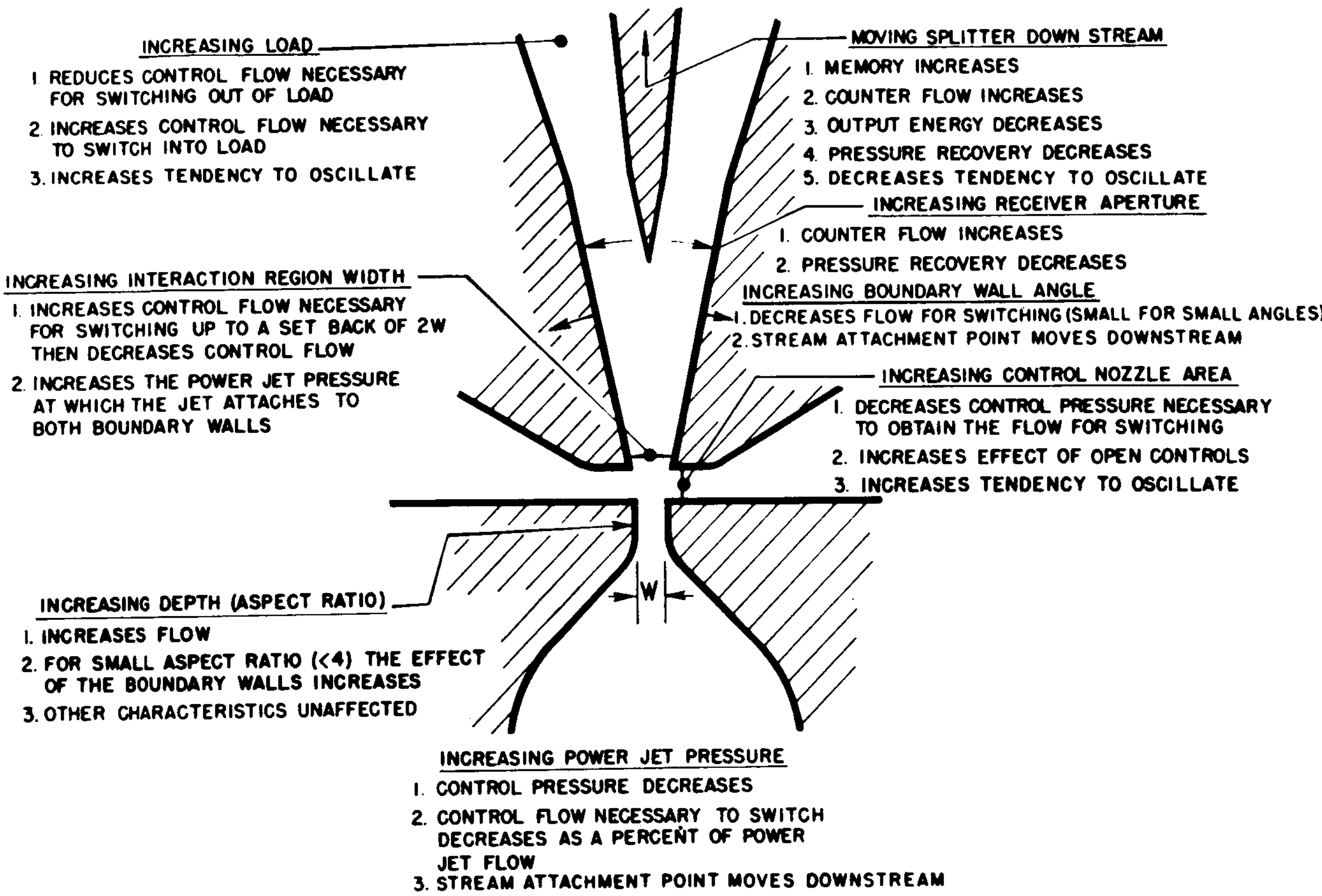


Figure 4. 20. Effect of Aspect Ratio (Reference 4-70).



(from ref. 4-65)

Figure 4.21 Effects of Geometry on Bistable Element

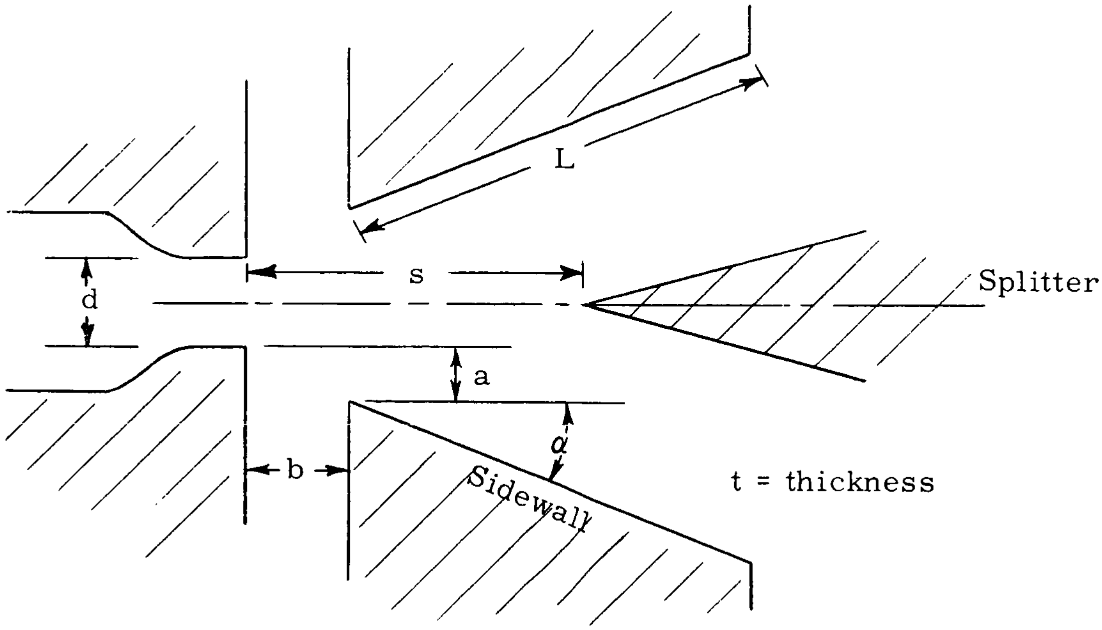


Figure 4.22. Typical Wall Attachment Geometry.

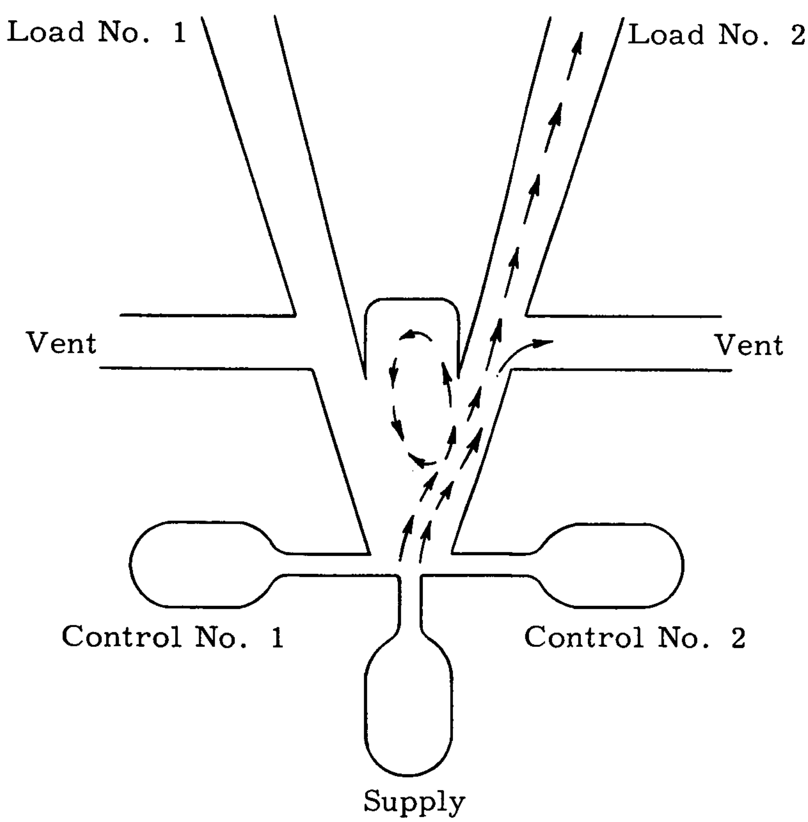


Figure 4.23. Empirically Designed Bistable Element.

4.5 Dynamic Response Analyses and Measurements

Many claims and references to fast response of amplifier elements exist in the literature. In many cases these references must be used with caution since there is not yet a standard form of response presentation. Usually, response is stated in the most impressive manner possible and is not always expressed in a form useful to circuit or system design. As a result, specific information on dynamics of fluid amplifiers is not plentiful.

The bulk of the available information on response is empirical in nature. Analytical treatment of amplifier dynamics has not received wide attention as yet. This is partially due to the wide variety of elements which exist. Recent work at General Electric [4-59], the University of Pittsburgh [4-51], and HDL [4-50] shows promise of simplified dynamic analyses. In this work, a proportional element analysis predicts dynamic performance quite adequately, making use of steady-state element characteristics determined by a simple test. Digital element analyses permit complete prediction of response of simple wall attachment devices after obtaining two response data points.

The following sections summarize the available experimental and analytical information on fluid amplifier dynamics. Since the natures of the dynamics of the proportional and digital elements are quite different from each other, they are treated separately. (See also Section 4.6 for a general linearized approach to system dynamics).

4.5.1 Proportional Amplifier Dynamics

The response of proportional fluid amplifiers is a function of the supply pressure, the working fluid and the specific configuration of the element. Operation with a gas results in a faster response than with a liquid at equivalent pressure due to the lower density and higher spouting velocity of a gas jet. In general, the speed of response of an element will decrease with increased size, due to the longer path lengths, although this may not always be true because of loading conditions. Faster response is attained with higher operating pressures. These factors must be considered in evaluating or comparing response information.

An analytical study of analog amplifier response [4-59] has been undertaken at General Electric, with success. It shows that time delays in proportional amplifiers can be attributed to three basic sources; 1) the lag due to inertia and compressibility of the fluid in the control ports, 2) the transport time for the power jet to travel from the nozzle to the receiver and 3) receiver and load dynamics.

The resistive component of control port impedance and receiver impedance is obtained by steady state tests. Air tests show that the input and output resistance of the elements can be presented in normalized form that holds true over a range of supply pressures extending up to the sonic flow region. The dynamic components (inductive and capacitive effects) of the impedances are predicted using the linearized lumped parameter analytical approach [4-73]. Transport time is included and is predicted from the jet spouting velocity and the nozzle-to-receiver distance.

Tests to determine the validity of this method of predicting response have been performed. These were done using a sinusoidal input pressure to the control ports, for various volumes as loads on the output. Results using the lumped parameter assumption become less accurate for smaller load volumes since the distributed effects in the receivers become predominant. Figure 4.24 shows the test results for a "worst" case (load volume negligible). Predicted results, by the above technique, are also shown. A fair correlation exists, particularly with the phase shift prediction. Better correlation was obtained with larger load volumes. Fair correlation was also obtained with water tests using constants predicted from steady state air test results.

In comparing various reported responses of proportional amplifiers, it is difficult to quote a "typical" response of analog amplifiers since virtually all results are expressed in a different manner. For example, the test results of Figure 4.24 show a 3 db attenuation at 1 Kc and 90^{o} phase lag at 1200 cps. The tests were performed on a General Electric element using 15 psig air, a 0.040 x 0.040 in. power nozzle and a high impedance load. Figure 4.25 shows the only comparable data found in the open literature. The data were obtained from tests on a Giannini Double Leg Elbow Amplifier (DLEA) [4-52], operating at much lower supply pressures (see Figure 4.25). A Giannini Single Leg Elbow Amplifier (SLEA) [4-52] has about a 2-1/2 db attenuation and 45^{o} phase lag at 20 cps with a recognizable (but highly attenuated) output at 1200 cps. Although the response of the GE and Giannini amplifiers are quite different, a comparison is not meaningful since the DLEA and SLEA elements shown were much larger in size and operate at a much lower pressure.

Other information on dynamic response is less specific. Dexter [4-54] reports an analog amplifier consisting of three stages of beam deflector elements which was "measured to 200 cps without detecting any appreciable attenuation or phase shift". Bowles [4-62] reports an oscillator running at 100 Kc. It is assumed that an analog element is used in this oscillator, although it could consist of Helmholtz resonator or a similar device. The Johnson Service Company [4-55] reports data on their analog amplifier (proprietary concept) to 20 cps and transmission of pulses at 200 cps observed at some unevaluated attenuation level. This element has an attenuation-response curve of the form shown in Figure 4.26 over the range tested, using air. Minneapolis Honeywell has also obtained frequency response results[4-56]. The tests were performed as part of specific development programs and the elements were tested only to the frequencies necessary to meet performance specs. No significant attenuation or phase shift was encountered inside the frequency range of interest, except for a lead that occurred at 10 cps in smaller gas operated amplifiers.

Data on liquid operation of proportional amplifiers are much more scarce. The only known tests were performed by General Electric[4-59], and at Minneapolis Honeywell[4-56]. The tests at the latter organization were at relatively low frequency and showed no attenuation or phase shift. The tests performed at General Electric were carried out under identical conditions to those shown in Figure 4.24 except that water was used as the working fluid. The results indicated a 3 db attenuation at 80 cps which is believed due primarily to the relatively high "inductance" of the water.

4.5.2 Digital Amplifier Dynamics

The dynamics of digital amplifier elements have been studied and reported from a number of sources (4-51, 4-62, 4-56, 4-50, 4-67, 4-74, 4-57, 4-75). Katz and Dockery of HDL[4-50] and Johnston of IBM[4-51] have undertaken analyses of the phenomenon. Both analyses are based on the assumption that the jet in a wall attachment amplifier will detach after the separation bubble reaches a critical size. Both conclude that switching time will decrease as the control flow level is increased.

Johnston describes experimental techniques for obtaining the necessary constants. He has two unknown constants, ΔV and Q_{eav}, for a given configuration. ΔV is the change in bubble volume to cause detachment and Q_{eav} is the average entrainment of control flow into the power jet during the switching cycle. Johnston's technique implies that Q_e (instantaneous value of entrainment flow) can vary with jet attachment position (Katz and Dockery assume constant Q_e). Johnston uses the relationship

$$t_s = \frac{\Delta V}{Q_c - Q_{eav}}$$

where t_s = separation time and Q_c = control flow level. By taking two response data points, one at relatively low control flow level, the other at a high value of control flow, it is possible to solve for ΔV and Q_{eav}, assuming they are independent of control flow level. Knowing ΔV and Q_{eav}, it is then possible to predict t_s as a function of Q_c, with the above assumptions. Figure 4.27 shows typical correlation obtained by Johnston, indicating that the assumptions of independence of Q_{eav} and ΔV from Q_c is valid. He further shows that ΔV is relatively insensitive to Reynolds number. As long as flow is turbulent, as shown in Figure 4.28, Q_{eav} increases with Reynolds number and a typical case is shown in Figure 4.29. The scatter in Q_{eav} values is attributed to small differences of large numbers which must be used to obtain Q_{eav}. The results in Figure 4.27 were obtained from a relatively large (1/4" throat), single sidewall test model with no receivers.

Tests were also run by Johnston with double sidewall receiverless models in 1/8" and 1/16" nozzle sizes to determine effects of Reynolds number and control flow level on switching time. Switching time, expressed as Strouhal number, was found to be relatively insensitive to Reynolds number. Typical values are shown in Figure 4.30. Strouhal number is defined as switching time divided by calculated nozzle-to-receiver transport time. Switching time for the same model is shown as a function of control flow in Figure 4.31. As expected, the same trend exists in double sidewall models as in the single sidewall element (Figure 4.27). Comparin[4-69] reports a similar trend, expressing his results in terms of Strouhal number vs. control pressure ratio.

Data on complete digital amplifiers (including receivers) are not as complete, and methods for arriving at switching times were found to vary considerably. One technique is to apply a square wave of pressure to the control port and observe the time delay between its application and the corresponding switching of the output. Using this approach, Bauer[4-67] reports a switching time of 0.5 milliseconds for a 1 psig, 0.020" nozzle width amplifier. Switching times of from 0.6 to 0.7 milliseconds were obtained at General Electric[4-57] with a 0.040" nozzle width amplifier at supply pressures from 0.5 to 5 psig.

A second technique for determining switching time of digital elements is the use of a feedback oscillator circuit consisting of a digital amplifier with external feedback lines from the receiver to control ports. Frequency is measured with decreasing path lengths until the path length is the minimum possible. A curve of half-oscillation period vs. path length can then be plotted. The curve is extrapolated back to zero path length to determine switching time. This technique has been used by Minneapolis Honeywell's MPG Research Lab[4-56] and G.E.'s Computer Lab[4-75]. Switching times as low as 0.1 milliseconds are reported by Minneapolis Honeywell. Typical values obtained at the General Electric are shown in Figure 4.32.

The above technique is simple and rapid. However, it is believed by the authors that some correlation between the step-function test and the oscillator test is needed. Among the unknowns in the oscillator test method are the control pressure levels and the degree of jet attachment. The effective control pressure level is dependent on frequency and Johnston[4-51] has demonstrated the effect of control pressure and flow levels on switching time. In addition to this pressure effect it is likely that, at high frequencies, fully attached flow may not be established during each cycle, resulting in switching characteristics quite different from switching with step signals. If the latter is true, the oscillator test may give optimistic switching times compared to those encountered in an actual working circuit.

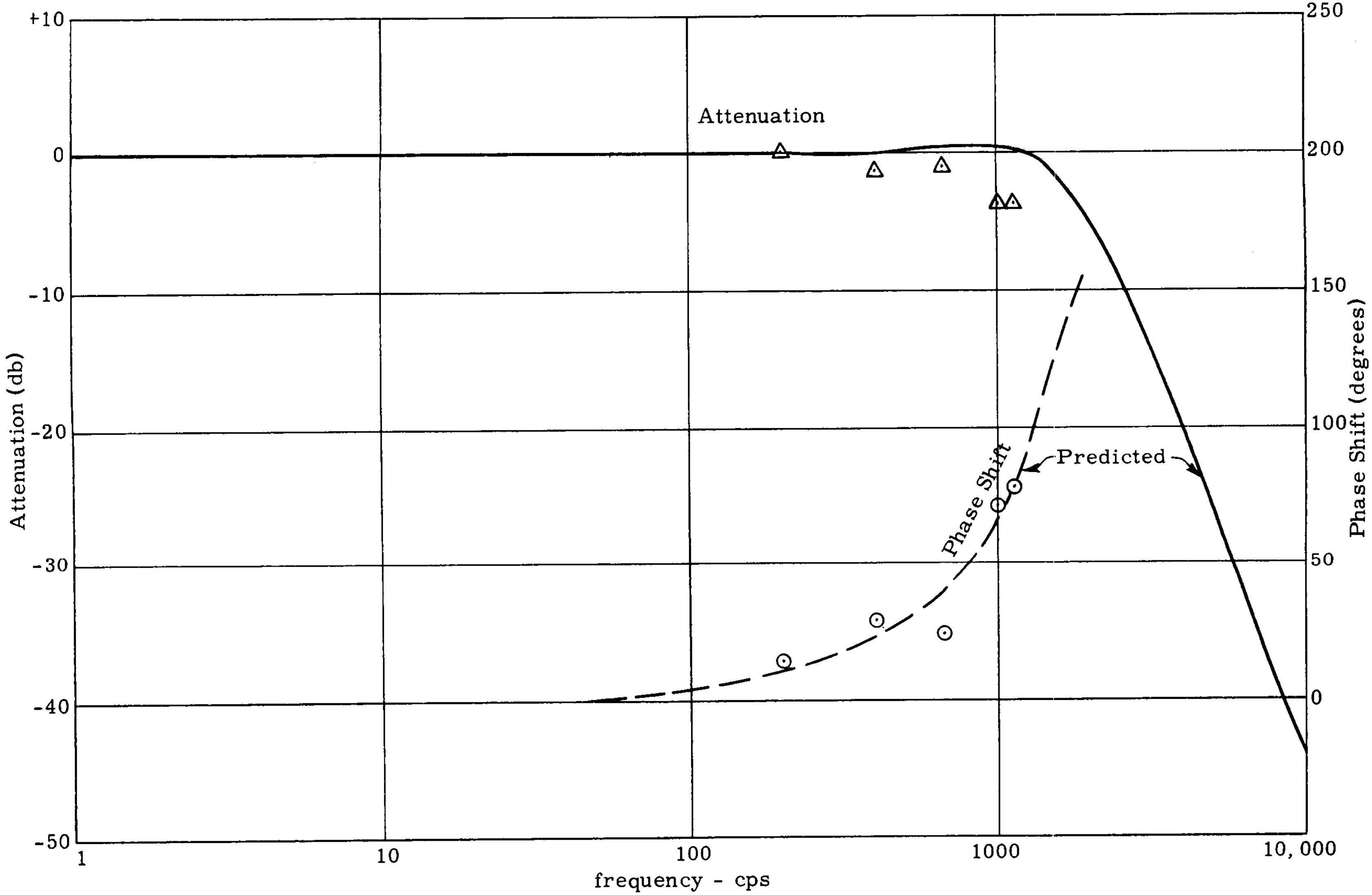
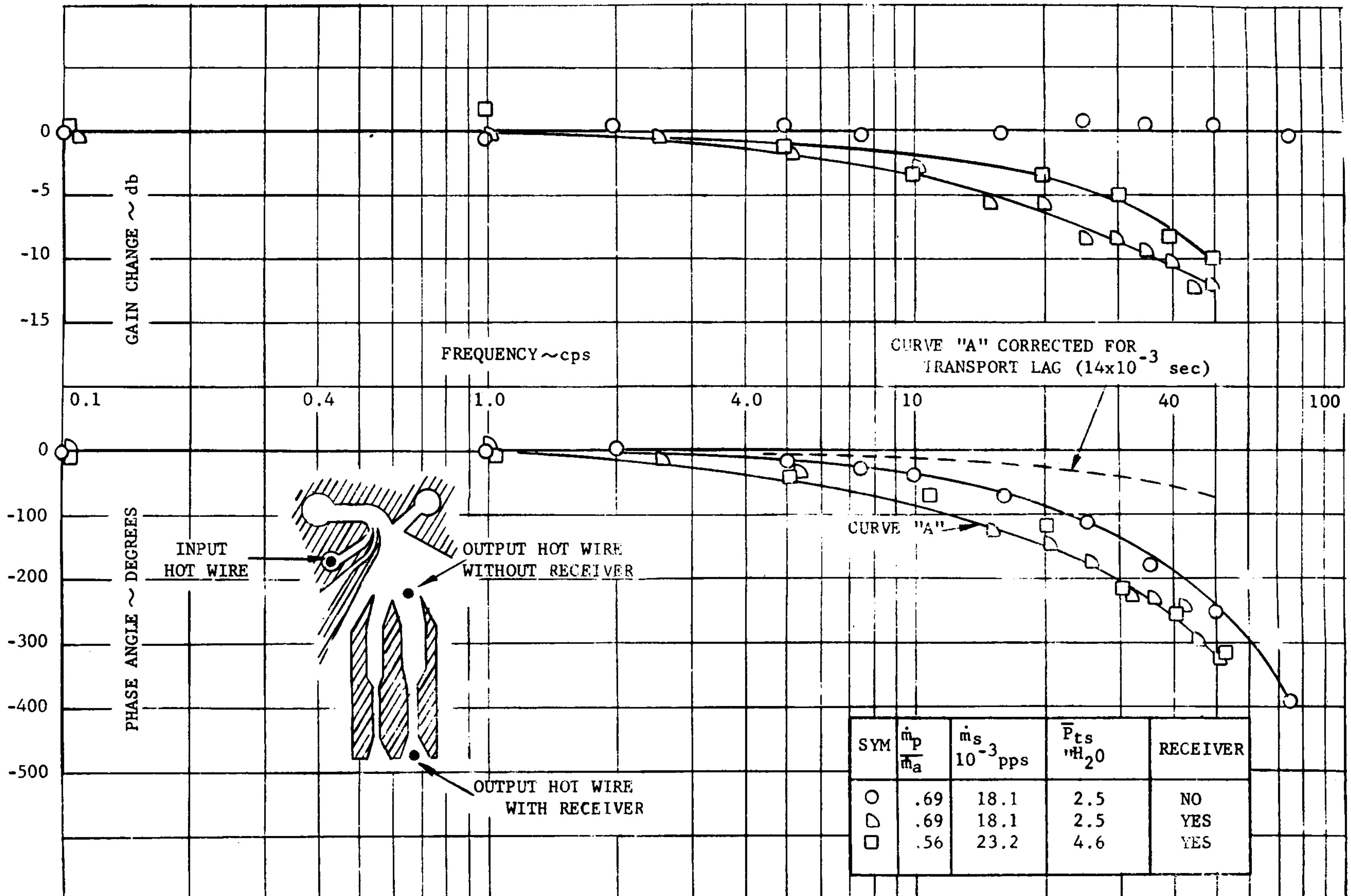


Figure 4.24. Comparison of Test Results to Predicted Frequency Response for Analog Amplifier. (Reference 4-59)



(from Refr. 4-52)

Figure 4.25 Bode Diagram of a Double Leg Elbow Amplifier

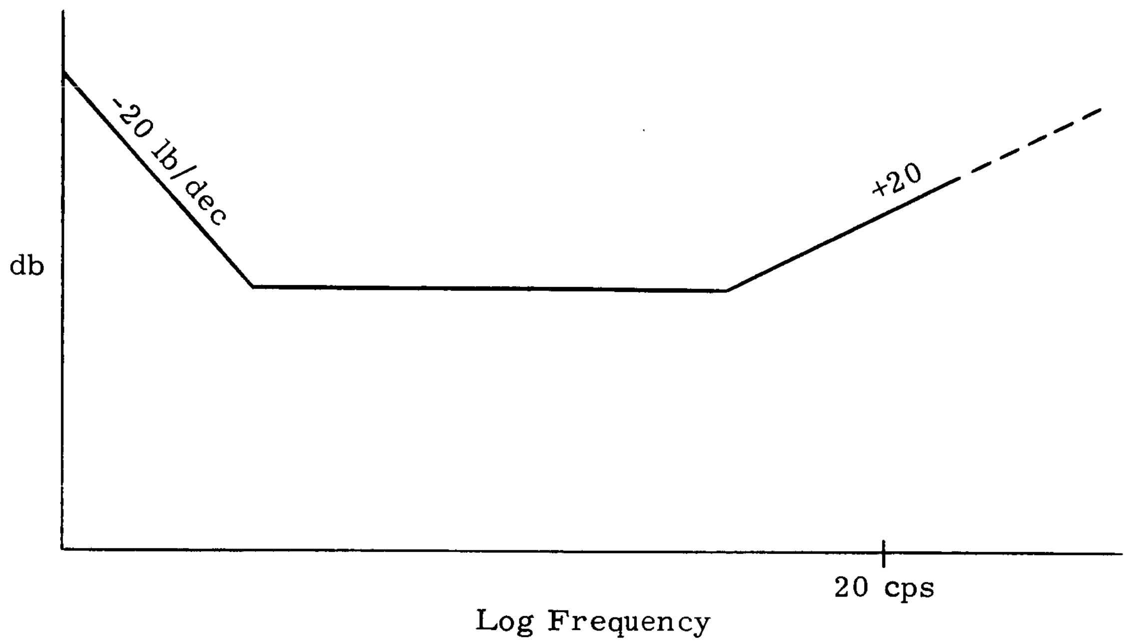
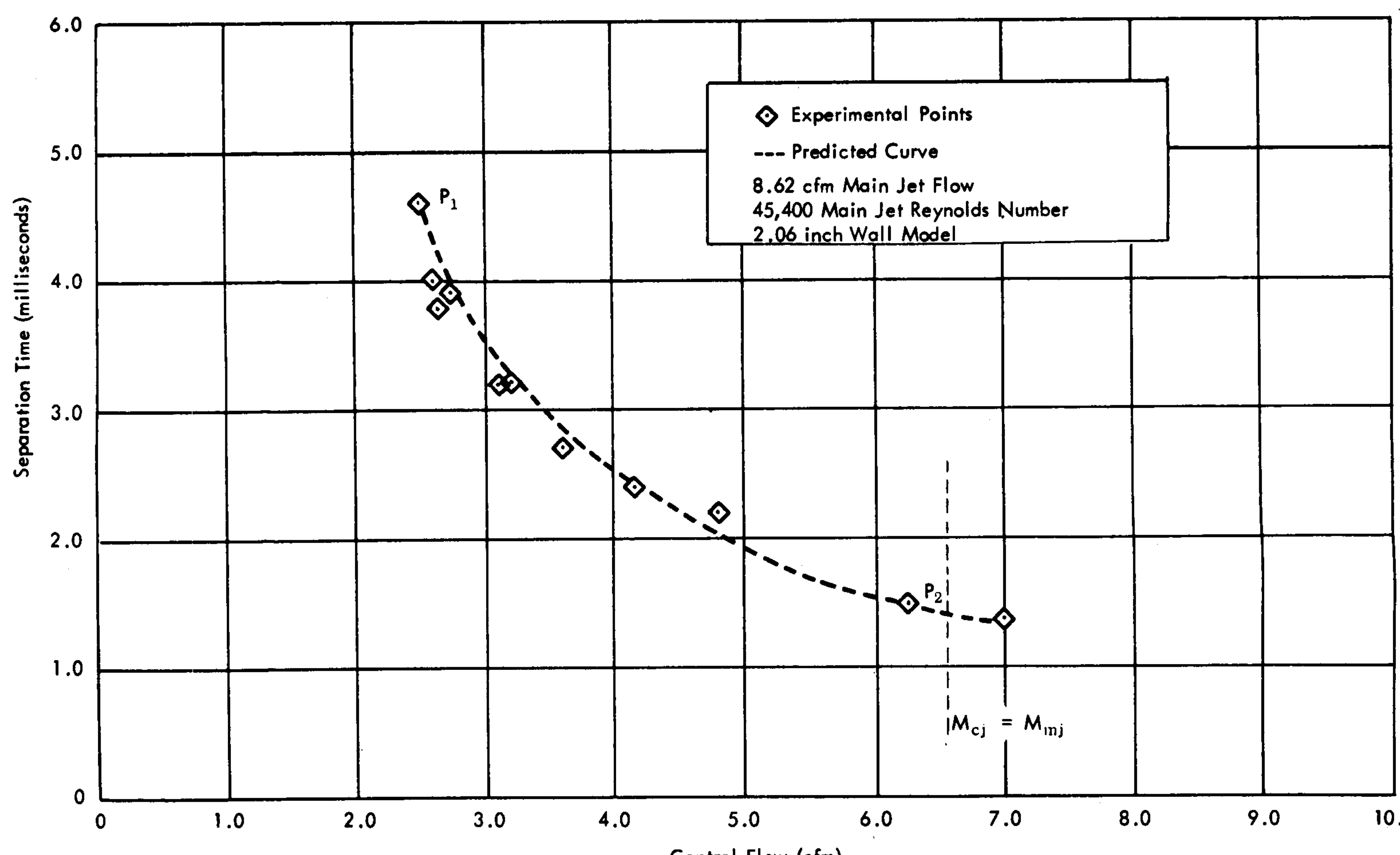
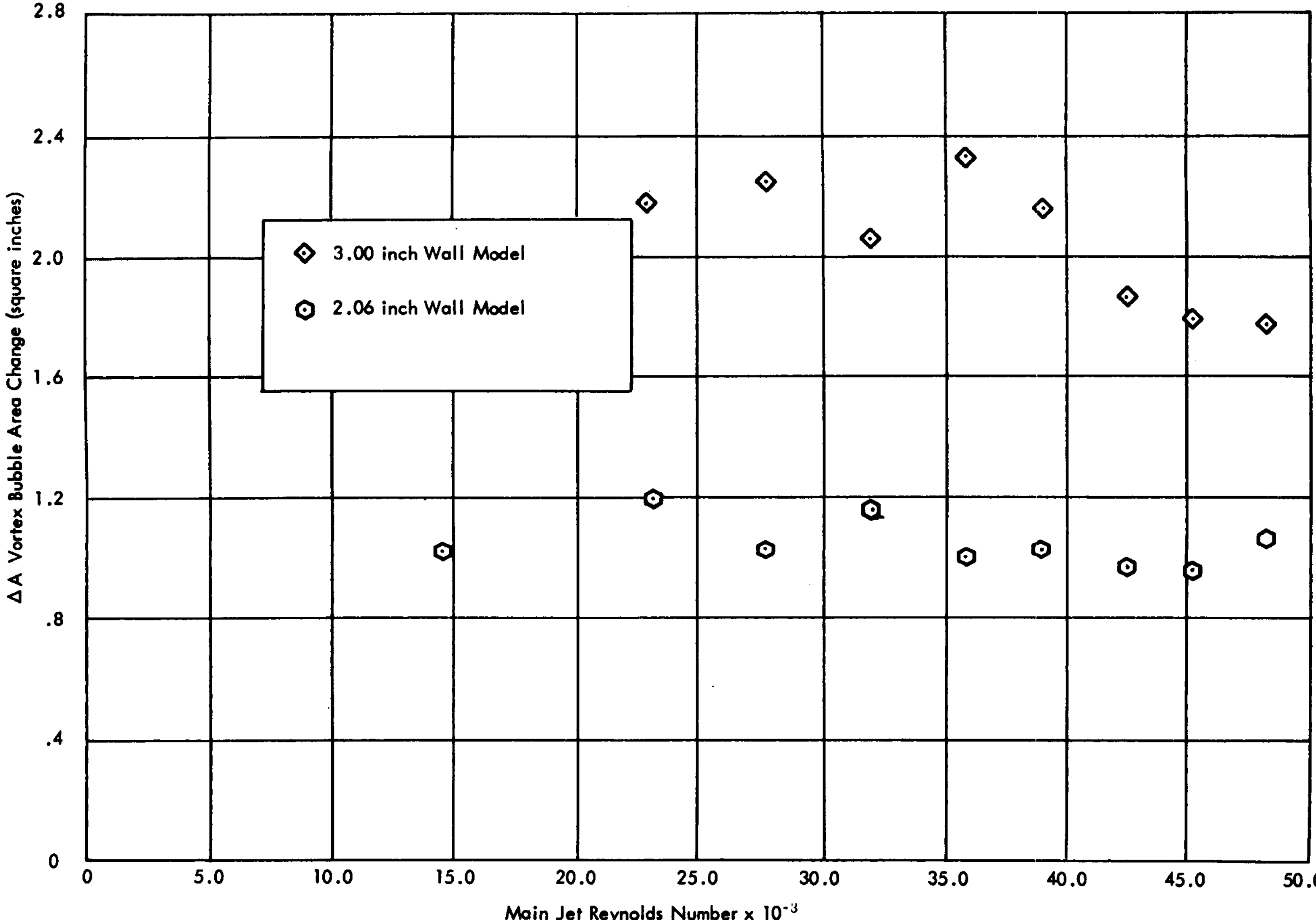


Figure 4.26. Attenuation-Frequency Characteristics of Johnson Service Amplifier (see text).



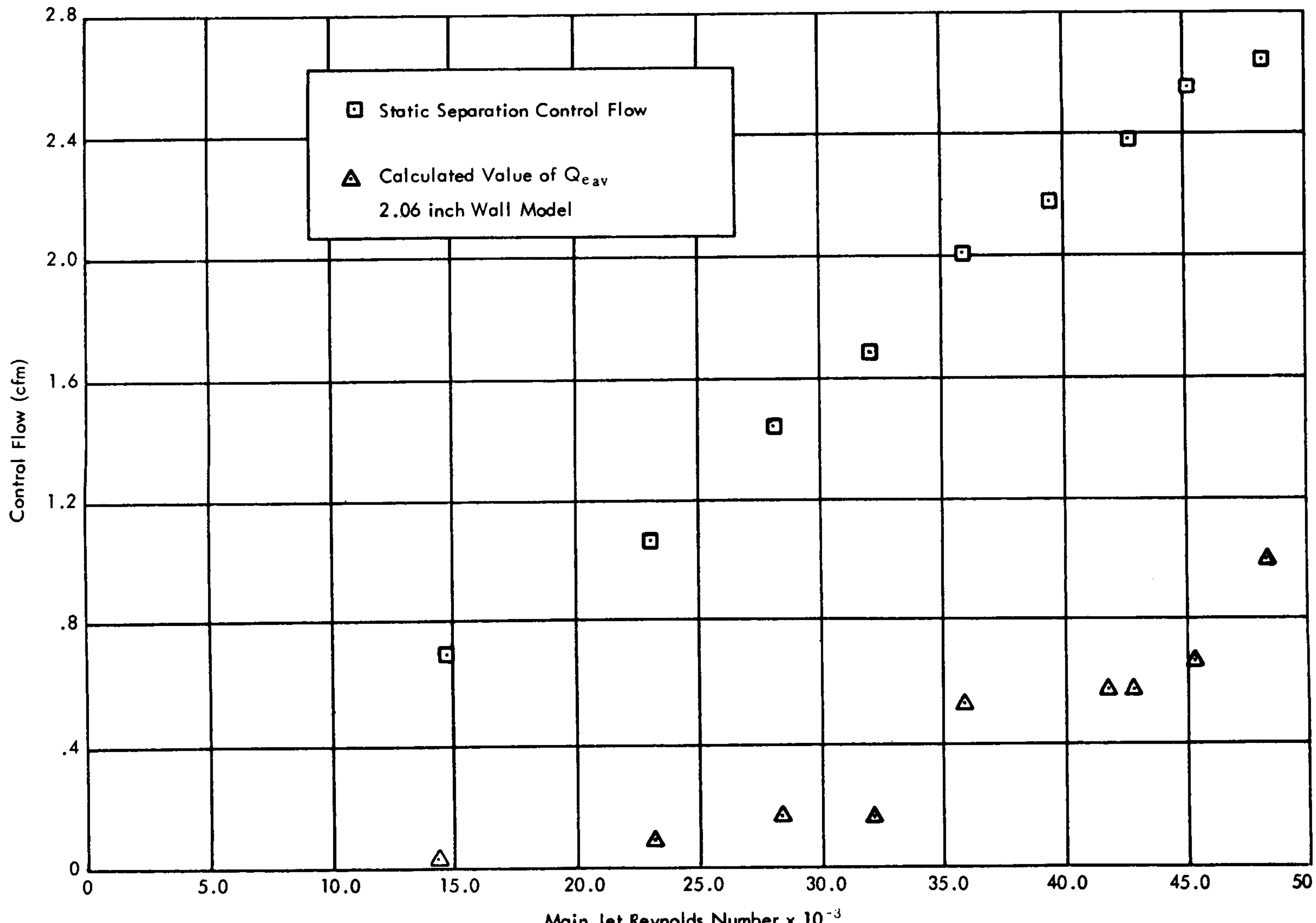
(from Refr. 4-51)

Figure 4.27 Experimental versus predicted separation times



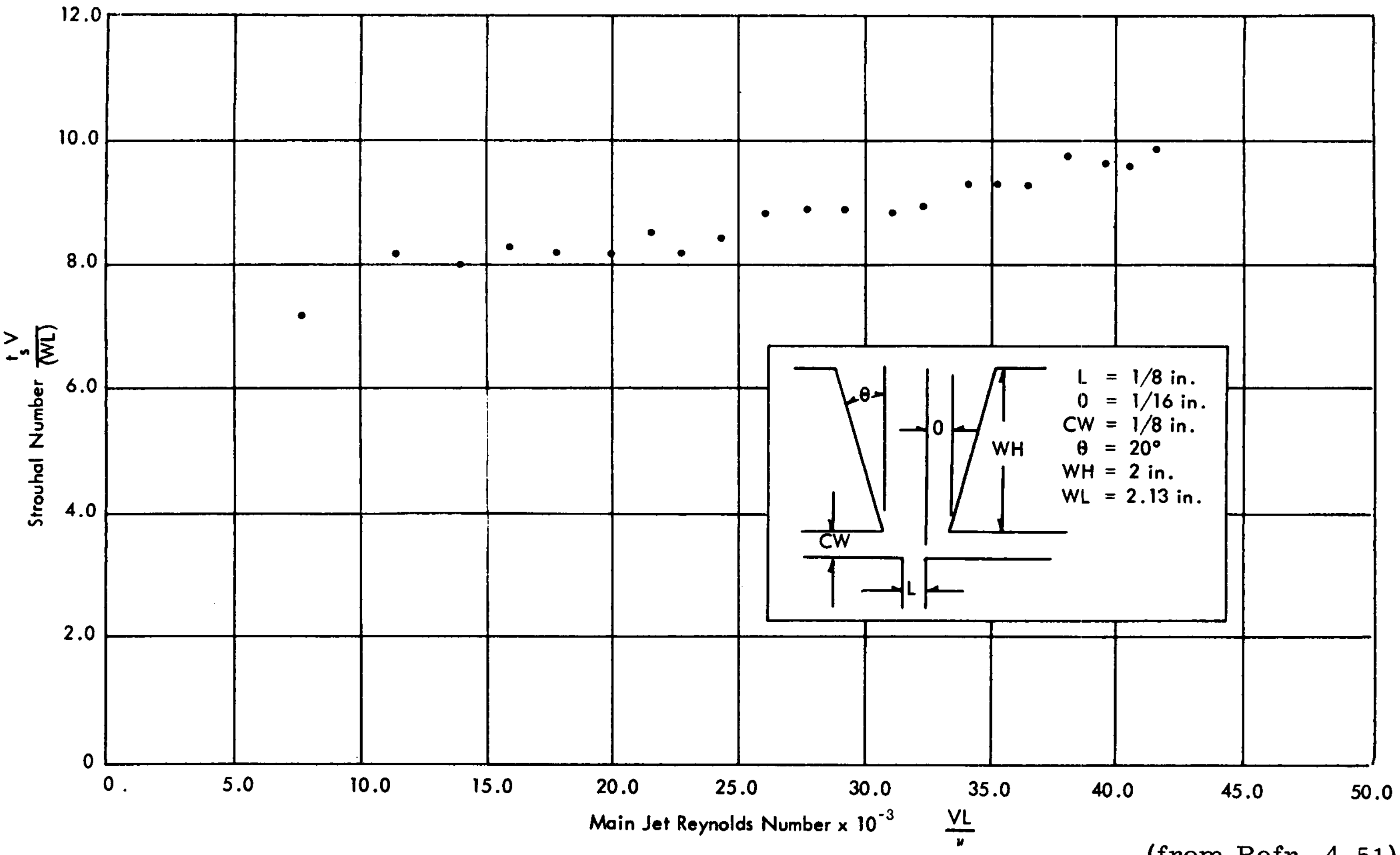
(from Refr. 4-51)

Figure 4.28 Dynamic vortex-bubble area change for models used



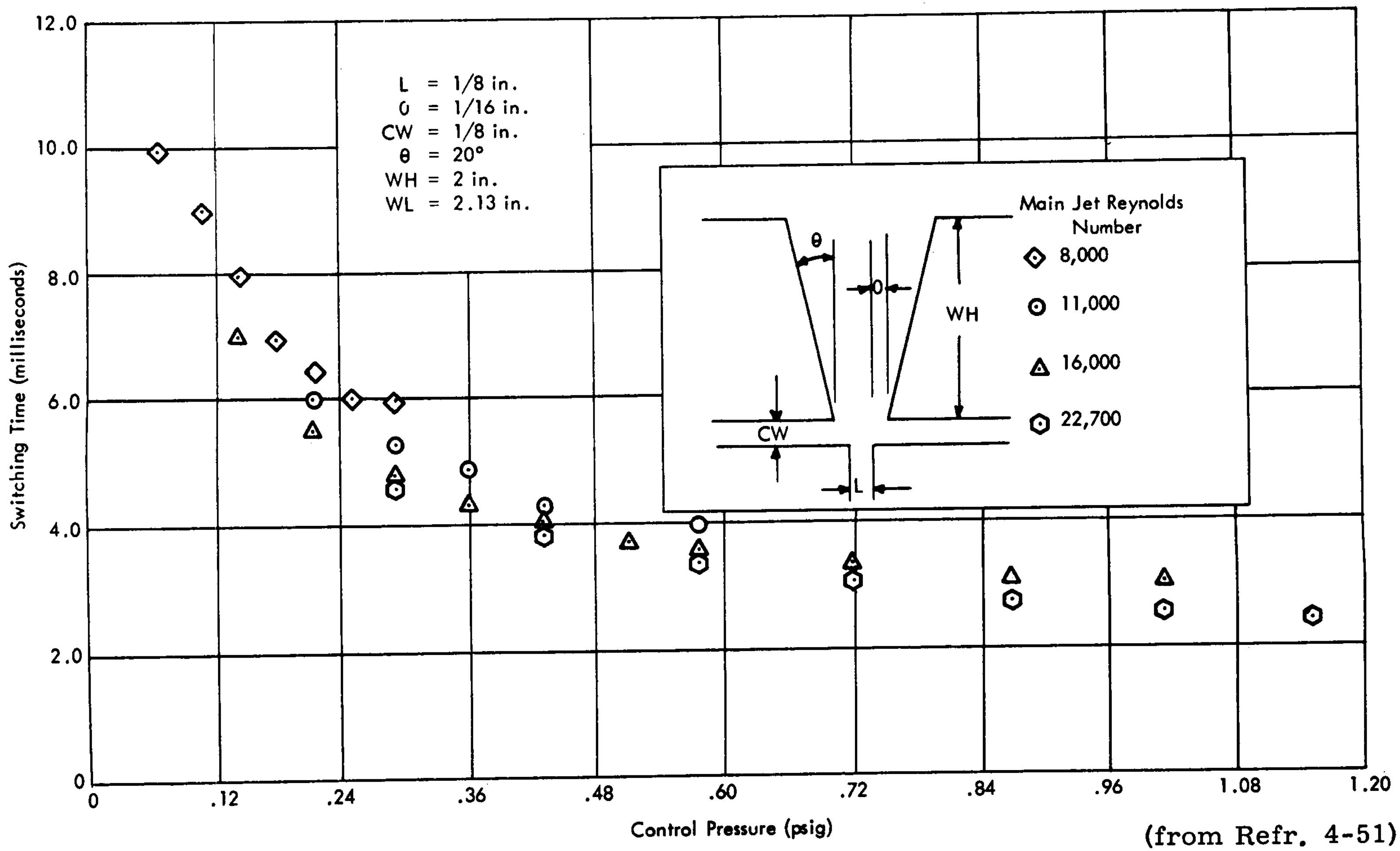
(from Refr. 4-51)

Figure 4.29 Statically entrained control flow versus calculated dynamically entrained control flow



(from Refr. 4-51)

Figure 4.30 Strouhal Number versus Reynolds Number



(from Refr. 4-51)

Figure 4.31 Control pressure versus switching times

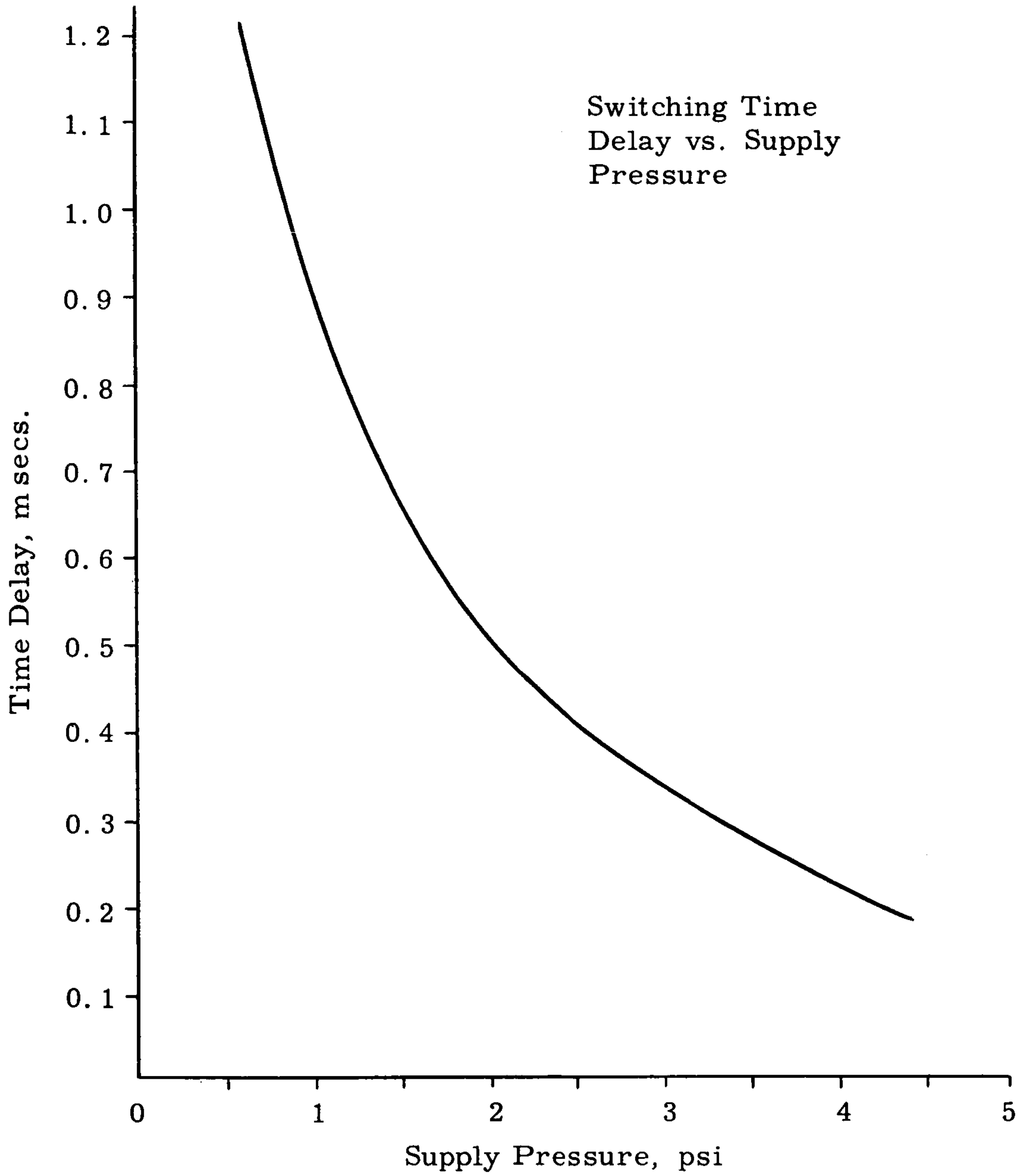


Figure 4.32. Element Switching Time Delay Due to Path Length (Reference 4-75).

4.6 Staging Techniques

Fluid amplifier elements usually have four to six ports with variable pressures and flows. One of each of the two variables at each port is independent; the other is dependent. For an n-port element 2^n choices of independent-variable combinations exist. Each dependent variable is then a nonlinear function of all the independent variables. For example, a particular control flow can be represented as a function of the pressures at all the ports, including the one in question. Staging then consists analytically in reducing the number of independent variables by supplying the various load characteristics; i.e. the pressure-flow relationships of the loads connected to the various ports. In general all relations are dynamic, involving differential operators and so forth. Similar statements exist for wide classes of devices, such as electronic elements in which the variables are voltage and current.

This general approach is extremely complicated, so that usually only devices which can be approximately described more simply are studied by scientists and engineers.

4.6.1 Assumption of Linearity

One simplification on the generalized equations involves assuming linearity. In general this assumption is valid only for small disturbances, although often it is useful for quite large disturbances. Again choosing the pressures as the independent variables.

$$dw_i = \left(\frac{\partial w_i}{\partial p_1}\right) dp_1 + \left(\frac{\partial w_i}{\partial p_2}\right) dp_2 + \cdots + \left(\frac{\partial w_i}{\partial p_n}\right) dp_n \tag{15}$$

$$= Y_{i1} dp_1 + Y_{i2} dp_2 + \cdots Y_{in} dp_n$$

in which Y_{ij} is a transfer admittance and Y_{ii} a self admittance. Linearity requires all these admittances, which can be measured directly, to be constant (although they may be time variable). Thus, in matrix notation, where $\mathbf{Y}$ is a square matrix,

$$\mathbf{w} = \mathbf{Y}\mathbf{p} + \mathbf{w}_o \tag{16}$$

in which the reference pressures (zero pressures) can be different from one another, however. Now, the individual flows at the ports of the element are related to the individual pressures by

$$\mathbf{w}_\ell = -\mathbf{Y}_\ell \mathbf{p} - \mathbf{w}_{\ell o} \tag{17}$$

where $\mathbf{Y}_\ell$ isthe load-impedance matrix, and the minus sign accommodates the definition of positive flow directed into the element, out of the load.

The load is thus viewed essentially as another multiport element, with the possibility of internal cross-coupling, etc.

Combining Equations (16)and (17)

$$\left(\mathbf{Y}+\mathbf{Y}_{\ell}\right)\mathbf{p} + \mathbf{w}_0 + \mathbf{w}_{0\ell} = 0 \tag{18}$$

For small disturbances about this equilibrium equations (16) and (17) become

$$d\mathbf{w} = \mathbf{Y}d\mathbf{p} \tag{19}$$

$$d\mathbf{w}_{\ell} = -\mathbf{Y}_{\ell}d\mathbf{p} \tag{20}$$

and since, in general, $d\mathbf{w} \quad d\mathbf{w}_1$

$$\left(\mathbf{Y}+\mathbf{Y}_{\ell}\right)d\mathbf{p} = 0 \tag{21}$$

Since the determinant $\left|\mathbf{Y}+\mathbf{Y}_{\ell}\right|$ is not generally zero, $d\mathbf{p}$ is constrained to zero, i.e., an equilibrium exists. We would like, however, to find the response to an input. To do this, let an "input flow" be injected into port i as in equation 22.

$$d\mathbf{w}_{\ell} - d\mathbf{w} = \begin{Bmatrix} O \\ \vdots \\ O \\ dw_i \\ \vdots \\ O \end{Bmatrix} = \left(\mathbf{Y}+\mathbf{Y}_{\ell}\right)d\mathbf{p} \tag{22}$$

hence

$$d\mathbf{p} \quad \left(\mathbf{Y}+\mathbf{Y}_{\ell}\right)^{-1} \begin{Bmatrix} O \\ \vdots \\ O \\ dw_i \\ \vdots \\ O \end{Bmatrix} \tag{23}$$

so that

$$dp_i = -\left(\mathbf{Y}+\mathbf{Y}_{\ell}\right)^{-1}_{ii} dw_i \tag{24}$$

and

$$dp_j = -\left(\mathbf{Y} \quad \mathbf{Y}_{\ell}\right)^{-1}_{ji} dw_i \tag{25}$$

Combining equations (24) and (25) gives the desired transfer function which in general is in time operator form:

$$\frac{dp_j}{dp_i} = \frac{(\mathbf{Y}+\mathbf{Y}_\ell)^{-1}_{ji}}{(\mathbf{Y}+\mathbf{Y}_\ell)^{-1}_{ii}} \tag{26}$$

Thus, for example, pressure gains can be predicted from <u>separate</u> measurements of the characteristics of the element and the loads to which it is attached. Steady-state gains result from the use of the steady-state values of the Y's; dynamic transfer functions result from inclusion of the dynamic effects. In the latter case Fourier and Laplace transforms are extremely useful analytical tools.

Belsterling[4-74] has approached the design of fluid amplifier circuits by describing the element performance in terms familiar to the control engineer. The work will include static and dynamic analogies of network parameters, equivalent electrical circuits and transfer functions. Analytical and graphical techniques are being developed for more convenient system analysis.

4.6.2 <u>Small Disturbance Stability</u>

Stability can be determined by considering that dw_i is not an input but is a transient divergence between the flows $dw_{\ell i}$ and dw_i resulting from a slight compliance or capacitance at the "i th" port. If a positive disturbance dp_i produces a negative dw_i, the negative divergence will reduce the pressure in the port correcting for the original disturbance. If the positive disturbance, dp_i, produces a positive dw_i, however, the system must be unstable. Thus, if $(\mathbf{Y}+\mathbf{Y}_\ell)$ is a matrix of real constants, equation (24) shows the criterion of stability to be

$$\left(\mathbf{Y}+\mathbf{Y}_\ell\right)^{-1}_{ii} > 0$$

for all diagonal elements ii. If $(\mathbf{Y}+\mathbf{Y}_\ell)$ involves time operators, the Nyquist criterion can be applied byusing the complex-number, frequency-dependent functions $(\mathbf{Y}+\mathbf{Y}_\ell)^{-1}_{ii}$. On the complex plane, as the frequency goes from $-\infty$ to $+\infty$, the necessary and sufficient condition of stability is a zero or negative number of net clockwise encirclements of the origin.

Consider the simplest case of all, namely two elements connected by a single port, in which the static characteristics are valid over the frequency range of interest. The criterion of stability becomes simply

$$Y + Y_\ell > 0 \tag{27}$$

An instability could be either cyclic or non-cyclic. If it is cyclic, it must occur at infinite frequency, which cannot happen physically, showing that the dynamics of the admittances would be important. If a volume or compliance exists at the port, the frequency of an oscillation would be finite and predictable.

The load admittance Y_ℓ often can be considered to be the surge admittance of a long transmission line attached to an element. Frequently in this case equation (27) shows an instability. This surge instability is usually oscillatory, and often accounts for very high frequency "noise" (higher than "organ-pipe" frequencies) in fluid jet amplifier systems.

If a transmission line connects two elements, an "organ-pipe" or wave instability also can occur. The preceding analysis is not so practical in this case, due to the dynamics of the line as an alternative analysis based on scattering variables and scattering operators. Consider this special single-line problem (the general technique will be presented at the planned Harry Diamond Laboratories symposium in May, 1964): Assume again that the static characteristics of the elements are valid for the organ-pipe frequencies of interest. If a small wave is present in the line, traveling toward the first of the two ports, it will be reflected with the same shape but a different amplitude, S_1 times the original wave. The new wave traverses back along the line and is reflected at the second port with the "gain" S_2. The reflection coefficients S_1 and S_2 are special cases of scattering operators. After the wave has made one complete round trip, stability is indicated if and only if the wave has not grown, namely if

$$| S_1 t S_2 | \leq 1 \tag{28}$$

in which t is the attenuation factor associated with the wall shear in the line. In this simple case the scattering coefficients are simply related to the termination admittances:

$$S = \frac{Y_c - Y}{Y_c + Y} \tag{29}$$

Here Y_c is the characteristic or surge admittance of the line, which is nearly equal to the area of the line divided by the speed of sound in the medium.

4.6.3 Stability with Nonlinearities

The three special cases discussed above, of static, surge, and wave stabilities of two elements with negligible internal dynamics connected to each other by one volume or line, are so simple as to be readily solved graphically, including the nonlinear effects. In Figure 4.33 the static case is shown (a volume or compliance can separate the two elements), in Figure 4.34 the cyclic surge instability, and in Figure 4.35 a special case of the cyclic wave instability showing the limit cycle. The graphical technique in this last case is the well-known method of characteristics for one-dimensional unsteady flow.

A study of a resonance tube with supersonic impinging jet was studied by Thompson[4-76]. The jet was underexpanded. The configuration was not too different from that of a single-sided beam deflector amplifier. No consideration of control flow was included however. Certain regions of axial spacing were found to produce instabilities in the resonance tube and other regions produce stable operations.

A considerable amount of wave stability work has been carried out by Powell. Although not specifically concerned with fluid amplifiers, his edgetone work[4-14, 4-77] can provide valuable insight to possible "noise" generation by a fluid jet impinging on a splitter such as used in proportional amplifiers.

4.6.4 Transmission Lines

Since the delay caused by long lines can result in attenuation and phase shift, a thorough understanding of their characteristics is highly desirable. Fortunately, this subject lends itself to mathematical treatment and a wealth of information exists for both compressible and incompressible fluids (e.g., references 4-78, 4-79, 4-80, 4-81, and 4-82).

A good introductory article and a general treatment of transmission lines and terminations can be found in the Handbook of Noise Control[4-83]. Brown[4-28] has extended the analysis of dispersion of fast and slow transients in pulse propagation in transmission lines. The theory for the tapered transmission line which theoretically can provide some signal amplification also is discussed and extended in this reference.

4.6.5 Currently Used Staging Techniques, Proportional Amplifiers

The techniques discussed above have not yet been applied since they are still being developed. In practice much has been achieved with less sophisticated methods. Many investigators have arrived at "optimum" staging by experimental methods. Examples of the approaches and results can be found in references 4-54 and 4-60, for example.

Techniques for staging beam deflector amplifiers have been presented by Katz[4-50] and Lechner[4-84]. Katz uses the criterion that two amplifiers should be staged so that they saturate simultaneously. This arrangement results in the largest linear range for the assembly of two amplifiers. Simultaneous saturation can be attained (assuming no bias problems) by adjustment of the supply pressures. The proper supply pressures can be predicted from characteristics of the amplifiers. The input characteristics of the driven amplifier first are superimposed on the output (saturation output difference pressure)from the driver. This saturation output value (for a given supply driver supply pressure) becomes the maximum input signal to the driven element. From characteristics of this element, the value of supply pressure can be chosen which will permit this input signal value to just cause saturation of the driven element. This procedure thus establishes the supply pressure of the two elements such that saturation occurs simultaneously.

Nearly complete similarity in the flow patterns of successive stages can be achieved by also increasing the size of the successive stages.

Lechner[4-84] presents an approach for determining the optimum buffer design to be used between two amplifiers. The basic criterion used is that the load or input impedance of the driven amplifier should be equal to the output impedance of the driver. The amplifier considered is a three-dimensional arrangement using an axial jet and receiver with a perpendicular control jet. Both jets and the receiver have a circular cross-section. Empirical relations were established from measurements of the amplifier characteristics. These empirical relations were then combined with approximation and simplifications to yield the desired expressions. These are plotted for typical parametric values so that a partial graphical solution can be made. The results produce the geometry and operating parameters required, such as power nozzle diameter and supply pressure, for optimum matching.

Simson[4-24] directs his analysis of pressure-controlled proportional amplifiers toward analytic expressions, with the physical parameters unspecified. Thus, not only can optimum single stages be found for particular applications, but optimum staging conditions can be determined. The analysis is largely static, and care must be used in accepting the various assumptions. A report to the U.S. Army Redstone Arsenal is being prepared by Brown (Simson's advisor) which uses Simson's work as its primary source but adds independent judgment and some new theory and experiment.

4.6.6 Currently Used Staging Techniques, Bistable Amplifiers

Thus far, published analyses of digital (as well as proportional) amplifiers have neglected any cross-coupling effects (transfer admittances) between the control and output ports. Brown[4-39] considers the cross-coupling between the two control ports, necessitating a complicated graphical technique to account for the nonlinearities. The commonly used technique illustrated in Figures 4.36 and 4.37 even eliminates this cross-coupling, by assuming constant load characteristics at all ports except one of the control ports. The "switch" is actually a monostable device operated only at jet-left and jet-right saturation. The flip-flop has a useful hysteresis band.

Characteristic curves such as these can be conveniently obtained with fluid amplifier testers incorporating an X-Y plotter, as described in Section 8. The slope of the curves (control port admittance) is approximately equal, since the control port admittance is not notably altered by switching. The change in pressure in the interaction region causes the shift in the curves. A switch can be converted to a flip-flop by decreasing the control port admittance. The control port admittance can be decreased by altering the design of the element, or by adding orifices. The effect produced on the switching characteristics of a switch by decreasing the control port admittance is shown in Figure 4.37. If a switch utilizes built-in restrictors to provide bistability with ambient control pressures, it is considered a flip-flop. Norwood[4-85] describes the effects of the addition of a restrictor on the control ports by considering the restrictor characteristic and the switch input characteristics, and arrives at a control port operating point by use of these curves. Further, he defines a criterion for determining an optimum restrictor impedance as a function of control signal pressure. This criterion apparently establishes the restrictor impedance which provides the best compromise between stability (large resistance desirable) and switching sensitivity (small resistance desirable) for a given control signal pressure. Norwood has also determined the effect of Reynolds number on the control port characteristics. Air and helium were used to provide Reynolds numbers from 3000 to 23,000. The curves, when normalized with respect to supply conditions, showed control port characteristics which were essentially independent of Reynolds number. Katz[4-50] and Krulewich[4-86] have shown similar input characteristics. Katz also has shown the effects of parameter changes such as supply pressure and dimensions on the input characteristic curves.

For staging, the output characteristics of the driving amplifier must be known. Typical curves are shown in Figure 4.38, which neglect cross-coupling effects of the output ports (for this assumption to be reasonable, a flow bleed must be present). Furthermore, effects of changes of the control pressures are neglected, or alternatively the control characteristics are held constant. The characteristic curve of the "inactive" port is also shown (the active port is the output port on which the jet is impinging). A criterion for staging is illustrated in Figure 4.39. This criterion is similar to one described in reference 4-86, and is one version of several described in reference[4-50]. The output characteristics of the driving element are shown superimposed on the input characteristics of the driven unit. The output curve must enclose the switching point for switching to occur. Reference[4-50] also illustrates a method of determining the switching requirements when more than one amplifier is switched by a single driver. The flow requirements are summed for each driven element and a total flow vs. pressure input curve is obtained which must be matched to the driver output. Katz also shows the effect of parameter changes, such as supply pressure and receiver area, on the output characteristics of an element. Sher[4-56] uses a method of staging based on steady state characteristics that is similar to that described above, except pressure is normalized in terms of a load factor. Dexter[4-54] describes a staging or matching technique for a shift register, using an "admittance" Q^2/p as one of the steady state parameters. The flip-flop and a non-bistable "TWIN AND" logic element (section 5) are cascaded to form the shift register circuit. Others have staged digital amplifiers without disclosing their staging criteria, such as Campagnuolo[4-68], who describes a three-stage digital amplifier with flow gains of 1500 to 2000.

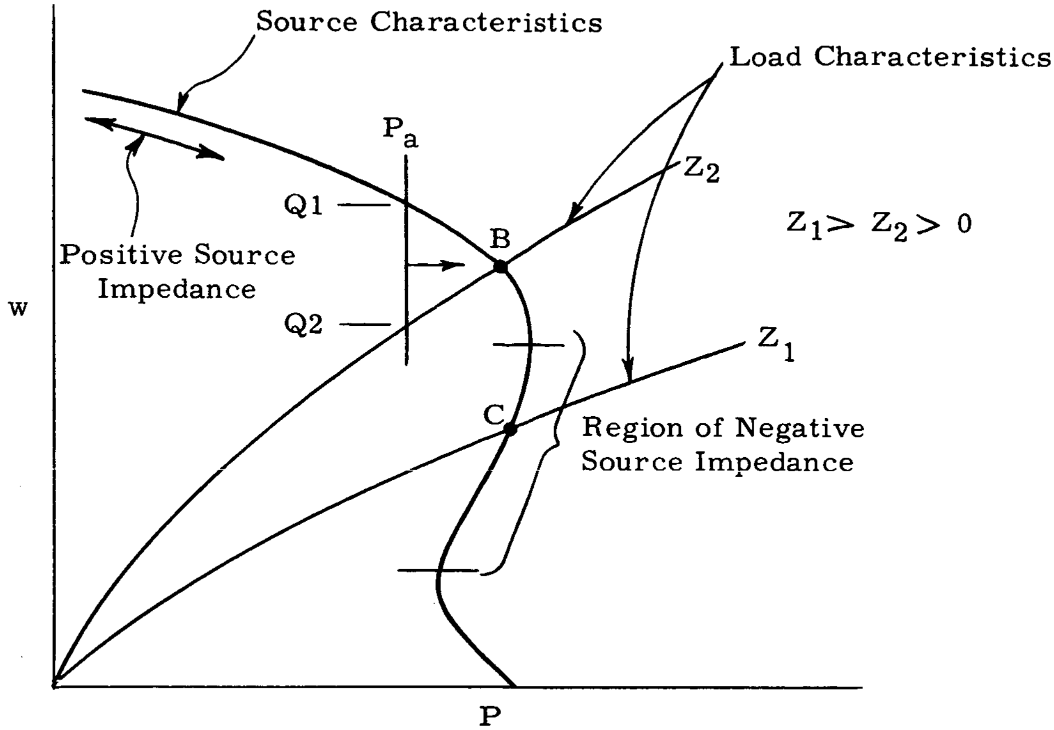


Figure 4. 33. Static Source - Load Matching.

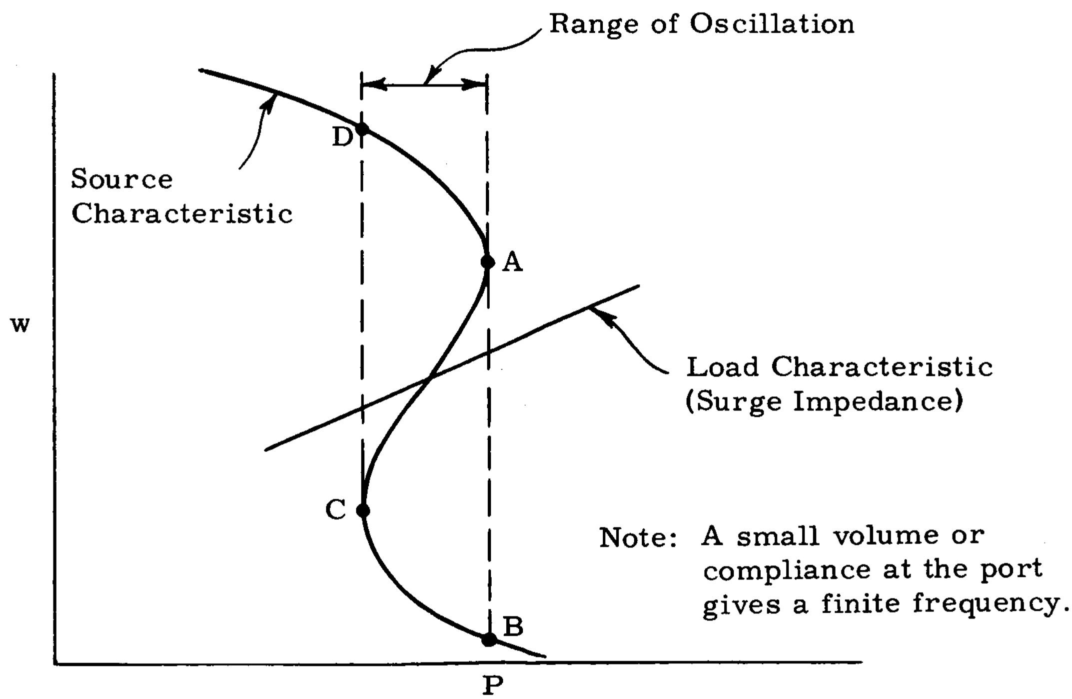
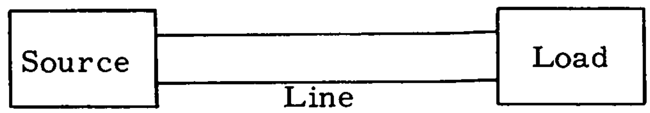


Figure 4. 34. Infinite Frequency Limit Cycle Oscillation.



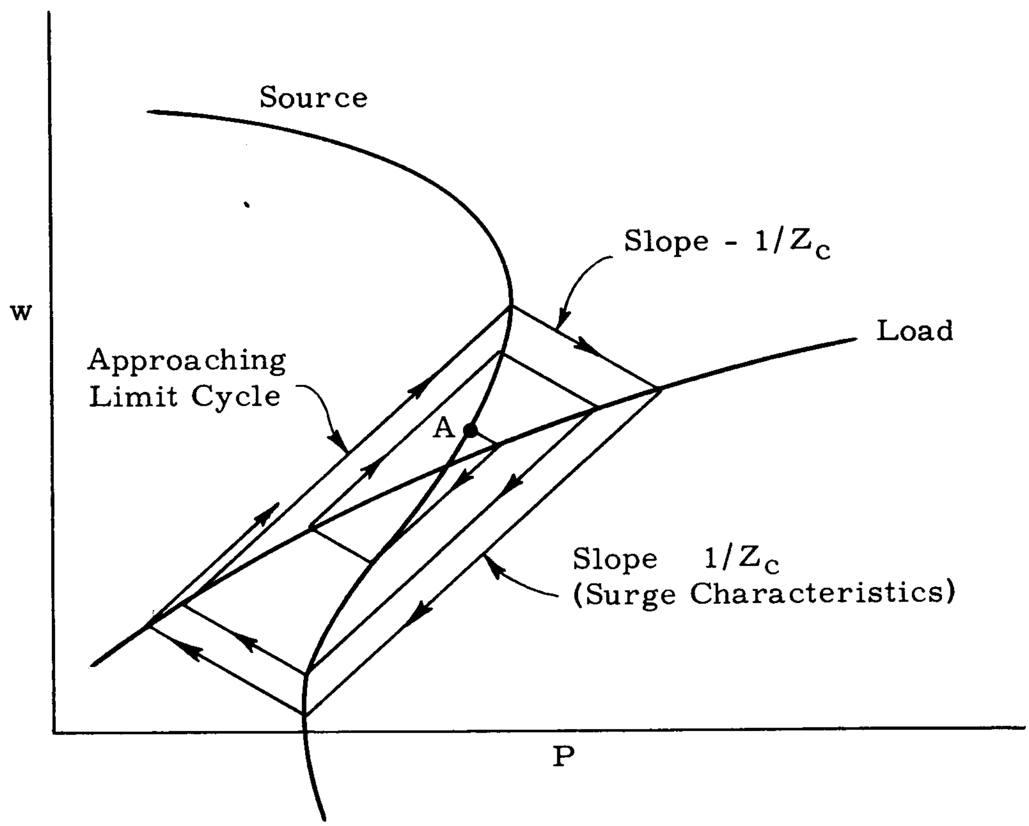


Figure 4. 35. Typical Wave Instability.

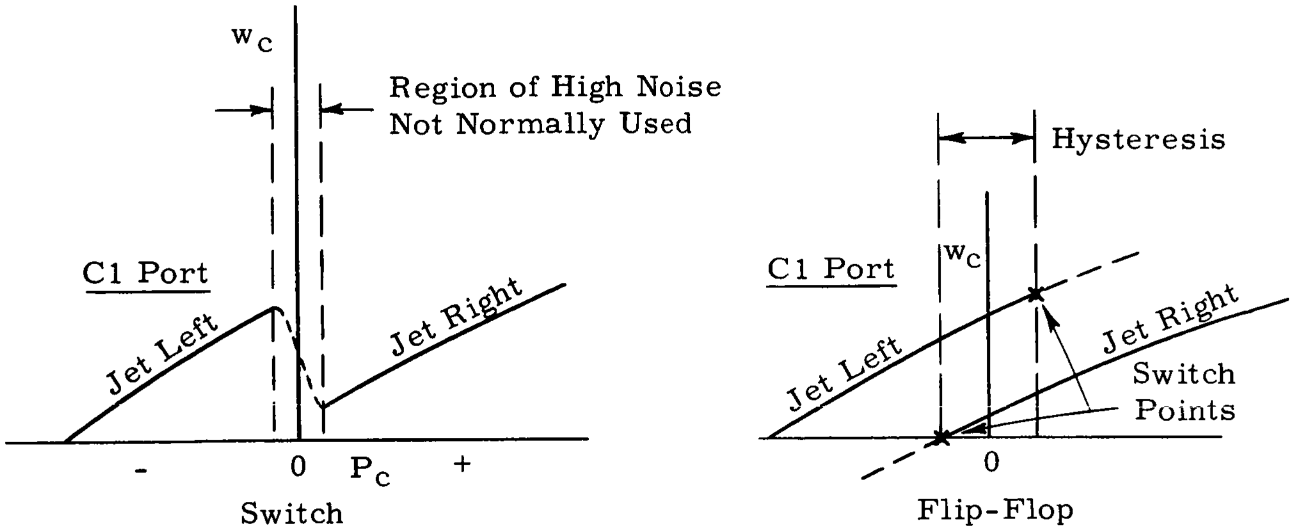


Figure 4. 36. Digital Amplifier Input Characteristics.

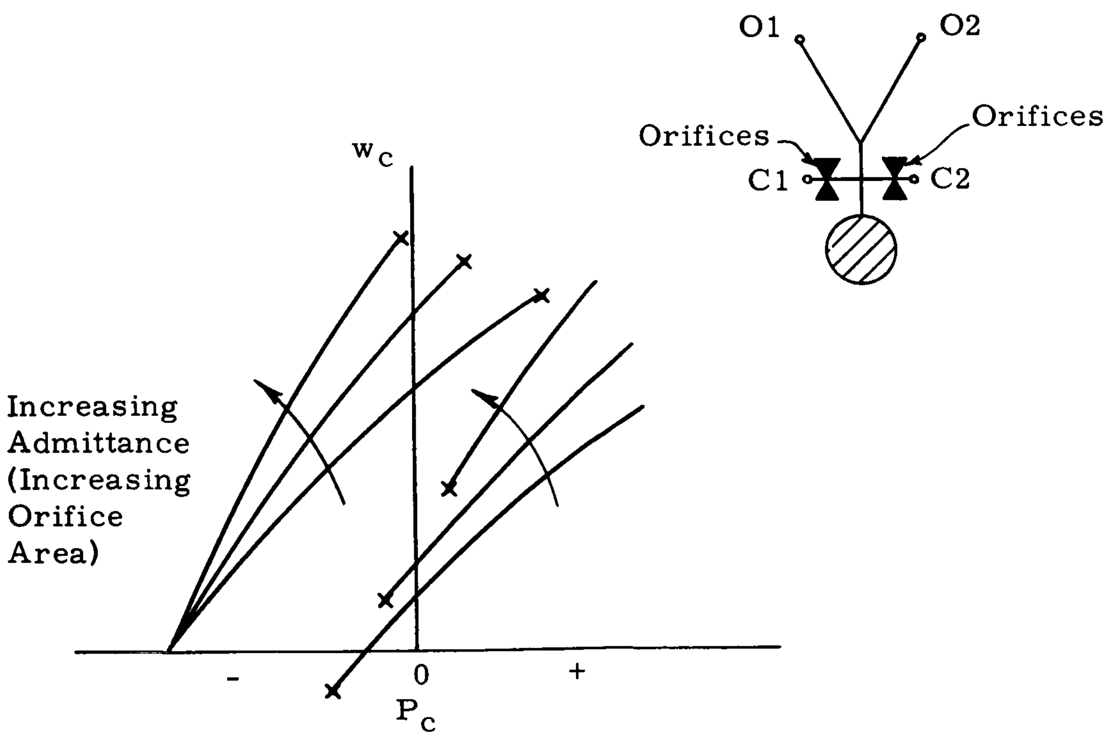


Figure 4. 37. Effect of Increasing Control Port Admittance.

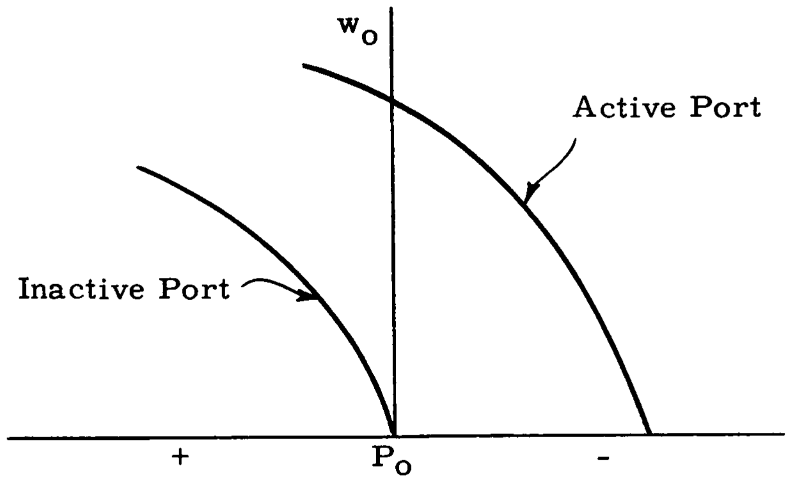


Figure 4. 38. Digital Amplifier - Typical Output Characteristic.

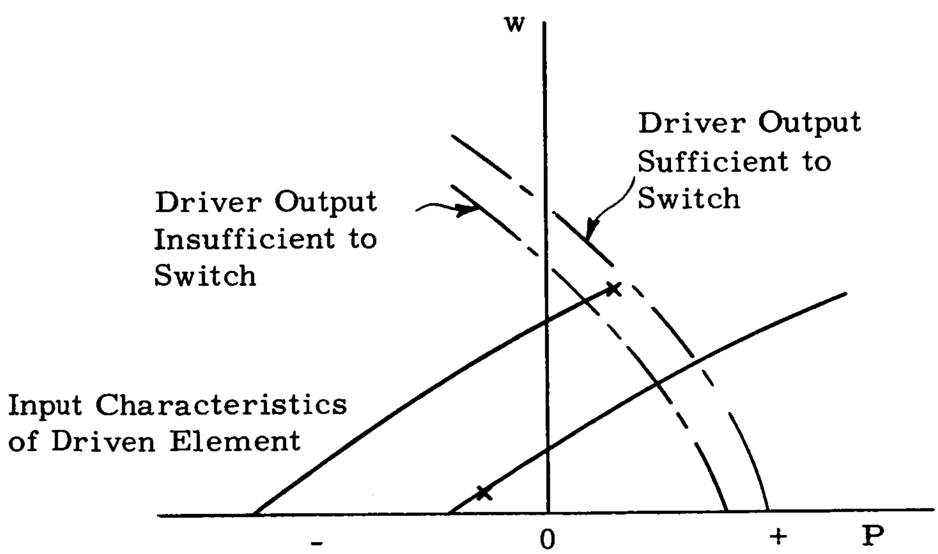


Figure 4. 39. Staging Criterion

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4-87 Forthmann, E., "Uber Turbulente Strahlausbrutung, Ing. Arch., Vol. 5, 1934, p. 42.

5.0 ELEMENTS

Fluid amplifier elements which are available commercially or are currently being used in experimental circuits are listed in this section. The intent in listing has been to include all known elements that are finished products, prototypes or at least considered "standard" elements within a laboratory. The "tube manual" method of presentation permits a rapid comparison of elements so that a general impression of configurations and performance can be obtained. The listing is complete only to the extent of available information; many of the performance data were unavailable and some concepts and geometries could not be included because of proprietary interests. It is believed, however, that the available information is more than adequate to judge the general performance and developmental status of "Fluid Amplifiers". Some elements are also listed in Vol. III (classified).

5.1 Definitions

Many fluid amplifiers have design refinements to improve performance. These refinements are defined and discussed below. Other comments are included to aid in interpreting the information presented.

Vents

Vents, (also known as bleeds, drains, exhausts) are flow channels from the interaction region or from the receivers to the ambient. In digital elements they are generally used to decrease load sensitivity, improve stability and to minimize coupling between the output ports. Typical locations range from the interaction region up to the output ports as shown in Figure 5.1. If venting ports are located external to the element they are defined as bleeds. The function of vents and bleeds is to vent the "excess" flow delivered by the power nozzle, not delivered to the load.

Vent geometry in proportional amplifiers is generally similar to that shown in Figure 5.2. A center vent is sometimes used in addition. Vents are used in proportional amplifiers to duct excess flow and improve stability. Elements which are vented to the ambient are identified as "open" amplifiers. Elements with no vents or with internally interconnected vents are known as "closed" amplifiers. If an amplifier were used to drive a load such as an actuator, it would require vents to vent the power flow when load flow is zero.

Cusp

A cusp or notch at the tip of the splitter is often used in digital elements to improve stability. The circulating flow produced by the cusp produces an "over-center" or toggle characteristic. Typical configurations are shown in Figure 5.1.

Power Nozzle Dimensions

The dimensions refer to the cross-sectional width and height of the nozzle if rectangular or the diameter for circular cross-section nozzles.

References

Two types of references may be identified. One identifies the source of information which is located at the end of section 5. The Report Section reference indicates where principles of operation or other information are provided within this report.

Symbols

The abbreviation N.A. indicates information was not available. An "X" after "gas" or "liquid" under "Media" indicates the fluid for which the element was designed.

Data

Where available, typical data is included after each of the standard forms. All information on operating conditions for the test which were provided are given on the data sheet.

5.2 General Performance Summary

A review of the data for the elements listed in this section and additional information obtained from personal contacts yields the following general picture of fluid amplifier performance:

Gain

Typical pressure and flow gains range from 5 to 20, and power gains of 100 to 200 are typical for digital and beam deflector proportional amplifiers. Pressure gains as high as 200 are claimed by Johnson Service Co. and Marquardt for their proprietary amplifiers. The Marquardt amplifier is known to utilize a vortex. Noise apparently is quite low. Giannini has revealed an amplifier with a flow gain of 200 with low noise. Vortex amplifier gains have been reported to be as high as 5000. Since vortex amplifier characteristics can be made to range from proportional to digital operation, a region of infinite gain must exist. The practicability of using these gains then depends on noise level in the amplifier.

Response

Typical response values (45^{o} phase lag) for proportional beam deflector amplifiers seem to be about 1000 to 1500 cps based on reported data. Bowles has reported operation of a 100 KC oscillator. Response data on vortex amplifiers is not available. The response of wall attachment digital amplifiers generally has been reported as 0.3 millisecond up to 1 to 2 milliseconds. Methods of obtaining response by extrapolation of data have indicated ultimate response of about 0.1 millisecond. It is not well understood if the method is representative of operation in a typical circuit (see section 4.5).

Environmental Capabilities

One of the most attractive features of fluid amplifiers is their potential environmental capabilities. Some measurements have given an indication of these capabilities. Bendix has operated digital and proportional beam deflector amplifiers and vortex amplifiers at temperatures up to 1400^{o} F. and observed the expected performance. General Electric has operated vortex amplifiers on liquid N_2 and obtained predicted characeristics. General Electric has subjected a flip-flop to vibration environments up to 5000 cps and 50 g with no loss in memory. Vibration and acceleration testing are in progress at Minneapolis-Honeywell Regulator Company.

Size

The smallest fluid amplifier which has been known to be operated has a nozzle width of 0.002 inches (Stanford Research Institute). The largest elements available are flow diverters (digital and proportional) for 6" diameter pipe lines (Moore Products Co.).

Fluids

The fluid used most predominantly is air. Considerable work has been carried out with hydraulic fluids at Minneapolis-Honeywell Regulator Company. Water has also been used and some data for a digital amplifier has been presented by General Electric. The large diverter valves (proportional and digital) are designed for use with liquids (such as hot caustic solutions).

Pressure

Supply pressures have ranged from as low as 0.5" propane head (Minneapolis-Honeywell) up to pressures which provide Mach numbers of 2 to 3. Closed fluid amplifiers can be run at elevated pressure levels with a relatively small drop across the power nozzle (Moore Products). For example, the supply pressure level may be 1000 psi, and the pressure in the interaction region 900 psi, providing a 100 psi drop across the power nozzle.

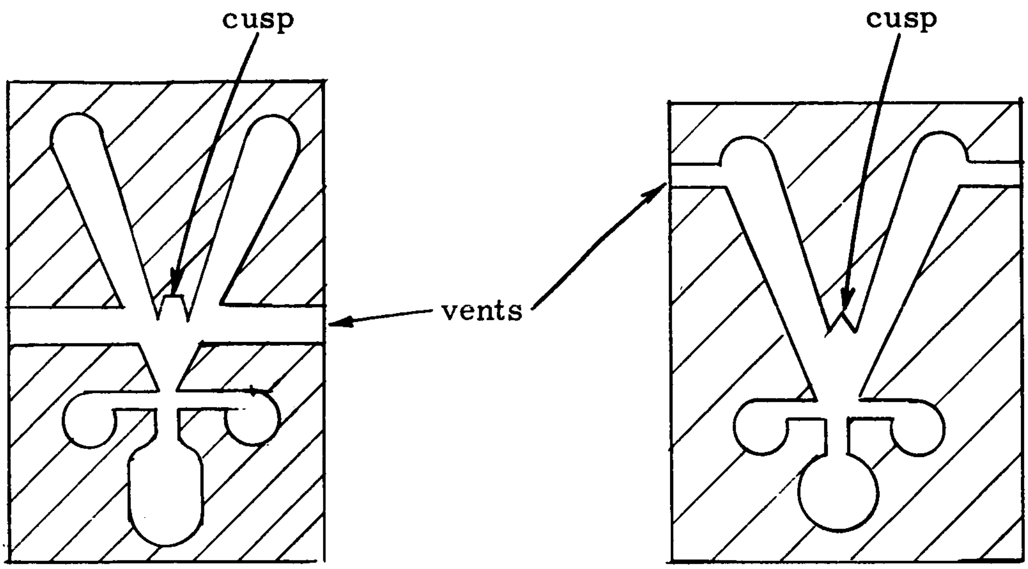


Figure 5.1 Vents and Cusps in Digital Elements.

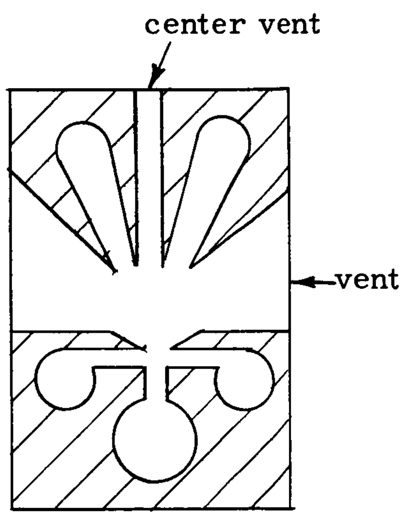


Figure 5.2 Vents in a Proportional Amplifier.

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** Flip-Flop

Manufacturer Bendix **Model Number** N.A.

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas X **Liquid** N.A.
Power Nozzle - Number 1 **Size (inches)** N.A.
Control Ports - Number 2
Cusps - Number 0
Vents - Number 2
Output Ports - Number 2
Special Features

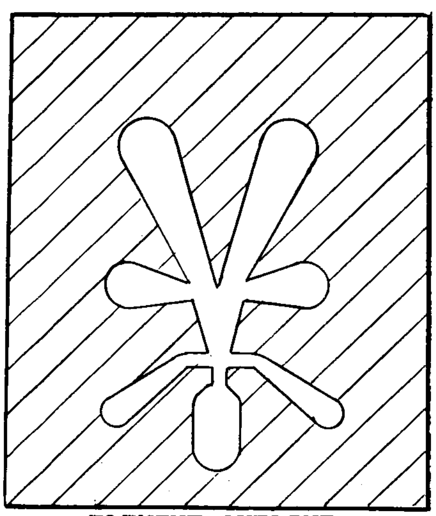
Response N.A.

Operating Phenomena Wall Attachment

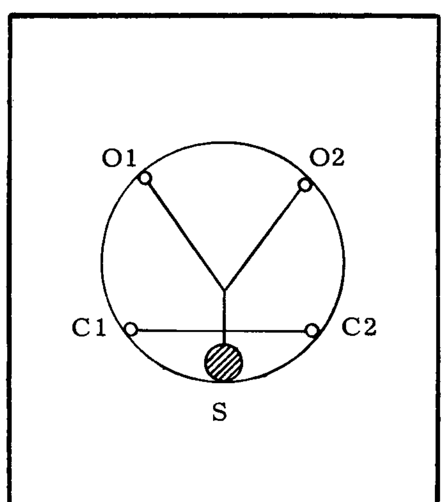
References 5-24 **Report Section** 3.1, 4.2

Remarks:

Has been operated over temperature range of 70°F to 1400°F



ELEMENT OUTLINE



SCHEMATIC DIAGRAM

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** Flip-Flop

Manufacturer Bowles Engineering Corp. **Model Number** Catalog No. 0246

Physical Description

Overall Size (inches) 1 13/16 x 1 9/16 x 3/8
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** N.A.
Control Ports - Number 2
Cusps - Number 0
Vents - Number 0
Output Ports - Number 2
Special Features

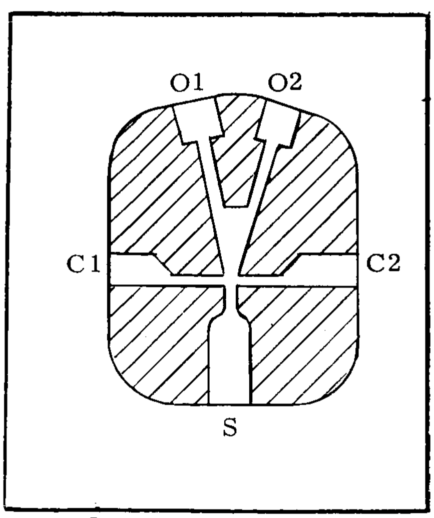
Response N.A.

Operating Phenomena Wall Attachment

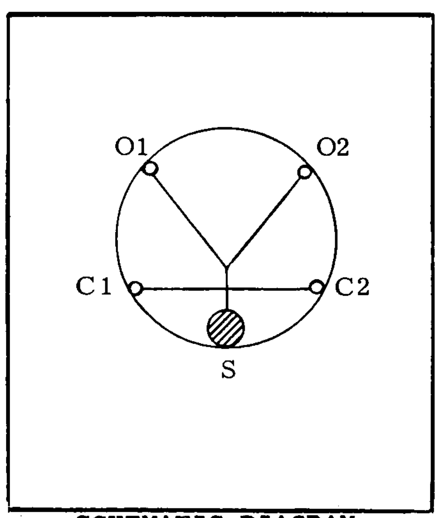
References 5-3 **Report Section** 3.1, 4.2

Remarks:

See Attached Data Sheet



ELEMENT OUTLINE



SCHEMATIC DIAGRAM

<u>DATA SHEET</u>

<u>Typical Operation:</u>

With outputs near atmospheric pressure and output from 01 before switching. All pressures are gauge pressures.

	AIR				WATER				
Supply Pressure, p_1	2		10		5		30		lb/in^2
Power Jet Flow Q_1	0.54		0.80		.038		.090		ft^3/min
Blocked Pressure, p_2 -Set	-0.4^{o}	$-0.4^{\square}$	-1.6^{o}	$-1.5^{\square}$	-2.1^{o}	-2.1^{*}	-7.4^{o}	-7.4^{*}	lb/in^2
p_5-Reset	-0.1	0	-0.3	-0.1	-1.0	-1.0	-2.1	-2.1	lb/in^2
Switching Pressure, p_2-Set	0.2	0.2	1.0	0.7	-0.5	-0.5	2.0	1.3	lb/in^2
p_5-Reset	-0.1	-0.1	-0.3	-0.3	-1.3	-1.0	-2.4	-2.0	lb/in^2
Pressure Ratio, $p_1 / \Delta p_2$	3.3	3.3	3.9	4.5	3.1	3.1	3.2	3.4	

o With no load

□ With orifice load on output giving 1 ft^3/min at 1 lb/in^2 drop.

* With 0.1" diam. orifice load on output.

Δp_2 denotes change in set pressure necessary to switch.

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** Flip-Flop

Manufacturer Bowles Engineering Corp. **Model Number** Catalog No. 0134

Physical Description

Overall Size (inches) 2 7/8 x 2 x 7/8
Working Fluids - Gas X **Liquid**
Power Nozzle - Number 1 **Size (inches)** N.A.
Control Ports - Number 2
Cusps - Number 0
Vents - Number 0
Output Ports - Number 2
Special Features Magnetic piston which operates reed switch for electrical readout.

Response N.A.

Operating Phenomena Wall Attachment

References 5-3 **Report Section** 3.1, 4.2, 6.4.2

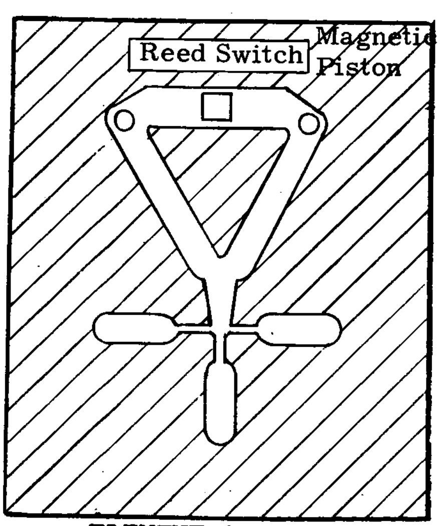
Remarks:

1.) Magnetic piston in cylinder between output ports actuates a reed switch to provide an electrical output.

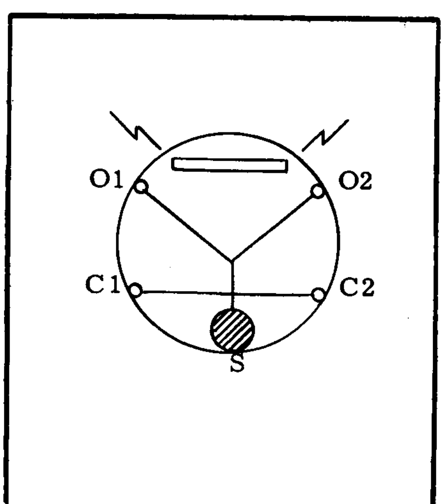
2.) Pneumatic output also available.

3.) Design Supply pressure 3 to 7 psig.

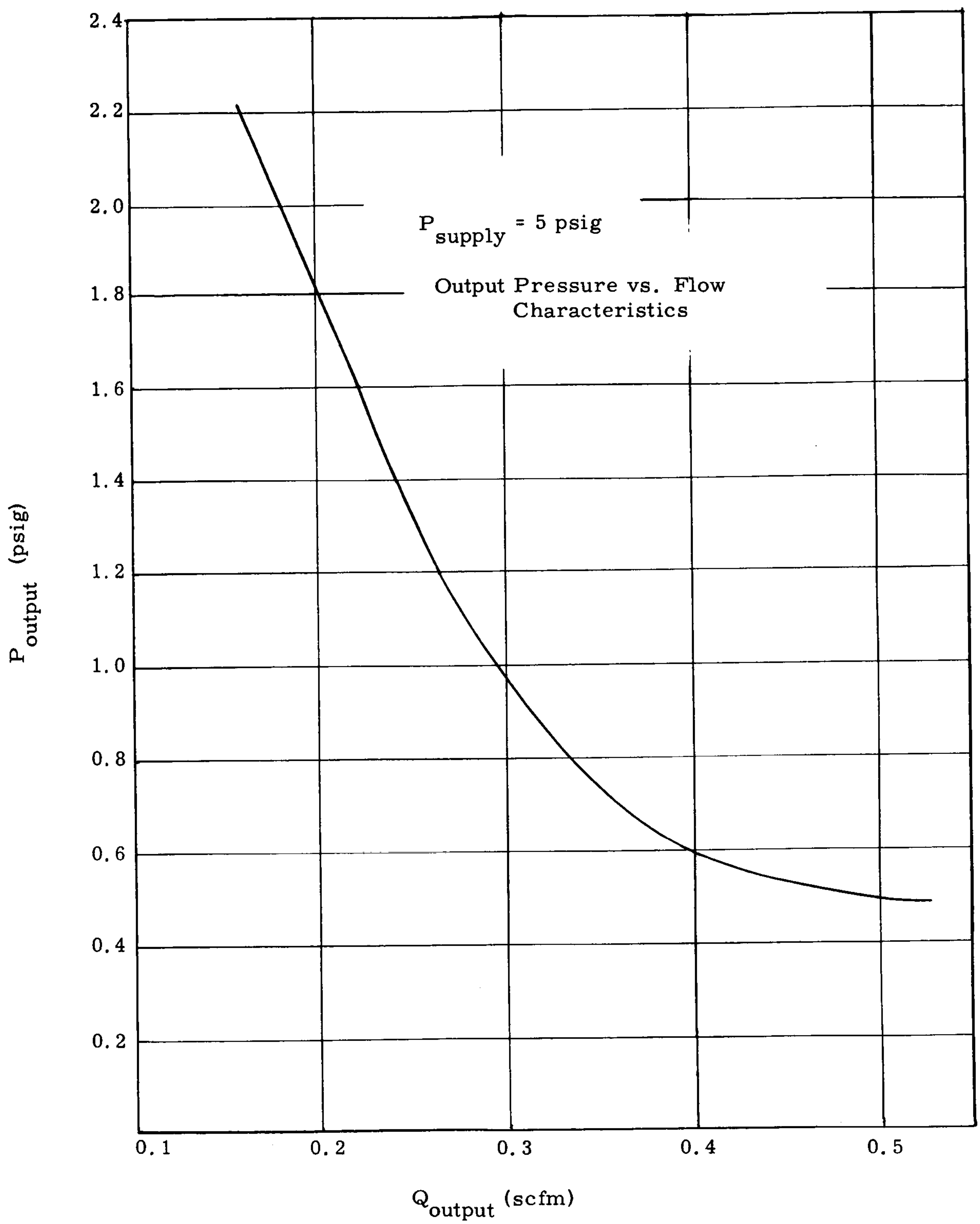
4.) See attached data sheet.



ELEMENT OUTLINE



SCHEMATIC DIAGRAM



2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
P output (psig)
P_{supply} = 5 psig
Output Pressure vs. Flow Characteristics
0.1
0.2
0.3
0.4
0.5
Q_{output} (scfm)

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** Flip-Flop

Manufacturer Corning Glass Works **Model Number** Unit 2041

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** N.A.
Control Ports - Number 2
Cusps - Number 0
Vents - Number 2
Output Ports - Number 2
Special Features

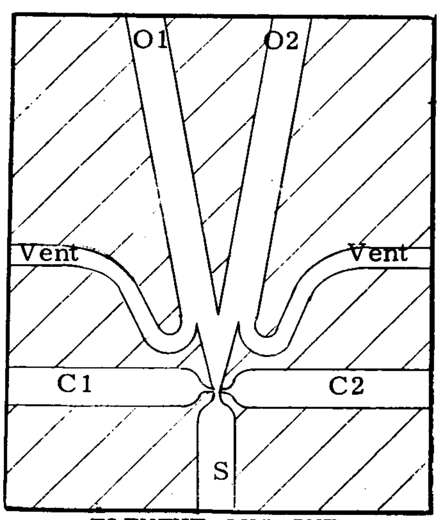
Response N.A.

Operating Phenomena Wall Attachment

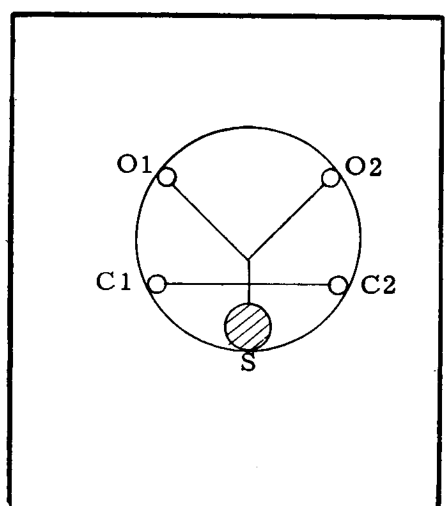
References 5-6 **Report Section** 3.1, 4.2, 8.2.4

Remarks:

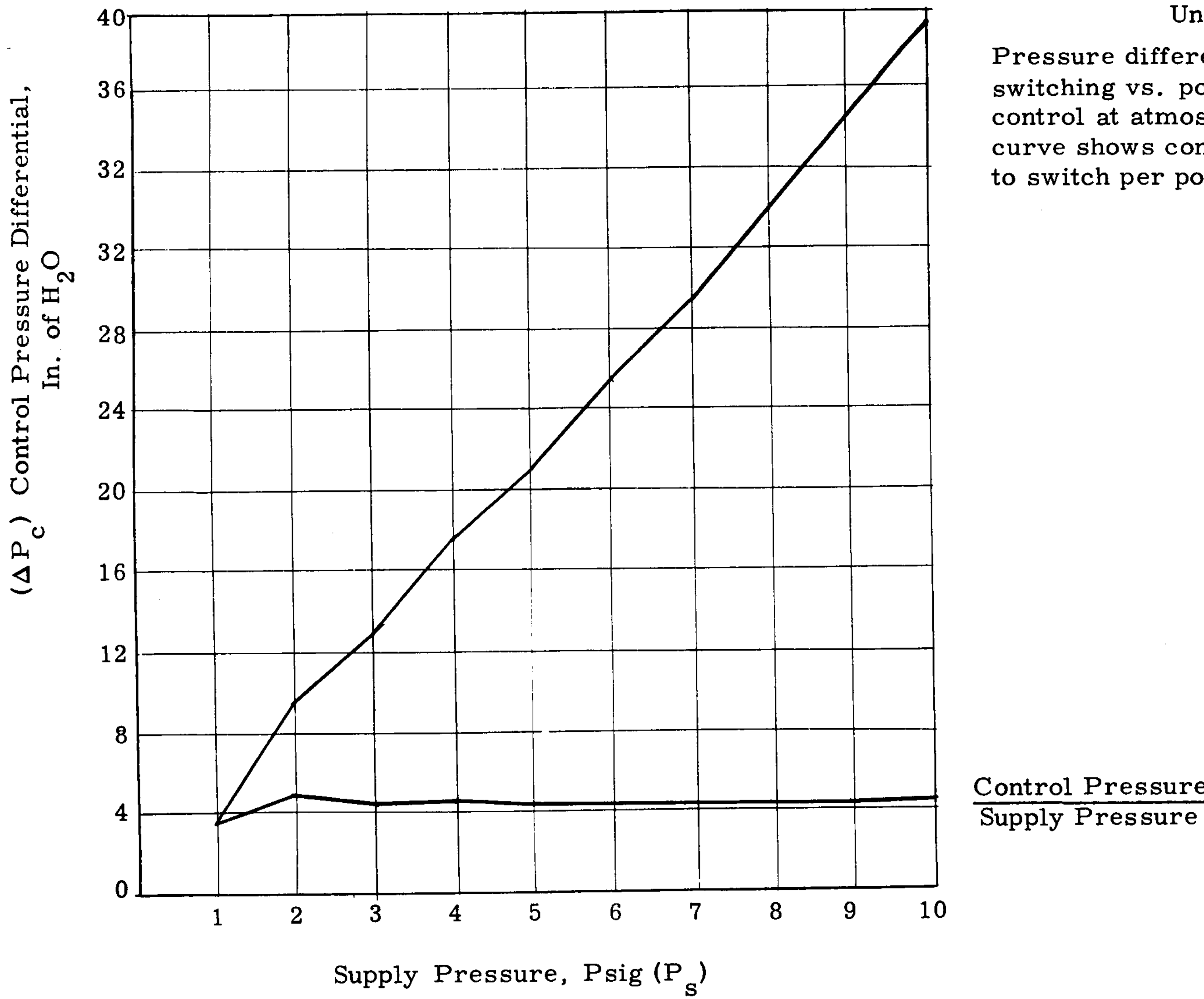
See Attached Data Sheet



ELEMENT OUTLINE



SCHEMATIC DIAGRAM



Unit 2041

Pressure differential required for switching vs. power jet press. - Bias control at atmospheric press. - Lower curve shows control press. required to switch per pound of supply pressure.

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** Flip-Flop

Manufacturer General Electric Co. (ATL) **Model Number** S44-2

Physical Description

Overall Size (inches) Approx. 1 7/8 x 1 1/2 x 3/8
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** .040 x .040
Control Ports - Number 2
Cusps - Number 1
Vents - Number 2
Output Ports - Number 2
Special Features

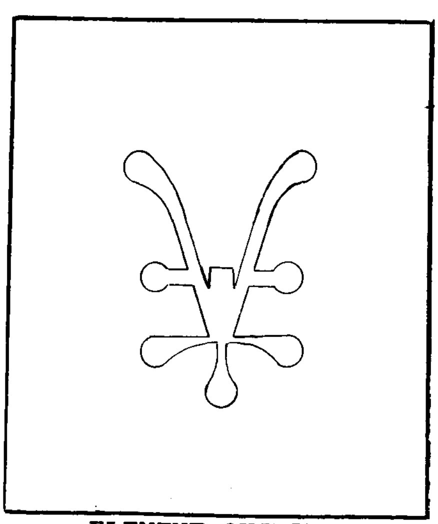
Response N.A.

Operating Phenomena Wall Attachment

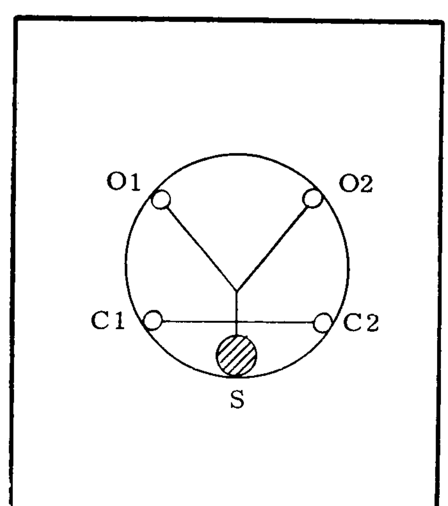
References 5-14 **Report Section** 3.1, 4.2

Remarks:

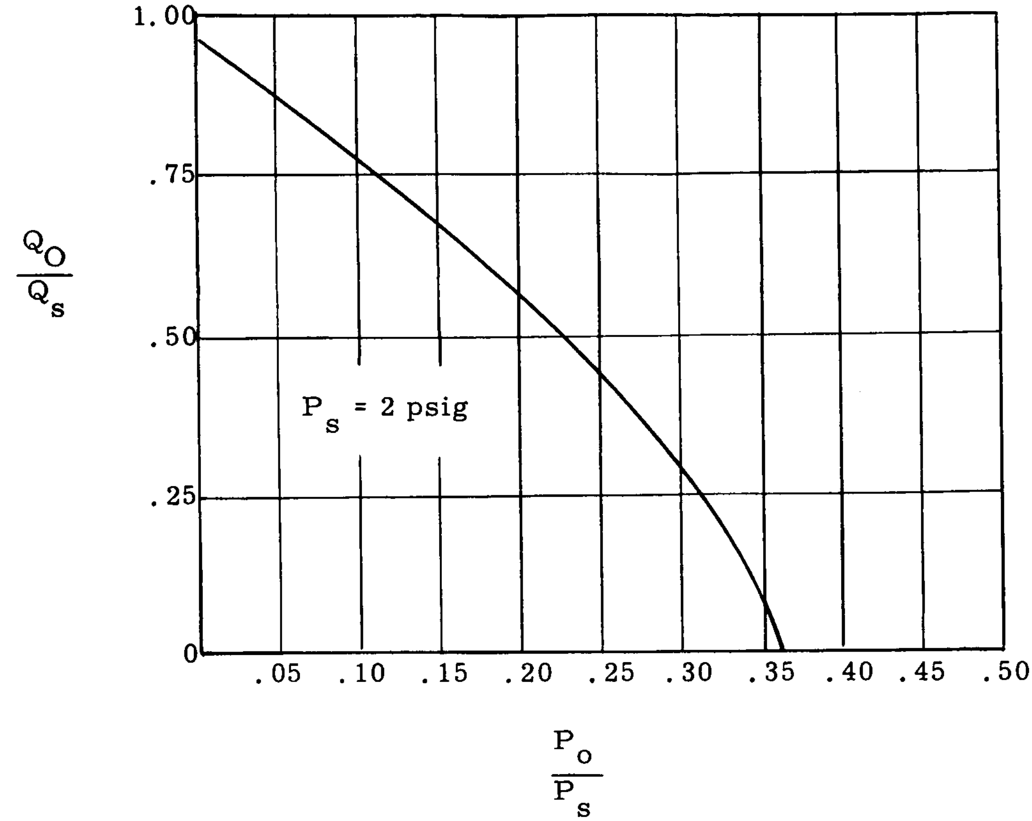
See Attached Data Sheet



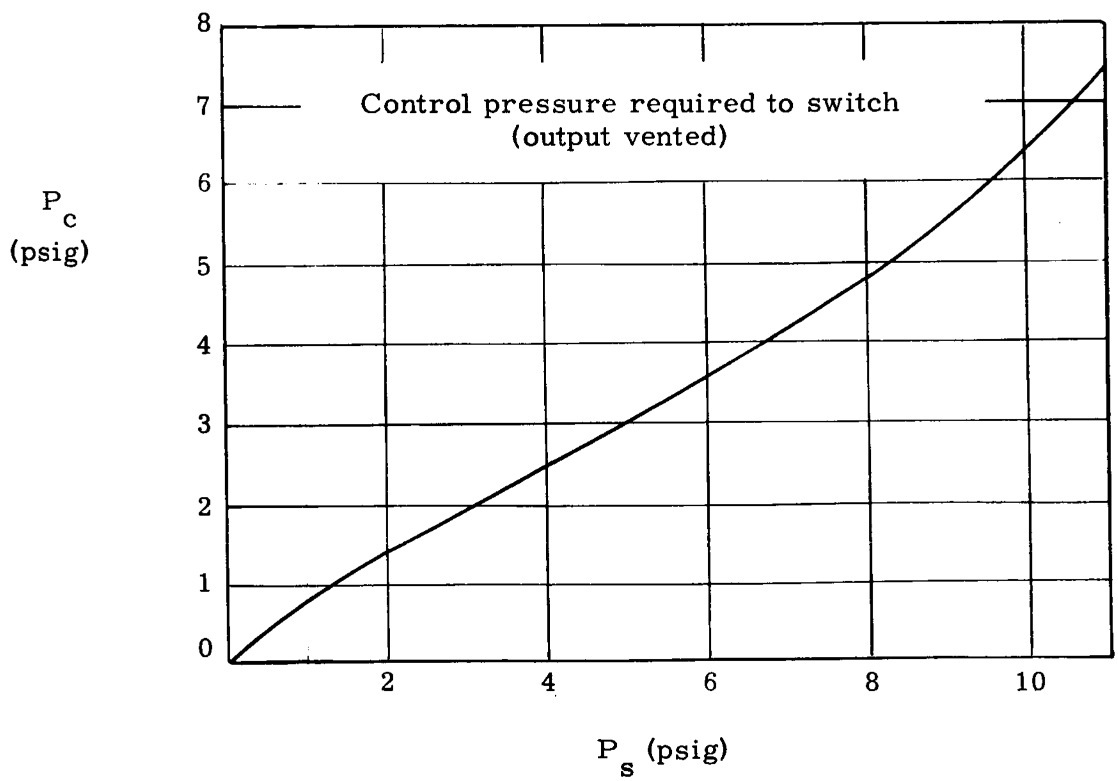
ELEMENT OUTLINE



SCHEMATIC DIAGRAM



1.00
.75
.50
.25
0
$\frac{Q_O}{Q_s}$
P_s = 2 psig
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
$\frac{P_o}{P_s}$



8
7
6
5
4
3
2
1
0
P_c (psig)
Control pressure required to switch (output vented)
2
4
6
8
10
P_s (psig)

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** Flip-Flop

Manufacturer General Electric Co. (Comp. Dept) **Model Number** N.A.

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** N.A.
Control Ports - Number 4
Cusps - Number 1
Vents - Number 2
Output Ports - Number 2
Special Features Dual Push-Pull Input

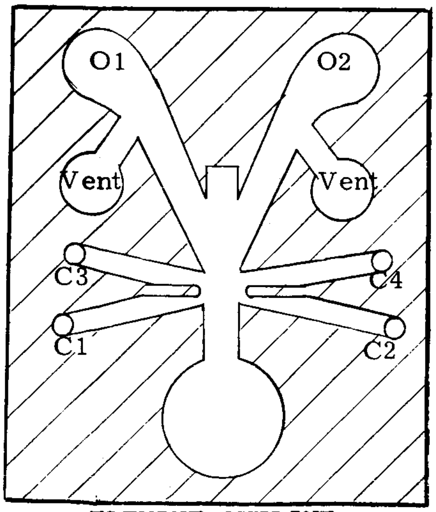
Response N.A.

Operating Phenomena Wall - Attachment

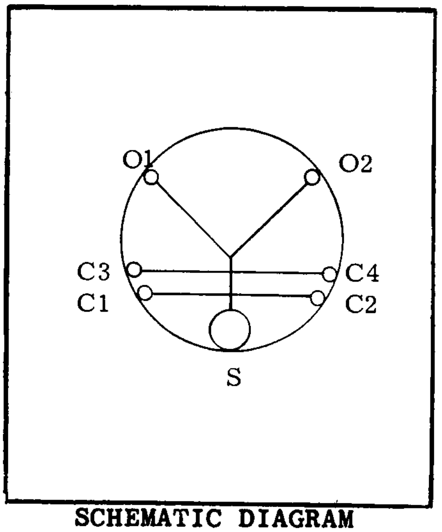
References 5-8 **Report Section** 3.1, 4.2

Remarks:

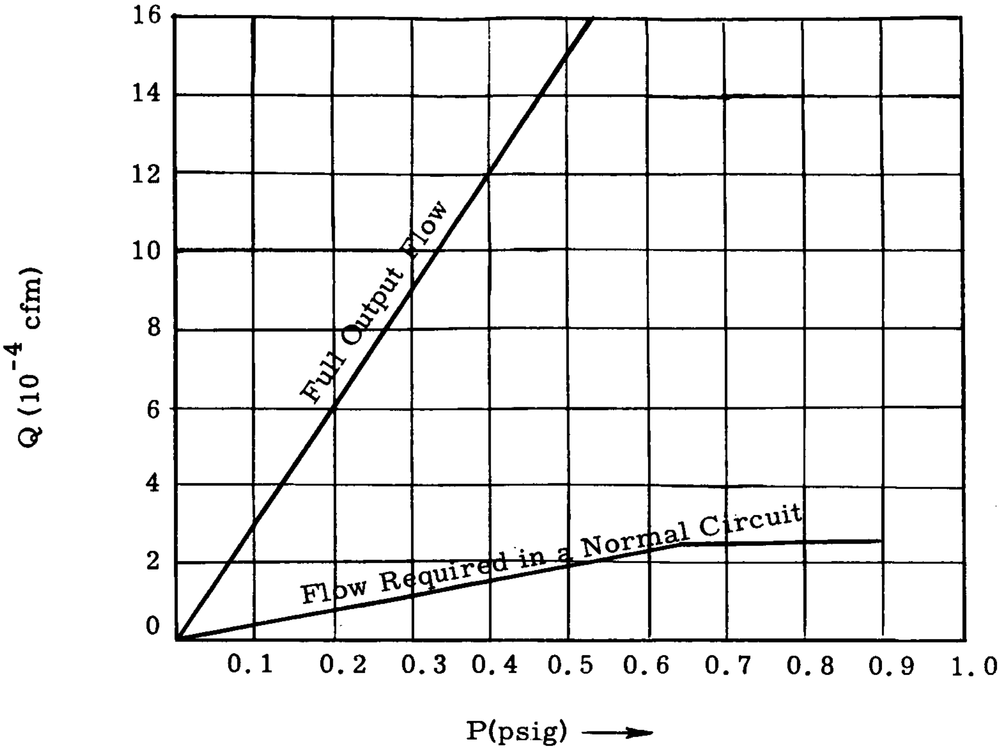
See Attached Data Sheet

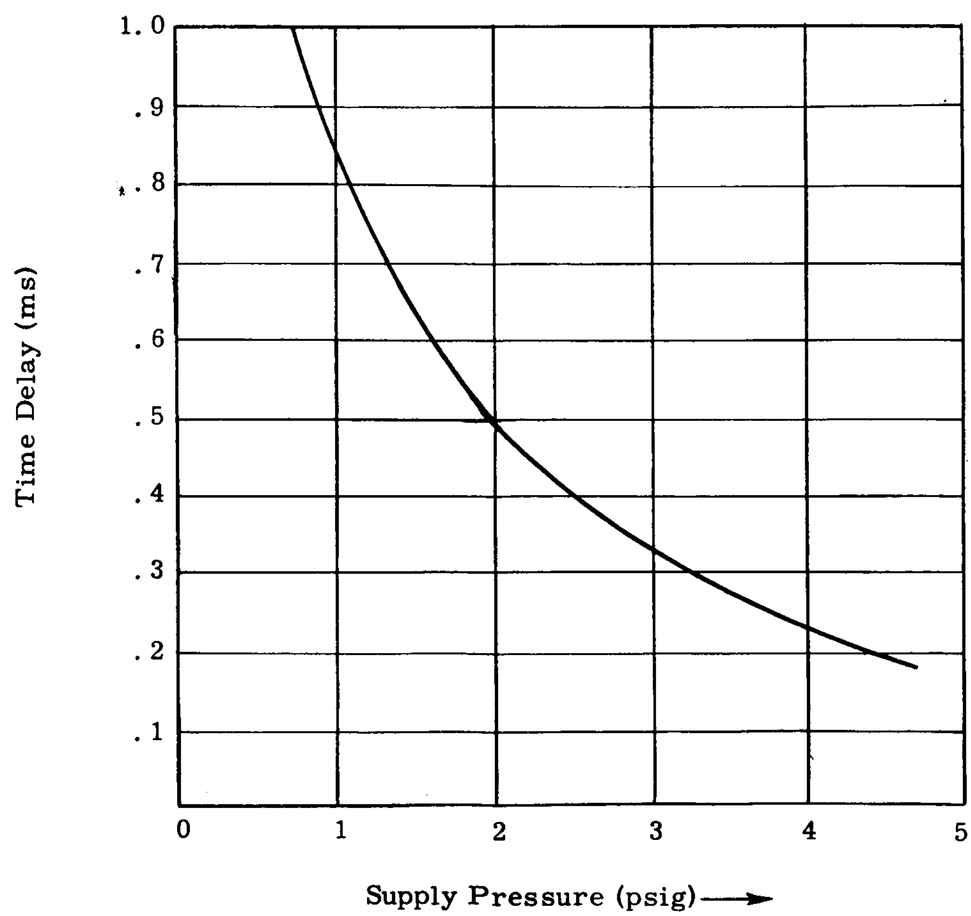


ELEMENT OUTLINE



SCHEMATIC DIAGRAM


16
14
12
10
8
6
4
2
0
Q (10^{-4} cfm)
Full Output Flow
Flow Required in a Normal Circuit
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
P(psig)


1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
Time Delay (ms)
0
1
2
3
4
5
Supply Pressure (psig)

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** Flip-Flop

Manufacturer HDL **Model Number** N.A.

Physical Description

Overall Size (inches) ______
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** 0.031W x 0.093
Control Ports - Number 2
Cusps - Number 1
Vents - Number 2
Output Ports - Number 2
Special Features ______

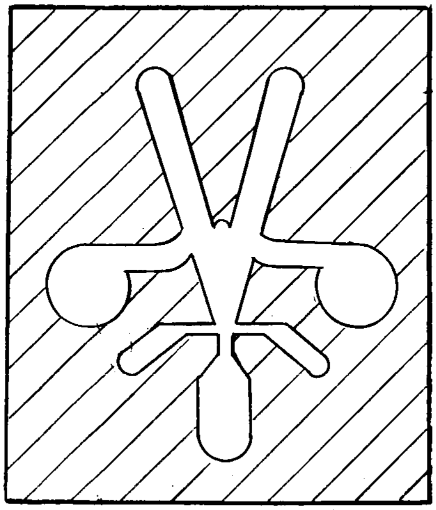
Response ______

Operating Phenomena Wall Attachment

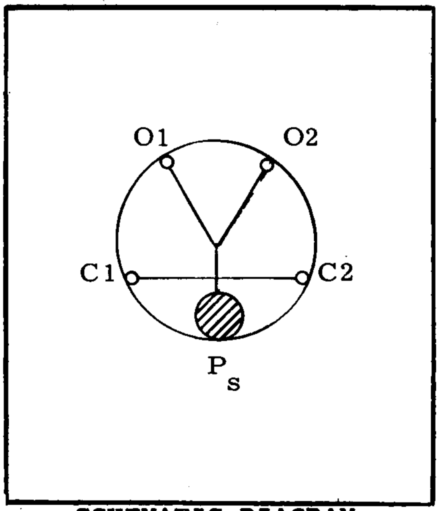
References 5-15 **Report Section** 3.1, 4.2

Remarks:

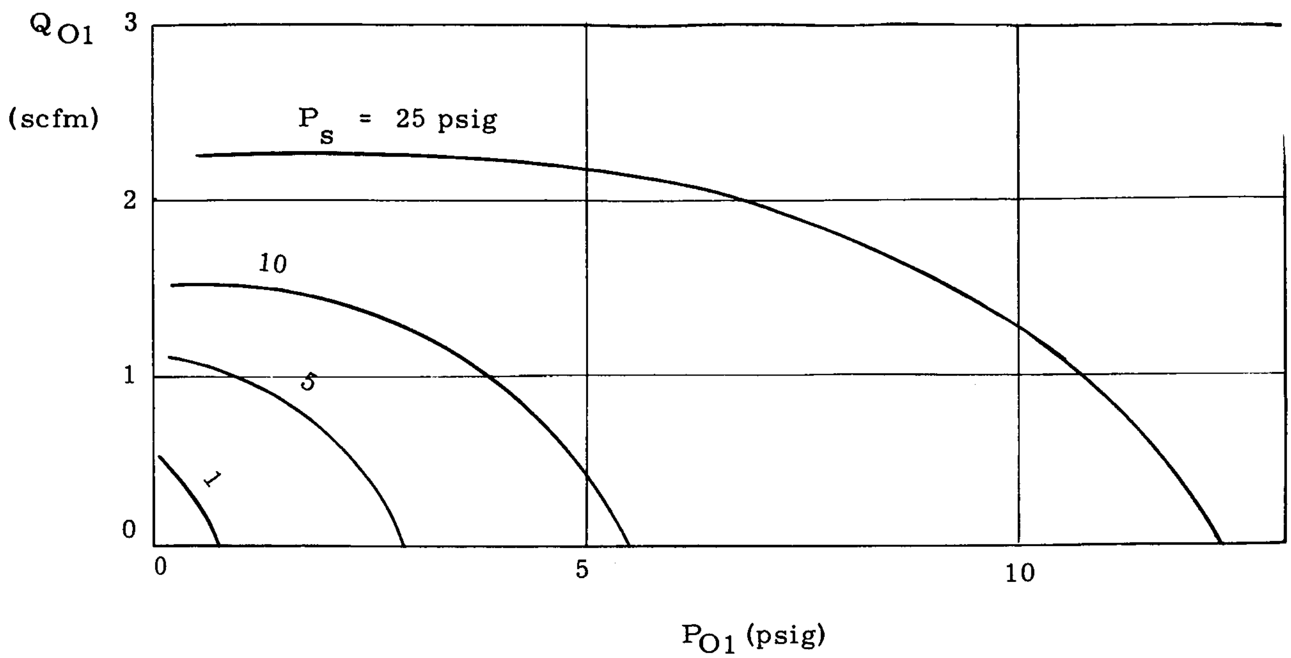
See Attached Data Sheet



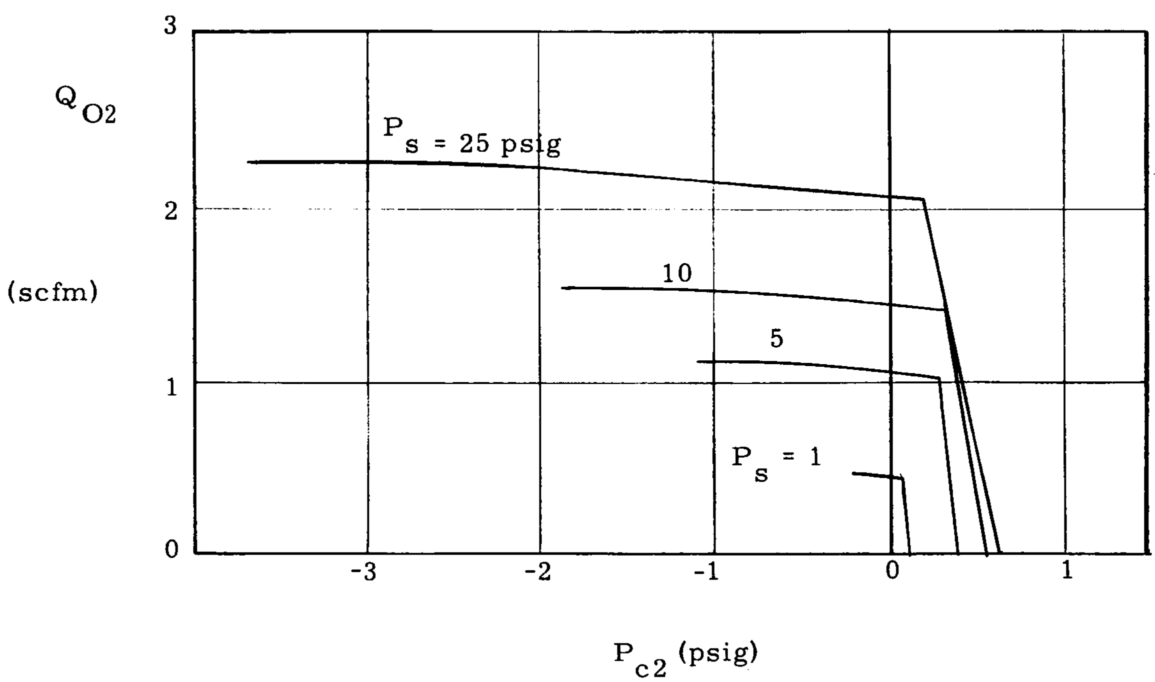
ELEMENT OUTLINE



SCHEMATIC DIAGRAM



Output Characteristics



Switching Characteristics

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** Switch

Manufacturer Bowles Engineering Corp. **Model Number** Catalog No. 0247

Physical Description

Overall Size (inches) 1 17/32 x 1 5/8 x 3/8
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** N.A.
Control Ports - Number 2
Cusps - Number 0
Vents - Number 0
Output Ports - Number 2
Special Features

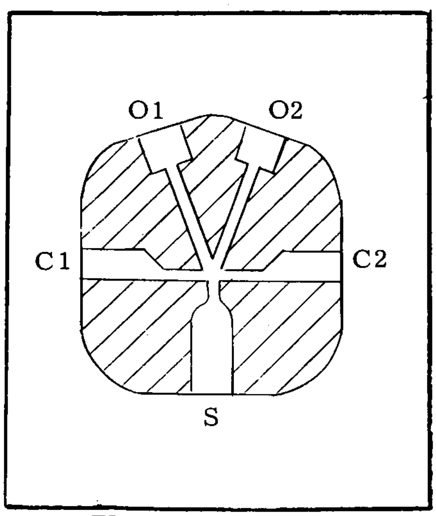
Response N.A.

Operating Phenomena Wall Attachment

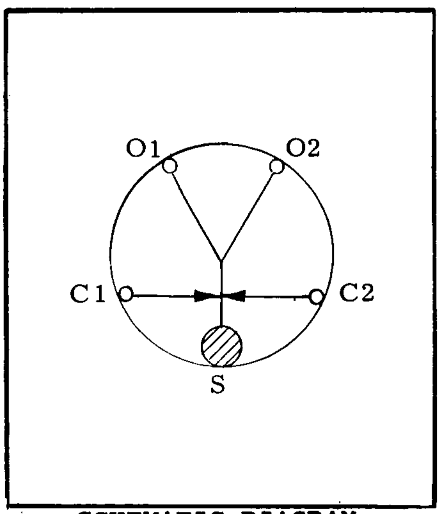
References 5-3 **Report Section** 3.1, 4.2

Remarks:

See Attached Data Sheet



ELEMENT OUTLINE



SCHEMATIC DIAGRAM

DATA SHEET

Typical Operation:

With outputs near atmospheric pressure and output from 01 before switching. All pressures are gauge pressures.

		AIR				WATER				
Supply Pressure, p_1		2		7		10		20		lb/in^2
Power Jet Flow, Q_1		0.25		0.37		.027		.037		ft^3/min
Blocked Pressure,	p_2 -Set	-0.5 o	-0.5 □	-1.6 o	-1.6 □	-4.4 o	-4.2 *	-7.0 o	-7.3 *	lb/in^2
	p_5-Reset	-0.1	-0.1	-0.3	-0.3	-1.9	-1.9	-2.5	-2.8	lb/in^2
Switching Pressure,	p_2-Set	-0.2	-0.3	-0.8	-1.0	-1.0	-3.4	-2.9	-5.4	lb/in^2
	p_5-Reset	-0.4	-0.5	-1.3	-1.4	-1.7	-3.8	-2.6	-6.0	lb/in^2
Pressure Ratio, $p_1/\Delta p_2$		6.7	10	8.7	12	2.9	12	3.9	11	

o With no load.
□ With orifice load on output giving 1 ft^3/min at 1 lb/in^2 drop.
* With 0.1" diam. orifice load on output.
Δp_2 denotes change in set pressure necessary to switch.

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** Switch

Manufacturer General Electric Co. (ATL) **Model Number** F-44-5

Physical Description

Overall Size (inches) Approx. 1 7/8 x 1 1/2 x 3/8
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** 0.040 x 0.040
Control Ports - Number 2
Cusps - Number 1
Vents - Number 2
Output Ports - Number 2
Special Features

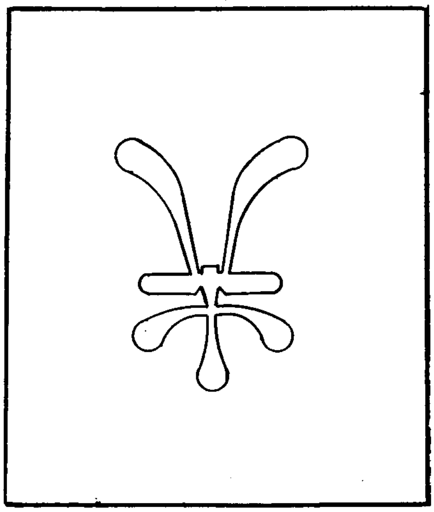
Response 0.50 millisec (includes acoustical and transport time)

Operating Phenomena Wall Attachment

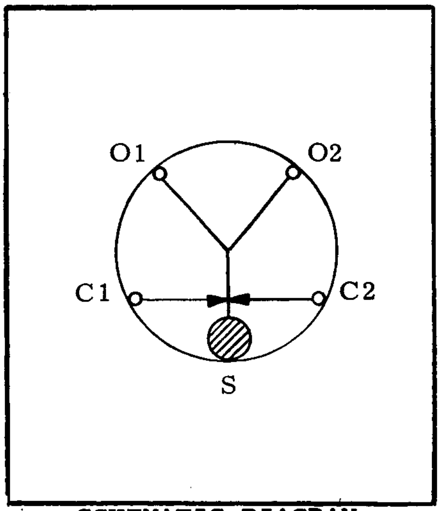
References 5-14 **Report Section** 3.1, 4.2

Remarks:

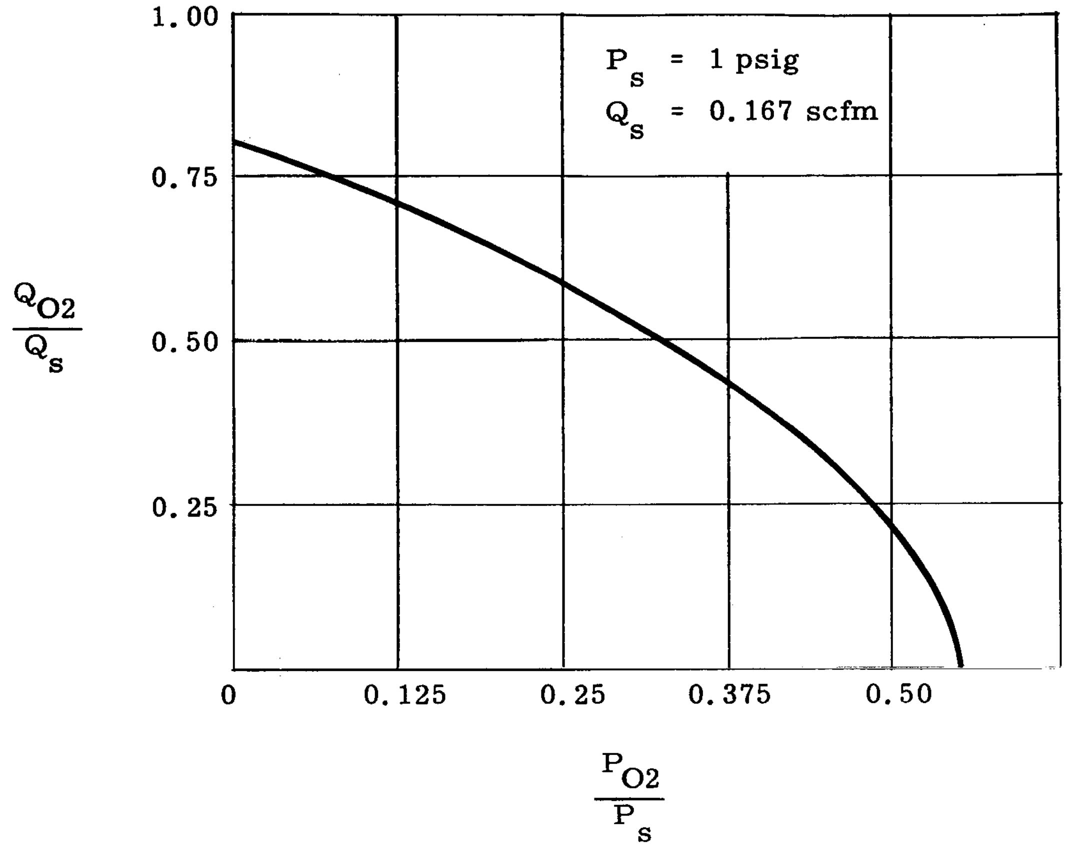
See Attached Data Sheet



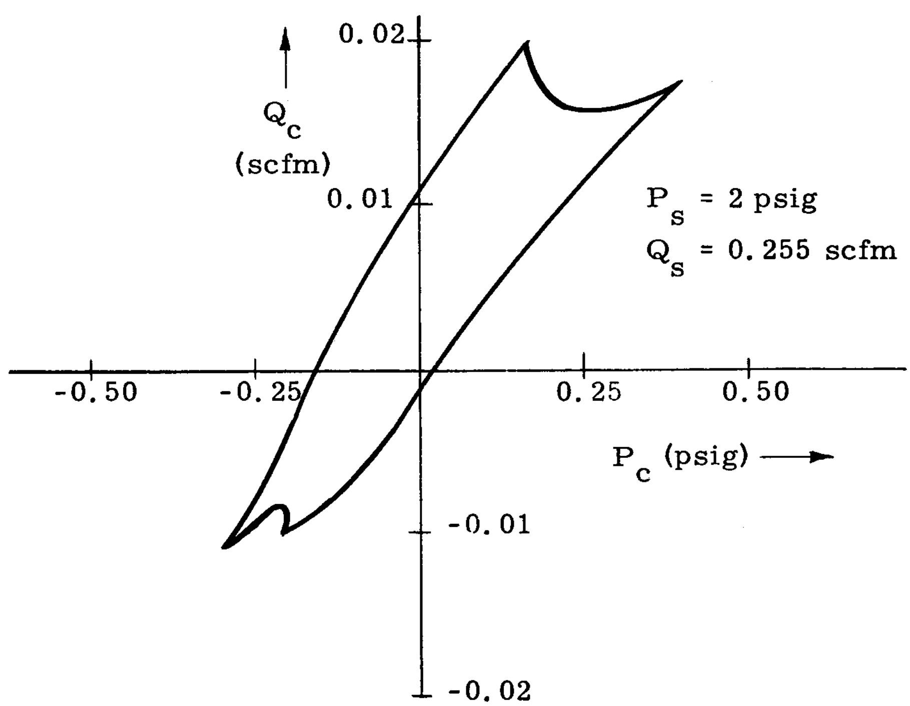
ELEMENT OUTLINE



SCHEMATIC DIAGRAM



P_s = 1 psig
Q_s = 0.167 scfm
1.00
0.75
0.50
0.25
$\frac{Q_{O2}}{Q_s}$
0
0.125
0.25
0.375
0.50
$\frac{P_{O2}}{P_s}$



Q_c (scfm)
0.02
0.01
-0.01
-0.02
-0.50
-0.25
0.25
0.50
P_c (psig)
P_s = 2 psig
Q_s = 0.255 scfm

FLUID ELEMENT DATA SHEET

Type of Element Digital

Function Switch (Flow Diverter)

Manufacturer Moore Products

Model Number (Several)

Physical Description

Overall Size (inches) Several Sizes
Working Fluids - Gas ____ **Liquid** X
Power Nozzle - Number 1 **Size (inches)** 1/2 to 6 Diam.
Control Ports - Number 2
Cusps - Number 0
Vents - Number 0
Output Ports - Number 2
Special Features ____

Response N.A.

Operating Phenomena Wall Attachment

References 5-12

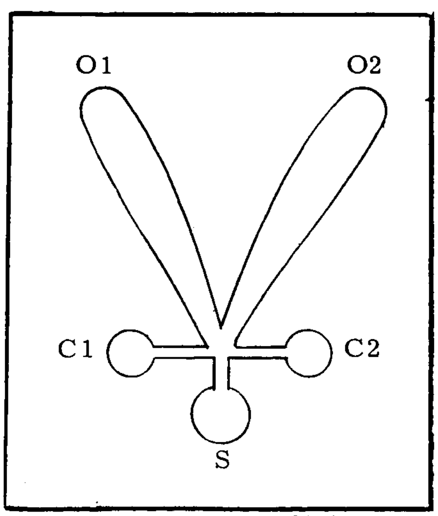
Report Section 3.1, 4.2, 7.2.1

Remarks:

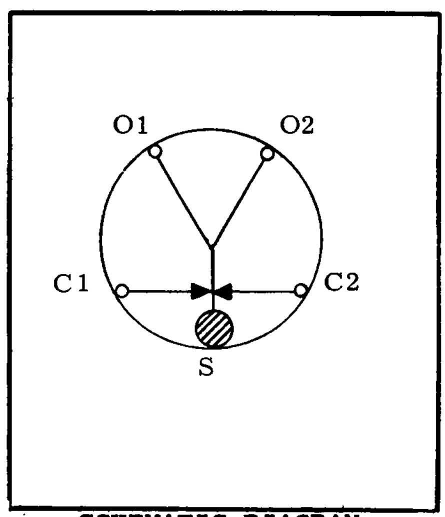
1.) Liquid flow may be switched with air flow in control ports.

2.) Guarantee 65% recovery of suppy nozzle pressure drop; report as high as 80%.

3.) Element outline below is hypothetical, actual outline not available.



ELEMENT OUTLINE
(See Remarks - 3)



SCHEMATIC DIAGRAM

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** Switch

Manufacturer Redstone Arsenal (AMC) **Model Number** N.A.

Physical Description

Overall Size (inches) See Figure 7.9
Working Fluids - Gas X **Liquid**
Power Nozzle - Number 1 **Size (inches)**
Control Ports - Number 2
Cusps - Number 0
Vents - Number 0
Output Ports - Number 2
Special Features . Special construction for operation 2000°F gas.

Response N.A.

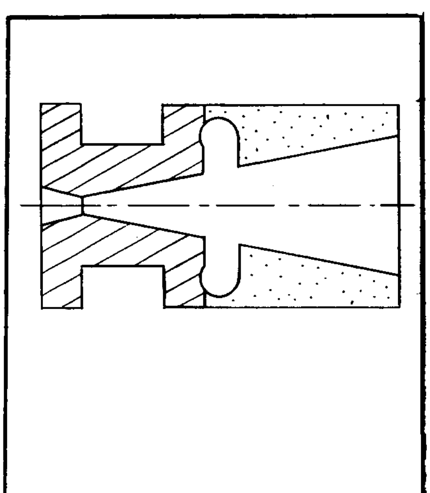
Operating Phenomena

References 5-13 **Report Section** 7.3.3

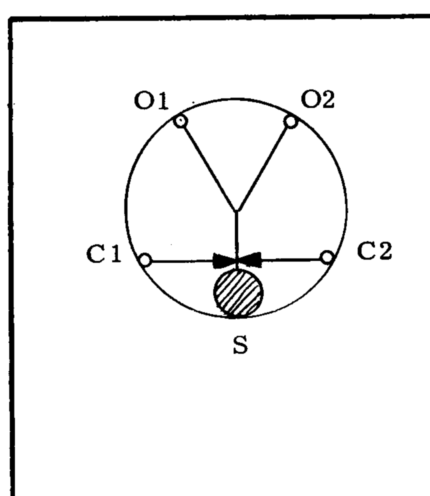
Remarks:

1.) See figure 7.9 for additional details of construction.

2.) Nozzle exit pressure 7 psi
Supply pressure 900 psi
Operating time 10 sec.



ELEMENT OUTLINE



SCHEMATIC DIAGRAM

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** OR-NOR

Manufacturer Bowles Engineering Corp. **Model Number** N.A.

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** 0.120 x .020
Control Ports - Number 2
Cusps - Number 0
Vents - Number 0
Output Ports - Number 2
Special Features

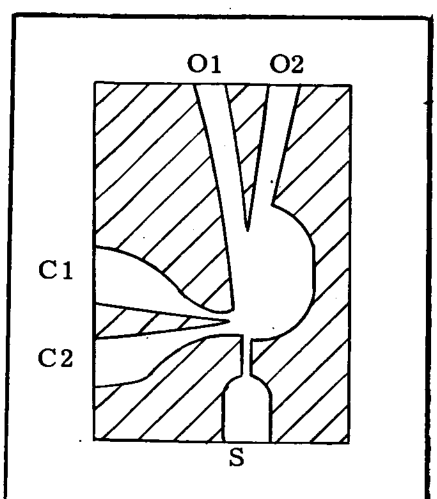
Response 0.5 ms (excluding the calculated sonic transport time)

Operating Phenomena Wall Attachment

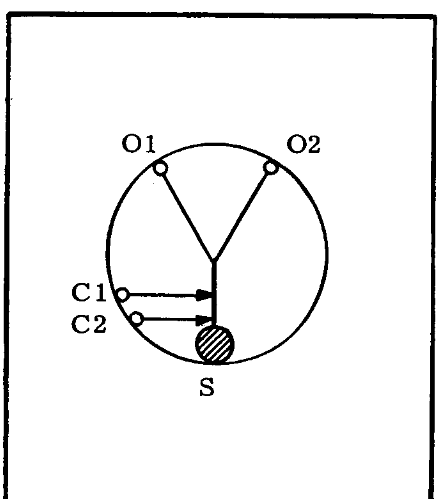
References 5-16 **Report Section** 3.1, 4.2, 4.5

Remarks:

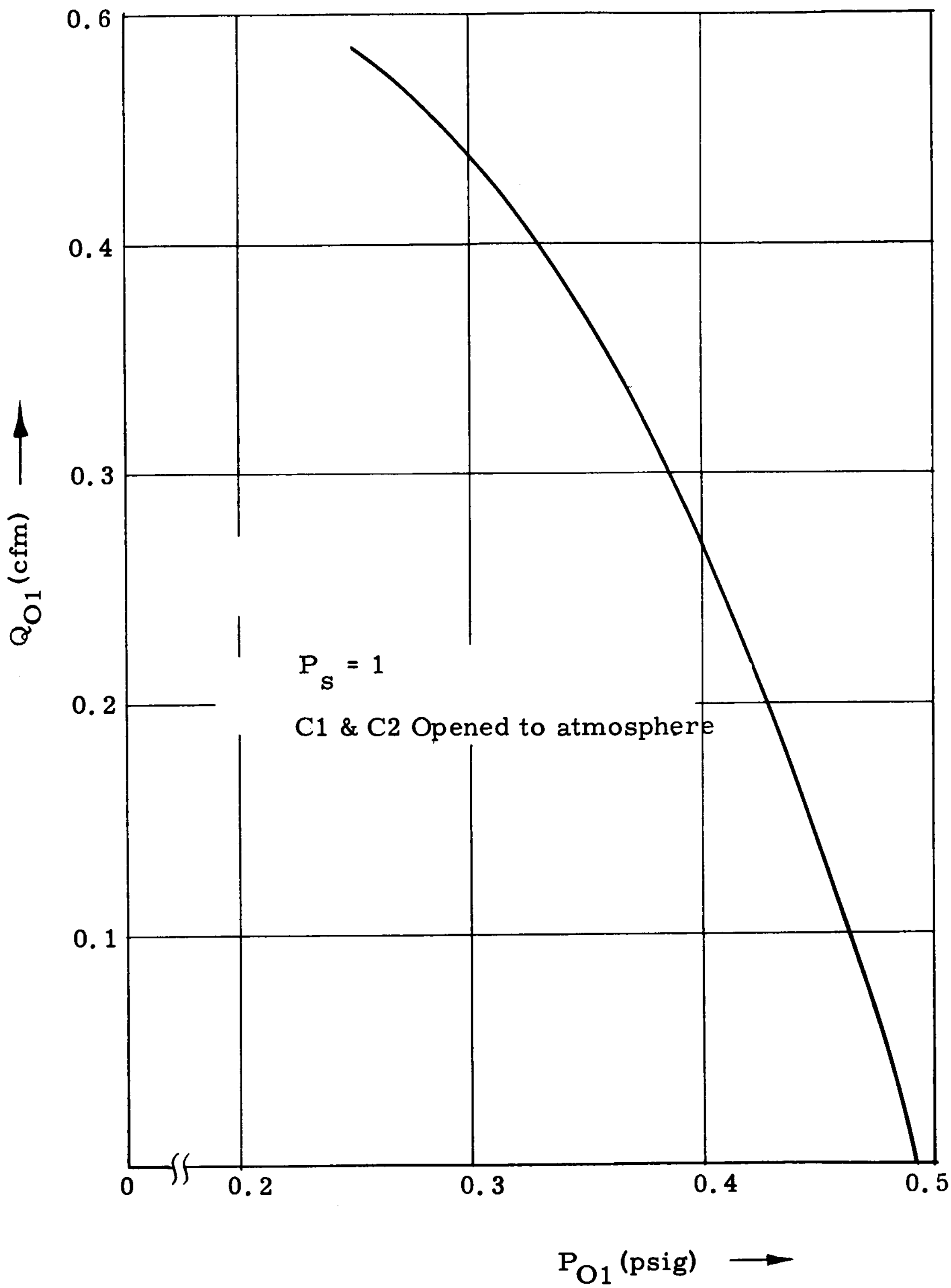
See Attached Data Sheet



ELEMENT OUTLINE



SCHEMATIC DIAGRAM


0.6
0.4
0.3
0.2
0.1
0
0.2
0.3
0.4
0.5
Q_{O1} (cfm)
P_{O1} (psig)
P_s = 1
C1 & C2 Opened to atmosphere

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** OR-NOR

Manufacturer General Electric Co. (ATL) **Model Number** ON 44-3

Physical Description

Overall Size (inches) Approx. 1-7/8 x 1-1/2 x 3/8
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** 0.040 x 0.040
Control Ports - Number 3
Cusps - Number 1
Vents - Number 2
Output Ports - Number 2
Special Features

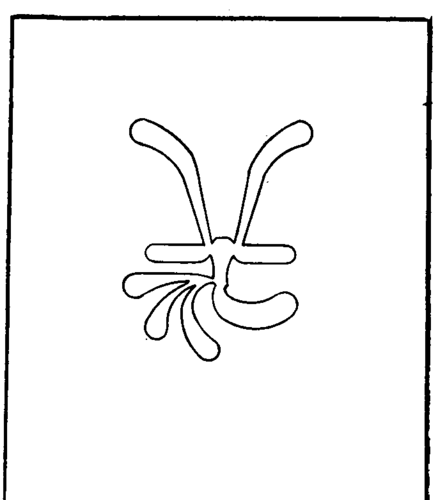
Response N. A.

Operating Phenomena Wall Attachment

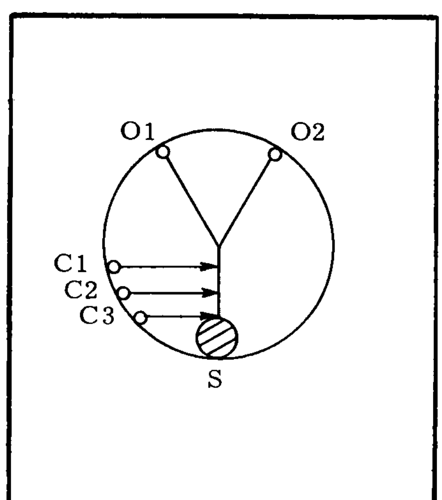
References 5-14 **Report Section** 3. 1, 4. 2

Remarks:

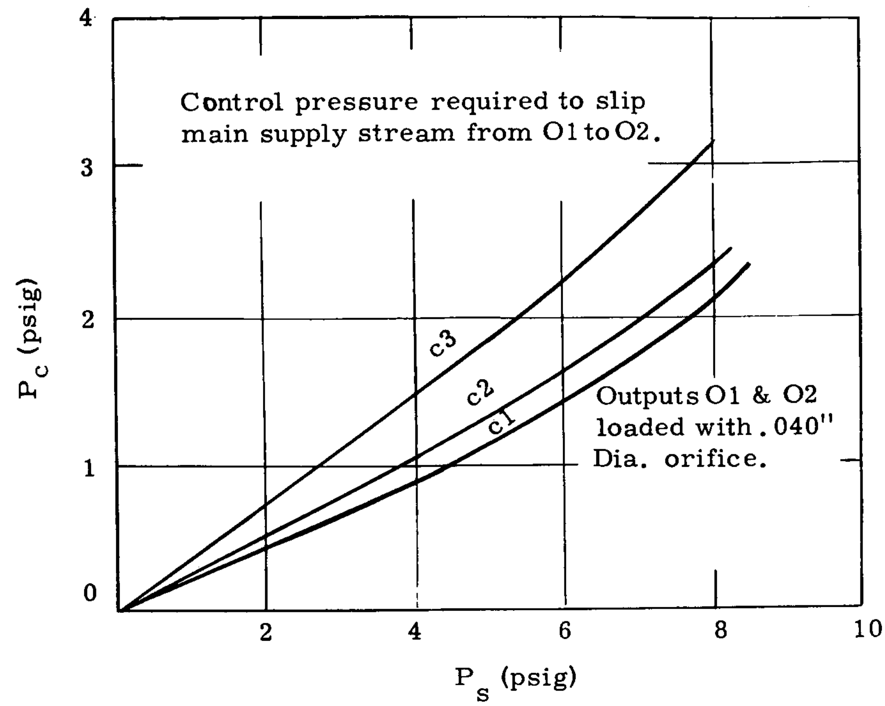
See Attached Data Sheet

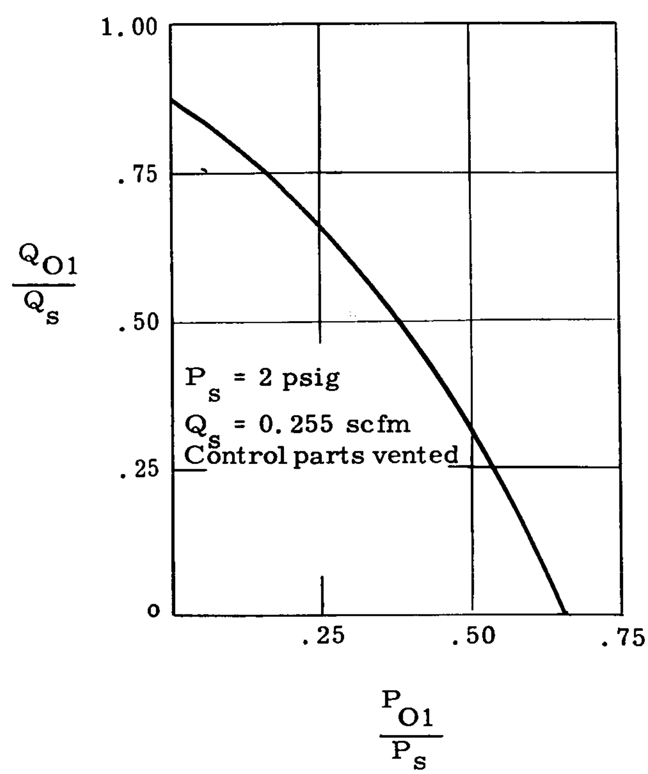


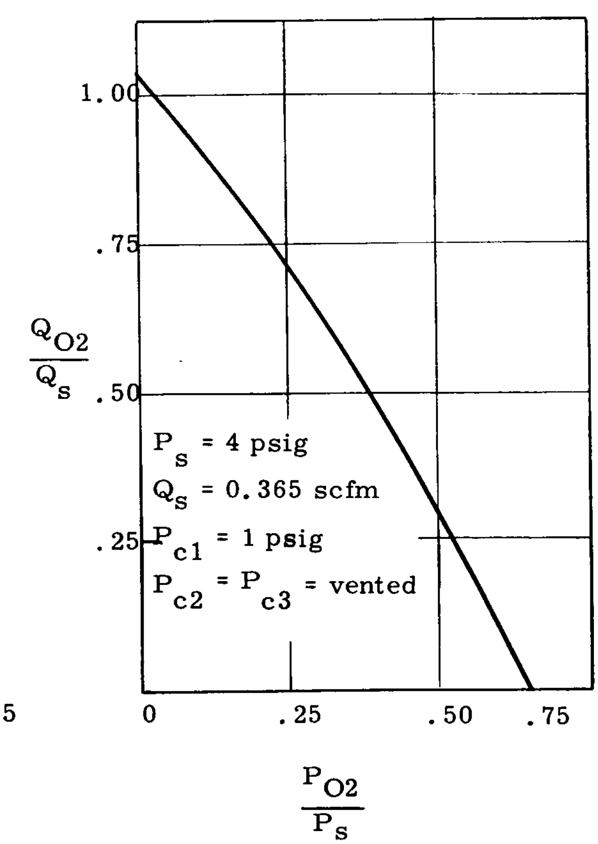
ELEMENT OUTLINE



SCHEMATIC DIAGRAM


Control pressure required to slip main supply stream from O1 to O2.
Outputs O1 & O2 loaded with .040" Dia. orifice.
c3
c2
c1
Pc (psig)
Ps (psig)
0
1
2
3
4
2
4
6
8
10


QO1/Qs
PO1/Ps
Ps = 2 psig
Qs = 0.255 scfm
Control parts vented
1.00
.75
.50
.25
o
.25
.50
.75


QO2/Qs
PO2/Ps
Ps = 4 psig
Qs = 0.365 scfm
Pc1 = 1 psig
Pc2 = Pc3 = vented
1.00
.75
.50
.25
0
.25
.50
.75

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** NOR

Manufacturer IBM Zurich (Auger) **Model Number** N.A.

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas X **Liquid** ____
Power Nozzle - Number 1 **Size (inches)** N.A.
Control Ports - Number 2
Cusps - Number 0
Vents - Number See Remarks (5)
Output Ports - Number 1
Special Features ____

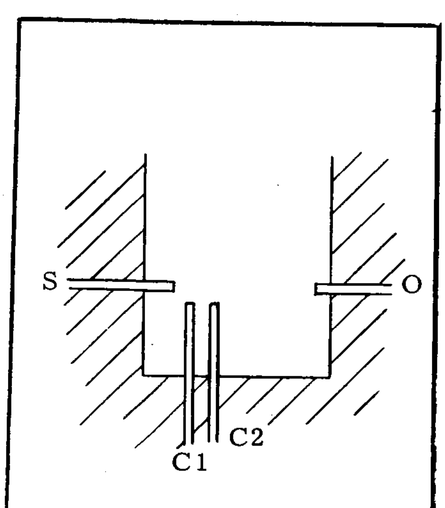
Response N.A.

Operating Phenomena Turbulence Generation

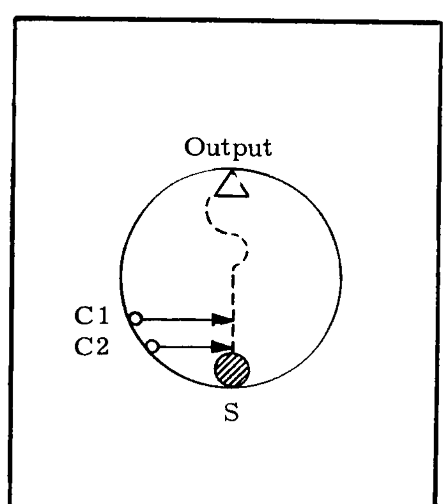
References 5-10 **Report Section** 3.1, 4.1

Remarks:

1.) Pressure gains as high as 1000 have been obtained with careful adjustment.
2.) Power gains of 40-80 have been obtained.
3.) Operating supply pressure is 4" H_2O.
4.) No load pressure recovery is approximately 50%.
5.) Required control pressure is approximately 0.3" H_2O (Typical)
6.) All ports exposed to atmosphere.



ELEMENT OUTLINE



SCHEMATIC DIAGRAM

FLUID ELEMENT DATA SHEET

Type of Element Digital **Function** Twin "AND"

Manufacturer Bowles Engineering Corp. **Model Number** N.A.

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 0 **Size (inches)** N.A.
Control Ports - Number 3
Cusps - Number 0
Vents - Number 0
Output Ports - Number 3
Special Features ·

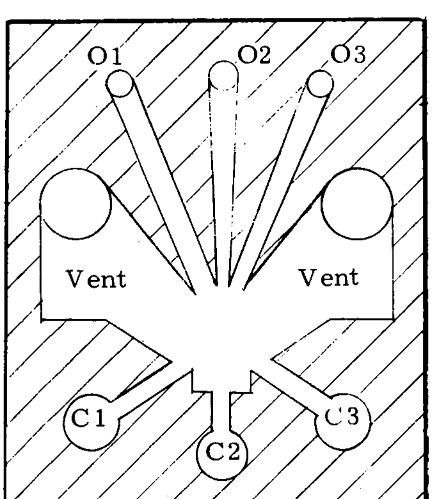
Response N.A.

Operating Phenomena Momentum

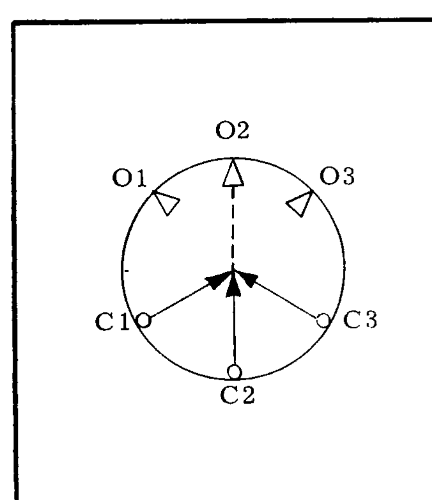
References 5-22 **Report Section** 3.1, 4.4

Remarks:

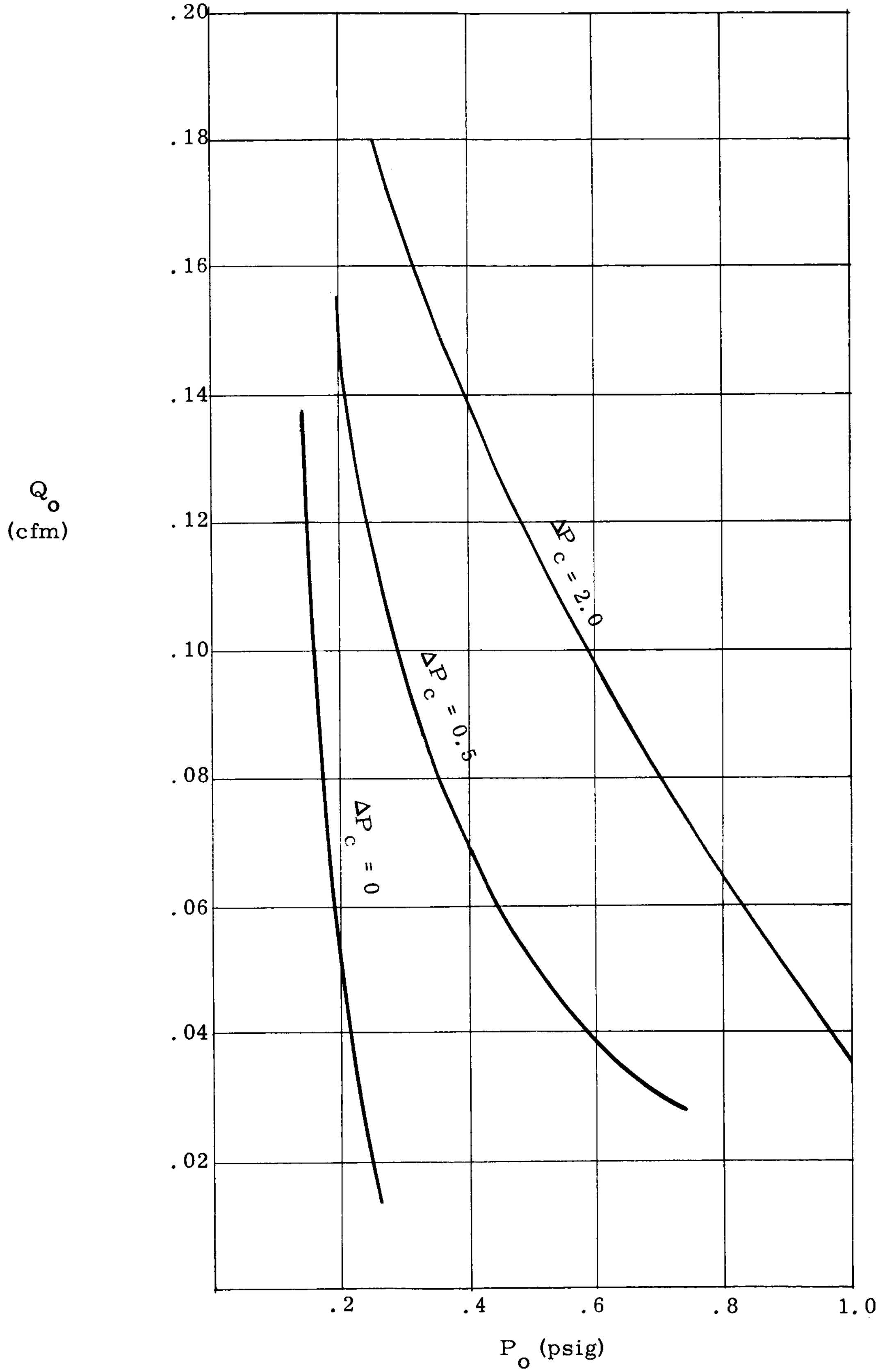
See Attached Data Sheet



ELEMENT OUTLINE



SCHEMATIC DIAGRAM



.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
Q
o
(cfm)
ΔP c = 2.0
ΔP c = 0.5
ΔP c = 0
.2
.4
.6
.8
1.0
P o (psig)

FLUID ELEMENT DATA SHEET

Type of Element Digital

Function Half Adder (And)

Manufacturer General Electric Co. (ATL)

Model Number DA 44-0

Physical Description

Overall Size (inches) Approx. 1 7/8 x 1 1/2 x 3/8
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** .040 x .040
Control Ports - Number 2
Cusps - Number 1
Vents - Number 2
Output Ports - Number 2
Special Features

Response N. A.

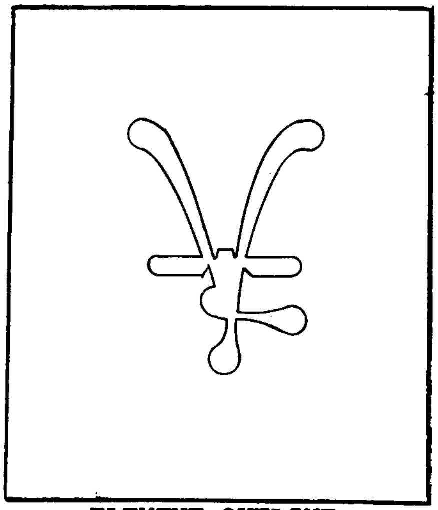
Operating Phenomena Wall Attachment

References 5-14

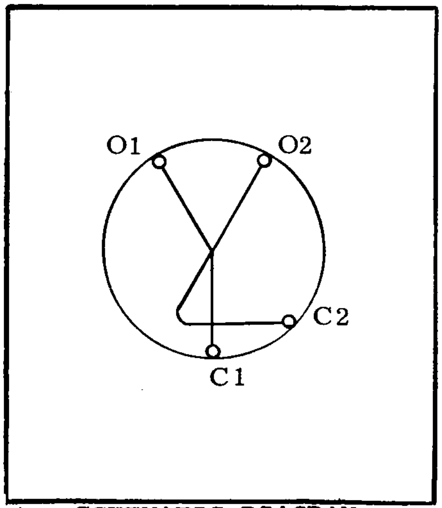
Report Section 4.2

Remarks:

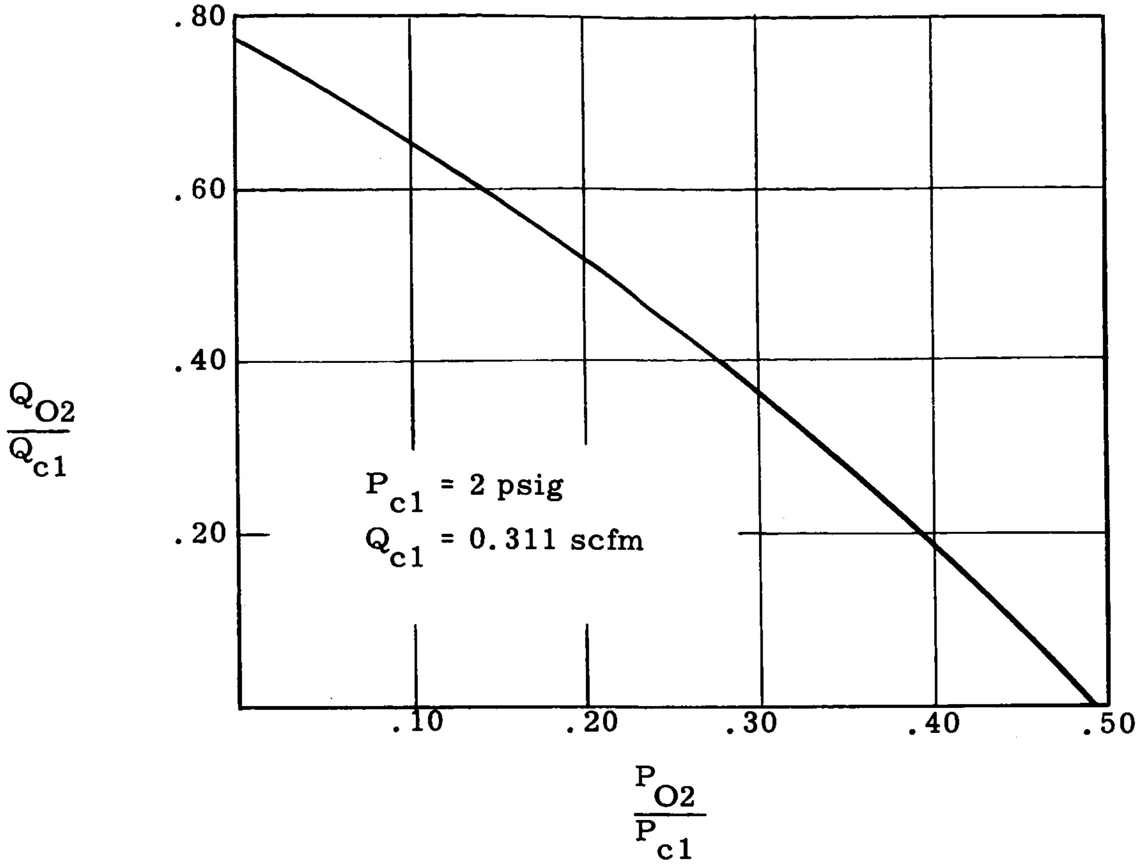
See Attached Data Sheet

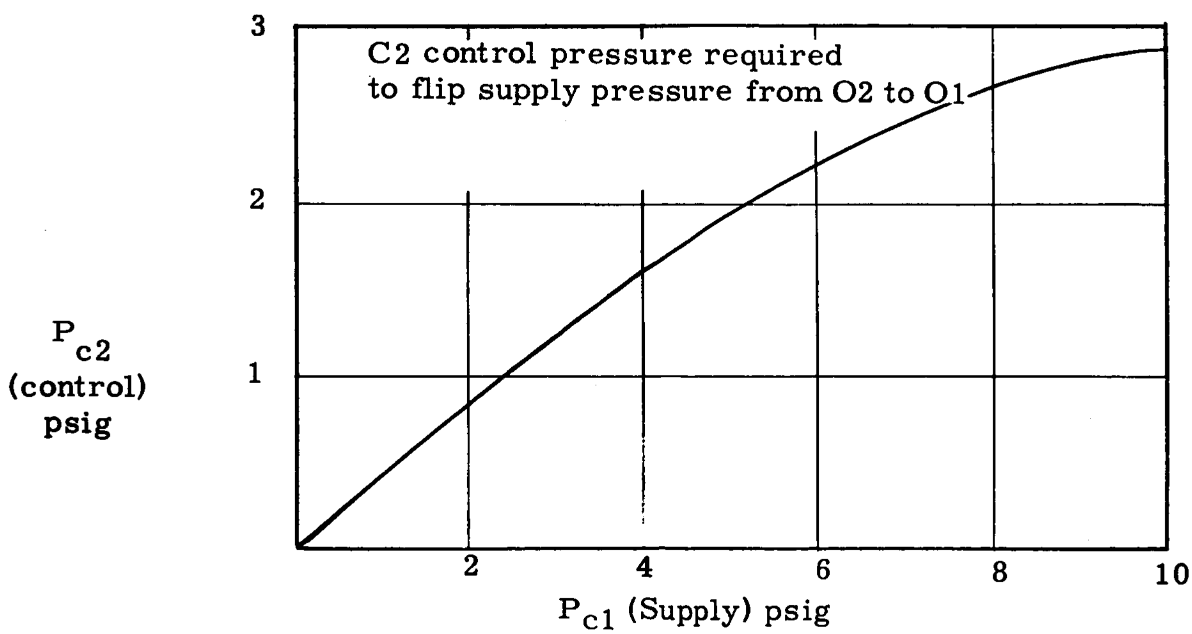


ELEMENT OUTLINE



SCHEMATIC DIAGRAM


.80
.60
.40
.20
$\frac{Q_{O2}}{Q_{c1}}$
P_{c1} = 2 psig
Q_{c1} = 0.311 scfm
.10
.20
.30
.40
.50
$\frac{P_{O2}}{P_{c1}}$


3
2
1
P_{c2} (control) psig
C2 control pressure required
to flip supply pressure from O2 to O1
2
4
6
8
10
P_{c1} (Supply) psig

FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Amplifier, Signal Summation

Manufacturer Bendix **Model Number** N.A.

Physical Description

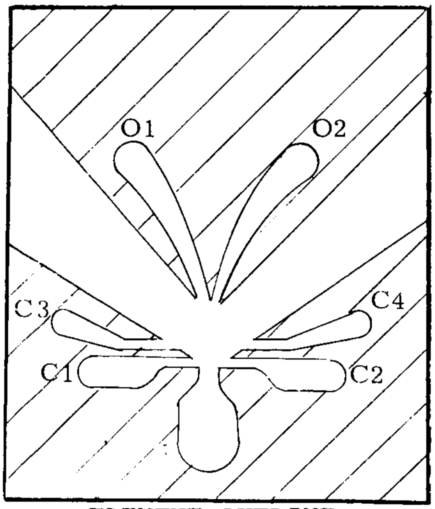
- **Overall Size (inches)** N.A.
- **Working Fluids - Gas** X **Liquid** N.A.
- **Power Nozzle - Number** N.A. **Size (inches)** N.A.
- **Control Ports - Number** 4
- **Cusps - Number** 0
- **Vents - Number** 2
- **Output Ports - Number** 2
- **Special Features**

Response N.A.

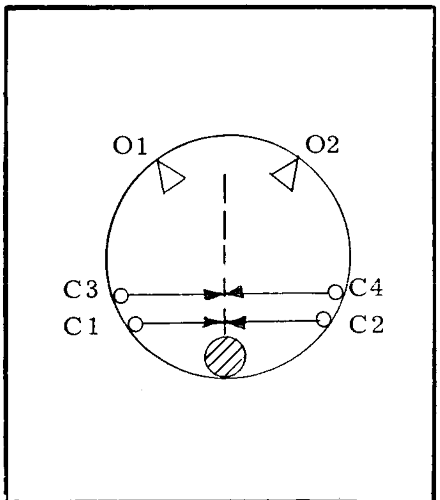
Operating Phenomena Momentum

References 5-24 **Report Section** 3.1, 4.1

Remarks:



ELEMENT OUTLINE



SCHEMATIC DIAGRAM

FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Amplifier

Manufacturer Bendix **Model Number** N. A.

Physical Description

- **Overall Size (inches)** N. A.
- **Working Fluids - Gas** X **Liquid** N. A.
- **Power Nozzle - Number** N. A. **Size (inches)** N. A.
- **Control Ports - Number** N. A.
- **Cusps - Number** N. A.
- **Vents - Number** N. A.
- **Output Ports - Number** N. A.
- **Special Features**

Response

Operating Phenomena Vortex

References 5-24 **Report Section** 3.1, 4.3

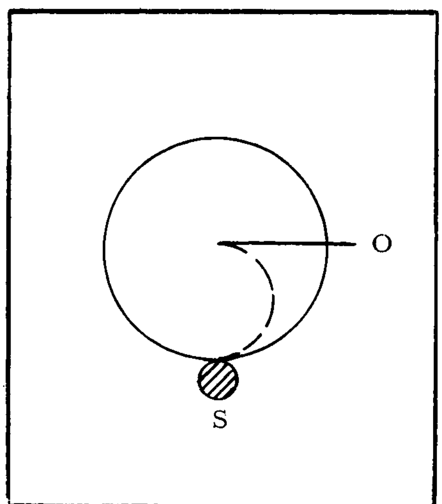
Remarks:

1.) See attached data.

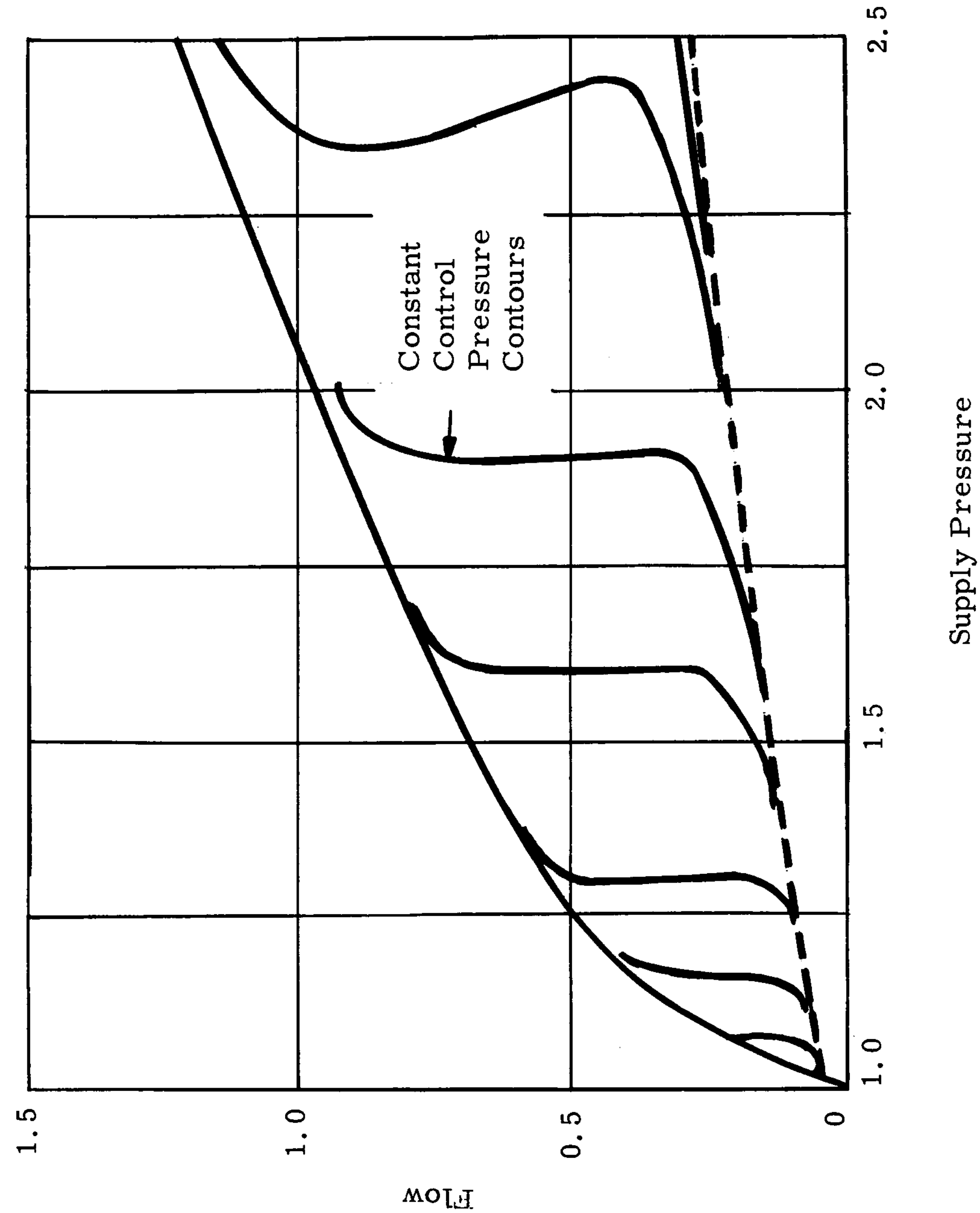
2.) Tested over temperature range of 60°F to 1400°F

N. A.

ELEMENT OUTLINE



SCHEMATIC DIAGRAM


Constant
Control
Pressure
Contours
Supply Pressure
Flow
1.0
1.5
2.0
2.5
0
0.5
1.0
1.5

FLUID ELEMENT DATA SHEET

Type of Element Proportional

Function Amplifier, Signal Summation

Manufacturer Bowles Engineering Corp.

Model Number N. A.

Physical Description

Overall Size (inches)		N. A.		
Working Fluids	- Gas	X	Liquid	X
Power Nozzle	- Number	1	Size (inches)	N. A.
Control Ports	- Number	4		
Cusps	- Number	0		
Vents	- Number	2		
Output Ports	- Number	3		
Special Features				

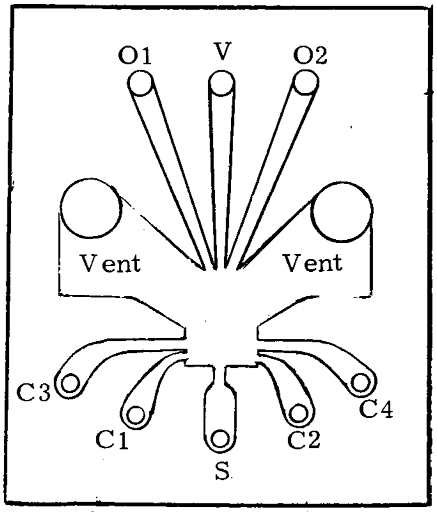
Response N. A.

Operating Phenomena Momentum

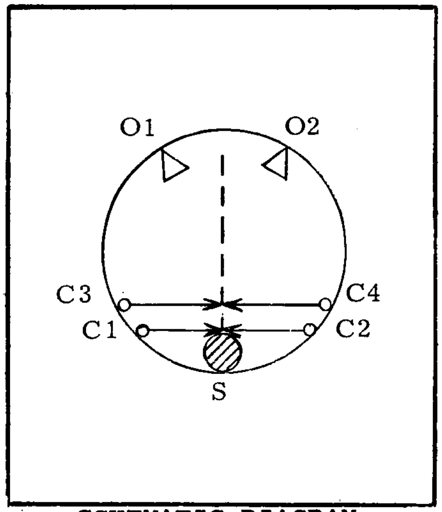
References 5-5

Report Section 3. 1, 4. 4

Remarks:



ELEMENT OUTLINE



SCHEMATIC DIAGRAM

FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Amplifier

Manufacturer Bowles Engineering Corp. **Model Number** N.A.

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** N.A.
Control Ports - Number 2
Cusps - Number 0
Vents - Number 3
Output Ports - Number 2
Special Features .

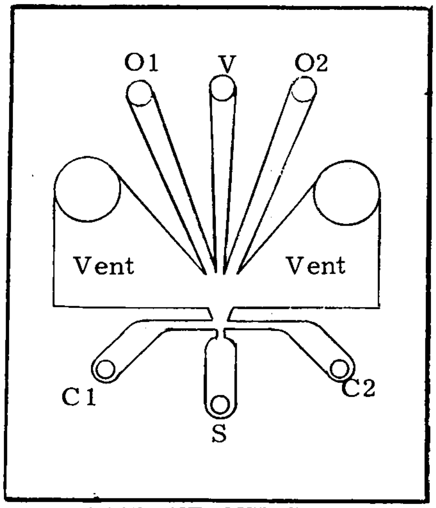
Response N.A.

Operating Phenomena Momentum

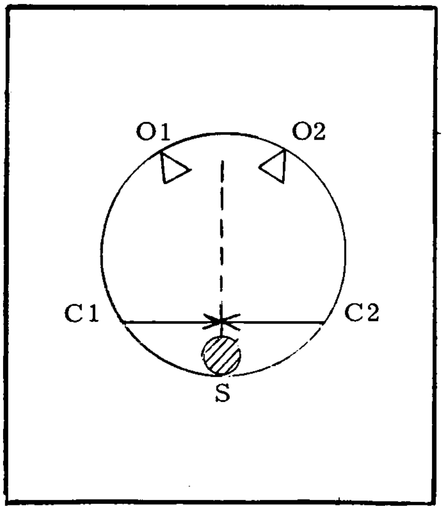
References 5-11 **Report Section** 4.1, 4.4

Remarks:

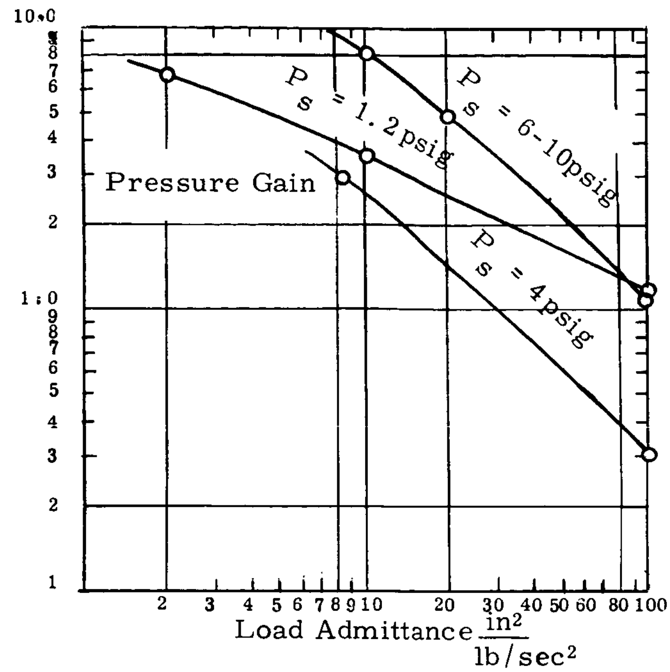
See Attached Data

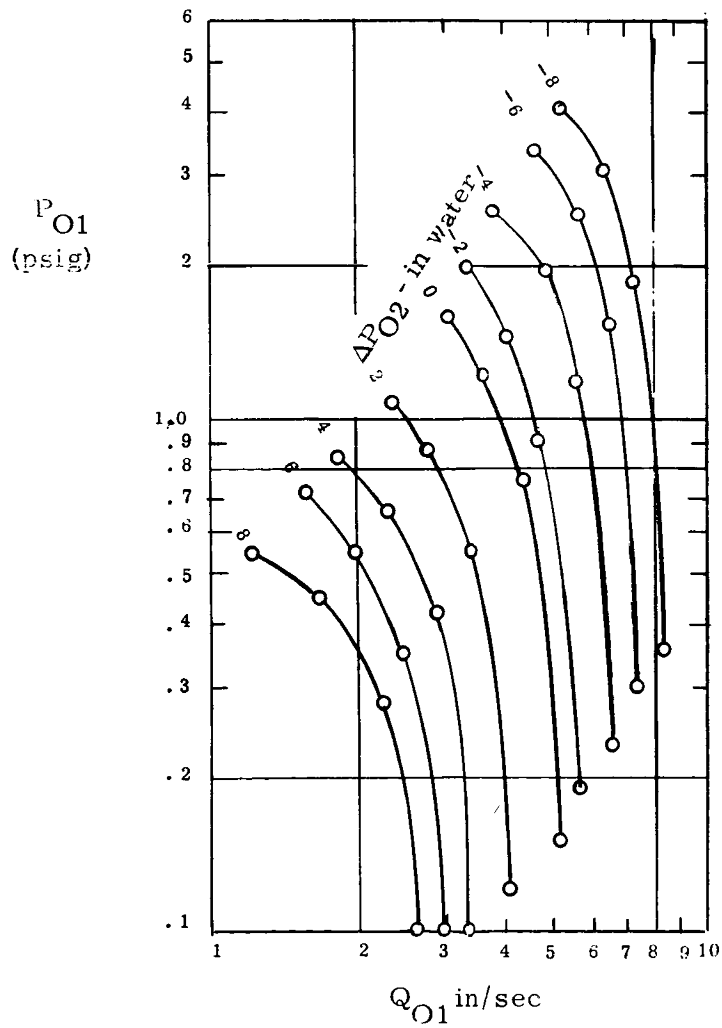


ELEMENT OUTLINE



SCHEMATIC DIAGRAM


Pressure Gain
Ps = 1.2psig
Ps = 6-10psig
Ps = 4psig
Load Admittance in²/lb/sec²


PO1 (psig)
ΔPO2 - in water
QO1 in/sec

FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Amplifier

Manufacturer Corning Glass Works **Model Number** Unit 2195

Physical Description

- **Overall Size (inches)** N. A.
- **Working Fluids - Gas** X **Liquid** X
- **Power Nozzle - Number** 1 **Size (inches)** N. A.
- **Control Ports - Number** 2
- **Cusps - Number** 0
- **Vents - Number** 2
- **Output Ports - Number** 2
- **Special Features**

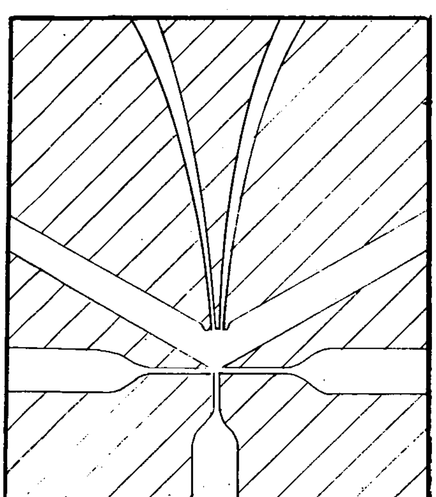
Response N. A.

Operating Phenomena Momentum

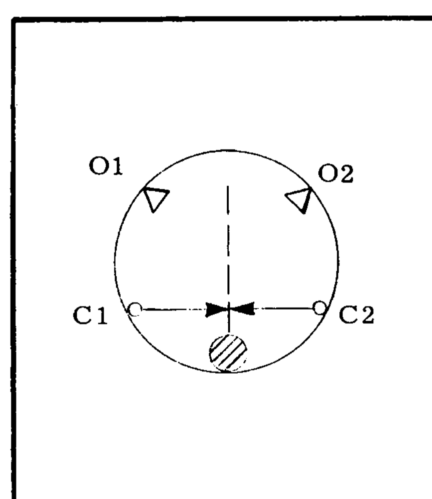
References 5-6 **Report Section** 3.1, 4.4, 8.2.4

Remarks:

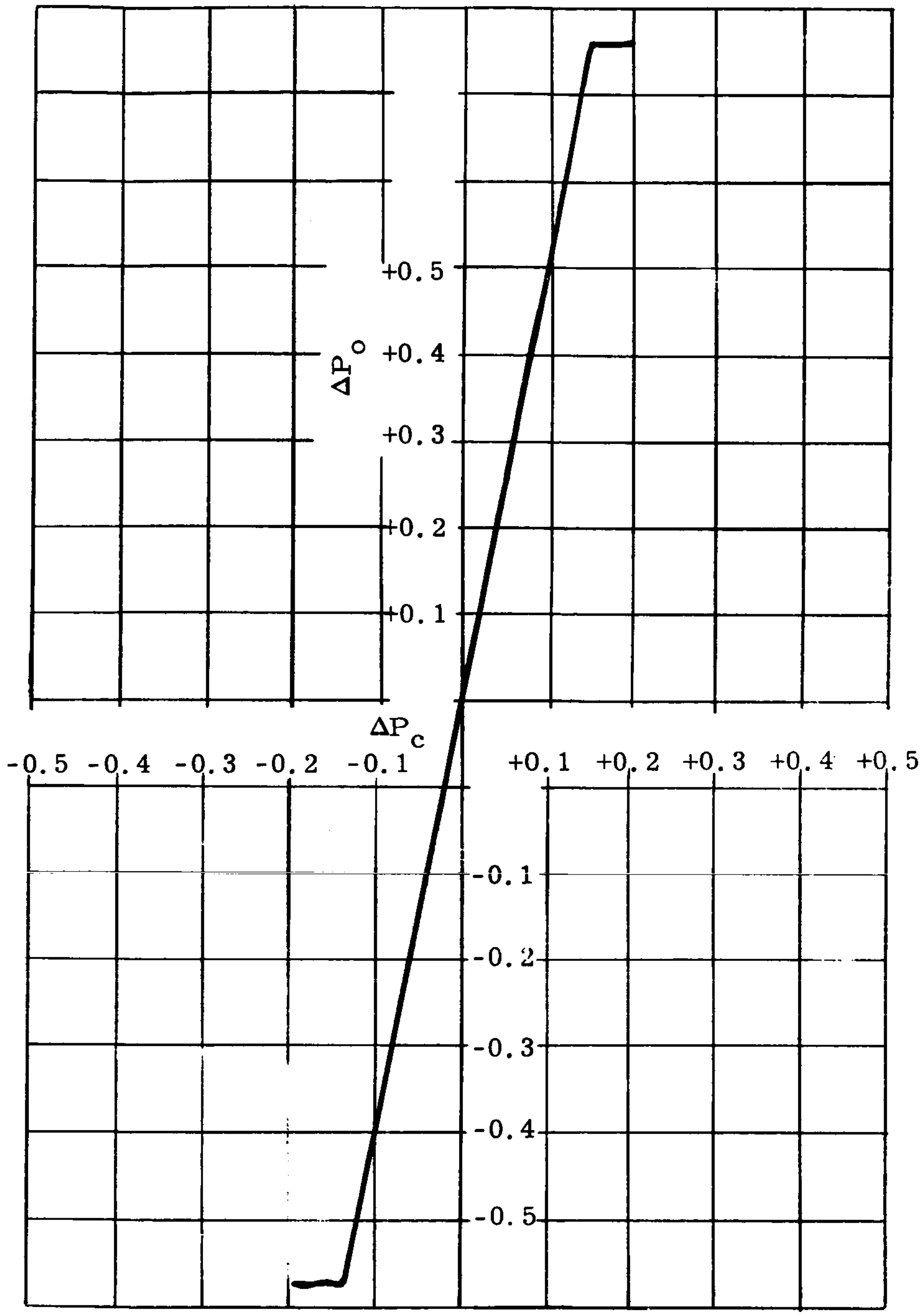
See Attached Data



ELEMENT OUTLINE



SCHEMATIC DIAGRAM



Unit 2195

Pressure Gain Curve; Output Pressure Differential vs. Control Press. Differential; Supply Pressure = 5 psig; Control Bias Press. = 0.5 psig; Gain = 5.0
Outputs loaded with restrictions = in area to receive apertures.

FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Amplifier

Manufacturer General Electric Co. (ATL) **Model Number** PA 44-2

Physical Description

Overall Size (inches) Approx. 1 7/8 x 1 1/2 x 3/8
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** .040 x .040
Control Ports - Number 2
Cusps - Number 1
Vents - Number 2
Output Ports - Number 2
Special Features ·

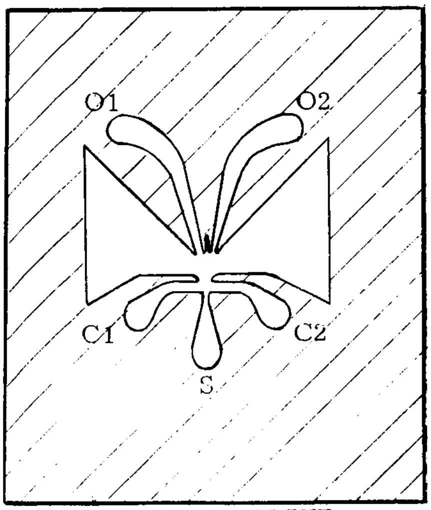
Response 0.4 ms (including acoustical and transport time)

Operating Phenomena Momentum

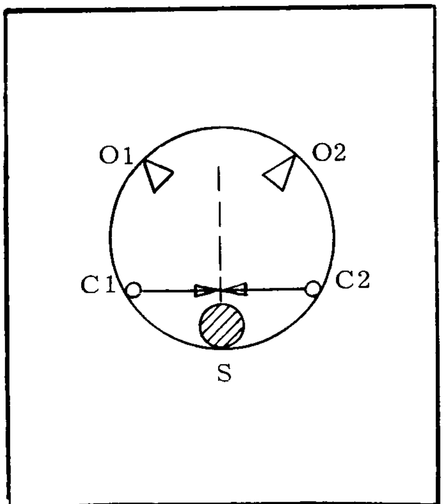
References 5-14 **Report Section** 3.1, 4.4

Remarks:

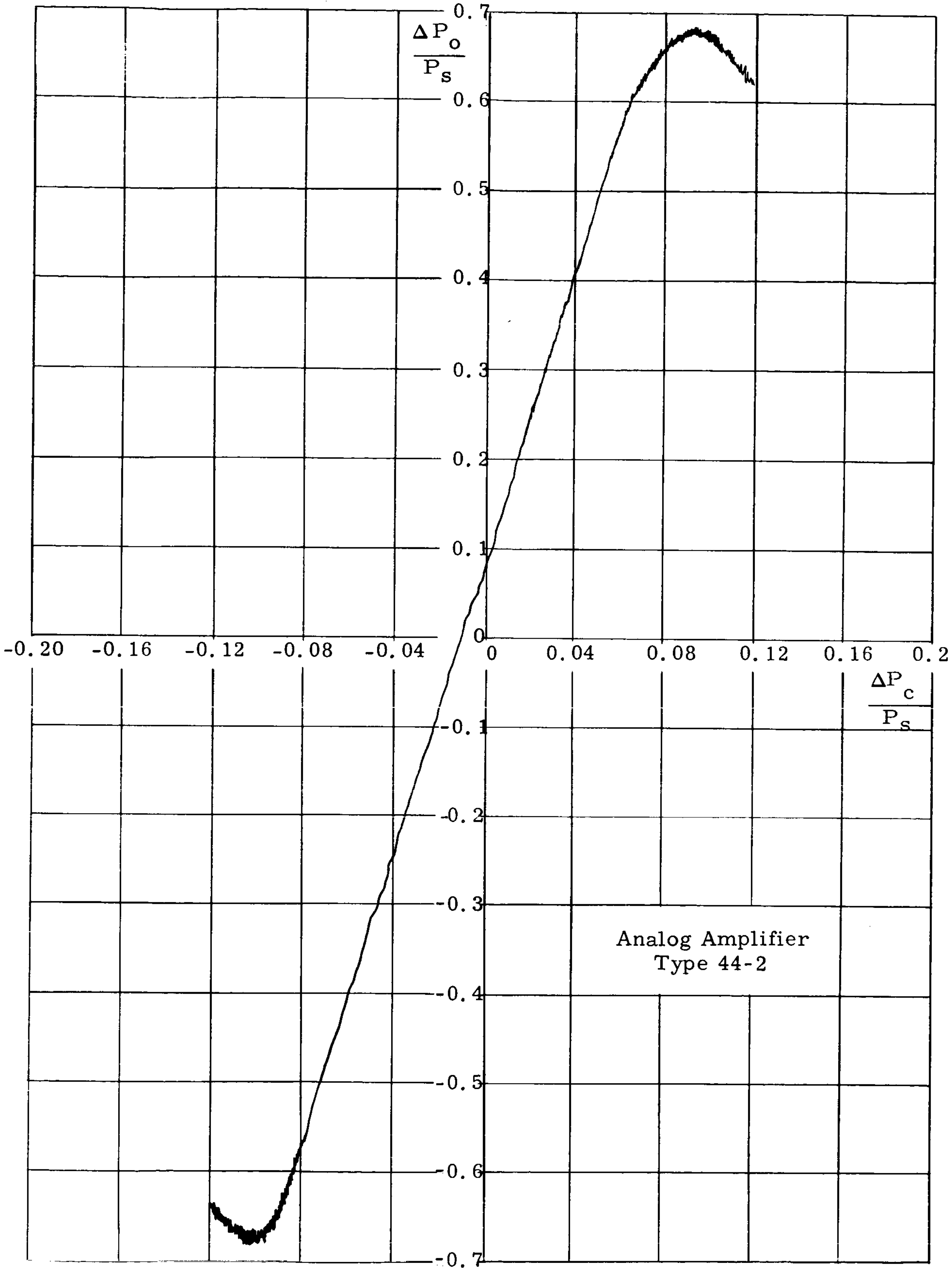
See Attached Data



ELEMENT OUTLINE



SCHEMATIC DIAGRAM



$\frac{\Delta P_o}{P_s}$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.20
-0.16
-0.12
-0.08
-0.04
0
0.04
0.08
0.12
0.16
0.2
$\frac{\Delta P_c}{P_s}$
Analog Amplifier
Type 44-2

FLUID ELEMENT DATA SHEET

Type of Element Vortex

Function Amplifier or Variable Restrictor

Manufacturer General Electric Co. (ATL)

Model Number N. A.

Physical Description

Overall Size (inches) N. A.

Working Fluids - Gas X **Liquid** X

Power Nozzle - Number 1 **Size (inches)** N. A.

Control Ports - Number 1

Cusps - Number 0

Vents - Number 0

Output Ports - Number 1

Special Features .

Response N. A.

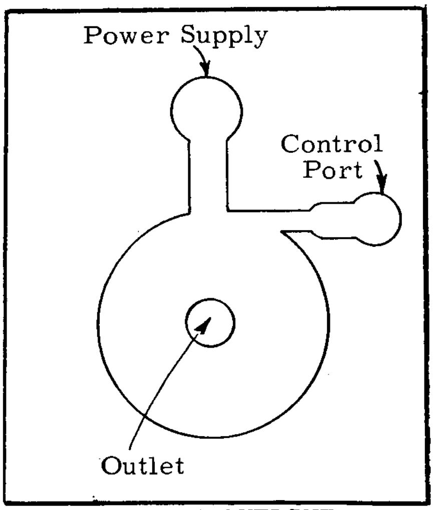
Operating Phenomena Induced Vortex

References 5-23

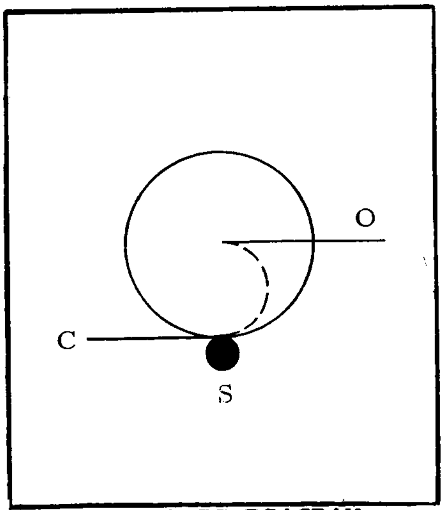
Report Section 3. 1, 4. 3

Remarks:

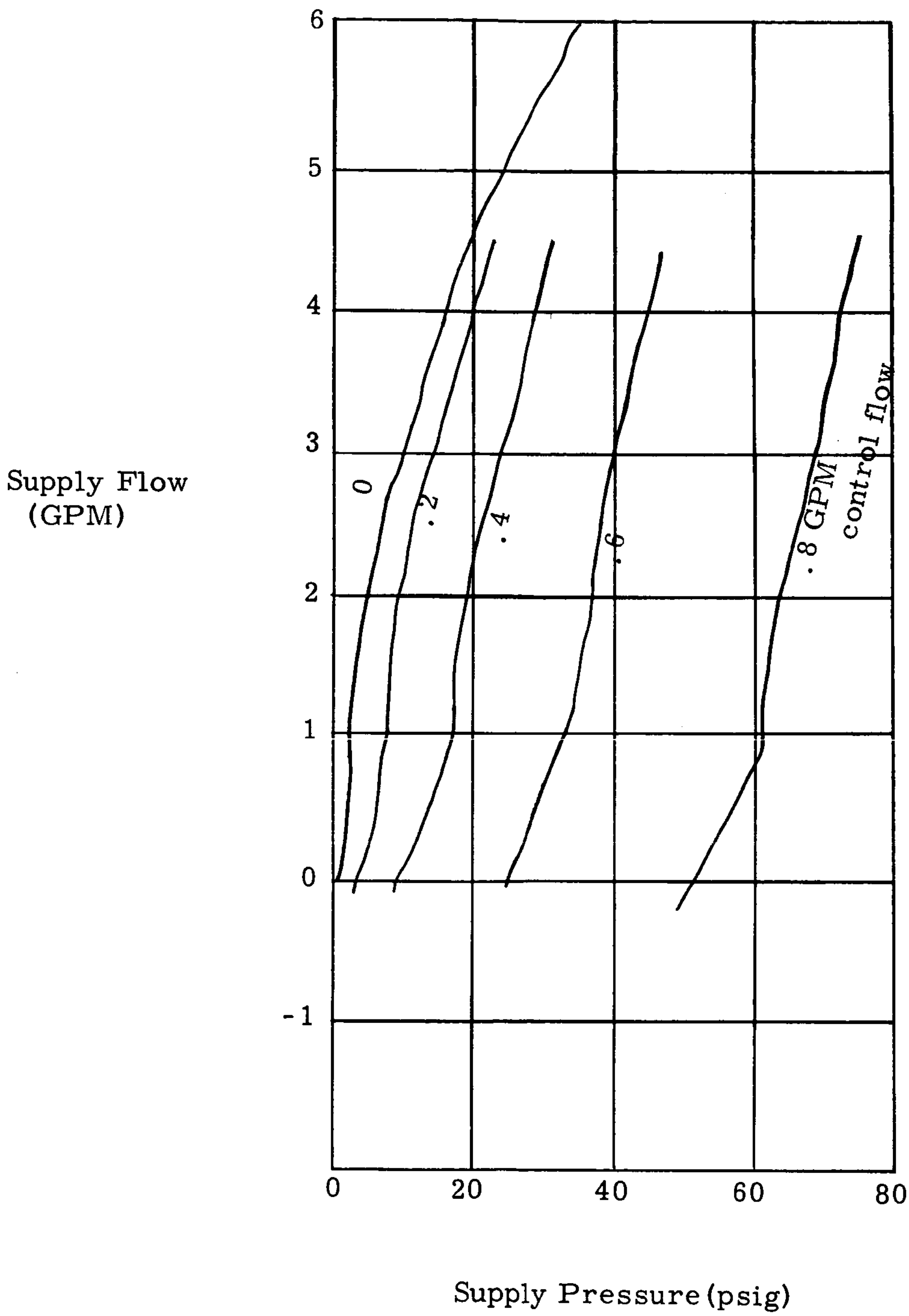
See Attached Data



ELEMENT OUTLINE



SCHEMATIC DIAGRAM



6
5
4
3
2
1
0
-1
Supply Flow
(GPM)
0
.2
.4
.6
.8 GPM
control flow
0
20
40
60
80
Supply Pressure (psig)

FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Amplifier

Manufacturer Giannini **Model Number** N. A.

Physical Description

- **Overall Size (inches)** N. A.
- **Working Fluids - Gas** X **Liquid** X
- **Power Nozzle - Number** 2 **Size (inches)** N. A.
- **Control Ports - Number** 1
- **Cusps - Number** 0
- **Vents - Number** 2
- **Output Ports - Number** 2
- **Special Features** · Uses Splitter Vane

Response 6ms (total time including acoustical and transport time).

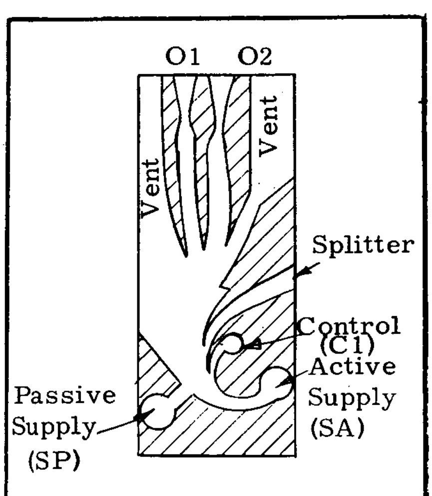
Operating Phenomena Boundary Layer and Momentum

References 5-4 **Report Section** 4.4

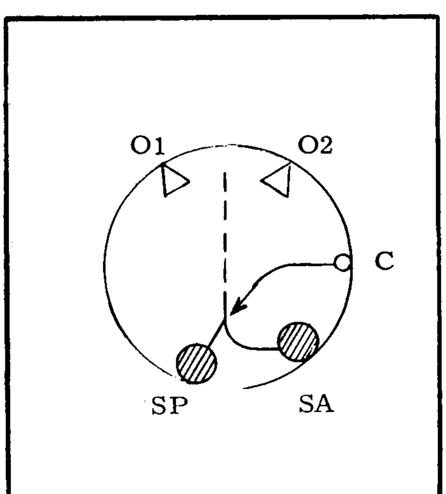
Remarks:

1.) Operating principle - control flow determines separation point of active supply flow inner radius thus varying the leaving angle of the active supply jet. Interaction of this jet with the passive supply jet produces a beam of fluid flow which can be swept across the receivers with small control flow.

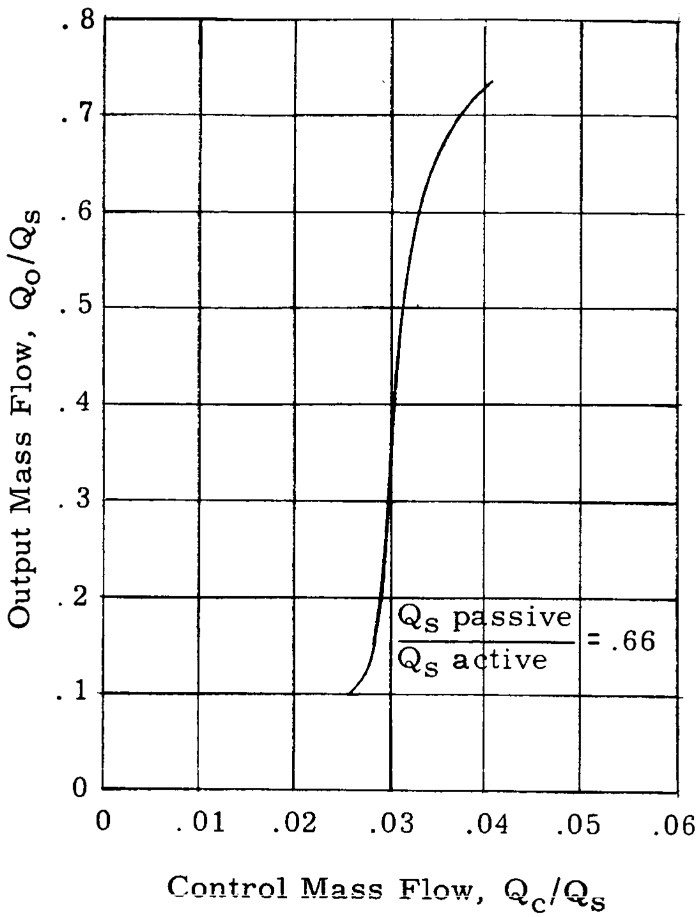
2.) See attached data.

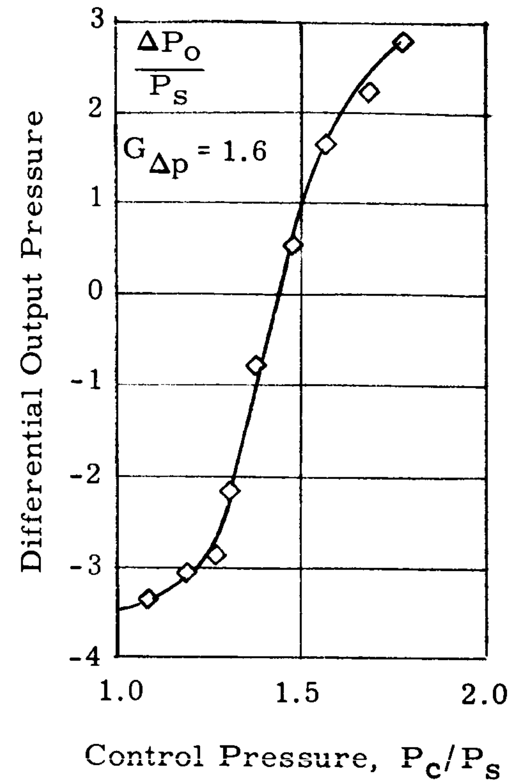


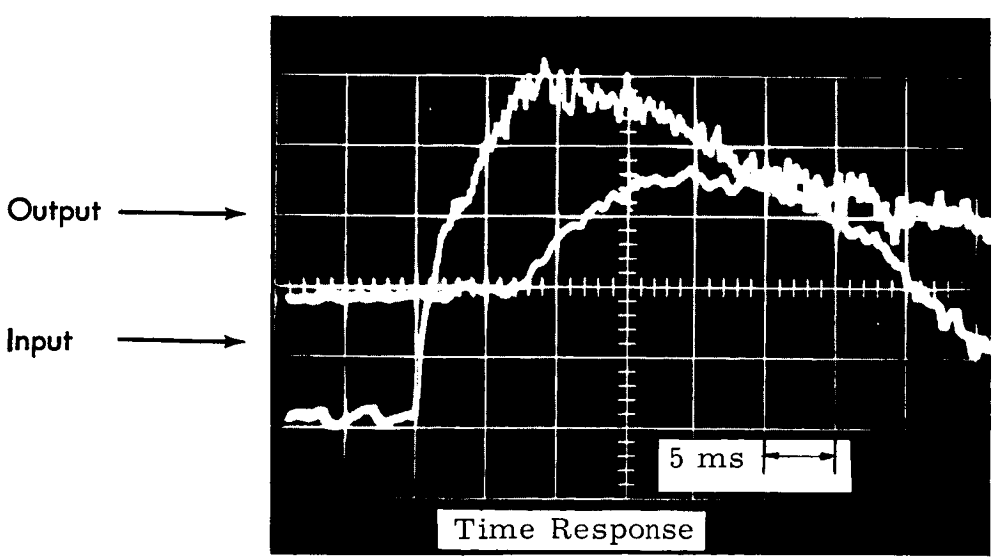
ELEMENT OUTLINE



SCHEMATIC DIAGRAM







(b) Model B Step Input
Time Scale: 5×10^{-3} Sec/cm

FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Amplifier

Manufacturer HDL **Model Number** N.A.

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas X **Liquid**
Power Nozzle - Number 1 **Size (inches)** 0.020" w x 0.050
Control Ports - Number 2
Cusps - Number 0
Vents - Number 2
Output Ports - Number 2
Special Features

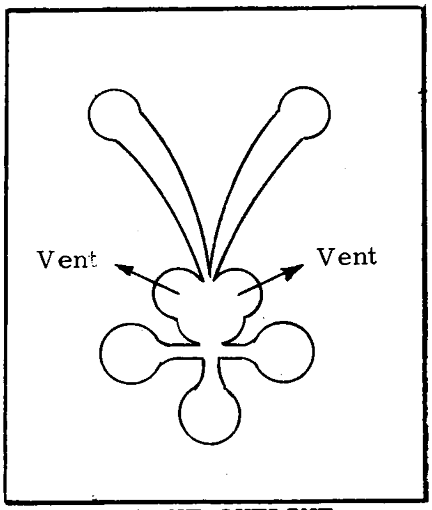
Response N.A.

Operating Phenomena

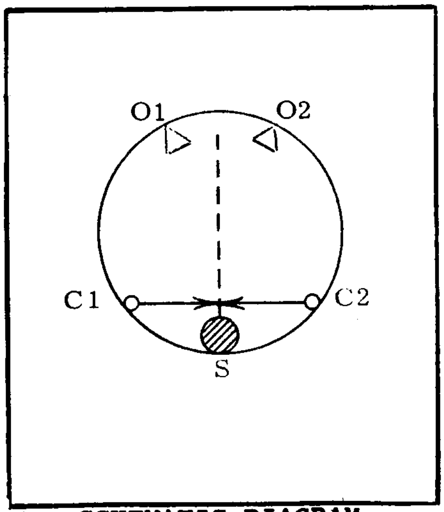
References 5-9, 5-21 **Report Section** 3.1, 4.1, 4.4

Remarks:

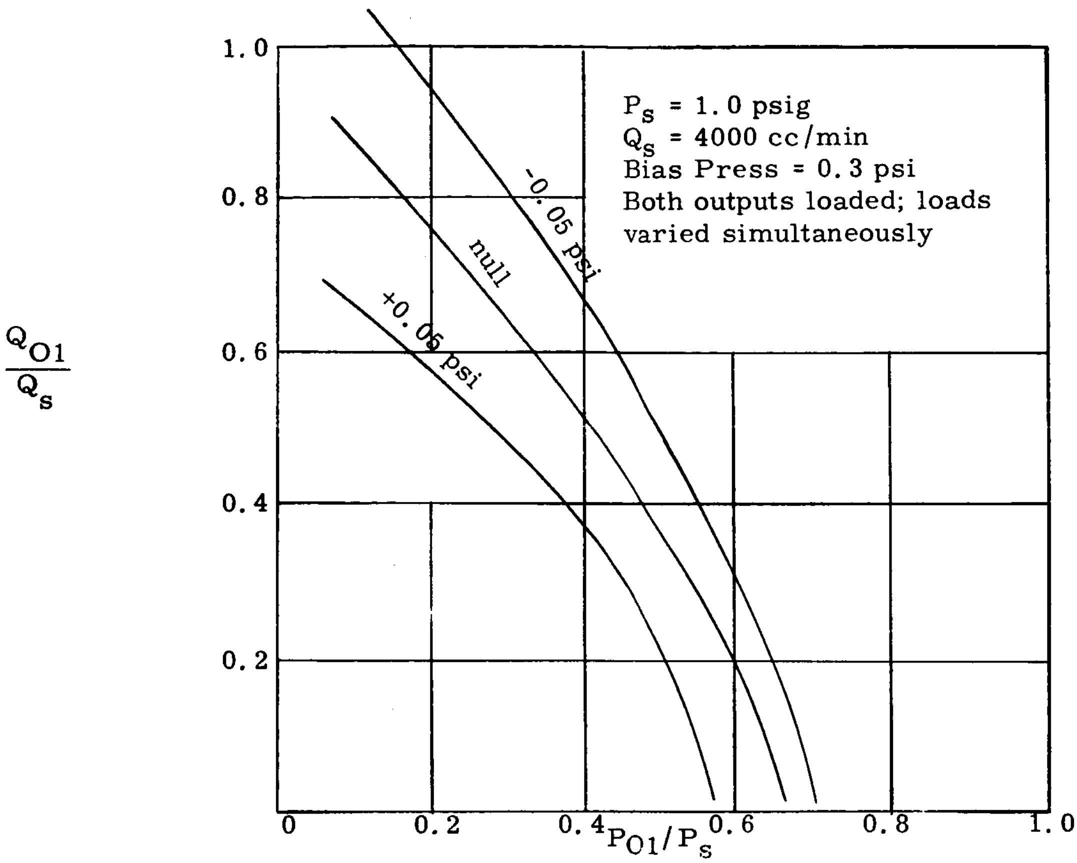
See Attached Data



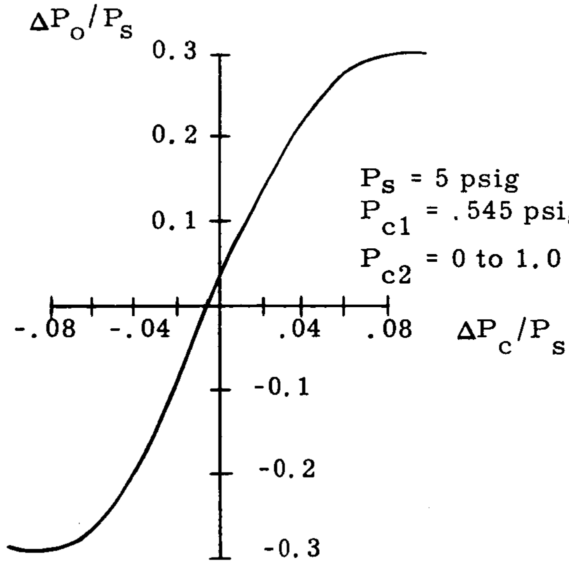
ELEMENT OUTLINE



SCHEMATIC DIAGRAM



Output Pressure-Flow Characteristics
(from ref. 5-21)



Input-Output Characteristics
(from ref. 5-9)

FLUID ELEMENT DATA SHEET

Type of Element Proportional

Function Amplifier, Signal Summation

Manufacturer Johnson Service Co.

Model Number N.A.

Physical Description

Overall Size (inches) 1/4" Cube
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number 1 **Size (inches)** .005 dia. & up
Control Ports - Number 1
Cusps - Number O
Vents - Number All port vented
Output Ports - Number 1
Special Features ·

Response N.A.

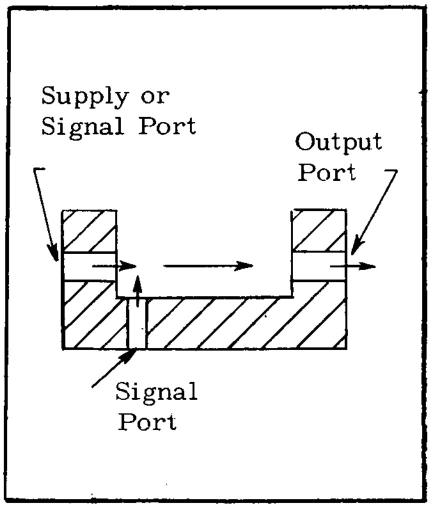
Operating Phenomena Momentum

References 5-19

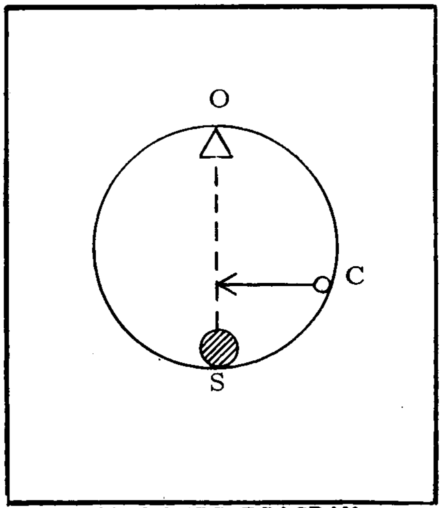
Report Section 4.1, 4.6

Remarks:

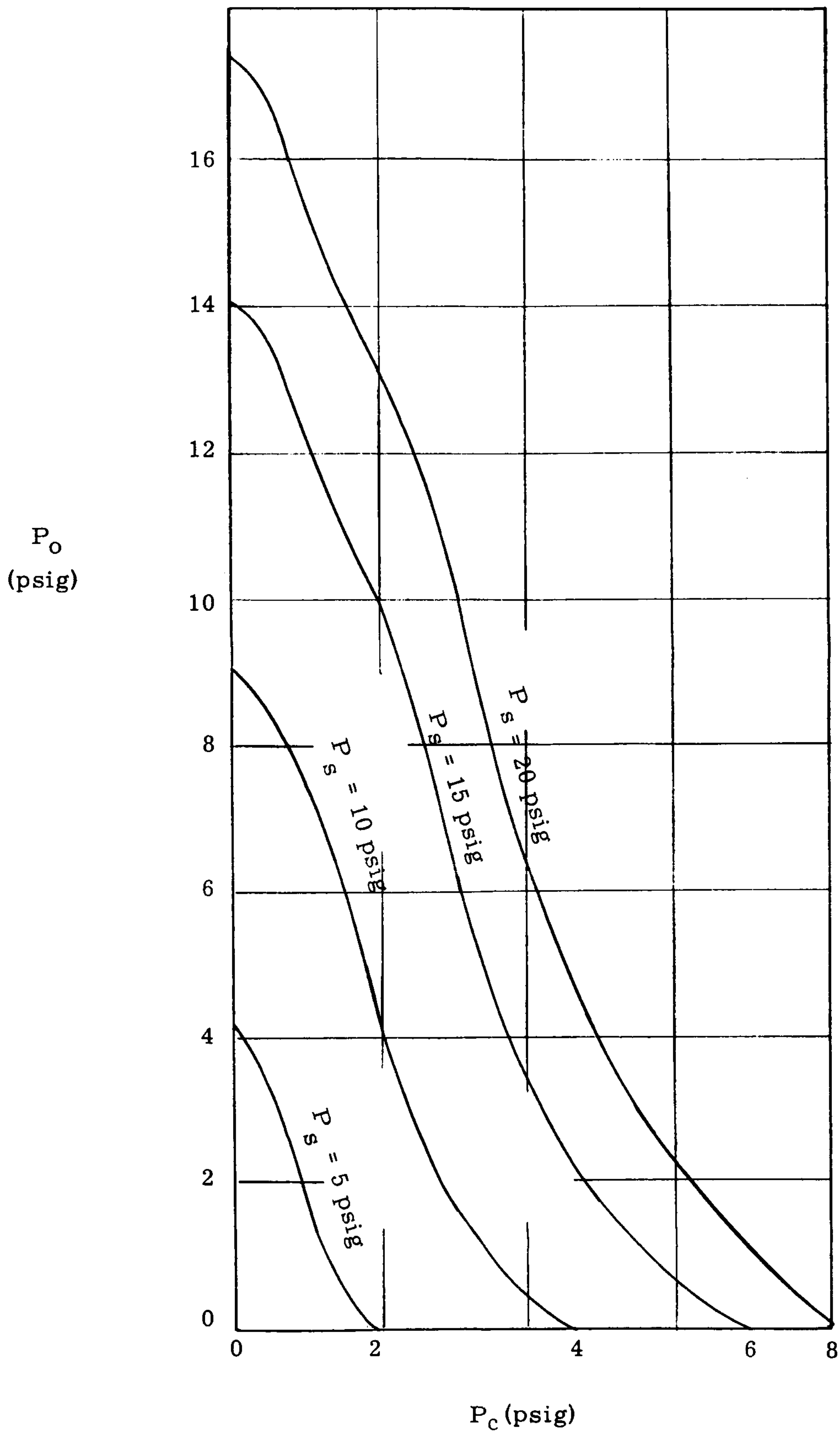
See Attached Data



ELEMENT OUTLINE



SCHEMATIC DIAGRAM


Po
(psig)
16
14
12
10
8
6
4
2
0
0
2
4
6
8
Pc (psig)
Ps = 20 psig
Ps = 15 psig
Ps = 10 psig
Ps = 5 psig

FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Amplifier

Manufacturer Johnson Service Co. **Model Number** N.A.

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas X **Liquid** X
Power Nozzle - Number N.A. **Size (inches)** N.A.
Control Ports - Number N.A.
Cusps - Number N.A.
Vents - Number N.A.
Output Ports - Number N.A.
Special Features · Can be made digital with pressure change

Response N.A.

Operating Phenomena N.A. (Believed to be Momentum)

References 5-20 **Report Section**

Remarks:

1.) Control and output ports well isolated from one another.

2.) Pressure gain of approximately 200, flow gain approaches ∞ in certain operating regions.

3.) Pressure recovery to 99% of supply.

4.) Control Sensitivity claimed to be 10^{-4} inches of H_2O

5.) Noise level down to 1% of total output.

ELEMENT OUTLINE	SCHEMATIC DIAGRAM
N.A.	N.A.

FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Amplifier

Manufacturer Marquardt Corp. **Model Number** N.A.

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas N.A. **Liquid** NA
Power Nozzle - Number 1 **Size (inches)** N.A.
Control Ports - Number 1
Cusps - Number NA
Vents - Number NA
Output Ports - Number 1
Special Features

Response N.A.

Operating Phenomena Vortex

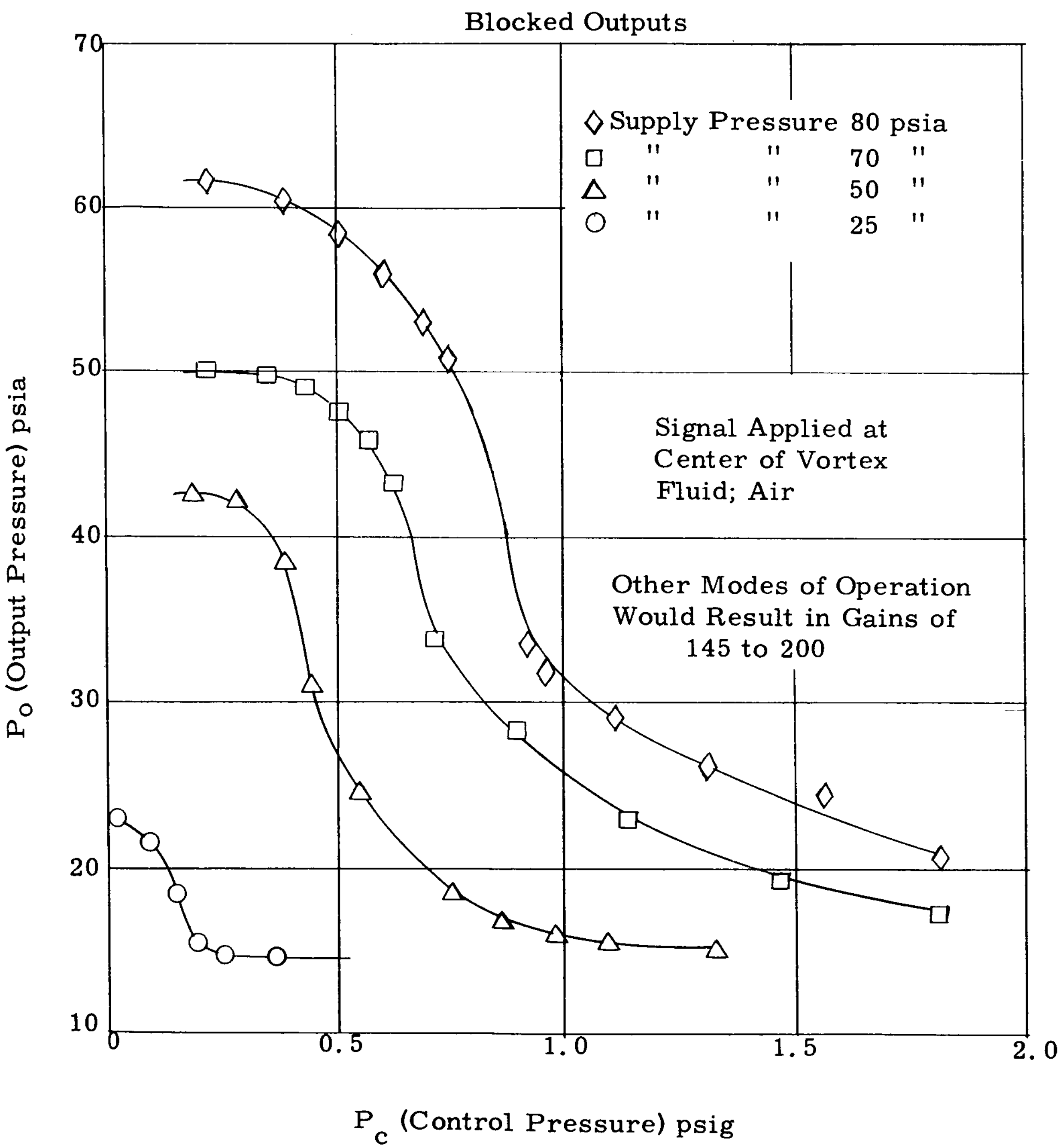
References 5-17 **Report Section** 3.1, 4.1

Remarks:

1.) Report Pressure Gains as High as 200.
2.) See Attached Data.

ELEMENT OUTLINE	SCHEMATIC DIAGRAM
N.A.	N.A.

PERFORMANCE OF TMC VORTEX AMPLIFIER



FLUID ELEMENT DATA SHEET

Type of Element Proportional

Function Flow Amplifier

Manufacturer Marquardt Corp.

Model Number N.A.

Physical Description

- **Overall Size (inches)** N.A.
- **Working Fluids - Gas** N.A. **Liquid** N.A.
- **Power Nozzle - Number** N.A. **Size (inches)** N.A.
- **Control Ports - Number** N.A.
- **Cusps - Number** N.A.
- **Vents - Number** N.A.
- **Output Ports - Number** N.A.
- **Special Features**

Response N.A.

Operating Phenomena N.A.

References 5-17

Report Section

Remarks:

1.) Two Dimentional Device.
2.) A Flow Gain Device, not Intended for Pressure Amplification.
3.) See Attached Data.

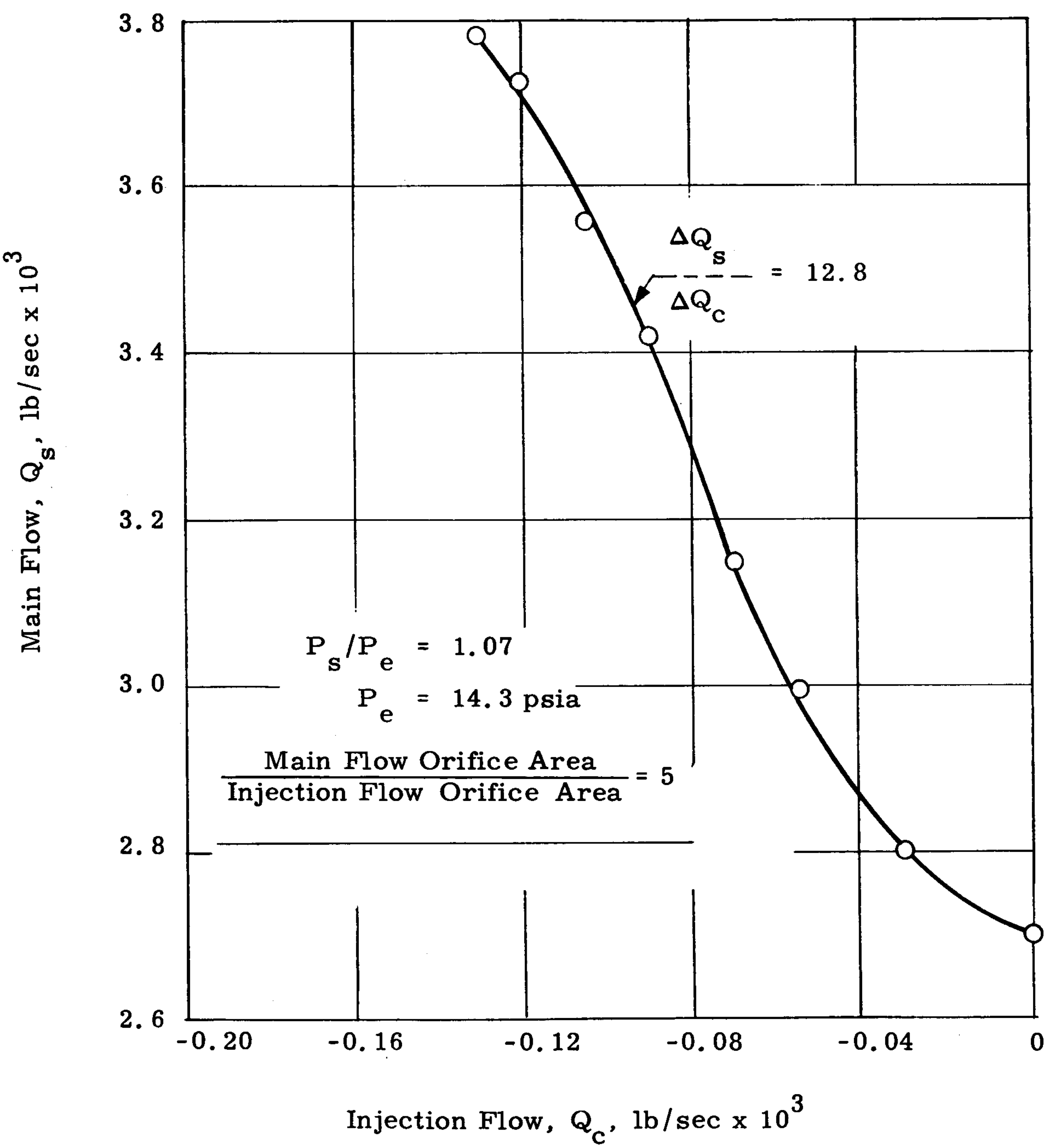
N.A.

ELEMENT OUTLINE

N.A.

SCHEMATIC DIAGRAM

FLOW CHARACTERISTICS OF TWO DIMENSIONAL PURE FLUID AMPLIFYING ELEMENT



FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Amplifier

Manufacturer Minneapolis Honeywell **Model Number** N.A.

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas N.A. **Liquid** N.A.
Power Nozzle - Number 1 **Size (inches)** N.A.
Control Ports - Number 2
Cusps - Number 0
Vents - Number 2-connected as shown below
Output Ports - Number 2
Special Features .

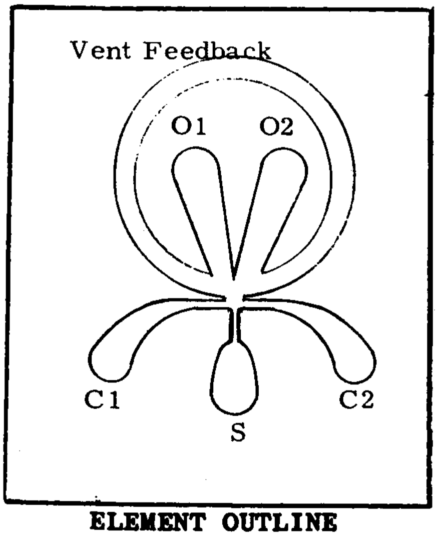
Response N.A.

Operating Phenomena Momentum

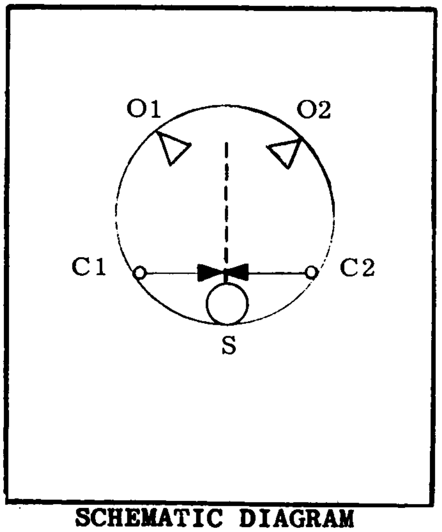
References 5-18 **Report Section** 3.1, 6.1.1

Remarks:

Has pressure gain of approximately 20 while simultaneously maintaining a flow gain of approximately 10.



ELEMENT OUTLINE



SCHEMATIC DIAGRAM

FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Proportional Flow Divider

Manufacturer Moore Products **Model Number** (Several)

Physical Description

Overall Size (inches) Several Sizes
Working Fluids - Gas ____ **Liquid** X
Power Nozzle - Number 1 **Size (inches)** 1/2 to 6 Diam.
Control Ports - Number 2
Cusps - Number -
Vents - Number 0
Output Ports - Number 2
Special Features ·

Response N. A.

Operating Phenomena Wall Attachment (Boundary Layer)

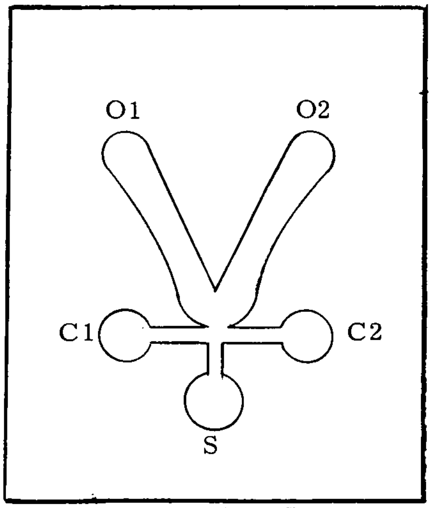
References 5-12 **Report Section** 3.1, 4.2

Remarks:

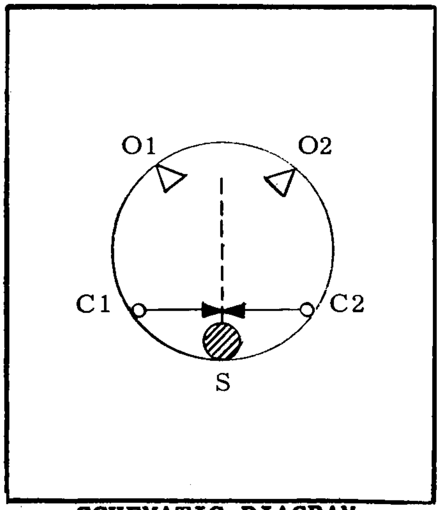
1.) Element outline below is hypothetical, no outline available.

2.) Flow from one output port can be modulated from 0 to 100% of supply flow.

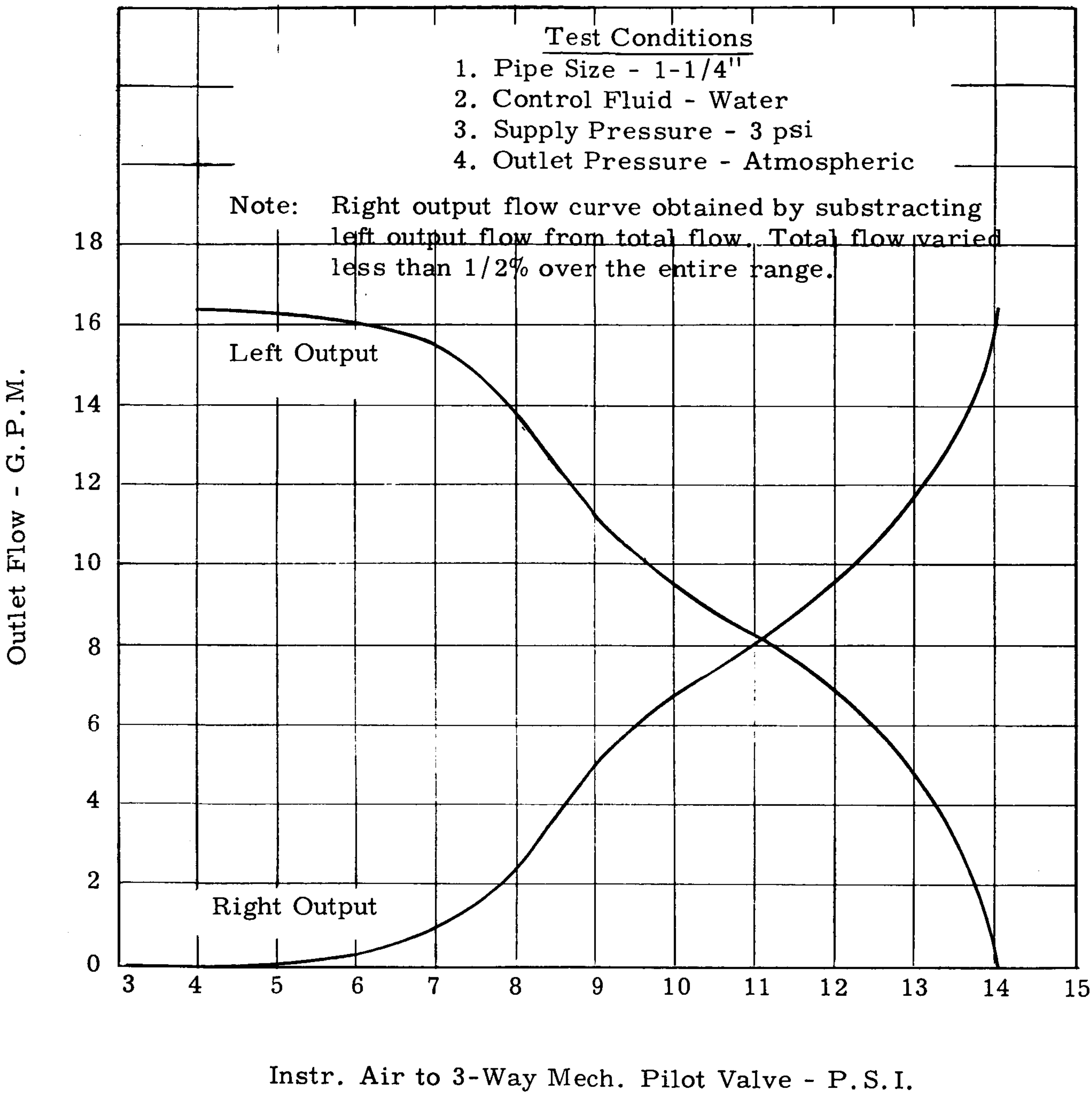
3.) See Attached Data



ELEMENT OUTLINE
(See Remarks -1)



SCHEMATIC DIAGRAM


Test Conditions
1. Pipe Size - 1-1/4"
2. Control Fluid - Water
3. Supply Pressure - 3 psi
4. Outlet Pressure - Atmospheric
Note: Right output flow curve obtained by substracting left output flow from total flow. Total flow varied less than 1/2% over the entire range.
Left Output
Right Output
Outlet Flow - G.P.M.
0
2
4
6
8
10
12
14
16
18
3
4
5
6
7
8
9
10
11
12
13
14
15
Instr. Air to 3-Way Mech. Pilot Valve - P.S.I.

FLUID ELEMENT DATA SHEET

Type of Element Various **Function** Various

Manufacturer Sperry Utah **Model Number** N. A.

Physical Description

Overall Size (inches) N. A.
Working Fluids - Gas N. A. **Liquid** N. A.
Power Nozzle - Number N. A. **Size (inches)** N. A.
Control Ports - Number N. A.
Cusps - Number N. A.
Vents - Number N. A.
Output Ports - Number N. A.
Special Features ________

Response N. A.

Operating Phenomena See below

References 5-2 **Report Section** ________

Remarks:

Device	Fluid Dynamics Effect Exploited	Type			Load Sens.			Gain			Speed			Fabrication		
		Flip-Flop	NOT	Proportional	Sensitive	Mod. Sens.	Insensitive	<5	5 - 10	>10	Fast	Medium	Slow	Easy	Moderate	Difficult
High Speed Logic Device	Proprietary	X			X					X	X				X	
Differential Flow Sensor	Proprietary			X		X				X			X		X	
Improved Turbulence Amplifier	Proprietary		X				X			X			X	X		
Focal Jet Logic Device	Proprietary		X				X		X			X			X	

N. A.

ELEMENT OUTLINE

N. A.

SCHEMATIC DIAGRAM

FLUID ELEMENT DATA SHEET

Type of Element: Digital

Function: See below

Manufacturer: USSR

Model Number: N.A.

Physical Description

- Overall Size (inches): N.A.
- Working Fluids - Gas: N.A. Liquid: N.A.
- Power Nozzle - Number: N.A. Size (inches): N.A.
- Control Ports - Number: N.A.
- Cusps - Number: N.A.
- Vents - Number: N.A.
- Output Ports - Number:
- Special Features:

Response: N.A.

Operating Phenomena: Wall Attachment

References: 5-1

Report Section:

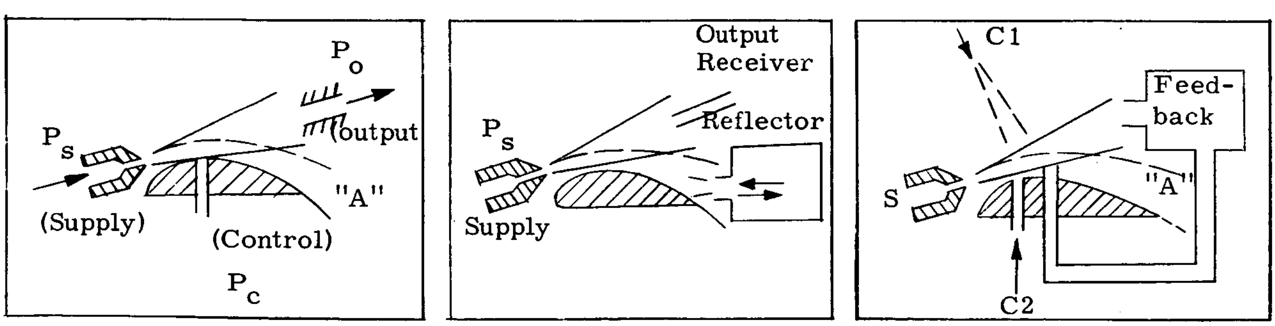
Remarks:

Functions

A. "Relay Cell" performs function of a switch; requires continual control pressure P_c to provide output P_o

B. "Pulse Generator" operates as a free-running oscillator. Transient energy storage in the reflector detaches jet from air foil.

C. "Memory Cell" has flip-flop characteristics. Two stable states exist. C1 is the set port and C2 is the reset port.



FLUID ELEMENT DATA SHEET

Type of Element Proportional **Function** Rectifier

Manufacturer Bowles Engineering Corp. **Model Number** N.A.

Physical Description

Overall Size (inches) N.A.
Working Fluids - Gas N.A. **Liquid** N.A.
Power Nozzle - Number 0 **Size (inches)** N.A.
Control Ports - Number 2
Cusps - Number 0
Vents - Number 2
Output Ports - Number 1
Special Features .

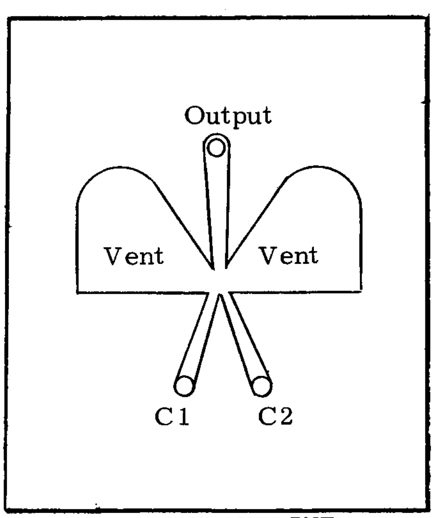
Response N.A.

Operating Phenomena Momentum

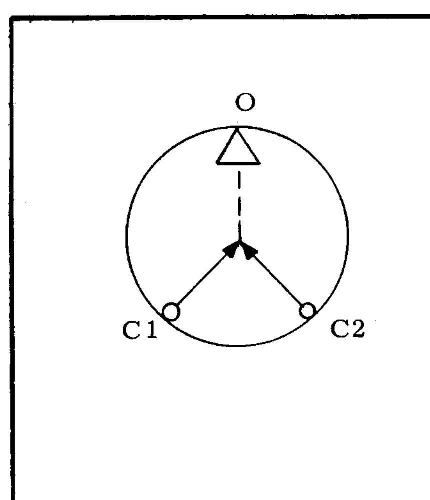
References 5-7 **Report Section** 3.1, 4.4

Remarks:

Signals to C1 dump in the right hand vent, and those to C2 dump in the left vent. If signals are applied to both C1 and C2 they appear at the output. If the signals to C1 and C2 are two different frequencies, the unit provides rectifications so that the output will be the difference frequency.



ELEMENT OUTLINE



SCHEMATIC DIAGRAM

FLUID ELEMENT DATA SHEET

Type of Element ——

Function Diode

Manufacturer MIT

Model Number N.A.

Physical Description

Overall Size (inches) Vortex Chamber 0.75" Dia.
Working Fluids - Gas X Liquid N.A.
Power Nozzle - Number 1 Size (inches) 0.125 x 0.125
Control Ports - Number -
Cusps - Number -
Vents - Number -
Output Ports - Number 1
Special Features

Response N.A.

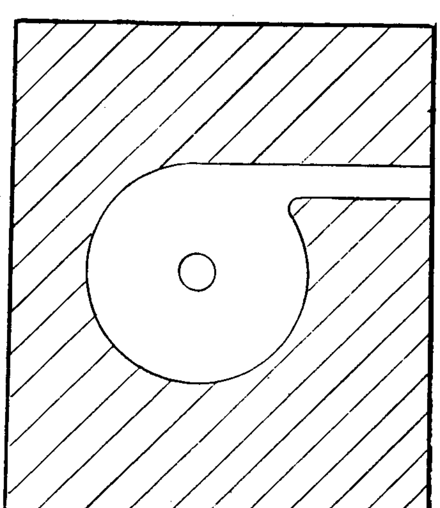
Operating Phenomena Vortex

References 5-25

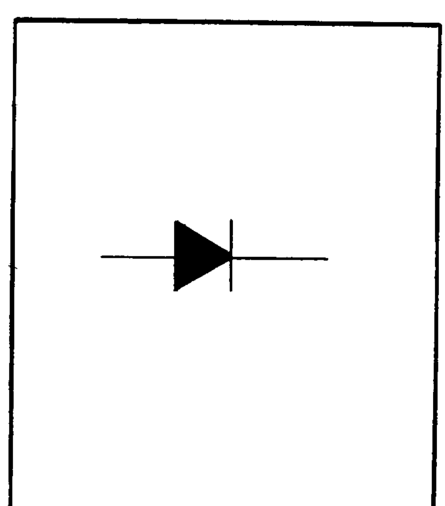
Report Section 3.1, 4.3

Remarks:

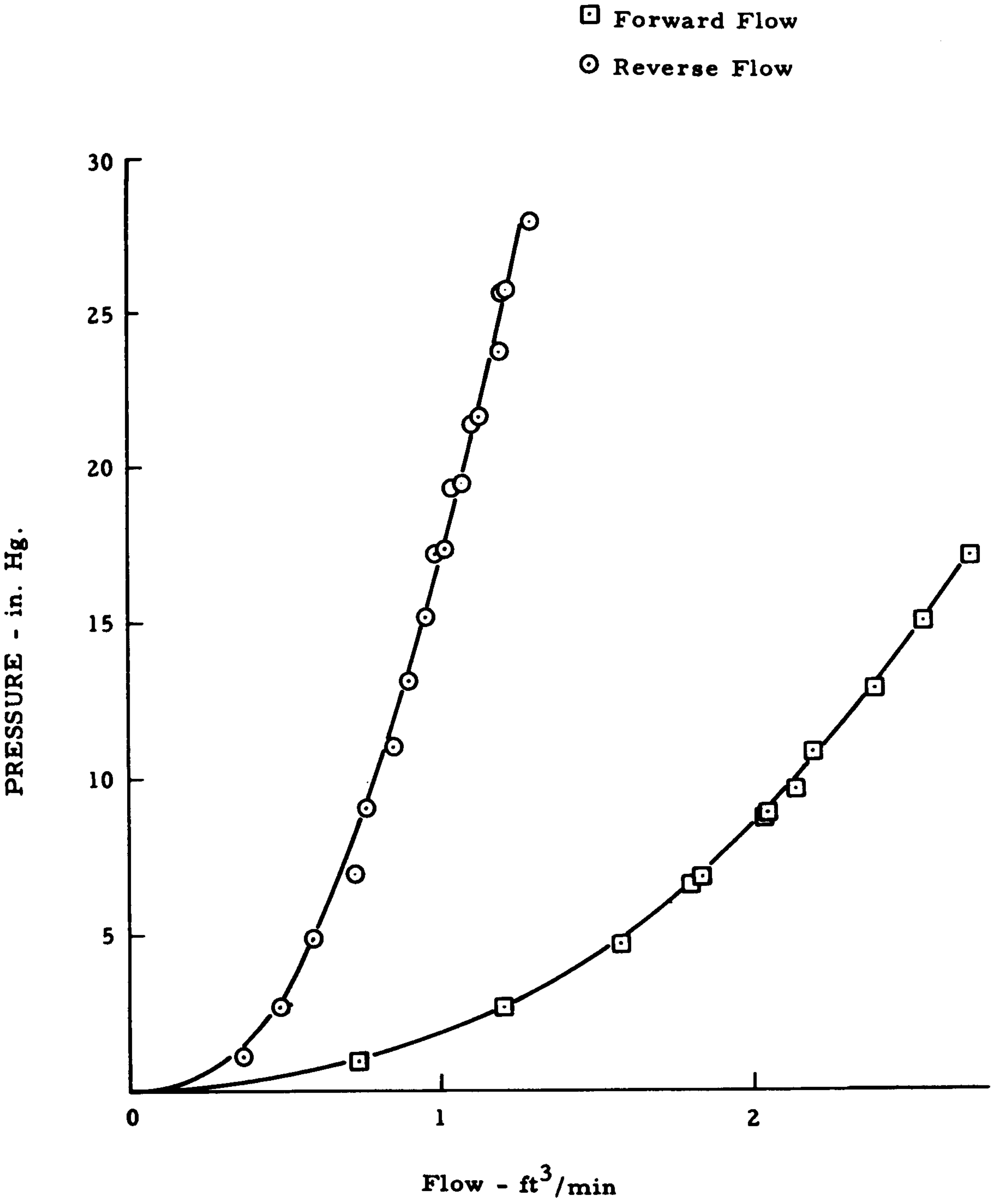
See Attached Data



ELEMENT OUTLINE



SCHEMATIC DIAGRAM



(From Ref. 5-25)

Pressure - Flow Characteristics
Vortex Diode

FLUID ELEMENT DATA SHEET

Type of Element ——

Function Diode

Manufacturer MIT

Model Number N.A.

Physical Description

Overall Size (inches)
Working Fluids - Gas X   Liquid N.A.
Power Nozzle - Number 1   Size (inches) N.A.
Control Ports - Number -
Cusps - Number -
Vents - Number -
Output Ports - Number 1
Special Features

Response N.A.

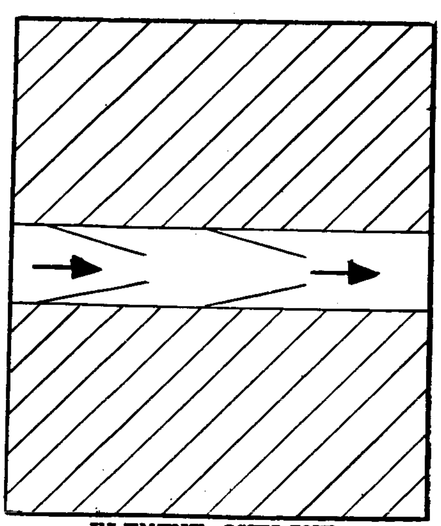
Operating Phenomena Wall Attachment

References 5-25

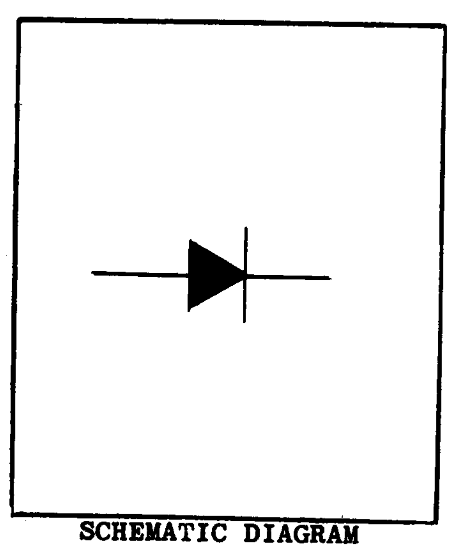
Report Section 4.2

Remarks:

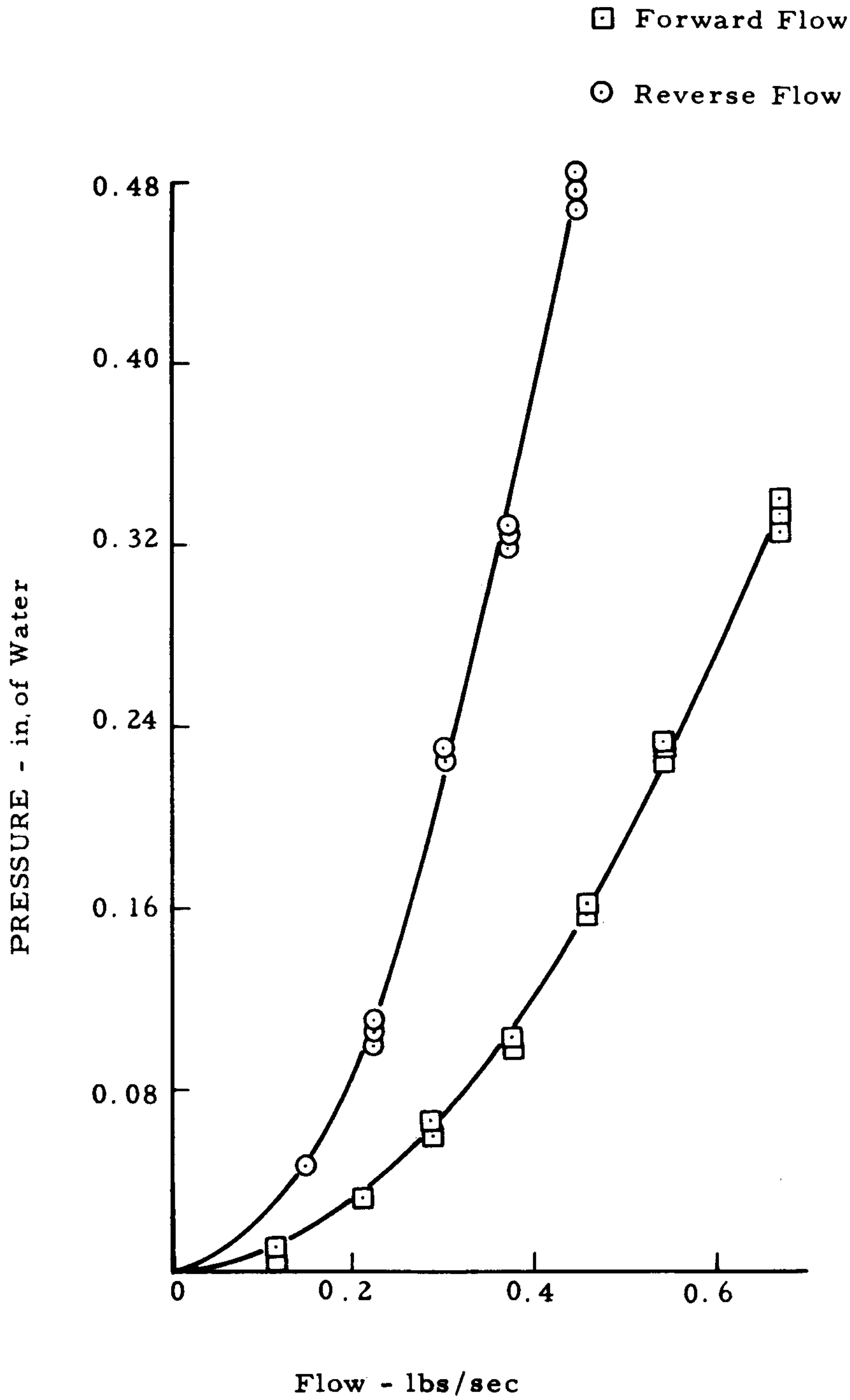
See Attached Data



ELEMENT OUTLINE



SCHEMATIC DIAGRAM



(From Ref. 5-25)

Pressure - Flow Characteristics
Nozzle Diode

REFERENCES

5-1 Aizerman, M. and Tal, A., "New Developments in Pneumoatuomation", International Federation on Automatic Control presented September 1963, Zurich, Switzerland.

5-2 Fox, H.L. and Wood, O.L., "A survey of Fluid Devices for Automatic Control Systems", Paper presented at 6th Region I.E.E.E. Technical Conference, April 26, 1963 (Sperry Utah Co.).

5-3 Information from Bowles Engineering Corp.

5-4 Curtiss, H.A. and Liquornik, D.J., "Research Studies in Proportional Fluid State Control Components" Final Report Contract, DA-36-034-ORD-3722RD, Redstone Arsenal, Alabama (Giannini Controls Corp.).

5-5 Bowles, R.E. and Brown, F.T., "Fluid Systems with no Moving Parts", Paper Presented September 1963, I.F.A.C. Meeting at Zurich, Switzerland.

5-6 Information from Corning Glass Works.

5-7 Colston, J.R., "A Pneumatic Pure Fluid Spud Control For A 500 KW Steam Turbine Generator", Bowles Engineering Report (Contract NONR-4033 (00) dated September, 1963.

5-8 Information from Computer Department, General Electric Co.

5-9 Van Tilburg, R.W. and Cochran, W.L., "Fabrication of Fluid Amplifiers by Optical Fabrication Techniques", Corning Glass Co. First Progress Report, Ending December 31, 1962 for Harry Diamond Lab. Contract No. DA-49-186-ORD-1076.

5-10 Auger, R.N., "Turbulence Amplifier Design and Application" Proceedings of the Fluid Amplification-Symposium, October 1962 Vol. I-DOFL-Washington, D.C.

5-11 Dexter, E.M., "An Anolog Pure Fluid Amplifier", ASME Symposium Report (Fluid Jet Control Devices, Dated November 28, 1962.

5-12 Information from Moore Products Co.

5-13 Experimental Design of a Fluid Controlled Hot Gas Valve, U.S. Army Missile Command, Redstone Arsenal, Alabama, Report No. RE-TR-62-9 also N6319598.

5-14 Information from the Advanced Technology Laboratories, General Electric Co.

5-15 Information from Harry Diamond Laboratory.

5-16 Bauer, P., Pure Fluid Digital Logic with a Single Switching Element Proceedings of the Fluid Amplification Symposium, October 1962, Vol. I - (DOFL) Washington, D.C.

5-17 Information from the Marquardt Corporation.

5-18 Information from the Minneapolis Honeywell Regulator Co.

5-19 Lechner, T.J. and Wambaganss, M.W., Proportional Power Stages for Impedance Matching Pure Fluid Devices,Proceedings of the Fluid Amplification Symposium, October 1962, Vol I, (DOFL) Washington, D.C.

5-20 Information from Johnson Service Co.

5-21 Katz, S. and Dockery, R.J., "Generalized Performance Characteristics of Proportional and Bistobb Fluid Amplifiers", Harry Diamond Lab Report R-RCA-63-13 dated April 17, 1963.

5-22 Dexter, E.M., "A Technique for Matching Pure Fluid Components Applied to the Design of a Shift Register", Proceedings of the Fluid Amplification Symposium DOFL, October 1962.

5-23 Information from The Advanced Technology Laboratories, General Electric Company.

5-24 Information from the Bendix Corporation.

5-25 Brown, F.T., et al "Research and Development of Pneumatic Jet Relay System for Propulsion System Control". Summary Report No. DSR 9159-1, USAF Contract AF 33(657)-8384, March 31, 1963 (MIT).

6.0 ASSEMBLIES , SENSORS, AND TRANSDUCERS

Assemblies are defined as fluid amplifier circuits which perform an often used standard function. Many of the assemblies discussed below are in the development stage and involve proprietary information and therefore details are not available. In some cases the only available information is the fact that the work is being carried on. All known work is included, however, for completeness. Descriptions of assemblies which are classified are given in Volume III. Unless noted by a reference, the information below was obtained by personal contact with the development laboratory.

6.1 Digital Assemblies

6.1.1 Oscillators and Multivibrators

The multivibrator is distinguished from the oscillator in that a digital element is used to produce switching and, as a result, the oscillatory output approaches a square wave at lower frequencies. Both the proportional and digital amplifier function as a free running oscillator by incorporating some form of negative feedback Some of the more common circuits are shown schematically in Figure 6.1. The type shown in sketch (a) uses lengths of lines attached to the control ports with the opposite ends open to the ambient. The line length must be adjusted to result in oscillation. The type shown in sketch (b), in which the control ports are interconnected, is less critical in line length and is more commonly used than (a). The type illustrated in sketch (c), using external feedback from output to input, is the most common circuit. The feedback path in an oscillator need not be external to the element. An oscillator under development at Wright-Patterson Air Force Base and HDL uses internally reflected waves to produce switching. An analysis of the criteria necessary for free running oscillation is presented in reference 6-1.

Specific examples of oscillator and multivibrator work are as follows:

1) Griffin[6-2] at MIT used a multivibrator to synchronously drive a notched wheel for a gyro drive. The multivibrator oscillated at 1330 cps with a 40 psig air supply.

2) General Electric has on life test a multivibrator operating on 1 psig shop air. The device is two-stage as shown in Figure 6.2. It has accumulated over 8700 hours of operation at 260 cps with no noticeable changes in characteristics. The test was initiated to determine the life of fluid amplifiers fabricated from epoxy. The nozzle cross-sectional dimensions are 40 mil x 40 mil.

3) Bowles Engineering Corp. has reported an oscillator operating at frequencies as high as 10^5 cps. The concept of the oscillator is not known.

4) The effect of ambient temperature and supply gas temperature on the frequency of a multivibrator is under study by General Electric in work for Picatinny Arsenal[6-3]. Figure 6.3 illustrates the temperature and pressure characteristics of one oscillator studied.

5) H.D.L. and Wright-Patterson Air Force Base are developing an oscillator for use as a temperature sensor. The oscillator uses internal feedback and is very insensitive to supply pressure changes.

6.1.2 Shift Registers

Shift register circuits utilize flip-flops connected in series, with gates between each flip-flop to block the flow of information as shown in Figure 6.4, a typical circuit. The gates are pulsed simultaneously to advance the information one stage for each "clock" pulse. Particular care must be taken to assure that the information is advanced only one stage for each clock pulse. In Figure 6.4 half adders serve as the gates. The volumes (C) and restrictors (R) provide a delay. The width of the clock pulse (T) must be somewhat shorter than the time constant of this delay in order to prevent multiple shifts. However, the clock pulse must be of sufficient duration to provide reliable switching of the flip-flops. Therefore, the width of the clock pulse can be quite critical. A circuit that alleviates this problem is shown in Figure 6.5. Two clock pulses are now used, T and $\overline{T}$ and the clock is arranged to have only one of these present at any given time. When a T pulse is applied, information is shifted into the primary storage flip-flop but can progress no further since $\overline{T}$ is not present. When $\overline{T}$ is applied (T is now absent) the information is shifted into the secondary storage flip-flop. Finally, the information is shifted out of this stage with the application of a second T pulse at the succeeding stage. This "push-pull" clocking arrangement prevents multiple shifts and clock pulse widths are not critical from the standpoint of reliable switching. The secondary storage type circuit, however, does require twice as many storage elements and gates as compared to the delay shift register.

Some shift register work has been revealed. Available information is summarized below.

1) General Electric has developed a shift register for use in industrial conveyor applications (see section 7.2.5 for a description). The shift register circuit is the intermediate storage type. The fluid used is air at supply pressures of about 1 to 2 psig. The shift register modules have been tested at 200 cps. For the intended application the operating speeds will be much lower, and reliability is of primary importance. A buffer amplifier is used between shift register stages to provide high switching reliability and to provide power to drive externally attached coincidence logic. A demonstrator capable of shifting 4-bit information through 20 stages is being fabricated.

2) IBM, Zurich, has designed a novel shift register circuit[6-4] illustrated in Figure 6.6. The circuit utilizes secondary storage

(an auxiliary cell) but requires only a positive clock signal (S). An $\bar{S}$ signal is not required for shifting into and out of secondary storage. When the clock signal, S, is relaxed, information passes from the main cell into the auxiliary cell. Application of S blocks information from entering the auxiliary cell and gates information out of this cell into the following main cell. Performance data on this shift register is not available.

3) Bowles Engineering Corp. has described[6-5] a shift register circuit using a "twin AND" element (see Figure 6.7) for use as the gate between flip-flop storage elements. The twin-AND utilizes a momentum summation to produce a beam at an angle to impinge on a receiver. This element would appear to require careful adjustment of the signal and clock flows to result in proper beam deflection for good recovery. Performance data were not revealed.

4) General Electric fabricated and tested a shift register circuit utilizing switches and OR-NOR elements. Air supply pressure for the register can range from 0.5 to 1.5 psig. In order to obtain a measure of reliability, several register stages were interconnected output to input of each succeeding stage to form a ring circuit. Information was shifted around the ring for over a million shifts without the loss of the information. The flip-flop used in the circuit was similar to that shown in section 5 (listed under G.E. Computer Dept.).

6.1.3 Counters

The type of counter which apparently has been receiving the most attention utilizes the binary flip-flop developed by Warren[6-6], although other types are also under development. Examples of counter work are listed below:

1) HDL is continuing fundamental work on counters using the Warren binary flip-flop. Dependable operation has been achieved to 250 cps.

2) Univac is making a parametric study of the HDL binary flip-flop[6-6] and developing a circuit analysis to provide better staging of the counter elements. A three-stage counter will be fabricated as a final phase of the program. The fluid used in this study will be air.

3) Bowles Engineering Corp. has developed a counter for operation on air with a supply pressure range of 0.1 psig up to 10 psig. Operating speed is at least 200 cps. The concept is not identified.

4) The General Electric Computer Department has developed a frequency divider or ring counter. The concept is illustrated in the block diagram, Figure 6.8. The flip-flops are essentially shift register stages (flip-flops with gates on the control ports). The register stages are connected output to input so that information progresses around the loop as

shift pulses are applied by the pulse generator. The oscillator frequency is divided by four in this case. The use of a single flip-flop would divide the frequency by two for binary uses. Air supply pressure generally used is in the range of 0.5 to 1.5 psig. This type of frequency divider has been operated at 200 to 300 cps.

5) The General Electric Advanced Technology Laboratories are developing an HDL type binary counter for use in a timer for ordnance applications[6-3]. A buffer, or amplifier stage, is used between the binary flip-flops to isolate the counter stages and assure reliable operation. Operating speed up to 250 cps is required. The fluid used is air.

6) Univac is developing a timer which utilizes a counter for the Sandia Corporation. Further information on the timer or application is not available.

6.1.4 Adders

As described in section 3.3, two half-adder elements may be cascaded to provide a full binary adder stage. These stages are then interconnected as shown in Figure 6.9 to provide the required bit capacity. This particular circuit uses the wall attachment half-adder and includes a buffer, or amplifier stage, to help isolate the adder stages. An example of the addition process is illustrated. Signals representing the sum will appear at the "C" ports. The decimal equivalent is shown in parentheses at each "C" port. The three known adder circuits are described below.

1) General Electric Company has fabricated and tested a circuit similar to that shown in Figure 6.9. Input capacity was four bits. The assembly operated on air with a supply pressure of the order of 4 psig. The initial model used elements with 40 mil x 40 mil nozzle cross-sectional dimensions. A later version used elements with 10 mil x 10 mil nozzles and the buffer amplifiers were eliminated.

2) IBM, Zurich, has designed an adder circuit[6-4] using a stacked geometry as shown in Figure 6.10. The circuit shown in sketch (a) illustrates the use of an OR element to generate the carry signal. Its function is similar to the buffer stage shown in Figure 6.9. Performance data on this binary adder were not available.

3) General Electric has assembled an adder using flip-flops and OR-NOR logic elements in a circuit similar to the electronic counterpart. Low pressure air was used as the fluid source (0.5 to 1.5 psig).

6.1.5 Other Digital Assemblies

Other noteworthy digital assemblies being developed are itemized below.

1) A three-stage digital amplifier was designed and tested by DOFL[6-7]. The maximum calculated output power for an input pressure of 15 psig was about 950 watts. Power gain at this point was calculated to be about 8000 to 9000.

2) A coder was designed and demonstrated by General Electric. A punched card is inserted into the device to provide the desired coding (e.g., binary, Gray). The coder could be used on teletypes, for example, to convert the keyboard information to the desired pneumatic code.

6.2 Proportional Assemblies

6.2.1 Staged Amplifiers

Staged proportional amplifiers have been described for use in two general areas; 1) Applications in which large output power is to be controlled with small signals, and 2) Operational amplifiers where high gain is desired to generate functions more accurately with input and feedback impedances.

A staged amplifier for power control is described by Palmisano[6-8] for use in an HDL demonstration vehicle. The amplifier assembly uses five stages to provide an overall gain of 100,000. The unit operates on 40 psig air. It was used on the vehicle to demonstrate reaction steering with small input signals (.0045 lbs/min. maximum input).

Information on staged proportional amplifiers for use as operational amplifiers is quite limited. The following listing identifies some of the known laboratories that have used or are using staged amplifiers as operational amplifiers:

1) Bowles Engineering Corp. - 3 stage and 6 stage available.

2) Corning Glass Works - 5 stage amplifier to be marketed shortly. (Outline is shown in Figure 6.11)

3) Johnson Service Company has cascaded the three-terminal amplifiers (described by Lechner in reference 6-9) and have used them as operational amplifiers. The use of a high flow gain diaphragm relay was necessary for impedance matching.

4) Johnson Service Company under contract from HDL is refining a high gain amplifier (concept proprietary) for use as an operational amplifier. The stage pressure gain is of the order of 200 with low noise characteristics and a high input impedance.

6.2.2 Feedback Techniques, Integrators, Differentiators

Information of forward and feedback circuits for operational amplifiers to generate functions such as integrators and differentiators is practically non-existent.

The Johnson Service Company, using the staged amplifier with relay described above, has developed circuits to provide constant gain, differentiation and integration. A resistive feedback line for obtaining constant gain improved linearity and eliminated hysteresis from the diaphragm relay. The differentiator and integrator block diagrams are illustrated in Figure 6.12. A third order differential equation was solved using the differentiators (better performance than integrators). The solutions had errors of the order of 10% which were expected because of the unrefined design.

Feedback was used by both Colston and Boothe in their respective speed control designs (see section 7.34 and 7.35) to produce a lead-lag circuit. The lead-lags were used for stabilization. The circuit uses negative feedback through a restrictor and pneumatic capacitance. Thus high frequency components of the feedback are attenuated and high forward gain results. The low-frequency feedback signals are not attenuated and limit the gain of the amplifier.

6.3 Sensors

Aside from the work on rate sensors, little work has been done or at least revealed on these devices. As a result of visits and contacts, it has been learned that laboratories have or are developing certain sensors. The concepts are proprietary or are in such a fundamental stage of development that the only information available in most cases was that a specific sensor was being developed. Following is a summary of sensors and the laboratories carrying out work on them. The reader is referred to Volume III for classified information on the vortex rate sensor and the concept of another sensor.

6.3.1 Angular Rate

The major effort on sensors has applied to the vortex rate sensor[6-10]. Performance data is classified, however, and a pickoff at the center of the device developed by Minneapolis-Honeywell Regulator Company is classified, proprietary and has a patent secrecy order on it. The principle of the device is simply to use a free or potential vortex to amplify the angular rate of the outer periphery. The major problem is apparently to obtain an adequate signal-to-noise ratio from the pickup near the center of the vortex. This sensor is discussed in more detail in Volume III (classified). Laboratories developing vortex angular rate sensors include:

The Harry Diamond Laboratories

Minneapolis-Honeywell Regulator Company

Bowles Engineering Corporation

Bendix Corporation

Development Laboratories Inc.

6.3.2 Pressure Ratio

The use of a vortex for a pressure ratio sensor has been studied by HDL[6-11]. Experimental work indicated that the static pressure at the center of the vortex, P_e, varied approximately as:

$$P_e = \log P_1$$

where P_1 was the supply pressure at the outer periphery of the vortex chamber. Two units were used and the difference in center pressures, ΔP_e, was the output signal with input signals applied at the outer peripheries. Thus,

$$\log P_1 - \log P_2 = \log P_1/P_2 = \Delta P_e$$

or $$P_1/P_2 = \text{antilog } \Delta P_e$$

where P_2 is the second input pressure. The performance of the device is illustrated in Figure 6.13.

Other laboratories investigating pressure and pressure ratio sensors included

Minneapolis-Honeywell Regulator Company

Bowles Engineering Corp.

6.3.3 Temperature

The frequency of an oscillator or multivibrator is a function of temperature. Signal in the feedback paths propagates at acoustic velocities and therefore varies as the square root of absolute temperature. This characteristic is shown in Figure 6.3. The frequency of an oscillator is also a function of pressure as shown in this plot. HDL and Wright-Patterson Air Force Base have been developing an oscillator for use as a temperature sensor which is relatively independent of pressure for supply pressure ranging from about 15 psig up to 60 psig. A listing of those known to be developing a temperature sensor include:

HDL and WPAFB

General Electric

Bowles Engineering Corp.

Bendix Corp.

6.3.4 Other Sensors

Stall Sensor - MIT is studying a stall sensor concept for use on jet engines. The concept utilizes a high response flip-flop which senses stall "cells" that rotate at an angular velocity past the sensor when incipient compressor stall is reached. One control port is designed for high response while the signal passing through the other control port is filtered with a restrictor and volume as shown in Figure 6.14. This arrangement results in a pulse-width modulated signal from the flip-flop. The pulse width depends on the size of the stall cell. The desired information, the pulse width modulation, is independent of pulse rate (stall cell rotational velocity). The signal can be filtered or used to drive a digital-to-analog converter to obtain an analog signal.

Bendix Corporation is also developing a stall sensor. The concept and performance are not known.

Enthalpy Sensor - Bowles Engineering Corporation is developing an enthalpy sensor. The concept and performance are unknown.

Liquid Level - Bowles Engineering Corporation is developing a liquid level sensor. General Electric has tested a liquid level sensor which utilizes a flip-flop for the principal element. The open-end of a line, attached to one control port, is placed at the desired level of the liquid. If the liquid level is low the open end aspirates ambient air into the flip-flop control port. When the liquid covers the open end of the line, switching of the flip-flop occurs. The flip-flop is powered with water.

6.4 Transducers

Transducers will be required in systems where fluid amplifier circuits must be coupled to systems using media other than fluid power for operation. The most common transduction required perhaps will be fluid/electrical and electrical/fluid. Transducers will be needed where mechanical systems are involved. These, however, will probably involve moving parts because of the nature of the system. For example, an input transducer could be a flapper-nozzle arrangement which involves moving (but no sliding) motion. The available information on transducers is listed below:

6.4.1 Electrical-Pneumatic Input Transducers

1) General Electric developed[6-13] an "arc" transducer which utilizes the wave front generated by an electrical discharge to switch a flip-flop. The electrodes were placed in the control ports. The major disadvantage with this concept is the high power consumption for typical duty cycles.

2) HDL devised a thermal transducer which uses an electrically heated coil to heat the gas in the control port and thus cause switching. The response was slow - up to tenths of a second.

3) Another concept under consideration by HDL is the use of high frequency acoustic energy (from a voice coil type driver) to change the flow around a cylinder. The flow change could then be used for the fluid input signal. The basic concept of utilizing acoustic energy in the boundary layer is not well understood.

4) Input transducers have been fabricated by General Electric using piezoelectric materials. Although the concept utilizes moving parts (flapper-nozzle) the power consumption is very small, making the concept attractive.

5) Bowles Engineering Corporation is understood to have an electro-pneumatic input transducer.

6.4.2 Pneumatic-Electrical Output Transducers

1) General Electric has used the hot wire anemometer principle for an output transducer.

2) Bowles Engineering Corporation has marketed an output transducer that utilizes a reed switch operated by a permanent magnet. The magnet is incorporated in a small piston driven by pressure difference, thus moving parts are involved.

3) Univac has developed an output transducer. Concept and performance are unknown.

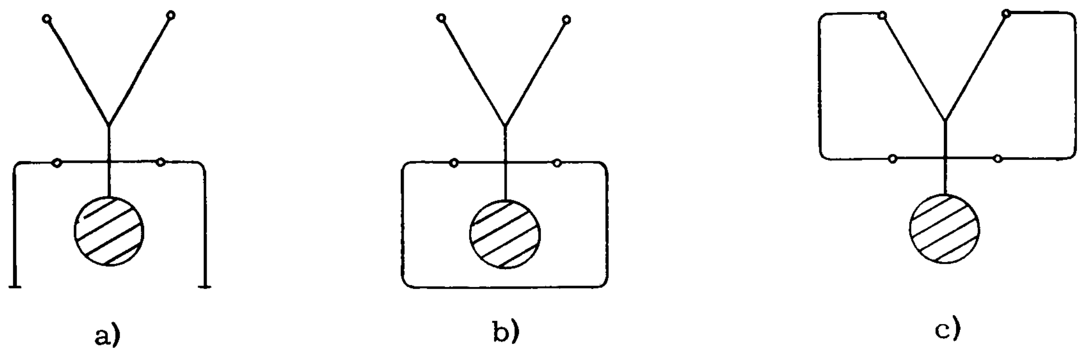


Figure 6. 1 Multivibrator Circuits

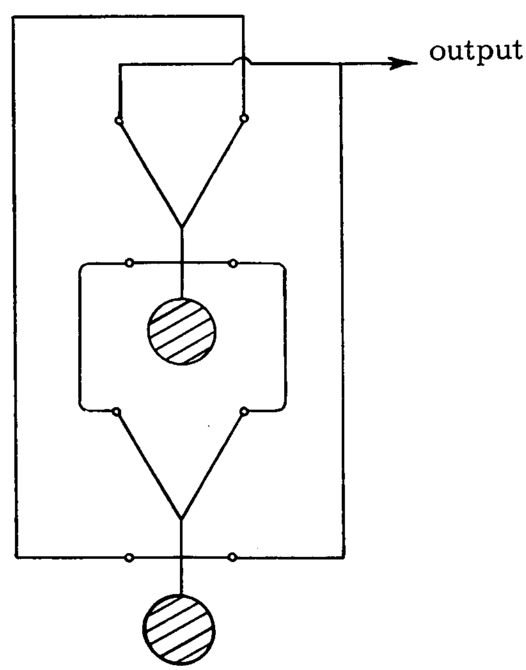


Figure 6. 2 Two Stage Multivibrator

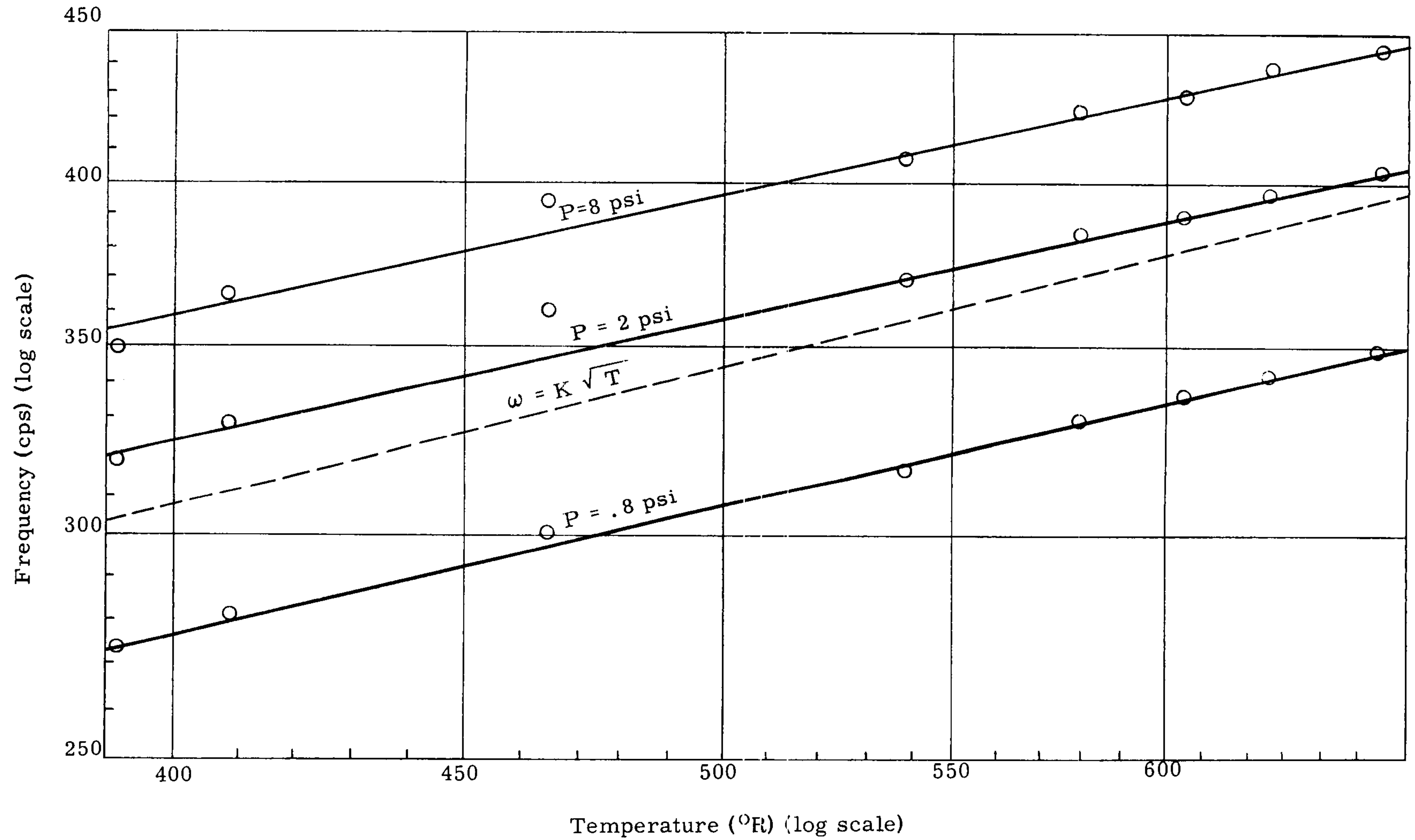


Figure 6.3 Temperature and Pressure Characteristics of a Multivibrator

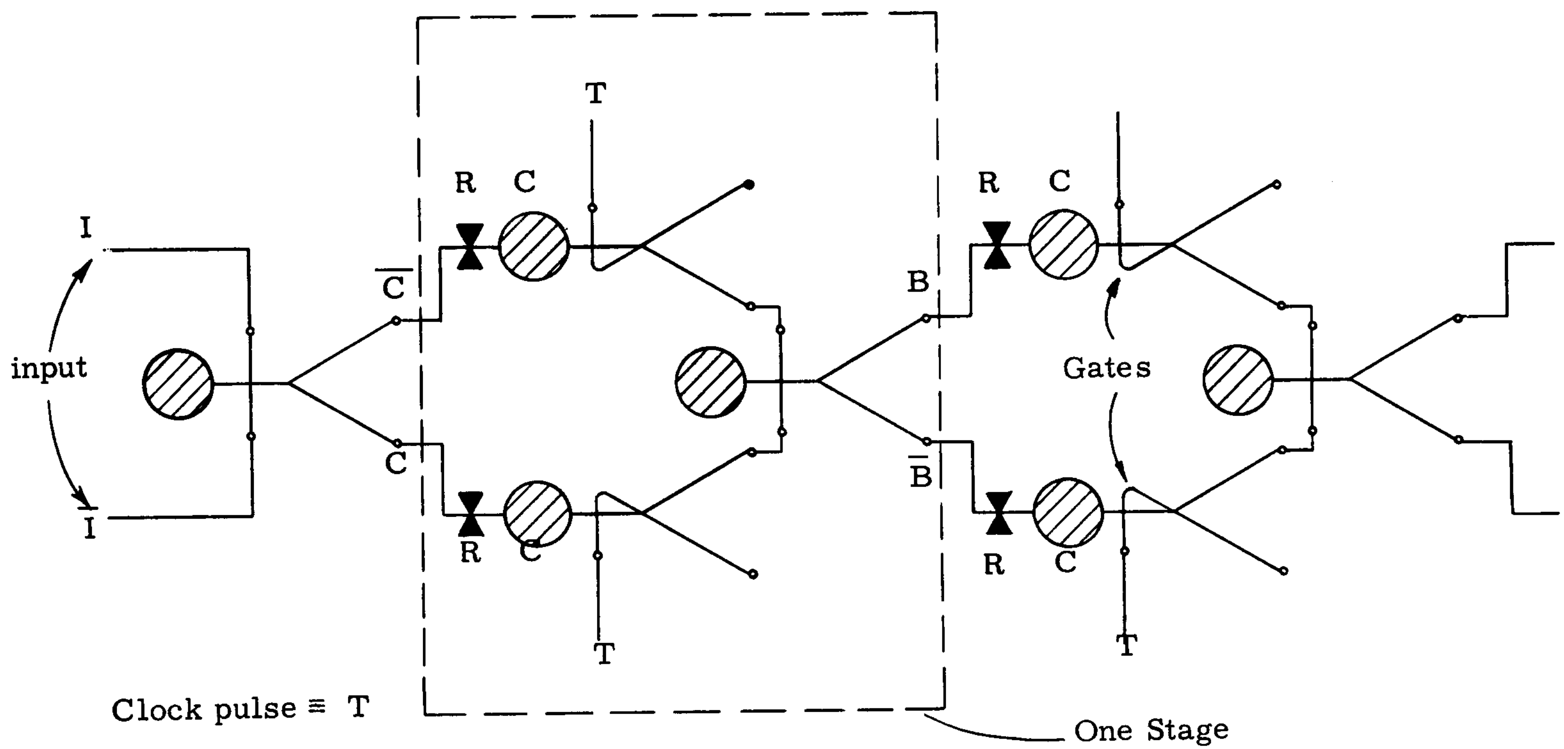


Figure 6.4 Shift Register Circuit Using Delays and Gates

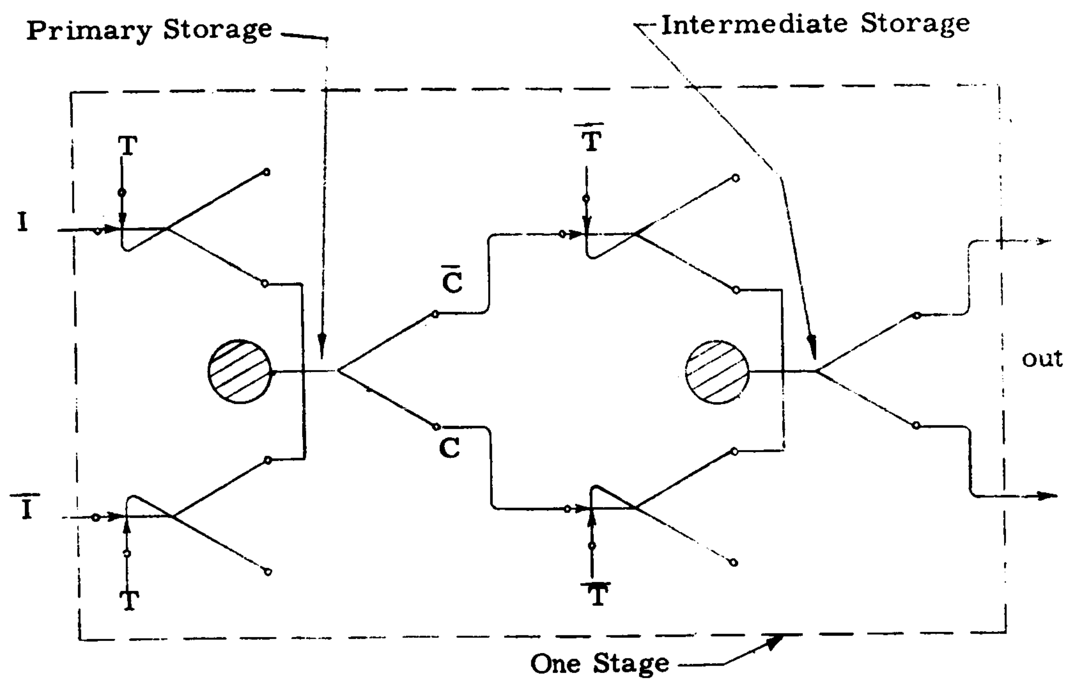
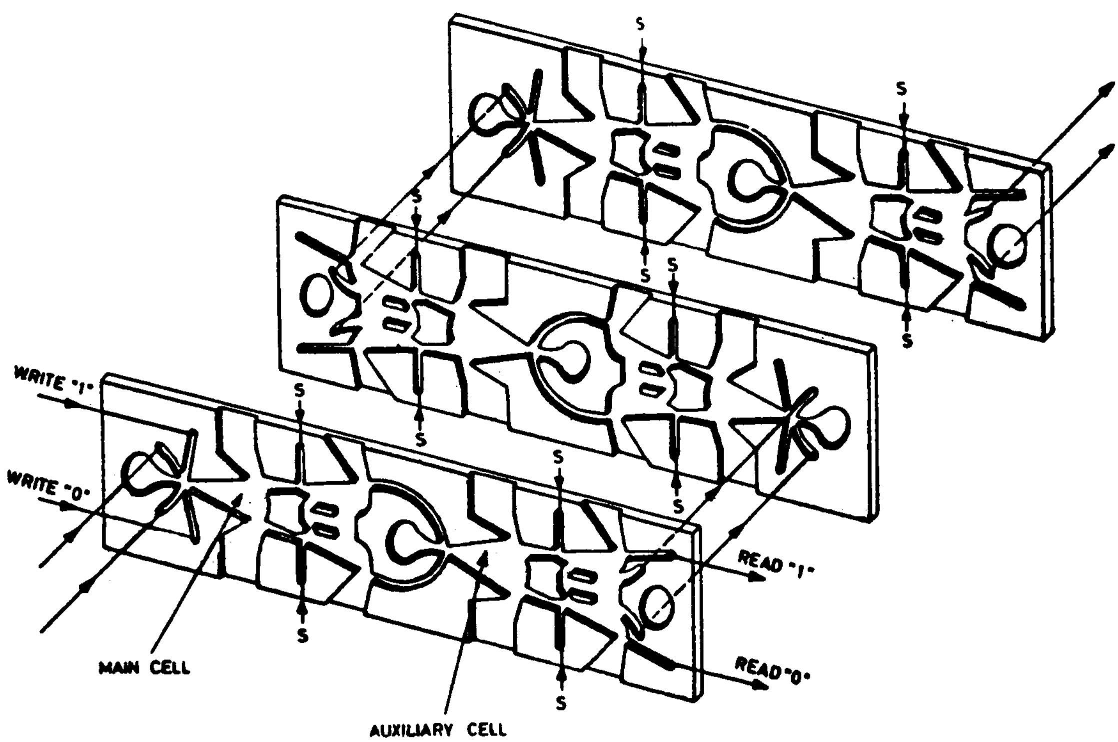


Figure 6. 5 Shift Register Using Intermediate Storage



Circuit diagram of shift (3 stages)

Figure 6. 6 Secondary Storage Shift Register (from reference 6-4)

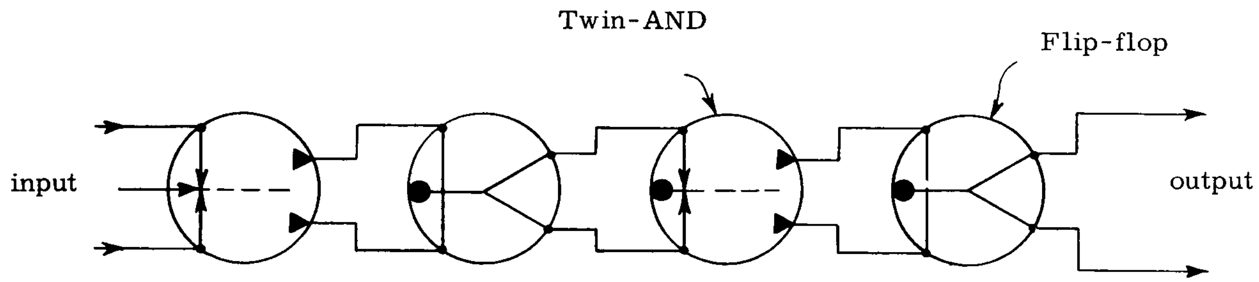


Figure 6.7 Shift Register Circuit Using Twin-AND Gates

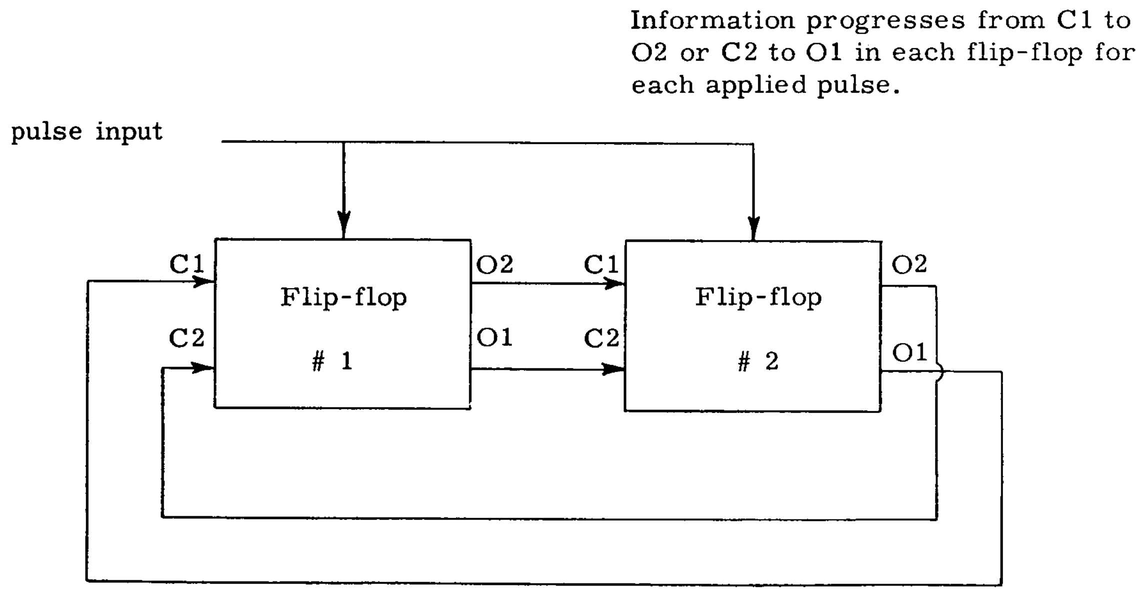
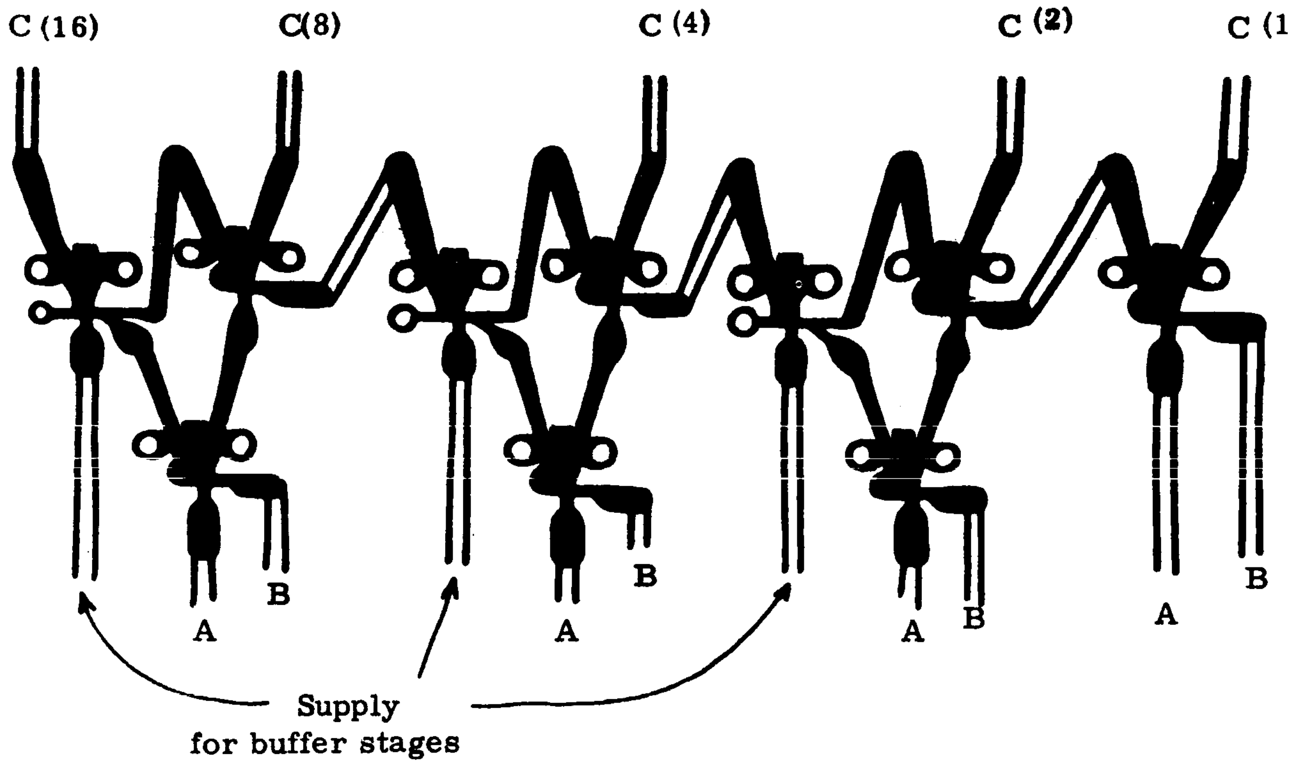


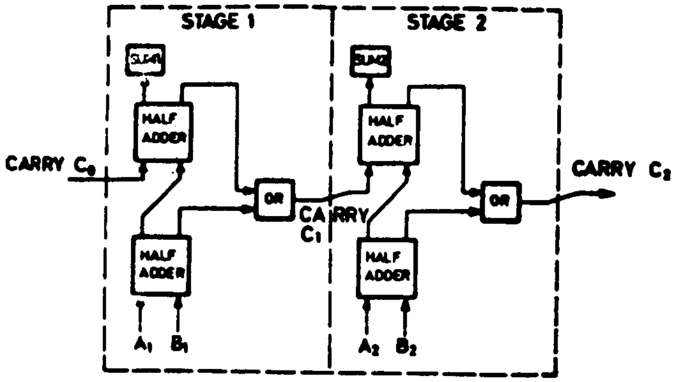
Figure 6.8 Frequency Divider Block Diagram



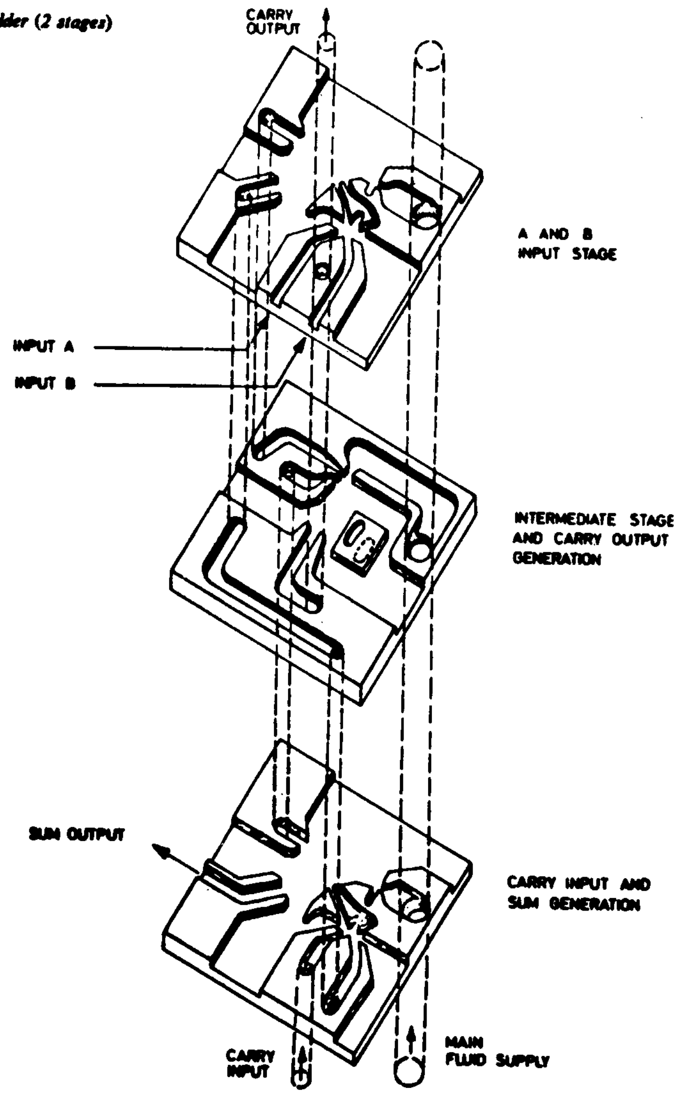
EXAMPLE

Number	A		0	1	1	0
Number	B		1	0	1	1
Sum	C	1	0	0	0	1

Figure 6.9 Adder Circuit



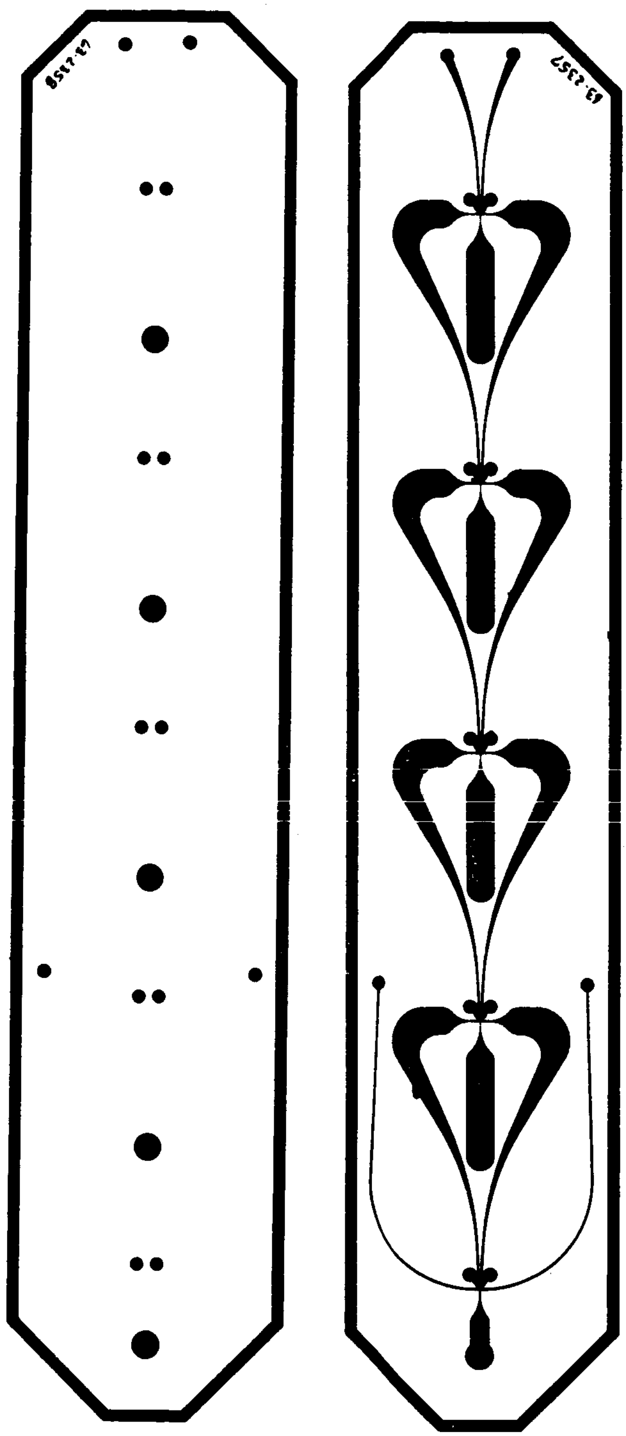
(a) Circuit diagram of Full Adder (2 stages)



(b) Exploded view Binary Full Adder

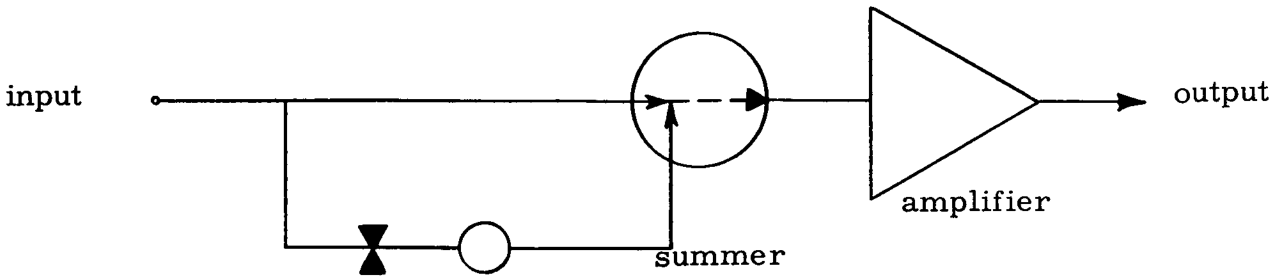
(from ref. 6-4)

Figure 6.10 Binary Adder Stage

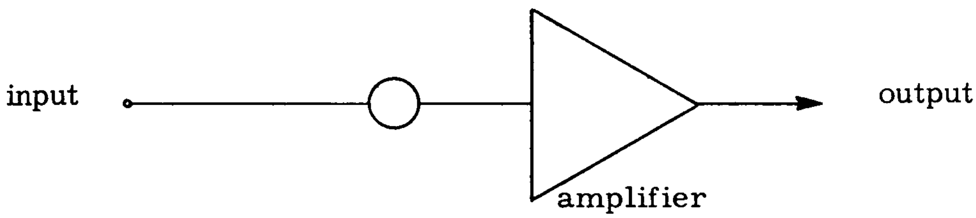


(Information from Corning Glass Works.)

Figure 6.11 Staged Proportional Amplifier



Differentiator



Integrator

Figure 6. 12 Differentiator and Intergrator Circuits

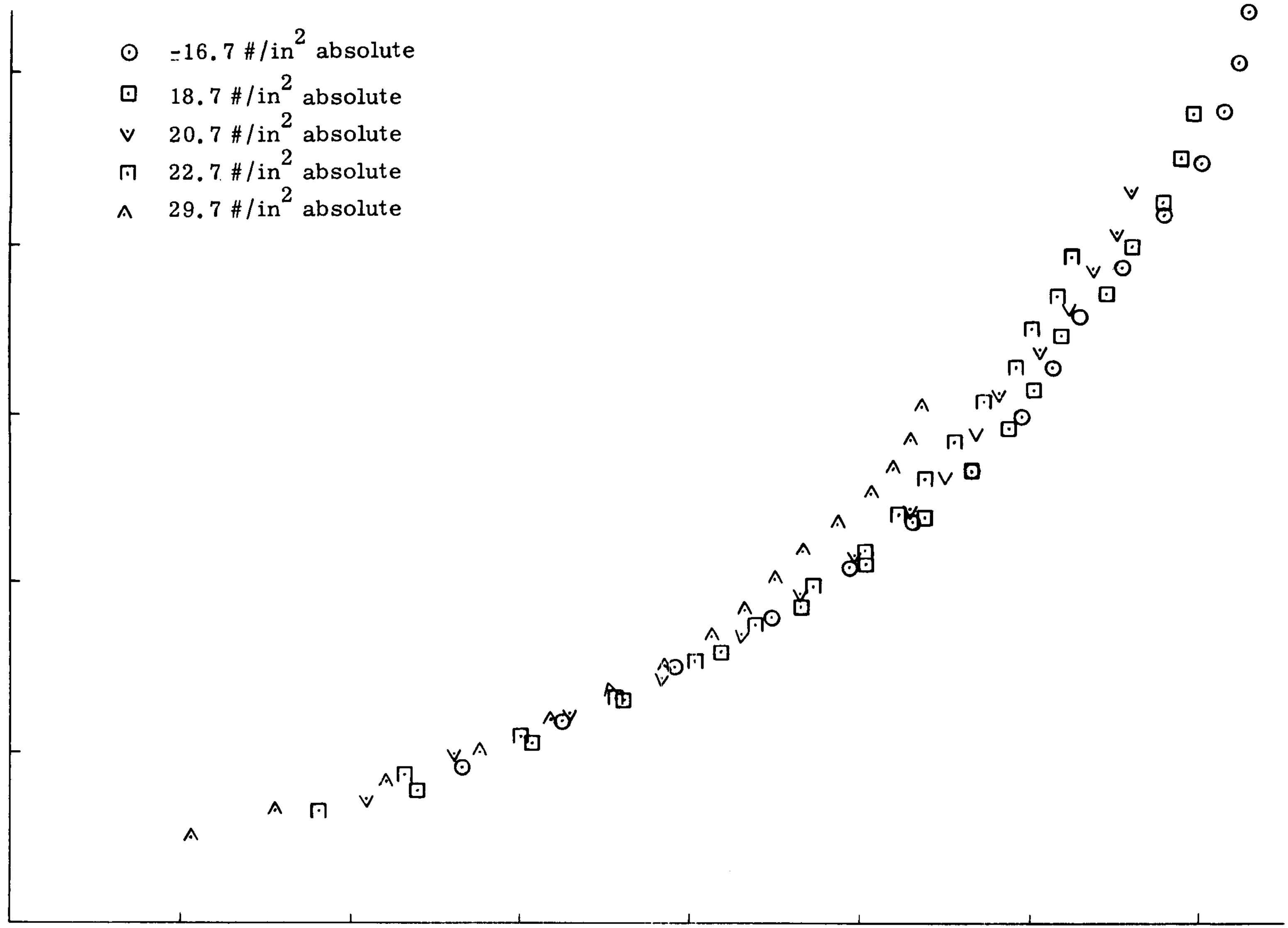
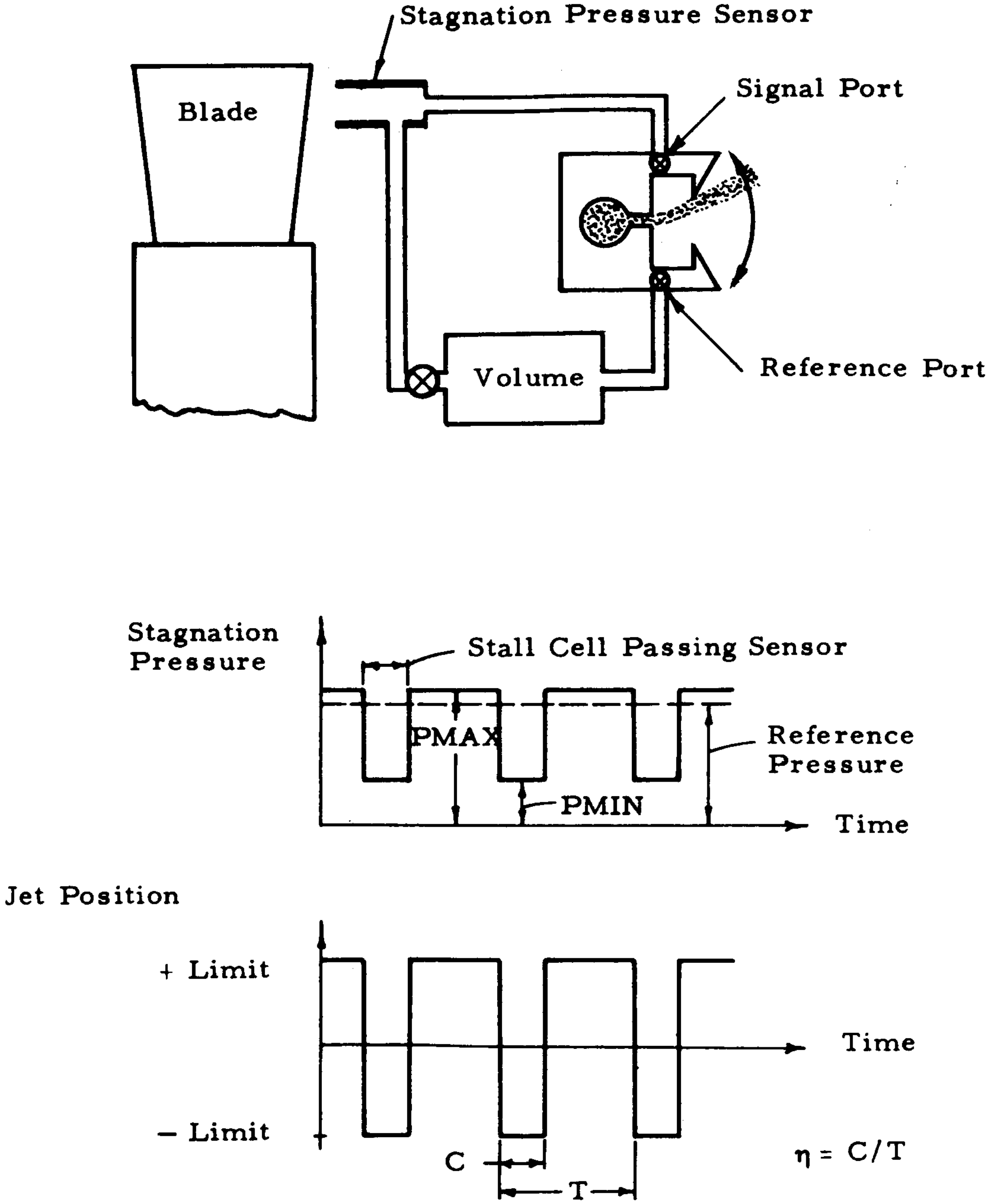


Figure 6.13 Performance of Pressure Ratio Sensor (from Ref. 6-11)



(from Ref. 6-12)

Figure 6.14 Stall Sensor Concept and Hypothetical Signals

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7.0 APPLICATIONS

7.1 Introduction and Commentary

Considerable current effort is directed toward applying fluid devices. In a few cases, elements are available in the commercial market for application by the purchaser. In most cases, however, the work in progress is of a development nature where the elements and the system are emerging simultaneously. This section gives a brief description of each application to the extent that it has been described in available literature, or by oral report from the contractor performing the work. Some of the projects are of a military nature under Government funding and are classified. These are listed here and described in Volume II. With few exceptions, little performance information is available since work is still in progress, and especially since most of the applications work involves the exploitation of proprietary knowledge.

The early state of development of the fluid devices has led to an extremely broad diversity of applications. In most cases the application requirement is directing the course of development of the fluid elements and functional assemblies; the need for new elements or assemblies is just being identified. This is in sharp contrast to the present state of the art of solid-state devices, which are generally available as a great diversity of "building blocks" to fit an application that comes under consideration. The situation is representative of the field of solid- state devices several years ago, however, when a few early developments in diodes and transistors sparked interest in applications which then helped to identify the needs within a growing family of solid-state devices. This same evolution is anticipated for the fluid devices. Each of the representative applications which follows could grow into a large family of related applications as new and improved elements and assemblies are available.

7.2 Industrial Applications

Moore Products Company of Spring House, Pennsylvania, is the only known company marketing a commercial product using fluid amplifiers. These products are a "comparator" and a "process optimizer." They also produce a series of large flow valves which are commercially available. These products are described briefly in sections 7.2.1, 7.2.2, and 7.2.3. Also see reference 7-1.

Other industrial applications that have been revealed are under development by the General Electric Company, the Johnson Service Company, and the Minneapolis-Honeywell Regulator Company. The Advanced Technology Laboratories of General Electric has modified a small parts manipulator to use fluid controls (section 7.2.4). The Industry Control Department of General Electric is developing logic for automatic conveyor lines (section 7.2.5).

Minneapolis-Honeywell has demonstrated a fluid amplifier rate damper for light plane use, and Johnson Service is developing a fluid amplifier control for ventilating ducts (section 7.2.6).

7.2.1 Flow Valves

Both diverting and proportional flow valves are available and are in industrial use [7-1]. They are available, made from several materials, in sizes from 1/2 inch to six inches. A diverter valve is presently used in an application involving the switching of the flow of 700° F molten caustic soda. The Moore Company plant uses several proportioning valves in the heat pump used for heating and air conditioning of their building.

7.2.2 Optimizer

The optimizer [7-2] is a peak-seeking apparatus which systematically changes one variable to seek an optimum in a second variable such as production rate or efficiency. A reversal control is performed with a flip-flop operating on air. The remainder of the elements in the optimizer consists largely of standard Moore devices which utilize bellows, diaphragms, flapper-nozzles and poppet valves for operation.

7.2.3 Gaging Device

A gaging device is presently in use on a conveyor application to measure parts at a rate of 750 per minute. [7-1, 7-2] The system checks a particular dimension on each part and rejects those that are oversize. The actual measurement is made in less than 10 milliseconds and a fluid amplifier flip-flop is used to store the measurement signal. If a part is over-size, the memory of the flip-flop momentarily stores the "oversize" signal to permit rejection of the over-size part beyond the gaging head. The flip-flop is then reset in preparation for the next measurement. The function performed by the fluid flip-flop was previously performed by 12 mechanical-electrical switches which were a continual source of failures.

7.2.4 Small Parts Manipulator

The electrical logic and rotary air valve used on a small parts manipulator were replaced with fluid amplifiers to demonstrate the reliability of a "no-moving parts" control. [7-3] The manipulator transferred parts by providing the motion of grasping, vertical lift, horizontal translation, lowering, and releasing the part. The apparatus would retrace this path in retracting to pick up the next part to begin a new cycle. This motion was performed by three pneumatic cylinders coupled as shown in Figure 7.1. Electrical limit switches were used to provide a signal where the actuators were either fully extended or retracted. These signals were used to control the operation of the manipulator as shown by the logic in Figure 7.2.

The limit switches for the fluid amplifier control were formed by relief grooves cut in existing guide rods. When an actuator is in its retracted or extended position, a groove is lined up between a supply port and a signal line port which results in flow which indicates the position of the actuator. These pneumatic limit signals are fed into the fluid amplifier logic shown in Figure 7.3 which controls the power flow to the actuators.

An experimental control was fabricated using cast epoxy elements. All elements had 40 mil x 40 mil power nozzles except the switch which powered the "A" actuator (Figure 7.1); its dimensions were 125 x 125 mils. As can be seen by the schematic diagram, Figure 7.3, half adders were used for the two input AND elements. Switches with orifices in the control ports to make them bistable were used for the flip-flops. A photograph of the manipulator and experimental control is shown in Figure 7.4. The experimental fluid control is sufficiently small to fit within the original container below the "A" actuator where the electrical controls and the rotary pneumatic valve had been housed. Figure 7.4 also shows these parts which were replaced by the fluid controls. Although insufficient operating time has been accumulated on the fluid amplifier control to prove its apparent reliability, it has already exceeded the operating life experienced on the electrical control by many times.

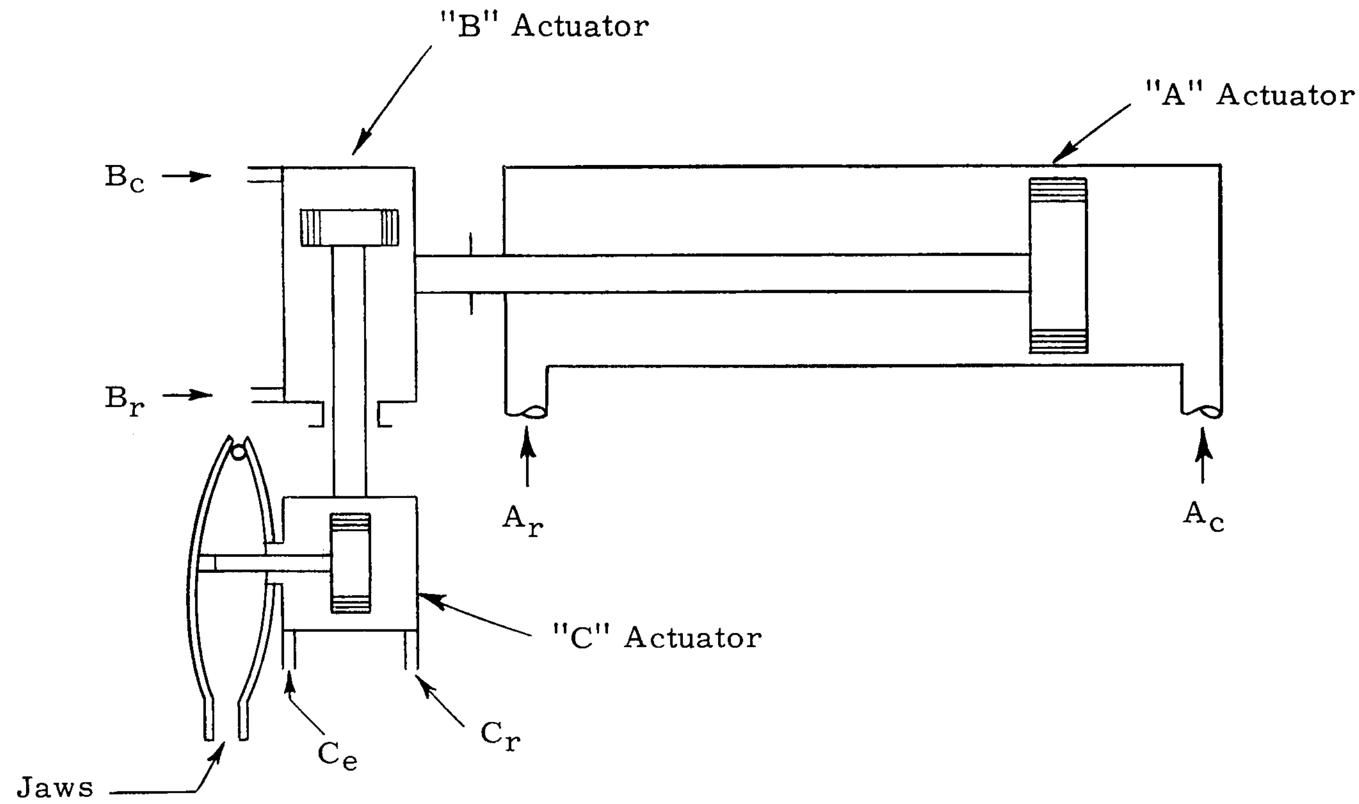


Figure 7. 1. Schematic of Small Parts Manipulator.

Step	This Signal	"and"	This Signal	Produce This Actuation
1	a_r	·	b_e	C_e
2	c_e	·	a_r	B_r
3	b_r	·	c_e	A_e
4	a_e	·	c_e	B_e
5	b_e	·	a_e	C_r
6	c_r	·	a_e	B_r
7	b_r	·	c_r	A_r
8	a_r	·	c_r	B_e

Nomenclature:

A - Power flow, horizontal actuator

B - Power flow, vertical actuator

C - Power flow, jaw actuator

a - Limit signals, A actuator

b - Limit signals, B actuator

c - Limit Signals, C actuator

Subscripts;

e - Extended position (grasp for C actuator)

r - Retracted position (release for C actuator)

Figure. 7.2. Logic Required for Positioner to Pick up Extend and Deposit Part.

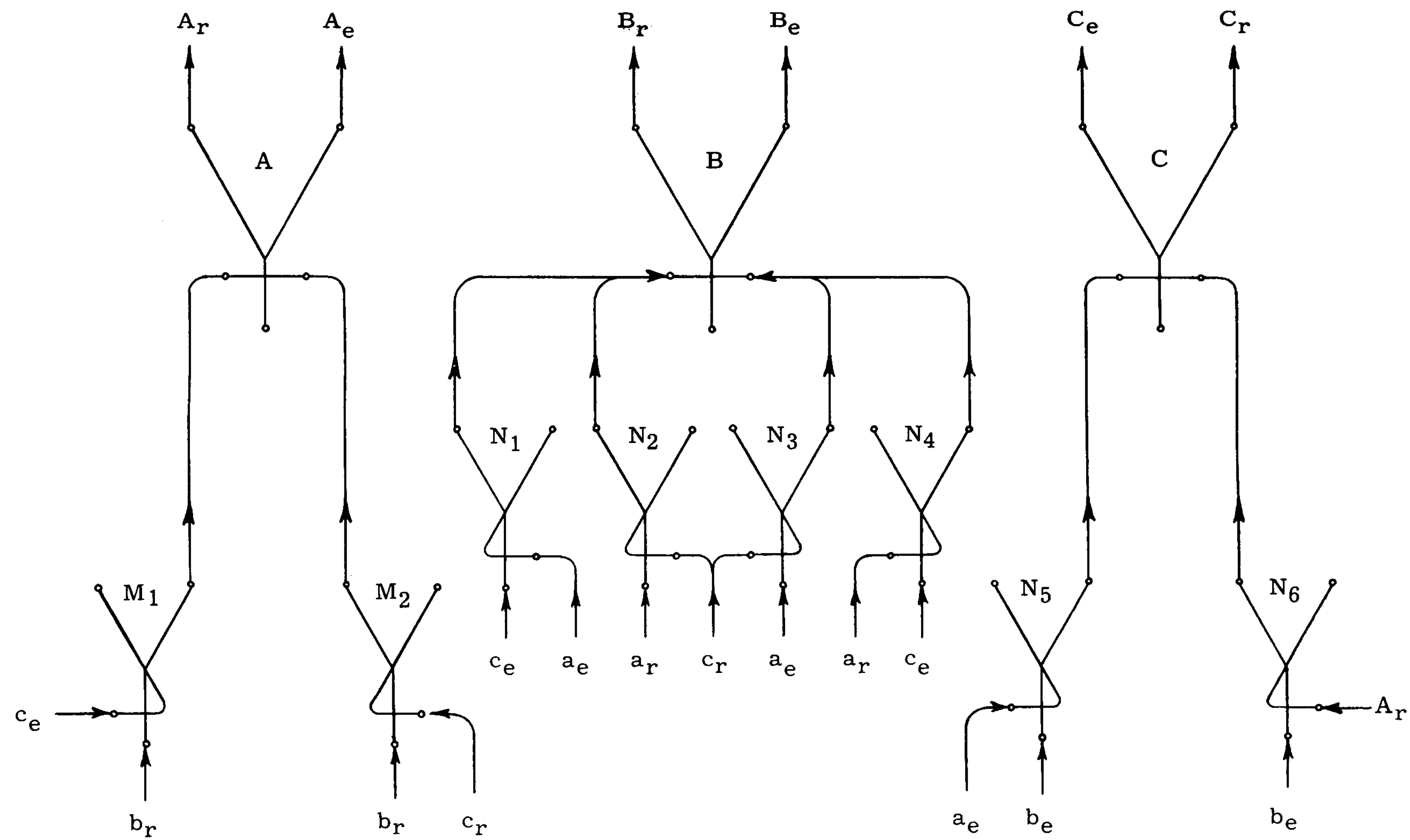


Figure 7. 3. Fluid Transistor Circuit Diagram for Small Parts Manipulator.

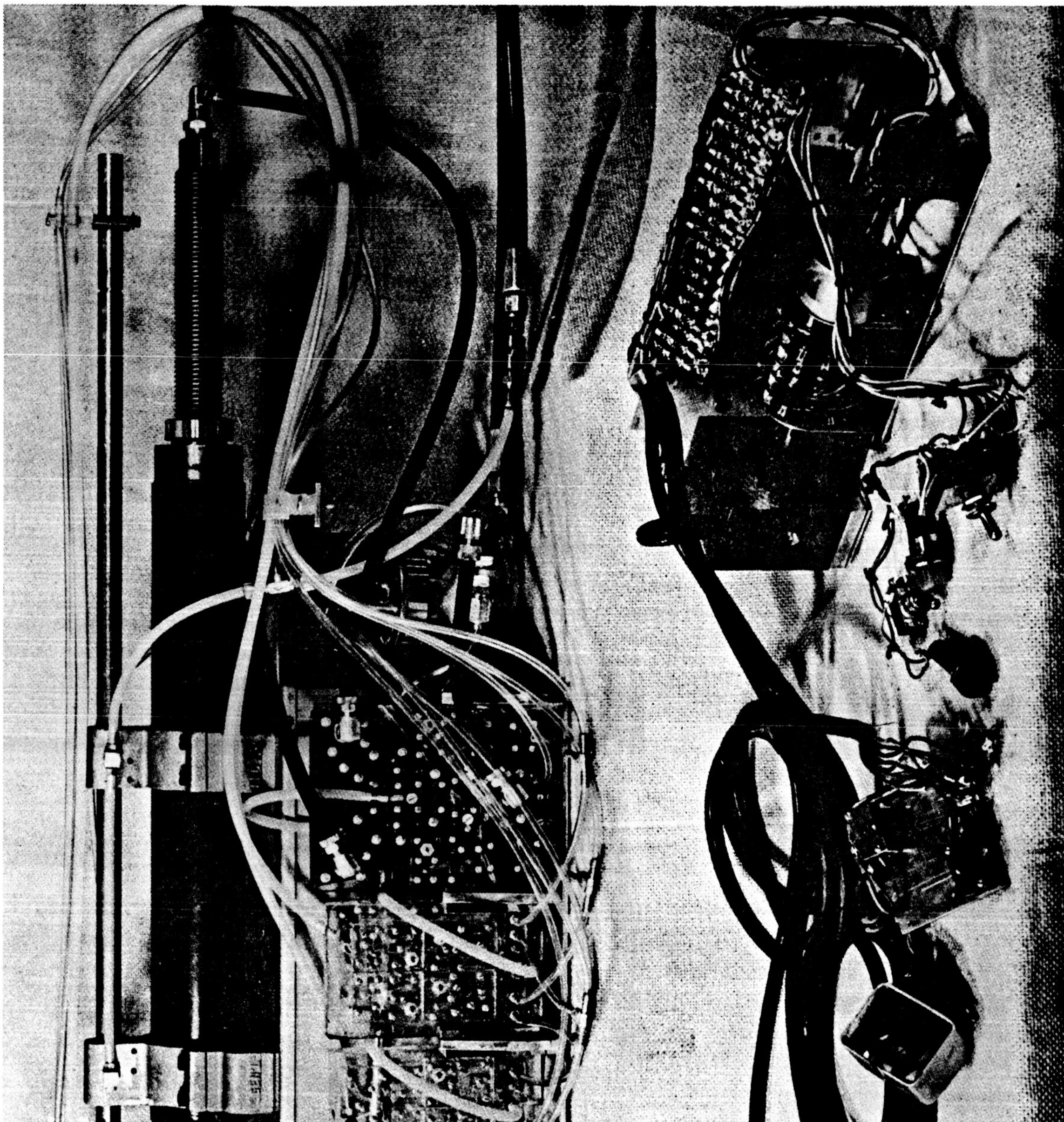


Figure 7.4 Small Parts Manipulator
(Completely Controlled by Fluid Transistors)

7.2.5 Logic for Automatic Conveyor Lines

Pneumatic logic using fluid amplifiers is being developed for automated conveyors [7-3]. A model of a complete system for mailbag handling is presently undergoing test. The principle assembly in this system is a shift register which can accept 4 bit binary numbers and has a capacity of 20 shifts; i.e., a 4 x 20 shift register. In addition, read-out logic is used between the shift register modules for signaling the actuation of mechanical gates and chutes to divert material at predesignated stations. In operation, the operator "reads in" a binary number corresponding to the station at which the material is to be diverted from the conveyor. The conveyor and clock of the shift register are synchronized so that the binary number is shifted through the shift register at the same rate as the material passes diverter stations. When the material and the corresponding binary number in the shift register arrive at the stations which correspond to the identification number on the material, coincidence logic actuates the diverter equipment.

Figure 7.5 is a simplified block diagram of the system to illustrate the operation. The figure shows a portion of a 3 bit capacity register, viz., stations 4, 5, and 6. The coincidence logic for station 5 is illustrated. The OR-NOR logic is arranged so that an output occurs at station 5 only when the binary number 101 (decimal 5) is stored in the shift register stage 5. All other binary numbers will not provide coincidence and hence result in no output from the logic. Thus, every time the number 5 passes through stage 5 of the shift register, the coincidence logic actuates the diverter equipment at station 5 along the conveyor which diverts the material into the chute.

Each shift register module is made up of a primary and secondary storage circuit which are identical except that one is shifted with a positive clock (T), and the other with a negative or inverse ($\overline{T}$) signal. Figure 7.6 is a circuit for one half of a module. Two identical halves are used in a complete module. An amplifier is needed for the coincidence logic and therefore is included as part of each half-module for simplicity. The half-module exterior geometry is shown in Figure 7.6b. The design is such that the half modules are simply stacked to provide the desired shift capacity and the interconnections, and ducts for supply pressure and clock signal are arranged to interconnect when they are stacked. Suitable gasketing is used between each half-stage. Fabrication material for the early test half-modules were Dycril; epoxy castings are being used for the demonstration model. Plastic-moldings are being procured for future systems.

7.2.6 Other Applications Under Development

The Minneapolis-Honeywell Regulator Company has demonstrated an experimental light plane rate damper [7-4] which utilizes the vortex rate sensor. Pitch rates are sensed by this device and the signal is amplified and fed into a conventional auto pilot.

The Johnson Service Company is developing a control for ventilating ducts using fluid amplifiers [7-5]. The device utilizes duct pressure for a fluid supply.

R. N. Auger of Fluid Logic Control Systems Co. is reported to have incorporated a number of fluid amplifiers in conveyor and inspection applications.

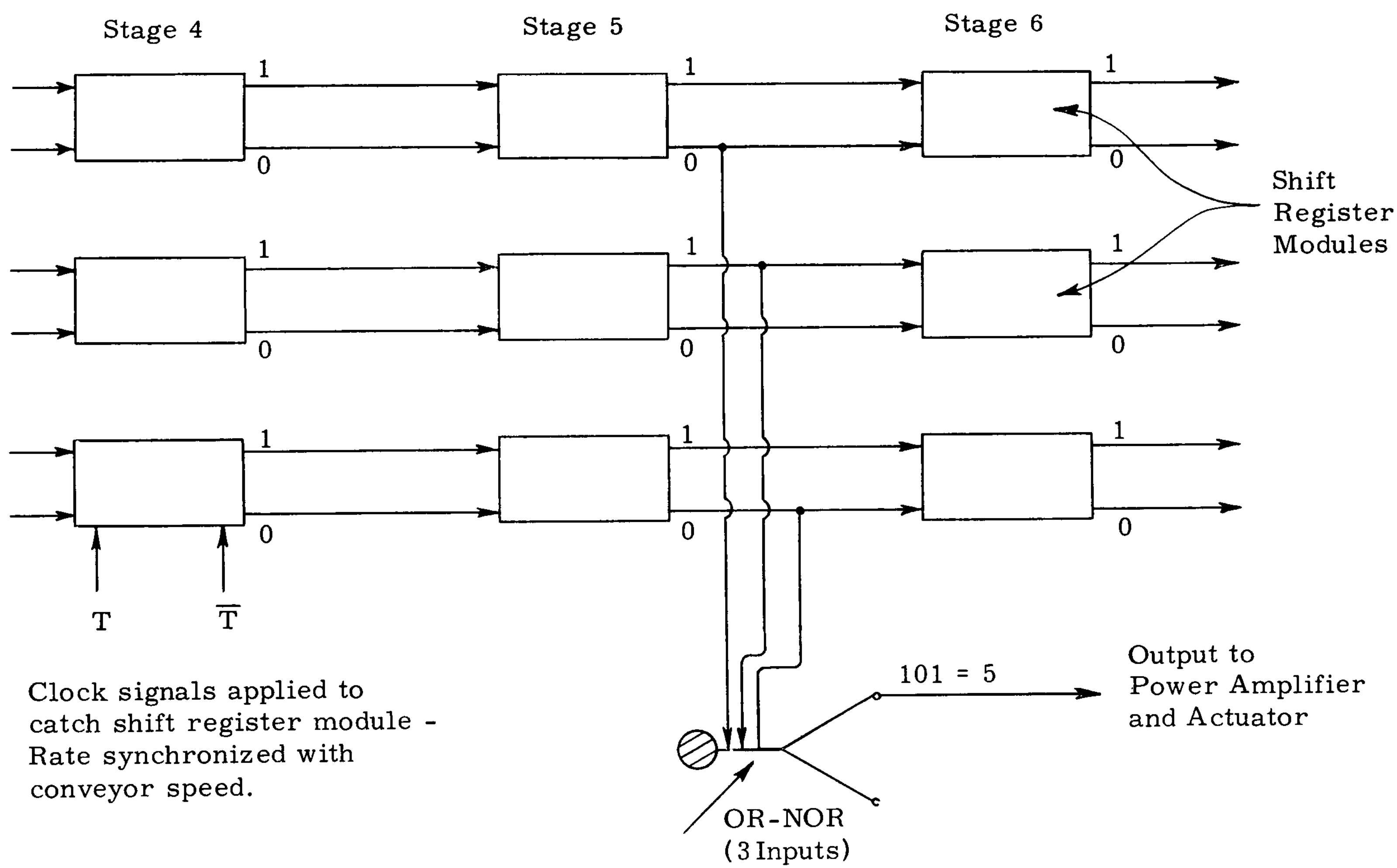
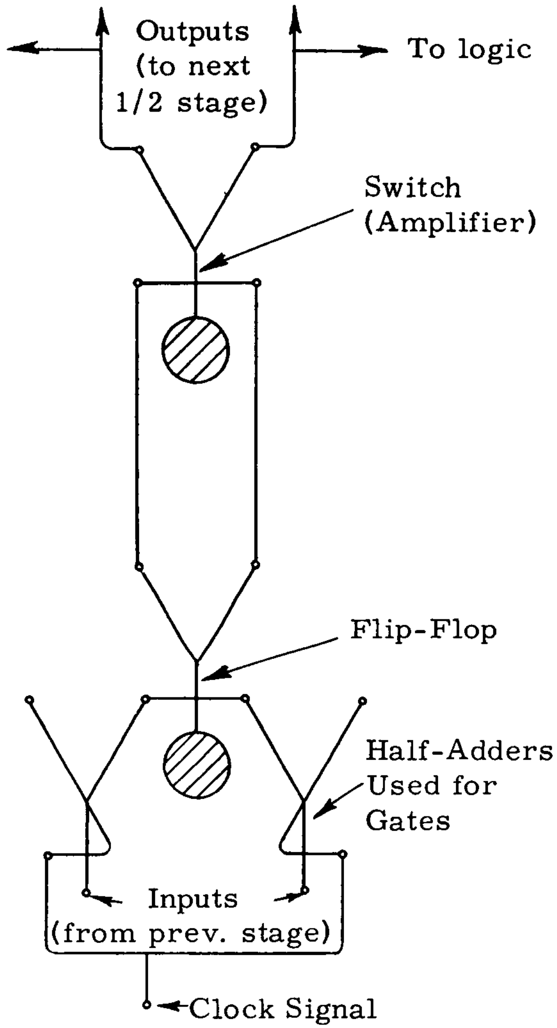
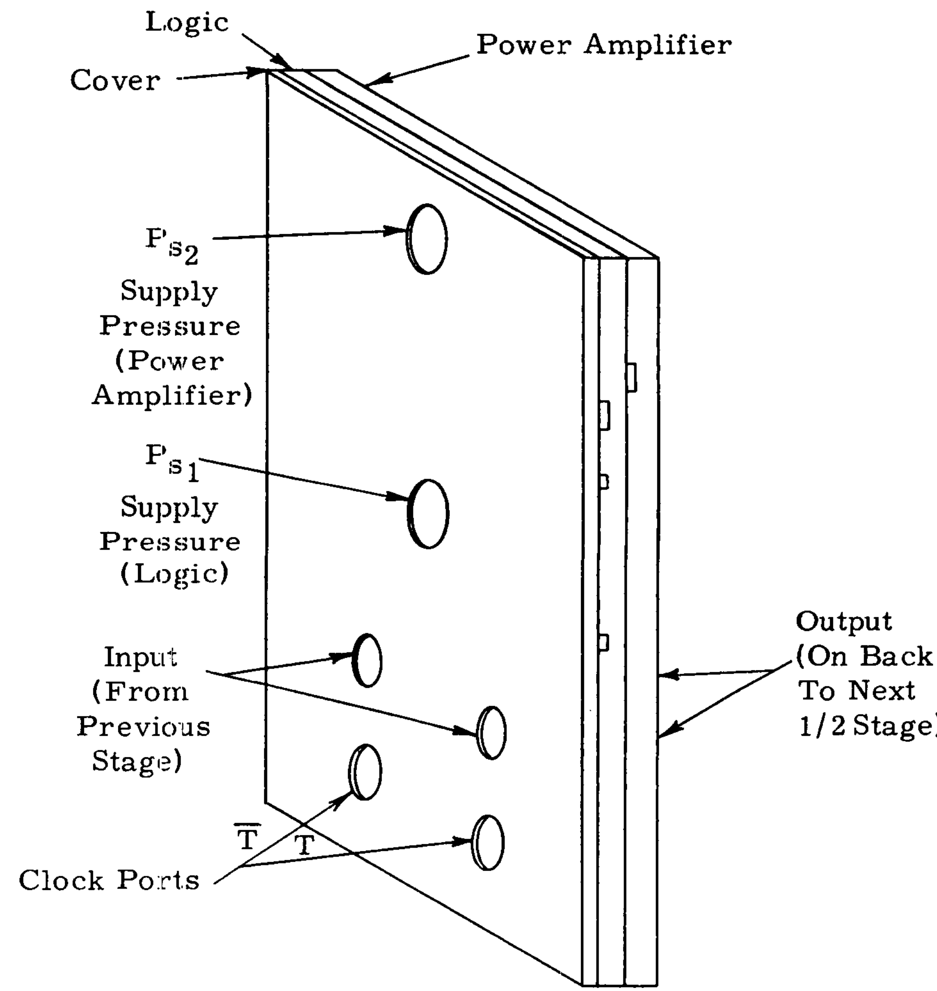


Figure 7.5. Shift Register Readout Logic.



a) Schematic of Half Module
Shift Register Elements.



b) Assembly of Module
(Shift Register Half Module)

Figure 7.6. Shift Register Module.

7.3 Military and Space Applications

The environmental tolerance, shelf life and reliability predicted for fluid amplifiers and logic has led to considerable interest in applying them in military and space applications. Most of this work is being sponsored on Government contracts; many projects are classified. Table 7.1 lists all identified applications in the military and space category and indicates where the work is described in this report, who is sponsoring the work, and the contractor performing the work. Descriptions and references for the unclassified applications are given in the paragraphs which follow.

Table 7.1

Military and Space Applications

Report Section	Application	Sponsor	Contractor
Vol. III-7	Jet Engine Control (classified)	Wright-Patterson Air Force Base; USAF	Minneapolis-Honeywell, Aero Division
Vol. III-7	Thrust Vector Control (classified)	Special Projects Office, Dept. of Navy	Pratt-Whitney Aircraft
Vol. III-6	Missile Attitude Control (classified)	Redstone Arsenal, U. S. Army	Minneapolis-Honeywell, Aero Division
Vol. III-6	Tank Gun Control (classified)	Harry Diamond Laboratories, U. S. Army	Minneapolis-Honeywell, Ordnance Division
Vol. III-6	Navigation & Guidance Computer (Classified)	Wright-Patterson Air Force Base; U. S. Air Force	Minneapolis-Honeywell, Aero Division
Vol. III-6	Fire Control Platforms (classified)	Frankford Arsenal, U. S. Army	Minneapolis-Honeywell, Ordnance Division
Vol. III-6	Flight Control (classified)	Wright-Patterson Air Force Base; U. S. Air Force	Minneapolis-Honeywell, Aero Division
7.3.1	Artificial Heart Pump	Harry Diamond Laboratories and Walter Reed Army Inst. of Research	HDL and Walter Reed Army Inst. of Research
7.3.2	Fluid Timer for Ordnance	Picatinny Arsenal, U. S. Army	General Electric, Missile & Armament Dept.
7.3.3	Hot Gas Valve for Shillelagh Missile	Redstone Arsenal, U. S. Army	Electromagnetics Lab. U. S. A. M. C.
7.3.4	Turbine Speed Control	Office of Naval Res., Dept of Navy	Bowles Engineering
7.3.5	Turbine Speed Control	Office of Naval Res., Dept of Navy	General Electric, ATL
7.3.6	Marine Boiler Control	Bureau of Ships, Dept. of Navy	Bowles Engineering
7.3.7	Reactor Control System	Lewis Research Center, NASA	General Electric, ATL
7.3.8	Reactor Rod Control	U. S. A. F. and A. E. C.	General Electric Company Nuclear Mtls. & Propulsion
7.3.9	Satellite Attitude Control	General Electric Company	General Electric Company Light Mil. Electronics Dept.
7.3.10	Ram Jet Spike Positioner	Wright-Patterson Air Force Base USAF	Marquardt Corporation
7.3.11	Hydrofoil Control	Bureau of Ships, Dept. of Navy	Bowles Engineering Corp.
7.3.11	Fluid Timer for Ordnance	Frankford Arsenal, U. S. Army	Bowles Engineering Corp.
7.3.11	Gyro Rotor Drive	Wright-Patterson Air Force Base USAF	Massachusetts Institute of Technology

7.3.1 Artificial Heart Pump

A heart pump which utilizes a fluid amplifier is being developed for use in open heart surgery [7-6]. The principle features of the pump are: 1) It more closely approximates the operation of the human heart, thus promoting less blood damage and 2) It has the potential of higher reliability since the use of the fluid amplifier element reduces the number of moving parts. A schematic of the system is shown in Figure 7.7. The blood is pumped by the alternate collapsing and filling of the ventricle. The valves for directing the flow of blood closely simulate the valves of the human heart.

The principle element in the fluid amplifier circuit is a switch that operates as an oscillator. Assume the output from the switch is initially from O1. Flow into the chamber around the ventricle causes the ventricle to collapse until the control port is uncovered. Opening of the control port allows flow to enter the control line and to switch the fluid amplifier to output O2. Gravity then fills the ventricle with blood and expands it back to the maximum position (dotted line). During the filling of the ventricle, flow in the control line and the reverse flow through O1 maintain the state of the switch to the O2 output. When expansion of the ventricle is complete, the aspiration through O1 and C1 ceases and aspiration into C2 causes the fluid amplifier to switch back to O1, thus completing the cycle. The fluid amplifier circuit operates on air. The characteristics of this pumping system approach a "pressure" source and thus more accurately simulate the heart as compared to previous mechanical pumps. This characteristic and the use of a ventricle and valves for pumping that minimize high shear are among the principle advantages of the device. Controls are provided as shown in Figure 7.7 for controlling the blood pressure, pulse rate and pulse duration. A number of heart pumps of this design have been fabricated and are undergoing life tests to obtain a measure of reliability and to determine possible modes of failure. They will be tested shortly with open heart surgery of animals to prove their capabilities. More details can be found in reference 7-6.

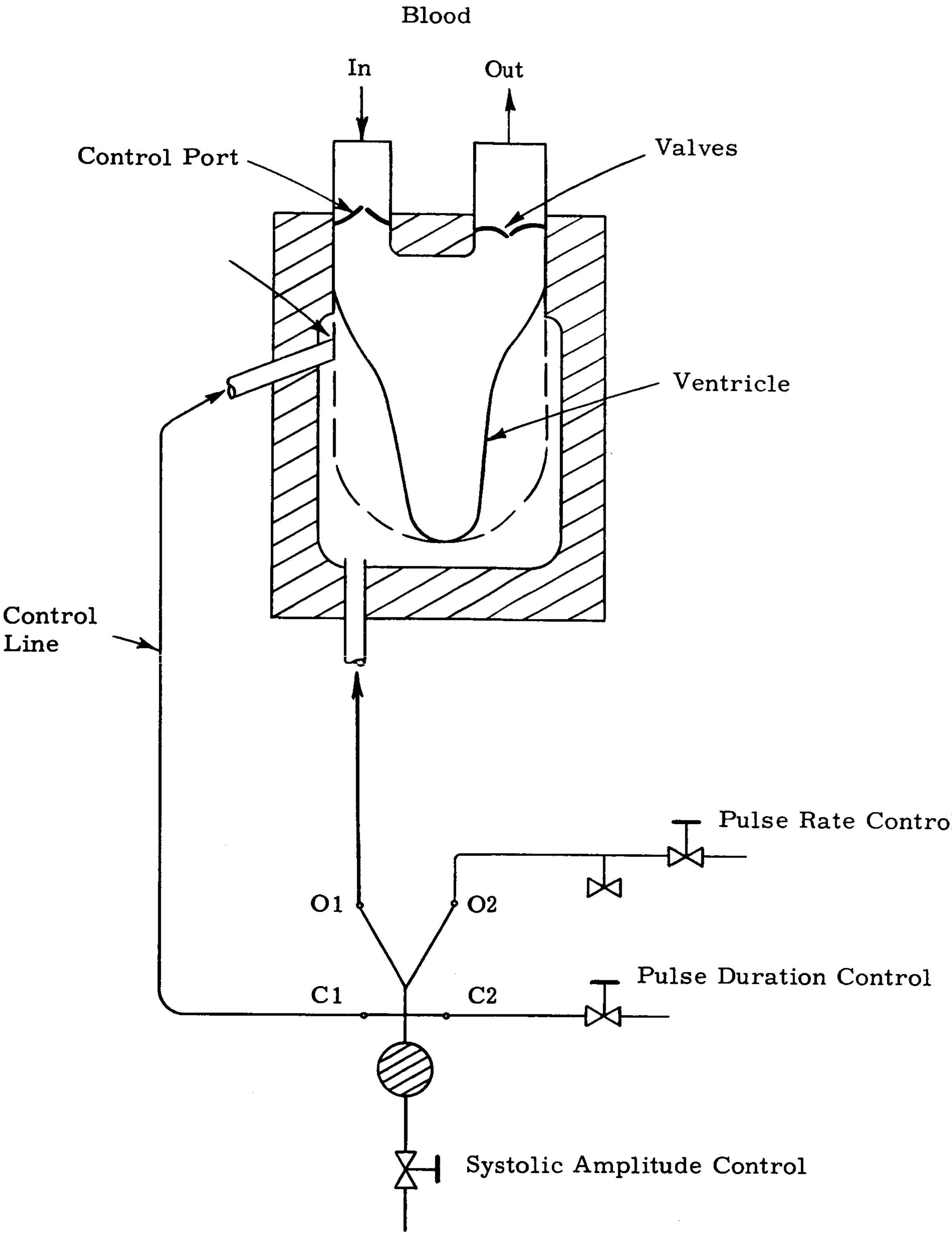


Figure 7.7. Heart Pump Schematic

7.3.2 Fluid Timer for Ordnance Applications

A fluid timer for safing, arming, and fuzing applications in ordnance weapons ranging from artillery projectiles to tactical missiles is being developed [7-7]. The basic concept involves an oscillator driving a presettable counter for providing time intervals from 0 to 200 seconds (Figure 7.8). The pneumatic power is to be obtained from a small gas bottle or ram air. The present development work is being concentrated on the counter and oscillator. The counter which uses binary flip-flops with presetting ports, has a capacity of 256 counts, and receives input pulses at a rate of 0.5 per second. To set the desired timing period, the counter is preset to the difference between 256 (its total capacity) and the desired number of pulses for the timed interval. When the desired number of pulses is received, the counter is filled and the overflow provides a signal indicating the completion of the timing period. The critical assembly in this timer system is the oscillator, which ultimately must have 0.1 percent accuracy over a -65° F to 165° F temperature range. This key assembly is receiving much of the effort in the program.

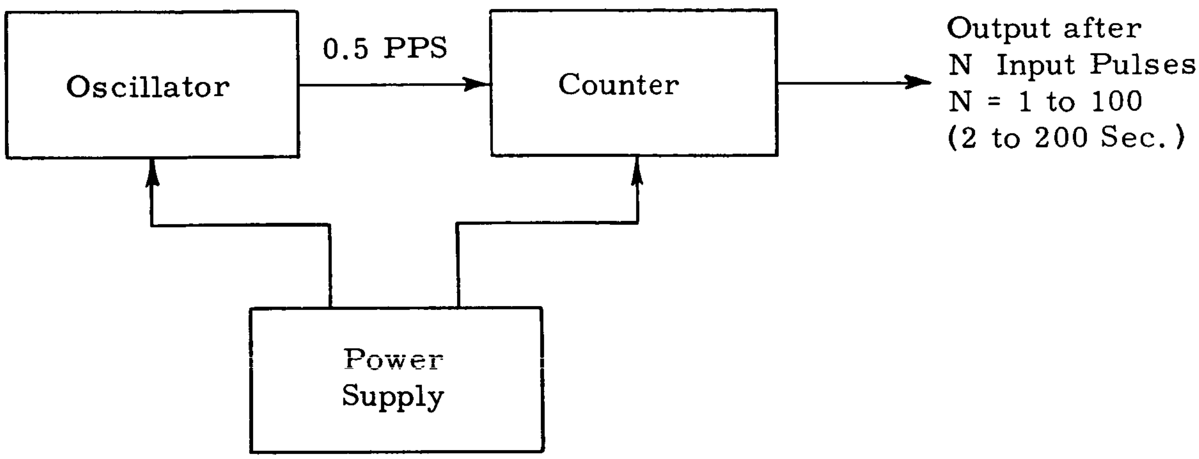


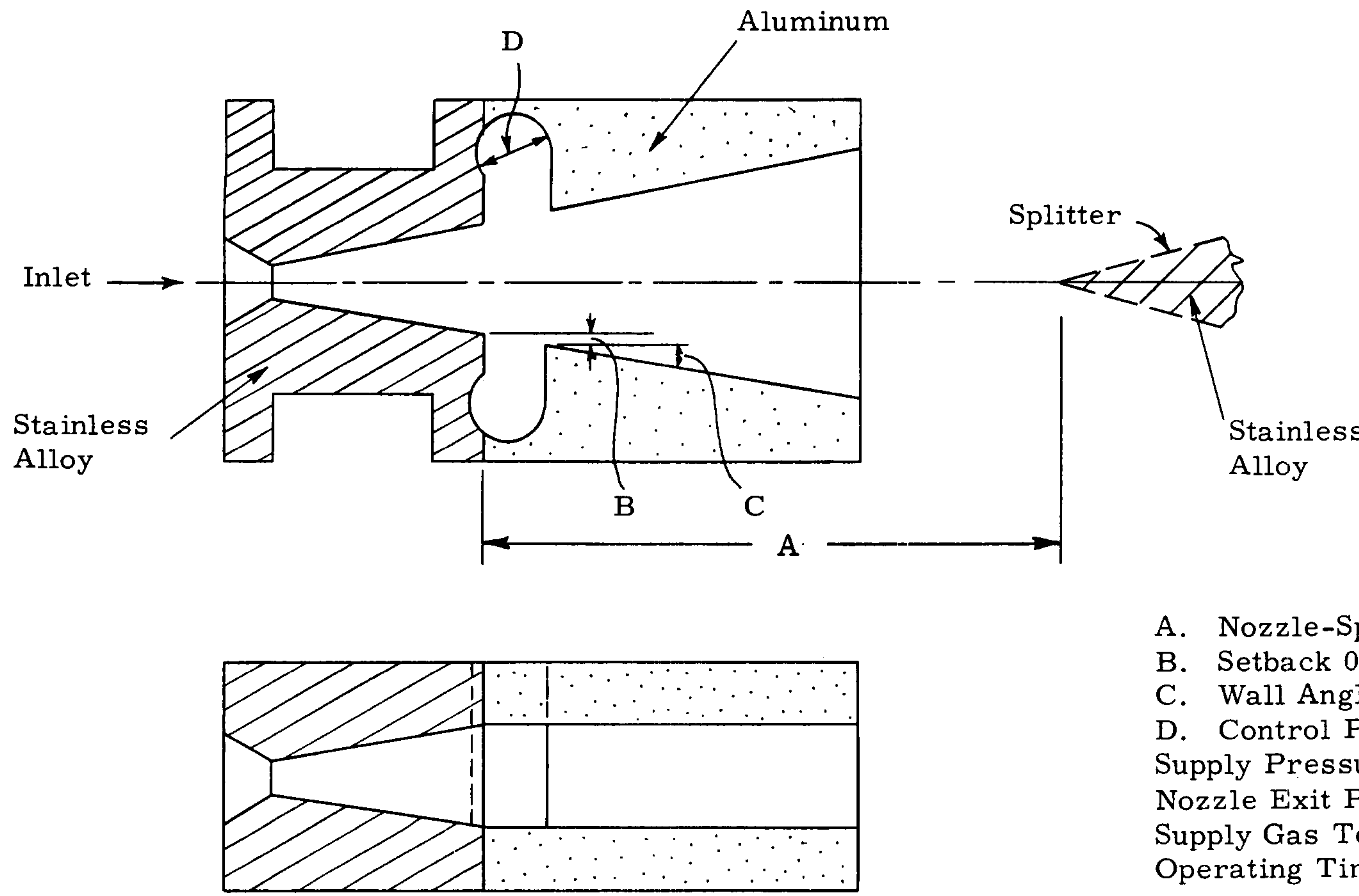
Figure 7. 8. Block Diagram of Timer.

7.3.3 Hot Gas Valve for the Shillelagh Missile

Because of a potential valve problem in the Shillelagh missile, the requirements for the valve were chosen as typical for the development of a fluid amplifier switch [7-8] to divert gases for reaction control of the missile. The energy for yaw, pitch and roll control is supplied by a solid propellant gas generator which supplies gas at about 900 psi and 2000°F for 10 seconds. The concept under development involves fluid amplifiers for switching the flow from the gas generator to the appropriate reaction ports at the rear of the missile. The thrusts required from the control system are 12 pounds for roll, 18 pounds each for pitch and yaw.

The work to date has been concentrated on the development of a fluid switch that can be operated on solid propellant gases for the 10 second duration. Because of the high pressures involved, the switch geometries previously developed by Harry Diamond Laboratories were not suitable and an experimental program was carried out to optimize the performance. Initial efforts were on cold gas, and the final work made use of the solid propellant gases. Figure 7.9 illustrates the geometry of one of the final switch configurations. The throat and expansion region are of circular cross-section while the attachment walls and receivers are two-dimensional. The nozzle provides the proper expansion for a 7 psig back pressure.

Switching of the amplifier is accomplished with an electrimechanical flapper valve on the control ports. The flapper alternately closes one or the other control port and effects switching by admitting aspiration flow in one control port while limiting it in the other control port. The control gas, therefore, is low temperature ambient air. The use of stainless steel for the nozzle sections and splitter and aluminum for the receivers has been found adequate for the 10 second duration even though the gas temperatures are of the order of 2000°F. Figure 7.9 indicates some of the significant dimensions of the fluid switch. The initial plans were to use a diffuser on the switch to recover static pressure and then to re-expand the gases through sonic nozzles at the skin on the missile. Test results were discouraging, so the high velocity flow was simply ducted from the receivers to the outlets on the missile skin. The efficiency of the switches operating in this mode is reported to be 70 percent of ideal.



A. Nozzle-Splitter distance 2.05"
B. Setback 0.090"
C. Wall Angle 15°
D. Control Port Diameter 0.250"
Supply Pressure ~ 900 psi
Nozzle Exit Pressure 7 psia
Supply Gas Temp. ~ $2000^{\circ}F$
Operating Time 10 Sec.

Figure 7.9. Fluid Switch for Missile Control.

7.3.4 Turbine Speed Control System

In order to obtain more reliable operation of shipboard turbine-generator sets, the Navy is studying the concept of sealed sets. For this type of a system, the use of "no-moving-parts" controls is particularly attractive and as a result, the Navy has contracted studies of fluid amplifier speed control systems. This study by Bowles Engineering Corporation and a similar study by General Electric (described in section 7.3.5) have shown that such a speed control system is feasible. Model systems have been demonstrated to emphasize the practicability.

The block diagram of the Bowles system [7-9] is shown in Figure 7.10. The system design considers a 500 KW machine requiring 1/2 percent speed control accuracy. In order to more easily sense small variations in the output frequency, a tuning fork heterodyne (Figure 7.10) was used to produce a difference frequency (40 cps nominal). For example, a 20 cps deviation from the 40 cps nominal signal from this heterodyne is a 50 percent variation while 20 cps deviation on the 800 cps nominal signal is only a 2-1/2 percent variation. A schematic of the tuning fork heterodyne is shown in Figure 7.11. A discriminator is used to convert the frequency modulated signal into an analog signal (Figure 7.12). It uses two pneumatic tuned cavities, 30 cps and 60 cps to provide the characteristics illustrated in Figure 7.10. The power valve for the control system represents an integration since a flow type fluid amplifier (output flow proportional to input signal) is used to drive a lightly loaded actuator which controls the flow to the turbine. Thus the actuator velocity is proportional to the input signal. With two integrations in the control loop a lead is needed for stabilization and is provided with the lead-lag circuit shown in Figure 7.13. Preliminary testing of a proportional amplifier indicated essentially the same performance on steam as compared with air test results. This information is extracted from reference 7-9.

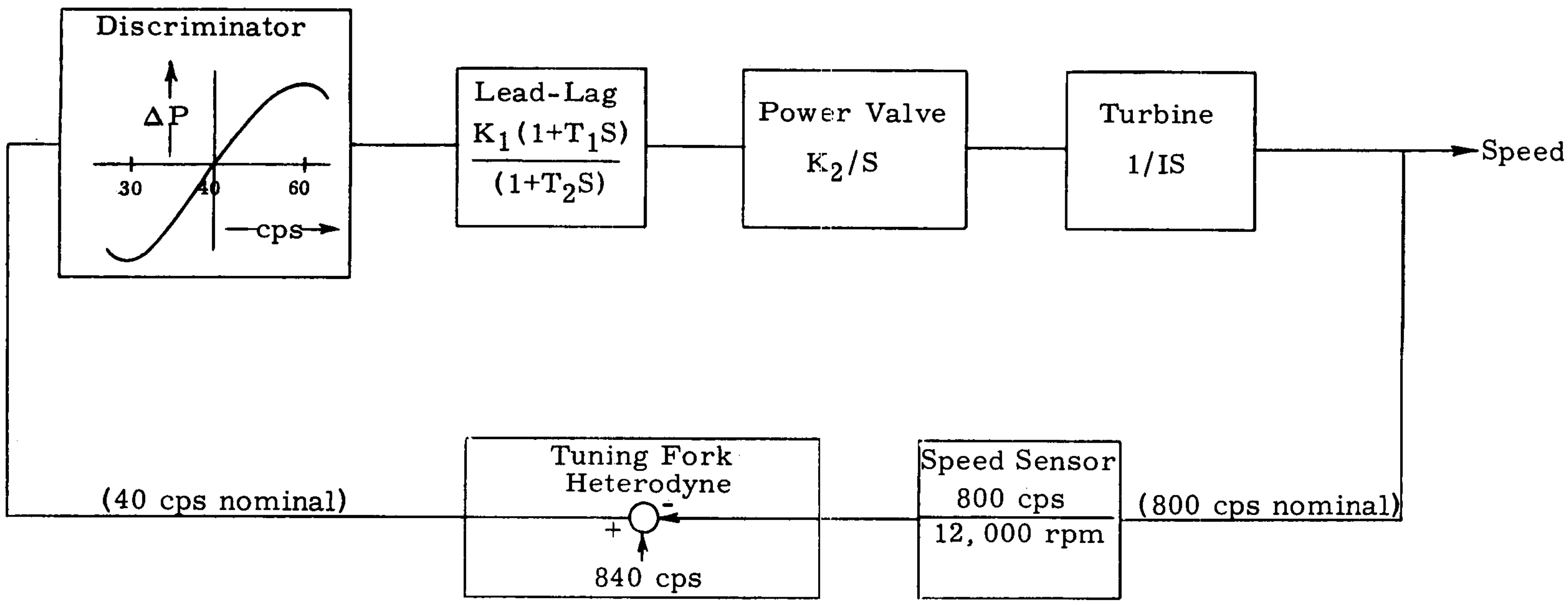


Figure 7. 10. Turbine Speed Control System.

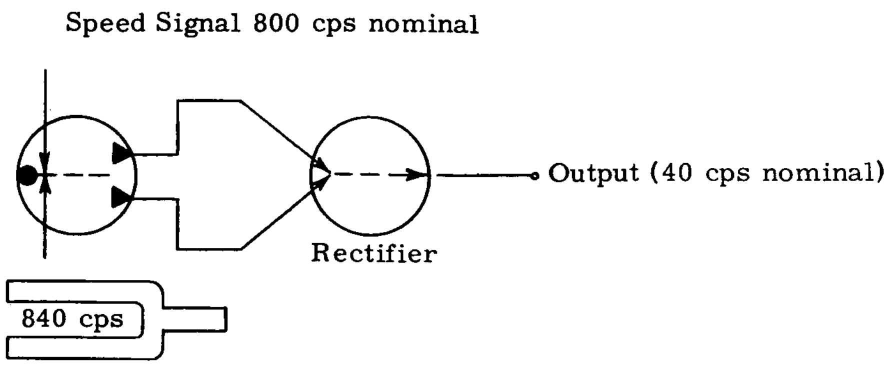


Figure 7. 11. Tuning Fork Heterodyne.

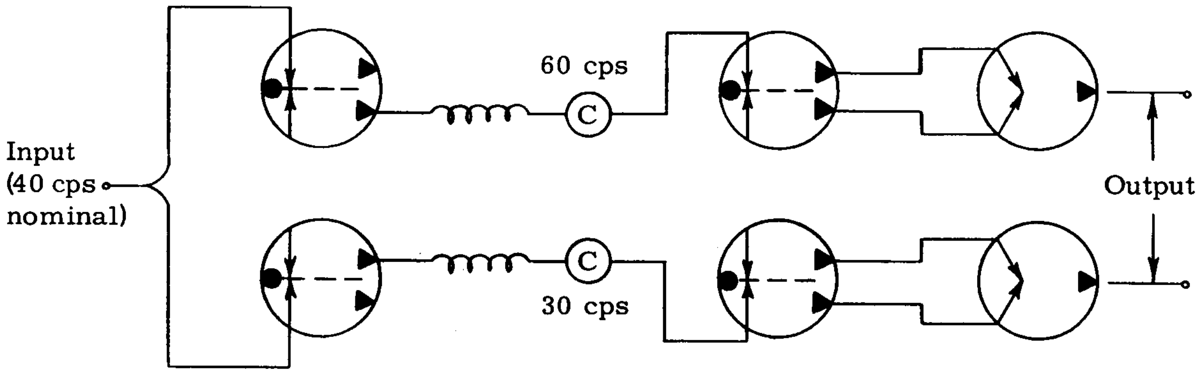


Figure 7.12. Discriminator Circuit

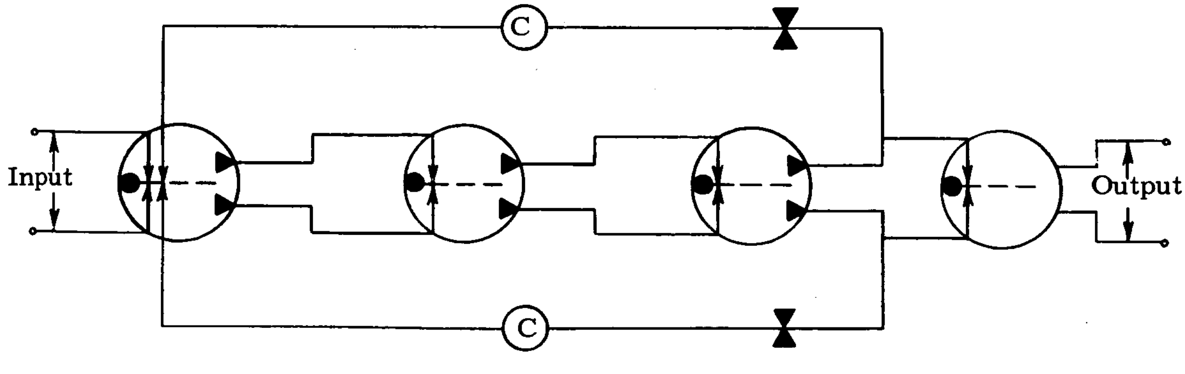


Figure 7. 13. Lead-Lag Circuit.

7.3.5 Turbine Speed Control System

This study was a parallel program to that described in the previous section (7.3.4) to determine the feasibility of a fluid amplifier speed control system for future encapsulated turbine-generator sets for shipboard service. In the study[7-10] various types of digital, proportional and hybrid systems were investigated. Analog computer studies were made for a 500 KW machine to determine the dynamic and steady state performance of the speed control concepts. A model of the most practical system was fabricated and tested to prove the concept. A block diagram of the system is illustrated in Figure 7.14. The key component in the system is the discriminator which produces a proportional output pressure signal from a frequency modulated input signal as shown. A schematic of the control loop is shown in Figure 7.15. The speed signal is generated by the "wobble plate" which produces a 200 cps frequency at the turbine nominal speed of 12,000 rpm. This signal is fed through amplifiers to excite two tuned reeds as shown in Figure 7.3-9. The reeds are tuned at different frequencies; the high speed reed is tuned to 202 cps and the low speed reed is tuned to 198 cps. If the reeds are excited with a 200 cps signal their amplitudes are essentially equal and, therefore, the oscillating tips of the reeds each allow the same amount of flow to pass from the reed jets to the control receivers. If, however, the speed decreases and approaches the low speed reed natural frequency, its amplitude will increase and the high speed reed amplitude will decrease. Now the tip of the low speed reed will cover its reed jet a lesser percentage of time and, conversely, the tip of the high speed reed will cover its reed jet a greater percentage of time. A greater flow thus occurs in the receiver of the low speed reed than in the high speed reed receiver. The 200 cps pulsating flow in the control receivers is filtered by line capacity so that the average pressure difference in the control lines of the turbine control amplifier is proportional to the speed error. The control amplifier drives a flow amplifier to increase the power flow to the turbine. The experimental system operates on air.

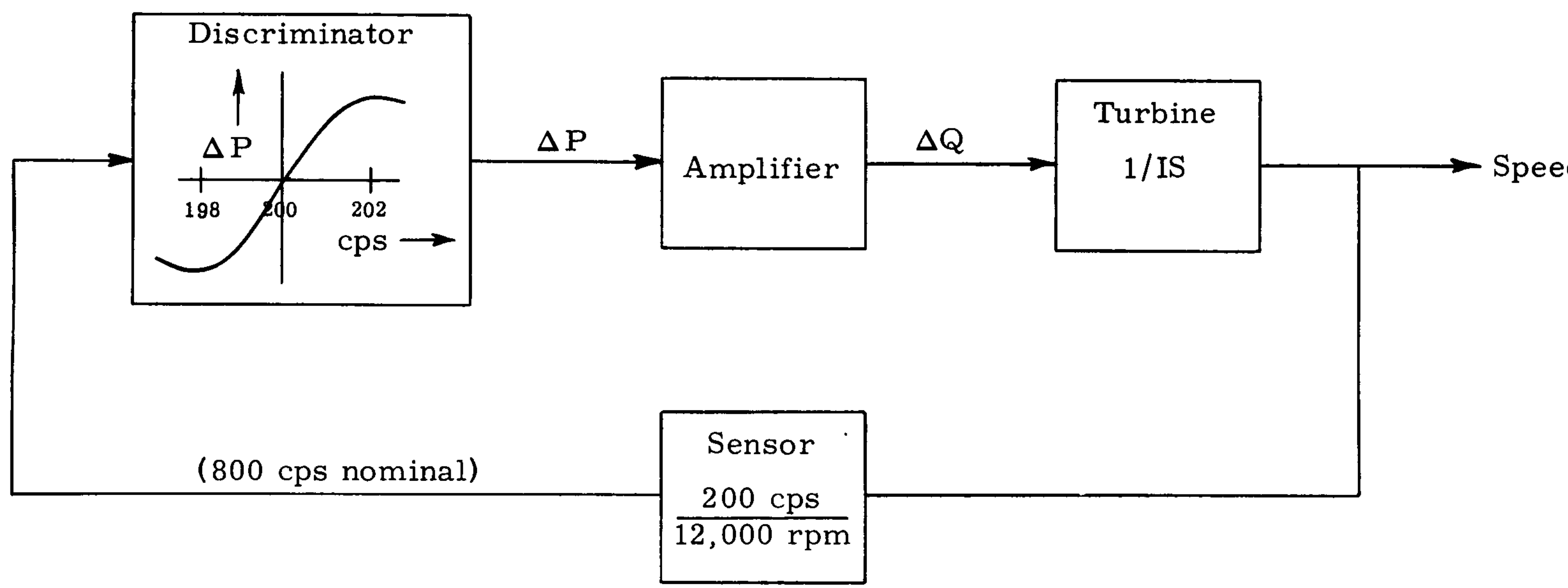


Figure 7. 14. Block Diagram of Speed Control.

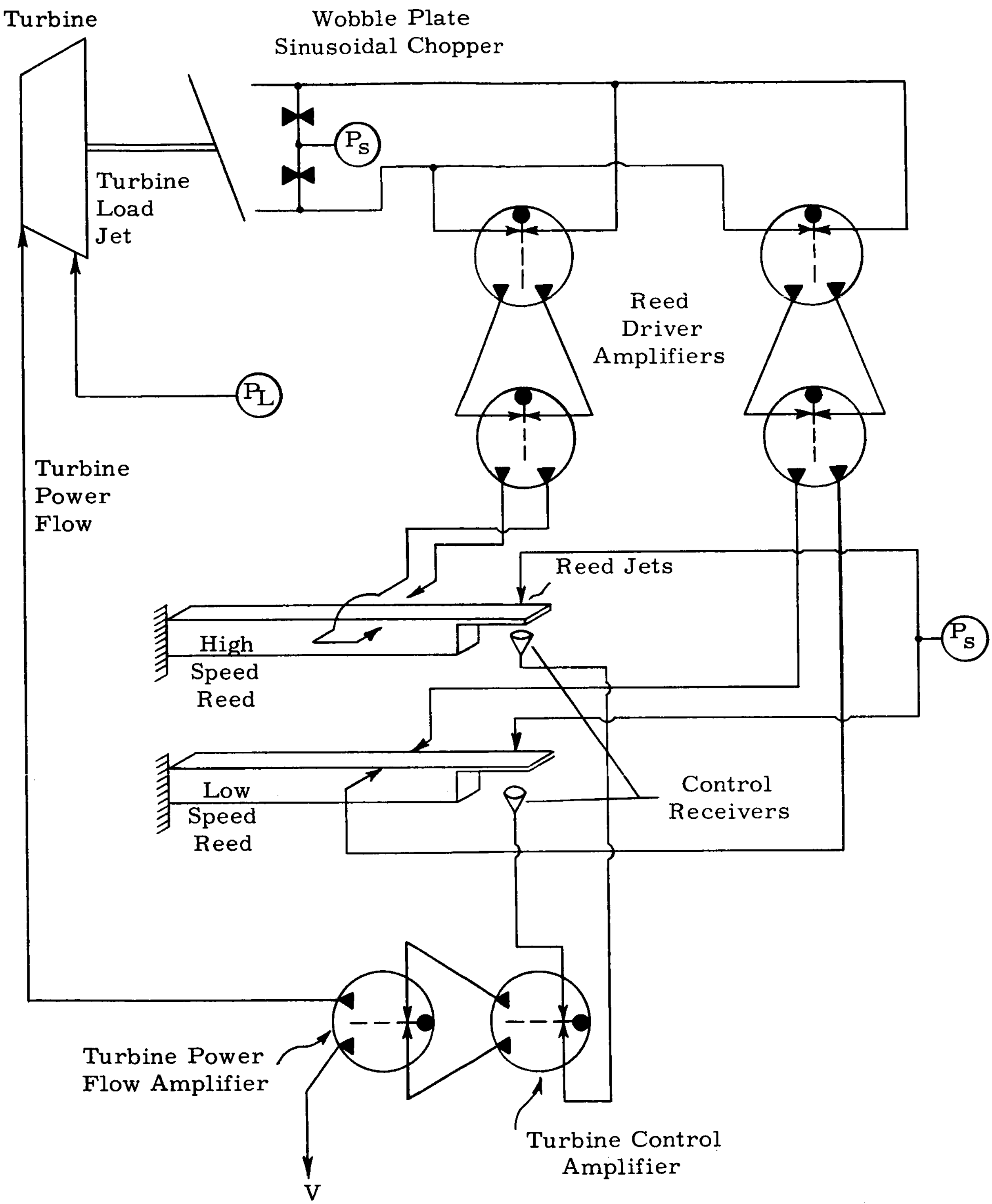


Figure 7.15. Schematic Diagram - Reed Governor Speed Control.

7.3.6 Marine Boiler Control

This program is in its very early stages. The goals are to demonstrate the use of fluid amplifiers to control a marine propulsion-system steam boiler. A typical control system includes a water-level control loop and a steam-pressure control loop [7-11]. The water-level control has, in addition to a level sensor, a steam-flow rate sensor and a feedwater-flow rate sensor. These feedback signals and the reference signal (the desired water level) are summed to provide an error signal which controls the feedwater regulator valve. The steam pressure loop controls the fuel and air flow in response to a pressure error signal. The extent to which fluid amplifiers will be applied to these control loops is unknown to the writers. No reports have been released as yet.

7.3.7 Reactor-Control System

An application study [7-12] was made to determine the feasibility of using fluid amplifiers to provide the required amplification and frequency response shaping networks for a gas servo system. The gas servo positions reactor control drums for rocket engines, such as the Nerva engine. The present gas servo system uses electronic equipmen t for the amplifier and networks. The use of fluid amplifiers would permit the gas servo to be a completely self-contained package with only power and signal input lines. The present arrangement with electronics requires remote installation of the electronics for protection from radiation.

A block diagram of the gas servo system as considered in the application study is illustrated in Figure 7.16. The study concentrated principally on the dynamics of the loop and the implementation of the amplifier and networks. The input signal was considered to be electrical and therefore would require an electro-pneumatic transducer similar to that presently being used on the servo valve. The typical requirements for the amplifier are to provide proper gain and to incorporate lead characteristics giving adequate phase margin at the loop cross-over frequency. Fluid amplifier circuits were conceived to provide these characteristics. A circuit was also designed to provide the lag-lead characteristics which, would be required with an alternate servo valve considered, in order to meet steady-state accuracy requirements. A feedback-position transducer would be required to convert mechanical position into a pneumatic signal which is fed into the frequency response shaping network. The results of the application study, which included consideration of power consumption using hydrogen in addition to the system dynamics, indicated that the fluid amplifier circuits were feasible.

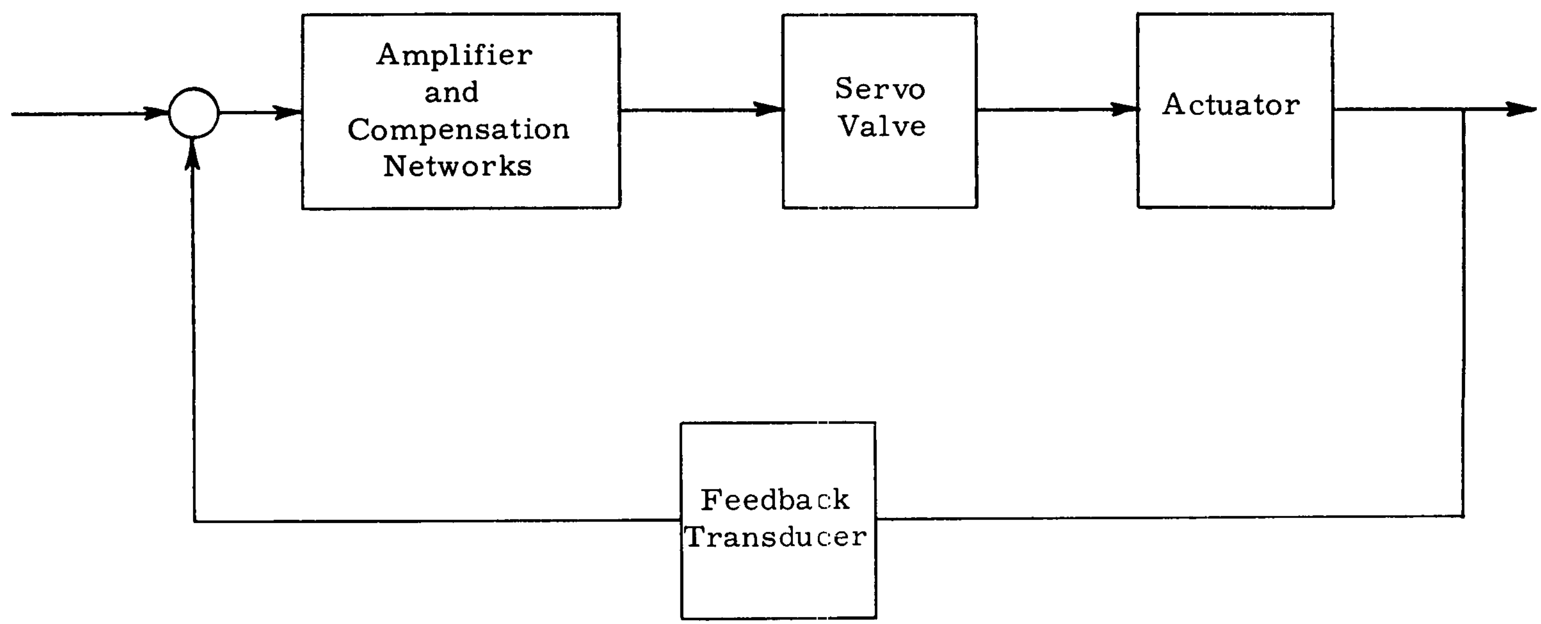


Figure 7.16. Gas Servo System for Reactor Drum Control.

7.3.8 Reactor Rod Control

An experimental reactor rod drive mechanism was fabricated and tested for feasibility [7-13]. The drive incorporated a gear-type air motor to drive a reactor rod. The air flow to the gear motor was controlled with a fluid amplifier flip-flop. Switching of the flip-flop was accomplished with an electro-pneumatic transducer which utilized an electrical discharge. The discharge ionized the gas and thus caused a pressure wave which switched the flip-flop. The electrodes of the transducer were mounted in the control ports. Feasibility of the concept was shown.

7.3.9 Satellite Attitude Control

A portion of one axis of a satellite attitude control is being assembled to demonstrate the potential of fluid-amplifier control systems for space applications [7-3]. A simplified block diagram of the system is shown in Figure 7.17. This is one of the class known as "time-in-deadband" controls, in which torque is applied to the vehicle with reaction jets to maintain the satellite at the desired attitude within a limit cycle. The system is basically second order with no damping. A velocity or pseudo-velocity feedback must be incorporated to provide the desired stability. To minimize power consumption, the reaction jet applies a programmed pulse as the vehicle leaves the position deadband. The pulse length is adjusted to the rotational energy level of the vehicle (i.e., a high energy level calls for a long pulse, while a low energy level calls for a short pulse). Both optimized operation and damping is produced by the fluid logic block which consists of digital fluid amplifier circuitry.

The sensor permits a limit cycle oscillation within a prescribed deadband. If the attitude of the vehicle wanders outside of this deadband, the sensor triggers the fluid logic which actuates the reaction jets so as to correct the attitude of the vehicle. The duration that a reaction jet is turned on (hence, the impulse applied to the vehicle) is a function of the time required for the vehicle attitude to coast across the deadband. Figure 7.18 illustrates a typical relationship between the output (reaction jet) pulse duration and the time required for a vehicle to coast across the deadband. As the figure shows, a region exists which will provide the proper damping for the desired performance. This control characteristic is simulated by a series of straight line approximations such as that shown for the 10 to 30 second deadband time in Figure 7.18. In the example, if the deadband cross-over time is ten seconds, the output pulse duration is about 0.33 seconds. As the vehicle angular rate slows down and requires 30 seconds to cross the deadband, the output pulse duration is reduced to 0.15 sec. Thus the orbital vehicle is brought into the desired limits with the damping and fuel economy provided by the logic block.

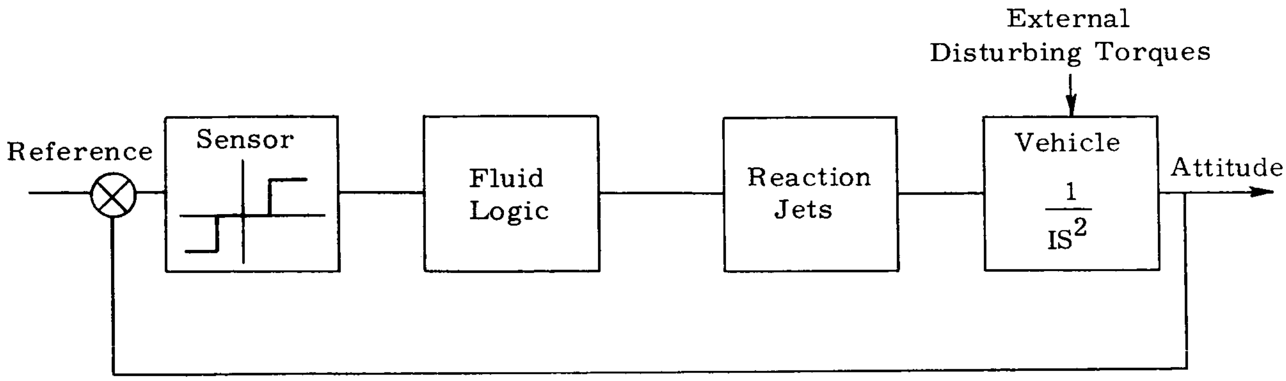


Figure 7. 17. Block Diagram of Satellite Attitude Control.

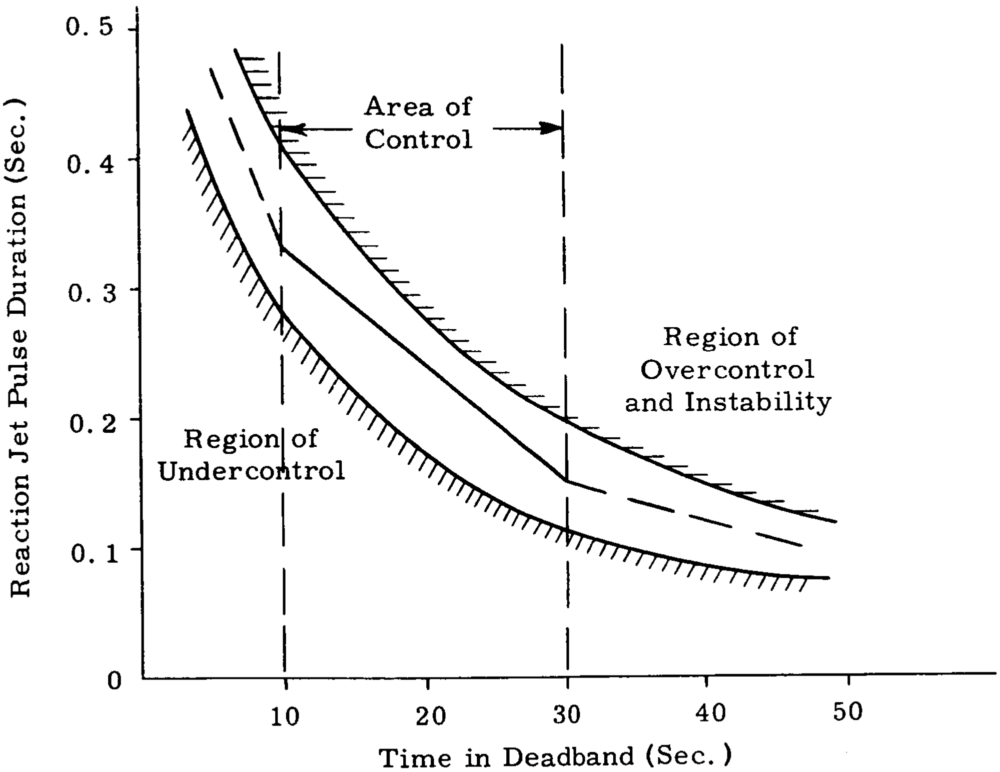


Figure 7. 18. Vehicle Control

7.3.10 Ramjet Spike Position Controller

The Marquardt Corporation is investigating the use of fluid amplifiers in a ramjet spike position controller [7-14] (sponsored by Wright-Patterson Air Force Base). The circuitry utilizes vortex-type logic elements of a proprietary design (see Sections 4.4 and 5.0 for performance data).

The basic function of a spike position controller is to position the spike at the engine air inlet so that the oblique shock from the spike intercepts the cowl lip regardless of flight conditions. In addition, in case of engine "unstart" or in case of "buzz", it is necessary to extend the spike. The main control loop is, therefore, based on the shock position, while the unstart and buzz inputs serve as over-rides. A diagram of the control is shown in Figure 7.19.

The shock position loop is a "bang-bang" type control since position is sensed digitally. The shock is sensed as being either forward or behind the reference location by means of two pressure pick-ups. A third pressure pick-up, located in the high-pressure section of the engine, provides the air supply for the logic elements. The shock position sensor provides the single input to the first monostable element which provides an inverting function. If the unstart and buzz signals are not present, the signal is inverted again in the second monostable element and amplified in the bistable element. The bistable element positions a spool valve which drives a rotary air motor and lead screw for spike extension and retraction. The unstart and buzz signals override the position signal due to the fact that the second monostable element performs a three input NOT-AND function. The logic is shown in the truth table in Figure 7.19.

The logic elements have been fabricated and are being operated in a "closed loop" configuration with an analog computer simulation of the ramjet engine. The logic fits into a cube of approximately four inches on a side.

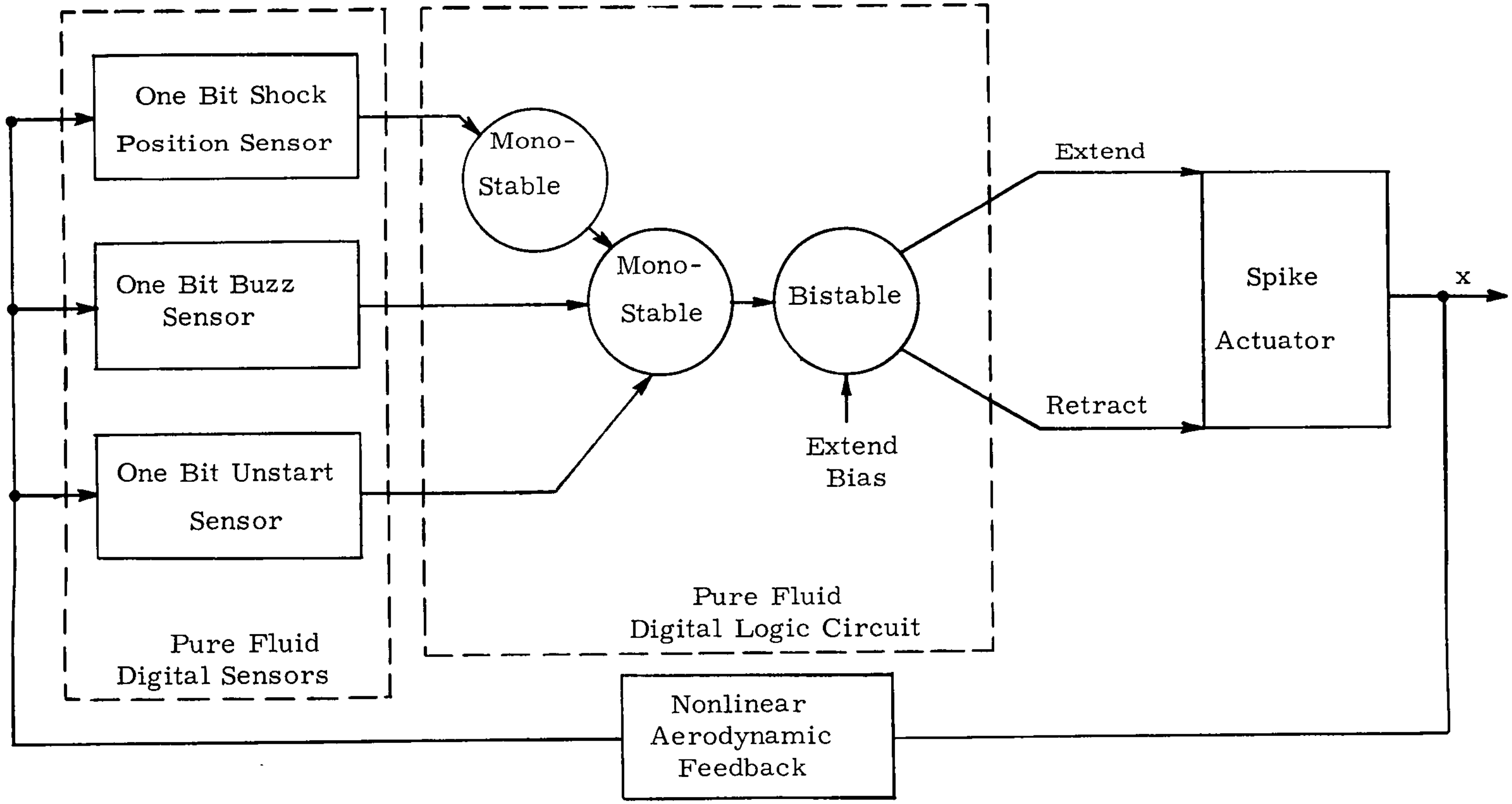
7.3.11 Other Military Applications

Several additional military applications which are under development are briefly mentioned below. Little information has been obtained about these applications but their existence is believed noteworthy.

A drive mechanism for a small air bearing gyro was developed by Griffin [7-15], using a fluid amplifier oscillator to drive the gyro. The oscillator pulsating output is directed on a notched wheel to produce torque to drive the wheel. The wheel (and gyro) accelerates to a speed which is synchronous with the oscillator frequency, thus providing speed control.

A timer for ordnance applications is under development [7-11] using a proprietary counter circuit.

A hydrofoil control system [7-11] is under development which makes use of a servo control.



Truth Table

B	U	S_s	R	E
0	0	0	0	1
0	0	1	1	0
0	1	0	0	1
0	1	1	0	1
1	0	0	0	1
1	0	1	0	1
1	1	0	0	1
1	1	1	0	1

Figure 7.19 Ramjet Spike Position Controller

REFERENCES, SECTION 7

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7-2 "Condensed Catalog of Moore Products", Ninth Edition.

7-3 Information from the General Electric Company.

7-4 Information from the Minneapolis Honeywell Regulator Company.

7-5 Information from Johnson Service Company.

7-6 Woodward, K.E. et al, "A Fluid Amplifier Artificial Heart Pump". Fluid Amplification Symposium Proceedings DOFL, October 1962.

7-7 Krulewich, E.B. and Shinn, J.N., "Fluid Timer for Ordnance Applications", 1st quarterly progress report, Contract DA-19-020-AMC-0213, Picatinny Arsenal, Dover, N.J. (General Electric Co.).

7-8 "Experimental Design of a Fluid-Controlled Hot Gas Valve", U.S. Army Missile Command, Redstone Arsenal, Alabama, December 31, 1962.

7-9 Colston, R.J. "A Pneumatic Pure Fluid Speed Control for a 500 KW Steam Turbine Generator", final report ONR Contract Nonr 4033 (00) September 1963.

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7-11 Information from Bowles Engineering Corp.

7-12 Boothe, W.A. "Application Fluid Amplifiers to Reactor Rod Control", final report, NASA Contract NAS 3-2567 October 24, 1963 (General Electric Co.)

7-13 Spivak, A.L., and Hemmingway, S.F., "Final Report on the Development Program of Advanced Control Components Unit", USAF Contract AF33(600) 38062 and AEC Contract AT (11-1)-171, January 1962 (General Electric Co.)

7-14 Information from the Marquardt Corp.

7-15 Griffin, W.S., "The Analytical Design and Optimization of a Pneumatic Rate Gyroscope for High Temperature Applications", ScD Thesis, Dept. of Meek Engr. MIT, October 3, 1962.

7-16 Information from Stanford Research Institute.

8.0 FABRICATION TECHNIQUES

8.1 Introduction and Commentary

The fabrication of fluid amplifier and logic elements requires processes which lend themselves to the complex shapes and reproducibility of close tolerances. Accommodation of the many environmental situations encountered by the various applications has also required that a number of materials be considered. These have included plastics, metal, glass, and ceramic. In addition, sizes required have varied from elements having nozzles of a few thousandths of an inch in diameter or width, to those of several inches. This broad range of requirements has led to investigation of a number of different fabrication techniques. Some of these are suitable to experimental work, some are more suitable to production. Costs will vary from pennies to hundreds of dollars per element. Table 8-1 represents an effort by the authors to present an objective assessment of the known techniques. Quite obviously, the advocates of each technique make more optimistic claims for their own process. A brief description of each technique is given in the following subsections, as listed in Table 8-1. References are cited if the reader wishes to investigate further.

It will be noted that all except the last of these techniques results in an "open" element consisting of one or two pieces into which the passages are relieved. Either the two parts must be assembled, or a cover plate placed on the single part to make a working element. This assembly problem, and the problem of assembling a number of elements into a package are areas that still require considerable attention. Some of the techniques for fabrication lend themselves to extreme miniaturization of the elements and to the fabrication of a number of elements in a single piece. Very little information has been released, however, on techniques for interconnecting such single or multiple elements. This situation is very comparable to the interconnection and "packaging" problems faced in microelectronics. One factor in these problem areas is the early state of the art, another is that size has not been a problem in the applications which are evolving most rapidly. This situation is certain to change rapidly in view of the heavy development effort now getting under way in military applications.

8.2 Description of Techniques

8.2.1 Scroll Sawing

The simplest and quickest method for making an experimental fluid element is to cut it from a textolite or plastic sheet. In order to get reasonable accuracy only larger scale elements can be produced, minimum channel dimension should not be less than 1/8 inch. By using a high quality scroll saw and hand filing the critical dimensions to final value a practical exploratory unit can be turned out.

This method is the least expensive one identified for making experimental models of a new design. No special equipment or facilities are required, even hand tools are adequate. If an experimental unit is made in this way with suitable care, it can then be used as a master to engrave duplicates to the same or other scale.

8.2.2 Photosensitive Plastic

A DuPont photopolymer plastic marketed under the trade name Dycril [8-1] is finding wide application for the fabrication of elements in development quantities. The process also seems appropriate to moderate production volumes.

Originally intended for the making of plates for the printing industry, Dycril exhibits many of the properties required for fluid element fabrication. It can be patterned in complex shapes with reasonable accuracy, cost and fabrication time is modest, and a fairly wide range of sizes can be produced.

Dycril elements are fabricated by an optical forming method. The Dycril plastic polymerizes under strong ultraviolet light, but is rather soft when not exposed. By covering the plastic with a properly prepared opaque master pattern and exposing the sandwich to ultraviolet light the plastic is "exposed". It is "developed" by washing in a weak sodium hydroxide solution which will attack the unexposed portions of the plastic. Hence, the pattern must be opaque wherever it is desired that the plastic be etched away.

Dycril is available in sheet form on metal backing in six different thicknesses, from 0.025 to 0.240 inches, including the backing which is steel in the thinner sizes and aluminum in the thicker ones. Reliefs in the plastic can be cut up to 0.040 inches deep. Available plate sizes vary with thickness, but all are available in at least an 18 x 24 inch size. Type 152, commonly selected, has an aluminum backing of 0.100 inches and a total thickness of 0.152 inches. Reliefs of up to 0.040 inches are possible, and the thick aluminum backing can be tapped for inserting hose connectors.

The Dycril has an upper temperature limit of 150° F for extended operation. The material is not satisfactory for use with water or in high humidity, as it swells and becomes weaker; see Figure 8.1. Table 8-2 gives a complete listing of the characteristics of Dycril.

Improvements have been necessary in the material and process for fabrication of fluid elements to increase the etching ratio. While this ratio was not particularly critical in printing applications, it is a source of inaccuracy in fluid elements. A proprietary fabrication process, called OPTIFORM*, is representative of the accuracies that are now possible with

* Bowles Engineering Corporation, Silver Springs, Maryland

Dycril. Figures 8.1 through 8.5 relate to the Optiform process. Figure 8.2 shows that the etched relief will have a maximum undercut of 1.5^{o} for a 0.040 inch depth. As indicated, the relief will also be approximately 0.001 inches outside the edge of the opaque pattern. The etched surfaces are very satisfactory as far as smoothness is concerned, and radii at corners will be less than 0.002 inches. Bowles Engineering Corporation provides a fabrication service using the Optiform process.

Minimum practical channel width is 0.025 inches because the etching fluid must be able to flow freely. Separator walls must be kept above a minimum of 0.015 inches. Standing posts with a minimum diameter of 0.012 inches, and holes with a minimum diameter of 0.030 inches can be fabricated. Figures 8.3, 8.4, and 8.5 illustrate these limits.

Processes like the one just described result in an open-channel element which must be covered for operation. Several approaches are in use, none of which are entirely satisfactory except for development work. The Dycril parts can be clamped against a greased surface as a cover for temporary operation such as checking the characteristics of the element. More permanent methods include the use of gaskets and clamps, and cements. The gasket approach requires that the flat surfaces be well finished to avoid leakage across narrow sections. A cement should be selected that does not leave a tacky surface in working channels to catch dirt or dust particles. A pressure-sensitive type of cement has been found fairly satisfactory.*

8.2.3 Epoxy Casting

This fabrication technique makes use of an RTV silicone rubber mold to cast elements from epoxy. The master from which the RTV mold is made can be produced by any one of a number of methods. A high precision engraving machine working from a large scale pattern does a very good job. The master, of course, is made as an exact positive of the element desired. A large number of epoxy materials are suitable and selection appears to be largely a matter of personal preference. The authors have used Stycast No. 2651MM** with good results. A material which has fairly low viscosity, low exothermic characteristics and low shrinkage is desirable. Fillers or color can be used to advantage. Reference 8-2 discusses epoxy casting techniques.

The equipment required is fairly simple and inexpensive. A low-temperature oven is necessary to cure most of the more satisfactory epoxy materials and the RTV mold. A vacuum chamber is very desirable. In preparing both the mold and the elements, care must be taken to eliminate bubbles. The vacuum is extremely helpful in this regard, although the bubbles

* Eastman 910

** Emerson and Cummings Company, Canton, Massachusetts can be removed by mechanical probing if one has sufficient patience. The mold can be modified with a sharp instrument after curing. The finished epoxy parts can also be modified, drilled or trimmed after curing. The curing cycle varies considerably with the formula and temperature selected, usually being in the range from 1 to 48 hours.

The epoxy elements can cover an extremely wide range of sizes. Channels as small as 0.005 inches have been cast successfully. If the formulation is properly selected and used, the finished parts will conform to the master within 0.001 inches.

These are also open-channel elements that require cover plates. Epoxy cements are fairly satisfactory. One interesting approach involves using a "soft" epoxy layer on a cover plate into which any necessary fittings have been molded. The soft material is self-gasketing; several elements can be clamped in sandwich fashion by pre-drilling required interconnections between the epoxy elements.

No source for fabrication services has been identified for the cast epoxy elements. The process is so simple that users apparently have been making their own.

8.2.4 Photosensitive Glass

The Corning Glass Works has developed a method for producing fluid elements from Fotoform Glass which is a glass material that can be made photosensitive. Much of this work has been sponsored by the Harry Diamond Laboratories (see reference 8-3).

The process (see reference 8-4) is very versatile in terms of the complexity of detail and variety of sizes that can be fabricated. Figure 8.6 shows two test pieces in approximately actual size. The method of fabrication involves exposing the sensitized Fotoform Glass to light with a standard photonegative of the desired pattern between the glass and light source. Exposed portions of the glass are transformed to a crystalline phase which is twenty times more soluble in dilute hydrofluoric acid than the unexposed portions. The rates of the etching process have been well established; the size and depth of the etched relief can be adjusted by controlling the etching time and properly designing the pattern. The total process time is less than twelve hours. The ability to use a photographic negative as a pattern makes it convenient to scale elements from one size to another. It is possible to etch through holes or relief chambers deeper than the main pattern, but this usually requires a double cycle. The holes or deeper parts are etched first, followed by the main pattern on the second cycle.

The process yields parts of good accuracy. Holes and channels up to 1/4 inch can be held to 0.001 inch, up to 1 inch within 0.002 inch.

Depth can be held to 0.002 inch in a plate as large as 5 x 5 inches, and centers can be held to 0.003 inch. Deviations of dimensions within a single element should be consistent within less than 0.001 inch, and differences between elements are less than 0.002 inch. Maximum depth currently achieved with the process is 0.125 inch. The thickest plates available are 1/4 inch. Taper of the side walls of a relief is less than 3^{o}. The minimum practical wall thickness is 0.020 inch. Blind holes and channels less than 0.010 inch will not reach the same depth as the wider sections due to the restriction of the acid flow. Sharp protruding angles are difficult to generate since they require a calculated compensating shape having the proper radius and a very closely controlled etching rate. Figure 8.7 shows a test piece used to establish some of these limits.

As in the other processes these units are open elements requiring a cover plate. A thermal lamination process has been developed whereby a permanent and reliable bond can be formed between the glass plates by fuzing them together. This can be accomplished at temperatures which will not harm the etched pattern. While individual glass elements are somewhat fragile, an assemblage of a number of fuzed elements becomes extremely strong. The fact that the glass is immune to damage from most solvents makes it possible to clean out the passages in such an assembly to remove foreign material without concern for methods of disassembly.

Corning provides a fabrication service for glass elements to the users design. As part of the DOFL contract they produced hundreds of elements which they reported showed very good reproducibility of characteristics.

8.2.5 Photosensitive Ceramic

A photosensitive ceramic, called Fotoceram, has also been developed by Corning Glass Works. Actually the material is the Fotoform Glass (described in the previous subsection) put through an additional process step to convert to a ceramic phase. The resulting product is said to be three times as strong as the glass, and to maintain its shape at temperatures as high as 500^{o} C. The fabrication process is the same as that described in 8.2.4 for Fotoform Glass except for the additional process step. Information on any deterioration in tolerances was not available.

8.2.6 Machined Metal

Elements can be machined using engraving machines or milling machines. A variety of materials can be used in these methods, but they are particularly adapted to working with metals such as steel and brass. These techniques, while somewhat costly, are very flexible for producing experimental elements or masters for molding or automatic tracing methods. Experimental work is also being carried on to investigate the use of electrolytic machining for fabricating high temperature elements from metal. There has been no indication that lasers or electron beam machining are in use.

Larger size stages can easily be fabricated with good accuracy using the machining techniques. The lower limit on channel width varies with the material in use: 0.010 widths are practical in all except the hardest materials, 0.005 widths are possible in brass and aluminum.

8.2.7 Transfer or Pressure Molding

Transfer or pressure molding of thermosetting plastics offers a relatively low cost method of fabricating the fluid elements in medium and high volume production. Because of the environmental limitations of the suitable molding materials this method will not apply to some of the military or space applications. Due to setup time and costs, the method is not well suited to making experimental or developmental units. Figure 8.8 shows a typical transfer molding setup.

The major problem with these approaches is shrinkage or distortion of the pieces which may affect accuracy. The units must also be sealed with a cover plate.

Molds for the process are easily made by the electroform process or from machined dies. The electroform process has been used widely for such things as making waveguides and phonograph record molds. In the process a removable or expendable master is used as a mandrel and plated, usually with copper and/or nickel. The plate may vary from a few thousandths to fractions of an inch. Sprayed metal can be used for larger pieces or for buildup. The back of the plating can then be reinforced and the original master removed. This then forms a die that will reproduce the original piece in considerable detail.

Standard electrotype techniques such as used in the printing industry can also be used to produce molds or even the elements themselves. No significant effort along these lines is evident at present, however.

8.2.8 Injection Molding

Injection molding promises to be the lowest cost, high production method of fabricating fluid elements. While the thermoplastic materials suited to the injection molding process have rather limited environmental capability, they will undoubtedly satisfy a large portion of the future commercial market. Tolerances can be held fairly close, and multiple element assemblies can be molded at one time. Figure 8.8 shows typical industrial injection molding equipment.

A number of firms are experimenting with this method, but it has little impact on most of the development work in progress on applications due to the small number of elements required and the fact that "standard" elements have not yet evolved. The major problem that will be faced in the injection molding method is the assembling of elements or assemblies, the problem of sealing two pieces or applying a cover plate. The "blown" plastic process now in common use for fabricating many plastic items does not appear suitable for fabricating elements because of the lack of control on tolerances of the cavities.

Molds for the injection molding process can be machined directly, or can be made by the electroform process described in section 8.2.7.

8.2.9 Laminating

The use of a stack of laminations to form an element has also received consideration by several people. Stanford Research Institute has successfully produced elements by this method with channels as small as 0.002 inch in width; no performance data is available. Metal laminations have been of primary interest in an effort to produce high temperature elements. Thin sheet stock of 0.001 to 0.005 inch can be die punched or etched. The element is constructed by stacking enough punched laminations to achieve the channel dimensions desired, covering these with cover laminations, and then clamping the entire stack.

8.2.10 Ceramic Molding

In an effort to fabricate high temperature elements and to avoid the problem of assembling elements to cover plates, General Electric Company is investigating ceramic molding using a "lost plastic" process. Polystyrene cores are first molded from a metal master. The cores are then molded into the ceramic which is fired at approximately 2000° F. This cures the ceramic and vaporizes the plastic core leaving a one piece element. Connecting fittings require the use of ceramic-metal bonding techniques. This work is still in the early phases and no results are available for publication.

Table 8-1

Fabrication Techniques

Technique	Report Section	Suitable Uses: Experiment	Low Prod.	Med. Prod.	High Prod.	Adaptability: Sizes	Shapes	Accuracy	Environmental Range	Relative Production Cost
Scroll Sawing	8.2.1	E	F	P	P	F	F	F	P	F
Photosensitive Plastics	8.2.2	G	E	G	F	G	E	G	F	F
Epoxy Casting	8.2.3	F	G	E	F	G	G	G	F	F
Photosensitive Glass	8.2.4	F	E	E	G	G	E	E	G	P
Photosensitive Ceramic	8.2.5	F	F	G	G	G	E	E	E	P
Machined Metal	8.2.6	G	G	P	P	E	G	G	E	P
Transfer/Pressure Molding	8.2.7	P	F	G	G	G	G	G	F	G
Injection Molding	8.2.8	P	P	F	E	G	G	F	F	E
Laminating	8.2.9	P	P	G	F	F	F	G	G	G
Ceramic Molding	8.2.10	P	P	G	F	G	F	G	E	P

Key
E = Excellent
G = Good
F = Fair
P = Poor

Table 8-2

Printing Plate Laboratory
Photo Products Department
E. I. Dupont de Nemeurs and Co., (Inc.)

PHYSICAL PROPERTIES OF DUPONT PHOTOPOLYMER*

The data given below represent the results of tests conducted on photopolymer supplied by DuPont commercially as DYCRIL printing plates. The material was processed as for printing plate usage from the standpoint of exposure source and time.

1.	Refractive Index	1.4890
2.	Thermal Conductivity, BTU/hr sq. ft. °F/in (Cence-Fitch)	1.67
3.	Surface Resistivity, (ohm/aq.)	1.5 x 10^{10}
4.	Volume Resistivity, (ohm-om)	5.59 x 10^{8}
5.	Dielectric Strength, (volts/mil)	250
6.	Dielectric Constant	
	10 kc	11.2
	100 kc	8.8
	1 mc	7.1
7.	Dissipation Factor	
	10 kc	0.234
	100 kc	0.134
	1 mc	0.12
8.	Density, (lb./in^3)	.042
9.	Specific Volume, (in^3/lb.)	24.1
10.	Tensile Strength, (psi) (50% RH, 77° F, STD Exposure)	4200 psi

(continued)

11.	Modulus of Elasticity, (E) (psi) (50% RH, 77° F)	111,000
12.	Modulus of Elasticity, (E) (psi) (50% RH, 150° F)	(Compressive)
	STD Post Exposed . . . . 14 min at 30"	78,000
13.	Compressive Yield Point, (psi) (50% RH, 77° F)	
	STD. Exposed	4160
	STD. Post Exposed	9460
14.	Compressive Strength, (psi)	4200 psi
15.	Water Absorption (24 hr).	Substantial
16.	Effect of Sun Light	None
17.	Effect of Weak Acids.	Slight Swelling
18.	Effect of Weak Alkalies.	Severe
19.	Effect of Strong Alkalies	Severe
20.	Effect of Strong Organic Solvents	None to severe depending on solvent
21.	Clarity.	Clear
22.	Hardness, KHN, (Knoop Hardness No.)	
	Exposed (20% RH, 77° F)	22.2 KHN
23.	Hardness, Duremeter Shore, "D" Scale	
	Exposed . . . . 80 - 84	
	Post Exposed . . . . 82 - 86	

*This data is preliminary and should be used for order of magnitude only.

EFFECT OF TEMPERATURE AND HUMIDITY

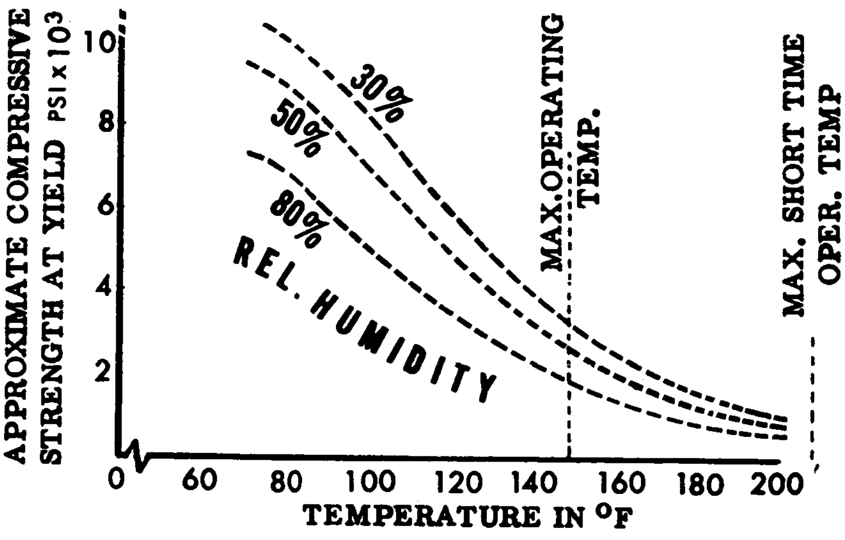


Figure 8-1

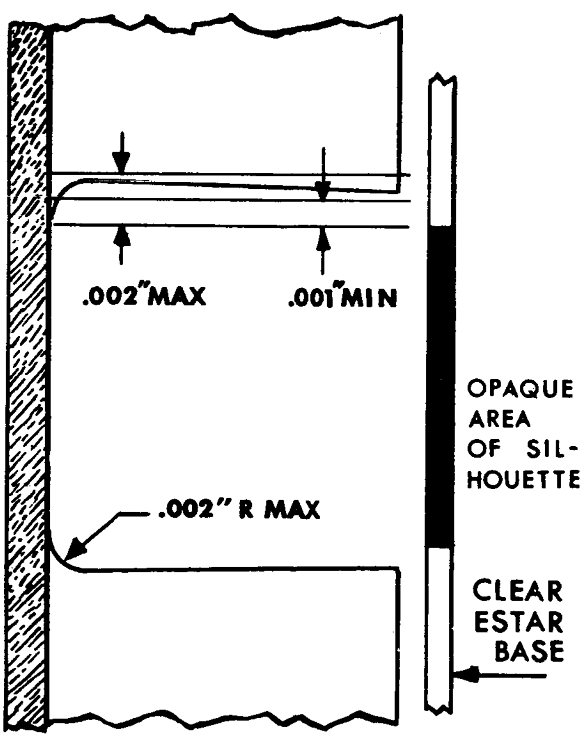


Figure 8-2

Short Channels, less than 2W long, minimum width, .015".

Long Channels, greater than 2W long, minimum width, .020".

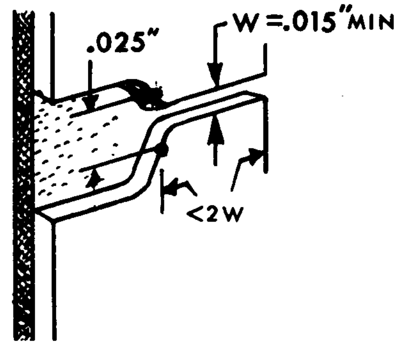
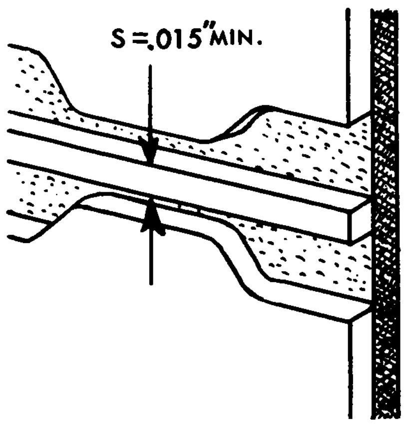
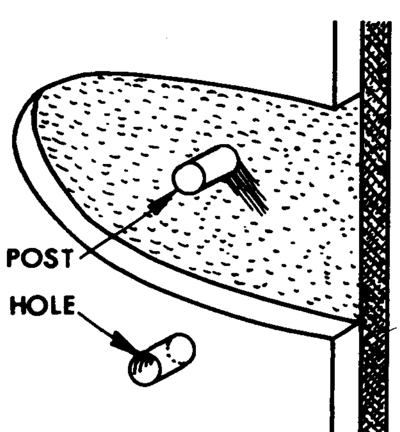


Figure 8-3



Separator Walls, minimum width, .015" (In some cases .010" can be obtained but these tend to develop a wavy character.)

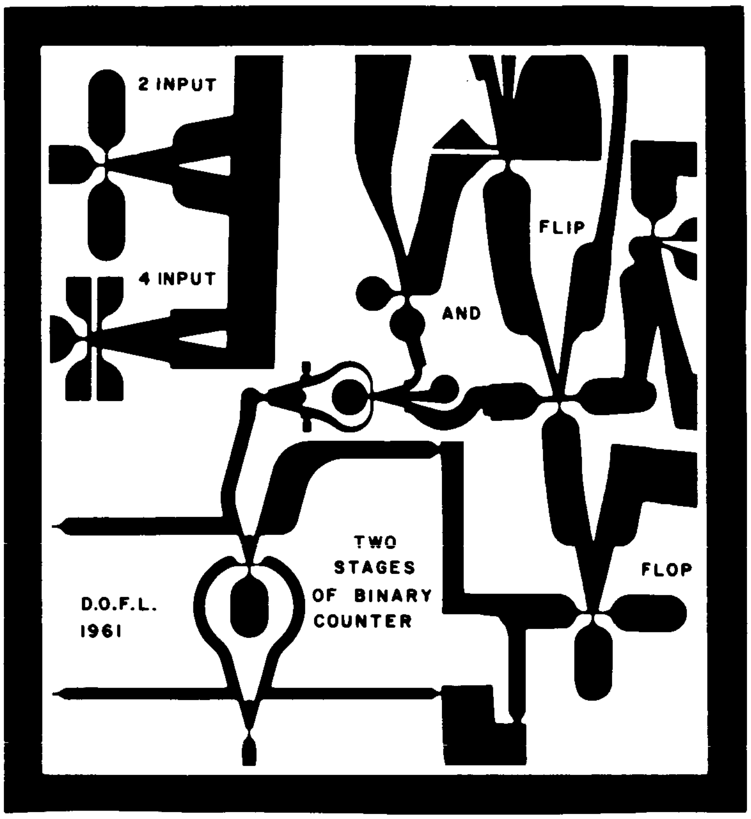
Figure 8-4



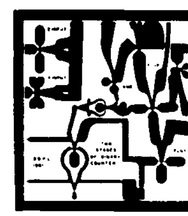
Posts, minimum diameter .012"

Holes, minimum diameter .030"

Figure 8-5



0.020" Nozzle Size



0.005" Nozzle Size

Figure 8-6 Fotoform Glass Test Patterns (Actual Size).

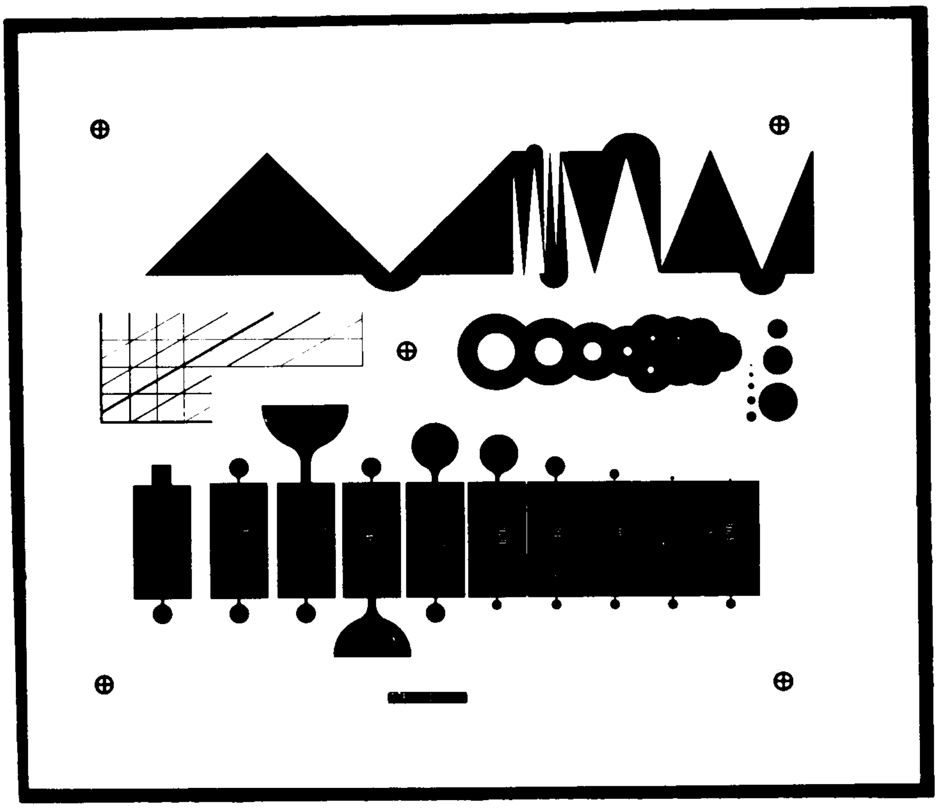


Figure 8-7. Fotoform Glass Test Pattern (to determine fabrication process limitations).

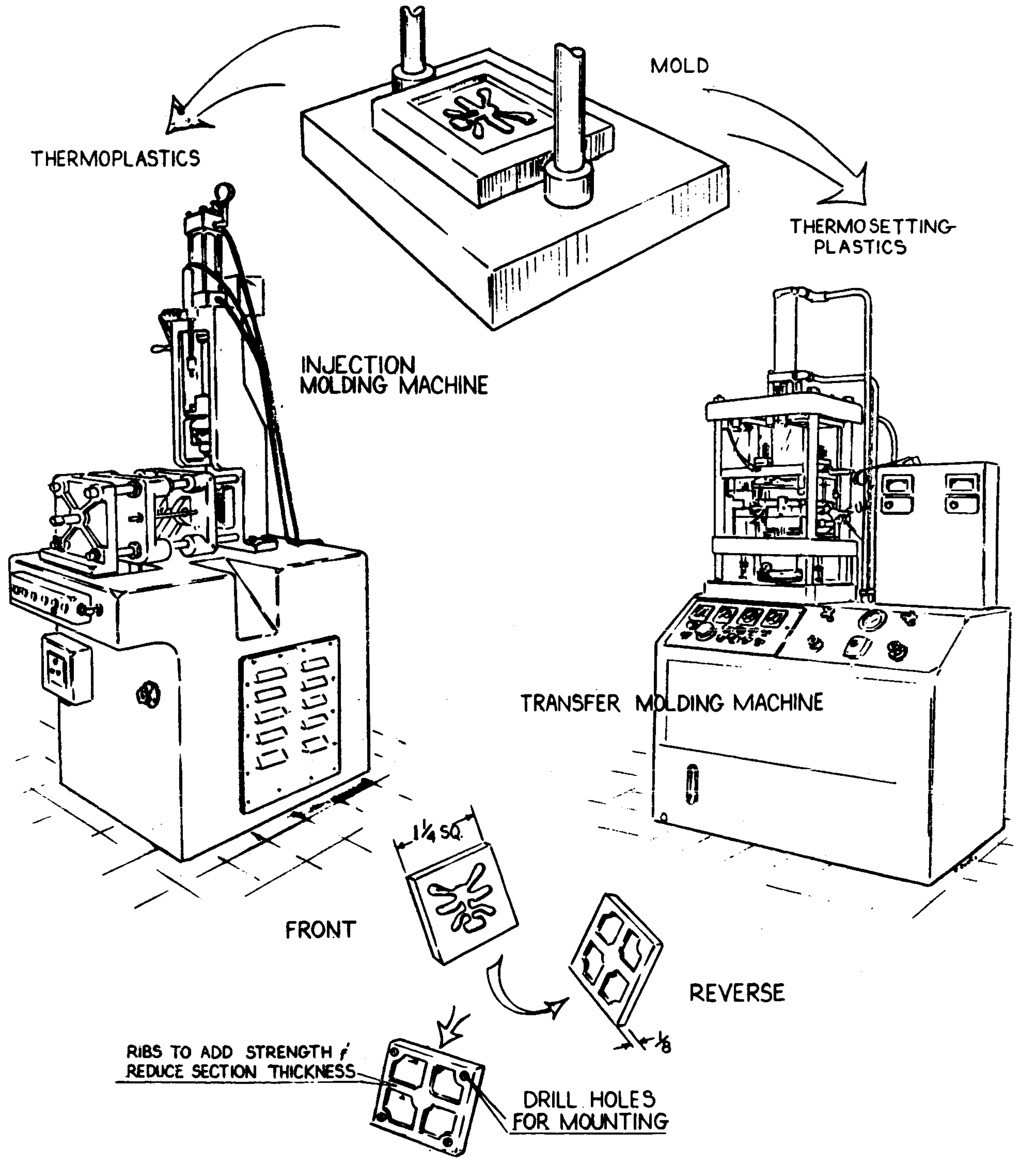


Figure 8-8

FLUID CONTROL ELEMENTS by TRANSFER AND INJECTION MOLDING

REFERENCES - SECTION 8

8-1 Bowles, R. E. and Colston, J. R. "'Optiform', Optical Machining of Pure Fluid Systems in Plastics" Fluid Amplification Symposium Proceedings, DOFL, October, 1962.

8-2 Marsh, D. S. and Hobbs, E. V. "Use of Epoxy Castings for Fluid Amplifier Design". Harry Diamond Laboratories Report No. TR-1102, 11 February 1963.

8-3 Van Tillburg, R. W. and Cochran, W. L. "Fabrication of Fluid Amplifiers By Optical Fabrication Techniques", final report HDL contract DA-49-186-ORD-1076 (Corning Glass Works).

8-4 Van Tillburg, R. W. "Production of Fluid Amplifiers By Optical Machining Methods", Fluid Amplification Symposium Proceedings DOFL, October, 1962.

9.0 INSTRUMENTATION

In the following paragraphs is a brief description of typical instrumentation being used by the many workers investigating the field of fluid amplifiers. There has been no attempt to list all equipment being used, but it is intended to give a representative picture along with sufficient references to enable one to explore this area in as much detail as he desires.

9.1 Pressure

The instrument chosen for measuring pressure in a fluid amplifier is primarily determined by the pressure range and dynamic response required. Other factors influencing the choice are: temperature range, physical size, effect on performance of the fluid element due to added volume or spring rate of the sensor, ease of calibration, type of readout, and accuracy[9-1]. Typical instruments are described below. Table 9-1 gives a summary of the various types and their characteristics.

For steady state measurements, a wide choice of instrumentation is available. For high pressures and ranges down to 15 psig full scale, the Bourdon type gage is the primary choice. For still lower ranges, the diaphragm gage is a satisfactory indicator, and these instruments cover pressures from 0.5 inch of water to 10 psig full scale either gage or differential. To obtain greater accuracy, various forms of manometers can be applied to the task. Pressures as low as 0.001 inch of water and as high as 150 inches of mercury can be read using commercially available instruments. A serious limitation in using manometers is the tendency to oscillate when connected to a load sensitive pressure source.

A large number of gages are available for measuring pressures below atmospheric and among the most convenient to use is the Alphatron manufactured by National Research Corporation. This gage covers the range from 1000 mm of mercury to 0.01 mm of mercury full scale in 6 steps. A radioactive isotope is used as a source of Alpha radiation in this instrument, and therefore some care is required in its use.

For dynamic pressure measurements, a commercial unit being widely used is the Dynisco Model PT-25. The Dynisco is an unbonded strain gage type instrument with a 9/16 inch diameter diaphragm that can be flush-mounted in a test setup. Typical sensitivity is 24 mv for full scale output with the lowest range being 0-10 psig. These devices have infinite resolution and a static error band, excluding environmental effects, of 0.75% of full scale. Temperature compensated models are available and repeatability is 0.1% of full scale. Frequency response is determined by a minimun natural frequency of 5000 cps. As far as this writer knows, this transducer has the smallest diaphragm that can be flush mounted in the 0-10 psig range and under, with a minimum frequency response of DC to 1000 cps and infinite resolution. In order to increase sensitivity, it is generally necessary to increase the diaphragm size and thus reduce frequency response. Solid state strain gages offer the prospect for greater sensitivity for the same size of smaller diaphragms, but none have reached the market place at this time.

If the requirements of true DC response can be eased, the use of piezoelectric transducers become feasible. A unit by Kistler has a 1/4 inch diameter face, can resolve pressures as low as 0.02 psig and has a natural frequency of about 150 KC. The resolution is infinite. When used with a charge amplifier, it can be calibrated using a dead weight tester. The material used is natural quartz and although more sensitive piezoelectric materials have been manufactured, temperature and humidity effects have limited their applications.

Molo-Christensen of MIT has fabricated probes less than 1/8 inch in diameter using these more sensitive materials[9-2]. Bowles Engineering has been developing a similar unit called the Miniducer which uses a 0.030 x 0.060 inch exposed area of a modified lead zirconate titanate ceramic, but temperature sensitivity has apparently limited its application, and it has not been marketed[9-3].

9.2 Flow

The variety of flow meters in general use today is quite large, and a good many types have found application as fluid amplifier instrumentation. As established by the American Society of Mechanical Engineers, fluid meters and methods of fluid measurement are classified into two major types which are the quantity meter and the rate meter[9-4].

The quantity type is further divided into weight and volumetric classifications. An example of the first type is the weighing tank which finds use in calibrating other types of meters because of the simplicity and inherent accuracy of the technique. Volumetric meters are also known as positive displacement meters and are used for measuring low pressure gas flows; the Bellows type is used throughout the country for metering natural gas. Though limited, some use is being made of this meter in fluid amplifier work because of its availability, ease of use and reasonable accuracy at low pressures (from 0.3 to 2% of full scale). Liquid meters of this type include the rotating and sliding vane, the rotating disk, and the reciprocating piston meters. The comments given above for gas meters also apply to this group, except that accuracy is better, being as low as 0.05 percent of full scale.

Rate meters are of much greater importance and are available in a wide variety of forms. A group known as head (kinetic) meters consists of the venturi, flow nozzle, square edge orifice, centrifugal, pitot tube and linear resistance meters. The orifice meters are a thoroughly investigated type that lend themselves to many applications. They are inexpensive, easily fabricated in nearly any size required and are basically a high accuracy device. Disadvantages include a limited range of flow for a given orifice size, the necessity of using a secondary element to measure the pressure drop, and the square root relationship between flow and differential pressure.

The linear resistance meter overcomes the problem of a non-linear relation between flow and pressure drop and is therefore widely used for measuring and plotting steady state flow vs. pressure characteristics of fluid elements. Two manufacturers known to be marketing such devices are the Meriam Instrument Company, and the National Instrument Laboratories, using the trade name Vol-O-Flo. These meters cause the fluid to pass through many small parallel passages where the Reynolds number is less than 1000. By so doing, the pressure drop vs. flow follows the linear relationship associated with laminar flow. Flow ranges available are 0.003 to 30 scfm full scale for one manufacturer and up to 2000 cfm from the other manufacturer. Pressure drops are nominally 10 inches of water but are available as low as 2 inches of water and as high as one-half the upstream pressure. Flow range of a given element is 100 to 1 being limited by the differential pressure measurement. Accuracy is quoted as a maximum of 0.5 percent for full scale, with calibrations of 0.1 percent available. Time constant for the National Instrument Laboratories model is quoted as 0.05 seconds. Temperature range is -60 to +160°F with a relative humidity below 90 percent. In addition to the measured pressure drop, there is an additional drop of about 2 inches of water and very little of this total drop is recoverable.

Pitot tubes have seen considerable use in fluid amplifier work for determining pressure profiles and thus, indirectly, flow rates. The calibration of hot wire anemometers discussed below often relies on a pitot tube for determining flow velocity in a miniature wind tunnel. Pitot tubes are frequently fabricated by the user following proven designs, or can be purchased from several companies such as United Sensor, Flow Corp., and Dwyer. It should be mentioned that use of these instruments is often limited to subsonic flows below Mach number 0.4 but can be used above this range if the proper, somewhat complex relationships are applied.

A second type of rate meter is the so-called area meter generally available in the form of a tapered tube and float. Several companies manufacturing this type meter are Fischer-Porter, Brooks, Schutte and Koerting, and Dwyer. Flow range for a given meter is approximately 10 to 1 with a full scale accuracy of 2 percent. Special meters can be calibrated to 1 percent of full scale. This type of meter is a versatile laboratory instrument that is both convenient to use and read. At least one manufacturer makes an interchangeable series of instruments in which various size tubes can be used in a single chassis and several floats can be used in a specific tube to allow a wide range of flows to be covered with a particular setup. For steady state measurements, this instrument sees more service than any other type in fluid element development work.

For dynamic flow measurements in a gas, a thermal type meter, the hot wire anemometer is the preferred choice. This is available in two types, the constant current and the constant temperature type. Flow Corp. manufactures both types, while Disa of Denmark supplies a very fine constant temperature unit. In addition, many experimenters are fabricating special instruments based on the principle of the hot wire.

The great attractiveness of this meter is its small size and high response. Many of the fluid element response measurements made to date have been made using this type equipment. It is also being widely used to measure signal to noise ratios of fluid elements.

The Disa equipment uses a probe made of 0.2 mil diameter platinum plated tungsten about 1 millimeter long which gives a nominal resistance of 3.5 ohms. Frequency response is DC to about 50 KC at a maximum rated flow of 150 meters per second and somewhat less as the flow rate drops off. Output of this equipment is a DC voltage which is proportional to the 4th root of velocity. A panel meter also displays the RMS value of this same signal. Life of the probes is dependent upon air velocity, cleanliness of the gas and care in handling, but an operating life of 50 hours is common. Repair of the probes can be accomplished by a competent technician but an exchange service is maintained by Disa which is quick and costs about $15.00 per probe.

While not considered as flow meters, there is a group of devices that are commonly used to determine the presence or lack of flow. Among these is the Bowles Engineering Corporation Flow-No Flow indicator, Cat. No. 0250. This device uses a small thermistor suspended in the flow channel as a sensor and gives a visual (light) output at the battery-powered control box. Sensitivity of the device is adjustable and can cover the range from 0.5 feet per second to 500 feet per second[9-3].

9.3 Pressure-Flow Testers

It has been found convenient by a number of laboratories* to assemble pressure and flow measurement equipment into a test facility to quickly determine the steady state characteristics of fluid amplifiers. Generally, these testers sense pressure and flow from a port using transducers and record the data on an X-Y plotter. For example, the output pressure-flow characteristics of an amplifier is recorded by placing a variable load on the amplifier and monitoring flow and pressure at the port. Typically the variable load is a motor-driven needle valve. The same equipment can be used to generate the input characteristics of flip-flops showing the switching points hysteresis (See Sect. 4.2). The testers generally have several pressure and flow transducers to cover a range of values. Pressure gages and flow meters are usually included for visual monitoring. Quick disconnect fittings

*Harry Diamond Laboratories, Corning Glass Works, and General Electric.

are typically used on the fluid "leads" to provide a means of quickly changing the test set-up. The X-Y tracings provide an excellent pictorial description of the test amplifiers performance and also provides a quick means of obtaining permanent data.

9.4 Flow Visualization

The flow of a compressible gas is amenable to optical visualization by utilizing either of two phenomena: that the speed of light is a function of the gas density, or that light passing through a variable density gas is diffracted.

The interferometer depends on the first phenomenon using the interference of two light beams to evaluate the local light speed through the test channel. A basic interferometer is illustrated in Figure 9.1. References 9-5, 9-6, 7, 8, 9 and 10 describe the operation and construction of optical systems. Schlieren and shadowgraph methods(9-9, 9-11, 9-12, and 9-13) depend on the deflection of light due to density gradients and thus are primarily useful in visualizing the shock and expansion waves as occur in supersonic flows. Pictures of supersonic flow are illustrated in Figures 9.1 through 9.4 along with typical optical systems. Keto[9-11] has reported on an advanced Schlieren system which has been used with fluid control elements having power jet nozzles of 0.30 inch width. A picture from that report is shown in Figure 9-3.

At subsonic flow optical methods are too insensitive to be of much value. Keto[9-11] illustrates methods of adding high or low density trace gas to a jet to define its boundaries, but these methods do not clarify the details of the flow.

Boundary flow can be visualized by coating a surface with neat's-foot oil and lamp black solution. After a short period of exposure to flow, the oil evaporates, leaving a lamp black trace of the flow pattern along the wall. Figure 9.5 shows a flow pattern obtained by this method. Similar methods using fluorescent oil or china clay have been developed to indicate boundary layer flow direction and transition.[9-14]

When flow is laminar, smoke trace techniques are useful as described in references 9-15 and 9-16. Unfortunately laminar conditions do not often prevail in fluid amplifier applications and the rapid diffusion of smoke in turbulent flow limits the utility of this method.

A water table is a device which facilitates experimentation under either open or closed channel conditions and can be used to visualize most of the phenomena occurring in fluid amplifiers. A closed full-flowing water channel is characteristic of an incompressible viscous fluid. However, with a free surface, compressible flow phenomena are simulated. Matthews[9-6] describes the use and design of typical water tables while Byrd and Williams[9-17] apply this technique to simulate a typical fluid amplifier problem. The dynamics of the analogy are clearly reviewed by Byrd and Williams.[9-17]

Since the water level height is a most significant variable in the simulation, methods of accurate height determination are described in references 9-6 and 9-17. Also, a stereophotographic technique is described by Mann[9-18] which allows simultaneous determination of height over large sections of the flow field.

9.5 Response

Determining the response time of a fluid element presents two main problem areas. The first is generation of a suitable input signal and the second is selecting adequate transducers and locating them properly.

The desired input signal is usually an approximation of either a square wave or a sine wave at frequencies from 0.1 cps to above 1000 cps. Square wave signals have been successfully generated using a chopper consisting of a rotating disk with holes or slots interrupting flow between a nozzle and receiver. The exact wave shape is highly dependent upon the transmission time between generator and transducer and can be varied by changing line length, volume, and restrictions.

Sine wave generation of pneumatic signals has successfully been accomplished using a cylindrical slide valve for frequencies up to 70 cps for a load of less than 3 cubic inches. For higher frequencies, the wobble plate and nozzle approach has worked very well for frequencies as high as 2000 cps. This last method takes the form shown schematically in Figure 9.6.

Another approach used by Giannini is similar to the nozzle and receiver square wave generator, but uses a shaped passage on the rotating disk as shown in Figure 9.7.[9-19]

Swarthout manufactures a pneumatic relay which converts an electrical signal to a pneumatic pressure. This has been used in a modified form by Johnson Service Company to generate sine wave inputs from DC to 30 cps, and beyond for special conditions.

A penumatic function generator has recently become available from Bowles Engineering Corp. It is reported to generate sine, square or triangular waves in the frequency range to 600 cps.

The most common sensors used in measuring response in air-operated devices has been the hot wire anemometer, and in liquid devices the pressure transducer. A third type of sensor that has been used (developed by Bowles Engineering) is a Fiber Optics Monitor, and still a fourth approach has been high speed photographs of either a shadowgraph or Schlieren setup.

As detailed elsewhere, the hot wire anemometer has the advantages of very small size, and thus minimum obstruction to flow, and has excellent response. Unfortunately, considerable care must be used in handling them, calibration is time-consuming, and the output is a fourth power function.

Pressure transducers can be flush-mounted in a test setup but the diameter of the sensing diaphragm is frequently larger than the source of pressure. As discussed under pressure sensors, the Kistler 601A transducer is the smallest, high response, commercially available unit known and has been successfully used by many researchers.

The Fiber Optics Monitor is used in conjunction with a Schlieren system to detect changes of density in a compressible flow medium. A description of this equipment appears on Page 172 in the Proceedings of the Fluid Amplifier Symposium, October, 1962, sponsored by the Diamond Ordnance Fuze Laboratories. As stated, this monitor can also be used with a shadowgraph or interferometer.

At least two organizations have made use of the Panoramic Sonic Analyzer Model LP-1a to determine the level vs. frequency distribution of a pressure transducer or microphone input. This equipment is of particular help in investigating frequency sensitive devices such as oscillators; the relatively wide bandwidth and low sweep rate (once per second) are quite adequate for many fluid element applications.

9.6 Dimensional

As development of fluid elements progresses, there has been a marked decrease in the size of individual elements. Nozzle sizes of 0.010 x 0.010 have been successfully operated, and it is expected that even smaller units will be, or possibly already have been, developed. As a result, a gaging system for measuring the dimensions of these devices must be of very high caliber.[9-20] Both optical and mechanical gaging methods are used.

9.6.1 Optical

A primary technique for measuring dimensions to the nearest 0.0001 inch has been the toolmaker's microscope. Precision micrometers are used to position the part to be measured under a 100 power microscope where linear distances as well as angles to the nearest minute can be determined. It is possible to measure either through openings or depressed shapes in transparent or opaque materials. Ernst Leitz of Germany and Gaertner Scientific Corporation of Chicago are two manufacturers of these instruments.

A second technique is the use of an optical comparator which, however, is limited to translucent or transparent materials. In this equipment the part being inspected is inserted in an optical projection system which displays the outline on a screen where it is magnified up to 100 times, allowing measurements to the nearest 0 . 0001 inch and 1 second of arc. Jones and Lamson and Optical Gaging Products, Inc. are two manufacturers of this equipment.

The sealing of fluid elements has taken many forms but occasionally it has been necessary to effect a seal using nearly perfectly flat surfaces. Provided the work surface is reflective, the use of precision optical flats and a monochromatic light source allows flatness measurements to within 4 microinches. Round or square flats are readily available in sizes from 1 inch to 16 inches, and larger on special order. In this country, Van Keuren and DoAll are major supplies of these items.

9.6.2 Gaging

The conventional tools of the machinist trade can generally be applied to measuring the contours of fluid elements. A partial list of such items are scales, vernier calipers, micrometers, dial indicators and the special-purpose gages known as plug, taper, ring, etc. With the exception of the scales, the above devices listed are potentially capable of measuring to the nearest 0.001 of an inch. To obtain still higher resolution, it is necessary to use gage blocks with the assistance of a mechanical, electronic, or penumatic comparator. Using this approach, resolution of a few micro-inches can be obtained under ideal conditions. Experience has shown, however, that optical measuring techniques are far superior in ease of use than any listed above.

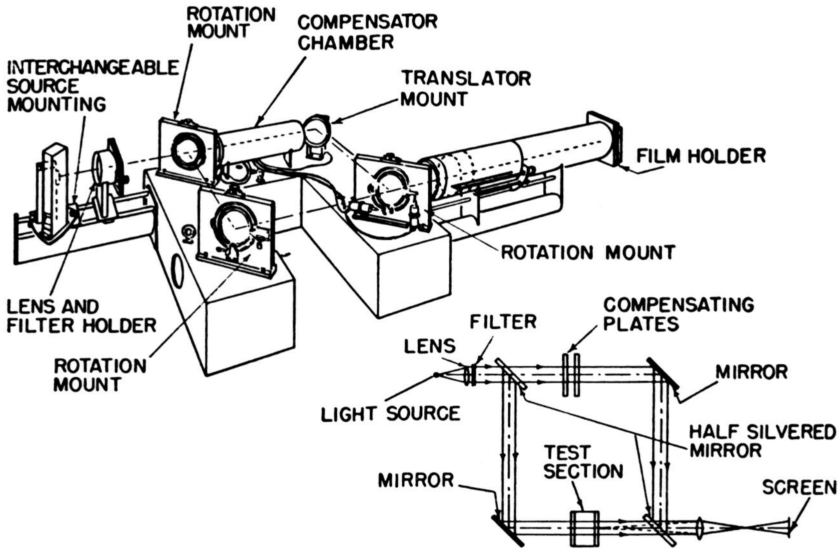
9.7 Commentary

The instrumentation, equipment and techniques, with one exception, appear adequate for current fluid amplifier research and development. Standardization in test procedures is lacking and is badly needed to permit comparisons of performance or adherence to specifications for elements and circuits. The major item needed in the way of instrumentation is a low level, small size pressure transducer, perferably with a linear electrical output signal. Frequency response of the transducer should be flat at least to 10 kc. There has also been a need for a function generator for input signals in taking frequency response. As indicated in section 9.5 there is a unit available now which covers a large portion of the desired range for gases. No comparable unit has been found for liquids.

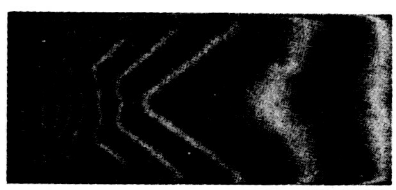
Table 9-1

Static Pressure	Lowest Full Scale	Best Accuracy % Full Scale	Highest Full Scale	Typical Manufacturer
Bourdon Tube	0-15 psig	0.1%	0-100,000 PSI	Heise US Gage Helicoid
Diaphragm gage	0-0.5 in. of H_2O	1.0%	0-300 inches of H_2O	Dwyer Marshalltown
	In the following instruments, the actual pressure is dependent upon the fluid used. Therefore, ranges are quoted in inches of fluid being used. Typical fluids available from Meriam have specific gravities of 0.827, 1.000, 2.95 and 3.57.			
Manometers				
U Tube	0-6 inches	0.1 inch	0-130	Meriam
Well Type	0-6 inches	0.1 inch	0-150	Trimount
Inclined	0-.5 inches	0.01 min. grad.	0-16	Dwyer
Micromanometer	0-10 inches*	0.001 inches	0-20 inches*	Meriam
	*(Differential at pressure levels to 15 psig)			
Hook gage	0-2 inches	.001 inches	0-2 inches	Dwyer
Alphatron gage	0.01 mm Hg	2%	0-1000 mm Hg	National Research Corporation

SUMMARY OF STATIC PRESSURE INSTRUMENTATION



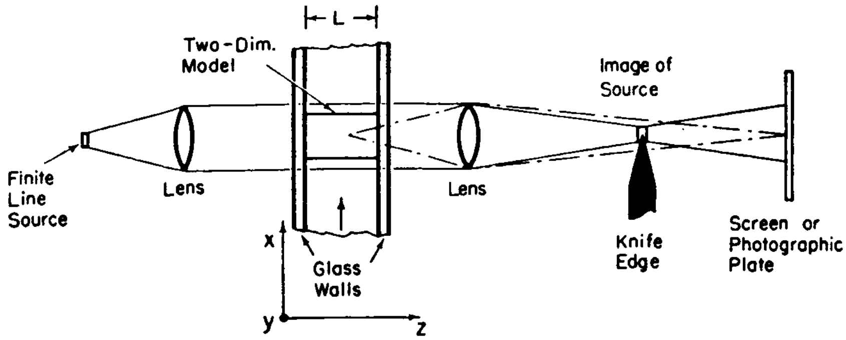
Schematic Diagram - Interferometer



Interferogram - Flow thru supersonic nozzle.

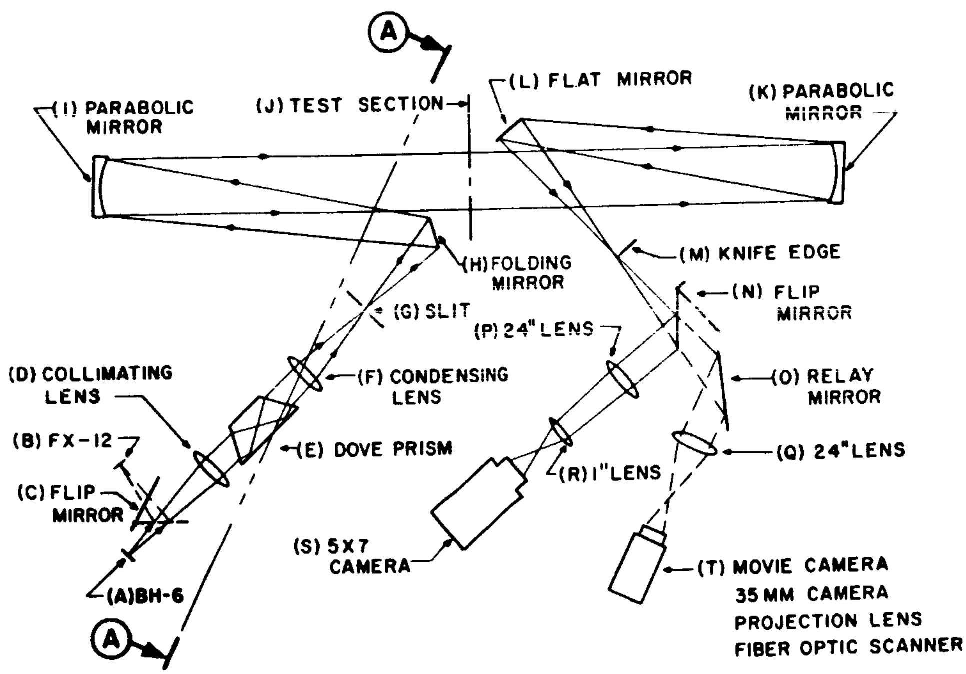
(from Ref 9-9)

Figure 9.1 Interometry



(from Refr. 9-9)

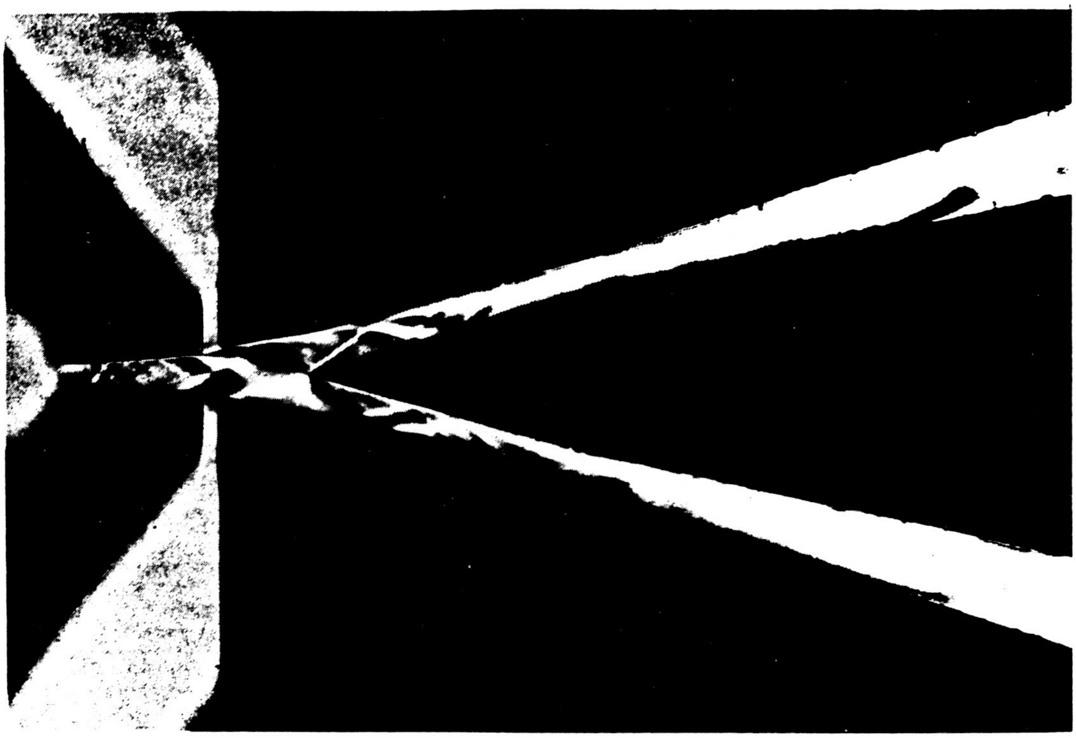
Simple Schlieren System



(from Refr. 9-11)

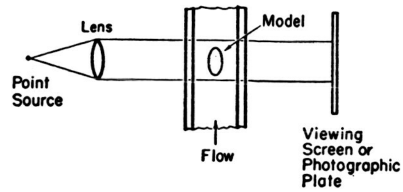
Advanced Schlieren System

Figure 9.2 Schlieren Systems

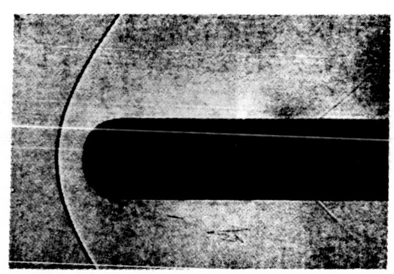


Nozzle throat - 0.030"   (from Ref 9-11)

Figure 9.3 Schlieren Picture - Supersonic Flow.



Schematic Diagram - Shadowgraph.



(a)

Shadowgraph - Detached shock for blunt body.

Figure 9. 4 Shadowgraph

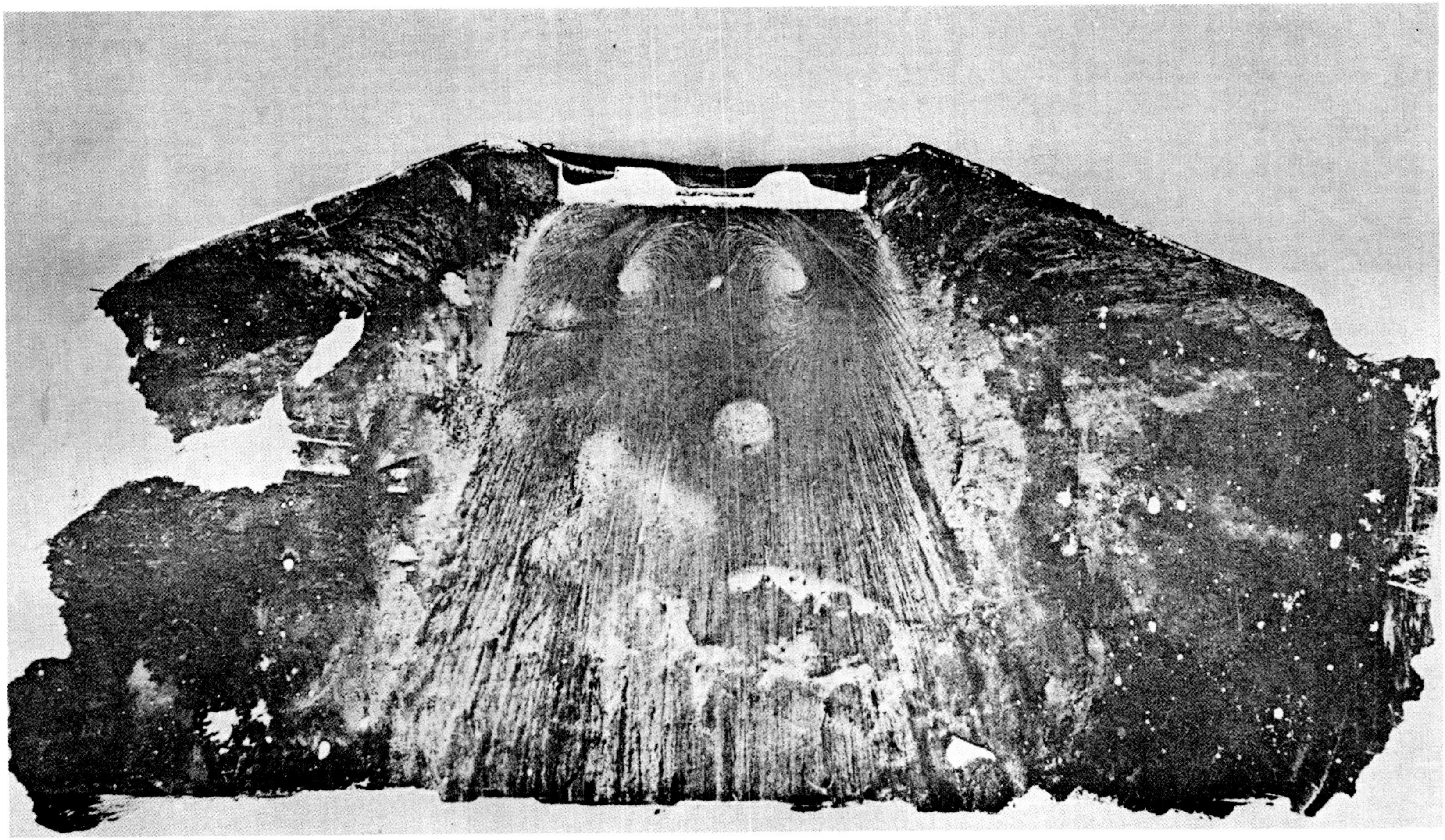


Figure 9.5 Lampblack and Neat's-foot Oil Trace - Centerline of a combustion chamber.

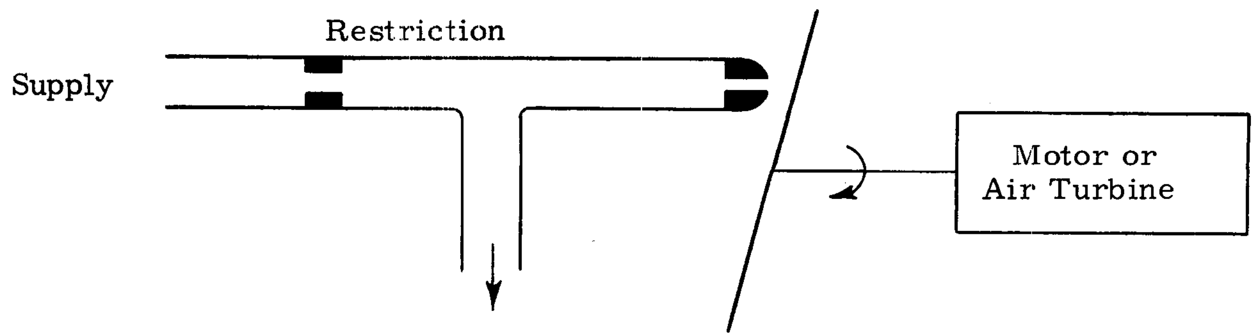


Figure 9.6

Schematic-Frequency Source

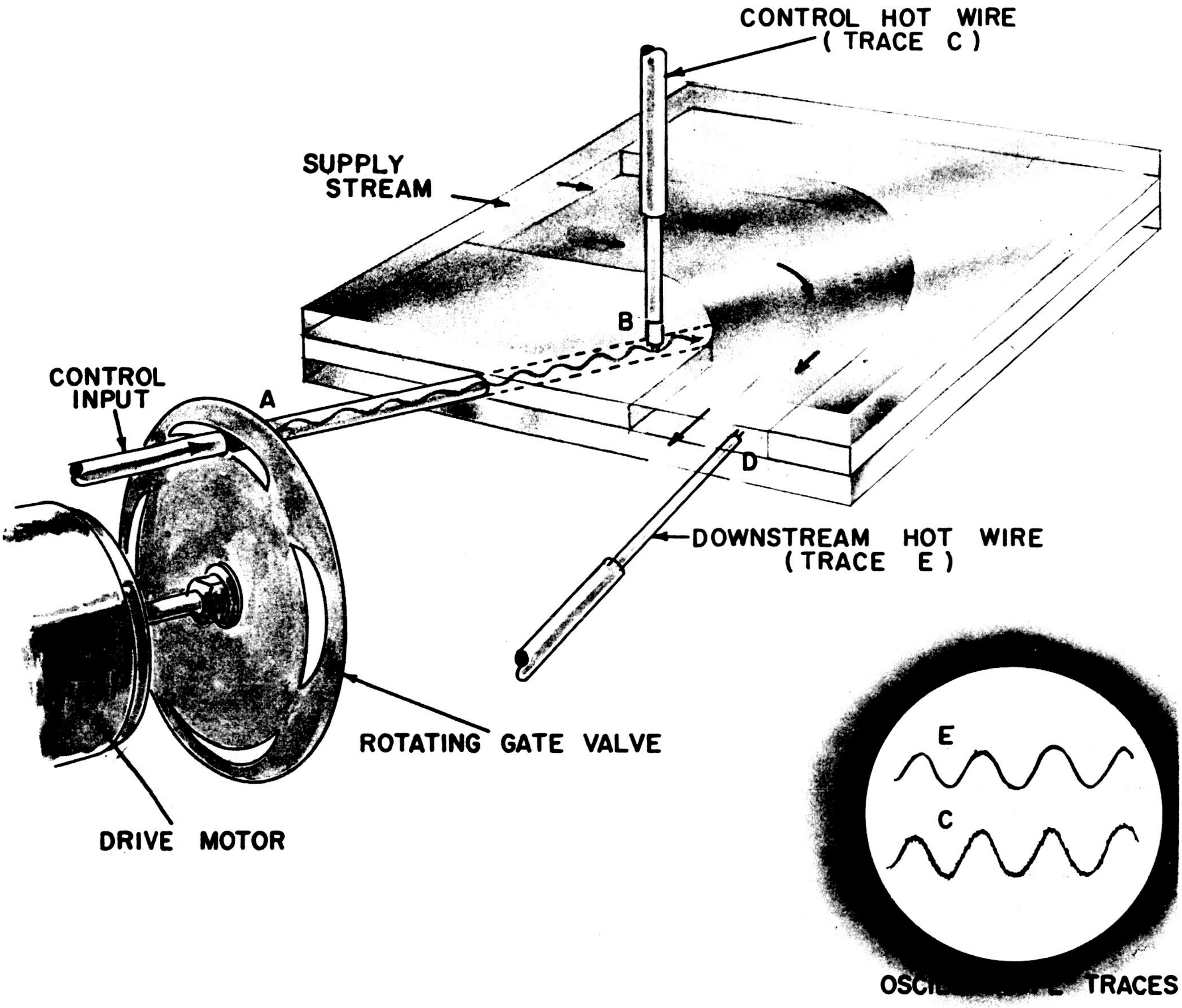


Figure 9. 7 Dynamic test of elbow amplifier

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10.0 POWER SUPPLIES

10.1 Discussion

When no-moving-part fluid amplifiers are operated on compressible fluids the flow process approaches a throttling process. No work is extracted from the system (such as with pistons or expanders). In ideal throttling no heat transfer occurs and all the energy at the source would leave at the exhaust; the inlet and outlet temperatures would be the same. Power consumption in this case can be thought of in terms of the work necessary to compress the gas to the supply pressure. Figure 10.1 shows a calculated curve for power consumption on this basis, using air as the fluid. A 0.010 x 0.010 inch nozzle operating at 0.1 psi, for example, would require 2×10^{-5} watts per square mil, or 2 milliwatts. This is the equivalent power consumption that would be required for a single element in terms of the work of supplying flow to produce a 0.1 psi drop across the nozzle.

In the case of ideal incompressible fluids, a pressure drop results in an enthalpy drop with no temperature change, and therefore represents a true power consumption. Figure 10.1 shows a calculated power consumption curve for water. The 0.010 x 0.010 inch nozzle at 0.1 psi, in this case, consumes 0.05 milliwatts of power.

Whether power consumption is considered in terms of the work necessary to produce the supply flow and pressure, or in terms of power dissipation in the amplifiers, there must be a source at sufficient pressure head to maintain the flow. Three general classes of "power supplies" have been identified:

a) Parasitic Supplies - where power for the fluid elements is bled off from some other source of fluid power such as the propulsion gases in a missile. In some cases the source of flow would have been dumped anyway, for example, the boil-off of liquefied rocket fuels. For high speed vehicles ram air pressure can be used as a supply source and this may also be classed as a parasitic supply.

b) Through-Flow - In many cases fluid is stored or delivered at much higher pressure than that at which it is finally used, and a throttle or regulator is placed in series. The fluid amplifier elements can sometimes function as a portion or all of the regulator and at the same time perform computation or control functions. Diverter valves in process controllers are a simple example.

c) Self-Contained - Where no other supply source is available the fluid amplifier system will require its own source of flow at pressure. Hot gas cartridge type generators have been considered for short-time missions. Redstone Arsenal has tested an experimental missile attitude control system using a hot gas generator. See section 7.3.3 for a description of the system. Closed loop compressor systems using solar power for example, have been discussed for long life missions. There is no evidence of any work having been done in this area, however.

10.2 Commentary

The lack of emphasis on power supplies is additional evidence of the early stage of development of fluid amplifiers. Convenient sources of flow and pressure are available in the laboratory for experimental work; it is when specific applications are considered that the overall system problems get attention. It will be noted from section 7 that the more advanced applications (in terms of completion) are simple ones where the fluid supply source was not a problem. As more complex applications are taken up, the source of supply will become a more important part of the system integration. This problem will probably be critical in many space applications because of the requirements for extreme reliability over very long time periods. All three classes of power supplies will probably find use. To conserve the supply of fluid the trend will be toward closed systems or the use of the through-flow type system. In the latter case it is almost certain that some marriage of the no-moving-part fluid elements with simple moving-part elements will be needed to get complete shut-off of flow when the system is not in use. It should be possible to use simple diaphragm and bellows devices without greatly reducing overall reliability. Such devices would not be any less reliable than the electro-mechanical ones now in use.

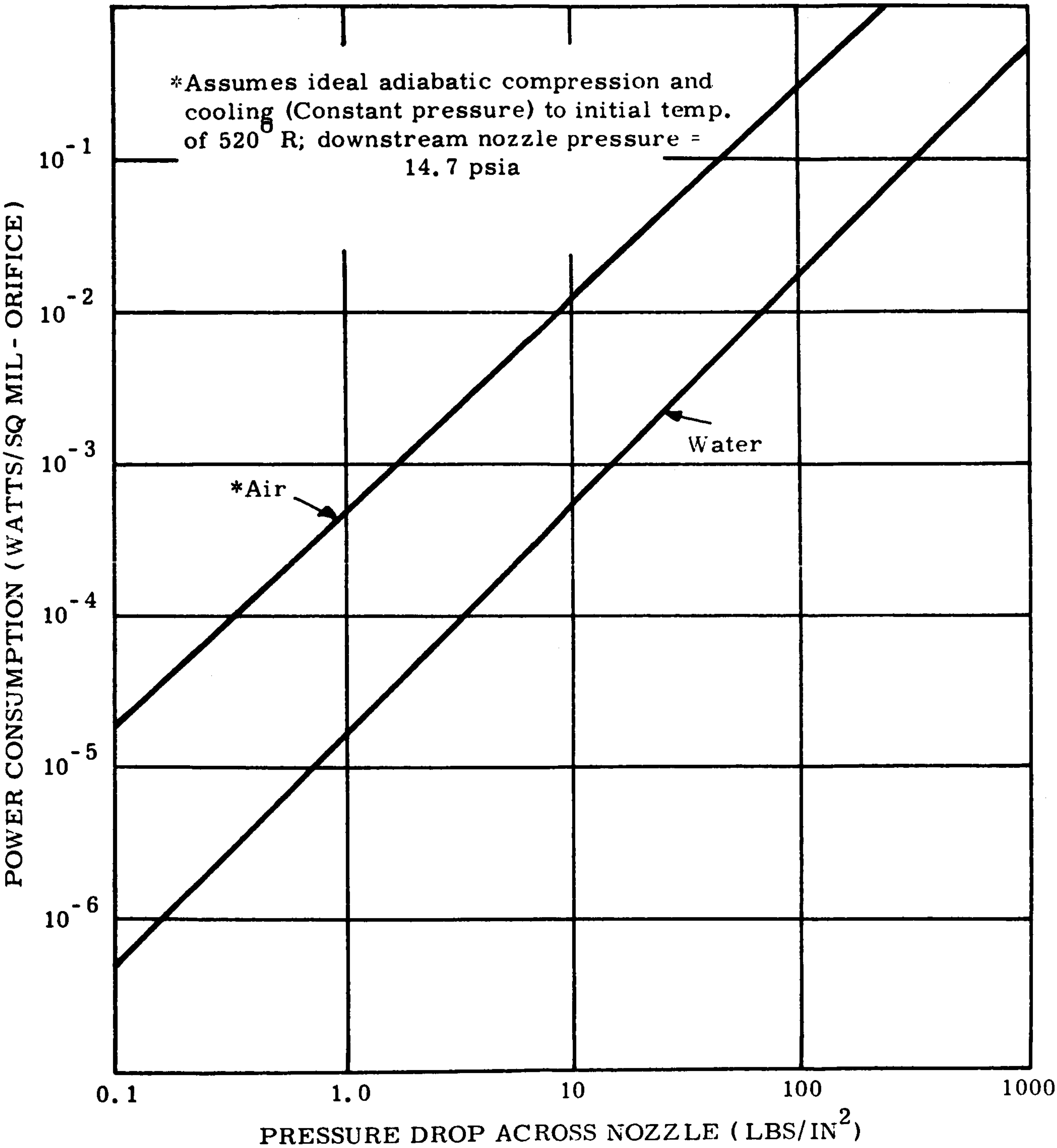

Figure 10-1 - Calculated Nozzle Power Consumption

Appendix A

A listing of all known contracts on fluid amplifier development work is presented below. The listing provides an indication of the level of Government interest on these devices. Contract numbers which could not be obtained are marked "not available". Where exact titles of the programs were not available, the general program subject is included in parenthesis.

Sponsor	Contract No.	Title	Contractor
USAF			
	AF61(514)-1409	The Coanda Effect	SFERI, Clichy Frame
	AF33(600)-38062	(position servo)	General Electric Co.
RTD, Wright Patterson AFB	AF33(657)-8172	(rate sensor)	Minneapolis Honeywell Regulator Co
"	AF33(657)-9142	(flight control)	" "
"	AF33(657)-11133	(navigation computer)	" "
"	AF33(657)-10787	(jet engine control system)	" "
"	AF33(657)-7535	Basic Applied Researchiin Fluid Power Control	Massachusetts Institute of Technology
"	AF33(657)-12146	(propulsion control system)	Marquardt Corp.
US ARMY			
Aberdeen Proving Ground	(not available)	(timer for leaflet bundle breaker)	Bowles Engineering Corp.
Frankford Arsenal	DA-11-022-AMC-692A	(missile flight control)	Minneapolis Honeywell Regulator Co
Harry Diamond Laboratories	DA-49-186-AMC-28X	Analytical and Experimental Studies on Proportional Fluid Amplifier Characteristics	Johnson Service Co.
" " "	DA-49-186-ORD-913	Flow Visualization in Staged Binary Amplifiers	University of Maryland
" " "	DA-49-186-AMC-51X	Vortex Studies	University of Nebraska
" " "	DA-49-186-ORD-1066	(Tank Gun Stabilizing System)	Minneapolis Honeywell Regulator Co
" " "	DA-49-186-ORD-912	Analytical and Experimental Study of Free and Attached Jet	United Aircraft Corp.

Sponsor	Contract No.	Title	Contractor
US ARMY (Cont'd)			
Harry Diamond Laboratories	DA-49-186-AMC-34X	Logic Element Circuitry	Univac Corporation
" " "	DA-49-186-502-ORD-1076	Unit Fabrication	Corning Glass Company
" " "	DA-49-186-AMC-83D	Intersecting Jets	Purdue Research Institute
Picatinny Arsenal	DA-19-020-AMC-0213	Fluid Timer for Ordnance Applications	General Electric Company
Redstone Arsenal	DA-11-022-ORD-4203	(Missile Flight Control	Minneapolis Honeywell Regulator Co.
" "	DA-36-034-ORD-3722-RD	(Double leg elbow amplifier and aero-dynamic throad modulation	Giannini Controls Corp.
NATIONAL AERONAUTICS & SPACE ADMINISTRATION			
Astrionics Laboratory (Huntsville)	NAS-8-5408	Research and Development Fluid Amplifier and Logic	General Electric Company
"	NAS-8-11021	(military logic)	Univac Corporation
Lewis Research Center (Cleveland)	NAS-3-2567	(amplifier for rod control system)	General Electric Company
DEPARTMENT OF NAVY			
ONR	NONR-4001(00)(FBM)	Study of Feasibility of Applying Fluid Controls to Turbine	General Electric Company
ONR	NONR-4003(00)	Pneumatic Pure Fluid Speed Control for a 500 kw Steam Turbine Generator	Bowles Engineering Corporation

Sponsor	Contract No.	Title	Contractor
DEPARTMENT OF NAVY (Cont'd)			
ONR	NONR-4141(00)	(application survey)	Minneapolis Honeywell Regulator Co.
Bu Ships	88625-15	(boiler controls)	Bowles Engineering Corporation
Bu Weps (RUTO)	(not available)	(torpedo applications)	" " "
"	NOW62-0770-C	(sensor)	Development Laboratories Inc.
OTHER			
Sandia Corporation	(not available)	(timer)	Bowles Engineering Corporation
(not available)	(not available)	(hydrofoil control)	" " "

APPENDIX B

The organizations which contributed information for this survey are as follows:

Research and Technology Division
USAF
Wright-Patterson Air Force Base
Dayton, Ohio

The Bendix Research Laboratories
The Bendix Corporation
Southfield, Michigan

Bowles Engineering Corporation
Silver Spring, Md.

Corning Glass Works
Bradford, Pa.

Franklin Institute
Philadelphia, Pa.

General Electric Company
Schenectady, N. Y. and
Sunnyvale, California

Giannini Controls Corporation
Malvern, Pa.

Harry Diamond Laboratories
Washington, D. C.

International Business Machines Corp.
Endicott, N. Y.

International Business Machines Corp.
Zurich, Switzerland
(information via F. T. Brown)

Johnson Service Co.
Milwaukee, Wisconsin

Marquardt Corp.
Van Nuys, California

Massachusetts Institute of Technology
Cambridge, Mass.

Minneapolis-Honeywell Corp.
Minneapolis, Minnesota

Moore Products Co.
Spring House, Pa.

NASA, Lewis Research Center
Cleveland, Ohio

Special Project Office
Department of Navy
Washington, D. C.

Sperry Utah Company
Sperry Rand Corp.
Salt Lake City, Utah

Stanford Research Institute
Menlo Park, California

Syracuse University
Syracuse, N. Y.

United Aircraft Corp.
Research Laboratory
East Hartford, Conn.

Univac Corp.
Blue Bell, Pa.

U. S. Army Missile Command
Redstone Arsenal, Alabama