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Quarterly Report

DESIGN, FABRICATION AND TEST OF A FLUERIC SERVOVALVE

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ABSTRACT

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The design of a breadboard model of a pneumatic-input flueric servovalve, which operates without moving parts, was completed. Developmental tests of the pilot stage components were completed and tests of the power stage are nearing completion. The tests were conducted using nitrogen and hydrogen as the working fluid. The servovalve is designed to operate with H_2 at temperatures from 56°K (100°R) to 333°K (600°R), supply pressure of 148 N/cm^{2}a (215 psia), exhaust pressure of 34.5 N/cm^{2}a (50 psia), and maximum control pressure of 48.5 N/cm^{2}a (70.4 psia). This report presents the results of tests performed during the second three-month period of the program.

author

SECTION 1

INTRODUCTION

The objective of this program is to develop a high-performance, pneumatic-input, four-way flueric servovalve with dynamic load pressure feedback. A flueric servovalve has no moving parts and therefore offers advantages in reliability and maintenance, particularly when it must operate in severe environments of nuclear radiation, temperature, shock or vibration.

Earlier flueric servovalve development efforts were presented in NASA report CR-54463, entitled "Design, Fabrication, and Test of a Fluid Interaction Servovalve." As an advancement stemming from that earlier development, the servovalve described in this report achieves higher performance by incorporating regenerative feedback for higher gain, along with dynamic load pressure feedback. The design procedure and a description of the present servovalve was presented in NASA report CR-54783, entitled "Design, Fabrication, and Test of a Flueric Servovalve." A schematic, a photograph (exploded view), and an assembly drawing of the breadboard servovalve are shown in Figures 1-1, 1-2, and 1-3, respectively.

This development effort is divided into two phases. In Phase I, a breadboard model of the servovalve will be designed, fabricated, and tested at room temperature. In Phase II, a prototype servovalve will be designed to fit a flueric position servo for the control drum of a nuclear rocket and will be tested throughout the specified temperature range. This report covers the second calendar quarter of Phase I.

The results of this second quarter effort are summarized in Section 2. Sections 3 and 4 describe test results of the breadboard servovalve components. A prediction of the servovalve performance is given in Section 5. Goals for the next quarter are listed in Section 6, and the specifications of the breadboard servovalve are presented in Appendix A.

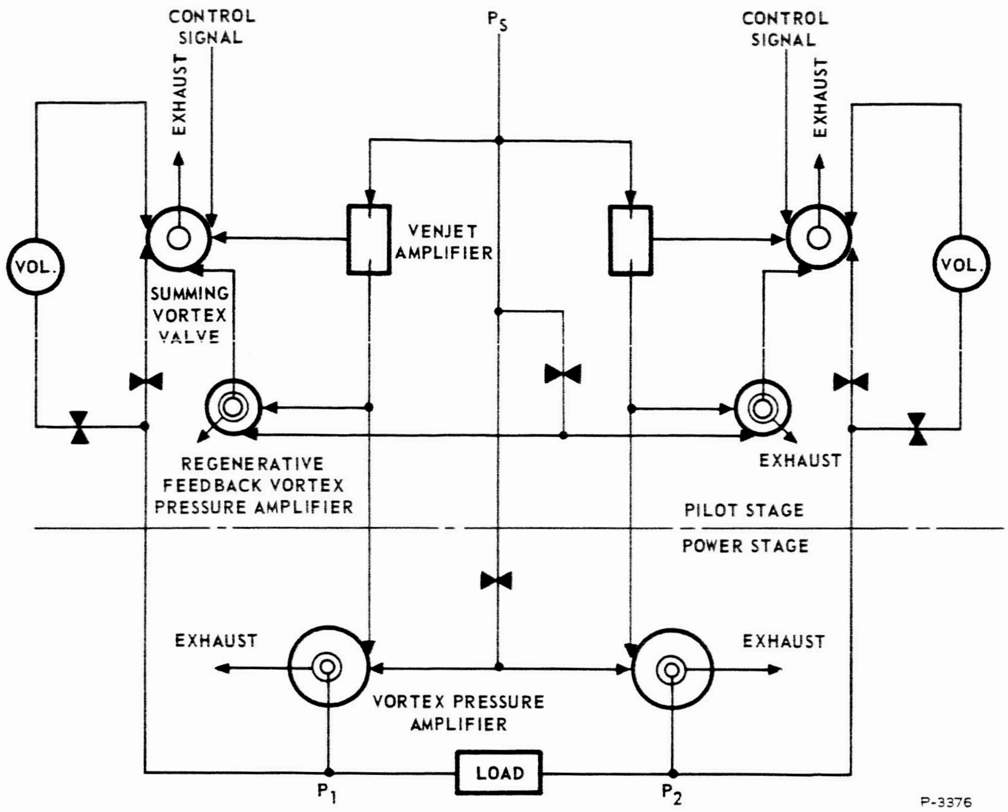

Figure 1-1 - Schematic of Flueric Servovalve

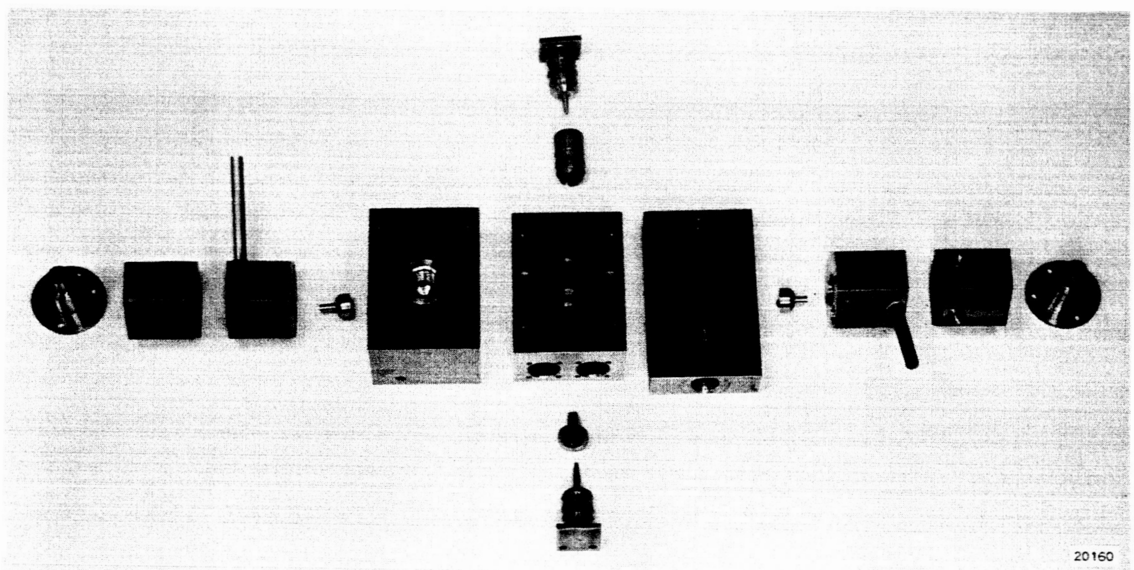

Figure 1-2 - Photograph of Breadboard Servovalve (Exploded View)

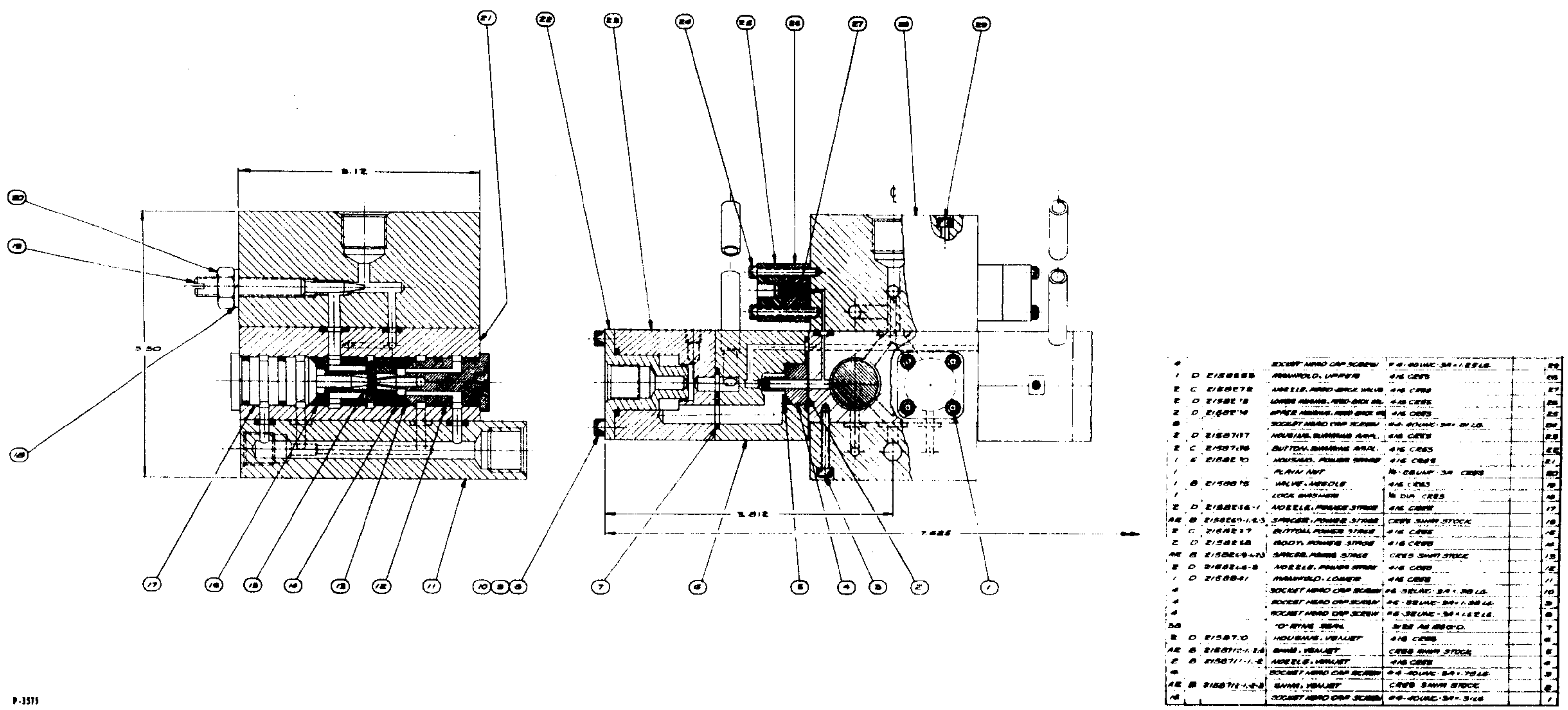

Figure 1-3 - Layout Assembly Drawing of Breadboard Model Flueric Servovalve

SECTION 2

SUMMARY

The servovalve consists of a pilot stage and a power stage. The power stage has two vortex pressure amplifiers* that are operated in push-pull. The pilot stage has two Venjet pressure amplifiers, two summing vortex valves, and two regenerative feedback vortex pressure amplifiers. In addition, dynamic pressure feedback is connected from the load to each summing valve. The output of each Venjet amplifier is the control signal to one of the power stage vortex amplifiers. Each Venjet is controlled by one of the summing vortex valves, which in turn is controlled by an input signal and by the feedbacks.

In the previous quarter, design layout of the servovalve and detail drawings of the Venjet amplifier and summing vortex valve had been completed and one of the Venjet amplifiers had been built. In the present quarter, the remaining detail drawings were completed and all of the breadboard servovalve parts were built, except for one of the two power stage vortex pressure amplifiers.

Developmental tests of the pilot stage components were completed and tests of the power stage are nearing completion. Component geometry and sizes that must be established through actual testing to achieve the desired performance were obtained from room temperature tests, using nitrogen as the working fluid. A Venjet amplifier and a power stage vortex pressure amplifier also were tested with room temperature hydrogen, and it was found that performance characteristics of these components were the same with hydrogen as with nitrogen.

*THE OPERATING PRINCIPLES, TERMINOLOGY, AND SYMBOLOGY OF VORTEX PRESSURE AMPLIFIERS, VORTEX VALVES, AND VENJETS ARE GIVEN IN THE REPORT ENTITLED "DESIGN, FABRICATION, AND TEST OF A FLUID INTERACTION SERVOVALVE", (FINAL REPORT), NASA CR-54463 (N65-31178), MAY 17, 1965. REQUESTS FOR COPIES SHOULD BE REFERRED TO THE FEDERAL SCIENTIFIC AND TECHNICAL INFORMATION OFFICE, PORT ROYAL ROAD, SPRINGFIELD, VIRGINIA 22151. IDENTIFICATION NO. N65-31178, CATEGORY CSCL 13G. TWO DOLLARS FOR FULL-SIZE COPY; FIFTY CENTS FOR MICROFILM COPY.

Developmental testing to eliminate the negative resistance and noise characteristics remain to be completed on the power stage vortex pressure amplifier.

It was found that the turndown ratio of the power stage vortex pressure amplifier is lower than the required value and the effect will be to lower the flow recovery of the servovalve to 0.46 as compared to the specified value of 0.55. The input signal bias pressure will be about 9 percent higher than the specified value. It was concluded from the test results that there should not be a significant difference in the room temperature servovalve performance between using nitrogen or hydrogen as the working fluid.

Goals for the next period include completing the developmental testing of the power stage and servovalve assembly, acceptance testing of the breadboard servovalve and initiation of the design of the prototype servovalve.

SECTION 3

PILOT STAGE TESTS

3.1 VENJET AMPLIFIER TEST

The objectives of the Venjet amplifier tests were to determine the pressure gain characteristics and the maximum pressure and flow recovery. A schematic of the Venjet amplifier is shown in Figure 3-1. The nozzle and receiver diameters are both 0.079 cm (0.031 inch). The distance between the nozzle and receiver is 0.076 cm (0.030 inch).

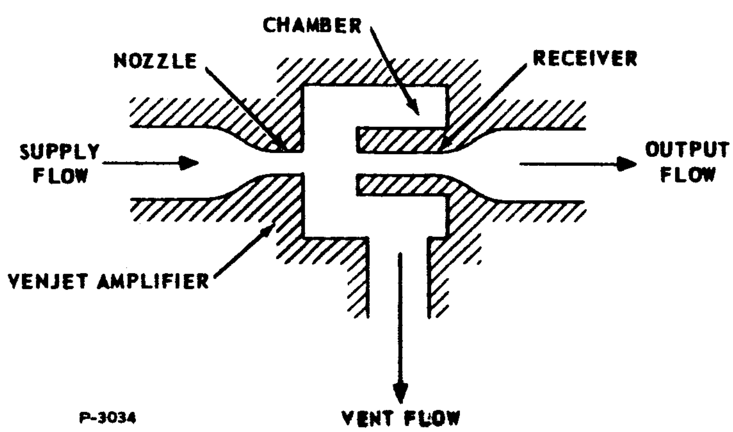

Figure 3-1 - Schematic of Venjet Amplifier

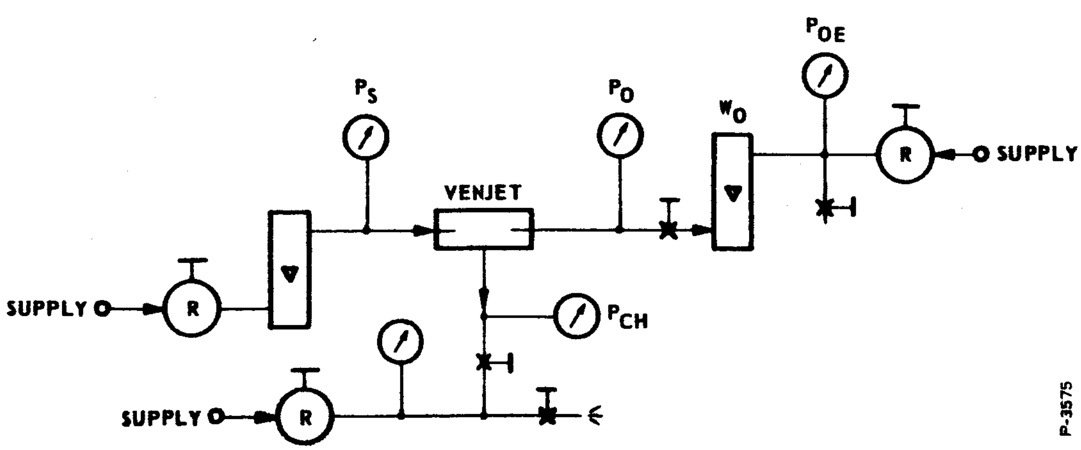

Figure 3-2 - Schematic of Venjet Amplifier Test Setup

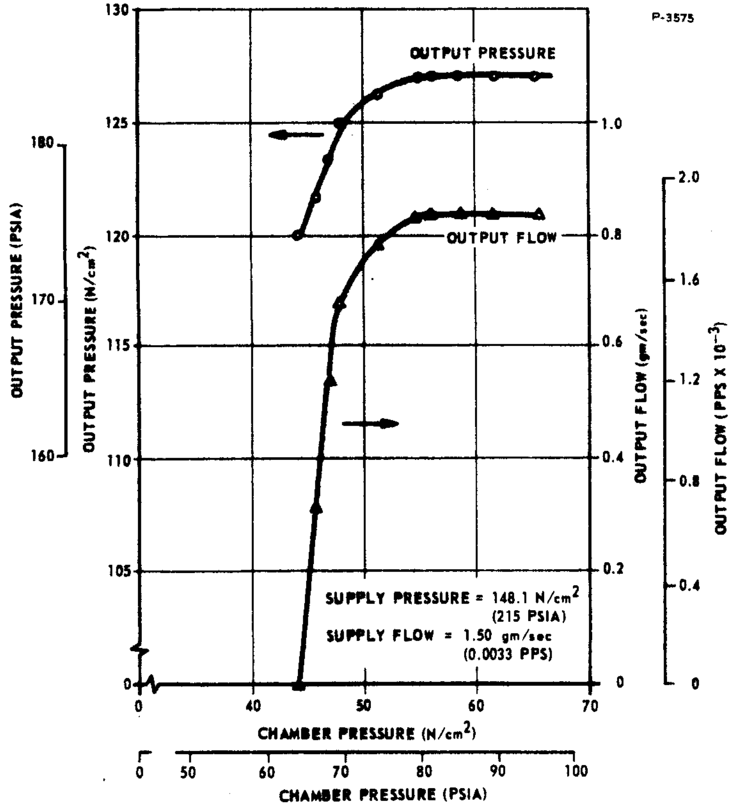

Figure 3-3 - Output Pressure and Flow Versus Chamber Pressure of Venjet Amplifier with Simulated Load

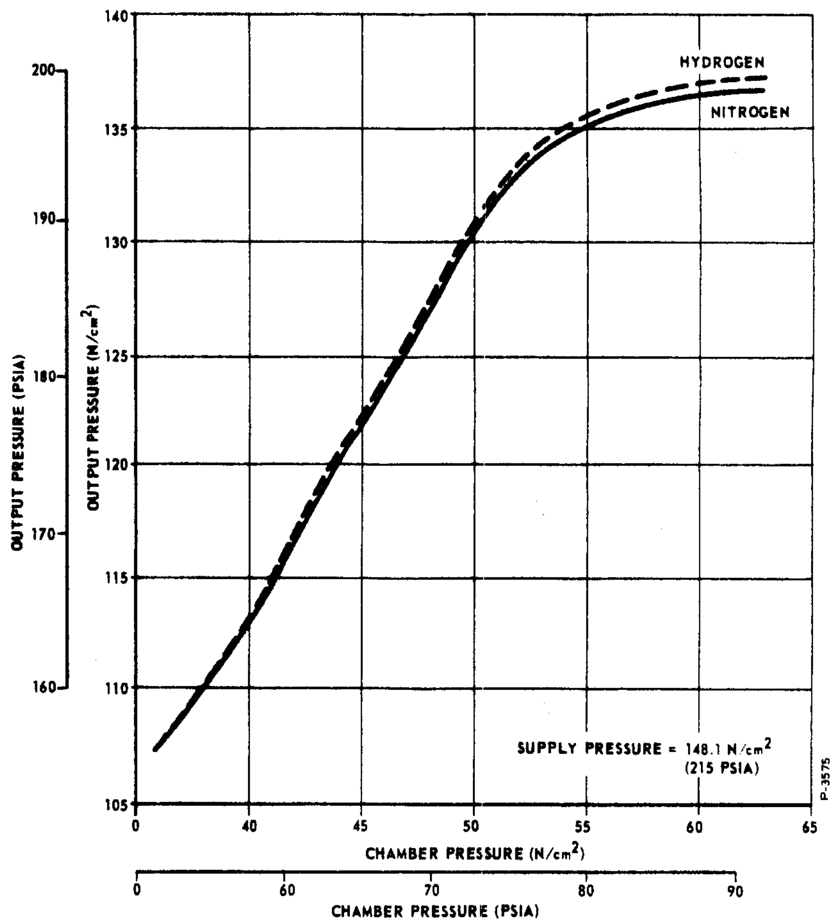

Figure 3-4 - Comparison of Gain Characteristics of Venjet Amplifier with Hydrogen and Nitrogen with Blocked Load

A schematic of the test equipment is shown in Figure 3-2. Flows were measured with float-type flowmeters, and pressures were measured with standard bourdon tube pressure gauges or plotted directly with an X-Y plotter using pressure transducers as inputs. The Venjet was tested at room temperature with both hydrogen and nitrogen. The output pressure and flow characteristics are shown as a function of the chamber pressure in Figure 3-3. The load was an orifice simulating the orifice area of one of the servovalve power stage vortex amplifiers, and the pressure downstream of the load was 120 N/cm^2 (175 psia), which corresponds to the supply pressure of the power stage. The supply pressure to the Venjet was 148.1 N/cm^2 (215 psia). Under the test load condition, the maximum output pressure was 127 N/cm^2 (184 psia) with a flow recovery of 56 percent. The blocked output (zero load flow) versus chamber pressure is shown in Figure 3-4.

This test was performed using both nitrogen and hydrogen. Previous to the performance of this test, it was uncertain whether or not there would be a shift in the output pressure versus chamber pressure curve in changing from nitrogen to hydrogen. The data indicates that there is virtually no difference in performance.

3.2 SUMMING VORTEX VALVE TEST

The primary objective of the summing vortex valve test was to determine the turndown ratio. A schematic of the valve is shown in Figure 3-5.

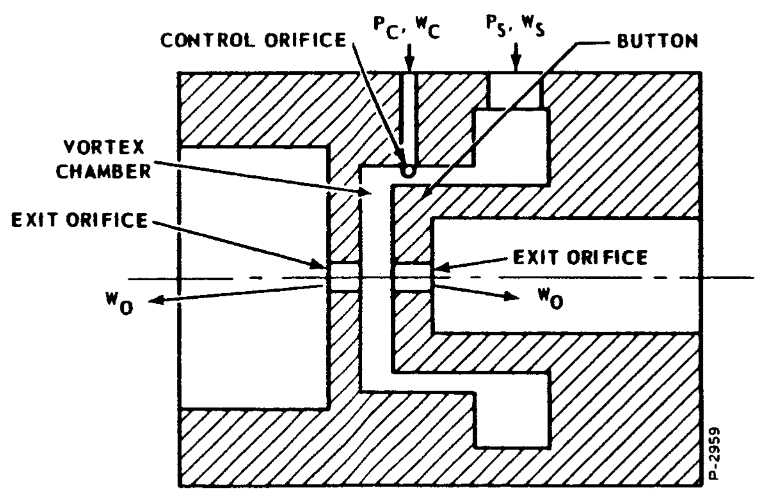

Figure 3-5 - Dual-Exit Vortex Valve

The summing vortex valve is of the dual-exit type with four control inputs: the input signal, the regenerative feedback signal and two inputs from the dynamic pressure feedback network. The significant dimensions of the summing vortex amplifier are as follows:

Vortex Chamber Diameter	1.12 cm	(0.441 in)
Vortex Chamber Length	0.16 cm	(0.063 in)
Button Diameter	1.05 cm	(0.412 in)
Exit Orifice Diameter (Two Orifices)	0.16 cm	(0.063 in)
Control Orifice Area:		
No. 1 (Input Signal)	$2.58 \times 10^{-3} cm^2$	$(4.0 \times 10^{-4} in^2)$
No. 2 (Regenerative Feedback)	$0.93 \times 10^{-3} cm^2$	$(3.0 \times 10^{-4} in^2)$
No. 3 and No. 4 (Dynamic Pressure Feedback)	$0.26 \times 10^{-3} cm^2$	$(0.4 \times 10^{-4} in^2)$

A schematic of the test equipment is shown in Figure 3-6. The test was performed at room temperature with nitrogen. The supply pressure was 44.6 N/cm^2 (64.7 psia). The supply flow and control flow were measured at various control pressures. The data is shown in Figure 3-7. A turndown ratio of 8.3-to-1 was obtained. A negative resistance region was found which results in a hysteresis effect if the supply pressure is held constant. However, in the servovalve, the supply pressure to the summing vortex valve increases as the control pressure increases, so that the negative resistance does not cause this problem.

3.3 REGENERATIVE FEEDBACK VORTEX PRESSURE AMPLIFIER TEST

The objective of this test was to determine the turndown ratio and the pressure-flow recovery characteristics of the regenerative feedback vortex pressure amplifier. A schematic of the pressure amplifier is shown in Figure 3-8. The amplifier is of the dual exit type with dual receivers. The significant dimensions are as follows:

Vortex Chamber Diameter	0.178 cm (0.070 in)
Vortex Chamber Length	0.203 cm (0.008 in)

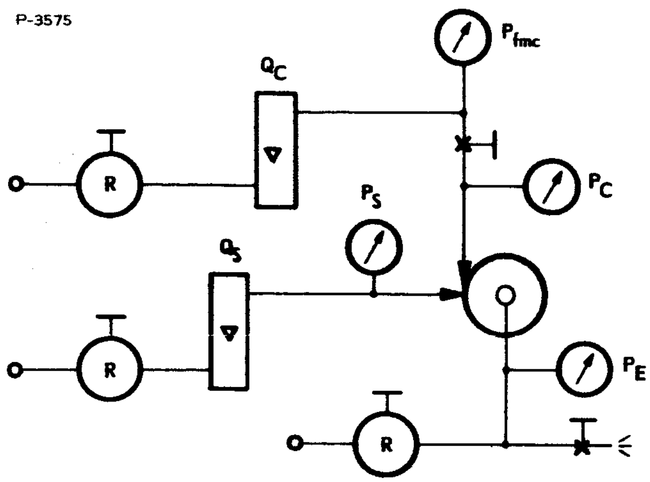

Figure 3-6 - Schematic of Summing Vortex Valve Test Setup

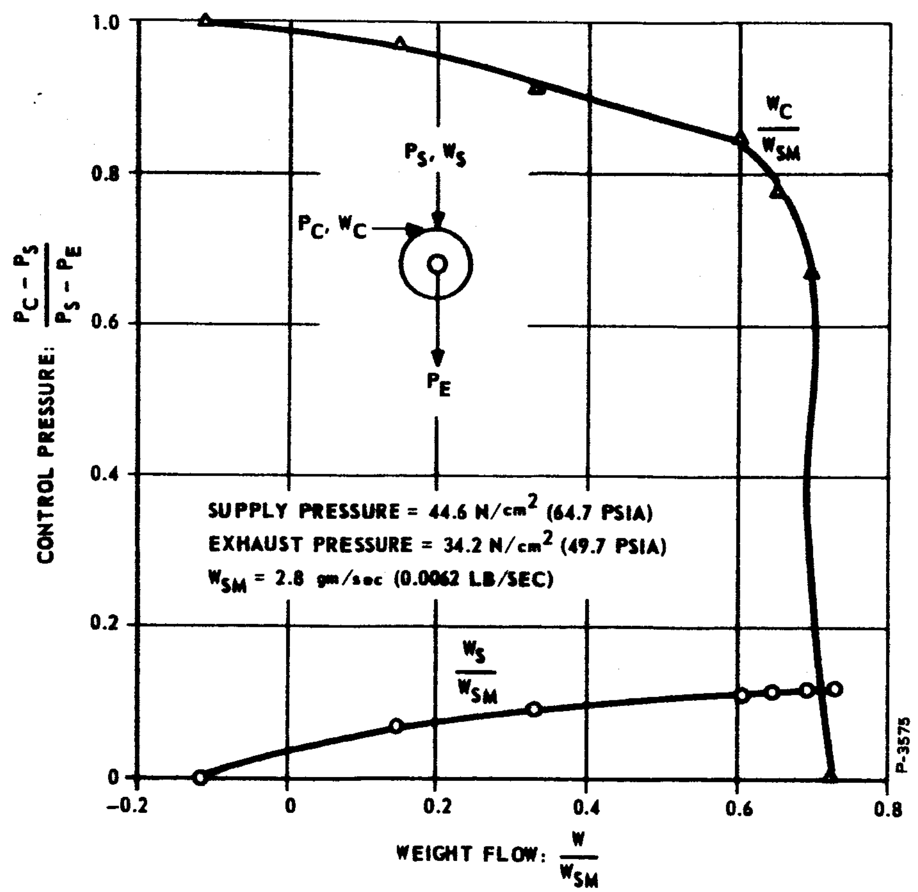

Figure 3-7 - Flow Versus Control Pressure Characteristics of Summing Vortex Valve

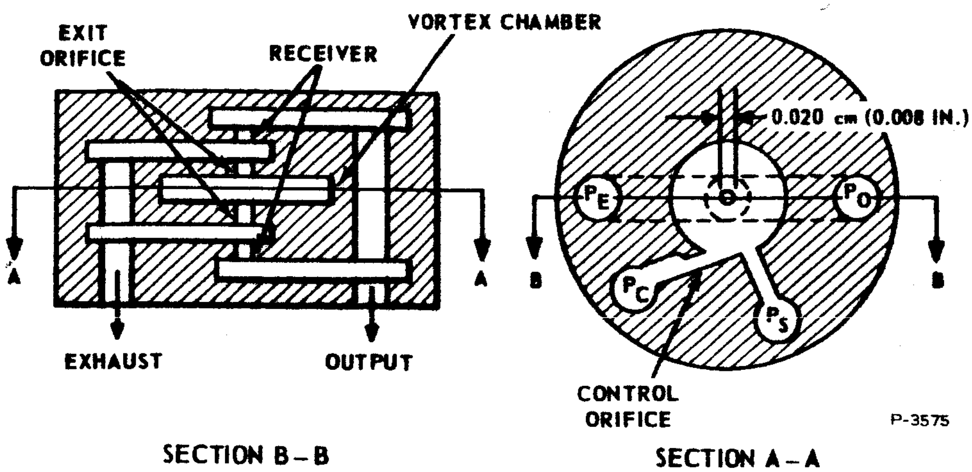

Figure 3-8 - Schematic of Regenerative Feedback Vortex Pressure Amplifier

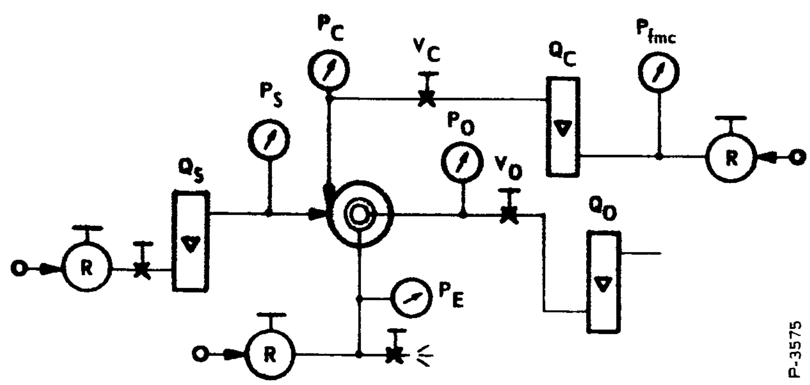

Figure 3-9 - Schematic of Test Setup Vortex Pressure Amplifier

Exit Orifice Diameter	0.203 cm (0.008 in)
Receiver Diameter	0.203 cm (0.008 in)
Distance Between Exit Orifice and Receiver	0.097 cm (0.003 in)

A schematic of the test equipment is shown in Figure 3-9. The test was performed with room temperature nitrogen at a supply pressure 127 N/cm^2 (185 psia). The supply flow, control flow and output pressure were measured at various values of control pressure. The control flow, supply flow, and blocked output pressure are plotted as a function

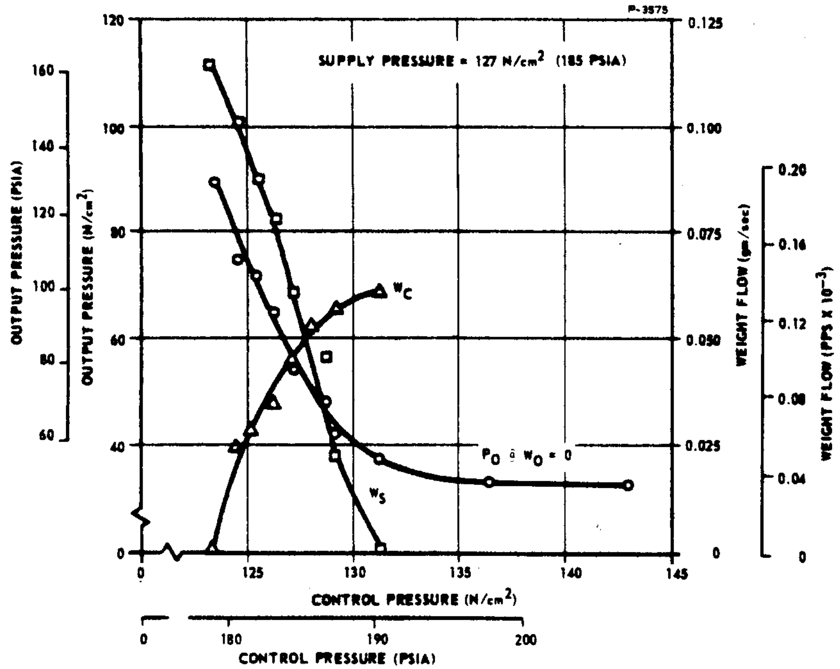

Figure 3-10 - Flow and Output Pressure Versus Control Pressure Characteristics of Regenerative Feedback Vortex Pressure Amplifier

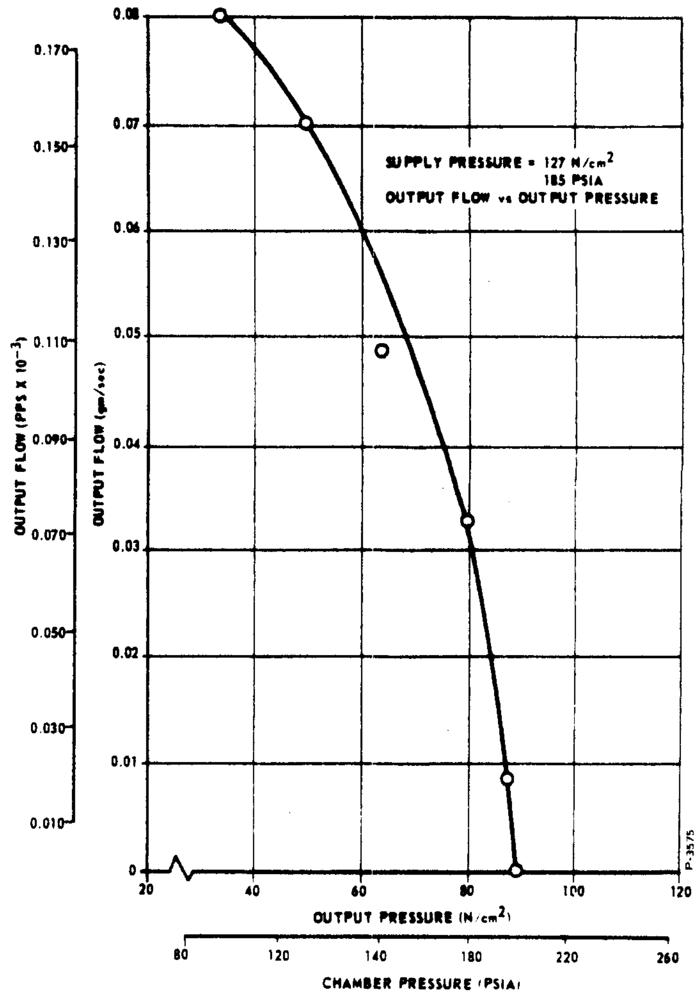

Figure 3-11 - Flow-Pressure Recovery Characteristics of Regenerative Feedback Vortex Pressure Amplifier of supply flow in Figure 3-10. The turndown ratio of this small device is only 1.65-to-1 but is still adequate for this application. The output flow versus output pressure characteristic with zero control flow is shown in Figure 3-11.

SECTION 4

POWER STAGE VORTEX PRESSURE AMPLIFIER TESTS

The objectives of the power stage vortex pressure amplifier tests were to determine the control flow requirements, the output pressure versus control pressure characteristics, and the load pressure-flow characteristics. A schematic of the vortex pressure amplifier is shown in Figure 4-1. The significant dimensions of the amplifier are as follows:

Vortex Chamber Diameter	0.660 cm (C.260 in)
Vortex Chamber Length	0.094 cm (0.037 in)
Button Diameter	C.604 cm (0.238 in)
Exit Orifice Diameter (Two Orifices)	C.094 cm (0.037 in)
Control Orifice Diameter (Two Orifices)	C.C46 cm (0.018 in)
Receiver Diameter	0.104 cm (0.C41 in)
Distance Between Exit Orifice and Receiver	0.028 cm (C.011 in)

A schematic of the test equipment is shown in Figure 4-2. The supply pressure to the vortex pressure amplifier was 120 N/cm^2 (174.7 psia) while the exhaust pressure was 34.3 N/cm^2 (49.7 psia).

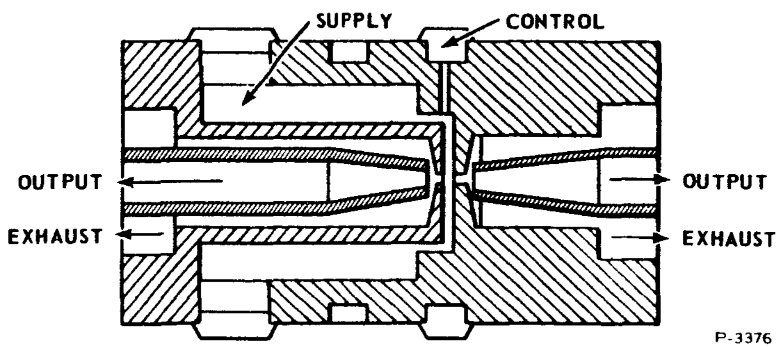

Figure 4-1 - Dual-Exit Vortex Pressure Amplifier

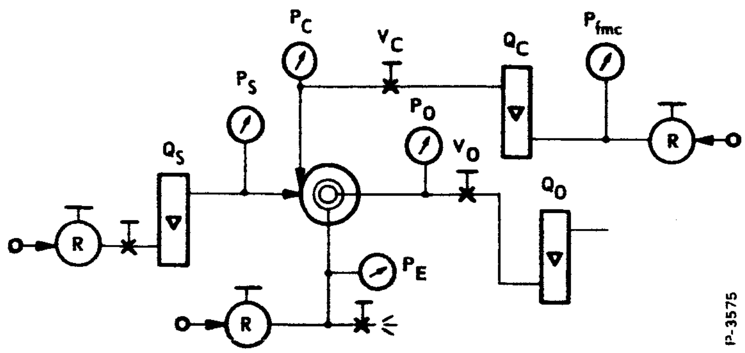

Figure 4-2 - Schematic of Vortex Pressure Amplifier Test Setup

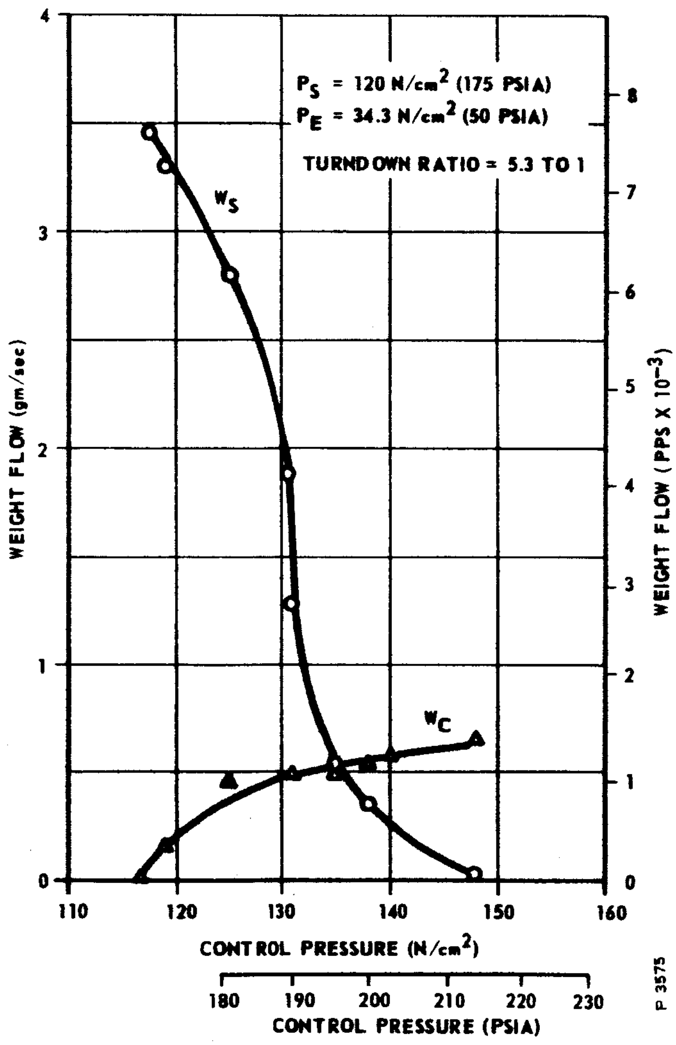

Figure 4-3 - Flow Versus Control Pressure Characteristics of Power Stage Vortex Pressure Amplifier

The supply flow and control flow are plotted as a function of the control pressure in Figure 4-3. The turndown ratio obtained was 5.3 to 1. The control pressure required to shut off the supply flow was too high. This will be remedied by increasing the control orifice area. The output pressure versus control pressure is shown in Figure 4-4. A negative resistance region was found which results in a steep portion of both the supply flow versus control pressure curve in Figure 4-3 and the output pressure versus control pressure curve in Figure 4-4. An attempt was made to eliminate the negative resistance region by decreasing the chamber length but this was not successful. It should be possible to eliminate this problem by increasing the vortex chamber diameter.

The load flow versus pressure characteristics are shown in Figure 4-5. The forward flow curve indicates the pressure-flow characteristic in the receiver-to-load direction with no control flow in the vortex chamber. The reverse flow curve illustrates the pressure-flow characteristic in the load-to-receiver direction with maximum control flow to the vortex chamber. The two curves can be used to predict the load pressure-flow characteristic of the complete power stage with a variable orifice load. The rated no-load flow is found, from the intersection of the forward and reverse flow curves, to be 2.85 gms/sec (6.3 pps x 10^{-3}) with nitrogen at room temperature. This is almost exactly equal to the required rated no-load flow for these conditions. Also from Figure 4-5, the pressure recovery is found to be 77.9 N/cm^2 (113 psi), which is about 5 percent low. The pressure recovery is found from the difference between the output pressures where the forward and reverse flow curves have zero flow. Better pressure recovery can probably be obtained by optimizing the exit orifice length and the distance between the exit orifice and the receiver.

The above tests of the power stage vortex pressure amplifier were all performed with nitrogen. The turndown ratio and several points on the pressure gain curve were measured in a test where data was taken at room temperature, first with nitrogen and then with hydrogen. The actual weight flow changed, of course, but the turndown ratio and data points on the pressure gain curve were essentially the same.

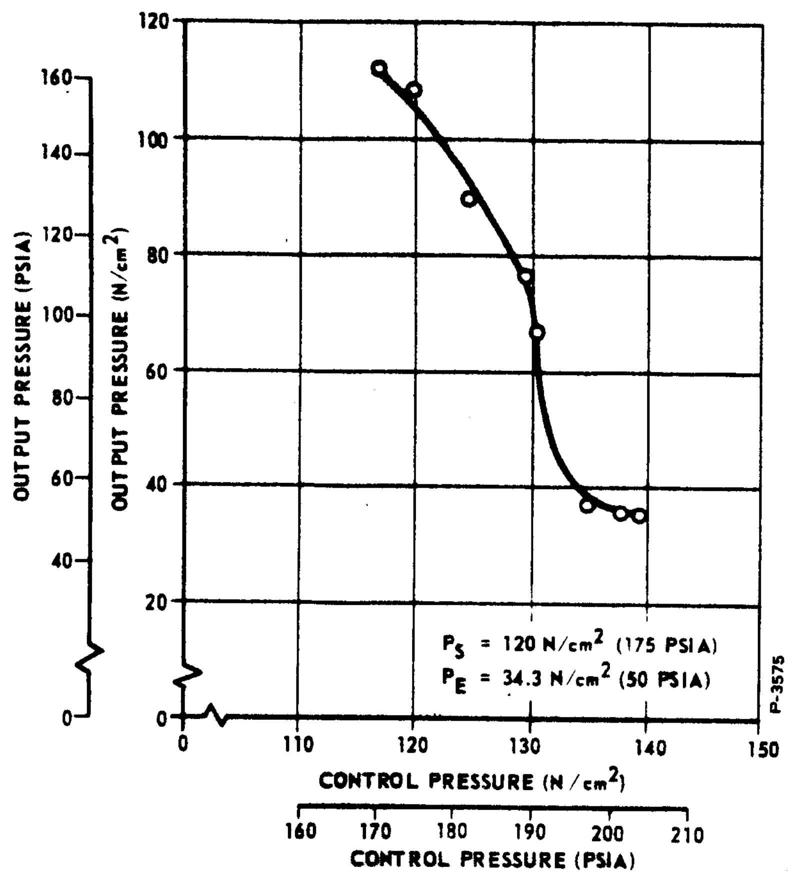

Figure 4-4 - Output Pressure Versus Control Pressure Characteristics of Power Stage Vortex Pressure Amplifiers

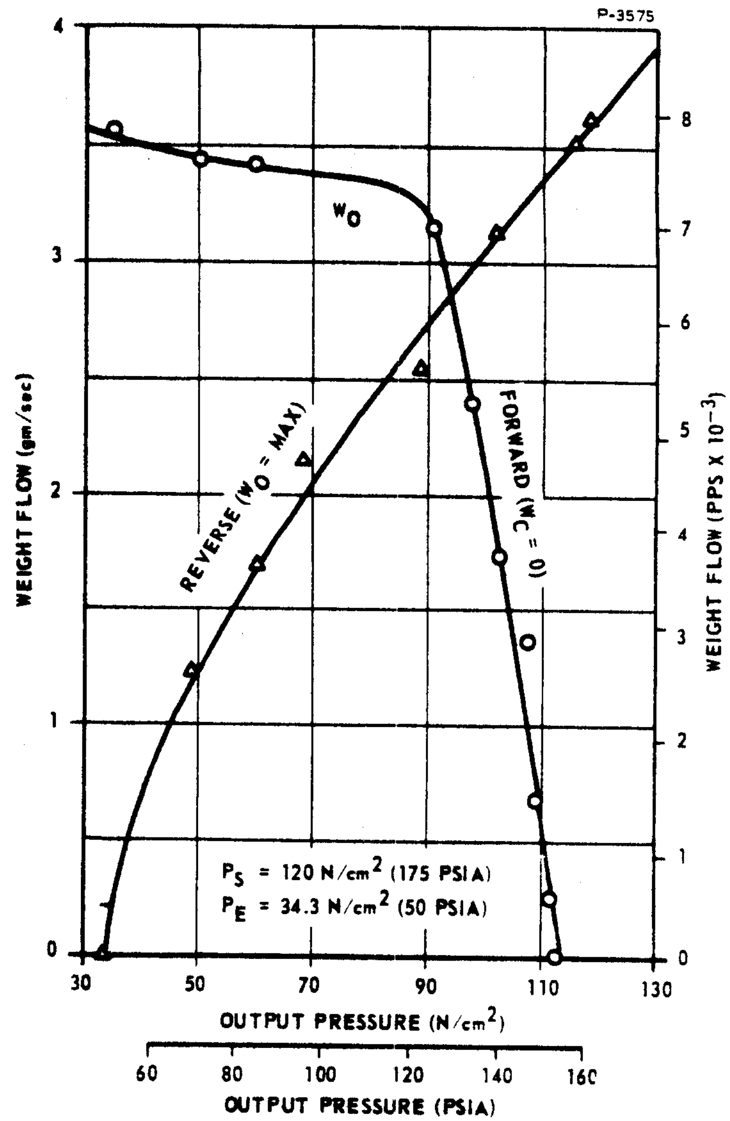

Figure 4-5 - Output Flow Versus Output Pressure of Power Stage Vortex Pressure Amplifier

SECTION 5

SERVOVALVE PERFORMANCE PREDICTION

Several items of the servovalve performance, including flow recovery, pressure recovery, input signal bias pressure, input signal power, and rated no-load flow, were projected on the basis of the previously completed analysis of the servovalve and the present component test results. These performance values were then compared with the specified performances. It should be possible to meet these specified performance items, except for the flow recovery and the input signal bias pressure.

The predicted flow recovery is 0.46 versus the specified flow recovery of 0.55. The low flow recovery is mainly caused by the power stage vortex pressure amplifiers having a turndown ratio of only 5.3-to-1 versus the required value of 7-to-1. The turndown ratio is lower in this pressure amplifier than that of other larger vortex valves or pressure amplifiers because of its small size. It is probable that the viscosity effects become increasingly significant as the size of a vortex valve decreases. With the present state-of-the-art, the turndown ratio of 5.3-to-1 is probably close to the maximum obtainable value for the given output flow, supply pressure, and maximum control pressure conditions.

The predicted input signal bias pressure is $48.9 N/cm^2$ (71 psia) versus the required maximum bias pressure of $45 N/cm^2$ (65.3 psia). This is due to the fact that the Venjet amplifier output pressure versus chamber pressure curve is at a higher chamber pressure level than that required. With further Venjet development, it might be possible to shift the output curve to achieve the specified performance.

It was concluded from the Venjet amplifier and the vortex pressure amplifier tests that there should not be a significant difference in the room temperature servovalve performance between using nitrogen or hydrogen as the working fluid.

SECTION 6

GOALS FOR NEXT PERIOD

The next quarter goals will be to:

1. Complete developmental tests of the individual components and the assembled breadboard servovalve.
2. Conduct acceptance tests of the breadboard servovalve.
3. Conduct low-temperature tests of the breadboard servovalve.
4. Begin the design and fabrication of the prototype servovalve.

APPENDIX A

DESIGN SPECIFICATIONS FOR FLUERIC SERVOVALVE

1. SCOPE

The specification covers a valve to be designed to meet the requirements of NASA Contract Number NAS 3-7980, entitled "Design, Fabrication and Test of a Flueric Servovalve."

2. DESCRIPTION

The servovalve shall be a four-way valve with dynamic negative feedback of the output pressure. The servovalve shall contain no moving mechanical parts such as bellows, variable orifices, and jet-pipes. The principle of operation shall be the interaction of fluid streams.

3. SUPPLY AND EXHAUST SPECIFICATIONS

3.1 Phase 1 - Breadboard Model

3.1.1 Working Fluid: The working fluid shall be both nitrogen and hydrogen gas.

3.1.2 Temperature: Supply gas shall be room temperature.

3.1.3 Supply Pressure: The supply pressure shall be 148 ± 7 newtons per square centimeter, absolute (215 ± 10 psia).

3.1.4 Exhaust Pressure: The exhaust pressure shall be 34.5 ± 3.5 N/cm^2a (50 ± 5 psia).

3.1.5 Supply Flow: Under all operating conditions, the flow through the supply port shall be less than 1.82 times the rated no-load output flow. where "rated no-load output flow" is defined here as the mass flow through the wide open load-throttle for rated input signal. "Rated input signal" is defined in Paragraph 5.2.

3.2 Phase II - Breadboard Model and Prototype Servovalve

3.2.1 Working Fluid: The working fluid shall be dry hydrogen.

3.2.2 Temperature: Supply gas temperature shall be variable from 56 to 333 degrees Kelvin (100 to 600°R).

3.2.3 Supply Pressure: The supply pressure shall be 148 ± 7 N/cm^2a (215 ± 10 psia).

3.2.4 Exhaust Pressure: The exhaust pressure shall be 34.5 ± 3.5 N/cm^2a (50 ± 5 psia).

3.2.5 Supply Flow: Under all operating conditions, the flow through the supply port shall be less than 1.82 times the rated no-load output flow.

4. LOAD SPECIFICATION

The two output ports shall be connected to a load consisting of a series arrangement of a volume-throttle-volume combination. The load shall contain no vents. The load volumes shall be adjustable to the extent that the difference between the two volumes can vary between plus and minus 115 cubic centimeters (7 in^3). The total of the two volumes shall remain equal to 164 cm^3 (10 in^3). The load-throttle shall be a two-way valve adjustable from closed to wide open passageway. With wide open load throttle, the differential output pressure shall be less than 5 N/cm^2 (7 psi).

5. INPUT-SIGNAL SPECIFICATIONS

5.1 Input-Signal: The input-signal shall be a two-port differential pneumatic signal. The working fluid shall be the same as the supply gas for the servovalve. "Input-signal pressure" is defined here as the pressure difference between the two input ports.

5.2 Rated Pressure: The rated input-signal pressure shall be less than 7 N/cm^2 (10.2 psi) for flow in both directions through the load-throttle. "Rated input-signal" is defined here as the input-signal that produces the rated no-load flow specified in Paragraph 6.2.

5.3 Quiescent Pressure: For zero input-signal, the pressure bias of the input-signal shall be less than 45 N/cm^2a (65.3 psia); where "pressure bias" is defined here as the average pressure of two lines.

5.4 Admittance: Variation in the admittance of each input port, resulting from changes in the load-throttle, shall be less than 10% of the maximum input admittance for the complete range from closed to wide open load-throttle; where "admittance" is defined here as the mathematical derivative of volumetric flow with respect to the absolute pressure in the input port. No specification is placed upon variation in the input admittance as a function of the input-signal.

5.5 Power: Under all operating conditions with dry hydrogen at 56°K (100°R), the combined power delivered to the input ports shall be less than 4 watts; where "power" is defined here as the product of the gage pressure (i.e., pressure relative to the exhaust pressure) and volumetric flow.

6. OUTPUT SPECIFICATIONS

6.1 Output: The servovalve shall have two output ports. "Differential output pressure" is defined here as the pressure difference between the output ports. "Output flow" is defined here as the mass flow through the load-throttle.

6.2 Rated No-Load Flow: With wide open load-throttle, the output flow of dry hydrogen at 56°K (100°R) shall be 2.1 grams per second (0.00463 lbs/sec) for the rated input-signal.

6.3 Pressure Recovery: With closed load-throttle, the differential output pressure shall be greater than 82 N/cm^2 (119 psi); i.e., 73% pressure recovery.

6.4 Pressure-Flow Characteristics: For all values of constant input-signal, the output flow shall be equal to or greater than

$$\dot{m}_o \left(1 - \frac{p}{p_o}\right)$$

where quantity $\dot{m}_o$ is a constant and equals the output flow for the given input signal with closed load-throttle; p_o is a constant and equals the differential output pressure for the given input-signal with closed load-throttle; and p is a variable term equal to the differential output pressure for the given input-signal and is a function of the load-throttle setting.

6.5 Linearity: Deviation from a straight line of input-signal pressure versus differential output pressure for closed load-throttle shall be less than 10% of the rated values. The pressure gain for all values of input-signal shall be less than two (2) times the average pressure gain, where "pressure gain" is defined here as the mathematical derivative of the differential output pressure with respect to the input-signal pressure during steady operating conditions with closed load-throttle.

6.6 Pressure Feedback: Dynamic negative feedback of the pressure of each output port shall be an integral part of the servovalve. The feedback gain at zero frequency shall be less than 1% of the rated input-signal. The feedback gain at the corner (break) frequency of 5 hertz shall be 8 ± 1% of the rated input-signal. Construction of the servovalve shall allow easy exchange of components for changing the pressure feedback characteristics.

6.7 Stability: Peak-to-peak ripple of frequencies above 3 hertz shall be less than 0.4 N/cm^2 (0.58 psi) measured after filtering an electrical signal of the differential output pressure with a $1/(0.05S + 1)^2$ filter, for various load-volume settings and for all values of input-signal with closed load-throttle.

6.8 Transient Response. From any initial value and for step input-signals that produce a 20 N/cm^2 (29 psi) change in the differential output pressure, the differential output pressure shall reach 62.5% of the step in a time period of less than 0.055 seconds and shall settle within 2 N/cm^2 (2.9 psi) of the final value in a time period of less than 0.210 seconds when tested with closed load-throttle and with equal load-volumes.

6.9 Frequency Response: With zero load-volumes and blocked output ports, the phase shift of the differential output pressure for a 2% rated input-signal at 6 hertz shall be less than 20 degrees, and at 60 hertz the phase shift shall be less than 90 degrees. The differential output pressure amplitude variation for a constant input-signal shall be less than ± 2 db from 0 to 60 hertz.

6.10 Threshold: For all values of input-signal, the increment of input-signal required to produce a change in the output shall be less than 0.5% of the rated input-signal.

6.11 Hysteresis: The difference in the input-signal required to produce the same output during a single input cycle shall be less than 3% of the rated input-signal.

7. ENVIRONMENT SPECIFICATIONS

Items 7.2, 7.3, and 7.4 shall not apply to the breadboard model of the servovalve.

7.1 Ambient Temperature: The servovalve shall be capable of operation under ambient temperatures that vary between 56 and 333°K (100 and 600°R).

7.2 Vibration: The servovalve shall be operational when subjected to 6 g's amplitude from 0 to 20 hertz and then linear amplitude to 20 g's at 200 hertz and then constant at 20 g's to 2000 hertz along any axis.

7.3 Shock and Acceleration: The servovalve shall operate after a 6 g shock and/or a 8 g acceleration along any axis.

7.4 Radiation Field: The servovalve shall be operational under a total dose of 6×10^6 rads (ethylene) 1 hour, a fast neutron flux rate ($E > 1.0$ nev) of 3×10^{11} neutrons/cm^2-sec; a thermal neutron flux ($E < 1.86$ EV) of 1×10^{10} neutrons/cm^2-sec; and a gamma heating equivalent to 770 watts/kilogram aluminum (350 watts/lbm aluminum).