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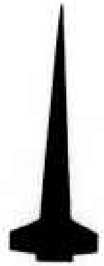

EXPERIMENTAL DESIGN OF A FLUID-CONTROLLED HOT GAS VALVE

31 December 1962

U S ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA

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Electrodynamics Branch
Electromagnetics Laboratory
Directorate of Research and Development
U.S. Army Missile Command
Redstone Arsenal, Alabama

ABSTRACT

This report describes an effort toward development of a hot gas jet reaction valve utilizing boundary layer techniques to control a high pressure, high temperature gas stream. The result of this work has been the successful design of a hot gas valve in a reaction control system utilizing fluid-controlled bi-stable amplifier principles and requiring no moving parts in the gas stream. This preliminary status report on the work gives the experimental design approach and results achieved with no particular attempt being made to develop the theory.

Valves have been fabricated and successfully tested to control gas at pressures to 1200 psi and temperatures to 2350°F with flow rates as high as 0.16 lb/sec at the highest temperatures. Efficiencies comparable to standard valving techniques have been realized.

FOREWORD

The work described in this report represents the combined efforts of several individuals of the Electrodynamics Branch of the Electromagnetics Laboratory. It is appropriate to give recognition to several individuals participating in the program: To Mr. Kenneth C. Evans for leadership of the group engaged in this effort and for the original basis on which the program has been based; and to Messrs. Carroll Godwin, J. C. Dunaway, W. E. Lane, and Vernon Ayre for their particular contributions to the effort.

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I. BACKGROUND

A solid propellant gas generator (GG) offers an excellent source of power for short-life, missile-borne control systems if the components of these systems can tolerate the high temperature and contaminants of the working fluid. Conventional valving techniques which expose moving parts and temperature-sensitive materials to the gas stream have been continuously plagued with problems of deformation, erosion, binding, etc. Grave doubts exist throughout the missile industry about their usefulness in tactical weapons systems. Thus the Electromagnetics Laboratory began in 1961 to look for better means of utilizing hot gases either from a rocket motor or from a separate gas generator to produce missile control forces. Two methods which appeared possible are as follows: (1). Steering the exhaust gases from the main motor nozzle by various mechanical means to produce side thrusts, and (2). Developing a cheap, reliable, and rugged valve to enable exhausting hot gas through transverse nozzles to produce reaction forces directly or indirectly by secondary injection.

At this time several visits were made to the Harry Diamond Laboratory to become familiar with the concept of pure fluid devices. Even though to this point all work had been done with cold gases, at low pressures, and flow rates primarily for computer type application it was conceivable that some of the techniques could be extrapolated for this new use.

The original concept of a valve which would meet the general requirements of this task was one which used the Diamond Laboratory pure fluid, bi-stable amplifier principle illustrated in Figure 1. In this valve a stream of fluid (power jet) from a pressure source of 100 psi or less is introduced through a straight-walled channel into an area called the receiver or mixing section. Located on opposite sides of the exit section of the straight-walled channel are two channels which introduce flow normal to the direction of flow of the power jet. Switching of the power jet from one output to the other is accomplished by the introduction of flow in one or the other of the flow channels. Momentum exchange between the power jet and the control stream forces the power jet to one side of the receiver section. Since the momentum of control flow required to direct the power jet from one output to the other is considerably less (10%) than the momentum of the power jet a power amplification is achieved. The receiver section is designed for bi-stable operation, i.e., flow is always either in one output or the other, never proportionally divided. This technique was not original, but the application to valving for jet reaction control systems was new. Thus considerable experimental work was deemed appropriate.

This experimental work soon showed that none of the design techniques learned previously proved satisfactory above a source pressure of

200-300 psi due to the inability to develop a power jet with good stream integrity. It showed further that exploratory work would be necessary to obtain a satisfactory design. This was initiated along with efforts to develop a more efficient means of control than is possible using a secondary pressurized source of gas, controlled to give flow in one control channel or the other.

As a result of the work initiated by this valving requirement a unique method of fluid control was discovered. This method of fluid control exposes no moving parts to the severe environment of the gases being controlled and in addition requires no secondary source of fluid for control when used within the atmosphere. The valve illustrated in Figure 2 utilizes the boundary layer effect to switch a supersonic stream issuing from a converging-diverging nozzle. A pressure source of up to 1200 psi exists at the entrance to the nozzle and is expanded to about 10 psia at the exit section. This expansion properly controlled through the converging-diverging nozzle permits the stream leaving the nozzle to retain the integrity of its pressure profile as it procedes down the receiver section at high velocity and low pressure. This stream is called the power jet.

Two control channels which exit to the atmosphere are located on either side of the exit section of the nozzle in a horizontal plane perpendicular to the power jet. For convenience of actuation these channels are faired to a circular opening to the atmosphere.

Starting at a distance downstream from the exit section of the nozzle equal to the width of the control channel, again in the horizontal plane, are the receiver section walls. These walls are offset slightly from the line projected by the nozzle exit and diverge at a small angle allowing the receiver section to expand into two output channels. Each channel is large enough to allow the power jet to flow from the valve without undue restriction. The separation of the two output channels is formed by a sharp edge called a "splitter."

Control of the supersonic stream is accomplished as follows: As the stream (power jet) issues forth from the exit section of the nozzle at a high velocity, eddies occur along the boundary of the stream which tend to entrain air particles. The result is a low pressure region occurring on either side; however, this low pressure is relieved by the influx of atmospheric air through the control ports. If one of the control ports is closed and the low pressure which tends to exist on either side is not relieved on one side, then a pressure differential exists across the power jet. This pressure difference along with the influx of atmospheric air through the open control port causes the stream to move toward the region of low pressure inside the receiver section. A slight movement of the stream causes it to come in contact with the wall of the receiver section and attach itself to this wall by forming a low pressure region from this point back to the nozzle exit section. After having attached itself to a wall the stream continues along the wall and enters the receiver section exit channel on one side of the splitter.

To cause the valve to change states, the control port previously closed is now opened and the one previously open is now closed. This causes the low pressure area to be relieved instantaneously by the inrush of air from the atmosphere. This along with the momentum of the flow from the atmosphere causes the stream to move away from the wall to which it was previously attached. At the same time a low pressure region forms on the opposite side due to closing the control port. These combined effects cause the stream to move against and attach itself to the opposite wall. Again the flow continues along the wall past the splitter and into the other exit channel.

For a small missile operating in the atmosphere this method of switching is particularly inviting. In the fall of 1961 there appeared to be a potential valve problem in the SHILLELAGH Missile development. Since this weapon system operates in the atmosphere it appeared to be a good place to attempt the use of this fluid control technique. Thus all work thereafter and all of the experimental work described here was aimed toward this application.

II. REQUIREMENTS FOR SHILLELAGH

A. Control Force Requirement

The SHILLELAGH Missile control force requirements are 12 pounds for roll and 18 pounds each for pitch and yaw.

B. Gas Generator

The gas generator for SHILLELAGH originally utilized MDB-7 propellant provided by Picatinny Arsenal but is now changing to LFT-3 propellant provided by the AMOCO Company. Nominal characteristics of MDB-7 are:

Temperature - 2350°F
Pressure - flat at 970 psi
Weight of propellant - 3.5 pounds
Burning time - 10 seconds

Nominal characteristics of LFT-3 are:

Temperature - 2000°F
Pressure - flat at 870 psi
Weight of propellant - 3.9 pounds
Burning time - 10 seconds

The experimental hot gas work reported here has been done with MDB-7 as the gas generator propellant. The present requirement on SHILLELAGH is for LFT-3 as the GC propellant; this means that designs will need to be extrapolated to utilize the different weight, temperature, and pressure characteristics of LFT-3.

C. Electrical Power

Electrical power supplied to each of the SHILLELAGH valves from on-board thermal batteries is approximately 3 amperes at 34 volts. It would be desirable to reduce this requirement as much as possible to save on battery weight.

D. Environmental

Acceleration	- 50 g (during flight boost)
Vibration	- 20 g (up to 2000 cps)
Shock	- 250 g (during tube boost)

E. Space Available

A particularly difficult requirement exists in the present SHILLELAGH Missile on the space configuration for the reaction control system. This is true because the valve must be packaged about 5 inches forward of the point where the jet reaction force is developed. This means that the reaction control gases must be piped from the valve to the rear, which proves to be a difficult job since two tubes from the main propulsion system to the rocket nozzles and the transmitter and receiver must all be located rearward of the control valves. (See Figures 3 and 4.)

III. EXPERIMENTAL PROGRAM

The fluid-controlled hot gas valve program has been primarily an experimental one since the phenomena which exist in the entrained air valve are complex and not yet well understood.

The approach to the experiments has been to establish valve switching techniques and to establish efficiencies of side forces which can be developed. Both compressed cold air and hot gases of the MDB-7 propellant have been utilized in this program. Some effort has been made to establish theory which will correlate with experiment; however, this is not yet developed sufficiently to report here. SHILLELAGH Missile requirements have been the ruling factors in this program.

First efforts toward design of a valve which would satisfy the SHILLELAGH requirements entailed the use of a simple subsonic bi-stable amplifier fabricated from a design based on parameters obtained from the Harry Diamond Laboratories. (See Figure 1.) It became obvious immediately that above a supply pressure of about 120 psi the expansion of the power jet leaving the exit channel was not being properly controlled. The result was a total filling of the receiver section causing it to act like a manifold, i.e. flow occurred through each of the exit channels. Introduction of a secondary flow through the control ports had little effect other than increasing the flow rate from each of the exit channels.

It had been observed in previous efforts to implement a proportional fluid amplifier that a device of this type could be made to change state partially or completely (with the proper internal configuration) by simply opening and closing simultaneously the secondary control ports to the atmosphere. Realizing the advantage that a valve of this type could offer when operating within the atmosphere, the laboratory proceeded with this approach in mind.

Since a straight channel did not provide good control of the expansion of the power jet at high upstream pressures the integrity of the stream could not be retained. Control of the power jet was therefore not possible. It was then decided to substitute a sonic or supersonic nozzle.

At this time the objective was to control the stream of working fluid in the valve after expansion, then recover the pressure in a diffuser section so that it could later be exhausted through a supersonic nozzle at the skin of the missile to develop the necessary side forces.

The first nozzle to be designed and fabricated was a converging nozzle. In this case the objective was to expand the power jet a minimum amount and reduce the problem of pressure recovery. Pressure profiles and Schlerin photographs showed that stream integrity could not be retained in any one of several configurations of this type with the supply pressure above 330 psi (which provides an exit pressure of 175 psi). The results are given in Table I, Experimental Valve No. 1. (See Fig. 5.)

In view of this, a valve was designed using a supersonic nozzle expanded to 175 psi exit pressure. The valve was provided with movable walls in the receiver section which allowed such parameters as divergent angle, setback, and control port cross sectional area to be varied. The unit was tested using compressed air while varying all parameters possible with the setup.

The highest source pressure that could be controlled was 600 psi which gave a nozzle exit pressure of 104 psia. The configurations and pressures over which complete switching occurred are shown in Table I, Experimental Valve No. S-1.

Utilizing the high velocity and low pressure available from this valve, efforts were made to recover pressure utilizing various supersonic diffuser configurations. It was learned that pressure recovery efficiencies were less than 10%, and thus it was decided to abandon the approach which would recover the source pressure after it had been valved and re-expand it through a supersonic nozzle at the skin of the missile. A new approach was selected which would retain the high velocities obtained when expanding the source pressure through the nozzle of the valve and use its momentum as it was exhausted at the skin of the missile to develop the required side forces. All work since that time has utilized this approach.

Thus the primary objective became the development of a technique which would allow control of the power jet at an upstream pressure of 1000 psi. Previous experiments had indicated that the switching problem was less severe as the exit pressure of the power jet decreased. It was decided therefore to design and fabricate a valve whose power jet was expanded to 27 psia with a source pressure of 1000 psi. The receiver section of this valve was as described in Table I, Experimental Valves 2 and 3. It can be seen that satisfactory switching was accomplished up to 800 psi with a splitter (the point of separation between the exit ports of the receiver section) installed.

The next nozzle design further reduced the exit pressure to 14.7 psia. The receiver section of this valve was provided with movable walls which allowed the setback, divergent angle, and control port area to be varied. The configurations used and results obtained are shown in Table I, Experimental Valve No. 4.

The encouraging results obtained at 14.7 psia exit pressure prompted the design of a valve with a nozzle exit pressure of 10 psia. A description of this valve is given in Table I, Experimental Valve No. 5, along with results achieved with various splitters installed and also with an exhaust manifold which turned the controlled stream 90° to the longitudinal axis of the valve in either of two opposite directions. Extensive testing of this valve, using an electromagnetic actuator to open and close the control ports, showed that it would switch reliably at rates up to 50 cps. This was the upper limit of the frequency response of the actuator, not of the valve itself.

Utilizing the parameters established on the cold air tests three hot gas valves were designed and fabricated utilizing 303 and 347 stainless steel. A description of these valves is given in Table II, valves 1, 2, and 3 with results obtained on each. No sign of erosion was observed on any of these valves after seven 10-second hot gas tests except for the splitter. This usually had to be replaced if the valve failed to switch properly and allowed the hot gas to impinge directly on the splitter for the full duration of the test. The instrumentation setup used on hot gas tests is shown in Figure 6.

A problem was encountered with the stainless steel, however, in that measurements taken on the valve after each hot gas test showed that the throat had closed down in width during or after the test, sometimes by as much as .005 inch. This was attributed to warpage of the valve body which occurred as the metal stress relieved itself on cooling after the test. Since the condition which existed upon inspection after cooling would have permitted leakage around the nozzle during the test and no leakage was apparent, it was assumed that the warpage occurred after the test was completed. This problem was solved by having the throat machined to its original size after each test and having the two mating surfaces of the valve body lapped to re-establish a tight seal about the nozzle.

The first three valves fabricated permitted flow rates of .085 lb/sec (1) and .16 lb/sec (2). At this time the control force requirements were given as 21 pounds for yaw, 18 pounds for pitch, and 12 pounds for roll. A total of 3.9 lbs of propellant was available for the 10-second flight time allowing .39 pounds of mass flow per second through the three control valves. Thus the .085 lb/sec flow rate was designed with the roll requirement in mind and the .16 lb/sec flow rate valves were designed with the yaw requirements in mind. The flow allowable for pitch control was .145 lb/sec. Dimensional imperfections of the fabricated hardware sometimes caused the flow rates to vary from the design value.

Hot gas valve No. 4 was designed to flow .145 lb/sec of MDB-7 gas with an upstream pressure of 1000 psi at 2350°F. In the interest of reducing the total length of the valve the divergent angle of the receiver section was increased from 15° to 23½°. It was determined that this angle was such that wall attachment of the power jet could not be effected with the control port size used, and the design was dropped after the first hot gas test. A description of the valve is given in Table II.

Valve number 5 was the second valve designed to flow at .145 lb/sec. A description of this valve and its performance is also given in Table II. Test results on compressed air and hot gas indicated that the configurations used on valve numbers 1, 3, and 5 were satisfactory from the standpoint of reliable control of the hot gas stream into single and dual-channel exit manifolds. Hot gas tests numbers 9 and 10 also revealed that the side forces being obtained were not satisfactory and work was concentrated in this area. Cold gas tests of all the supersonic nozzles used previously were run to establish the thrust efficiency of each. These showed that their efficiencies were on the order of 75 percent, which indicated a need to improve the nozzle efficiency of the valve to increase the side force.

As can be seen in the description of the valve designs, up to this point in the program all nozzles were expanding the power jet in two dimensions with a vertical offset of about .007 inch at the exit section of the nozzle. Several "cut and try" methods were used in an effort to improve the nozzle efficiency. Table II describes a design, valve numbers BLs1 and BLs2, which showed promise on cold air but failed to perform satisfactorily on hot gas. The failure was attributed to thermal expansion of the nozzle walls which caused the flow rate to decrease sharply.

Recognizing that maximum efficiency should be obtained from a three-dimensional nozzle, a two-dimensional design with an aspect ratio of 1:1 at the throat was designed so that three-dimensional expansion could be approached as much as possible with a two-dimensional configuration. A description of valve design (#7) and the results of its tests are given in Table III. This valve yielded measured side forces on test numbers 21 and 24 which were satisfactory for the requirements of SHILLELAGH in pitch and yaw, with excellent switching being observed.

The encouraging results obtained on this valve prompted a new design, termed 10-A (see Fig. 7) which utilized a three-dimensional expansion into a two-dimensional receiver section. This valve design and its test results are given in Table III. The valve was fabricated using stainless steel for the nozzle, aluminum for the receiver section, and a stainless steel splitter. Copper tubing and machined aluminum were used to duct the flow to exhaust 90° from the longitudinal axis of the valve. No signs of erosion or significant dimensional changes appeared after six hot gas tests of 10 seconds duration each.

The purpose of this new design was to simplify the nozzle and thus reduce fabrication costs. As can be seen from Table III, test number 22 with more optimum duct work yielded side forces up to 19.3 pounds with excellent switching characteristics. The efficiency of this valve at the temperature and pressures existing during the test was as high as 75% of the maximum, assuming idealized no-loss flow through a perfectly expanded nozzle.

As previously explained, control of the valve is effected by opening one port to the atmosphere and closing the other. To accomplish this a low power electromechanical actuator has been devised. A special innovation has been included in the design to allow lower electrical power requirements. The actuator (see Fig. 8) is a two-pole circular magnetic circuit with a flapper arm suspended between the poles. Upon the application of the DC current to one of the coils, the flapper is pulled to that pole face causing the opposite end to seal one of the actuator control ports. Attached to the center of the port hole is a piston applying an opposing force to the magnetic pull and vacuum generated by the switching pressure at that point. The piston is energized by the difference in switching pressure and external pressure. When the magnetic circuit is de-energized, the piston force breaks the flapper seal and overcomes any residual magnetism in the magnetic circuit. The opposite coil is energized at the same instant the first coil is de-energized providing an additional force to move the actuator to its new position. Since the switching pressure does not exist except when the control port is energized, small magnetic force is required to obtain actuator switching and thus a lower power requirements exists than on the jet reaction control package now on the SHILLELAGH system.

Use of this low-power actuator in turn allows considerable economy in the driving circuits. Only medium power transistors are required. The circuit, as adapted from that used to drive the SHILLELAGH valve, is shown in Figure 9. The power supply requirement is approximately 1.5 amperes from the -30v supply, 750 ma from the -10v supply, and 300 ma from the +5v supply.

IV. CONCLUSIONS

The results of this program to date strongly indicate that the availability of a low cost, reliable, light weight, long storage life valve suitable for use with high temperature, high pressure gases is imminent. Measured efficiencies have run as high as 70% of those calculated under ideal lossless conditions or about 80% of the maximum, assuming normal losses.

The inherent simplicity (a block of metal with holes) lends itself to low cost fabrication techniques and assures high reliability and long storage life. Since the technique eliminates much of the extreme conditions of temperature and pressure to velocity, the problem of containing the stream is reduced and overall weight can be reduced by using thinner walls on portions of the valve and the duct work.

The maximum temperature at which the valve can operate has not been established. However, it is felt that since no moving parts are exposed to the power jet stream the materials problem will be similar to that existing in a rocket thrust nozzle. By permitting the use of higher temperature gas generators in applications such as SHILLELAGH, significant advantages are possible in weight savings, reduction in solid exhaust products, extension of range, and other areas.

The high efficiencies that have been measured were achieved using duct work through which the high velocity gases are exhausted perpendicular to the center line of the valve through a turning radius of from 0.75 inch to 1.25 inches at lengths up to 4 inches. Efficiencies will, of course, be greatly affected by the manner in which the supersonic power jet stream is ducted to the missile surface. If optimum use is to be made of this valve in the SHILLELAGH Missile, it will be necessary to locate it in such a manner as to reduce the pipe length as well as the number and radius of turns in the exhaust ductwork. Design work is proceeding with the expectation of flight tests in the middle of 1963.

With the possibility of much of the onboard electronic circuits and sensors being replaced by pneumatic elements in future systems a valve of this general type would be able to accept the outputs of these elements through a pneumatic preamplifier or perhaps directly. Many other uses suggest themselves, including the control of secondary flow in systems which utilize the principle of thrust vector control by secondary injection. In particular a secondary injection system using direct bleed gases from the main propulsion system could benefit greatly by application of this valving technique since progress toward direct bleed secondary injection has been slow because of the nonavailability of a suitable hot gas valve.

Although much encouraging data has been derived from this program a great deal of work has yet to be done, particularly toward the completion of a valid theoretical explanation of the phenomena which occur.

Table I. - EXPERIMENTAL COLD GAS VALVES

Experi-mental valve No.	Test No.	Supply pres-sure, psi	Exhaust pres-sure, psia	Nozzle div ½ angle, deg	Nozzle throat aspect R	Nozzle exit aspect R	Nozzle exit (in^2) area	Control port-area exit area	Setback, in.	Offset, in.	Receive wall ½ angle, deg	Receiver wall length, in.	Dist to splitter, in.	Remarks
S-1	1	125-375	22-65	15	.7	.7	.01	1.3	.2		15	3	.275	Sharp splitter switching range 125-375 psi
	2	125-375	22-65	15	.7	.7	.01	1.3	.2		15	3	None	No splitter switching range 125-375 psi
	3	125-375	22-65	15	.7	.7	.01	1.3	.25		15	3	None	No splitter switching range 125-375 psi
	4	125-600	22-104	15	.7	.7	.01	1.9	.25		15	3	None	No splitter switching range 125-600 psi
	5	125-375	22-65	15	.7	.7	.01	1.7	.25		15	3	None	No splitter switching range 125-375 psi
	6	125-600	22-104	15	.7	.7	.01	2.9	.32		25	3	None	No splitter switching range 125-600 psi
	7	No switch	22-104	15	.7	.7	.01	2.9	.32		25	3	1.45	Sharp splitter, no switching
1	1	0-1000	0-528	None	8:1	8:1	.0069							No satisfactory results were obtained
2	1	0-1000	0-27	15	8:1	2:1	.0135	2	.084	0	15	.75	None	Switching, stream width unsatisfactory
3	1	0-1000	0-27	7½	8:1	2:1	.0135	2	.084	0	15	1.5	1.3	Good to 800 psia
4	1	0-1000	0-14.7	7½	8:1	2:1	.0428	1.5	1N*	0	22.5	1.5	None	Switching unsatisfactory
	2	0-1000	0-14.7	7½	8:1	2:1	.0428	1.5	½N	0	22.5	1.5	None	Switching 500-750 psia
	3	0-1000	0-14.7	7½	8:1	2:1	.0428	1.0	¼N	0	22.5	1.5	None	Switching 900-1000 psia
	4	0-1000	0-14.7	7½	8:1	2:1	.0428	1.5	0N	0	22.5	1.5	None	Switching 500-1000 psia
	5	0-1000	0-14.7	7½	8:1	2:1	.0428	1.5	2N	0	15	1.5	None	Switching unsatisfactory
	6	0-1000	0-14.7	7½	8:1	2:1	.0428	1.5	1½N	0	15	1.5	None	Switching unsatisfactory
	7	0-1000	0-14.7	7½	8:1	2:1	.0428	1.5	½N	0	15	1.5	None	Switching 500-1000 psia
	8	0-1000	0-14.7	7½	8:1	2:1	.0428	1	0N	0	7½	1.5	None	Switching unsatisfactory
	9	0-1000	0-14.7	7½	8:1	2:1	.0428	1	½N	0	7½	1.5	None	Switching good except 900-1000 psia
	10	0-1000	0-14.7	7½	8:1	2:1	.0428	1	1N	0	7½	1.5	None	Switching good except 900-1000 psia
	11	0-1000	0-14.7	7½	8:1	2:1	.0428	1.5	1½N	0	7½	1.5	None	Switching good except 900-1000 psia
	12	0-1000	0-14.7	7½	8:1	2:1	.0428	1.5	2N	0	7½	1.5	None	Switching good
	13	0-1000	0-14.7	7½	8:1	2:1	.0428	1.5	2½N	0	7½	1.5	None	Unsatisfactory
5	1	0-1100	0-10	7½	8:1	1.74:1	.0555	1.25	.1	.07	15	1.5	1.30	.06 convex splitter switching 850-1100 psia
	2	0-1100	0-10	7½	8:1	1.74:1	.0555	1.25	.1	.07	15	1.5	1.33	.07 concave splitter switching 750 psia
	3	0-1100	0-10	7½	8:1	1.74:1	.0555	1.25	.1	.07	15	1.5	1.37	.12 concave splitter no switching
	4	0-1100	0-10	7½	8:1	1.74:1	.0555	1.25	.1	.07	15	1.5	1.20	.09 convex splitter switching 750-1100 psia
	5	0-1100	0-10	7½	8:1	1.74:1	.0555	1.25	.1	.07	15	1.5	1.00	.07 concave splitter switching 750-1000
	6	0-1100	0-10	7½	8:1	1.74:1	.0555	1.25	.1	.07	15	1.5	1.30	.06 convex splitter switching 700-800 psia
	7	0-1100	0-10	7½	8:1	1.74:1	.0555	1.25	.1	.07	15	1.5	1.33	.07 concave splitter switching 850-1050
	8	0-1100	0-10	7½	8:1	1.74:1	.0555	1.25	.1	.07	15	1.5	1.37	.12 concave splitter switching 1025-1100
	9	0-1100	0-10	7½	8:1	1.74:1	.0555	1.25	.1	.07	15	1.5	1.20	.09 convex splitter no switching
	10	0-1100	0-10	7½	8:1	1.74:1	.0555	1.25	.1	.07	15	1.5	1.00	.07 concave splitter switching 850-900

Experimental nozzle No. 5, tests 6 through 10 were conducted with .51 ID manifold and were used as a model for further work.
*N is width of nozzle at exit section.

Table 11. - HOT GAS VALVES (1 THROUGH 5, BLs1, BLs2)

Valve No.	Test No.	Flow rate, lb/sec	Exit pressure, psia	Nozzle half angle, deg	Exit aspect ratio	Vertical offset, in.	Control port dia, in.	Control port width, in.	Setback, in.	Wall half angle, deg	Distance nozzle to splitter, in.	Pipe size, in.	Switching	Gas pressure range, psi	Gas temperature range, deg F	Range on air, psi	Throat area, in.^{2}	No. of pipes	Sp dia, in.	Force R of pipes, lb	Throat aspect ratio
1	1	.085	10	10	1.74:1	.141	.212	.08	.11	15	1.3	N/A	Some	875/920	2100/2300			N/A	.045		
	2	.085	10	10	1.74:1	.141	.212	.08	.11	15	1.3	.625	None	910/1075	2200/2330			2	.070		
	3	.085	10	10	1.74:1	.141	.212	.08	.11	15	1.3	.625	Good	1010/2495	2355/			2	.045		
	4	.085	10	10	1.74:1	.141	.212	.08	.11	15	1.3	.625		822/687	1050/800			2	.045		
	5	.085	10	10	1.74:1	.141	.30	.15	.06/.07	15	1.3	.53	Poor	860/965	1980/8790		.01054	2	.045		
	6	.086	10	10	1.74:1	.141	.30	.15	.093/.089	15	1.3	.625	Good, Sk	865/925	2030/2245	900 1050	.01054	2	.045		
	7	.086	10	10	1.74:1	.141	.30	.15	.065/.065	15	1.3	.625	Exc	825/895	N/A		.01023	2	.045		
2	1	.16	10	7½	1.74:1	.070	.30	.15	.10	16½	1.3	.73	Some	875/920	2100/2320			2	.090		
	2	.16	10	7½	1.74:1	.070	.30	.15	.10	16½	1.3	.73	None	910/1075	2200/2330				.070		
	3	.16	10	7½	1.74:1	.070	.30	.15	.10	16½	1.3	.73	None	1010/2495	2355				.045		
	4	.16	10	7½	1.74:1	.070	.30	.15	.10	16½	1.3	.73		687/822	290/1050				.045		
3	1	.16	10	7½	1.74:1	.010	.30	.15	.10	16½	1.3	N/A	Fair	875/920	2100/2320			N/A	.045		
	2	.16	10	7½	1.74:1	.010	.30	.15	.10	16½	1.3	.9	Poor	910/1075	2200/2330			2	.05		
	3	.16	10	7½	1.74:1	.010	.30	.15	.10	16½	1.3	.9	None	1010/2495/	2355				.045		
	4	.16	10	7½	1.74:1	.010	.30	.15	.10	16½	1.3	.9		822/687	890/1050				.045		
	5	.16	10	7½	1.74:1	.010	.348	.15	.063/.071	16½	1.3	.55	Exc	860/965	1980/2270		.01591	4	.045		
	6	.144	10	7½	1.74:1	.010	.348	.15	.063/.073	16½	1.3	.55	Fair	865/925	2030/2205	700 900	.0176	4	.045		
	7	.144	10	7½	1.74:1	.010	.348	.15	.063/.073	16½	1.3	.55	Good	825/985	N/A		.0204	4	.045		
4	5	.1275	7	7½	1.73:1	.076	.348	.15	.10/.11	23	1.3	.74	None	850/065	1980/2290			2	.045		
5	6	.141	7	7½	1.87:1	.076	.35	.137	.11/.116	15	1.3	.73	None	865/925	2030/2205	900 1000	.0157	2	.045		
	7	.141	7	7½	1.85:1	.076	.35	.137	.063/.067	15	1.3	.5	Good	885/895	N/A	750 1150	.01656	4	.045		
	8	.141	7	7½	1.87:1	.076	.35	.137	.063/.067	15	1.3	.45	N/A	835/905	2225/2375	750 1000	.0168	4	.045		
	9	.141	7	7½	1.87:1	.076	.35	.137	.063/.067	15	1.3	.45	Exc	860/975	2060/2330	950 1100	.0154	4	.045	S(a) 14.5-9	
	10	.141	7	7½	1.87:1	.076	.35	.137	.063/.067	15	1.3	N/A	N/A	825/890	2400	950 1100	.0161	N/A	None	T(b) 15.8-10	
BLs1	11	.085	7	7½	2.48:1	None	.3	.11	.10	15	.8	.4 x.75	Good	900/1040	2080/2290			2	.045	S 8.2.3-.9	53:1
	12	.085	7	7½	2.48:1	None	.3	.11	.10	15	.8	.4 x.75	Exc	885/975	2180/2105					S 9.5-2.9	53:1
BLs2	15	.0975	7	7½	2.48:1	None	.35	.13	.07	15	N/A	None	N/A	860/940	1810/2100			None	None	T 14-B.5	

a - "S" is force 90° from nozzle centerline.
b - T is force along nozzle centerline.

Table III. - HOT GAS VALVES (7, MOLY 1, 10-A, 87)

Valve No.	Test No.	Flow rate	Pe, psia	Exit as-pect ratio	Verti-cal off-set, in.	Con-trol off-set, in.	Con-trol port dia, in.	Set-back, in.	Wall half angle, deg	Distance nozzle to splitter, in.	Pipe size, in.	Switch-ing	Gas pres-sure range, dsi	Gas temper-ture range, deg F	Switching range on air, psi	No. of pipes	Splitter diameter, in.	Force, lb	R of pipes	Nozzle half angle, deg
7	13	.146	7	1.42:1	.04	.35	.15	.07	15	1.45	None	N/A	875/885	1230/1630		None	None	T[a] 20.7-20.4		10
	14	.146	7	1.42:1	.04	.35	.15	.07	15	1.45	.750	Fair	875/885	2310/2390		2	.045	S[b] 16.9-12.6		10
	17	.146	7	1.42:1	.04	.35	.15	.07	15	1.45	.75D	Fair	860/990	2150/2290		2	.045	S 16.5-15		10
	21	.146	7	1.42:1	.04	.35	.15	.10	15	2.05	.75x.65	Exc	897	1428	200-500 800	2	N/A	S 18.17		10
	28	.146	7	1.42:1	.04	.35	.15	.10	15	2.05	Cu.550^{Z}	Exc	880/920	2180/2370	500 1000	4	Shp	S 14-.5	$\frac{3}{4}$	10
	24	.146	7	1.42:1	.04	.35	.15	.10	15	2.05	.75x.65	Exc	793/965	N/A		2	Shp	S 18.3-17.1	3.15	10
Moly 1	16	.0975	7	3.9:1	.042	.437	.185	.075	15	$1\frac{3}{8}$	None	N/A	860/940	1650/2150		None	N/A	T 13.3-11.5		12
	20	.0975	7	3.9:1	.042	.437	.185	.090	15	$1\frac{3}{8}$	.87x.53	Exc	525/982	392/2937	250 1300	2	N/A	S[c] 28-6.2		12
	25	.0975	7	3.9:1	.042	.437	.185	.090	15	$1\frac{3}{8}$	.87x.53	Exc	640/1042	2275/2513	500 1300	2	.040	10.9-8.5	1.20	12
10-A	18	.146	7	R	None	.39	.25	.070	15	2.05	.8x.55	Exc	870/940	2030/2260		2	.045	S 16.5-15.1		10
	19	.146	7	R	None	.39	.25	.070	15	2.05	.95x.55	Exc	900/960	N/A		2	.045	S 16.4-14.6		10
	22	.146	7	R	None	.39	.25	.090	15	2.05	.750D	Exc	870/970	500 1300		2	Shp	S 19.3-17		10
	23	.146	7	R	None	.39	.25	.090	15	2.05	.550D	Q	712/975	N/A		4	Shp	S 16.6-1.4	$\frac{3}{4}$	10
	27	.146	7	R	None	.39	.25	.090	15	2.05	.5500	Exc	813/923	165/1892	500 900	4	Shp	S 14.7-1.5	$\frac{3}{4}$	10
	29	.146	7	R	None	.39	.25	.090	15	2.05	SS 0.50D				200 800	4	Shp		$3\frac{1}{2}$	10
87	26	.0875	7	Rd	None	.3	.17	.090	15	1.65	.63D	Exc	610/1005	2090/2350	600 1100	2	Shp	S 11.9-10.4	1	10

(a) Thrust along center line.
(b) Side force perpendicular to center line.
(c) Thermocouple blew out on side of manifold giving high side force.

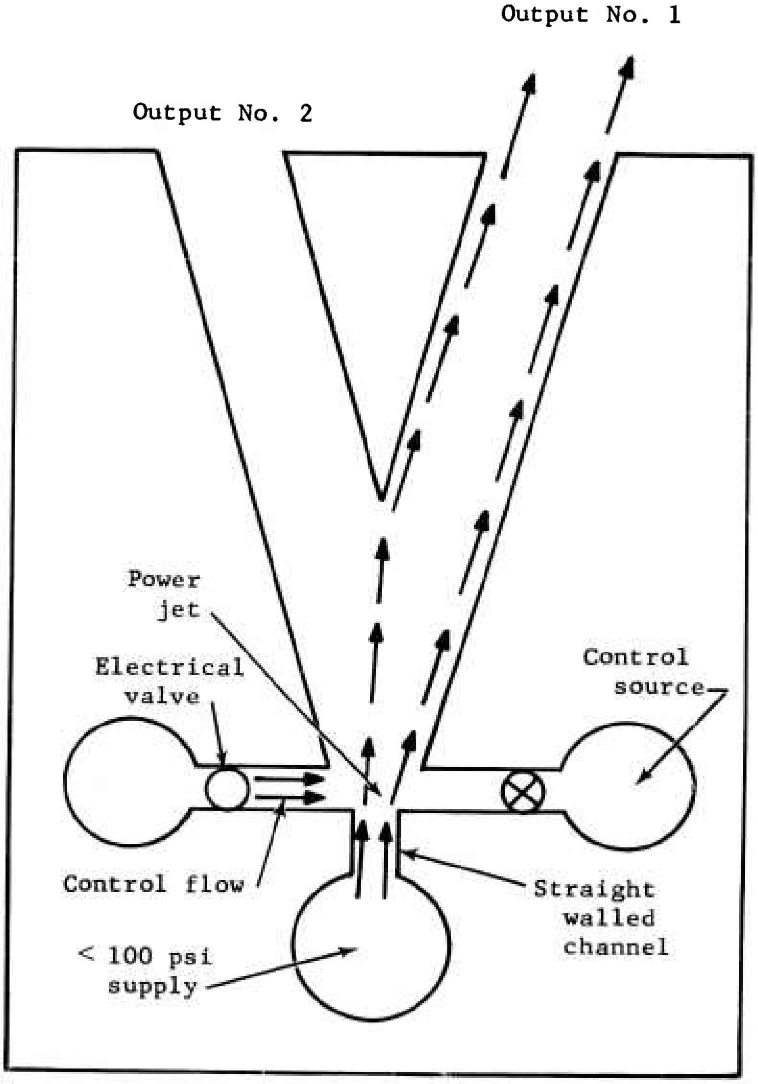
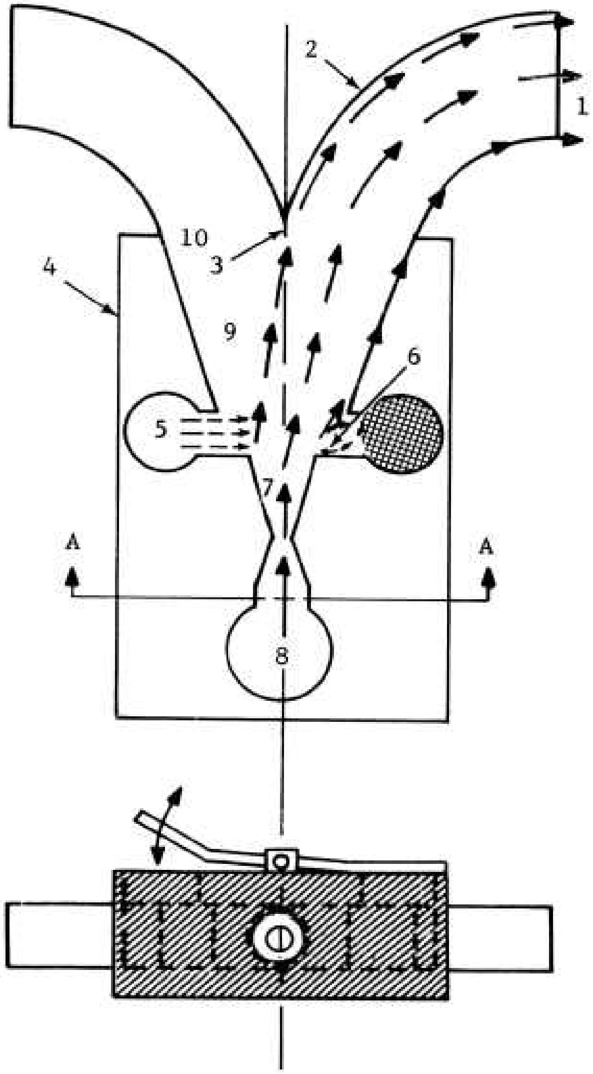


Figure 1. FLUID-CONTROLLED BI-STABLE AMPLIFIER



1	Output
2	Ducting
3	Splitter
4	Valve body
5	Control
6	Low pressure bubble
7	Power jet
8	Power supply
9	Receiver section
10	Exit channels

Figure 2. USAMICOM VALVE (CROSS SECTIONAL VIEWS)

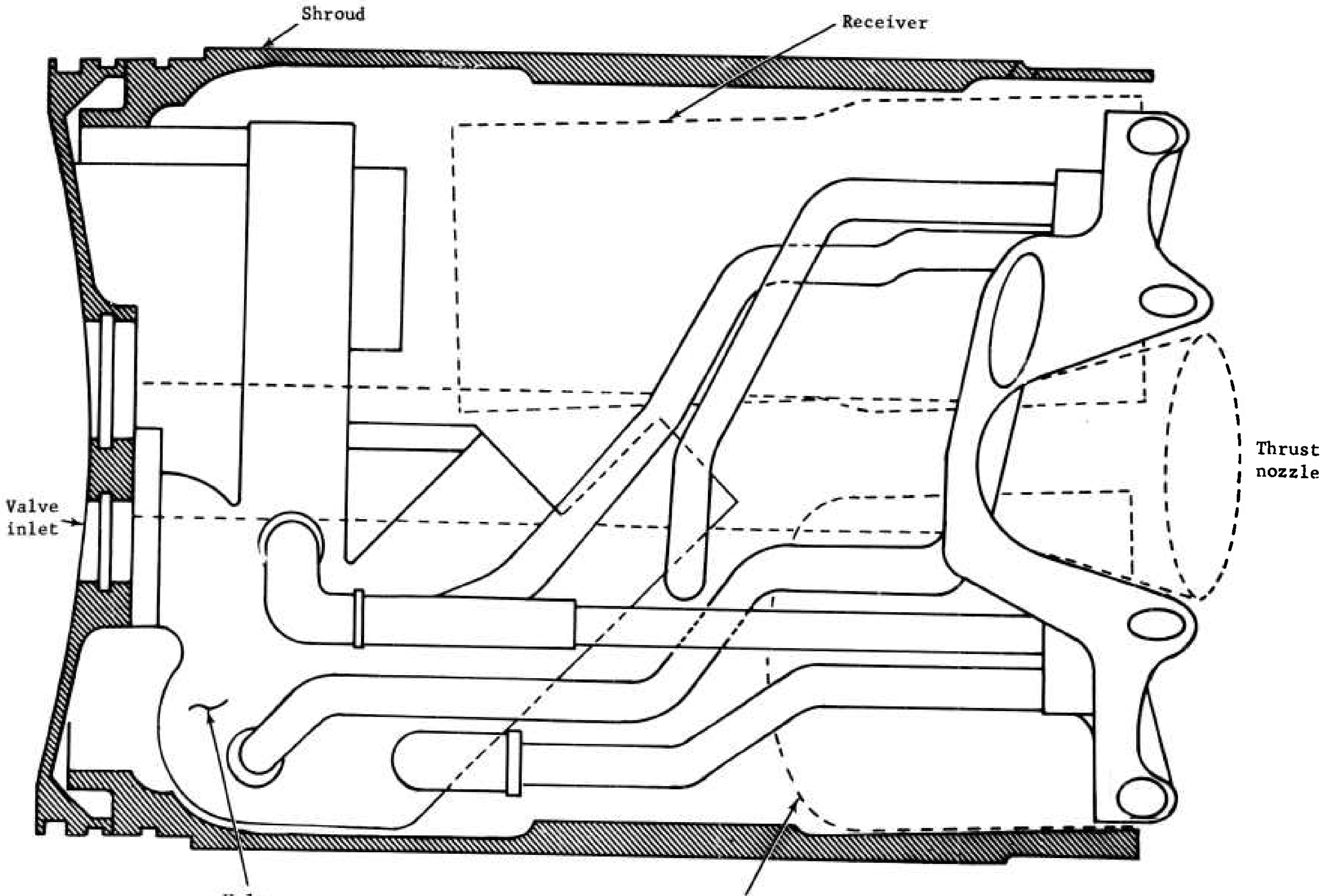


Figure 3. SHILLELAGH AFT SECTION SIDE VIEW

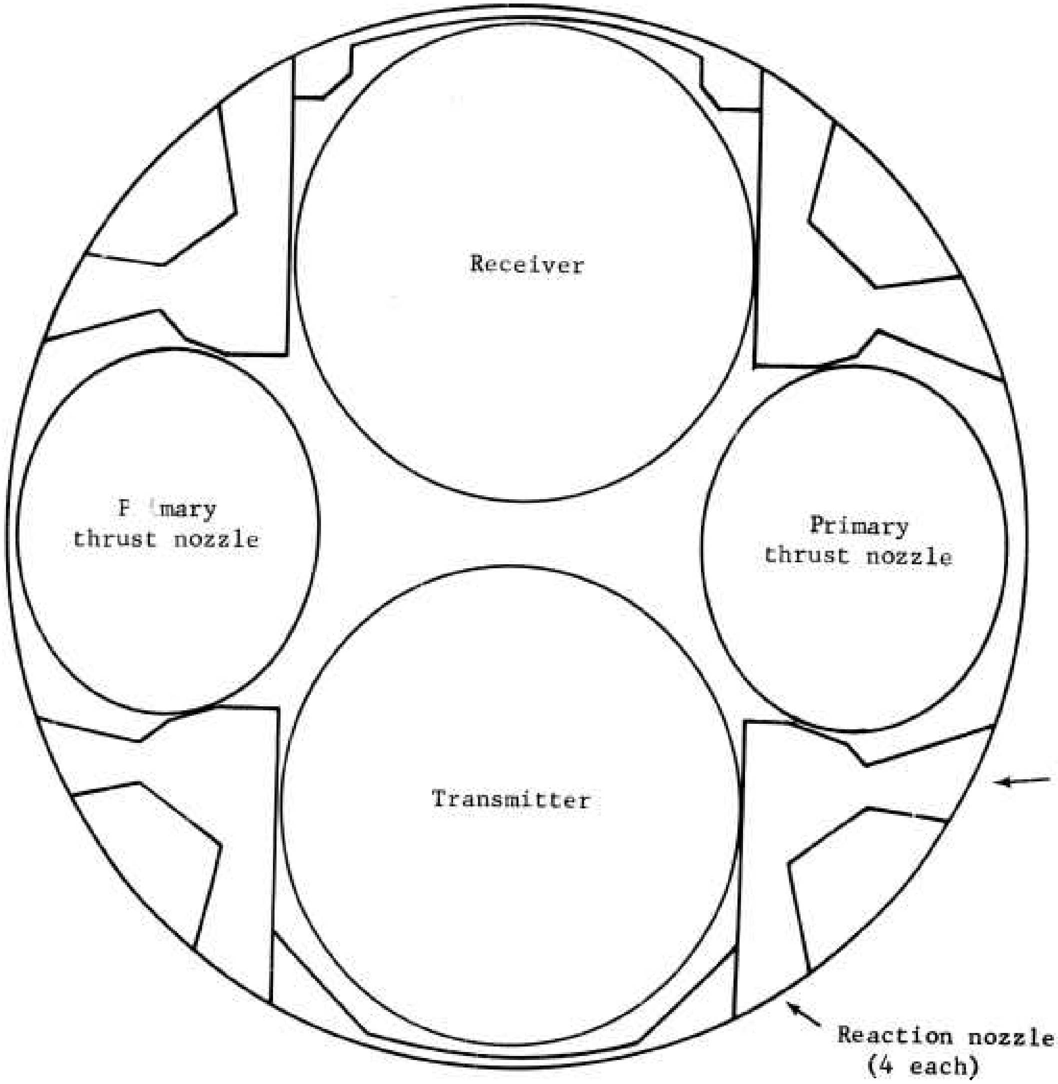
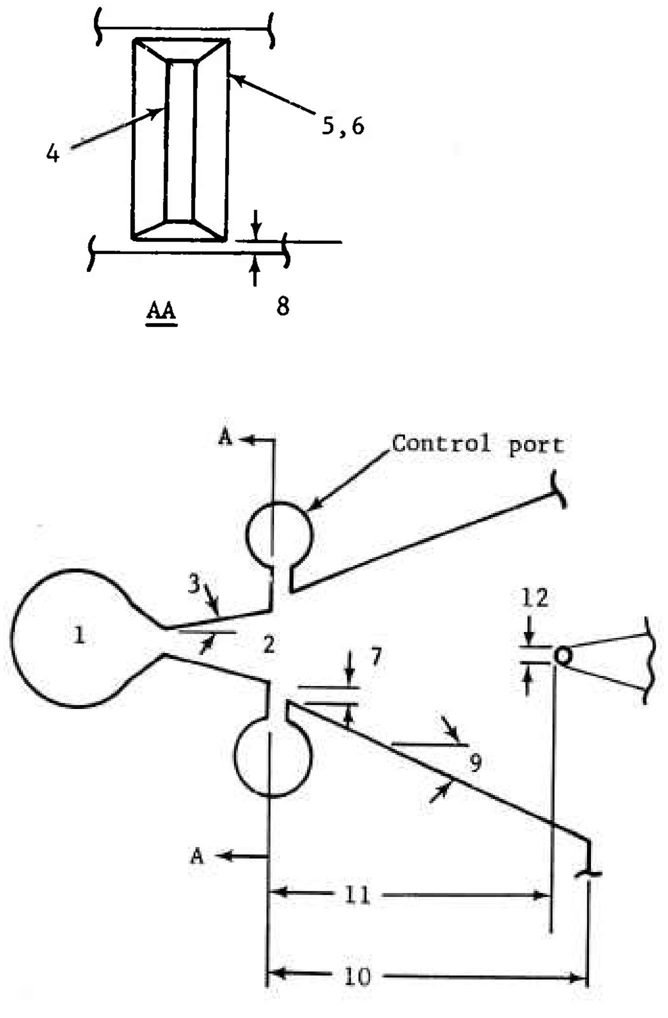


Figure 4. SHILLELAGH AFT SECTION - REAR VIEW



1. Supply pressure
2. Nozzle exit pressure
3. Nozzle divergence ½ angle
4. Nozzle throat aspect ratio
5. Nozzle exit aspect ratio
6. Nozzle exit area
7. Set-back
8. Offset
9. Receiver wall ½ angle
10. Receiver wall length
11. Distance to splitter
12. Concave or convex splitter dimension

Figure 5. VARIABLE PARAMETERS ON EXPERIMENTAL VALVE

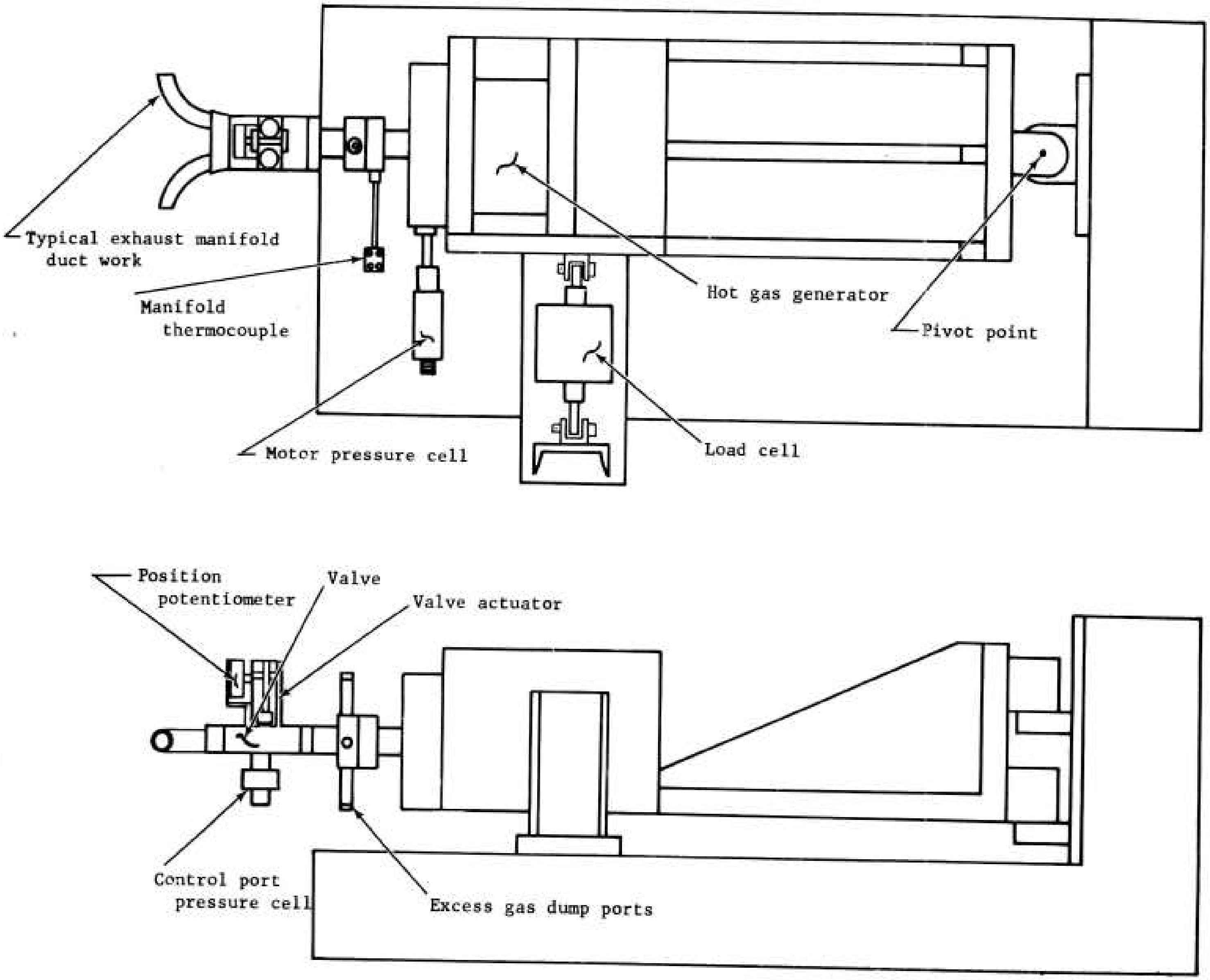


Figure 6. INSTRUMENTATION SETUP FOR USAMICOM VALVE

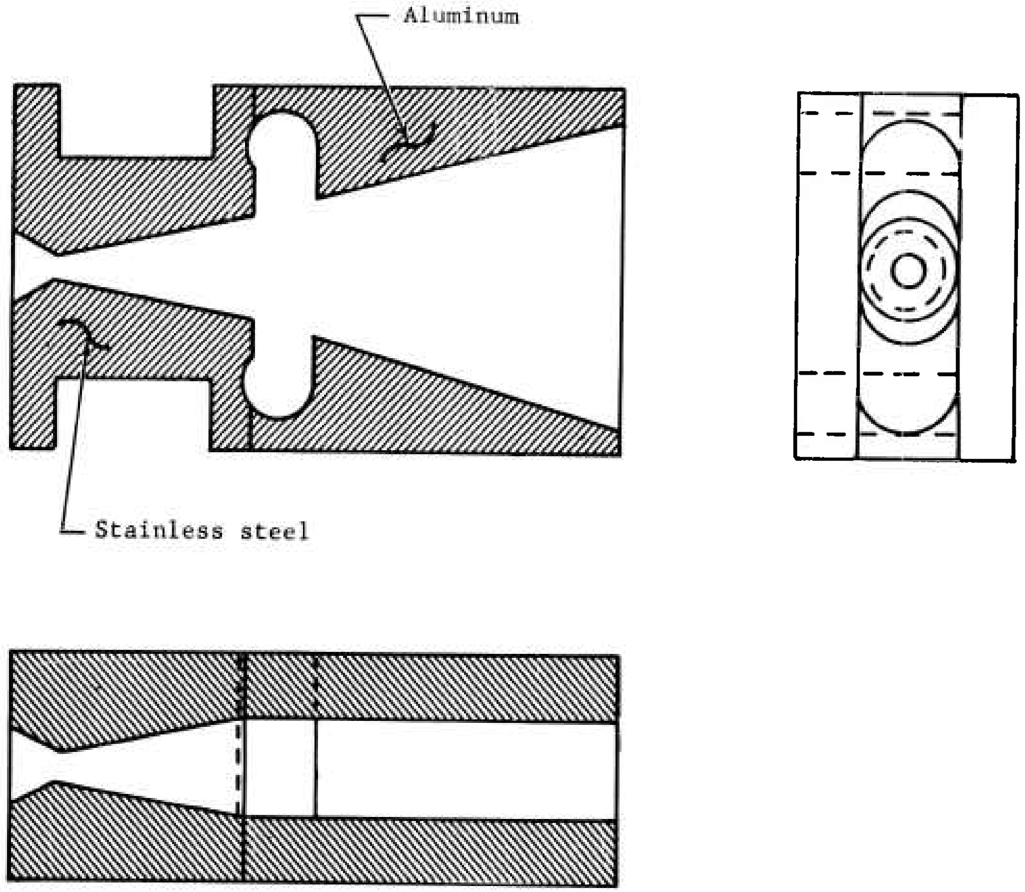
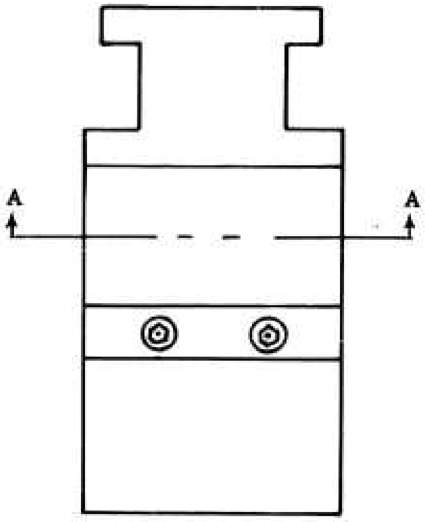
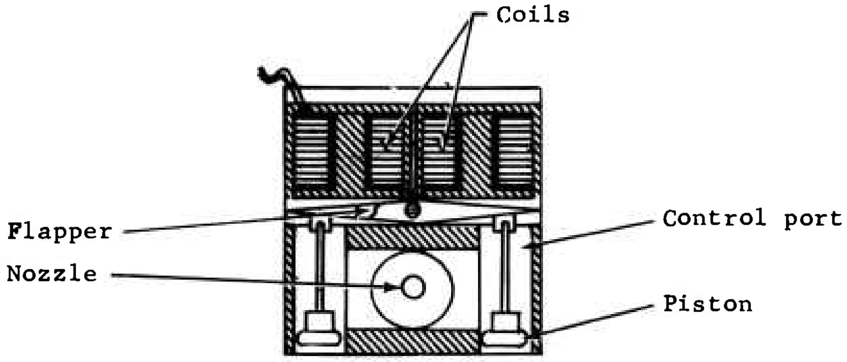


Figure 7. VALVE 10-A





A - A

Figure 8. VALVE ACTUATOR

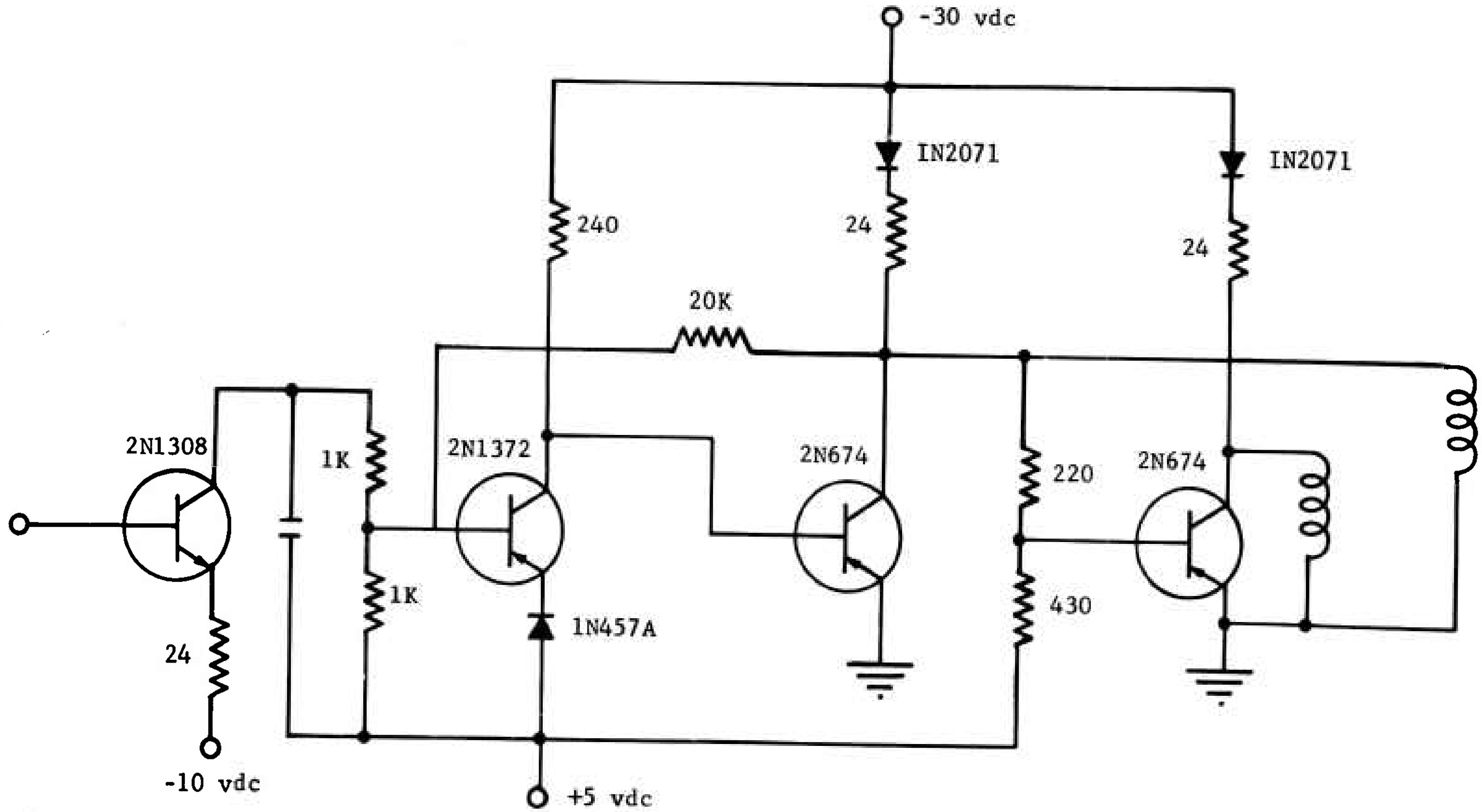


Figure 9. ACTUATOR DRIVING CIRCUIT

31 December 1962 Report No. RE-TR-62-9

APPROVED:

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