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249-1

MINIATURE FLUIDIC DIGITAL DIFFERENTIAL
ANALYZER
Final Report

by
Warren Depperman

15 July 1966



U.S. ARMY MATERIEL COMMAND

HARRY DIAMOND LABORATORIES

WASHINGTON, D.C. 20438

Prepared by:

MARTIN MARIETTA CORPORATION
ORLANDO, FLORIDA

Under contract number:
DA-49-186-AMC-249 (D)

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SUMMARY

This is the final report on Contract DA-49-186-AMC-249(D) for a Miniature Fluidic Digital Differential Analyzer (DDA). The purpose of the contract was to mechanize a demonstration model of a digital integrator to demonstrate the feasibility of utilizing miniature fluidic elements in complex digital logic systems. The DDA was to be mechanized using an integrated circuit technique with an element power nozzle size design goal in the 2 x 2 mil range. The final assembly was to be packaged in a test fixture employing suitable readouts and controls to permit demonstration of circuit operation.

This report describes the analytical and experimental processes used to scale an existing miniature element configuration to an element having a power nozzle of 2 x 2 mils. Problems associated with these elements are discussed and results of investigations in integrated circuit design using miniature elements are presented.

In addition to a discussion of DDA operation, this report includes element operating characteristics, a schematic of the final circuit, and a description of techniques used for art preparation.

This study demonstrated that miniature fluid elements can be used to mechanize complex logic circuits. Advances made in element characteristics, interconnection techniques, and fabrication and packaging procedures have extended the potential applications of fluid systems. In part, this study provided the following results:

- 1 An operational fluid logic element with a 2 x 2 mil power nozzle has been developed.
- 2 Current designs having 4 x 4 mil power nozzles provide very satisfactory operating characteristics.
- 3 Due to excellent stability features, these elements can be easily interconnected in complex logic arrays.
- 4 Under certain conditions, these elements are capable of operating up to 25 kilocycles.

5 Elements can be made with a low cost fabrication process suitable for high volume production.

These factors permit miniature fluidics to be considered for applications where conventional fluid circuits are not practical. They are suitable for use in severe inertial environments (such as those encountered in artillery projectiles and certain missile systems). Also, timers using a fluid oscillator in conjunction with a counter such as the one used in the DDA, can be used to provide sequenced signals in arming and fuzing systems.

Many potential applications for miniature fluidics exist in process control, machine tool control, and data processing systems. The advantages offered by miniature integrated circuits should provide interest in the utilization of fluid logic.

FOREWORD

This is the final report on Contract DA-49-186-AMC-249(D), Miniature Fluidic Digital Differential Analyzer, prepared by the Orlando Division of the Martin Marietta Corporation for the U.S. Army Materiel Command, Harry Diamond Laboratories, Washington, D. C.

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I. ELEMENT MINIATURIZATION

A. ANALYTICAL STUDIES

To obtain satisfactory operation and performance from digital fluid amplifiers, the main power jet, which is to be switched by auxiliary control jets, must be operating in a regime of turbulent flow. This requirement arises from two related operational effects of fluid jets - the mechanism of entrainment of stagnant fluid surrounding the boundaries of the jet and the Coanda attachment.

In considering the mechanism of entrainment of stagnant fluid surrounding the boundaries of the jet, the strictly laminar jet has but one mechanism of entraining flow or transferring momentum to the initially stationary fluid particles. A coupling effect due to the viscosity is the sole method by which a laminar jet may transfer its momentum to other particles at rest. However, in a turbulent regime, a second method of momentum transfer is present. Since the velocity, and hence the momentum vectors, of laminar flow lie collinearly with each other, transfer of momentum by collision is slight. In the turbulent case however, velocity and momentum vectors have components in all three major coordinate directions, and momentum transfer to the surrounding fluid, initially at rest, may take place by virtue of both viscous and collision coupling. The resulting entrainment capabilities of the jet are increased over the laminar case by the amount of the collision coupling.

The jet will exhibit the phenomenon known as Coanda attachment if a jet is properly turbulent and the characteristic dimensionless quantities (Reynolds number, mach number, etc.) associated with the flow are high enough in magnitude. This assumes that there are divergent walls sufficiently near to support this attachment. Because of the tendency of an expanding flow to detach or separate from walls bounding its motion, and through entrainment of the surrounding fluid, a circulation of the entrained particles is established. This circulation constitutes a region of low static pressure known as a low pressure separation bubble. The unbalanced forces between this bubble and the other side of the jet cause the main stream of the fluid, which contains the highest momentum density, to reattach to the wall and become stable again. The Coanda attachment is

a function of the entrainment capabilities which is in turn a function of the degree of turbulence present in the jet.

Ideally, the best condition for enhanced entrainment and attachment capabilities of a free jet such as is employed in fluidic amplifiers would be to have turbulence initiated in the nozzle section so that the jet would remain turbulent all the way downstream. In the nozzle size with which this effort has been concerned, however, the maintenance of a turbulent flow region in the rectangular nozzle channel is virtually impossible.

The development of equations and solutions to the problem of entrance flow to rectangular channels has been treated extensively by Sparrow¹ and Schlichting². In a method similar to that given by Sparrow, an analytic solution to the nozzle inlet problem was obtained in the interest of better understanding the phenomenon of developing flow and being able to cope with it.

This solution assumes a velocity profile which is a function of cross axial channel position and boundary layer thickness. A critical Reynolds number may be found above which the laminar flow regime will not exist. An approximate momentum integral solution was obtained by Sparrow to the laminar inlet problem. His results indicate that the boundary layers coalesce at the dimensionless downstream distance $x/aRa = 0.16$. Schlichting, through a similar analysis, obtained a series solution to the same inlet problem and his analytical point for the joining of the shear layers was at $x/aRa = 0.103$. The Reynolds number Ra is referred to the channel exit position and is defined as $Ra = V_0 a/\nu$. V_0 is the mean efflux velocity and a is the channel half width.

Schlichting, Toong³, and Lin⁴ have examined the stability of the Karman-Pohlhausen velocity profiles, which are the velocity solutions to the inlet flow problem.

Schlichting has determined a dimensionless shape factor $\Lambda = \delta^2/\nu dV_1/dx$. This shape factor relates the momentum thickness of the boundary layers (δ) to the downstream velocity gradient. The momentum thickness of the boundary layer is a function of velocity, so the critical value of the Reynolds number found analytically by C. C. Lin for this velocity profile may be found in terms of the parameters of this specific problem. The value given by Lin yields a critical Reynolds number, $Ra = 3,544$, where Ra is as defined before. Equating this critical value of Reynolds number to the curve for the shape factor Λ given by Schlichting (2:414), yields the equation for the curve of neutral stability in the rectangular inlet nozzle:

$$Ra (1 - 1/\sqrt{V}) = 645 \exp (0.568 \Lambda).$$

This equation may be solved for Ra as a function of X and the results of this solution are given in Figure 1. The two skewed lines originating at the origin represent the loci of points for which the boundary layers join (Sparrow and Schlichting solution). The connection between the joining of the shear layers and the existence of the fully developed profile is shown in dashed lines and represents an assumed path joining the lower limit of Reynolds number by Lin and the upper curve given by the solution in X of the stability equation. The portion of the plot above and to the right of the defining curve represents the region of turbulence and the points coincident with the curves are the conditions which give marginal stability. As the Reynolds number increases, the tendency for the flow to become turbulent or maintain turbulence is increased. For a channel length of ten nozzle widths, the stability plot shows that a Reynolds number of greater than 23,000 is required to maintain turbulent flow in the nozzle section. This may be logically explained by the fact that viscous forces which tend to retard the flow at the solid to liquid interface are surface forces and the volume to area ratio for the supply channels of the size in question is correspondingly small. These viscous forces therefore exert such a retarding influence that they dominate the flow. The development lengths for which the flow becomes a fully developed laminar flow is on the order of two to three nozzle widths. The Reynolds numbers found specifically in the small amplifiers under this study range from about 300 up to about 5000. From the results and data gained in these analytical investigations of the entrance development problem, it was apparent that a zone of transition control at the exit of the power jet was necessary to create the required turbulence in the power jets necessary for operation from an entrainment-attachment viewpoint.

Very few analytical predictions on transition from laminar to turbulent flow exist even for the simplest of cases. The problem of transition in a free jet has been studied to some extent both experimentally and analytically by Curle⁵, Sato and Sakao⁶, and Tatsumie and Kakutani⁷. Curle presents an analytical prediction on the distance downstream of the source of the jet at which an instability toward turbulence is indicated. This prediction arises from the linearized Navier-Stokes equation and perturbation analysis of the velocity profile. The analysis indicates an instability at a characteristic Reynolds number (based on jet width and root mean square efflux velocity) as low as four.

B. BIREFRINGENT FLOW VISUALIZATION STUDIES

In order to extend this analysis and aid in controlling the point of transition, a method of flow visualization was employed which proved to be a valuable aid in sizing and scaling of pure fluid amplifiers.

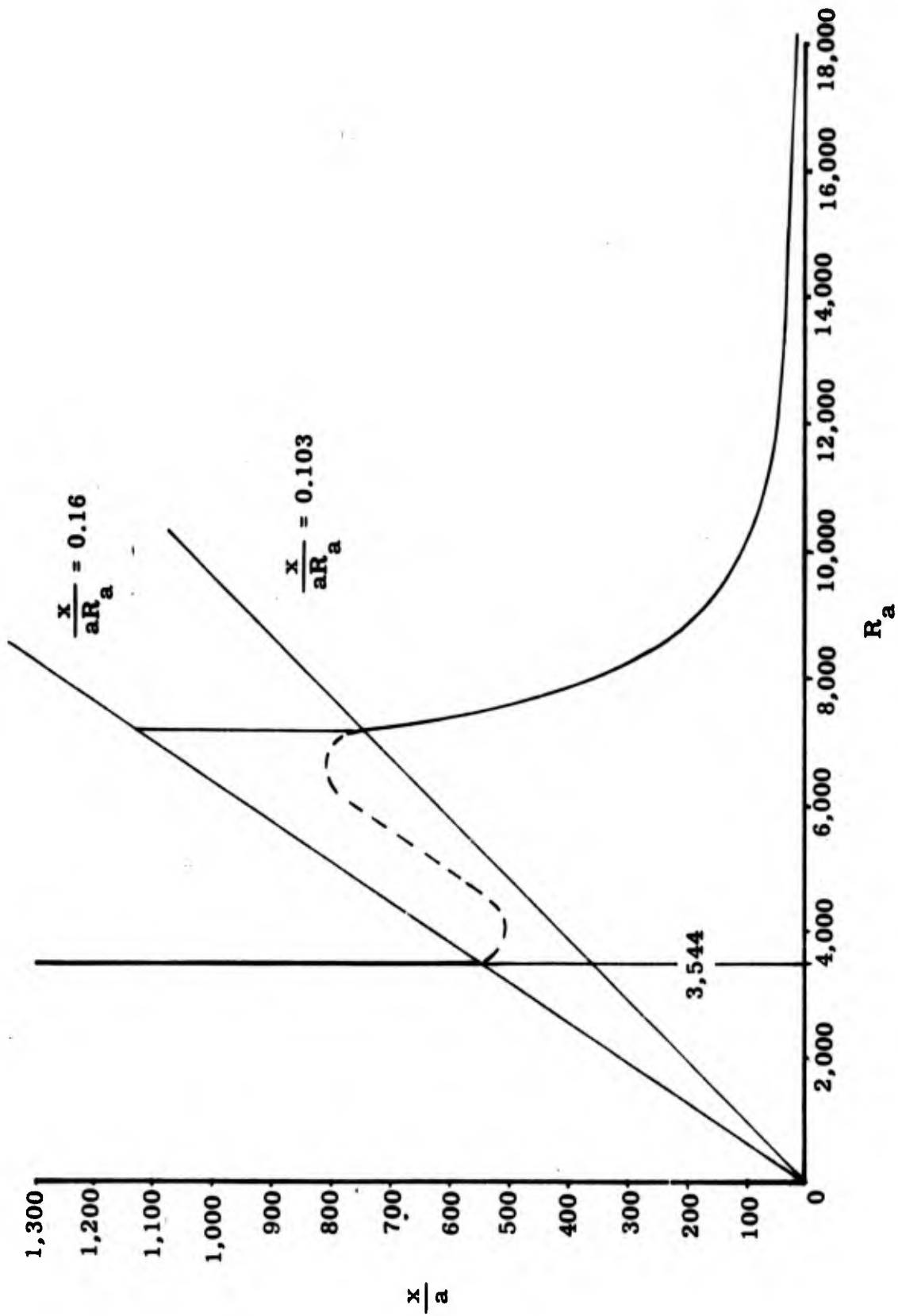


Figure 1. Neutral Stability for Laminar Inlet to Rectangular Channel

This birefringent flow visualization technique is analogous to photo-elastic stress analysis. The operating principle of the technique is that a normally optically isotropic media may be made optically anisotropic by an applied stress. In the case of birefringent flow visualization, a suspension of orientable particles of milling yellow dye are added to a water carrier solution. The applied stresses which cause the change in optical properties of the birefringent solution are shear stresses incurred in the flow field due to the presence of velocity gradients.

In a laminar flow region, colored fringes appear clearly defined as layers of nearly constant shear, the colors of which blend into the next layer of higher or lower stress. In a transition region, where the flow regime is changing from laminar to turbulent flow, the growth and finally established turbulent stream changes from the defined bands of laminar flow to a uniformly colored region of turbulence. The birefringent technique therefore provides an accurate method of pinpointing the position of transition to turbulence in an incompressible flow field.

A schematic of the test setup used in the flow visualization studies is shown in Figure 2. Figures 3 through 6 depict the regime of flow as a test amplifier is operated over varying nozzle pressures, and hence different Reynolds number ranges. The power nozzle size of this element is 31 x 31 mils.

Figure 3 shows the element operating at 17k Nt/m^2 nozzle pressure. At this pressure, flow throughout the element appears to be laminar and no attachment occurs. Figure 4 shows the element operating at 35k Nt/m^2 . Here the jet is going turbulent just upstream of the splitter tip, but still attachment does not occur. Figure 5 was taken with an operating pressure of 52k Nt/m^2 . The jet is going turbulent in the control port region but still does not attach.

Figure 6 shows the jet attached to the right hand side of the element. This photo was taken at a nozzle pressure of 76k Nt/m^2 . The jet is going turbulent shortly after it enters the V-shaped control zone. Although it is difficult to discern from the photographs, the point of attachment is upstream of the control ports. This is much easier to verify by direct observation of the device. This visualization technique can be used with much smaller channels than the one shown. In fact, useful data can be obtained with 4 mil nozzles. The larger test element was used merely to present a better visualization of the flow field after the photography and reproduction processes have been completed. Even with this size, much of the detail is lost in the recording process.

By use of the analytical studies of jet and channel flow phenomenon and the concurrent study of birefringent visualization of the incompressible

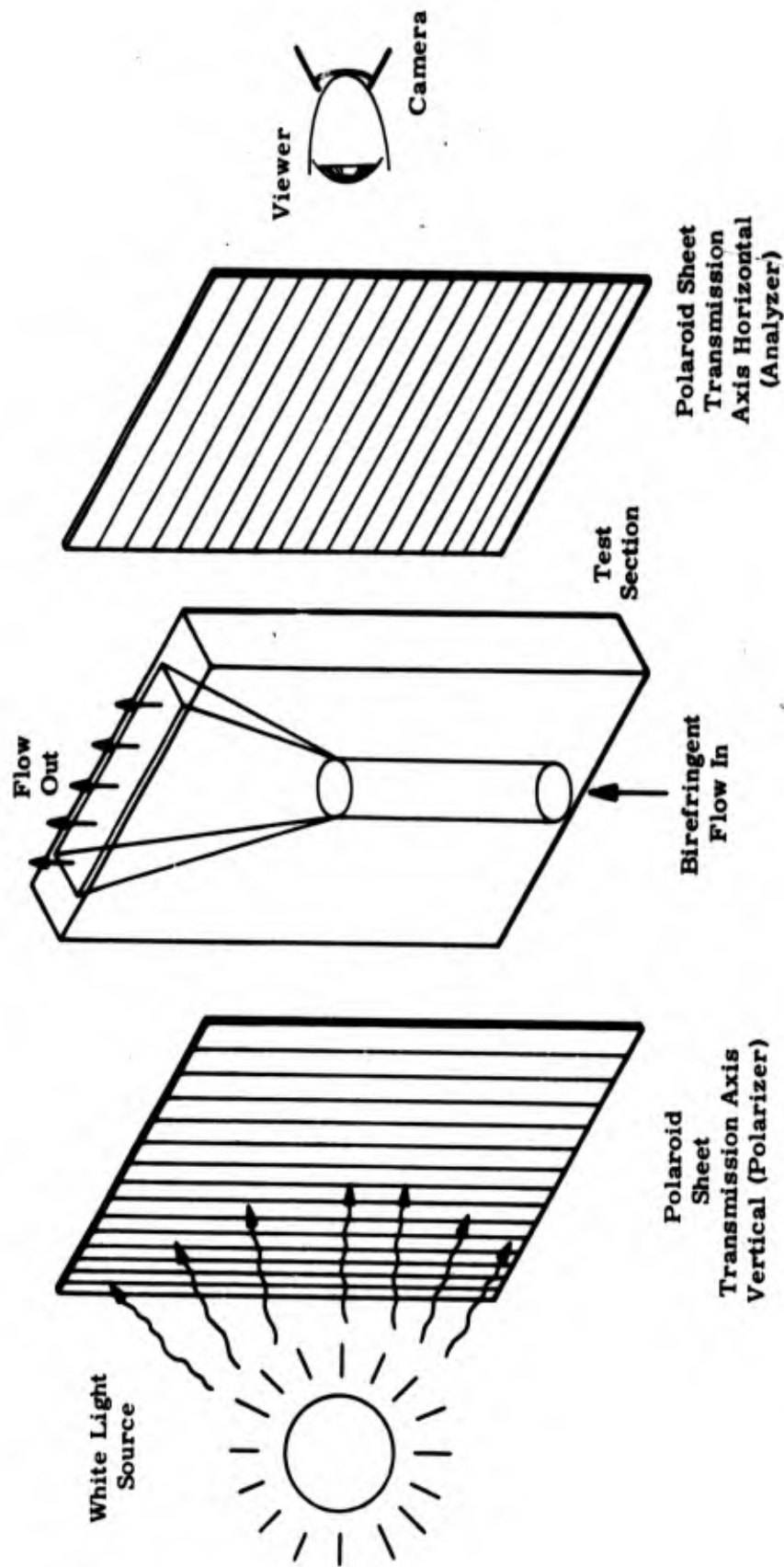


Figure 2. Birefringent Flow Analyzer

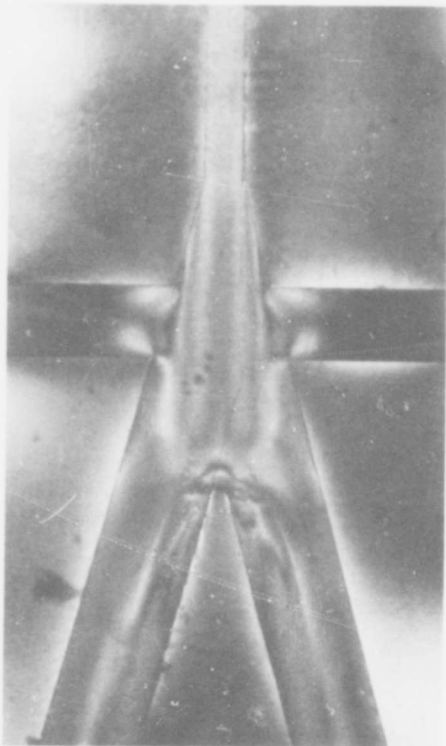


Figure 3. Flow Visualization in
Bistable Test Element, Nozzle
Pressure: 17k Nt/m^2

Figure 4. Flow Visualization in
Bistable Test Element, Nozzle
Pressure: 35k Nt/m^2



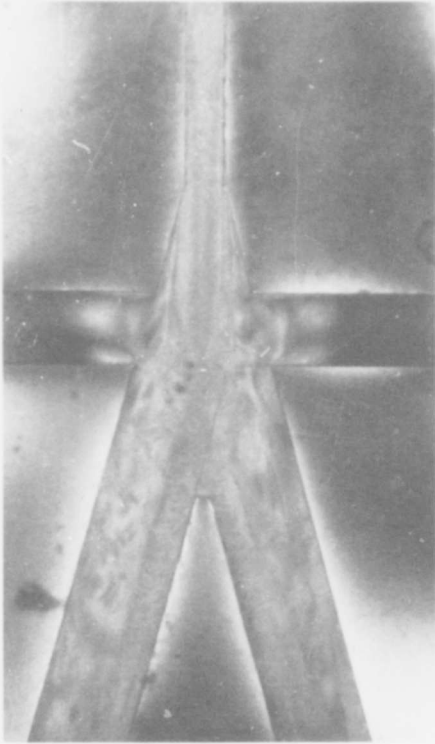
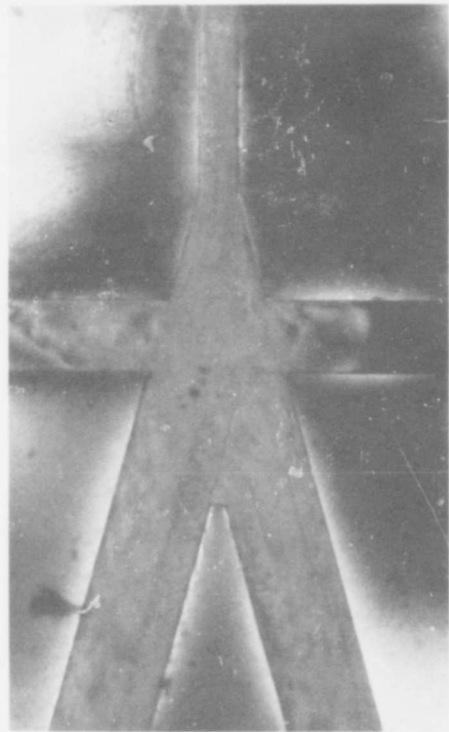


Figure 5. Flow Visualization in
Bistable Test Element, Nozzle
Pressure: 52k Nt/m^2

Figure 6. Flow Visualization in
Bistable Test Element, Nozzle
Pressure: 76k Nt/m^2



flow nozzles and receivers, it was found that existing element geometry would perform satisfactorily if proper similitude between the birefringent and actual case could be obtained. From this point on, it was a problem of making other modifications which would optimize element geometry until their operational characteristics were sufficient for circuit use.

C. ELEMENT CHARACTERISTICS

1. Bistable Element

Through studies such as those previously described, and with the aid of the birefringent flow visualization technique in conjunction with data from laboratory experiments designed to evaluate the effects of minor element geometry changes, an existing bistable element configuration was scaled to an operating configuration using a 2 x 2 mil power nozzle. Bistable operation of this device was achieved over a nozzle pressure range of 27k Nt/m² to the maximum test pressure of 380k Nt/m². Performance curves for a typical element are shown in Figure 7 for operating pressures up to 240k Nt/m². In this figure, the solid line represents the right hand output and control port, while the dashed line represents the left hand side of the element. Output pressures were obtained using a blocked load on the output channel under test with all other channels open to atmosphere. The control input is the pressure that will cause switching with all other channels open to atmosphere.

Although bistable operation was achieved over a wide operating pressure range and the element was stable in most cases, even when operating into a blocked load condition, pressure gains and recovery were in general quite low. Pressure recovery was nominally about 10 percent of power jet pressure, and pressure gains from 1.4 to 4.5 were recorded. Although pressure recovery was relatively consistent, pressure gains varied considerably with nozzle pressure, and were somewhat erratic.

Further experiments with elements using a 2 x 2 mil nozzle did not provide any significant improvement in performance. Slightly better gain values were achieved but they still were not sufficient. It appears that viscous losses are severely limiting pressure recovery, and that relatively high nozzle pressures are required to approach an operating region where a reasonably useful gain value can be achieved. Although it is possible that a useful circuit element may be developed in this size, the performance level of the current device was not adequate for use in the DDA circuit. Since time did not permit further investigations, it was decided to take another approach. It had been observed many times that increasing the aspect ratio would provide marked improvement in performance. Simply by stacking two elements similar to the one from which the data in Figure 7 were taken, which provided a 2 x 4 mil power nozzle, pressure recovery

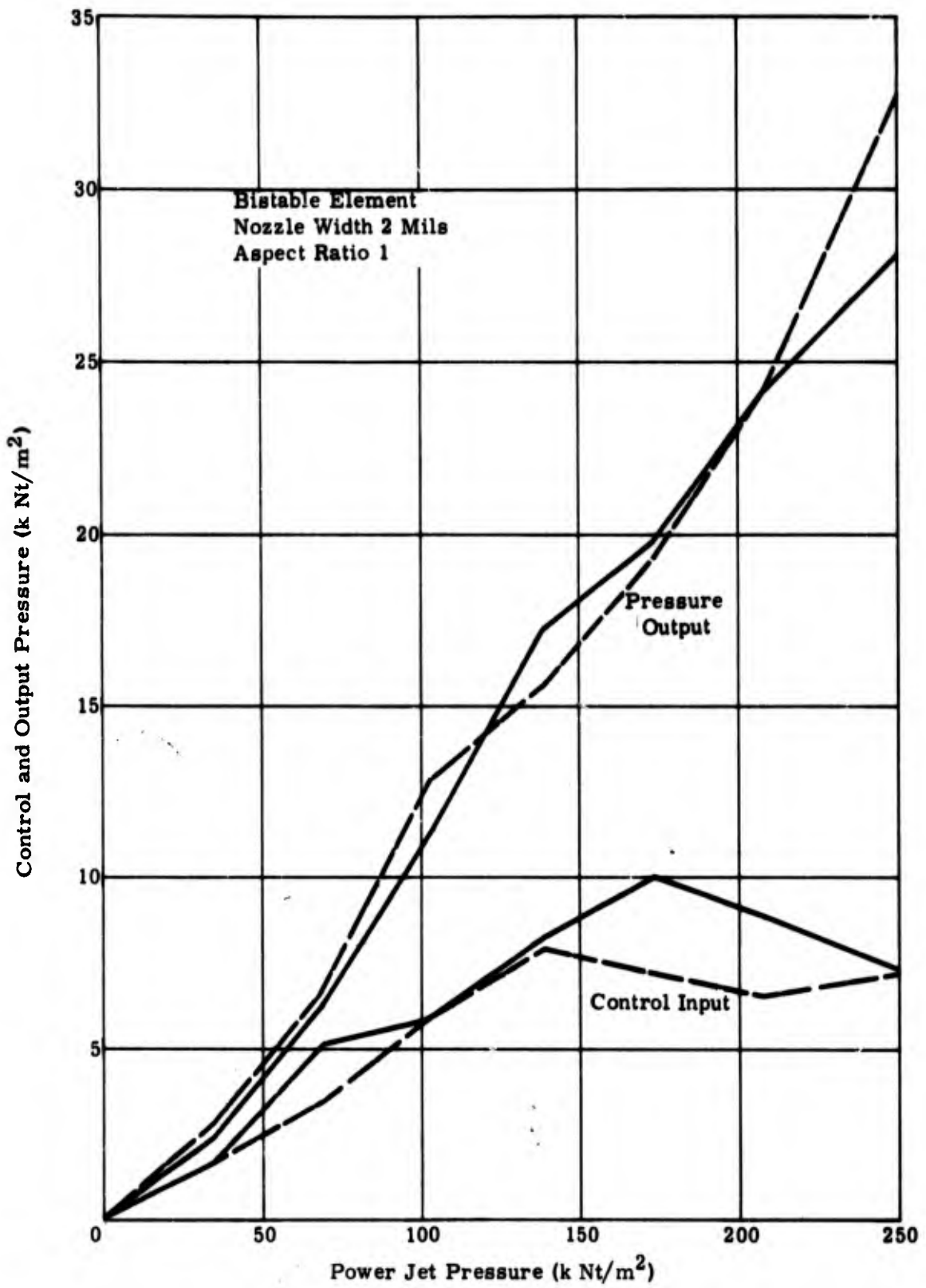


Figure 7. Performance Curves With Aspect Ratio of One

on the order of 25 percent and pressure gains as high as 15 were observed. Data from such a device using an aspect ratio of two are presented in Figure 8. Although the element is slightly unbalanced, its characteristics are much more consistent with respect to nozzle pressure and its gain and recovery are much better than when an aspect ratio of one was used.

This approach, although providing an element with acceptable characteristics, was not practical from the manufacturing and assembly standpoint. Since the manufacturing technique is limited to production of elements with an aspect ratio of about one, using an aspect ratio of two would require stacking two element planes. This technique would require prohibitively accurate tolerance control with respect to element dimensions, and very exacting indexing of planes to achieve the necessary alignment between elements. It also presents another possible leakage path in the final assembly. These problems could be eliminated if satisfactory operation could be obtained from an element with an aspect ratio of one. Since it did not appear that continued investigation of the 2 x 2 mil elements would permit timely completion of the contract, it was mutually agreed to attempt to mechanize the circuit using existing elements having 4 x 4 mil power nozzles. It was agreed that elements of this size would fulfill the intent of the contract as far as element miniaturization is concerned.

Initial work with this element had shown very encouraging results. With only minor changes in the control port region, a bistable element was evolved that would provide the necessary gain, fan-in, and fan-out capabilities to mechanize the DDA logic. Characteristic curves for a range of nozzle operating pressures for a typical element of the final configuration are shown in Figures 9 through 11. The output characteristic normalized flow (defined as recovered flow divided by power jet flow) is plotted as the abscissa. Normalized pressure (defined as output pressure divided by power jet pressure) is plotted as the ordinate. The control input characteristic is also included. It is plotted as normalized flow (defined as control flow divided by power jet flow) versus normalized pressure (defined as control pressure divided by power jet pressure). The switch points are indicated by a discontinuity in the control characteristic. After switching, control flow was reduced to zero and the pressure at that point was determined. The control characteristic was then continued from that point until it crossed the output characteristic.

A curve for each output leg and each control input is included on all plots. Curves plotted with a dashed line indicate the right hand output and control input of the element. Curves for the left hand side are indicated by a solid line. In all cases, the data were taken with all inputs and outputs open to atmosphere except the one under test. In some cases the element

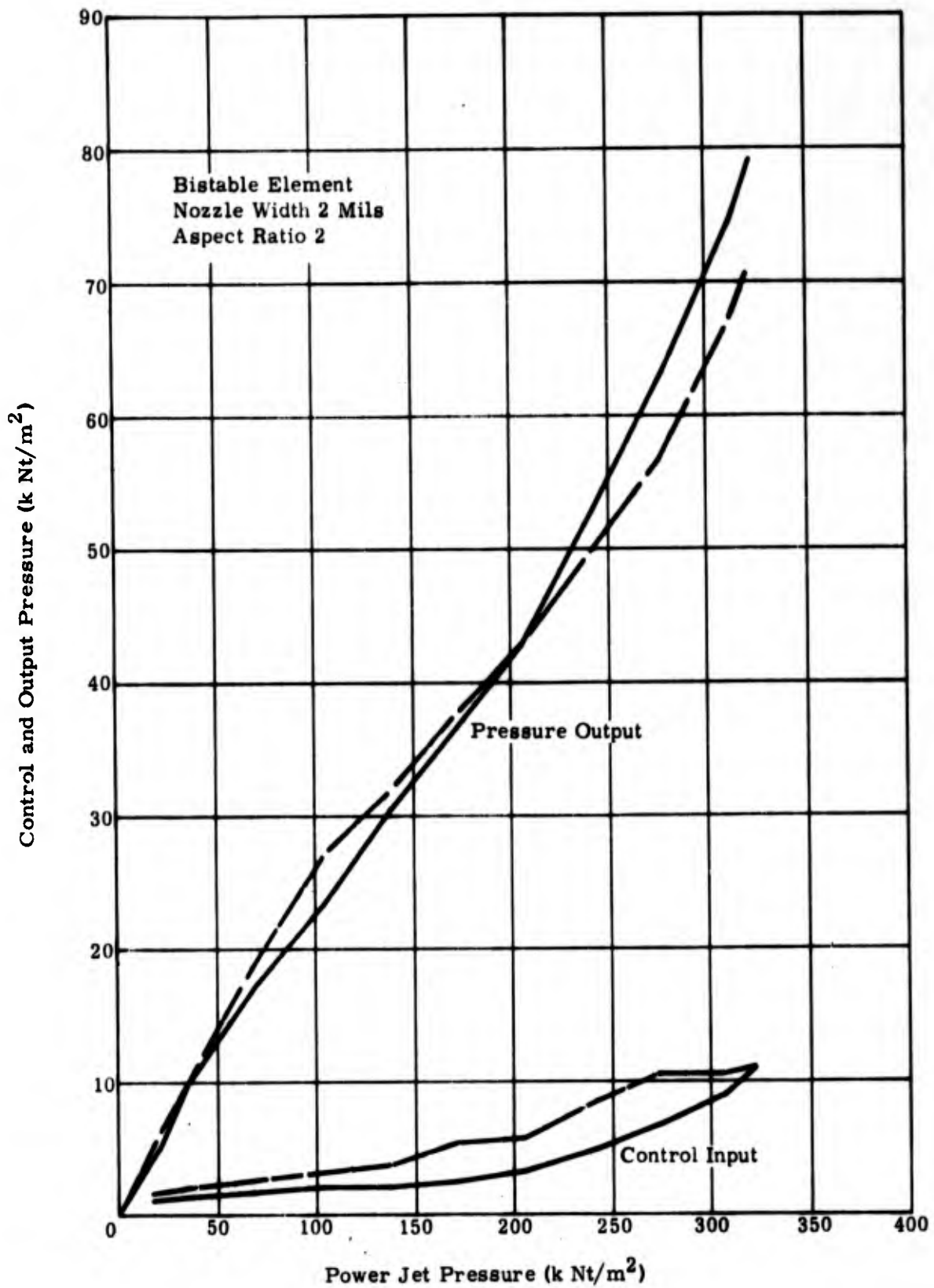


Figure 8. Performance Curves With Aspect Ratio of Two

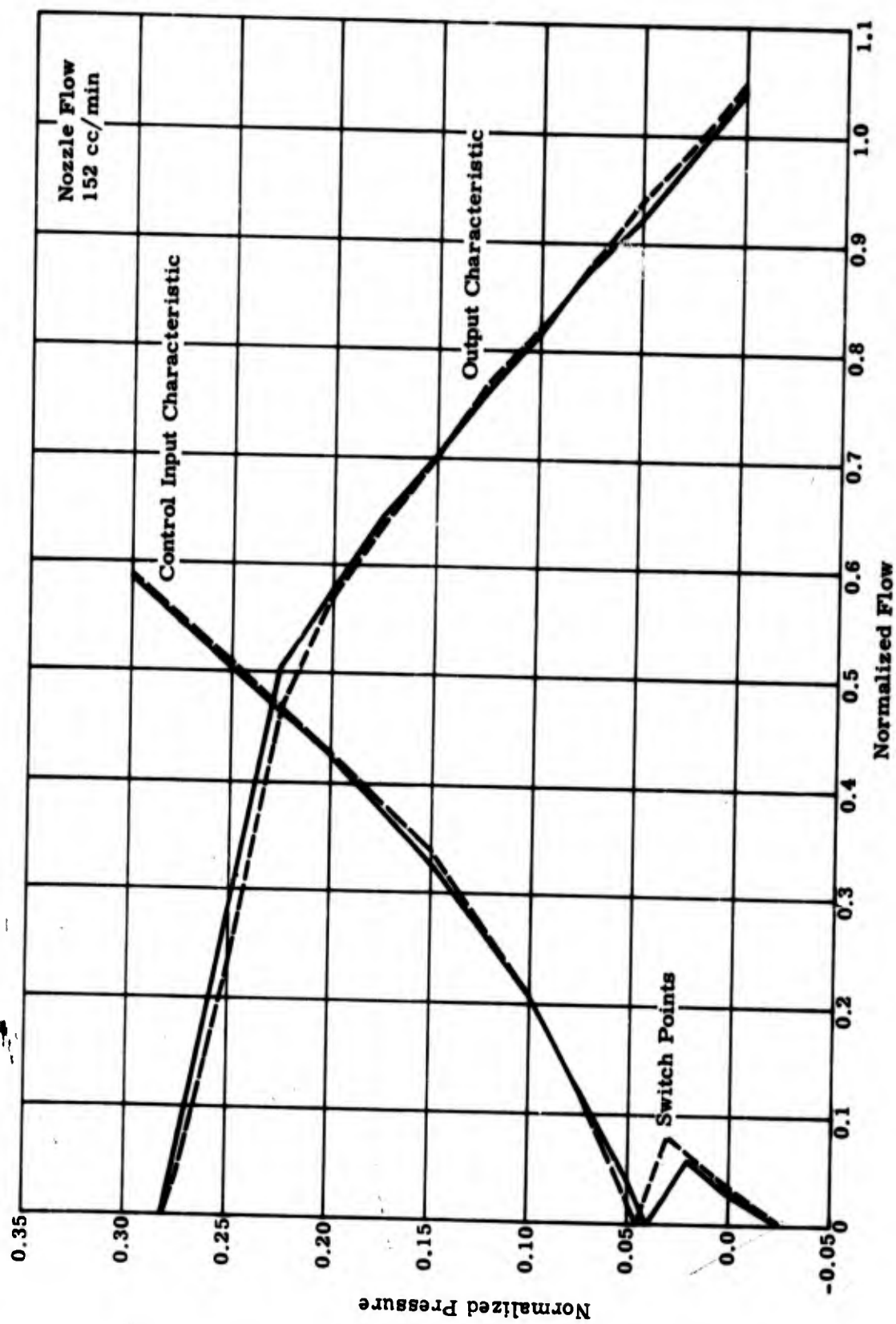


Figure 9. Bistable Characteristics at 69k Nt/m² (10 lb/in.²)

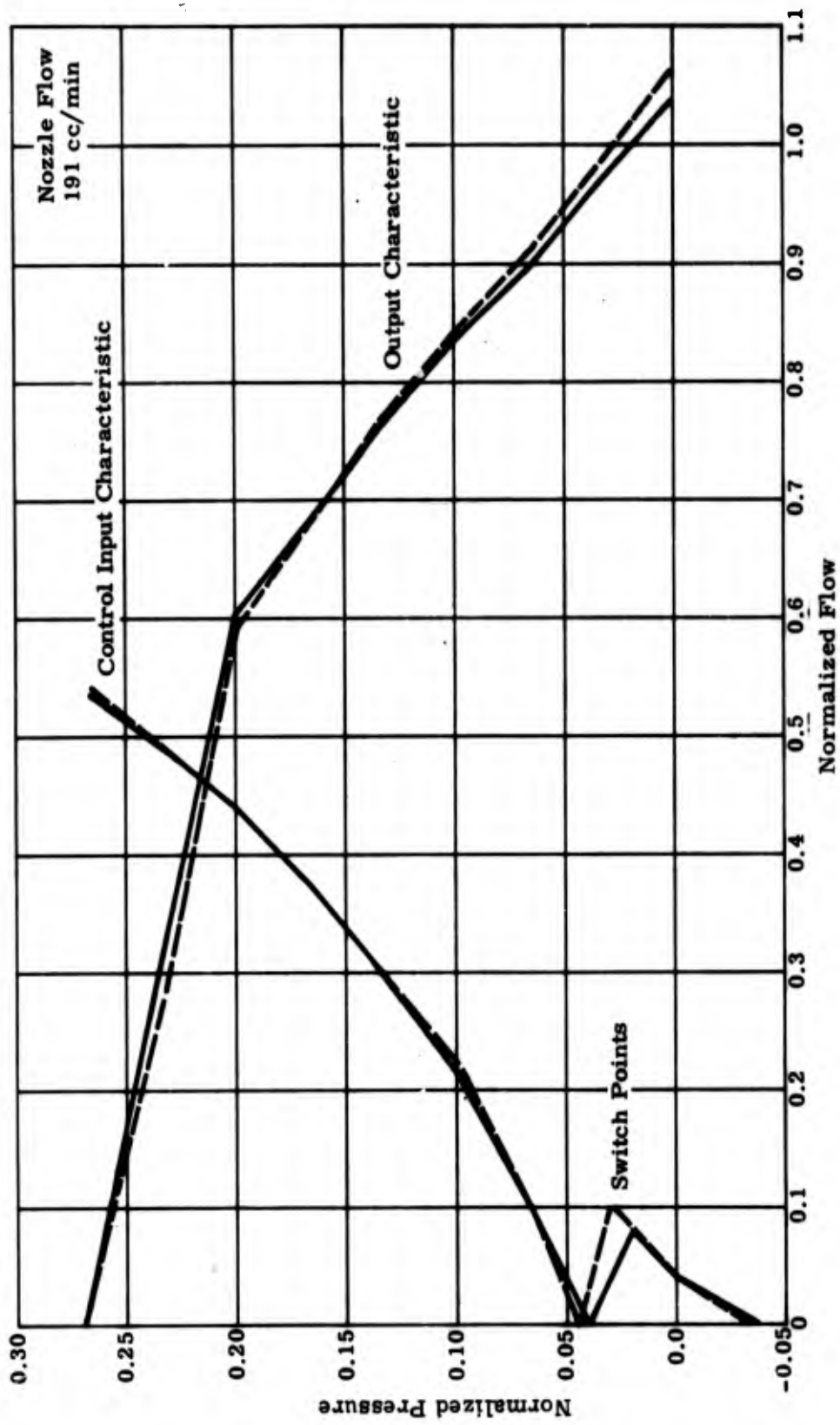


Figure 10. Bistable Characteristics at 103.5k Nt/m² (15 lb/in.²)

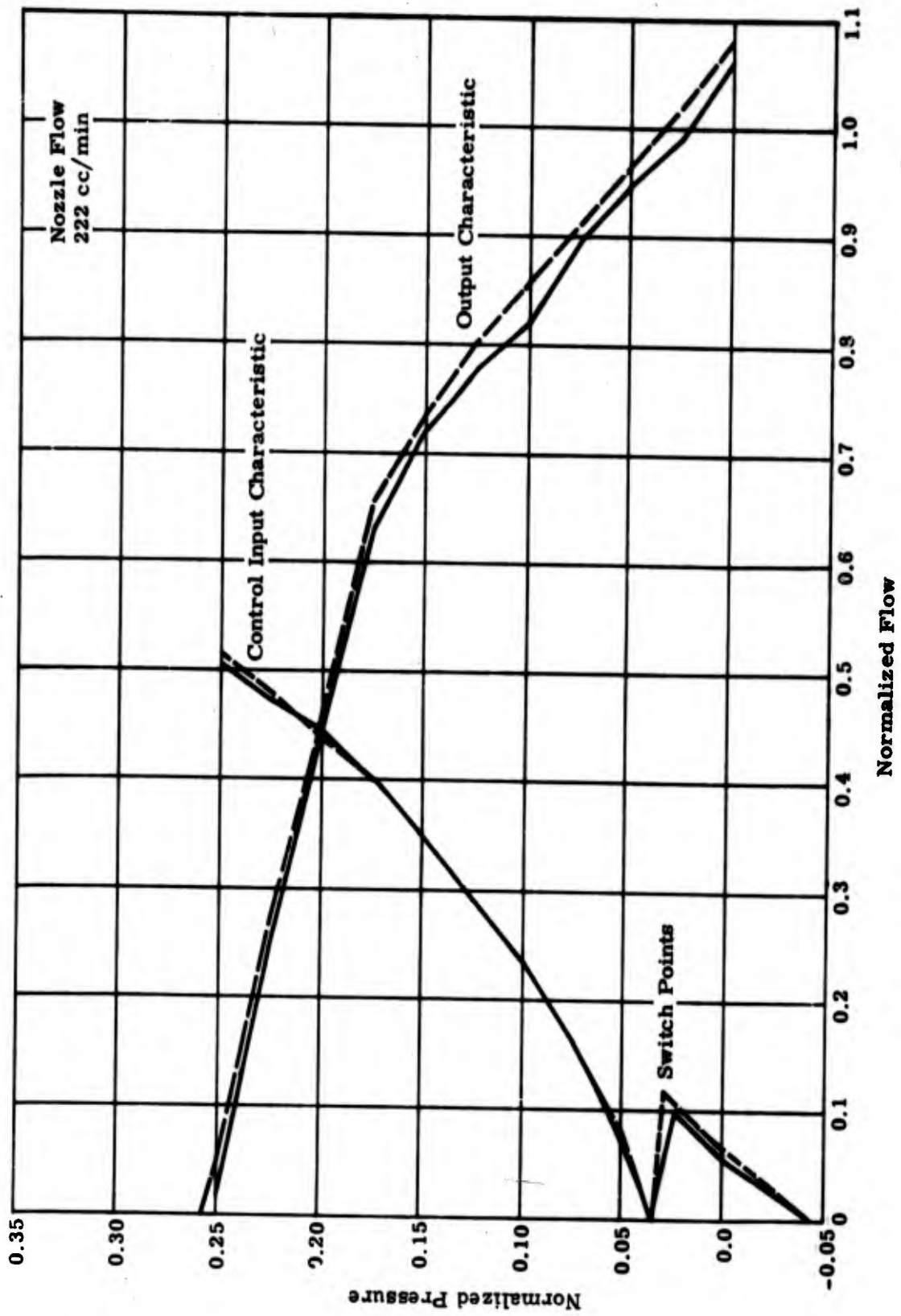


Figure 11. Bistable Characteristics at 138k Nt/m² (20 lb/in.²)

was marginally stable with the output blocked. This is most pronounced at the very high and very low operating pressures. Very good stability with respect to output loading is obtained over the pressure range shown. The output characteristics are terminated at the point where switching occurred due to loading.

Several conclusions can be drawn from these curves:

- 1 The element characteristics are very well balanced,
- 2 Variations in nozzle pressure do not appreciably affect performance except at very low and very high ranges,
- 3 A stable operating point is achieved in all cases with respect to cascaded elements,
- 4 A fan-out capability of at least seven is indicated.

Pressure gains can be determined from the characteristic plots by taking the output pressure at the flow required for switching and dividing by the switching pressure. Flow gains can be determined in an analogous manner. These values represent gains that can be expected under actual circuit operation. Pressure and flow gains greater than seven were obtained at all operating conditions.

Although it is not shown on the characteristic curves, it should be noted that off leg output is practically zero in all cases. When the on leg is unloaded, practically zero pressure and flow exists in the off leg. As the on leg load is increased to a blocked condition, off leg output rises to a maximum value of less than 1 inch of water. Thus, almost complete isolation between outputs is obtained regardless of load conditions.

2. Monostable Element

Another element required for the DDA is a monostable device. This element is used to mechanize OR and NOR logic functions encountered in the circuit. As with the bistable unit, an existing geometry was utilized. It is derived by introducing a bias in the bistable configuration. Again, adequate performance was not obtained using a 2 mil nozzle with an aspect ratio of one. However, this element shows very satisfactory operating parameters when made with a 4 x 4 mil power nozzle.

Characteristic curves for a typical element of the final monostable configuration are given in Figure 12. Normalized flow (the ratio of recovered flow to power jet flow) is plotted as the abscissa versus normalized pres-

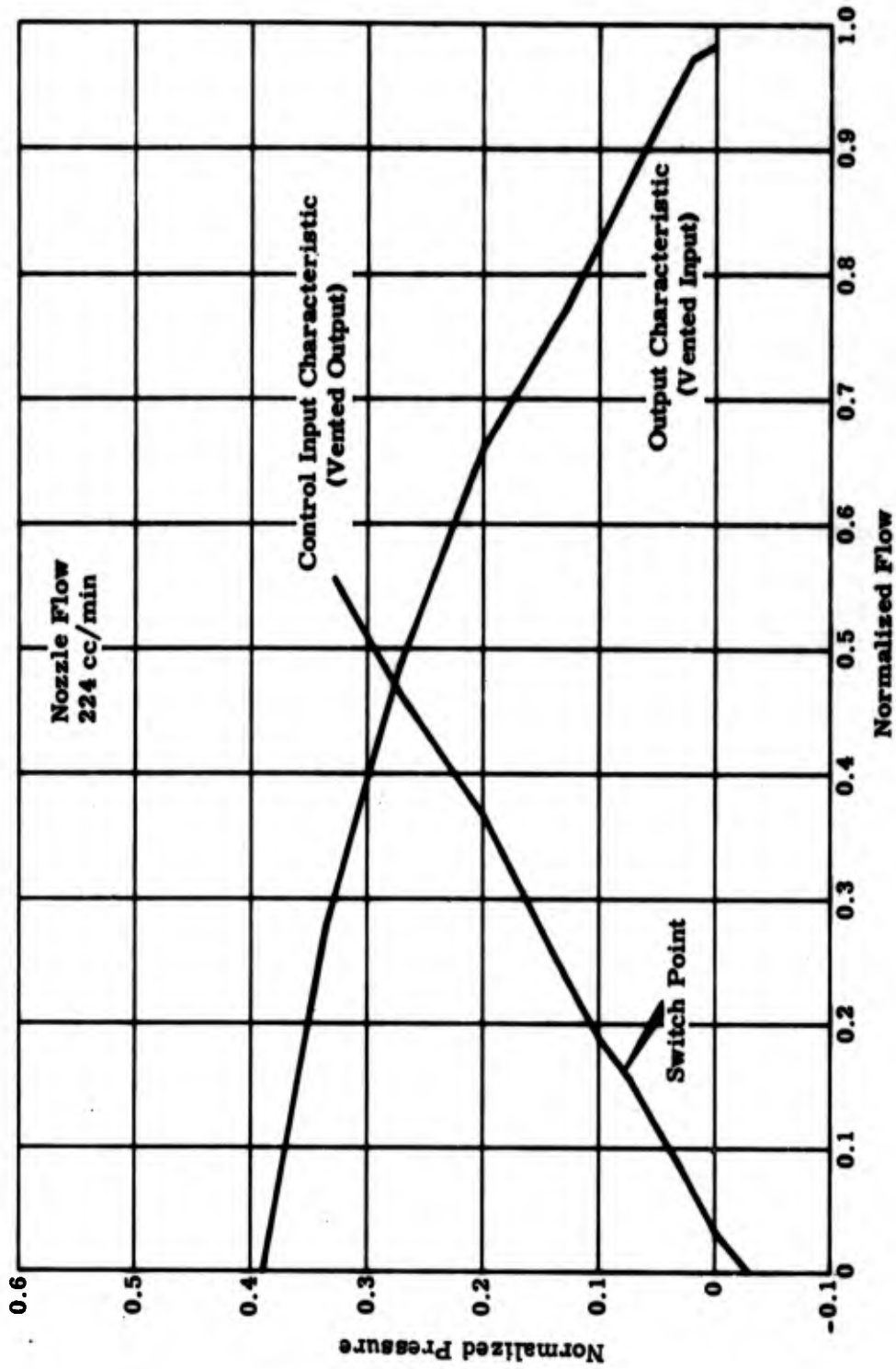


Figure 12. Monostable Characteristics at 103.5k Nt/m² (15 lb/in.²)

sure (defined in an analogous manner to normalized flow) as the ordinate. The two curves on this plot are the output characteristics and the control input characteristic. The output characteristic is typical for the "normally on" leg of the monostable element.

The point at which control input pressure and flow were sufficient to operate and hold the power jet to the "normally off" leg is designated as the switch point on the control input characteristic curve. It should be noted at this point that with the 2 mil monostable elements, some problems had been encountered with a portion of the "normally on" leg flow still being present after switching. With the current configuration, this problem has been resolved, and after switching, the output pressure and flow in the switched "normally on" leg is negligible. This unit is also extremely stable with respect to output loading, and it will operate into an infinite resistance with no tendency to switch or oscillate.

Pressure and flow gains may be obtained in the same manner as was outlined for the bistable element. These gains are both on the order of five for the configuration tested. The fan-out capability for the monostable element is also about five. As may be expected, pressure recovery for the monostable unit is somewhat greater than that for the bistable element. At low operating pressures, it approaches 50 percent and decreases somewhat as nozzle pressure is increased. Nominal values under typical operating conditions are about 40 percent.

3. Passive Bistable Element

The only other element required for the DDA is a load controlled passive bistable unit. This element is used in a counter circuit and is essentially a pulse relay which directs an input pulse to the proper control port of the counter memory element. Its state is controlled by a pressure differential from the control ports of the memory element which is imposed across the output legs of the passive element. In this mode of operation, the passive element is never required to switch when it is powered, so control ports are not required. It was evolved simply by removing the control ports from the standard bistable element geometry. Removal of the control ports provides two desirable results for this particular operating mode - it improves element stability and it tends to increase pressure recovery. Pressure recovery of 35 percent is typical of a passive unit when operated with the power inputs shown in Figure 13. These characteristic curves are similar to those shown previously for the bistable element.

4. Element Switching Speed

One of the most frequent criticisms of fluid systems is their relatively slow operating speed. Since this operating speed is inversely related to

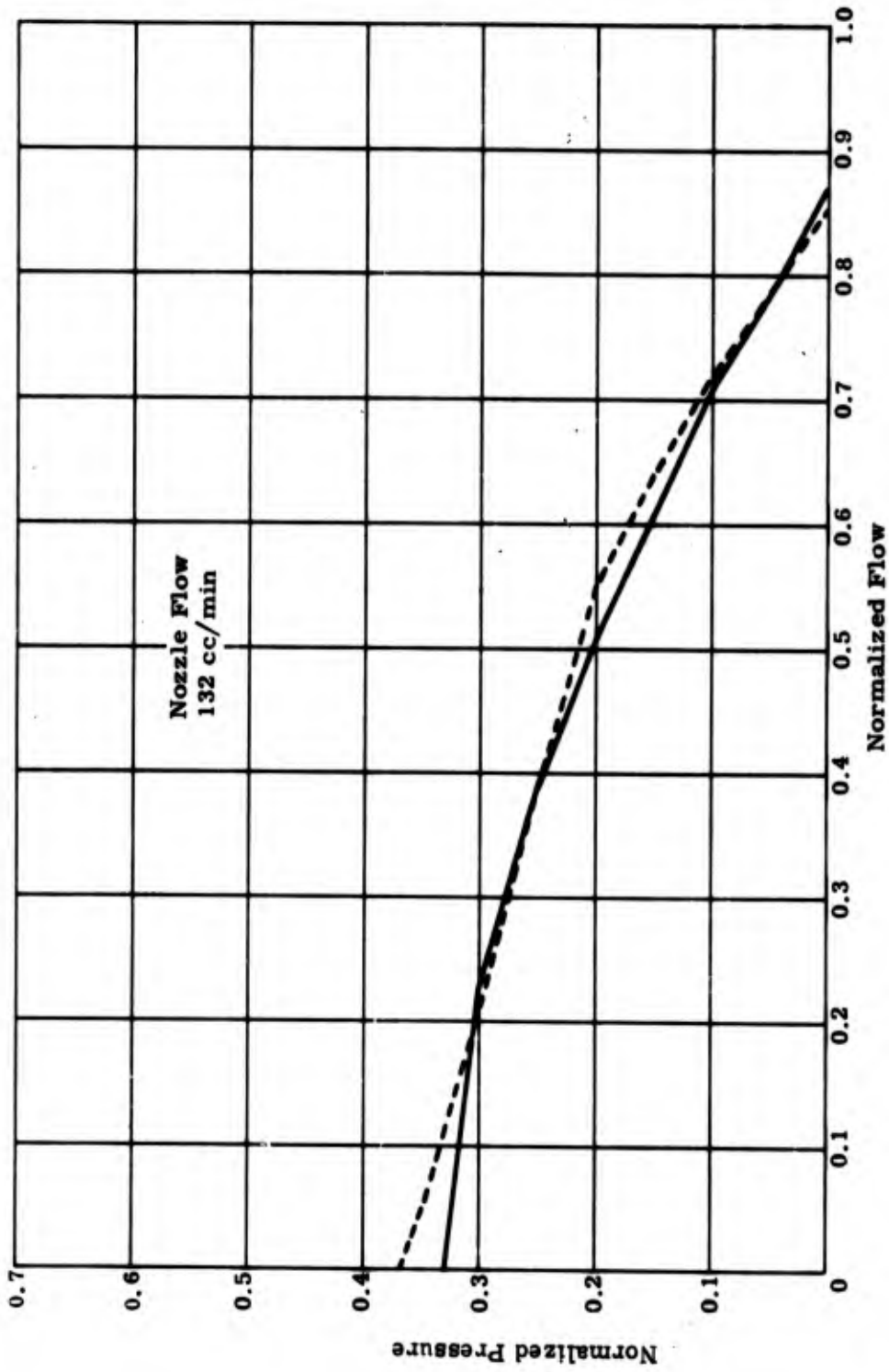


Figure 13. Passive Characteristics at 34.5k.Nt/m² (5 lb/in.²)

element size, one primary objective of element miniaturization is to increase circuit operating rate. Using logic elements with 4 x 4 mil power nozzles, operating rates as high as 10 kilocycles have been achieved in practical integrated circuits. Using special test circuits, operating rates up to 25 kilocycles have been observed.

Switching speed of these elements was determined by two methods. First, a test element similar to the bistable unit used to mechanize the DDA was instrumented as shown in Figure 14. The geometry of one output channel and one control port channel was altered to permit installation of a hot wire anemometer in each channel as close to the interaction area as possible.

As shown in the instrumentation block diagram, two constant temperature anemometer probes were located inside the element channels. One probe was used to monitor the flow into the control port. The second probe was located in the corresponding output leg of the element. Switching times were observed on a dual trace oscilloscope by displaying the amplified probe signals simultaneously. A permanent record was obtained with a camera mounted on the oscilloscope. Common triggering circuits to the solenoid valve controlling the pneumatic input signal to the element and the oscilloscope were necessary to ensure film exposure in the camera at the moment the element was switching to its alternate mode of operation. A delay of approximately 0.05 seconds was observed between the moment the solenoid valve was energized until control flow was applied to the element. This delay was caused by the length of pneumatic line connecting the solenoid valve to the element and the relatively slow response of the valve.

The test element had a power nozzle width of 3 mils and was made of a stack of four layers of 2 mil thick base material. It was necessary to use the larger aspect ratio for instrumentation requirements; however, it was felt the dynamic data would be indicative of lower aspect ratio element performance.

Switching time obtained from these tests could not be determined to a high degree of accuracy. A very low signal to noise ratio of the hot wire probes made it difficult to interpret the results accurately and time constants could only be approximated. This was caused primarily by insufficient space to properly mount the anemometers. Another problem was that the oscilloscope sweep rate had to be held to 1 millisecond per centimeter to assure any success of catching the switching transients on the camera. This resulted in a severely compressed time scale.

As well as could be determined, switching times (including all transport delays) were on the order of 200 microseconds. This time includes two

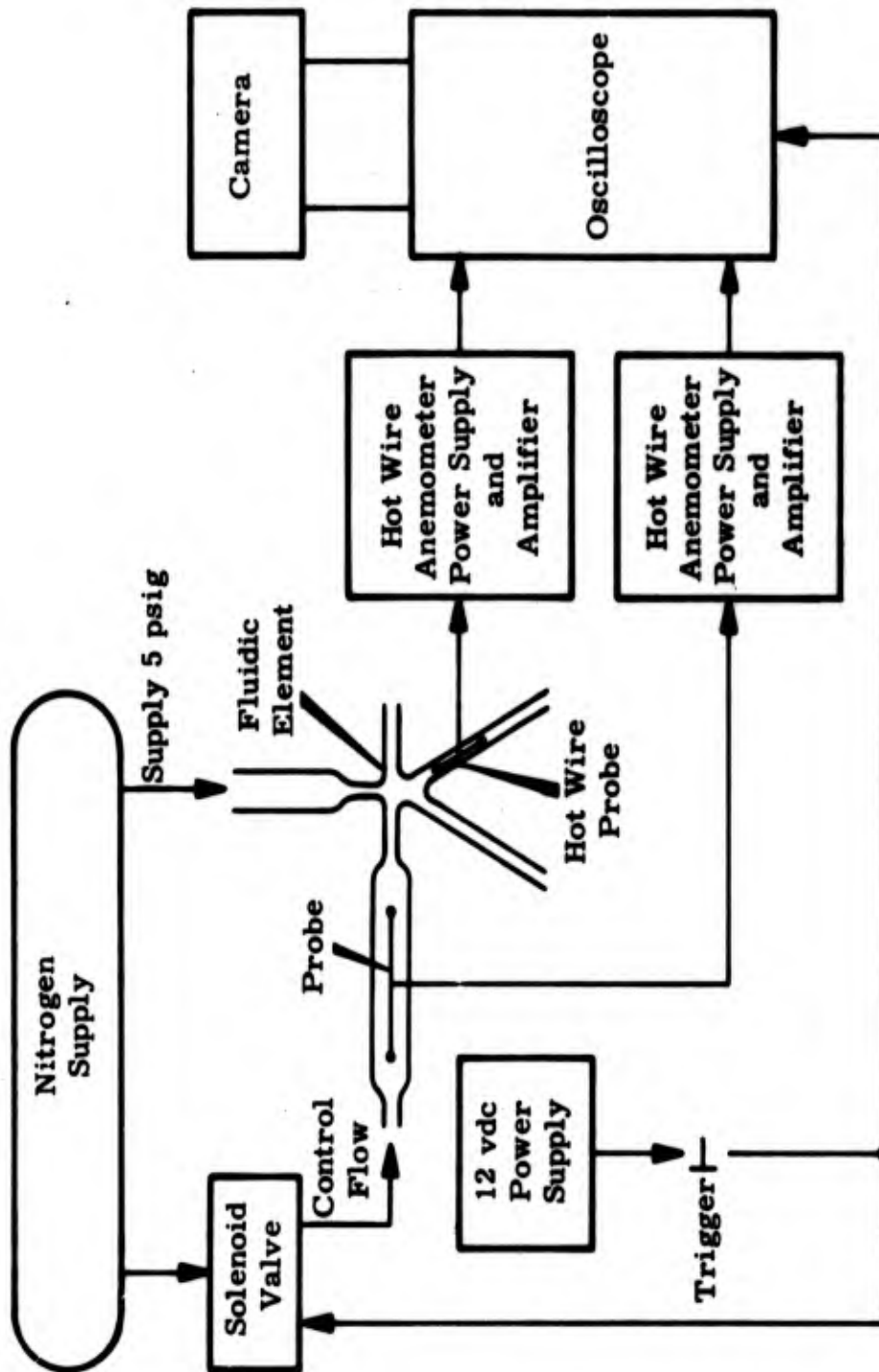


Figure 14. Switching Speed Instrumentation Layout

transport delays; first, the one from the control channel probe location to the interaction area; and second, from the nozzle exit through the output leg of the element to the output probe location. The total value of these delays were calculated to be on the order of 175 microseconds, leaving 25 microseconds as the time required for the power jet to switch from one output to the other.

Transport delays encountered in this instance were felt to be somewhat larger than those that would be observed in an actual circuit because of the relatively large space requirements of the hot wire probes. Another method to determine operating rates under actual circuit conditions is to build an oscillator consisting of a chain of a number of elements, where the output of the last element is connected back to the input of the first element in such a manner that the complete system is unstable. Under certain conditions a portion of the DDA circuit will fulfill these requirements. An equivalent circuit of this portion of the DDA logic under conditions for oscillation is shown in Figure 15. Tracing through this logic, one finds that if element A is in the (1) state, the NOR logic between element A and element B will set element B to the (0) state. This, in turn, sets element A to the (0) state, which causes the intervening logic to set up so element B is switched to the (1) state. This action then switches element A back to the (1) state, from which point the cycle is repeated. The circuit was tested in this condition, and the frequency of this chain oscillator was determined. This frequency was somewhat dependent on power nozzle pressure, running at about 1000 cps at low pressure and rising at a maximum of about 1200 cps at higher nozzle pressures. This is the free running frequency of the actual circuit that was delivered. The mechanics of switching element A from the (0) state to the (1) state requires propagation of logic signals through a series connected chain of eight elements. Since this completes only half of the total cycle, the chain of eight elements must complete their switching in half of $1/1200$ second, or 417 microseconds, when using the 1200 cps oscillation. Therefore, the switching time required for each element, including the transport delay of its associated interconnections, is 52 microseconds. This is a figure that can currently be attained in integrated logic circuits using an element with a 4 x 4 mil power nozzle. This would indicate that single element logic functions can now be performed at frequencies up to approximately 10 kilocycles. By optimizing circuit layout to minimize interconnection line length, this value can approach the basic element switching frequency which is in the neighborhood of 25 kilocycles. Obviously, such response is adequate to satisfy the requirements of many applications.

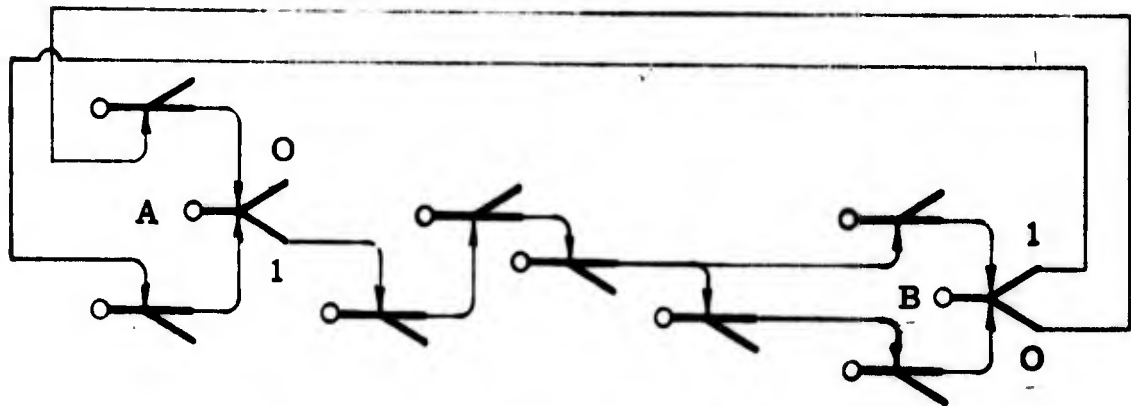


Figure 15. Chain Oscillator Circuit

II. MECHANIZATION OF THE DDA

A. CIRCUIT OPERATION AND REQUIREMENTS

A digital differential analyzer essentially performs a numerical integration of the area under a time dependent curve. It does this by successively summing small area increments under the curve. Figure 16 shows a block diagram of the DDA and also includes a curve which depicts the integration process. The DDA consists of two binary circuits - a counter and a summer. The initial value of the dependent variable y is stored in the counter and can be changed by supplying pulses to the dy input shown. The summer contains a sum register and an addend register and the necessary carry logic to complete requirements for the addition process. In operation the summer is supplied with two periodic, 180 degree out of phase signals. These are the add, or dt , and shift inputs shown in Figure 16. In the delivered item, these signals are supplied through manually operated valves rather than through a fluidic signal generator.

The dt input essentially divides the time scale into small increments each dt units wide. When it is momentarily interrupted, it commands the system to add the number in the counter (the y value) to the number that exists in the addend register. The number in the addend register is the value of the previous sum that was stored in the sum register. This value is transferred to the addend register by a momentary interruption of the shift input.

Assume that some number (y) is stored in the counter and the sum and addend registers are set to zero. The first dt command adds this value (y) to the value in the addend register (0) and stores the answer in the sum register. This value represents the area of the first ydt area block under the curve of Figure 16. Now the shift input is pulsed which transfers this value to the addend register. The second dt command then adds the value in the counter to the value in the addend register (the previous sum) and stores this new value in the sum register. This value corresponds to the area under the curve represented by the first two ydt area blocks.

The sum register of a digital differential analyzer has a finite capacity determined by the number of binary bits making up the system. When enough of these ydt area blocks are added into it, the register will over-

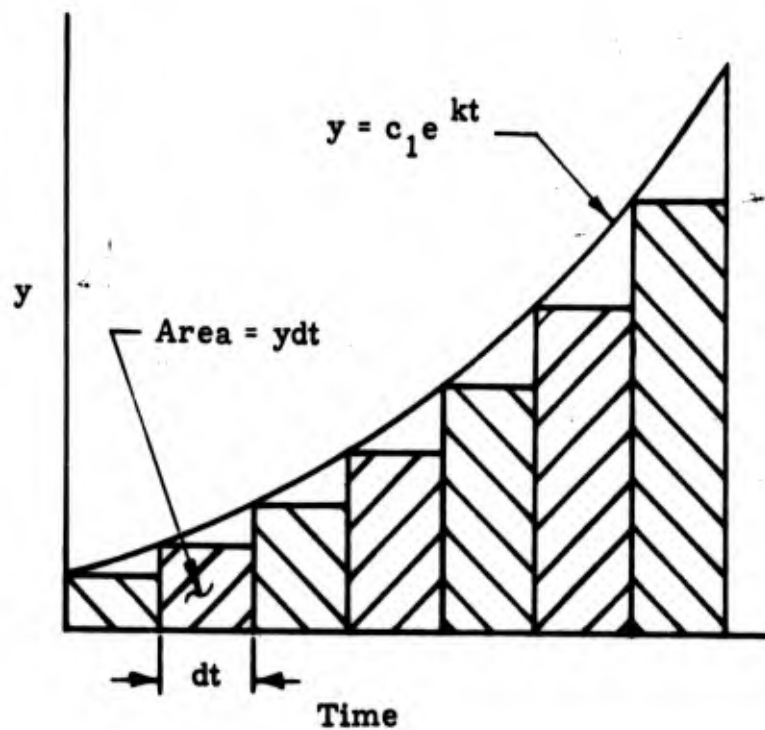
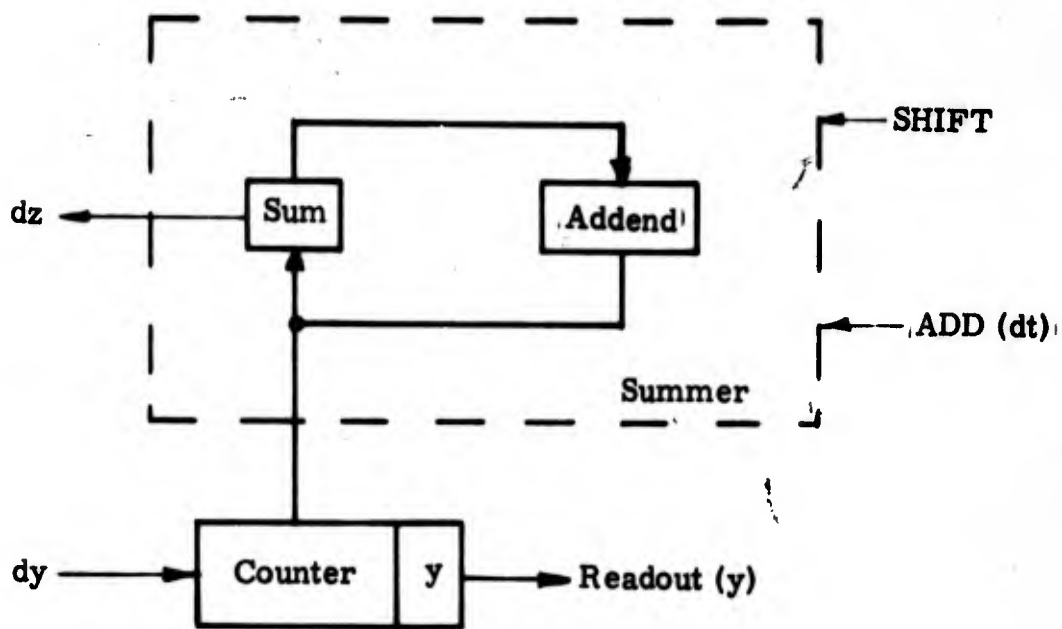


Figure 16. DDA Operation

flow and generate a dz output. This dz output is proportional to a known amount of area under the y time curve and is equal to kydt. If the value of y is decreased, a greater number of additions will be required to generate a dz output. If the value of y is increased, fewer additions will be required. Each dz pulse represents an area under the curve of kydt and to obtain the total area, or the integral of kydt, it is only necessary to count the number of dz pulses that appear.

Consider what happens when the dz output is connected back to the dy input. Since $dz = kydt$, and in this case $dy = dz$, by substitution $dy = kydt$ is obtained. Separating variables produces $dy/y = kdt$, and integrating produces $\log y = kt + C$. Solving for y gives $y = e(kt + C) = C_1ekt$. So the number y that appears in the counter is the solution to the simple differential equation $dy/y = kdt$. One DDA has the ability to solve this equation only; however, with a suitable interconnection of a number of DDA's, many very complex differential equations can be solved.

The purpose of this effort was to mechanize such a circuit using miniature fluidic elements to demonstrate the feasibility of a fluid logic approach to complex digital circuits. The delivered item was a demonstration model with appropriate readouts and manual controls to permit visual verification of the counting, adding, and shifting operations. Mechanizing this circuit required refinement of existing counter and summer circuits and integration of these circuits into a functional matrix in addition to optimization of miniature element geometry previously discussed. This work is described in the following sections.

1. The Counter

Several basic counter circuits were evaluated for this application, including both unidirectional and reversible units. To keep the device as simple as possible from the control standpoint and to minimize the number of elements required, a unidirectional counter was selected. However, in an operational unit, a reversible counter would be required in most cases. Two preliminary circuits were evaluated extensively. These are shown in schematic form in Figure 17.

One version consists of a Warren type single input flip-flop with two monostable interstage amplifiers. The other version uses a single input flip-flop which has control channels on the passive element. In the latter circuit, the passive element is controlled by a pressure differential derived from jet pumps in the output legs of the memory element. This pressure differential is fed back to control ports in the passive element and control its state as a function of memory element position during pulse application

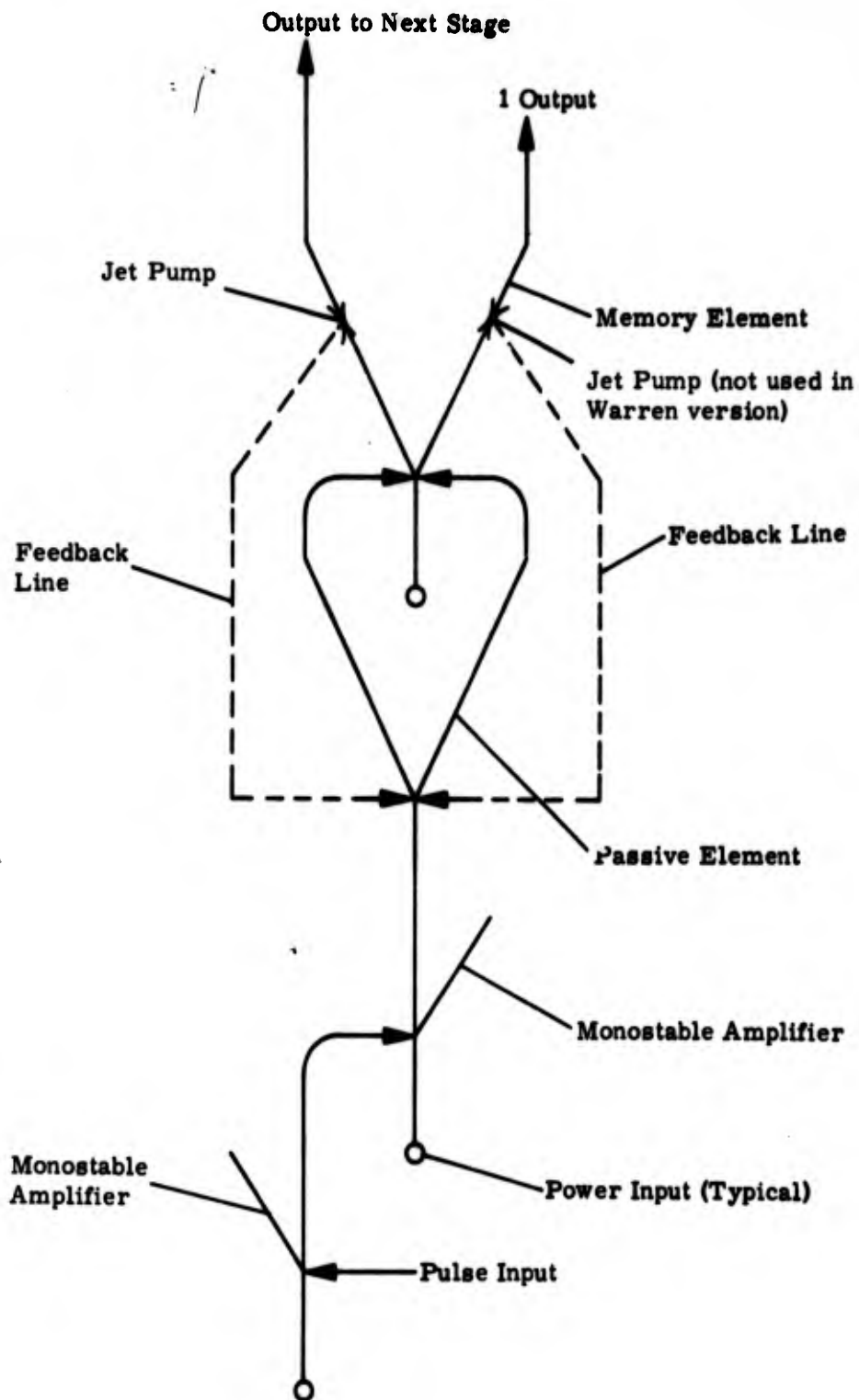


Figure 17. Initial Versions of Counter Circuit

to the passive element power nozzle. The only difference between the two versions, schematically, is the feedback lines that are shown as dotted lines in Figure 17 and the jet pump sections in the output legs of the memory element. The Warren circuit does not incorporate these channels or the jet pumps.

Two major problems were encountered with both versions of this circuit; the primary one being low stage gain. The other problem was the inability to correctly control the passive element. The former, of course, was a result of element characteristics, and as individual element gain was improved, this problem was eliminated. The function of the passive element in both circuits is to direct an incoming pulse, which is applied to its power nozzle, to the appropriate control port of the memory element to effect switching of the memory element to its alternate state. Therefore, a technique to control the passive element's state during pulse application as a function of memory element state must be evolved.

In the jet pump version of the circuit, this is accomplished by a negative feedback loop. For example, in Figure 17, suppose that the memory element power jet is set to the right hand channel, and that the monostable amplifier supplying the passive element power nozzle is off. The jet pump in the right hand output leg of the memory element develops a low pressure in the right hand control port of the passive element. Now when the monostable element is turned on, it will power the passive element and the low pressure in its right hand control port will direct the power jet to its right hand channel where it stabilizes and locks on. The output of the passive element then enters the right hand control port of the memory element and switches it to its left hand channel. As the memory element switches, the feedback control pressure differential is reversed, since the left hand jet pump is now in operation and it tends to evacuate the left hand control port of the passive element. To prevent system oscillation, this reversal of the feedback control pressure must not switch the passive element. Fortunately, when using negative feedback, this problem can be easily avoided due to certain characteristics of the passive element. As the power jet is being established due to application of an input pulse, it can be driven to the desired side by a very small pressure differential. However, once the jet becomes attached, a much larger signal is required to cause switching. This permits one to establish a feedback pressure level that will ensure proper passive element control, but that will be too low to cause oscillation.

This circuit works very well as long as memory element loading is kept low. However, as output loading is increased, jet pump operation is impaired and the feedback control signal is decreased. Output loading imposed rather severe restrictions on feedback circuit design since one

output of the memory element is used to drive the following counter stage while the other output is needed to drive a portion of the summer logic. To avoid this problem, attention was focused on the alternate circuit version which uses feedback from the memory element control ports into the passive element outputs as the sensing technique.

A complete description of the operation of the single input flip-flop portion of this circuit will not be presented here as it has been thoroughly discussed by Warren⁸. However, one significant difference between the circuit described by Warren and that used here should be pointed out. In both circuits, a pressure differential of appropriate sign is impressed across the output legs of the passive element causing a flow circulation in its interaction area which causes the pulsed power jet to select the proper output channel. The difference between the two circuits is the manner in which this pressure differential is derived. In the Warren circuit it is established by entrainment from the control port of the memory element that is on the same side as the output channel that has been selected by the power jet. This causes a low pressure in the corresponding leg of the passive element which results in the desired flow circulation.

The miniature elements developed at Martin do not exhibit this entrainment capacity. Instead, the control port of our miniature elements that is on the same side as the output channel that has been selected by the power jet usually runs at ambient or slightly positive pressures. However, due to certain characteristics, the opposite control port operates at a substantially positive pressure. This provides the desired pressure differential to the passive element and results in similar operation to the Warren circuit.

It should be noted that the problem encountered with this circuit during earlier tests was the inability to obtain correct passive element control. This was caused by an initially low differential pressure across the memory element control ports when using 2 mil nozzles. However, with the final element configuration using a 4 mil nozzle, this differential is quite sufficient to provide accurate control over very broad operating ranges.

This circuit enables one to remove the control ports from the passive element thus providing two desirable results. Both element stability and pressure recovery are increased. This facet, coupled with additional improvement of bistable and monostable element characteristics, permitted elimination of one of the interstage amplifiers. The final counter circuit is shown in Figure 18.

This circuit has been tested successfully in a three bit, a six bit, and several four bit assemblies. It is capable of operating over very broad nozzle pressure ranges. Typical pressures run from 35 to 175k Nt/m²

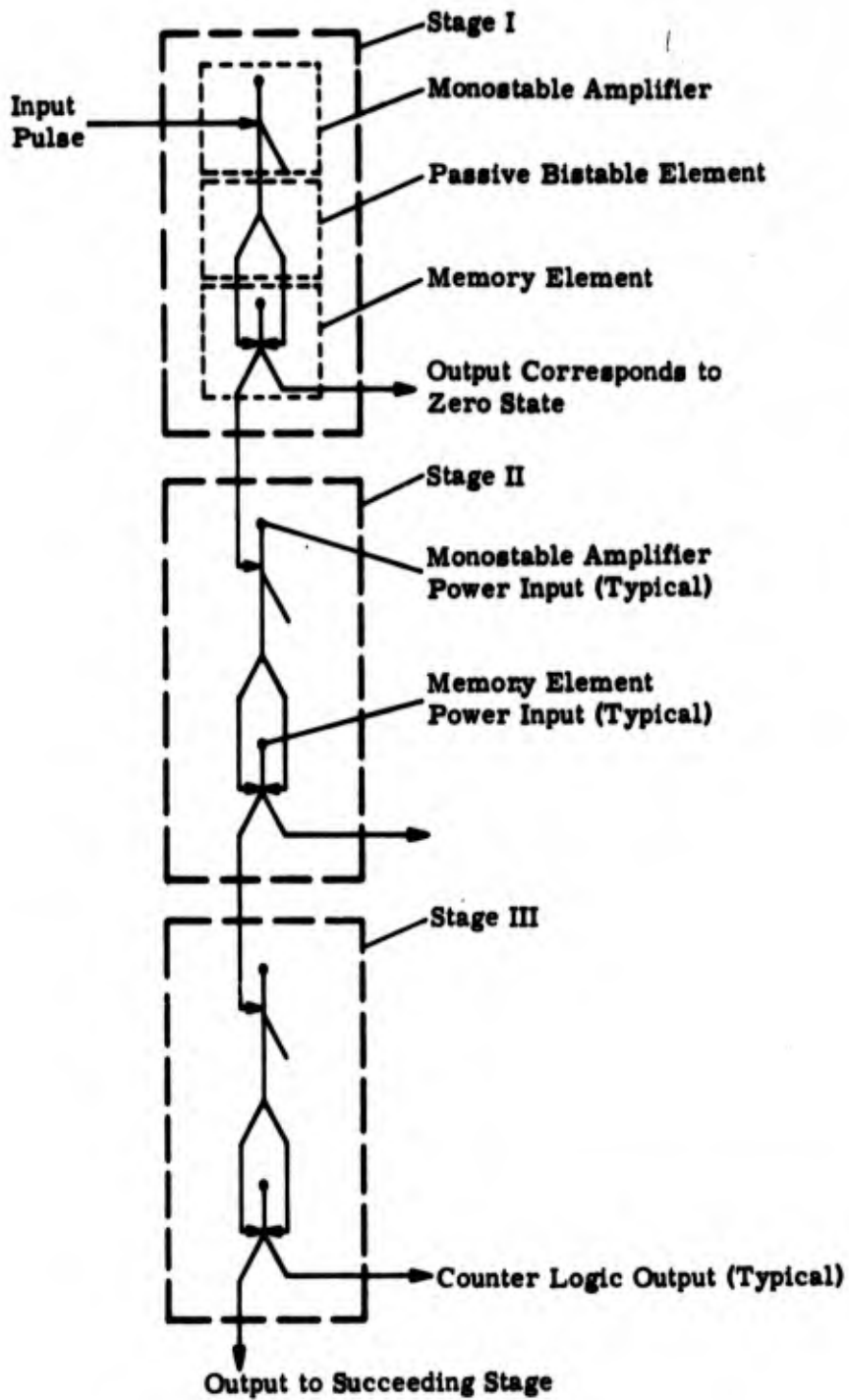


Figure 18. Schematic of Final Counter Circuit

on the monostable element nozzles. Once the monostable element pressure is selected, reliable operation can be obtained by running the memory element over a range of approximately 50 to 100 percent of monostable element pressure. The circuit is relatively insensitive to memory element loading and can be operated reliably up to a blocked load on the output leg.

Dynamic data has been taken using variable pulse amplitudes, pulse lengths, and frequencies. Reliable operation was obtained under relatively static conditions through manual pulse application and by driving the unit at various frequencies using pneumatic oscillators. Oscillator frequencies of 3, 800, 900, and 1000 cps have been used. It has also been driven by a mechanically interrupted jet at frequencies up to 1200 cps. In all cases reliable operation was obtained. Although it has not been tested above 1200 cps, the element switching data indicates this counter can be reliably driven at frequencies approaching 10 kilocycles.

2. The Summer

The binary summer was developed by making minor changes in an existing logic circuit and then mechanizing this circuit with fluidic elements. A schematic of this summer is shown in Figure 19. A detailed description of its operation will not be presented here, as the logic is rather conventional. Suffice it to say that the device has the ability to sum three signals, the carry from the preceding stage, the augend, and the addend. It performs this operation when the ADD control input is momentarily interrupted, and when this occurs the answer is stored in the sum register. The augend value is supplied by the counter, and the carry in is supplied by the preceding stage. The value in the addend register is supplied by the sum register. The sum value is shifted to the addend by a momentary interruption of the SHIFT control input. This technique allows an accumulative addition process to be performed. A carry out to the succeeding stage is generated as required by certain combinations of three inputs: the augend, the carry in, and the addend. A carry out will be generated when any two or more of these signals exist in the binary "1" state. For all other combinations of these signals, a not carry out will be generated.

This circuit imposes several rather stringent fan-in and fan-out requirements. First, five elements with a fan-in of three are required. Second, one element must fan-out from both its NOR and OR output legs into two elements each having fan-ins of three. Also, two elements are required to fan-out from their OR output leg into three elements each having fan-ins of two. With the miniature elements, it has not been possible to incorporate separate control channels for each input signal an element must receive due to space limitations. As a result, when an element must operate with

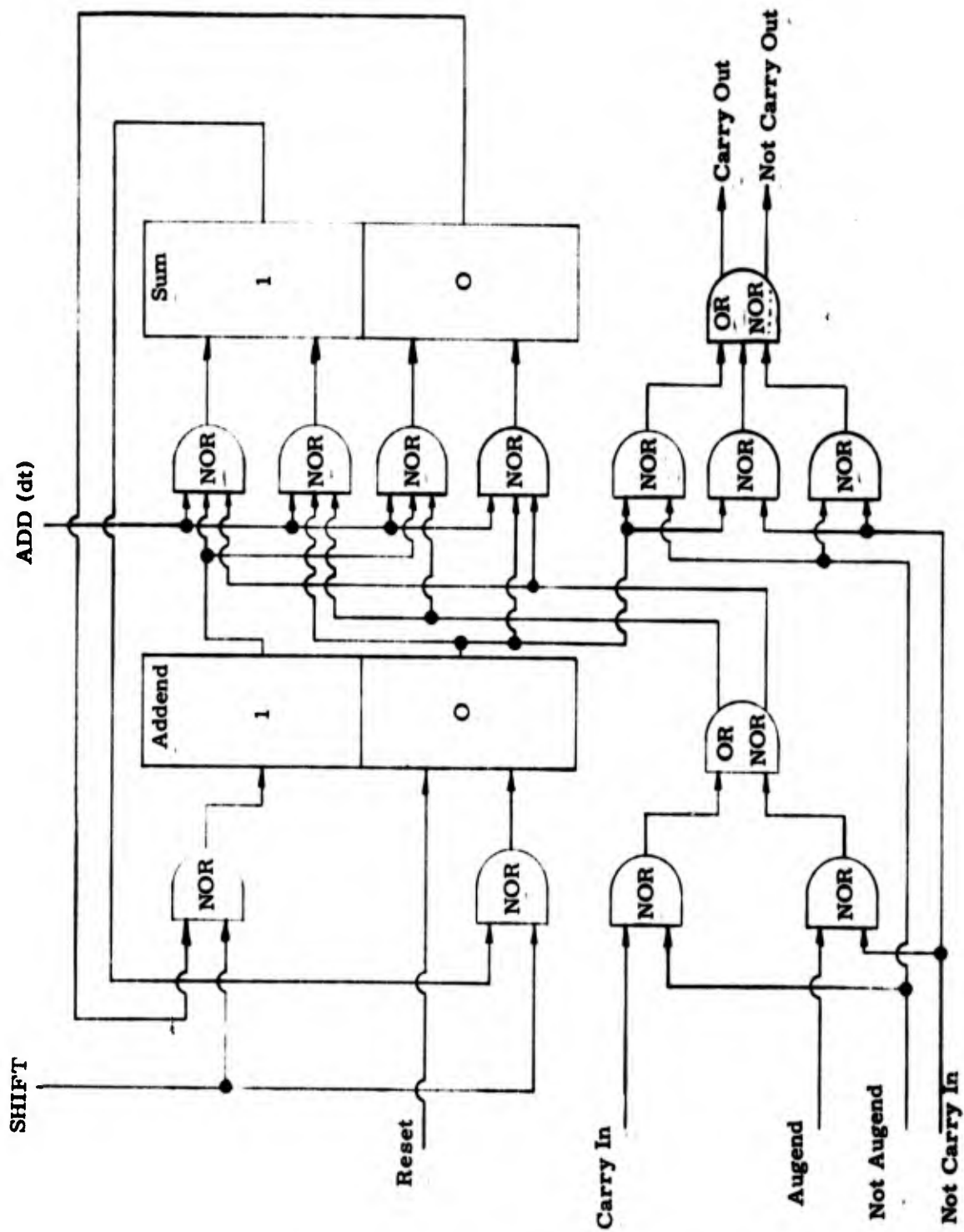


Figure 19. Original Binary Summer Stage Logic Diagram

a fan-in greater than one, all input signal channels must meet at a common point and enter the element from a common control port. This has imposed serious restrictions in circuit design.

For example, the characteristic curves of the monostable element indicate that the output of one element should be able to fan-out into five other similar elements and drive them reliably. The characteristics of the bistable elements indicate a fan-out of at least seven can be expected. These values have been verified by laboratory experiment; in fact, fan-outs of nine have been obtained with bistable units. However, these tests were performed under conditions where the driven elements had only one control input. This requires that all the flow leaving the output of the driving element must enter the control ports of the driven elements, so there is no control flow loss in the system.

However, when an element is fanned-out into several elements having more than one control input, this is not the case. As previously stated, when an element has more than one input line, these channels must be joined at a common point at the entrance to the element control port. In this case these additional inputs present a leakage path for the output flow from the driving element. This results in a considerable loss of control flow available to drive additional elements. Under such conditions, where one element must fan-out into several elements having multiple inputs, it was determined that a fan-out of two was the maximum value that could be used reliably when all elements were operating under similar conditions.

This problem could be solved by a suitable fluid diode. Several diode configurations were evaluated, including the Tesla diode and a vortex unit. However, in the channel sizes and flow rates being used, suitable diode action could not be attained. In all configurations tested, the difference between forward resistance and reverse resistance was very low. The inability to produce a functional diode forced redesign of the summing logic to circumvent the fan-out, fan-in problem. However, it is felt that additional research should be devoted to diode development as a functional diode would considerably enhance the potentials of miniature fluidics.

Since it was necessary to alter the summing circuit, it was decided to simultaneously incorporate other minor refinements. As indicated in Figure 19, two signals, a carry and a not carry, must be transmitted from stage to stage. Two signals are also required from the counter to satisfy the augend requirements. The logic was changed so only one signal was needed in each case to minimize interconnecting between stages. Also, tests indicated the OR output leg of the monostable elements was not as stable with respect to output loading as the NOR leg, so it was decided to eliminate all instances where this output was used to drive other elements.

With these changes, the final schematic of one stage of the DDA is shown in Figure 20. This schematic includes both the summer and counter circuits. This circuit is presented using fluidic element symbols rather than the conventional logic symbols used in Figure 19. The summing section of this circuit will perform the same logic functions as the one discussed previously; in addition, it contains provisions for readouts of the counter and sum register values. This summer circuit contains thirty elements as opposed to a requirement for only fifteen elements in the original circuit. These additional elements are required to provide readouts, eliminate the not carry and not augend signals, and to avoid the fan-in and fan-out problems discussed earlier. These extra elements reduce the maximum operating speed of the new circuit from that of the original since the signals must travel through more series connected logic levels than before. However, at the current state of element development and without the use of a functional fluid diode, the additional series circuitry is required.

B. LAYOUT PHILOSOPHY

Once the circuit had been established, the next problem was to develop a suitable art layout for use in the photo-etch fabrication technique. Since each binary stage of the device contains 33 logic elements, including the counter, and each of these elements requires a minimum of 7 interconnections including bleeds, signal inputs and outputs, and power inputs, the layout can become extremely complex. In addition, each element must be located in the three dimensional matrix in such a position that its interconnections can be kept as short and direct as possible, and pointed in the proper direction to minimize signal losses. Efficient transfer of carry signals from stage to stage must also be considered.

Examination of the schematic diagram of Figure 20 indicates the logic would lend itself particularly well to a circular layout. Two distinct signal loops exist: one is the addend and sum loop and the other is formed by the carry section. Interconnections between the addend and sum loop and the carry loop are held to a minimum and the counter has only one input to the carry logic. In this device, information that is unique to one stage travels around the addend and sum element circle and folds back upon itself. Since the final assembly was to consist of a vertical stack of four such binary stages, signals that are transferred from stage to stage must exit from the bottom of the preceding stage and enter the top of the following stage in corresponding locations throughout the stack. The counter and carry signals are the only ones that must be transferred from stage to stage. The counter can be connected directly, while the carry signals circle through the carry and logic loop of each stage spiral through the stack.

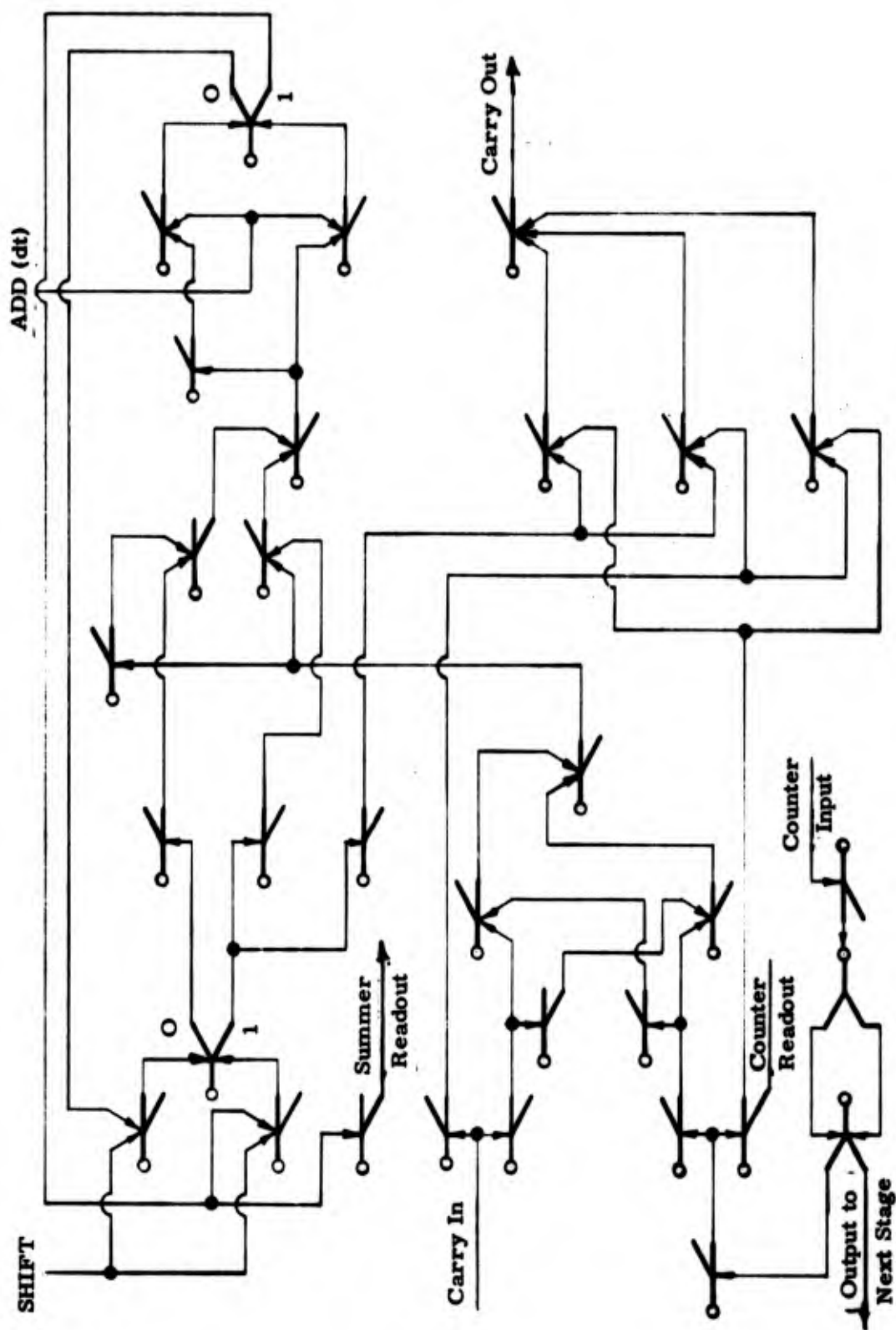


Figure 20. Integrated Counter and Summer Stage Schematic

It was determined that each logic loop could be mechanized with a series connected chain of five element columns, therefore, the basic format provides five element positions spaced around the center vent. Since the counter circuit does not logically fit in either loop, it is located in one corner of the logic plane, and its signal is injected in the carry loop at the required position.

Each column of elements is powered from a common pressure port which appears as a vertical hole through the stack. By far the largest majority of elements used in the system are monostable and only the NOR side of these elements are used in most cases. This allows most interconnections to be made directly from one element column to the next, keeping them short and pointed in the proper direction. In no instance is it necessary to transmit a signal farther than two element columns downstream.

Once the format has been prepared, it is necessary to plan the locations of the elements and interconnections in the three dimensional matrix. When this is done the art is laid out 32 times actual size. Element outlines are provided by use of standard element templates made by a 10 to 1 photographic reduction of a 320 times actual size layout of the element geometry. These templates are placed in position on the layout format and taped in place. The required interconnections and alignment and assembly holes are provided by applying printed circuit tape. When the art is finished, it is photographically reduced by a factor of 32 and printed on sensitized 4 mil copper sheets. These planes are then etched, cleaned, and gold plated to provide the finished logic planes.

C. FINAL ASSEMBLY

The complete assembly consists of a stack of four of the binary stages shown in schematic form in Figure 20. Each stage requires 34 logic and interconnection planes, resulting in a total of 146 planes. Figure 21 is a photograph showing an expanded view of the resulting stack of planes, including eleven other planes required for routing input signals and readouts. The resulting module measures 2.9 x 2.5 cm and is 1.6 cm high when assembled. This stack is mounted on an aluminum base which serves as a power manifold and contains valves for controlling the counter, shift, add, and reset inputs. The manifold also contains a filter for contamination protection, and an orifice plate to allow adjustment of the counter memory element pressure. A photograph of the DDA is shown in Figure 22.

A readout block is mounted on top of the column of planes. The readouts consist of tiny flowmeters made by inserting precision steel balls in bored tubes. Because of the limited flow output of the miniature elements, clearance between the ball and tube had to be held to one mil to ensure

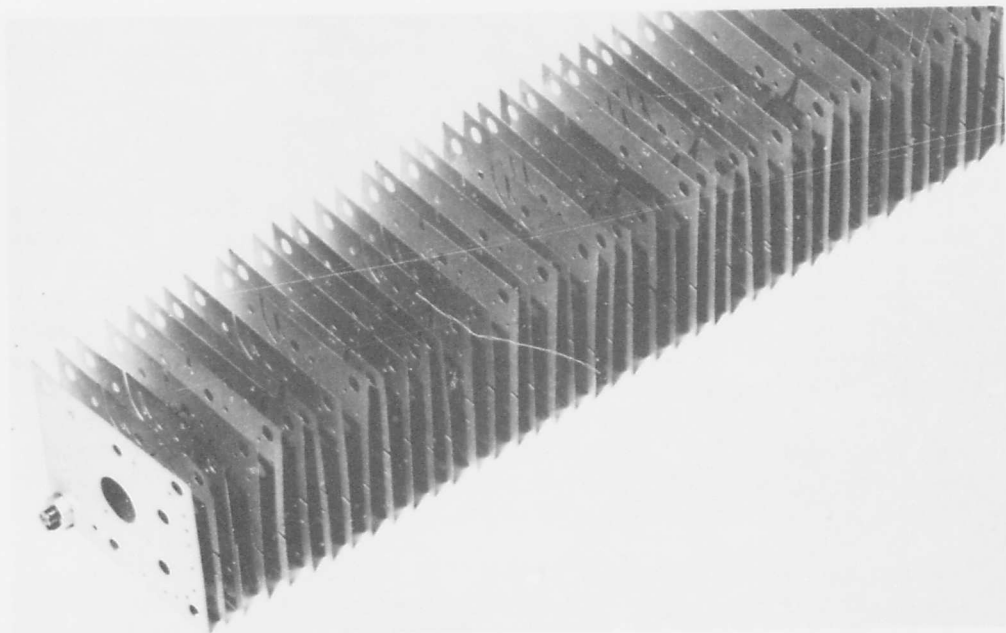
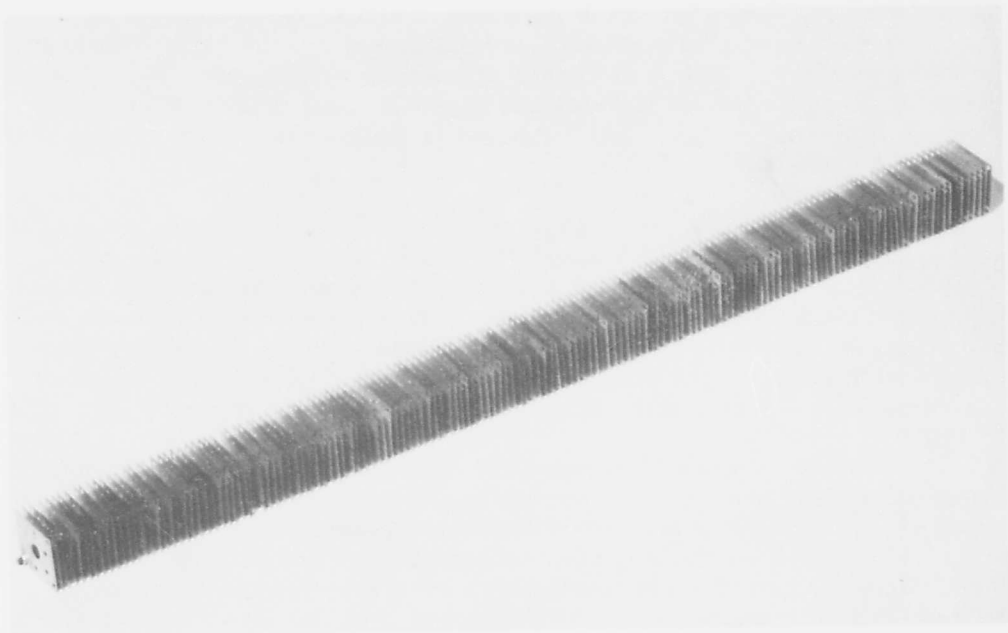


Figure 21. Stack of Planes

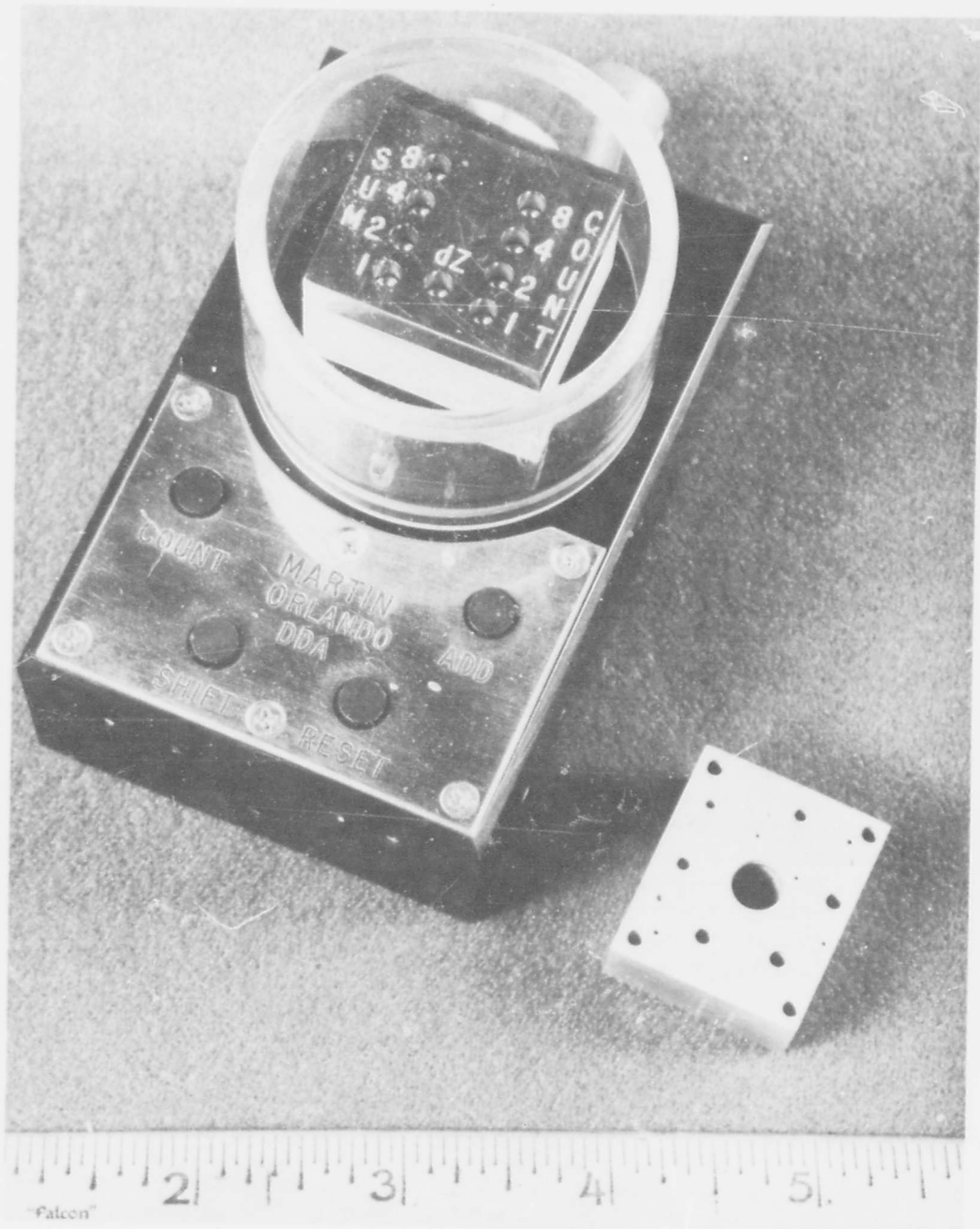


Figure 22. Assembled DDA

proper operation. A readout is provided for each counter and summer stage and for the dz output.

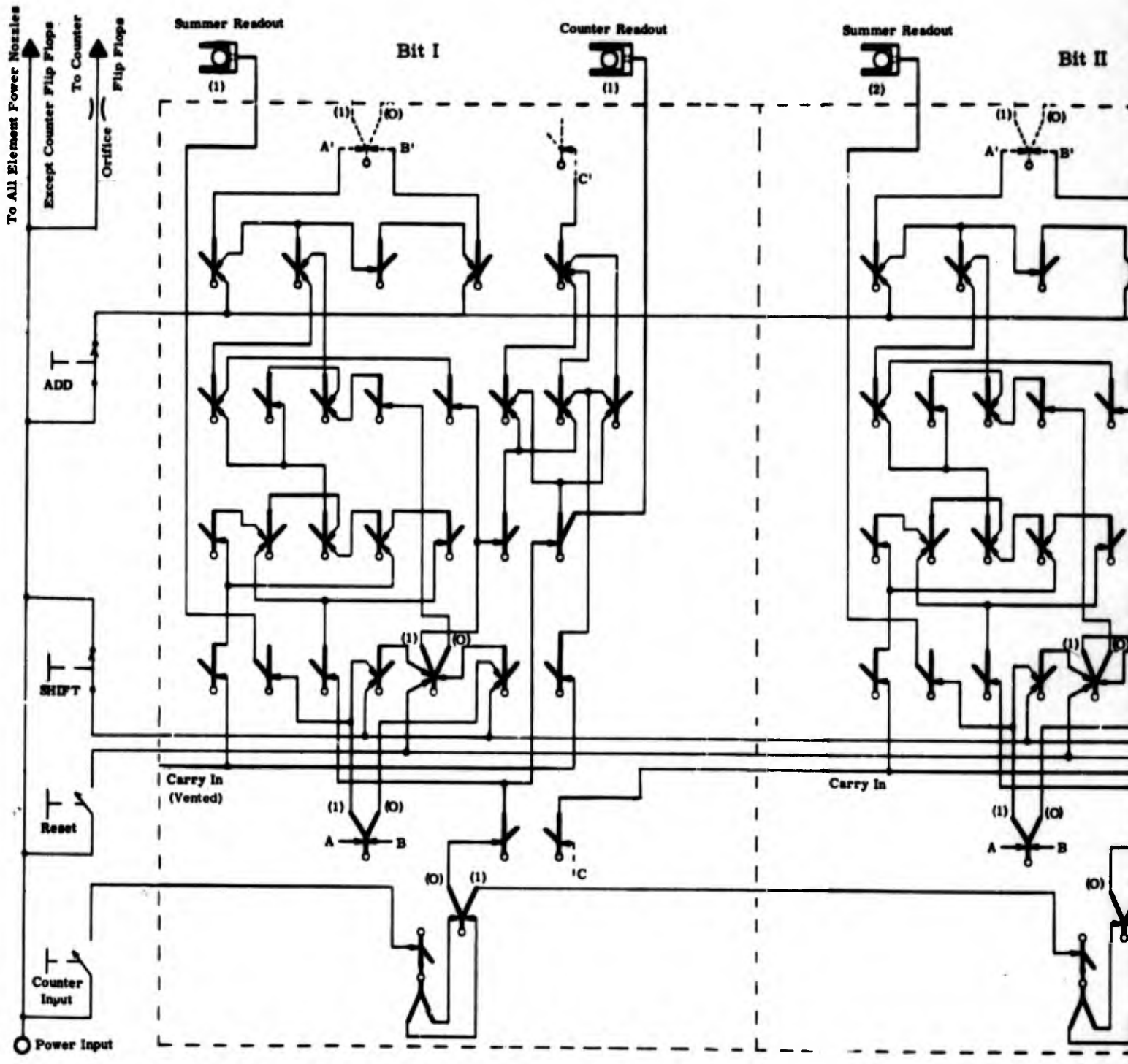
As further insurance against contamination, all valves used in the manifold block were specifically designed to eliminate rubbing surfaces. Also, the complete assembly is protected from the environment by a sealed plastic dome. This dome also serves to equalize the exhaust pressure between the inside vents and the outside of the column. Exhaust gas entering the internal vents is ported to the outside through a bleed passage in the manifold. This passage runs at a pressure slightly above atmospheric. Without the dome, the outside vents are ported directly to the atmosphere, resulting in a pressure differential across the bleed ports of the elements. In some cases, this pressure differential is adequate to cause erratic operation. The dome forces exhaust gas leaving the outside vents to pass through the same bleed channel as gas from the internal vents, thus equalizing exhaust pressure across the elements.

A schematic of the complete four stage assembly is shown in Figure 23. Here each bit represents a stack of 34 planes. Beginning at the top there are three planes containing interconnections and vents. The first horizontal row of logic elements appears in the fourth plane, followed by three interconnection planes. Some planes contain only one element; the bistable units, for example, are all on single element planes. Normally, each logic plane contains three to four elements, and in one instance, five monostable elements are included in a single plane.

Each vertical column of elements represents one of the five columns in the module, and all elements in each column are powered from a common supply port. The first column on the left, excluding the counter circuit, is reproduced in phantom on the right where necessary to complete interconnections around the loop. For example, point A on the left is the same as A' on the right, B corresponds to B', and C is the same as C'. As previously explained, the counter circuit does not fit in the element ring, and it is shown isolated on the left hand side of the schematic.

A carry in signal is not required for the first stage, so this line is vented through passages in the cover plates. In a like manner the counter output of the last stage is also vented since it is not required. The carry out of the final stage is used to provide the dz output for the system. This signal indicates when the sum register overflows.

As shown in the schematic, a total of 132 logic elements were used to mechanize the circuit. The volume of the logic module is 11.5 cubic centimeters, including all readout and input routing planes. This results in a packaging density of about 12 elements per cubic centimeter. For circuits



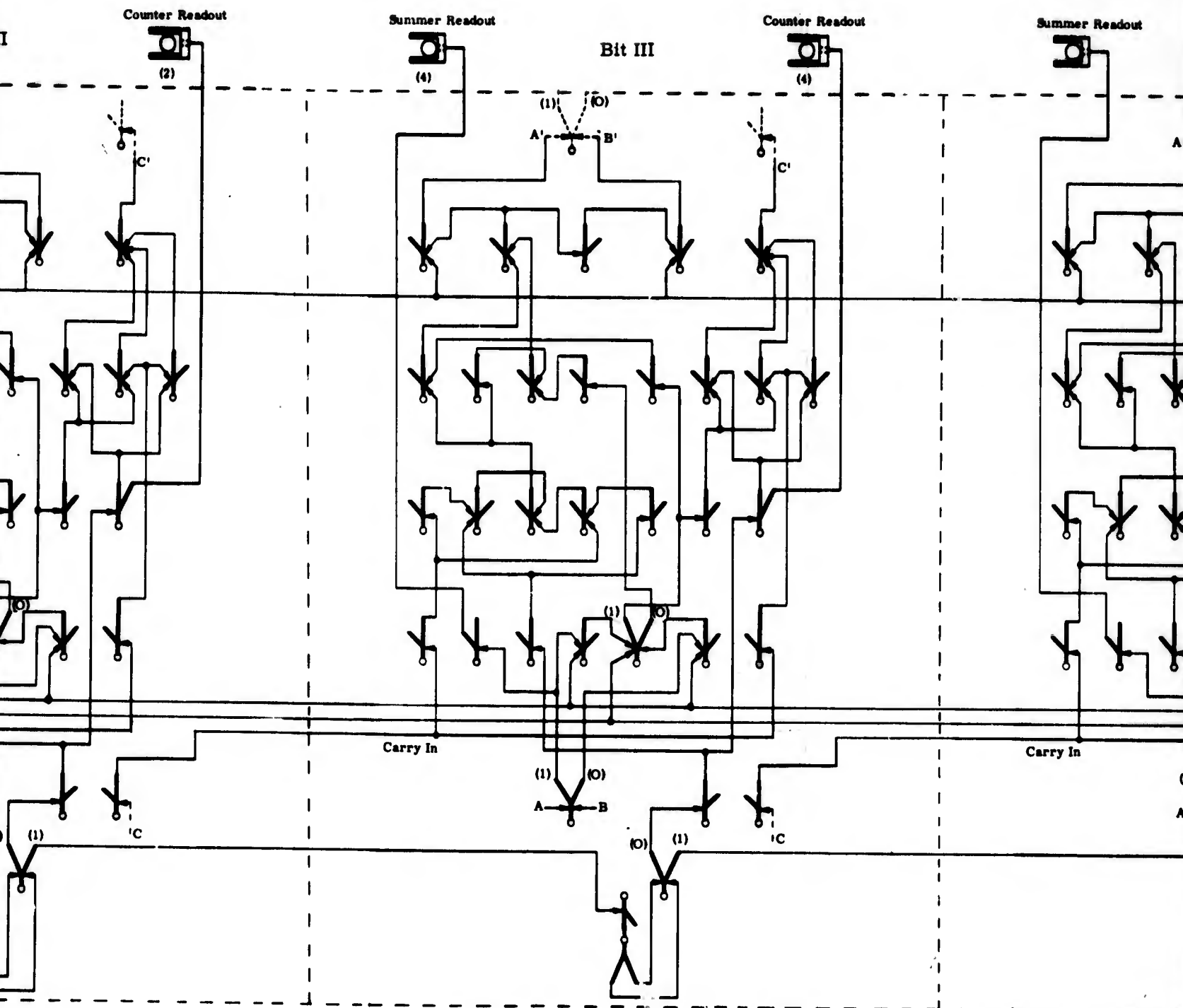


Figure 23. DDA S

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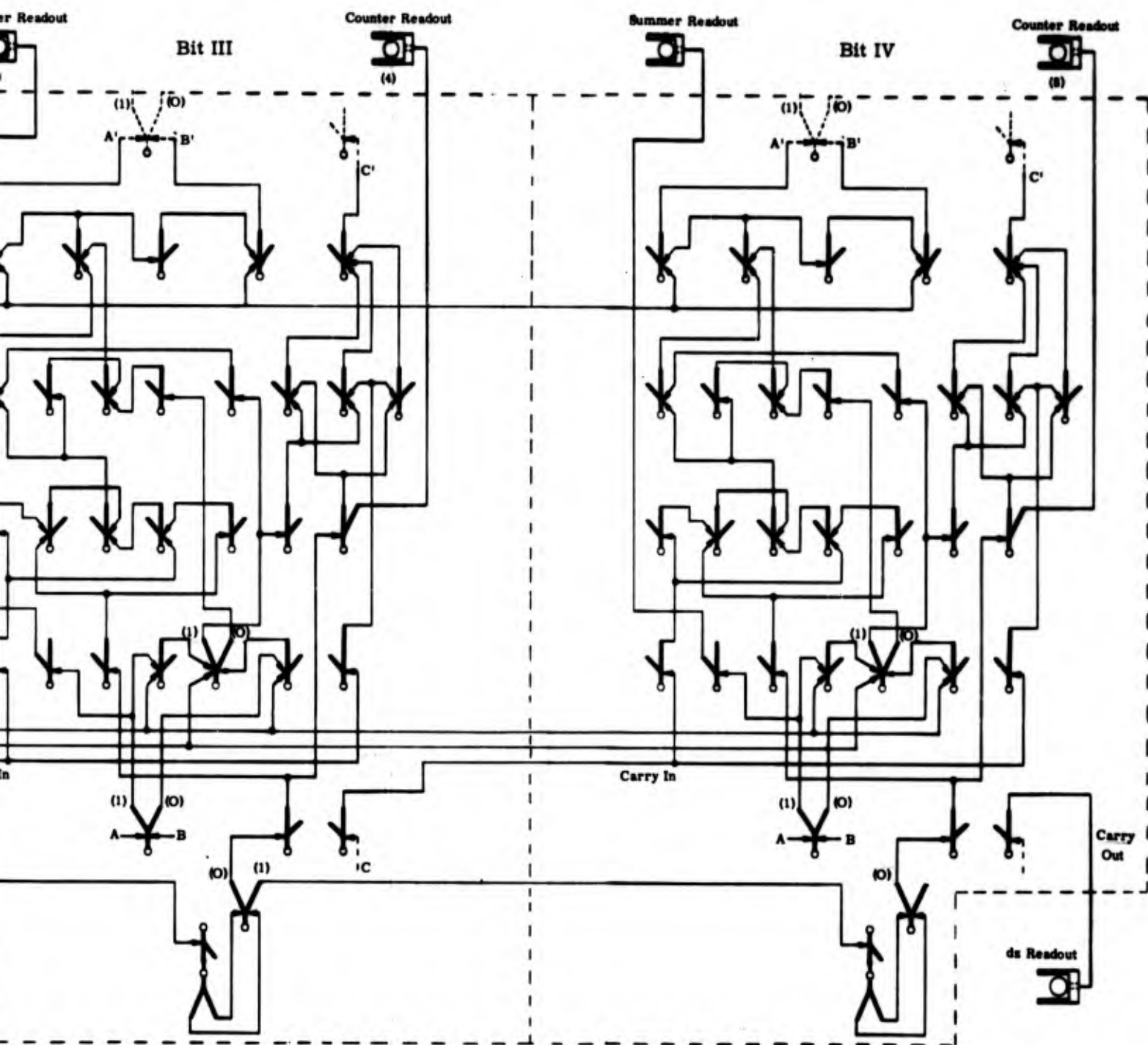


Figure 23. DDA Schematic

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with less complex interconnections, such as a simple counter, packaging densities on the order of 30 elements per cubic centimeter have been achieved. This is a significant improvement over conventional techniques.

D. TEST DATA

Each stage of the DDA was tested under all possible combinations of inputs and outputs before assembling the stages in the final package. Each stage was assembled from logic planes that were microscopically inspected to ensure adequate etching. They were tested over a pressure range of 60 to 120k Nt/m². If any erratic operation was detected over this operating range, the problem was isolated and repaired. Malfunction isolation was performed by using a tiny stethoscope to monitor element operation by listening to the outside vents.

One distinct problem was evident in several sections of the circuit. It is caused by the inability to obtain a functional fluid diode. Figure 24 is a reproduction of a portion of the carry logic, and will be used to illustrate the problem.

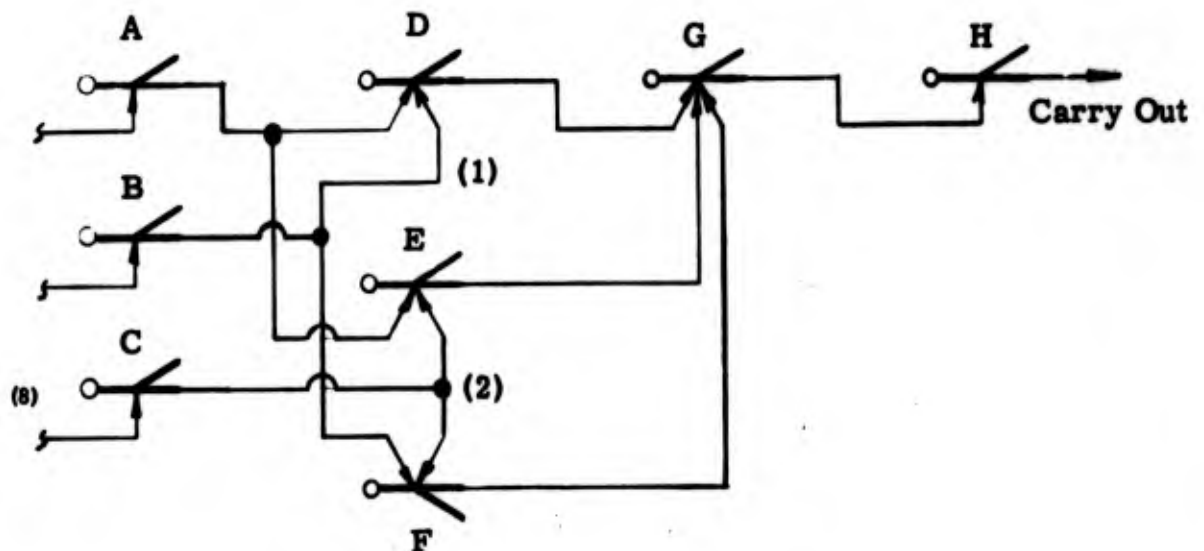


Figure 24. Section of Carry Logic Circuit

If any one of elements A, B, and C are on, it will hold the corresponding two elements of the column composed of elements D, E, and F in the off condition. The other element, however, will stay on, which holds G off and permits H to turn on and generate a carry out. For example, if element A is on while B and C are off, the output of A will hold D and E off. Element F will remain on. This sets G and H to the correct state. However, the outputs of element A are joined to the outputs of elements B and C at the control ports of elements D and E. This permits part of the output of element A to feed back on lines (1) and (2) to the control port of element F. If the magnitude of this feedback signal is high enough, it can cause erroneous switching and/or oscillation of element F, resulting in an improper carry out signal.

This problem appears in other portions of the circuit, but in no case is it as severe as in the case illustrated. One case is the shift input, which can feed back into the control port of the summer readout element and cause an erroneous readout. In this case, the summer portion of the circuit does not malfunction - only the output indication is wrong. This problem limits the maximum pressure that can be applied to the shift control port. In all cases the malfunction could be eliminated by a simple diode.

This was the only general problem associated with the circuit. When it occurred, the circuit was repaired through careful selection of elements and interconnection line sizes. Occasionally an element would have to be replaced due to poor characteristics, but this was only in a few isolated cases.

Four functional stages were assembled for each DDA and each stage was carefully tested over the range indicated. A range of pressure for the shift and add signals was also determined. For these signals, a lower limit was established for which proper operation could be obtained. The signal pressures were then increased until feedback caused erroneous switching of the summer readout, as previously explained. This value was established as the upper limit. An operating range for the counter memory element was also determined. The data for four of the stages used to assemble one DDA are given in Table I. Values obtained for the other assembly are quite similar and are not included. The maximum counter memory element test pressure was 100k Nt/m^2 , so where this pressure is indicated in Table I, it is only known that the counter will work at least to this value. Proper operation was achieved over the pressure ranges indicated. After individual stage tests, the four stages were assembled and again tested in a similar manner. In general, the pressure ranges over which satisfactory operation could be obtained were somewhat less than the range of an individual assembly. This is, of course, to be expected. Again, the major problem was erratic switching caused by feedback of signals through common control lines. Table II shows operational pressure ranges for the complete assembly.

TABLE I

DDA Stage Test Data

Stage	Monostable Element Pressure k Nt/m ²	Counter Memory Element Pressure k Nt/m ²	Shift and Add Signal Pressure k Nt/m ²
I	60	24 to 55	17 to 34
	90	48 to 110	24 to 62
	120	69 to 110	41 to 117
II	60	31 to 57	20 to 48
	90	55 to 110	27 to 83
	120	76 to 110	41 to 103
III	60	34 to 62	20 to 48
	90	55 to 110	27 to 83
	120	76 to 110	41 to 110
IV	60	27 to 97	17 to 62
	90	41 to 110	34 to 83
	120	55 to 110	45 to 97

TABLE II

DDA Module Test Data

Monostable Element Pressure k Nt/m ²	Counter Memory Element Pressure k Nt/m ²	Shift and Add Signal Pressure k Nt/m ²
55	27 to 48	17 to 27
70	48 to 83	24 to 35
90	58 to 110	27 to 45

Reliable operation could not be achieved above 90k Nt/m², although the individual stages would operate up to 120k Nt/m². The major problem again was in the carry circuit, and is attributed to somewhat different loading conditions than those existing during the individual stage tests. However, the device will still operate over a relatively wide range of ± 24 percent of the nominal value.

These values were taken in a special test fixture which had separate power supplies for the monostable elements, the counter memory elements, the add and shift signals, and the counter pulse input. From this fixture, the module was installed on the manifold block which has only one pressure input. This block contains two normally open and two normally closed valves that are used to control the DDA. All these valves are supplied from the same source used to power the elements. An orifice plate is used to adjust the counter memory element pressure and pressure adjustment for the add and shift signals is accomplished by means of resistors and vents in the input signal routing planes.

Several problems were encountered when the DDA was first tested on the manifold. First, the shift and add signal pressures were not correct, and since there was no way to measure the pressure actually available in the module, these pressures were adjusted by trial and error using various resistor-vent combinations until proper operation was obtained.

Another problem observed was that the various element columns were not operating at the same pressure when installed on the manifold. These pressures could be measured by inserting an appropriately designed spacer between the module and the manifold and pressure variations between columns in excess of 8 percent were observed. This factor considerably decreased the usable operating pressure range of the DDA. However, little could be done about the situation without a complete manifold redesign. Since successful operation could still be attained over a limited pressure range, no changes were made to the manifold.

The most serious malfunction that occurred during tests on the manifold was improper counter operation. In many cases when an input pulse was applied to the counter, the first stage would trigger on the leading edge of the pulse as well as on the trailing edge. This problem had not been observed on any tests of the single stages or the complete module in prior tests using the special fixture. In fact, as long as the input pulse was of sufficient magnitude to drive the first stage counter amplifier, counter operation had been very satisfactory. However, when mounted on the manifold, this problem appeared time and again in all units tested.

Several factors were investigated to determine the cause of this malfunction. Since the valve that supplies the counter input pulse operates from the same power source that operates the elements, it was suspected that spikes were being generated on the element supply as the valve was opened and closed. The supply pressure to the counter memory element was checked for transients, and it was found that spikes of approximately 15 percent of supply pressure were being generated during valve operation. A temporary separate supply was provided for the counter to determine if

this would eliminate the problem. This helped to some extent, but by no means did it resolve the malfunction.

An instrumentation setup was provided to monitor the input pulse on an oscilloscope. In many cases when a malfunction occurred, a definite oscillatory or ringing tendency was observed on the leading edge of the input signal. Apparently this oscillatory tendency was adequate to trigger the first stage under certain conditions. This was attributed to a resonant condition in the line between the counter input and the valve. It was determined that over a certain pressure band the counter would operate properly in spite of this condition. Therefore, the counter memory element orifice was sized to provide for operation within this band.

With the restrictions imposed by the unbalanced supply pressures and the counter input pulse problem, the pressure band over which reliable operation could be assured was reduced to about ± 4 percent of the nominal value. This value depends on the input line being used. With the one used at Martin during the tests, the nominal input pressure was about 100k Nt/m^2 . This input to the manifold supplies approximately 70k Nt/m^2 to the element columns at the base of the module.

Mechanization of the DDA has demonstrated that miniature fluid logic can be applied to complex logic circuits. Operational elements having 2×2 mil power nozzles were evolved. Although their characteristics were not adequate to use in the DDA, they could be used in some simple applications. Additional work in this area could lead to 2×2 mil units with excellent characteristics. However, elements with a 4×4 mil power nozzle have shown highly effective operational characteristics. Using these units, the circuit was mechanized with little difficulty, which demonstrates their excellent characteristics and the ease with which they can be interconnected. The only serious problem encountered was in the interconnections themselves, and this could be eliminated through development of a miniature fluid diode. Operating rates of the elements have been extended to the point where reliable in circuit operation up to 10 kilocycles can be obtained, and under certain conditions this can be extended considerably. These factors now render fluid logic feasible for used in applications where it was previously considered impractical.

E. CONCLUSIONS

This effort has demonstrated that miniature fluid elements can be used to mechanize complex logic circuits. The advances made in element characteristics, interconnection techniques and fabrication and packaging

procedures have extended the potential applications of fluid systems. The following conclusions can be drawn from the results of this work and related research programs:

- 1 An operational fluid logic element having a 2 by 2 mil power nozzle has been developed. However, additional work will be required to optimize element geometry and improve operating characteristics.
- 2 Current designs of elements having 4 by 4 mil power nozzles provide very satisfactory operating characteristics.
- 3 Due to their excellent stability features, these elements can be easily interconnected in complex logic arrays.
- 4 Under certain conditions, these elements are capable of operating up to 25 kilocycles. With the relatively long interconnection passages required in the delivered circuit, operating rates up to 10 kilocycles were obtained.
- 5 The elements can be made with a low cost fabrication process suitable for high volume production.
- 6 Since the elements will operate with an aspect ratio of 1, the requirement for stacking several element planes to obtain a large aspect ratio is eliminated. This also eliminates the need for precise indexing between logic planes.
- 7 Layout techniques and art preparation processes are available that permit rapid transition from the original schematic to the finished product.
- 8 Element packaging density of 40 to 50 elements per cubic centimeter can be obtained with certain circuits.
- 9 The major problem encountered was the need for a functional miniature fluid diode. Additional research should be devoted to development of such a device, as a diode would enhance the potential of miniature fluid systems.

These factors permit miniature fluidics to be considered for applications where conventional fluid circuits are not practical. The integrated circuit approach provides a very small, practically indestructible package that is suitable for use in severe inertial environments such as those encountered in artillery projectiles and certain missile systems. Timers, using a fluid oscillator in conjunction with a counter such as the one used in the DDA,

can be used to provide sequenced signals in arming and fuzing systems for these devices. More complex fuzing systems, using fluid logic and digital fluid sensors developed at Martin, can be mechanized.

These are but a few of the potential applications for miniature fluidics. Many others exist in process control, machine tool control, and data processing systems. The advantages offered by the miniature integrated circuit approach should provide increased interest in the utilization of fluid logic.

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<i>(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)</i>		
1. ORIGINATING ACTIVITY (Corporate author) Martin Company Orlando Division		2a. REPORT SECURITY CLASSIFICATION Unclassified
		2b. GROUP
3. REPORT TITLE MINIATURE FLUIDIC DIGITAL DIFFERENTIAL ANALYZER		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report of Contract		
5. AUTHOR(S) (Last name, first name, initial) Depperman, Warren		
6. REPORT DATE 15 July 1966	7a. TOTAL NO. OF PAGES 59	7b. NO. OF REFS 8
8a. CONTRACT OR GRANT NO. DA-49-186-AMC-249(D)	8a. ORIGINATOR'S REPORT NUMBER(S) OR 8189	
b. PROJECT NO. c. d.	8b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
10. AVAILABILITY/LIMITATION NOTICES Qualified requesters may obtain copies of this report from DDC.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U.S. Army Materiel Command Harry Diamond Laboratories Washington, D. C.	
13. ABSTRACT This report describes the analytical and experimental processes used to scale an existing miniature element configuration to a suitable size. The purpose of the program was to mechanize a demonstration model of a digital integrator to demonstrate the feasibility of utilizing miniature fluidic elements in complex digital logic systems.		

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14 KEY WORDS Differential Analyzer - Digital Systems Fluidics Miniaturization	LINK A		LINK B		LINK C	
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