NASA CR–72145
BRL No. 3875
COPY NO. 39

Final Report

All-Fluid Amplifier Development for Liquid Rocket Secondary Injection Thrust Vector Control

By

J.T. Kasselmann and T.R. Delozier

November 1967

Distribution of this report is provided in the interest of information exchange. Responsibility for the contents resides in the author or in the organization preparing it.

Prepared Under Contract No. NAS 3–6299

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Bendix Research Laboratories

NASA CR–72145
BRL NO. 3875

Final Report

All-Fluid Amplifier Development for Liquid Rocket Secondary Injection Thrust Vector Control

By
J.T. Kasselmann and T.R. Delozier

November 1967

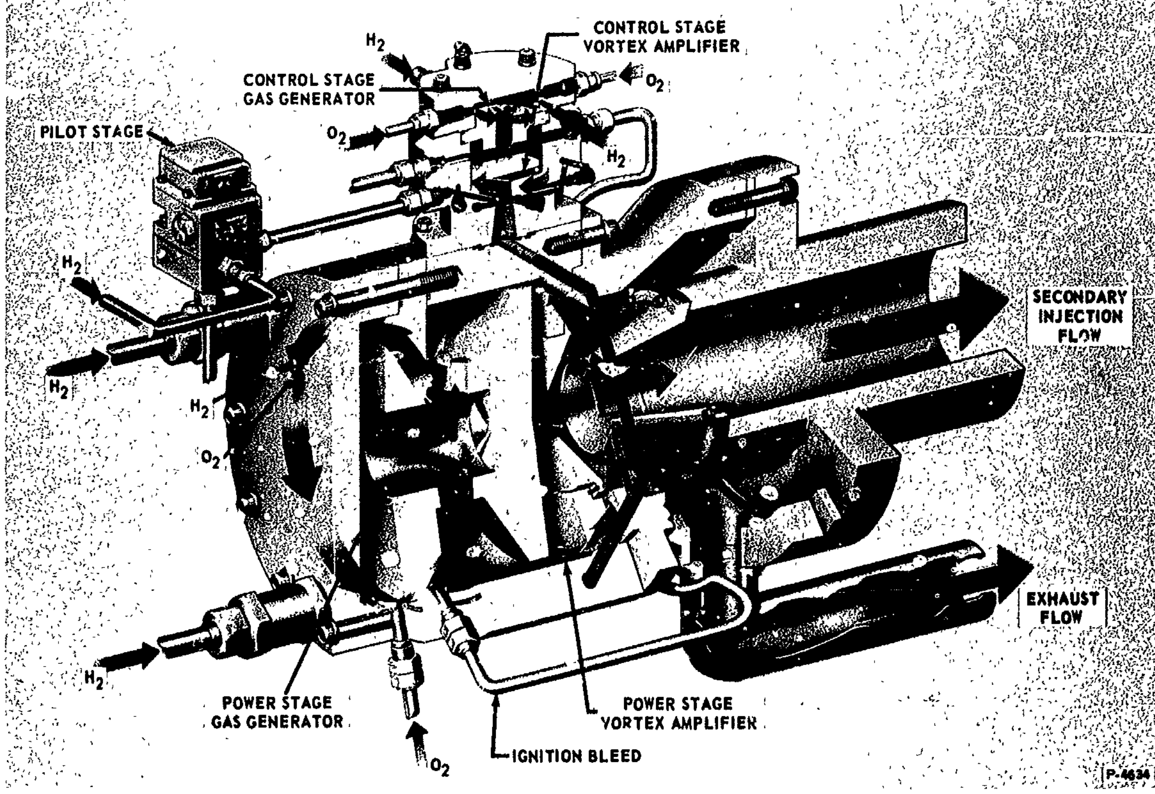
Prepared Under Contract No. NAS 3–6299

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Project Manager
NASA Lewis Research Center
Cleveland, Ohio
Theodore Male

Bendix
Research Laboratories

STAGED VORTEX AMPLIFIER FOR SECONDARY INJECTION THRUST VECTOR CONTROL



Libraries of contracts and of other qualified requesters may obtain additional copies of this report by submitting NASA Form 492 directly to:

Scientific and Technical Information Facility
Post Office Box 5700
Bethesda, Maryland 20014

FOREWORD

The work described in this report was performed by the Bendix Research Laboratories for the National Aeronautics and Space Administration under Contract NAS 3-6299. It was performed by the Propulsion Controls Department of the Energy Conversion and Dynamic Controls Laboratory. Mr. L. B. Taplin is Laboratory Manager, and Mr. J. G. Rivard is the Department Head. Mr. J. T. Kasselmann was Responsible Engineer, assisted by Mr. T. R. Delozier. The project was initiated on July 2, 1965, and was conducted under the program management of Mr. Ted Male of the NASA-Lewis Research Center, Cleveland, Ohio.

PRECEDING PAGE BLANK NOT FILMED.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SUMMARY

Experimental and analytical studies were conducted to develop the vortex amplifier as a hot gas valve for liquid rocket secondary injection thrust vector control. This work included the staging of two vortex amplifiers in series to improve flow gain and the development of a new vortex-doublet type of gas generator designed for direct integration with the two vortex amplifier stages. The program final objective was to demonstrate a complete 2.0 lb/sec flow rate, staged, single-axis† secondary injection thrust vector control system, under simulated rocket engine operating conditions. A schematic of this system is shown in the Frontispiece. The media from both control and power stage gas generators are the combustion products of hydrogen and oxygen to yield a bulk gas temperature of 1500°F.

The program produced two major accomplishments. The staging of two vortex amplifiers in series to increase flow gain was established, and a flow gain of 200 was obtained. The vortex-doublet gas generator was successfully developed through a series of tests that established ignition, throttling, shutdown and restarting with two sizes and two pressure levels.

The program was divided into three tasks. Task 1 developed the staging concept with a quarter-scale vortex amplifier using workhorse hydrogen-oxygen gas generators. Task 2 developed the compact vortex-doublet hydrogen-oxygen gas generators, and Task 3 developed the full-scale staged vortex amplifier which was integrated with the Task 2 gas generators to form a completed, self-contained SITVC system.

Task 1 was highly successful because all of the design objectives were met. A test series was performed in which a total flow gain exceeding 200 was established. The outlet or secondary injectant flow was modulated over a range from 90% of total flow to complete shutoff while the total flow was changed from 100% to 20% of maximum flow. Frequency response tests were not performed. However, in the previous contract, NAS 3-4198, a bandpass in excess of 85 hertz had been established with a single-stage vortex amplifier of the same flow capacity.

During Task 2, a compact hydrogen-oxygen gas generator was developed that could easily be integrated with a vortex amplifier. The development effort centered on the propellant injection region. Because of the extremely hot temperatures (6000°F) at which hydrogen combines with oxygen, it was necessary to design the injectors so that the propellants combined in a free space region inside the vortex chamber away from chamber walls and injectors. This problem was further aggravated by the need to throttle flow. A generator was developed that met all of the requirements of the vortex amplifier in the secondary injection thrust vector control application.

† Force in only one direction

The Task 3 two-stage vortex amplifier was a full-scale model designed from the quarter-scale amplifier developed in Task 1. The Task 3 system was cold tested and the performance obtained was slightly better than that obtained in Task 1. This was accomplished in the design hardware without modification, indicating the validity of the scaling technique. In initiating hot gas testing, several hardware problems arose from the necessity of conducting preliminary testing and adjustments, with hot control gas flowing through the cold power stage vortex amplifier body. The unit was very large, and the thermal transients caused stress cracking. As a result, it was not possible to demonstrate complete hot gas performance of the system.

However, correlation of Task 1 and Task 3 tests indicates that the Task 3 system was capable of the specified hot gas performance. The Task 1 tests established the almost 1 to 1 correlation between cold gas and hot gas performance. Therefore, the highly satisfactory cold gas performance of Task 3 indicates that its hot gas performance would be satisfactory also. Comparison of Task 1 and Task 3 cold gas tests established the validity of the scaling technique. Therefore, the successful Task 1 hot gas performance suggests satisfactory hot gas performance for the Task 3 system. For both of these reasons — scaling validity and correlation of hot gas versus cold gas performance — it is concluded that the Task 3 vortex amplifier system would have performed well on hot gas if the integrity of the hardware had been preserved.

The potential of the staged vortex amplifier with integral gas generators in the secondary injection thrust vector control application has been established. The performance of the vortex devices and the gas generators met specification without exception. The methods of fabrication, structural design and materials proved to be the limitation in performance of this contract. Future work in this area should be in lightweight insulated structures capable of withstanding the temperature shocks encountered during interrupted metering of hot gas.

INTRODUCTION

A spacecraft or missile can be steered by deflecting the rocket engine thrust vector. Conventionally, this thrust deflection is accomplished by mounting the engine so that its angular position can be varied whenever a course correction is required. This method requires the complication and added weight of a gimbal mounting and an actuation system. The large engine masses have slow dynamic response and require powerful actuators. In vehicles with very large thrust engines, it is customary to add auxiliary engines for the purpose of steering. This, of course, also adds weight.

Secondary injection thrust vector control (SITVC) is a method of thrust deflection that saves the weight and complexity inherent in mechanical thrust deflection systems. The engine is stationary and fluid jets deflect the rocket thrust gases to steer the vehicle. The fluid is injected into the thrust nozzle downstream of the engine (hence the name "secondary injection"). Response is fast, because the jets can be turned on and off rapidly, as needed.

Almost any fluid might be used for secondary injection, but it is most efficient to inject a hot gas; in fact, the gas might be bled from the engine, itself, upstream of the nozzle. This gas is extremely hot, and the valves that control the secondary injection must withstand temperatures of 1500°F and higher. It is unlikely that ordinary electromechanical valves could continue to function satisfactorily in this environment of high temperature, shock and vibration. On the other hand, vortex valves could be expected to operate with high reliability in this environment because these fluidic devices have no moving parts.

To test the application of vortex valves for hot gas secondary injection thrust vector control of liquid rocket engines, a development program was undertaken in July 1964 by Bendix Research Laboratories for NASA-Lewis Research Center under Contract NAS 3-4198. A vortex amplifier having a flow capacity of 0.5 lb/sec was developed for use with the combustion products of hydrogen and oxygen. The results of this program were reported in NASA CR-54446.

As an outgrowth of the foregoing program, the development reported herein was undertaken in July 1965 for NASA-Lewis Research Center under Contract NAS 3-6299. The hydrogen-oxygen hot gases are controlled by a high-gain two-stage vortex amplifier, and the control signal input is through an electropneumatic pilot valve, which operates with cold hydrogen gas. The staged vortex amplifier achieves high flow gain, so that flow modulation by the electropneumatic servovalve is very small in comparison with the total hot gas flow modulation (full-off to full-on) of the main stage vortex amplifier. With no moving parts exposed to the hot gases (the electropneumatic pilot valve handles only cold hydrogen), the system offers the potential of high reliability for SITVC applications in liquid rocket engines.

The system constructed and tested in this program is a "single-axis" system. That is, it includes the control valves and amplifier for a single injection nozzle. Typically, a rocket vehicle would incorporate three or four such systems spaced 120 degrees or 90 degrees apart around the thrust nozzle to provide full pitch and yaw control.

The system described in this report is completely self-contained, incorporating one H/O gas generator for the control stage vortex valve and another for the main stage vortex amplifier. The program, therefore, includes development of the two-stage vortex amplifier, development of the H/O gas generators (a unique design) and, finally, the integration and testing of the complete system.

For the future, it is anticipated that a self-contained system such as this could be applied to a rocket engine, drawing its fuel and oxygen from the engine supply, or the main stage gas generator could be eliminated and the hot gas flow for the injection nozzle could be bled from the engine.

OBJECTIVE

The objective of this program was further development of the vortex amplifier, including the evaluation of staging techniques to improve total flow gain. In addition, a new vortex-doublet type of hydrogen-oxygen gas generator was designed and developed for direct integration with both stages of the vortex amplifier. This configuration has the advantage of low L^*. The final objective was to demonstrate a complete staged single-axis, 2.0 lb/sec, secondary injection thrust vector control system, under simulated operating conditions.

DESCRIPTION OF PROGRAM

The program was divided into three separate tasks to accomplish these objectives.

Task 1

In Task 1, the hot gas vortex amplifier staging concept was evaluated and tested. The previous project had resulted in the demonstration of a vortex amplifier with good overall performance, with an output flow gain in excess of 30 being realized from a single vortex amplifier, using a bias flow technique. The purpose of Task 1 was to evaluate two vortex amplifier stages in series, to produce an output flow gain exceeding 200. The 0.5 lb/sec vortex amplifier developed during the previous contract was used as the power stage for Task 1. A smaller vortex unit was fabricated to serve as the control stage of the amplifier and was integrated with the power stage to form a two-stage amplifier that would demonstrate the desired gain. The control stage provided the initial amplification, and the power stage provided the final amplification. Both cold gas and hot gas tests were performed (with conventional H/O gas generators being used to provide the hot gas). The test results of Task 1 produced the design data required for building the high flow, 2.0 lb/sec SITVC system in Task 3.

Task 2

In Task 2, a vortex-doublet hydrogen-oxygen gas generator was developed to replace the previous gas generator. The vortex-doublet type of gas generator offers potential advantages in size, reliability and dynamic performance.

The previous gas generator configuration (as used in Task 1 and in the earlier contract) was a cylinder having a length greater than its diameter. In this type of generator, hydrogen is injected tangentially at the outer wall to provide a swirling layer of gas. Oxygen is injected axially at one end, and the mixture is spark-ignited. Combustion occurs as the two gases move through the chamber toward the exit at the other end. This configuration requires an unreasonably long chamber.

The new combustor configuration, developed by Bendix Research Laboratories, has a flat pancake-type combustion chamber, with both propellants injected at the outer radius. Oxygen is injected radially and hydrogen is injected tangentially at the same location (doublet injection). The mixed hydrogen and oxygen are spark-ignited and combustion occurs as the gases spiral toward the center of the combustion chamber in a vortex flow field. This unique configuration confines the combustion zone to the center of the chamber and reduces heat transfer to the outer chamber wall. It requires a reduced chamber volume (low L^*), which minimizes package size and improves dynamic performance.

This combustor was developed in two sizes in Task 2 so that the two generators could be designed intergrally with the two vortex amplifier stages in Task 3. Initially, a low-flow unit was developed. Its purpose was twofold: first, it established the feasibility of the vortex-doublet design; second, it was used to supply gas to the control stage of the SITVC system that was designed and built during Task 3. This generator had a flow capacity of approximately 0.35 lb/sec, with a pressure of 800 psig. With feasibility established, a full-scale unit capable of delivering a minimum hot gas flow of 2.0 lb/sec, with a pressure of range of 5 to 1 was built and tested and later was applied to the power stage amplifier in Task 3. This gas generator was required to have good combustion stability and accurate temperature control.

Task 3

In Task 3, a new, larger two-stage vortex amplifier was designed and fabricated, based on the results of Task 1, and a complete demonstration unit, simulating a single-axis secondary injection thrust vector control system, was assembled and tested. The power stage had a flow rate of 2.0 lb/sec and was built as an integral assembly with the larger of the two hydrogen-oxygen gas generators that had been developed in

Task 2. The control stage was built as an integral assembly with the smaller H/O gas generator that had been developed in Task 2. The two-stage vortex amplifier was controlled by using cold gas supplied from an electropneumatic pilot stage.

The output of the power stage amplifier was loaded with a fixed-area orifice simulating the secondary injection nozzle. Exhaust flow was vented through a loading orifice, simulating a large-expansion, low pressure nozzle capable of recovering available thrust. A conceptual design of this integrated system is shown in Figure 1.

The goal of Task 3 was to achieve an integrated design with optimized performance. The performance goals were: total flow gain of 200; power stage flow recovery of 90%; power stage flow turndown of 5:1; output flow modulation range varying from maximum recovered flow to zero flow. Another goal was a sinusoidal frequency response of 25 hertz; however, extensive preliminary ignition tests and hot gas tests had deteriorated the hardware to such an extent that dynamic response tests were not performed.

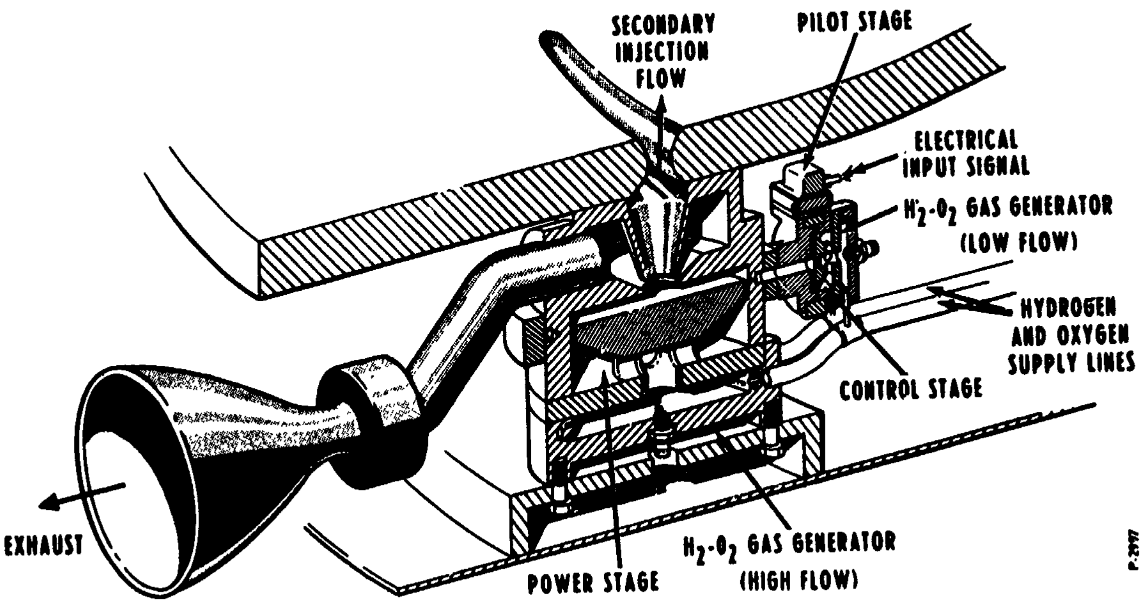


Figure 1 - Two-Stage Vortex Amplifier for SITVC

DEVELOPMENT OF STAGED VORTEX AMPLIFIER

(TASK 1)

The objectives of Task 1 were (1) to evaluate the concept of obtaining high flow gain by staging two vortex amplifiers in series, and (2) to develop normalized performance characteristics and design parameters that would be used in the design of the full-scale staged vortex amplifier in Task 3.

In a vortex amplifier, tangential control flow creates a swirling action in a vortex chamber that restricts supply flow. By varying the control flow input, total flow through the device can be modulated from maximum (full supply flow, no control flow) to a minimum flow (supply flow shutoff, only control flow passing through the device). The ratio of maximum to minimum flow is called the "turndown ratio." When two amplifiers are staged, the output flow of one (the control stage) becomes the control flow input of the second (the power stage), and the overall flow gain is the product of the gains of both amplifiers within their operating range.

To enable output flow to be reduced to zero, a tubular receiver is positioned facing the outlet orifice of the power stage vortex chamber. Under high flow conditions (i.e., zero control flow), most of the gas exiting from the chamber enters the receiver and flows to the load. Under minimum flow conditions, the swirling gases exit from the chamber in the form of a hollow cone and bypass the receiver so that no gas flows to the load. In tests, the load is simulated by a simple orifice.

The staged vortex amplifier system developed in Task 1 included: the power stage amplifier, which was sized for the specified capacity of 0.5 lb/sec flow; the smaller control stage amplifier which was sized to provide the necessary control flow the the power stage; and an electro-pneumatic pilot valve, which supplied a control flow input signal to the control stage.

PERFORMANCE REQUIREMENTS

The required vortex amplifier performance is plotted in normalized form in Figure 2. The curves represent overall performance of the staged vortex amplifier. The abscissa is the ratio of the control stage control pressure (pilot pressure, P_{c2}) to the power stage supply pressure (P_{s1}). This parameter (P_{c2}/P_{s1}) was chosen because this pressure ratio is a normalized expression of the input to the vortex amplifier from a signal source.

The ordinate is normalized weight flow in which unity represents the maximum total flow through the power stage. By including total, receiver, control and pilot flow curves, the chart defines performance completely. Exhaust flow can be computed, if desired, by subtracting receiver flow from total flow.

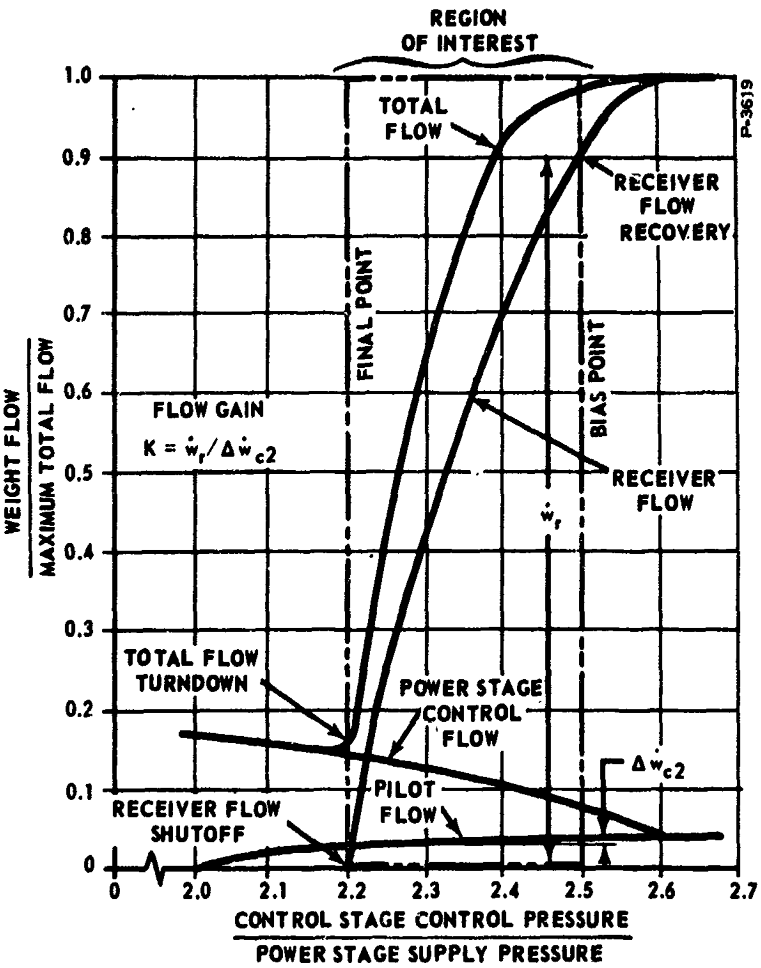


Figure 2 - Staged Vortex Amplifier Target Performance

The operating range extends from the bias point to the final point (receiver flow shutoff). All curves were extended beyond this region in order to completely define full-range performance. The curves were based on a design specification that the control stage supply pressure (P_{s2}) is two times the power stage supply pressure (P_{s1}). The operating region is bounded by normalized weight flows of 0 to 1 and by overall control pressure ratios of 2.2 and 2.5. The maximum system pressure is thus defined at 2.5 times the power stage supply pressure.

Flow Gain

Both stages are biased to operate in the high-gain part of the input-output curve. That is, control flow is never reduced to zero in either stage, so that the operating range is between full turndown and some point less than full flow. Without biasing, the maximum flow gain of each stage is about seven, since the maximum control flow is about one-seventh of the total flow of each stage. With biasing, the control flow range is a much smaller fraction of the total flow range. The gain of the power stage then is approximately 20 and the gain of the control stage is approximately 10, so that total flow gain is 200. The difference in the gains of these two stages is due primarily to the difference in loading of each stage. The total flow gain is defined as the receiver or output flow at the bias point divided by the total change in pilot flow (control stage control flow) to achieve complete flow modulation.

Because the total flow is slightly turned down at the bias point, the power stage vortex amplifier must be slightly oversized in order to pass the specified design flow. For the control stage, the amount of oversize is determined by the necessity of making the high-gain region of the control stage match the operating region of the power stage.

Receiver Flow Recovery

The receiver flow recovery ratio at the bias point is specified as 90% and is defined as the receiver flow divided by the total flow. This parameter is a measure of the ability of the receiver to collect the unswirled gas issuing from the vortex chamber. Complete 100% recovery is difficult because of the large axial spacing between the chamber outlet orifice and the receiver entrance, which is required to assure complete exhausting of the swirled gases at the zero receiver flow condition.

Receiver Pressure Recovery

Recovered pressure in the receiver is a function of the restriction caused by the secondary injection nozzle. The thrust nozzle pressure is near vacuum at the point of injection. Thus, a low maximum upstream injection pressure can be employed. The pressure is dictated primarily by the resulting size of SITVC components. Maximum receiver pressure is specified as 25% of the supply pressure. For test purposes, a fixed orifice simulated the restriction of the secondary injection nozzle.

Receiver Flow Shutoff

The output flow is required to decrease to zero with a pilot pressure-to-power stage supply pressure ratio of 2.2. Flow shutoff corresponds to the condition of the zero thrust vector and will be the long-term operating point in a normal rocket engine duty cycle. The output flow must modulate smoothly, and with reproducible linearity, from the condition of approximately 90% flow recovery at the bias point to complete flow shutdown.

Total Flow Turndown

In a normal rocket engine application, the SITVC system would operate most of the time with injection flow at zero while the residual flow is exhausted to an auxiliary thrust nozzle. Since this nozzle is less efficient than the main engine, it is desirable that the total flow be reduced to about 20% of maximum while in this operating condition. Therefore, a total flow turndown of 5:1 in the power stage is required. The turndown or throttling capability enables the vortex amplifier to conserve propellant. At full turndown, the flow is essentially all control flow.

Table 1 - Task 1 Test Summary

Test No.	Date	Power Stage	Control Stage	Gas	Purpose of Test	Results
1	8-27-65	VA2	VA3M1	N_2	Perform initial test on staged vortex amplifier	Performed well; control stage too small to supply required control flow for power stage turndown; P_{s2} supply pressure too high.
2	9-2-65	VA2	VA3M1	N_2	Evaluate increased size of control stage outlet orifice	Performance better; achieved desired P_{s2} pressure; gain of assembly low; control stage still too small.
3	9-23-65	VA2	VA4M1	N_2	Evaluate larger control stage and larger receiver diameter (D_p/D_o = 1.3) probe	Performance good; overall gain 117; control stage unstable.
4	9-24-65	VA2	VA4M1	N_2	Evaluate intermediate size receiver D_p/D_o = 1.2 probe	Performance quite similar to Test 3 except that higher power stage control pressure ratio P_{c1}/P_{s1} needed.
5	9-30-65	VA2	VA4M1	N_2	Chamber performance evaluation, receiver removed	Indicates that the receiver has little effect on the performance of the vortex chamber
6	10-6-65	—	VA4M1	N_2	Investigate control stage performance independent of the power stage	Control stage showed unstable performance; will be redesigned. New stage VA4M2.
7	10-12-65	VA2	VA4M1	N_2	Evaluate double receiver	Exceptional shutoff performance but relatively poor flow recovery.
8	10-19-65	—	VA4M2	N_2	Check out new control stage.	Instability problem encountered with VA4M1 eliminated.
9	10-19-65	VA2	VA4M2	N_2	Check out new control stage in staging application and experiment with receiver spacings for complete receiver flow shutoff	VA4M2 performed properly; also complete receiver flow shutoff obtained but flow recovery severely degraded. Receiver diameter ratio was D_r/D_o = 1.3

A series of short tests were performed to define the cone shape at maximum flow and turnoff conditions.

P-4634

Table 1 - Task 1 Test Summary (Cont'd)

Test No		Power Stage	Control Stage	Gas	Purpose of Test	Results	Performance Summary: Initial Flow Recovery %	Flow Recovery @ Bias Point %	Final Point P_{c2}/P_{e1}	Bias Point P_{c2}/P_{e1}	Total Flow Turndown	Initial Receiver Pressure Recovery %	Receiver Flow Shutoff %	Power Stage Flow Gain $\dot{w}_r/\Delta\dot{w}_{c2}$ K_p	Control Stage Flow Gain $\Delta\dot{w}_{c1}/\Delta\dot{w}_{c2}$ K_c	Overall Flow Gain $\dot{w}_r/\Delta\dot{w}_{c2}$ $K_p K_c$	
10	11-1-65	VA2	VA4M2	N_2	Evaluate larger diameter receiver. D_r/D_o = 1.6	Receiver performance remarkably improved. Indications are that further improvements will result with even larger receivers.	92.5	68.7	2.0	2.55	5.9	27	0	10.2	9.2	93.7	
11	11-1-65	VA2	VA4M2	N_2	Evaluate D_r/D_o = 1.7	No significant change from Test No. 10 performance	---	---	---	---	---	---	---	---	---	---	
12	11-2-65	VA2	VA4M2	N_2	Evaluate D_r/D_o = 1.9	Excellent performance was obtained. Complete receiver flow shutoff, good recovery, and a gain exceeding 200.	90	84	2.2	2.5	4.0	27	0	[illegible]	17.3	260	
13	1-19-66	VA2	VA4M2	H_2-O_2	Initial hot test on Task 1 Staged Vortex Amplifier. No configuration change from Test No. 12	Excellent receiver performance, bias point flow recovery and receiver flow shutoff. Overtemp. shutdown.	100	91	2.18	2.60	3.0	28	0	15.8	6.0	95	
14	2- 1-66	VA2	VA4M2	H_2-O_2	Rerun of Test 13. Improvements made in Test setup	Excellent overall performance.	100	94	2.26	2.52	6.2	28	0	20	9.4	188	
15	2-16-66	VA2	VA4M2	H_2-O_2	To obtain additional hot gas test data	Good performance, however, P_{e1} pressure not recorded. Data not reduced.	---	---	---	---	---	---	---	---	---	---	
16	4-29-66	VA2	VA4M2	H_2-O_2	Additional hot gas test data.	Overall performance below Test No. 14 because of poor P_{e1} pressure regulation.	86	86	2.53	3.19	4.15	27.2	0	31.8	4.5	143	(1)
17	4-29-66	VA2	VA4M2	H_2-O_2	Additional hot gas test data	Power stage gas generator did not ignite. Test not completed.	---	---	---	---	---	---	---	---	---	---	
18	5- 2-66	VA2	VA4M2	H_2-O_2	Checkout run in preparation for final Task 1 hot gas test	Good overall performance. System ready for final hot gas test.	91.5	91.5	2.34	2.53	4.03	27.2	0	51.0	---	153	(2)
19	5- 3-66	VA2	VA4M2	H_2-O_2	Final Task 1 hot gas test	Excellent overall performance. Several full-range modulations accomplished. Data exceeds specified performance.	94.5	91.9	2.295	2.510	6.13	27.4	0	14.4	15.3	220	

Task 1 Test Program Completed

(1) Poor gain resulted from a shift in power stage supply pressure.
(2) Facility checkout run, data incomplete.

SUMMARY OF RESULTS

A complete series of cold and hot gas tests resulted in the development of a 0.5 lb/sec staged hot gas system and in the demonstration of all static performance goals. The first 12 tests were accomplished with cold gas (N_2) and established the system's parameters. Development of a receiver was coupled with a control stage sizing program to optimize the system performance. The final system configuration, which met all requirements with cold gas, was demonstrated to have the same performance with hot gas.

The system was capable of modulating receiver flow from more than 90% flow recovery to complete shutoff, using either cold or hot gas. Flow gains in excess of 200 also were accomplished, both with cold gas and with hot gas. The final Task 1 system configuration dictated the Task 3 (2.0 lb/sec) hot gas system design.

A complete summary of the Task 1 tests is shown in Table 1. This table outlines in detail the Task 1 progress and summarizes the performance.

DESIGN OF FINAL CONFIGURATION

Power Stage - VA2

The power stage, VA2 (formerly designated the Phase 1 vortex amplifier in the previous test program, NAS 3-4198), which was used for all Task 1 tests, was modified at the start of the staged testing to improve the performance. The area of the annular inlet, located between the button periphery and the chamber cylindrical wall, was decreased from 4 times the vortex chamber outlet area (A_{o1}) to 3 times A_{o1}, and the number of control ports was decreased from 12 to 6 while maintaining the same total control flow area. Throughout the experimental development, the only changes to the power stage were various receiver diameters and receiver spacings to improve the system performance and to accomplish complete shutoff of the receiver flow. The final power stage design parameters are summarized in Table 2, and the power stage amplifier is shown in Figures 3, 4 and 5.

Table 2 - Task 1 Power Stage (VA2) Final Design Parameters

Chamber Outlet Diameter	D_{o1} = 0.695 in.
Chamber Diameter (approx. 6 D_{o1})	D_1 = 4.00 in.
Chamber Length (D_{o1}/3)	L_1 = 0.232 in.
Button Diameter	D_{B1} = 3.815 in.
Control Port Diameter (6 Ports)	D_{c1} = 0.077 in.
Receiver Diameter (D_{r1} = 1.9 D_{o1})	D_r = 1.320 in.
Receiver Spacing ($X_r \approx D_{o1}$)	X_r = 0.689 in.

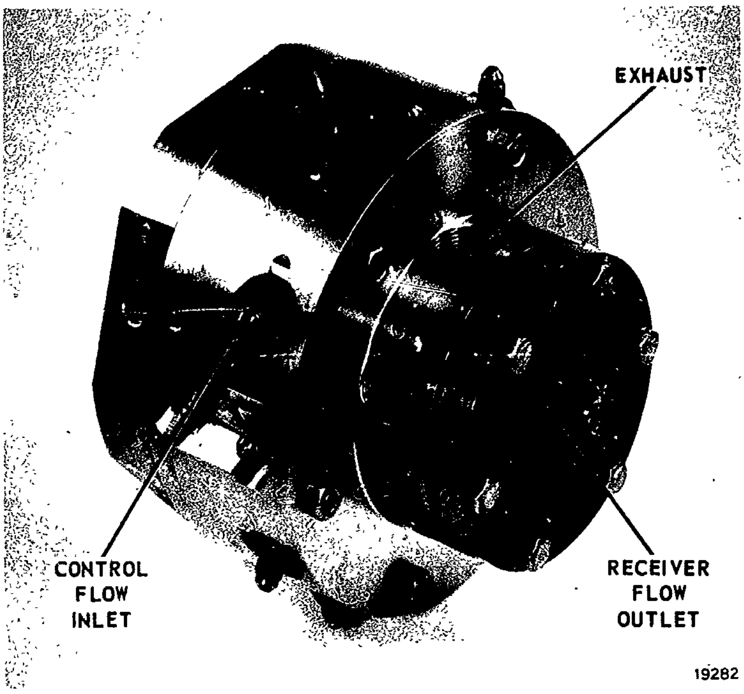


Figure 3 - Phase 1 Vortex Amplifier (Final Design)

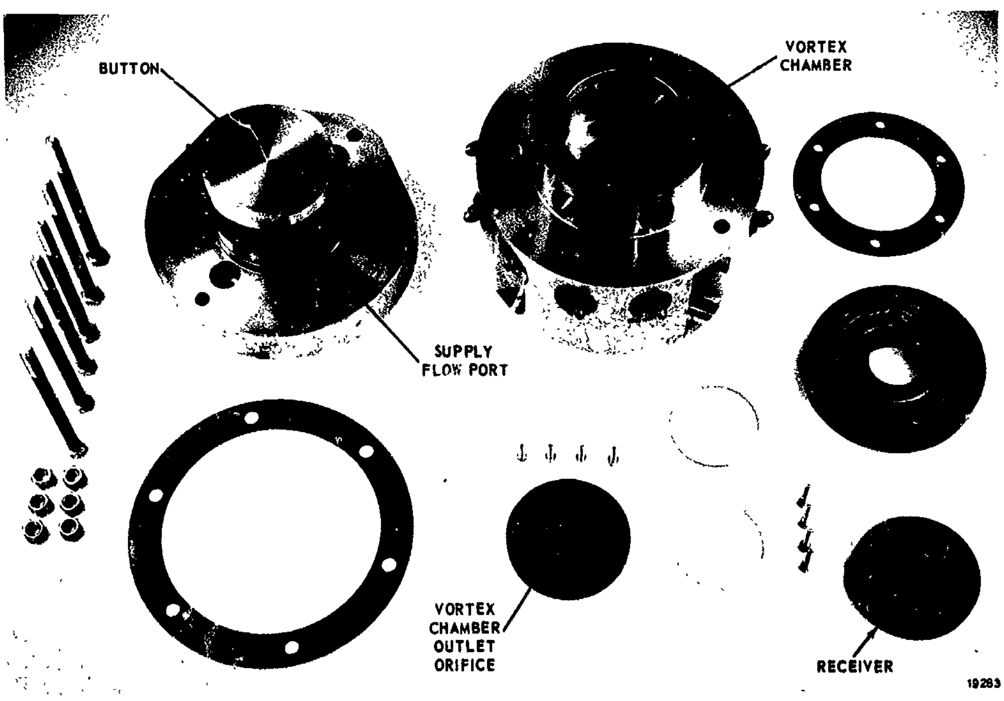


Figure 4 - Phase 1 Vortex Amplifier - Disassembled

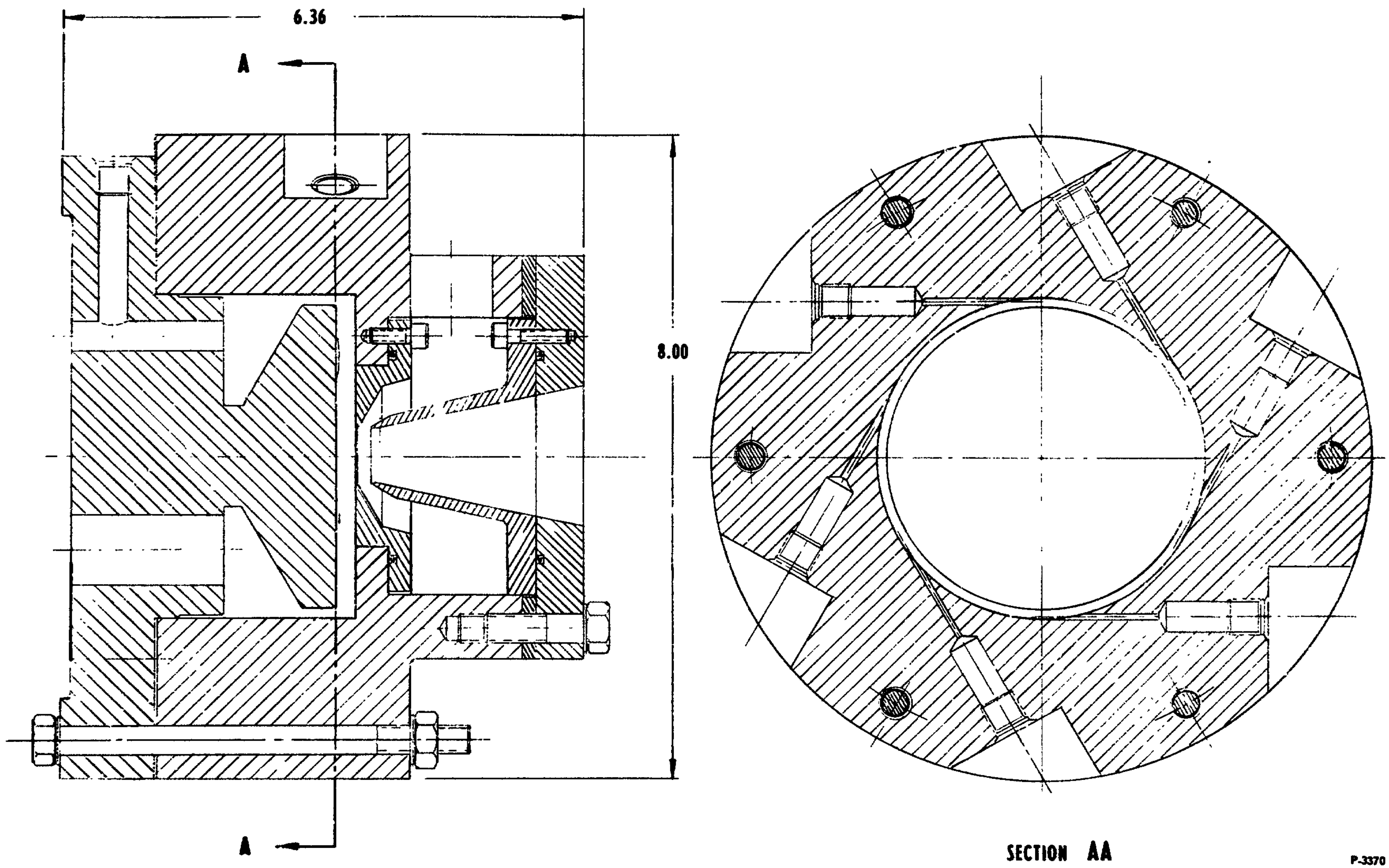


Figure 5 - Power Stage Vortex Amplifier, VA2

Control Stage — VA4M2

The final control stage design called for an increase in flow capacity over the design originally conceived at the beginning of Task 1. The increase in the maximum flow of the control stage allowed the control stage to operate in a partial turndown condition at receiver shutoff, thus shifting the modulating range of the control stage to a high-gain region. This resulted in an increase in the overall gain of the system.

The final control stage was designed for a total flow of 0.420 lb/sec (N_2) at a temperature of 500°R and a supply pressure of 800 psig. This maximum flow is delivered to the power stage at a pressure of 730 psig. The control stage vortex chamber outlet orifice size sets the capacity of the vortex amplifier. The orifice size is calculated as follows:

$$A_{o2} = \frac{\dot{w}_{c1}\sqrt{T}}{C_d\, C_2\, P_{s2}\, f_1\left(\frac{P_{c1}}{P_{s2}}\right)} \tag{1}$$

where

A_{o2} = outlet orifice area

$\dot{w}_{c1}$ = max control flow - 0.420 lb/sec (N_2)

T = gas temperature - 500°R

C_2 = constant - 0.523 $\sqrt{{}^\circ R}$/sec

P_{s2} = control stage supply pressure - 800 psig

P_{c1} = power stage control pressure - 730 psia

$f_1\left(\frac{P_{c1}}{P_{s2}}\right)$ = sonic flow function

C_d = discharge coefficient - assumed 0.7

From equation (1) the following dimensions are established:

A_{o2} = 0.0547 in^2

D_{o2} = 0.264 in. (vortex chamber outlet)

The chamber diameter was limited to approximately six times the chamber outlet diameter.

$$D_2 \cong 6\ D_{o2} \qquad (2)$$

A diameter of D_2 = 1.625 inches was used, which provided a diameter ratio of 6.18. The chamber length was established as one-third of the outlet diameter. Thus,

$$L_2 = \frac{D_{o2}}{3} = 0.088 \text{ in.}$$

The button diameter was sized to provide an annular inlet area around the button equal to 3 times the outlet area. In the design of the previous vortex amplifiers (NASA Contract NAS 3-4198) an area ratio of 4 to 1 was used. With this larger area, a portion of the supply flow apparently was unaffected by the influxing tangential control momentum, and this reduced the efficiency of the vortex flow field. The 3-to-1 area ratio was shown to increase the performance of the vortex amplifier in the very first cold gas staging test.

The annular area is determined by the button diameter which is calculated as follows:

$$D_{B2}^2 = D_2^2 - \frac{12A_{o2}}{\pi} \qquad (3)$$

The button diameter was calculated to be

$$D_{B2} = 1.558 \text{ in.}$$

Two important ratios evolved from the design of the control ports. The first is the unbiased flow gain which defines the control weight flow, and the second is the maximum control/supply pressure ratio. These ratios are:

$$\frac{\dot{w}_{c1}}{\dot{w}_{c2}} = 8 \qquad (4)$$

$$\frac{P_{c2}}{P_{s2}} = 1.3 \tag{5}$$

With four control ports, the weight flow through each is:

$$\dot{w}_{c2} = \frac{\dot{w}_{c1}}{32} \tag{6}$$

Using the orifice weight flow equation, the area of a single control port is defined as

$$A_{c2} = \frac{\dot{w}_{c1} \sqrt{T}}{32\ C_d\ C_2\ P_{c2}\ f_1\left(\frac{P_{s2}}{P_{c2}}\right)} \tag{7}$$

where

$T = 500°R$ (approximate temperature of nitrogen gas)

$C_d = 0.7$

$C_2 = 0.523\ \sqrt{°R}/\text{sec}\ (N_2)$

$P_{c2} = 1.3(815) = 1060$ psia

$\dot{w}_{c1} = 0.420$ lb/sec

$f_1\left(\frac{815}{1060}\right) = 0.860$

Solving the above equation, the area of a single control port was evaluated to be:

$$A_{c2} = 7.5 \times 10^{-4}\ \text{in}^2$$

and the control port diameter is:

$$D_{c2} = 0.031\ \text{in.}$$

The four control ports are equally spaced about the chamber circumference. Their centerlines are tangent to the chamber outer diameter and lie in a plane common with the face of the button.

Table 3 is a summary of the control stage final design parameters.

The control stage vortex amplifier final configuration (VA4M2) is shown in Figures 6 and 7 after completion of the test program.

Table 3 - Task 1 Control Stage (VA4M2)
Final Design Parameters

Chamber Outlet Diameter	D_{o2} = 0.264 in.
Chamber Diameter (approx. 6 D_{o2})	D_2 = 1.625 in.
Button Diameter	D_{B2} = 1.558 in.
Chamber Length ($D_{o2}/3$)	L_2 = 0.088 in.
Control Port Diameter (4 Ports)	D_{c2} = 0.031 in.

TASK 1 SYSTEM DEVELOPMENT AND EVALUATION

When two vortex amplifiers are staged in a series combination for maximum performance, it is desirable that the two vortex amplifiers operate simultaneously in their high-gain regions. Otherwise the full gain potential of connecting the amplifiers in series would not be achieved. This high-gain range must also coincide with the most effective receiver flow range, which is from complete receiver flow shutoff to at least 90% full flow recovery.

The high-gain matching of the two stages is accomplished by oversizing the control stage so that it can deliver the necessary control flow to completely turn down the power stage while the control stage itself is slightly turned down. The power stage, of course, also modulates within its high-gain region because of the biasing technique in which, even at maximum output, the power stage is subjected to some residual flow.

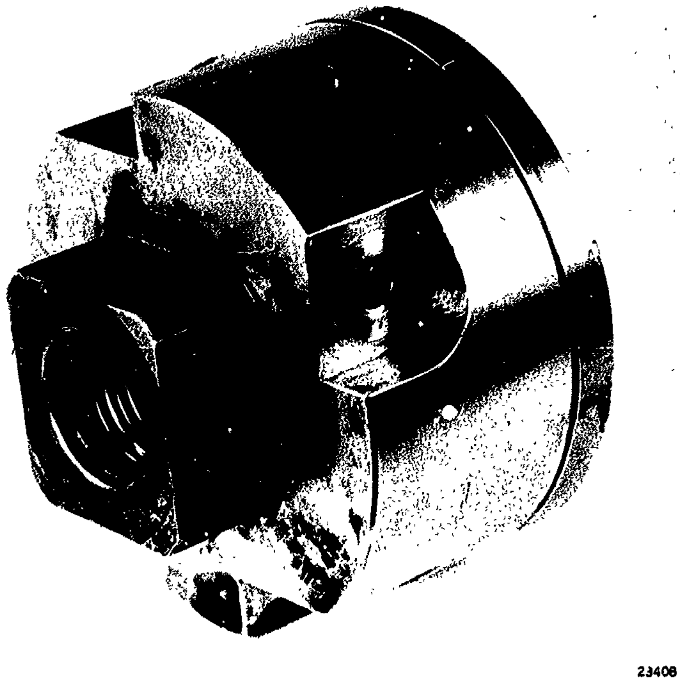


Figure 6 - Task 1 Hot Gas Control Stage VA4M2

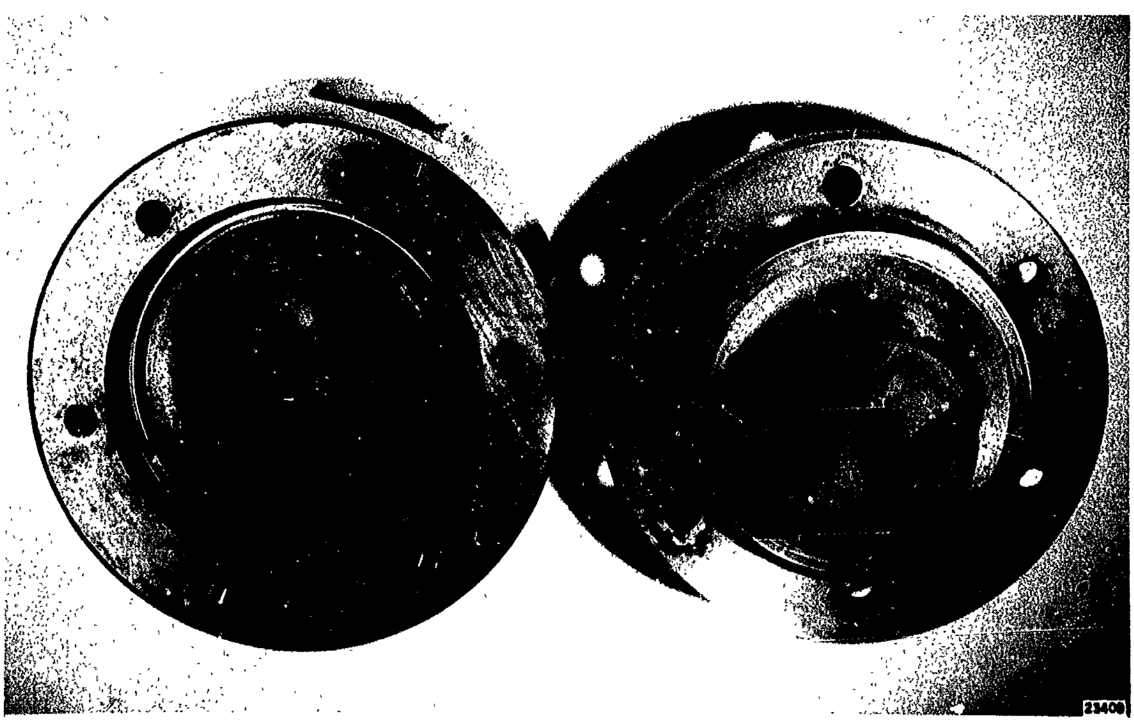


Figure 7 - Control Stage Vortex Amplifier VA4M2 Shown Disassembled After Test

These staging concepts were evaluated through both cold and hot gas tests, using the same facility for all tests. The Task 1 test facility was designed for 0.5 lb/sec hot gas flow tests, with provision for preliminary cold gas tests. The facility provided three cold gas sources which could be regulated at various pressure levels. It also provided two hydrogen-oxygen regulatory circuits capable of supplying H_2-O_2 at 0.8 O/F ratio to two gas generators which produced the 1500°F hot gas for the system.

The Task 1 hot gas test schematic is shown in Figure 8. The gas generator control system is shown in Figure 9 and a photograph of the hot gas test arrangement is shown in Figure 10.

The instrumentation, which consisted of two Sanborn recorders and a firing panel, was located inside the test building. Sixteen channels of data were used to measure gage and differential pressures and various temperatures. From this information, significant flows, pressures and temperatures throughout the system were measured or computed.

The general test procedure for both cold and hot tests was to initially set up 800 psig supply pressure in the control stage and 400 psig supply pressure in the power stage. The pilot pressure (i.e., the control pressure to the control stage) would then be varied from 1200 to 800 psig, thus modulating the system through a flow range from the bias point to full turndown. This procedure provided sufficient data for plotting the static performance nondimensionalized curves.

Control Stage Development

There were three control stages tested in Task 1. The first control stage, VA3M1 (Figure 11), which had been designated Breadborad No. 2 in the previous test program, was modified and employed in the initial staged cold gas test. This initial test revealed the necessity of increasing the control stage maximum flow. Even though the maximum flow was capable of turning off the power stage supply flow, the gain associated with the operating range was extremely low because of the low-gain characteristic of the control stage at maximum flow. This increase in capacity was incorporated into the first hot gas control stage, VA4M1, simply by increasing the outlet orifice diameter. This method of enlargement destroyed the original design parameter (D/D_o) of VA4 to the extent that the vortex amplifier exhibited erratic performance, which was attributed to an unstable vortex chamber. The instability was detrimental to the staging technique, since the system's performance was not repeatable. In the final control stage design, a new control stage, designated VA4M2, was manufactured which restored the diameter ratio of 6 to 1 and increased the flow capacity. This increase shifted the modulating range of the control stage to its high-gain region.

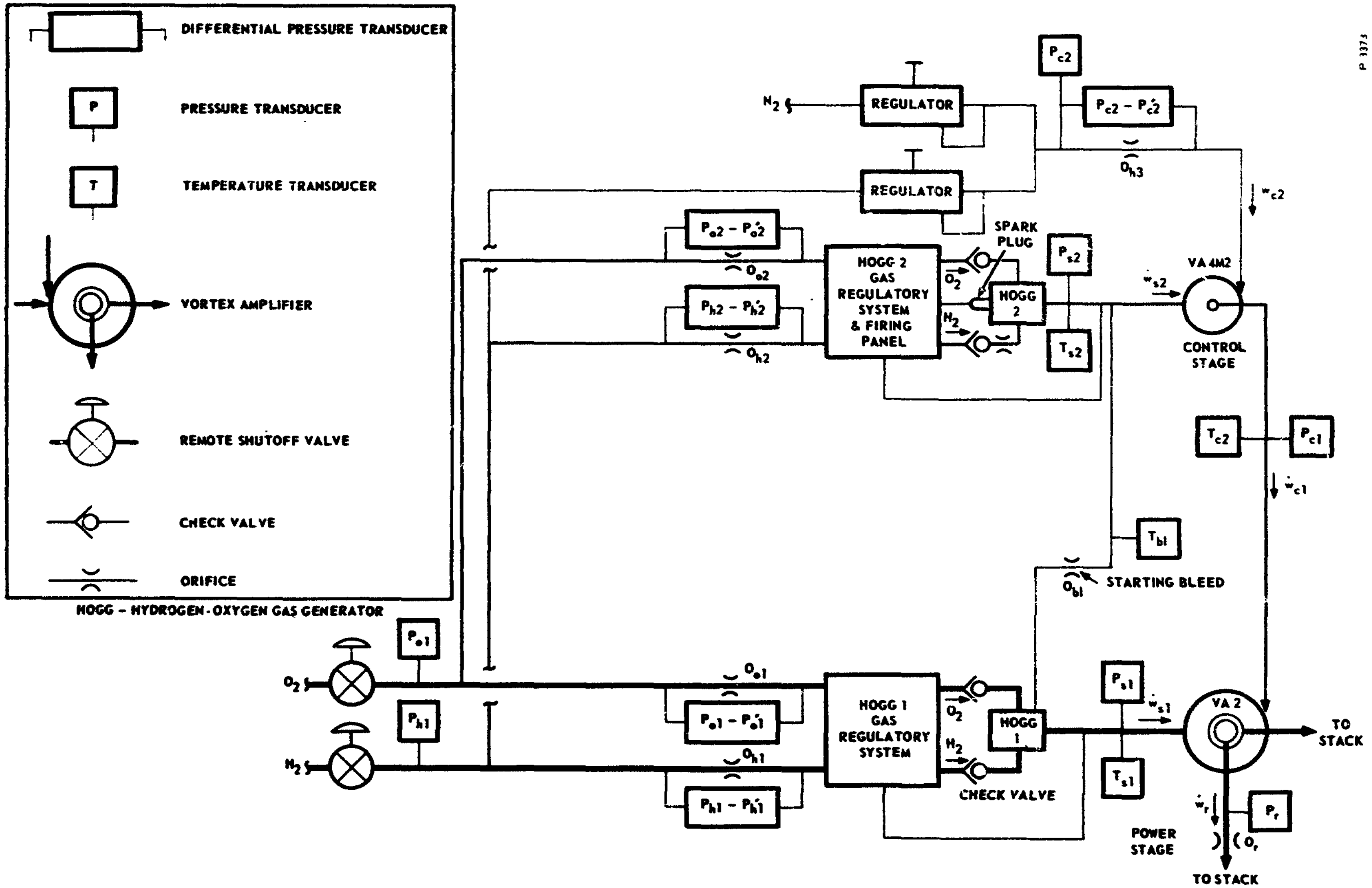


Figure 8 - Task 1 Hot Test Schematic

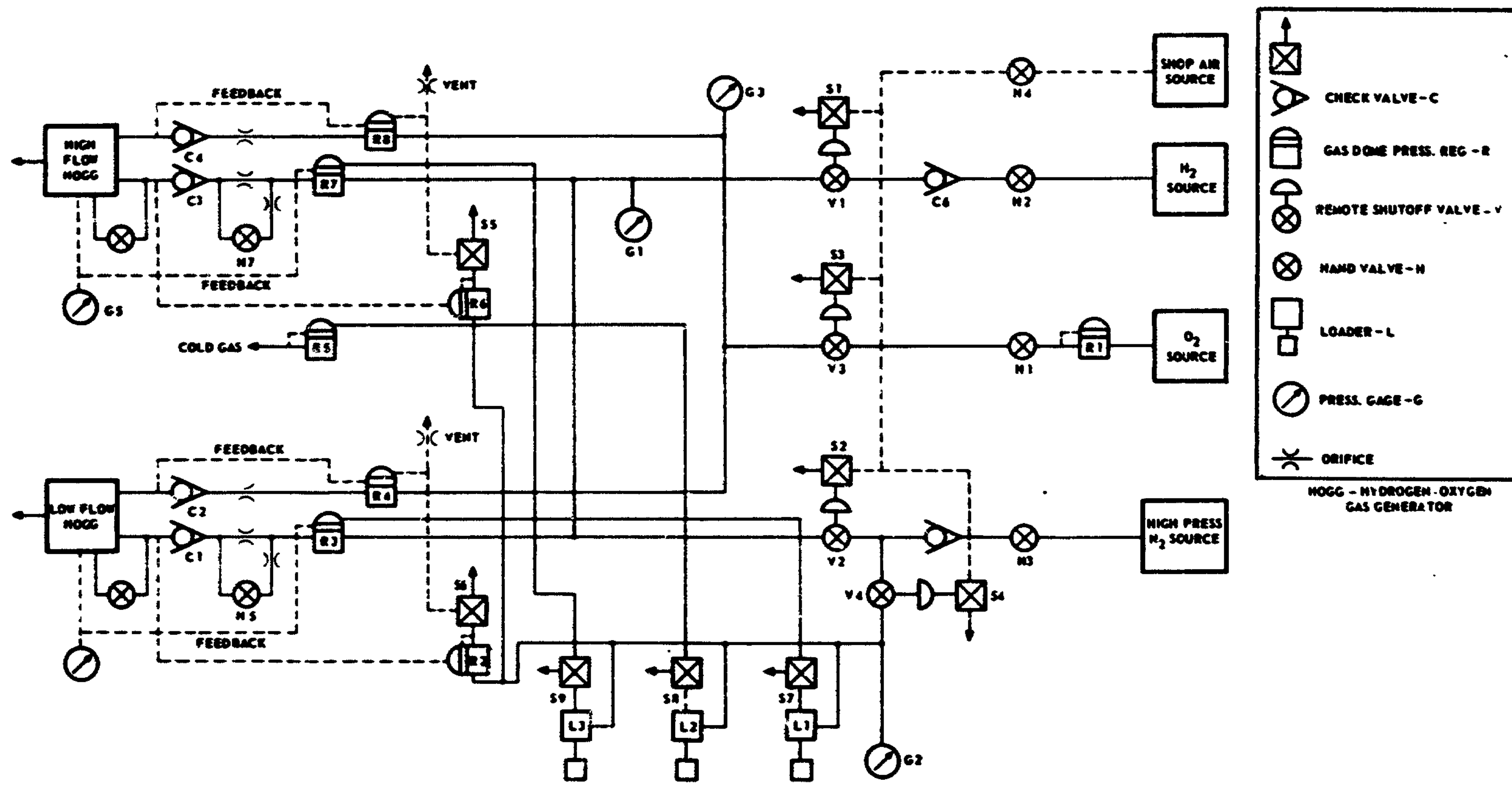


Figure 9 - Gas Generator Control System Schematic

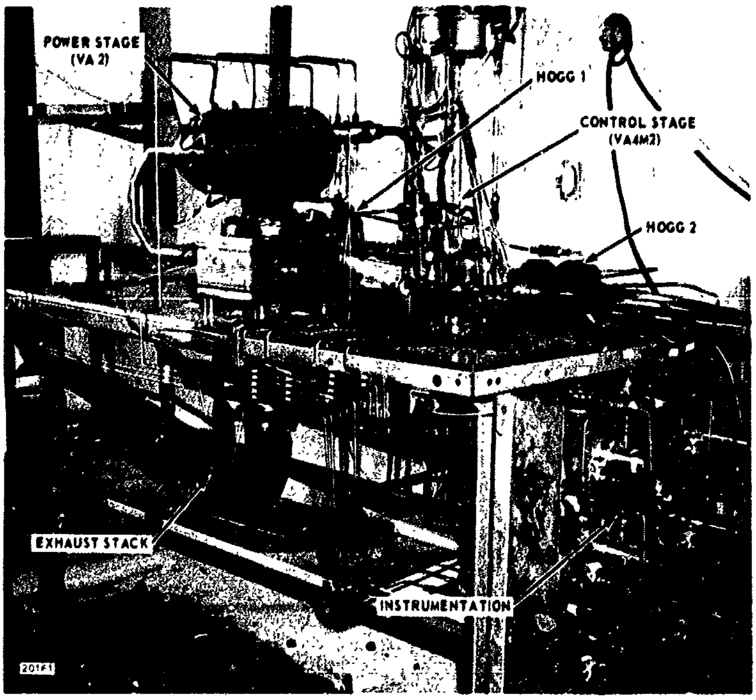


Figure 10 - Task 1 Test Stand (Setup for Hot Tests)

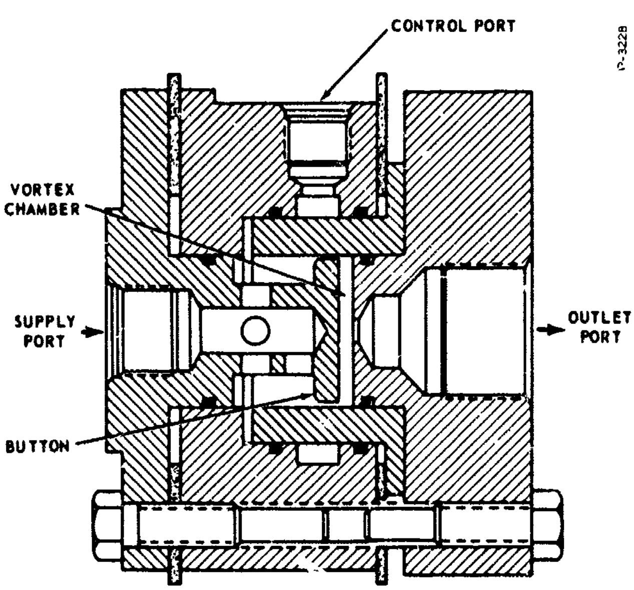


Figure 11 - Control Stage Vortex Amplifier VA3M1

Receiver Development

The position and diameter of the receiver determines the output performance of the staged system. For 90% flow recovery at the bias point and complete receiver shutoff, the receiver's diameter and position must be selected to allow the exiting gas of the vortex to miss the receiver at turndown; yet, at full flow, the receiver must catch a maximum amount of the gas. The receiver design which met these requirements (for both Task 1 and Task 3) was determined from an experimental analysis that was accomplished during the Task 1 testing. Complete details of this experimental analysis can be found in Appendix A. Essentially, the boundaries of the exiting gas were analyzed by a series of short tests, utilizing a series of receivers of different diameters so that the D_r/D_o ratio varied from 1.1 to 1.3. The various receivers were located at different positions and the maximum recovery and complete turndown recovery at each position were recorded. By establishing the points at which different size receivers would achieve either 100% flow recovery at maximum flow or zero recovery at full turndown, and plotting these points, a boundary mapping of the exiting gas was constructed, revealing a region in which the receiver theoretically could achieve both a maximum recovery of 100% and complete shutoff. The theoretical minimum receiver diameter was 1.7 D_o at a distance of 0.86 D_o. However, in the initial cold gas tests of Task 1, the diameter of the largest receiver used was 1.3 D_o.

Tests with larger receivers verified the experimental analysis. For the first time in the test program, both complete receiver shutoff at turndown and over 90% recovery at full flow were obtained. Overall gain for the system was 260 to 1. These tests finalized the receiver design at a receiver diameter of 1.9 D_o and at an axial position of 1.0 D_o from the outlet orifice of the power stage vortex chamber. The hot gas tests were then initiated to evaluate the design in a hot gas environment.

The seven hot gas tests in Task 1 completely verified the receiver design. These tests confirmed that the receiver design is one of the major factors in maximizing a staged vortex amplifier SITVC System. If the receiver diameter is correctly sized so that for a range of axial receiver locations the receiver remains in the theoretical region of maximum recovery and complete shutoff, the performance of the system is altered simply by moving the receiver. Figure 12 illustrates the graphical definitions of the system's performance for various receiver positions. The conclusions from this illustration are shown in Table 4.

Final Test Performance

The Task 1 test program was concluded with Hot Test No. 19. This test resulted in performance which met or surpassed specifications. A sufficient number of data points were obtained to firmly establish the system's performance. The data correlated well with the data from previous hot gas tests.

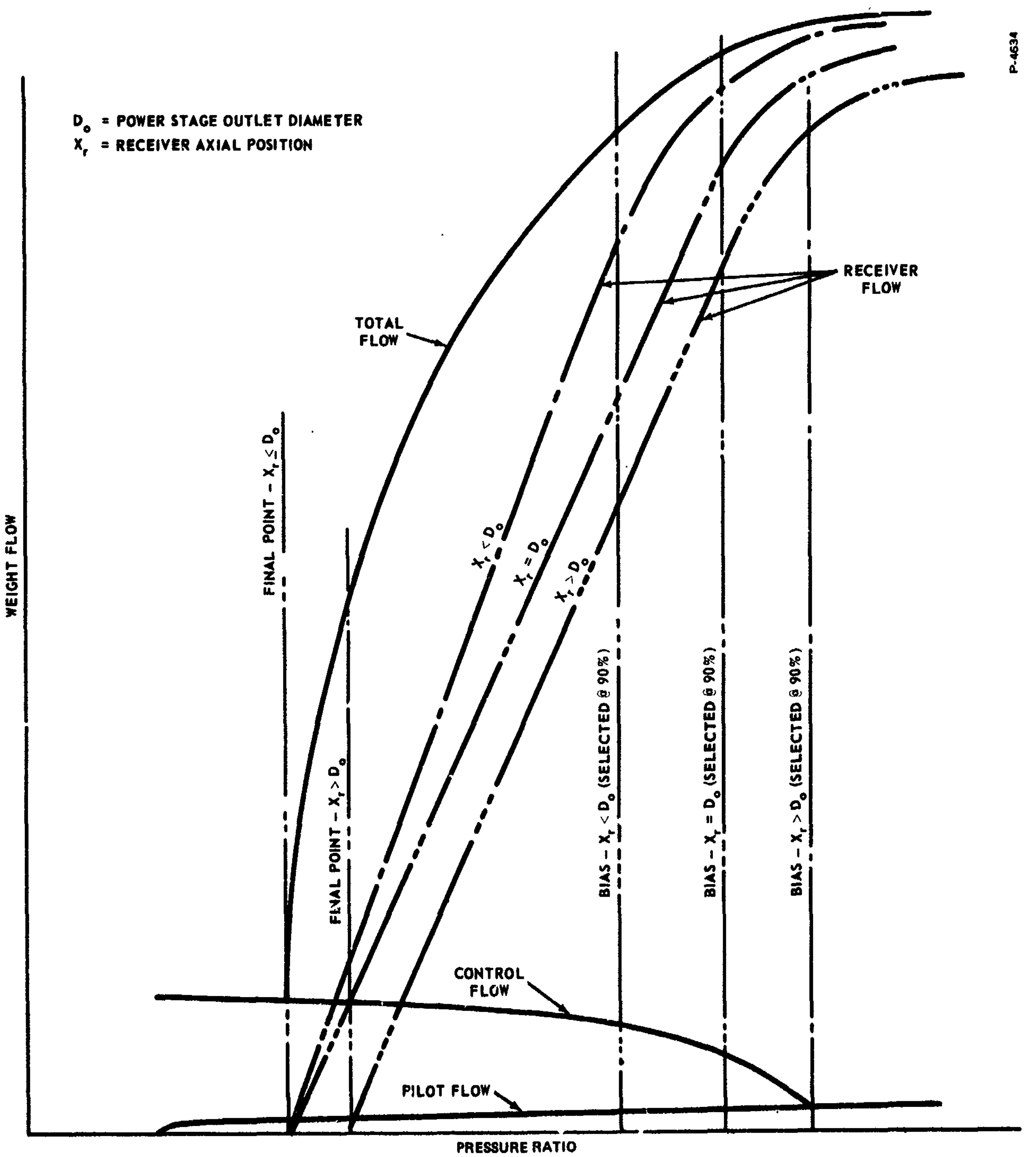


Figure 12 - Graphical Definitions of SITVC System Performance for Various Probe Positions

Table 4 - Performance Trends Related to Receiver Position

Receiver Position	Power Stage								Control Stage							
	Max. Total Flow	Max. Receiver Recovery	Receiver Recovery at Bias	Turndown of Total Flow at Receiver Shutoff	Receiver Shutoff	Pressure Ratio (P_{c1}/P_{s1}) at Receiver Shutoff	Max. Turndown Ratio	Power Stage Gain	Control Flow at Bias Point	Max. Pilot Pressure at Bias Point	Pilot Flow at Bias Point	Min. Pilot Flow at Receiver Shutoff	Control Flow at Shutoff	Control Stage Gain	Max. Pilot Press. to Power Stage Supply Press.	Total Gain
$X_r < D_{o_1}$	—	↑	Selected	—	—	—	—	↑	↑	↓	↓	↓	—	↓	↓	↓
$X_r = D_{o_1}$			Selected			OPTIMUM PERFORMANCE										
$X_r > D_{o_1}$	—	↓	Selected	↓	—	↓	—	↓	↓	↑	↑	↑	↓	↑	↑	↑

Key

↑ Increase in Performance

↓ Decrease in Performance

— Equal to Optimum Performance

P-4634

Table 5 - Test No. 19 Performance Summary

	Test Data	Specification
Bias Point (P_{c2}/P_{s1})	2.510	—
Final Point (P_{c2}/P_{s1})	2.295	—
Flow Recovery at Bias Point	91.9%	90%
Total Flow Turndown	6.13 to 1	5 to 1
Pressure Recovery	27.4%	25%
Receiver Flow Shutoff	0%	0%
Total Gain	200	200

The performance obtained in this test is compared with the specified performance in Table 5. Figure 13 shows the performance plotted on the conventional format, and Figure 14 shows the same performance plotted on an input-output basis in the secondary injection thrust vector control application.

A significant point of this test was that five full-flow modulations were accomplished. The gas generator supplying the power stage supply flow was extinguished and automatically reignited with each modulation. Maximum supply gas temperatures were 1550°F and 1250°F from the power and control stage gas generators, respectively. The test was operated for a period of 130 seconds and was manually shut down. The total flow turndown, including the ignition bleed flow between gas generators, was 6.13 to 1, which exceeds the specified requirement of 5.0 to 1. The ignition bleed flow is the difference between total flow and control flow at pressure ratios lower than P_{c2}/P_{s1} = 2.3 (Figure 13).

The initial receiver flow recovery was 94.5% at a total flow of 0.502 lb/sec, which slightly exceeds the specification flow of 0.5 lb/sec. A flow recovery of 91.5% was accomplished at the bias point.

An overall system flow gain of 220 was demonstrated. This gain is the product of a power stage gain of 14.4 and a control stage gain of 15.3. Receiver flow was modulated from 0.45 lb/sec to zero, while the modulation range of the pilot flow cold hydrogen gas was 0.002 lb/sec.

Thus, the two-stage vortex amplifier equaled or exceeded the specified performance in overall flow gain, flow turndown, flow recovery, pressure recovery and flow shutoff.

Although the best gain demonstrated in a hot gas test was 220, while the best gain in a cold gas test was 260, the hot gas performance of the amplifiers actually was better. This conclusion arises from the fact that in the cold tests the same gas was used throughout the system, whereas in the hot tests cold hydrogen pilot flow controlled the hot gas supply. If hot gas could have been used as pilot flow also, the gain would have been about 50% greater. The reason for this is that, for a given weight flow rate, the denser cold gas has a lower velocity through the control port and therefore a lower momentum; to achieve the same momentum, its weight flow rate must be higher.

Correspondingly, the pilot flow momentum change required to fully modulate the staged amplifier represents a higher input flow rate change with cold pilot H_2 gas than it would with hot pilot gas. Since gain is the ratio of output flow change to input flow change, the higher input flow rate change of the cold pilot gas reduces the gain in proportion.

A significant result of the amplifier tests has been the demonstration that cold gas performance corresponds very well with hot gas performance, both for individual amplifiers and for the staged system. Thus development programs can be expedited by using cold gas testing to optimize components or systems, and reserving hot gas testing for final system demonstration or for tests related to thermal effects and hardware endurance.

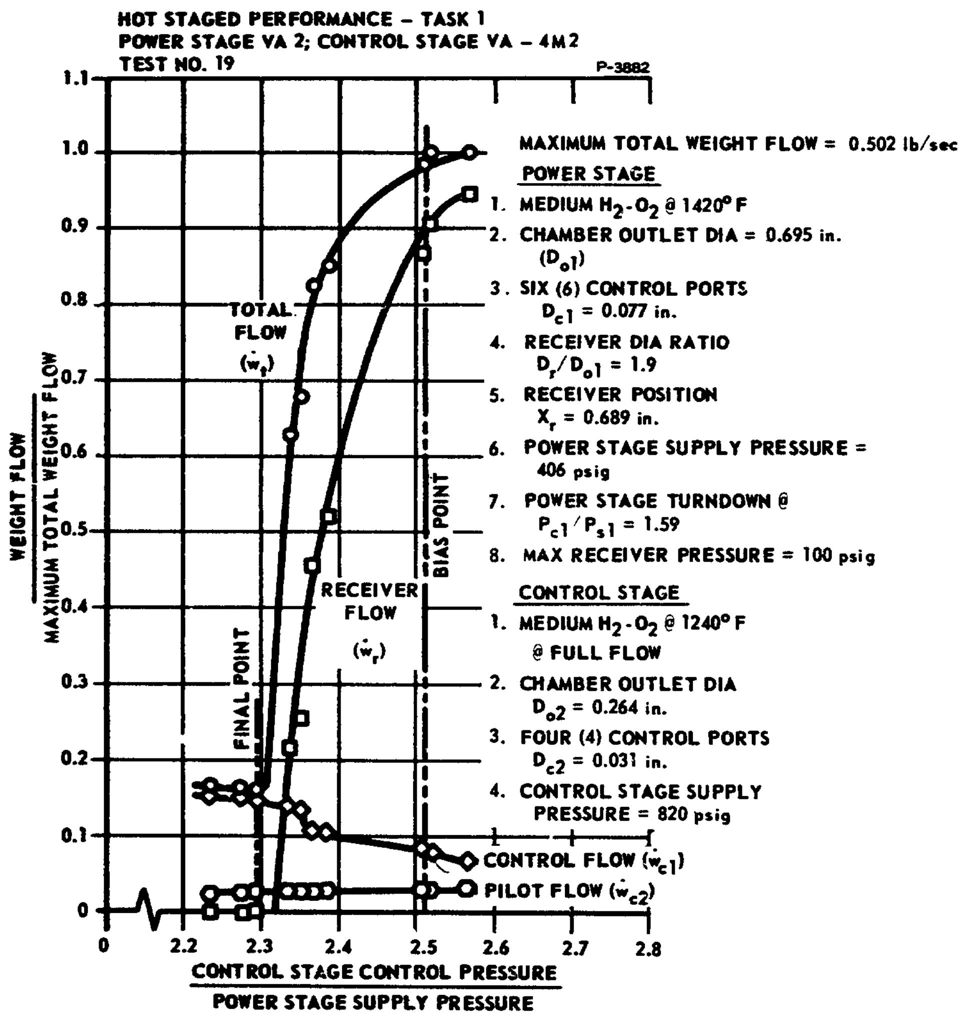


Figure 13 - Task 1 Test No. 19 Performance Curves

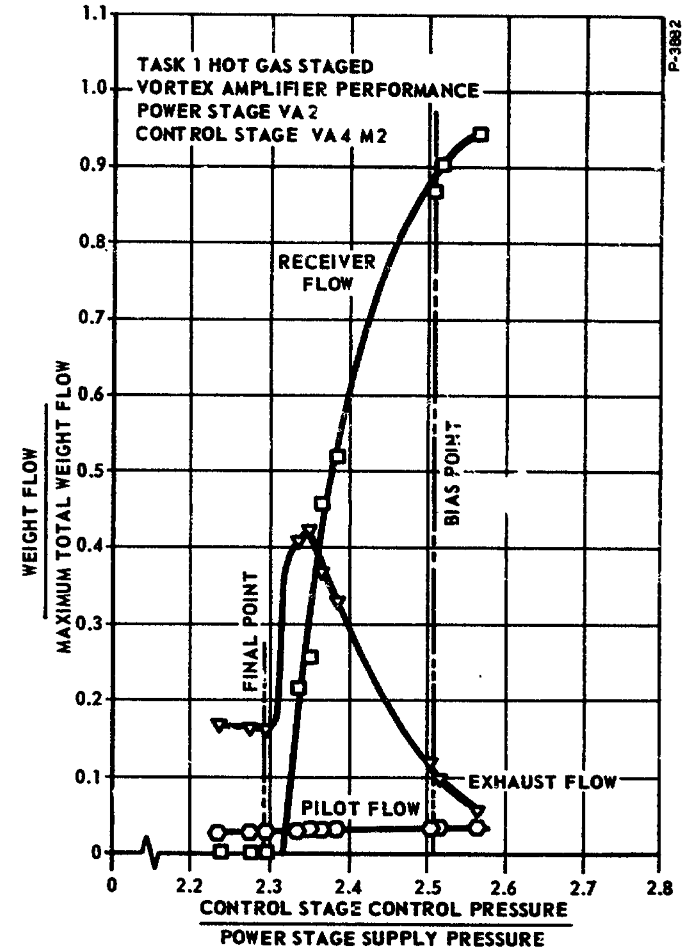


Figure 14 - Task 1 Test No. 19 Performance Curves Showing SITVC Flows

DEVELOPMENT OF VORTEX-DOUBLET GAS GENERATORS
(TASK 2)

The objective of Task 2 was to develop two compact hydrogen-oxygen gas generators that could be integrated with the control stage and power stage vortex amplifiers in the full-scale SITVC system in Task 3. It was desired that these gas generators be small and have low L^* (ratio of combustion volume to outlet area) to save space and weight and to improve response. Therefore, a vortex-doublet type of generator was developed. In this type of combustor, the fuel and oxidizer are injected together in a doublet and burn while flowing in a vortex toward the outlet at the center. The technique permits a long burn path in a small space and thus achieves efficient combustion in a compact configuration. The vortex-doublet type of combustor had been used successfully by Bendix with hypergolic bipropellants in small rocket engines. The task of the current program was to develop the concept for hydrogen and oxygen with spark ignition.

SUMMARY OF RESULTS

Task 2 resulted in the successful development of two hydrogen-oxygen gas generators of vortex-doublet design. These generators are designated HOGG3[†] and HOGG4 and were designed to provide the hot gas supply flow to the Task 3 control and power stages, respectively. Their principal performance parameters are summarized in Table 6.

Table 6 - Gas Generator Performance Parameters

	Hot Gas Output Weight Flow pps	O/F Ratio	Hot Gas Output Pressure psig	Gas Temp.
HOGG3	0.33	0.8	800	1500
HOGG4	2.00	0.8	400	1500

Most of the effort in Task 2 was in the development of the HOGG3 gas generator. HOGG4 was designed in this Task but was test evaluated in Task 3. More than eleven minutes of hot testing was accomplished on HOGG3 in seventeen individual tests during Task 2. Additional test time was accumulated in the Task 3 test program.

A summary of all of the Task 2 tests is shown in Table 7. The test series ended with test No. 3G-7B, in which three complete shutoffs and restarts were accomplished. Combustion was maintained through a turndown of 6:1. Modulation and shutoff of the gas generator was accomplished by throttling the output with VA5, the vortex amplifier that was used as the

[†]Hydrogen-Oxygen Gas Generator

Table 7 - Task 2 Test Summary

Test No.	Date	Configuration *	Chamber Pressure psia	Flow Range (Max. flow/ Min. flow)	Max. Temp. °F	Duration sec.	Results
3G-1A	11-15-65	I	Approx. 800	1	1280	19	Damaged housing and O_2 injector.
3G-1B	2-4-66	II	Approx. 800	1	660	28	Damaged housing and O_2 injector.
3G-1C	3-2-66	III	565	1	1460	17	No damage to housing. Oxygen injectors slightly eroded.
3G-2A	3-4-66	III	715	1	760	60	No damage to housing. Oxygen injectors slightly eroded.
3G-1D	3-14-66	III	775	1	775	26	No damage to housing. Quartz shields did not protect stainless steel oxygen injectors.
3G-1E	3-15-66	III	825	1	920	33	No damage to housing. Stainless steel oxygen injector slightly eroded.
3G-1F	3-16-66	III	835	1	1540	25	No damage to housing. S.S. O_2 injectors from test 3G-1E reused. No additional erosion.
3G-3A	3-18-66	III	815	1.9	1500	34	No damage to housing. S.S. O_2 tubes from 3G-1E reused. No additional damage to one injector. Other injector tube eroded.
3G-4A	3-28-66	III	815	2.1	2280	37	No damage to housing. One S.S. O_2 tube completely eroded, one slightly damaged.
3G-4B	3-30-66	III IV	845	2.2	2300	37	No damage to housing. O_2 injectors - one copper, one S.S. - no damage.
3G-4C	3-31-66	III IV	815	2.6	2400	58	No damage to housing. Same O_2 injectors (3G-4B). No damage.
3G-4D	4-1-66	III IV	815	2.5 approx.	1850	93	No damage to housing or injectors. Dummy vortex valve destroyed by high temp. gas. Oscillatory condition in propellant feed system due to damaged H_2 regulator. Drastic periodic shifts in O/F ratio.
3G-2B	6-10-66	III IV	715	1	1340	67	Slight damage to housing caused by free O_2 stream below chamber surface. Free O_2 stream a direct result of pretest damage to tip of S.S. O_2 injector.
3G-5A	6-27-66	III	799	4.3	1520	72	No damage to housing. O_2 injectors - both copper - no damage. Complete shutoff was accomplished.
3G-6	This Flow Range was evaluated during Tests 3G-7A and 3G-7B						
3G-7A	6-27-66	III	800 approx.	Complete Shutoff	2000	54	No damage to housing or injectors. 3 complete modulations to shutoff were accomplished.
3G-7B	6-28-66	III	835	Complete Shutoff	1900	70	No damage to housing or injectors. 3 complete modulations to shutoff were accomplished. Combustion maintained through 6-to-1 flow range.
Test Series Concluded							

*See Task 2 Testing Section for explanation of configurations.

control stage in Task 3. Nitrogen gas was used as the control flow to VA5.

Gas generator development was started in the preceding contract, NAS 3-4198, with the design and development of a long cylindrical configuration. The hydrogen was tangentially injected at the outer wall at the end of the cylinder to provide a swirling layer of fuel gas adjacent to the walls. The oxygen was injected axially at the same end of the cylinder, and the mixture was ignited by a spark plug. As the swirling gases moved down the cylinder they combined and burned before reaching the outlet hole. This design, though functionally satisfactory, was excessively large in size.

The vortex-doublet design developed at the Bendix Research Laboratories employs a flat pancake-type combustion chamber so that the L^* is very small. Both propellants are introduced at the outer radius, with hydrogen injected tangentially and oxygen injected radially. As in the previous design, the walls of the combustion chamber are protected against direct contact with the oxygen by a layer of hydrogen. Ignition is accomplished by a spark plug in an oxygen-rich, low pressure starting gas mixture. Combustion occurs as the two propellant gases combine in a swirling mixture and spiral to the outlet hole in the center of the combustion chamber.

This pancake configuration is suitable for integration with vortex amplifiers in general because its major diameter is approximately the same as the major diameter of the vortex amplifier which it supplies. The addition of this type of gas generator to a vortex amplifier increases the package length somewhat. But this added length is not very great because the vortex amplifier internal volume supplements the gas generator volume, thus permitting the generator combustion chamber to be very short. The volume of the combustion chamber, itself, is only a portion of the volume that is normally termed L^* in a combustor. The supply and vortex chamber volume of the vortex amplifier is added to the combustion chamber volume because the flow-restricting orifice for the system is the vortex amplifier outlet hole.

GAS GENERATOR DESIGN

The two hydrogen-oxygen gas generators, HOGG3 and HOGG4, were designed to be integrated with the two-stage vortex amplifier which was developed in Task 3.

Flows and Pressures

The control stage gas generator, designated as HOGG3, was designed to deliver 0.3 lb/sec of hot gas at a temperature of 1500°F and a pressure of 800 psig. The power stage gas generator, designated as HOGG4, was designed to deliver 2.0 lb/sec of hot gas at a temperature of 1500°F and a pressure of 400 psig.

Figure 15 shows a plot of the adiabatic bulk temperatures resulting from the reaction of oxygen with an excess of hydrogen for various reactant

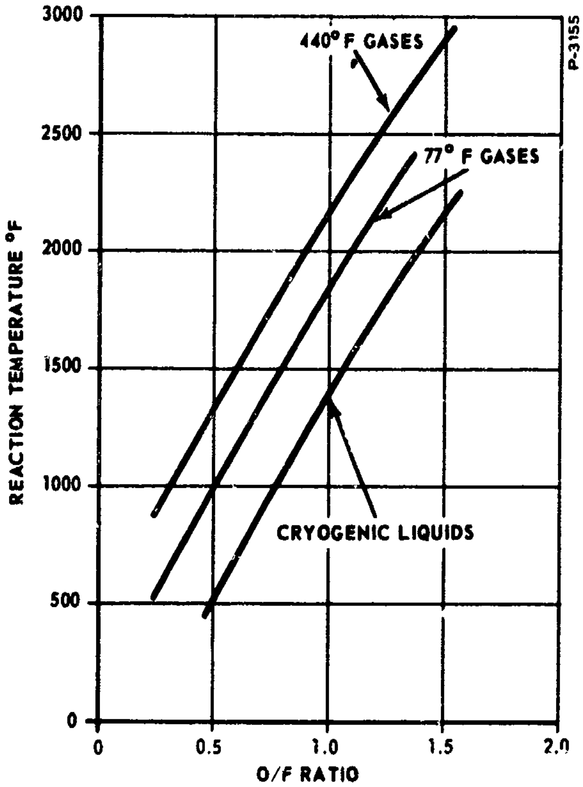


Figure 15 - Adiabatic Bulk Temperature as a Function of O/F Ratio

temperatures and oxidizer-to-fuel weight ratios (O/F). From this figure, the theoretical O/F ratio corresponding to a hot gas temperature of 1500°F and a reactant temperature of 77°F is 0.8. The actual O/F ratio required to obtain a hot gas temperature of 1500°F is somewhat higher because of heat losses from the system and must be determined experimentally. However, the theoretical O/F ratio is sufficiently close to the actual value to be suitable for design calculations.

For an O/F ratio of 0.8, the oxygen flow into the gas generator was computed from:

$$\dot{w}_{so} = \frac{0.8\ \dot{w}_s}{1.8} \qquad (1)$$

and the hydrogen flow was computed from:

$$\dot{w}_{sh} = \frac{\dot{w}_s}{1.8} \qquad (2)$$

where

$\dot{w}_s$ = hot gas flow into vortex amplifier supply - lb/sec

$\dot{w}_{so}$ = oxygen flow into gas generator - lb/sec

$\dot{w}_{sh}$ = hydrogen flow into gas generator - lb/sec

The hydrogen and oxygen were stored in gaseous form in pressure bottles. As the reactants were consumed, the storage pressure decayed from its initial value and eventually reached a value which was too low to operate the system. One obvious limitation on the minimum storage pressure was the maximum value of the control pressure for control stage vortex amplifier VA5, which was estimated as 1200 psig. It was assumed that the minimum gas storage pressure was 1200 psig; then the minimum pressure drop between HOGG3, which had a chamber pressure of 800 psig, and the reactant control valve inlets was 400 psid. Half of this pressure drop was allowed for the control valve and half for the injectors. Thus, the maximum inlet pressure drop for HOGG3 was 200 psid, which was approximately the value used with HOGG1 in Task 1. Since HOGG4 had a chamber pressure of 400 psig, the minimum pressure drop between it and its reactant control valve inlets was 800 psid. Of this differential, 300 psid was allowed for the drop across the gas generator inlet ports.

Gas generators HOGG3 and HOGG4 were designed on the basis of the following maximum flows and corresponding pressures:

$$\dot{w}_{so1} = \frac{0.8 \times 2}{1.8} = 0.89 \text{ lb } O_2/\text{sec}$$

$$\dot{w}_{sh1} = \frac{1 \times 2}{1.8} = 1.11 \text{ lb } H_2/\text{sec}$$

$$\dot{w}_{so2} = \frac{0.8 \times 0.3}{1.8} = 0.133 \text{ lb } O_2/\text{sec}$$

$$\dot{w}_{sh2} = \frac{1 \times 0.3}{1.8} = 0.167 \text{ lb } H_2/\text{sec}$$

$$P_{g1} = 400 \text{ psig}$$

$$P_{g2} = 800 \text{ psig}$$

$$P_{so1} = P_{sh1} = P_{g1} + 300 = 700 \text{ psig}$$

$$P_{so2} = P_{sh2} = P_{g2} + 200 = 1000 \text{ psig}$$

where

P_g = hot gas pressure - psig

P_{so} = gas generator O_2 inlet pressure - psig

P_{sh} = gas generator H_2 inlet pressure - psig

Subscript 1 refers to power stage HOGG4

Subscript 2 refers to control stage HOGG3

Vortex Amplifier Geometry

Since the gas generators and the vortex amplifiers form one integrated assembly, it was impractical to design the gas generators independently of the vortex amplifiers. The following vortex amplifier dimensions which are of significance to the gas generator design were estimated in Reference 1.*

$$A_{o1} = 1.77 \text{ in}^2$$

$$D_1 = 9.0 \text{ in.}$$

$$A_{(ann)1} = 5.31 \text{ in}^2$$

$$A_{o2} = 0.143 \text{ in}^2$$

$$D_2 = 2.50 \text{ in.}$$

$$A_{(ann)2} = 0.428 \text{ in}^2$$

*See Appendix B for list of references.

where

A_o = outlet area of vortex amplifier - in^2

$A_{(ann)}$ = area of annulus button of vortex amplifier chamber - in^2

These parameters represent the results of preliminary design calculations.

Connections to Gas Generator

Figure 16 is a schematic showing the relationships between the two gas generators, the two vortex amplifiers and the required porting for the gas generators. These are as follows:

(1) Hydrogen inlet

(2) Oxygen inlet

(3) Nitrogen inlet

(4) Feedback port

(5) Supply pressure sensing port

(6) Supply temperature sensing port

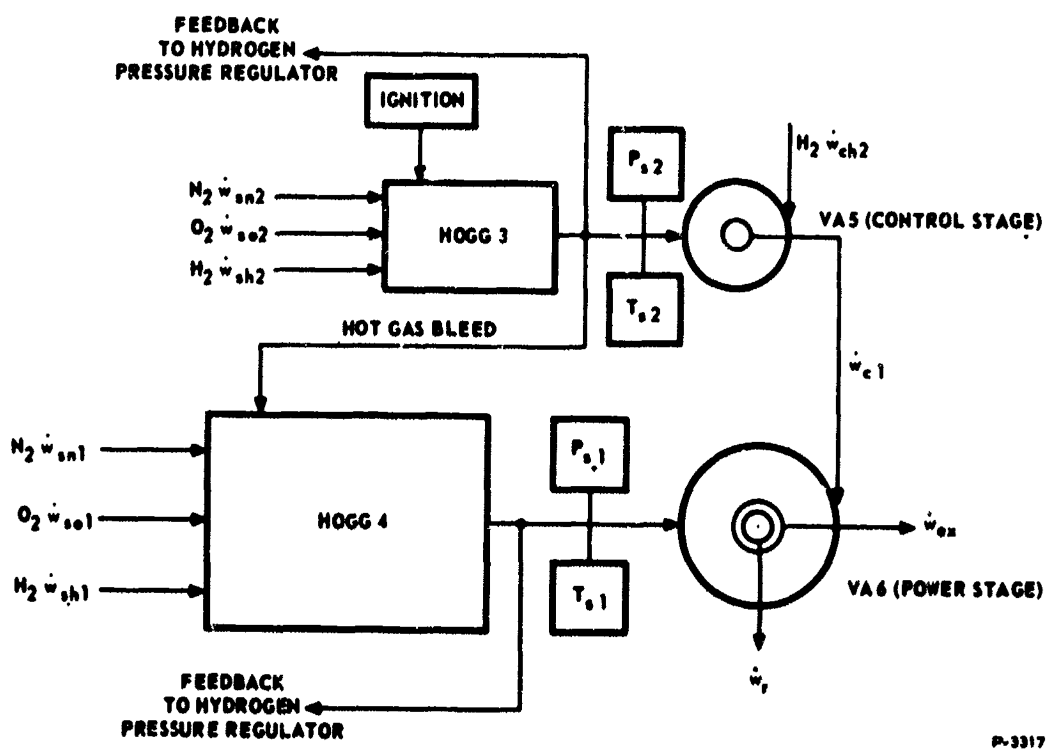


Figure 16 - Schematic Showing Connections to Gas Generators

(7) Connection to vortex amplifier

(8) Connection to ignition source

The purpose of the hydrogen and oxygen inlet ports is to admit the reactants into the combustion chamber. The purpose of the connection to the vortex amplifier is to deliver the hot gas to its point of use. The supply pressure and temperature sensing ports are required to permit measurement of these parameters. The feedback port is required to transmit the hot gas supply pressure to the hydrogen control valve which modulates the hydrogen flow to maintain the hot gas pressure at a desired value. The nitrogen inlet port is required to supply nitrogen used for room temperature testing of the system, because the hydrogen injection ports are not large enough to supply the flow of room temperature nitrogen necessary to fully pressurize the system. The low flow gas generator was started by using a spark plug as an ignition source. This was satisfactory, because there was continuous flow through this gas generator, making it necessary to ignite it only once during a run. However, the flow through the large gas generator was periodically shut off during a run and some method of automatic reignition upon the resumption of flow demand was needed. This was provided by bleeding a small quantity of hot gas from the small gas generator to the large one. The small gas generator was always at a higher pressure than the large one and this hot gas bleed flowed continuously, furnishing an ignition source for the large gas generator.

Calculation of Significant Chamber Dimensions

Figure 17 is a schematic of a vortex-doublet gas generator with as associated vortex amplifier. The schematic indicates the notation for geometry and pressures as follows:

A_o = outlet area of vortex amplifier - in^2

$A_{(ann)}$ = area of annulus around button of vortex amplifier - in^2

A_s = outlet area of gas generator - in^2

D_o = diameter of vortex amplifier outlet - in.

D = diameter of vortex amplifier chamber - in.

D_s = diameter of gas generator outlet - in.

D_g = diameter of gas generator - in.

D_{sh} = diameter of single H_2 inlet orifice - in.

D_{so} = diameter of single O_2 inlet orifice - in.

L_g = length of gas generator - in.

P_s = vortex amplifier supply pressure - psig

P_{so} = gas generator O_2 supply pressure - psig

P_g = gas generator pressure - psig

P_{sh} = gas generator H_2 supply pressure - psig

A major objective of the design was to minimize the size of the overall assembly of gas generators and vortex amplifiers. Hence, the combustion chamber volume was made as small as is consistent with combustion stability and acceptable temperature of the structure. The vortex-doublet gas generator is characterized by a "pancake-shaped" combustion chamber having $L_g/D_g < 1$. The name "vortex-doublet" implies a combustion chamber in which the propellants are injected at the periphery in a doublet and combine while traveling in a vortex, following a spiral path to a center outlet hole. The oxygen is injected into the chamber in a radial direction while the hydrogen is injected tangentially. The hydrogen flow induces a vortex flow field, and combustion is accomplished along a spiral flow path. This provides an extended average path for burning and results in a compact configuration. In other projects using hypergolic liquid bipropellants, stable, efficient combustion has been realized using a characteristic length, L^*, of 7 inches.

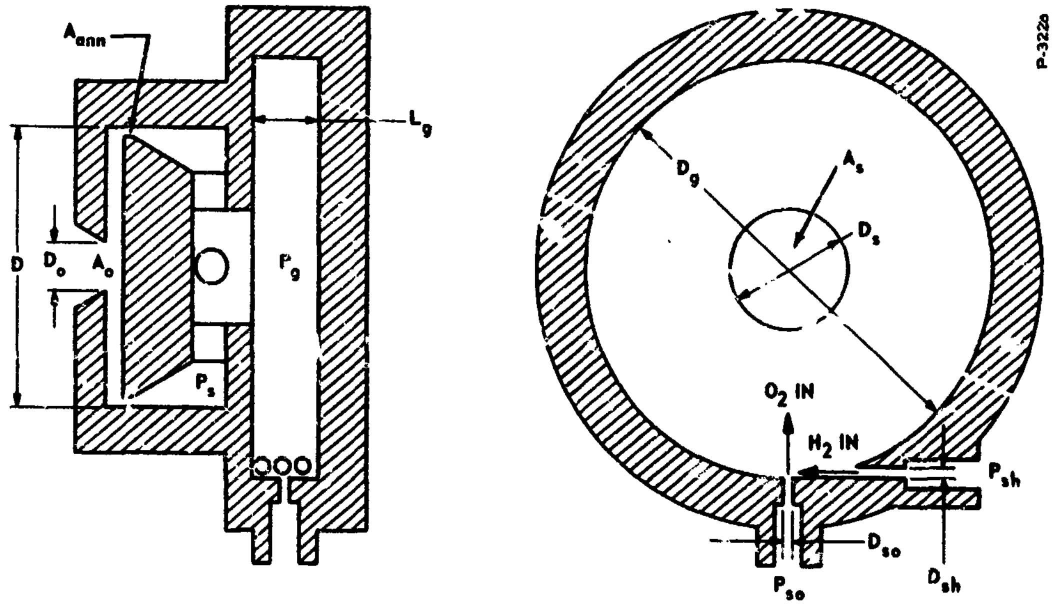


Figure 17 - Schematic of Vortex-Doublet Gas Generator with Associated Vortex Amplifier

The first step in sizing the gas generator was to determine the size of the inlet orifices. The effective areas of the orifices are given by:

$$(C_d A)_i = \frac{\dot{w} \sqrt{T}}{C_2 \, P_u \, f_1 \left(\frac{P_d}{P_u}\right)} \qquad (3)$$

where

$(C_d A)_i$ = effective area of inlet orifice - in^2

$\dot{w}$ = gas weight flow - lb/sec

T = absolute temperature of gas at zero velocity - °R

C_2 = characteristic coefficient of gas - $°R^{1/2}$/sec

P_u = upstream absolute pressure - psia

P_d = downstream absolute pressure - psia

$f_1 \left(\frac{P_d}{P_u}\right)$ = sonic flow function

$$C_2 = \sqrt{\frac{k \, g}{\frac{R^*}{M} \left(\frac{k+1}{2}\right)^{\frac{(k+1)}{(k-1)}}}} \qquad (4)$$

where

k = ratio of specific heats - dimensionless

g = gravitational acceleration at standard sea level- 386 in/sec^2

R^* = universal gas constant = 18,500 in-lb/lb-mole-°R

M = molecular weight of gas - lb/lb-mole

The following values were substituted into equation (3) where, as before, subscript 1 refers to the power stage HOGG4 and subscript 2 refers to the control stage HOGG3.

$$\dot{w}_{so1} = 0.89 \text{ lb/sec}$$

$$\dot{w}_{sh1} = 1.11 \text{ lb/sec}$$

$$\dot{w}_{so2} = 0.133 \text{ lb/sec}$$

$$\dot{w}_{sh2} = 0.177 \text{ lb/sec}$$

$$T = 520°R$$

$$C_2 \text{ for } O_2 = 0.560°R^{1/2}/\text{sec}$$

$$C_2 \text{ for } H_2 = 0.140°R^{1/2}/\text{sec}$$

$$P_{so1} = P_{sh1} = 700 \text{ psig} = 715 \text{ psia}$$

$$P_{so2} = P_{sh2} = 1000 \text{ psig} = 1015 \text{ psia}$$

$$P_{g1} = 400 \text{ psig} = 415 \text{ psia}$$

$$P_{g2} = 800 \text{ psig} = 815 \text{ psia}$$

The following inlet orifice effective areas were calculated using the above values in equation (3).

$$(C_dA)_{so1} = 0.0510 \text{ in}^2$$

$$(C_dA)_{sh1} = 0.254 \text{ in}^2$$

$$(C_dA)_{so2} = 0.00655 \text{ in}^2$$

$$(C_dA)_{sh2} = 0.0329 \text{ in}^2$$

In the initial design, each oxygen inlet was associated with three hydrogen inlets as shown in Figure 17. The central hydrogen stream impinged on the oxygen stream and deflected it into the vortex flow path along which combustion occurs. The outer hydrogen streams formed vortices which served to cool the two flat faces of the combustion chamber. Since only two streams of propellant impinge in each injector set, the injectors are classified as doublets, even though there are four orifices in each set.

HOGG3 used two sets of injector orifices and HOGG4 used three sets of injector orifices. These were equally spaced around the circumferences of the combustion chambers. Assuming an inlet orifice flow coefficient of 0.85, the orifice diameters were:

$$D_{so1} = 0.160 \text{ in. (3 orifices)}$$

$$D_{sh1} = 0.206 \text{ in. (3 orifices)}$$

$$D_{so2} = 0.070 \text{ in. (2 orifices)}$$

$$D_{sh2} = 0.091 \text{ in. (2 orifices)}$$

The hydrogen inlet orifices were spaced 0.1 inch from the faces of the gas generator and 0.1 inch apart from each other, and hence:

$$L_g = 0.4 + 3\, D_{sh} \tag{5}$$

Thus

$$L_{g1} \doteq 1.018 \text{ in.}$$

$$L_{g2} = 0.673 \text{ in.}$$

It can be shown that the pressure drop across the vortex amplifier button is only a small fraction of the overall pressure drop across the amplifier. A_s was set equal to $A_{(ann)}$, so that the pressure drop $P_g - P_s$ was also small. The fact that the P_s pressure was used as the source of the feedback signal to the gas generator control system further reduced the significance of the $P_g - P_s$ pressure drop. Because the pressure drops across both $A_{(ann)}$ and A_s were small, the restriction to the flow from the gas generator at full flow conditions was effectively A_o (the vortex amplifier outlet hole). It can therefore be said that:

$$L^* = \frac{V}{A_o} \tag{6}$$

where

L^* = characteristic length of gas generator - in.

V = internal volume of gas generator - in^3

L^* was calculated by using only the gas generator volume, as follows:

$$L^* = \frac{\pi D_g^2 L_g}{4 A_o} \qquad (7)$$

For convenience, it was assumed that the chamber diameter of each gas generator was equal to its corresponding vortex amplifier chamber diameter. That is

$$D_{g1} = D_1$$

$$D_{g2} = D_2$$

Substituting the previously calculated values of A_{o1}, D_1, L_{g1} and A_{o2}, D_2, L_{g2} into equation (7) gives:

$$L_1^* = 37 \text{ in.}$$

$$L_2^* = 23 \text{ in.}$$

The flat pancake shape of the vortex-doublet combustor, with the burning mixture spiraling toward the center, uses the full combustion volume efficiently and therefore can maintain stable combustion with a low L^* (i.e., low ratio of volume to outlet). Moreover, since these calculated values ignored the hot gas volume of the vortex amplifier, they appeared reasonable in view of previous experience with vortex-doublet gas generators operating with liquid bipropellants.

For the condition where $A_s = A_{(ann)}$ the following were calculated using the previously calculated values of $A_{(ann)} = 5.31 \text{ in}^2$ and $A_{(ann)2} = 0.428 \text{ in}^2$:

$$D_{s1} = 2.60 \text{ in.}$$

$$D_{s2} = 0.738 \text{ in.}$$

The gas generators had the following proportions:

For HOGG3 $D_{g2}/D_{s2} = 3.4$

$$D_{g2}/L_{g2} = 3.7$$

For HOGG4 $D_{g1}/D_{s1} = 3.5$

$$D_{g1}/L_{g1} = 8.8$$

Calculation of Port Sizes

Table 8 lists the port sizes of the external connections to the gas generators. These were all AND-10050 type.

Table 8 - Port Sizes of
External Connections to Gas Generators
(Units of 1/16 Inch)

Connection	HOGG3	HOGG4
Hydrogen inlet	8	16
Oxygen inlet	4	8
Nitrogen inlet	16	32
P_s sensing port	4	4
P_s feedback port	4	4
T_s sensing port	4	4
Hot gas bleed from HOGG3 to HOGG4	4	4

The nitrogen flow required to bring the vortex amplifier system to its normal pressure levels during cold gas testing was estimated from the ratio of the C_2 value for nitrogen divided by the square root of the absolute temperature to the C_2 value for the hot gas divided by the square root of its aboslute temperature. This did not take into account the effect of the slightly different specific heat ratios on the f_1 function, but the resulting error was small.

For nitrogen, k = 1.40 and M = 28. For the hot gas, k = 1.36 and M = 3.57. Hence, equation (4) gave C_2 = 0.523 °$R^{1/2}$/sec for N_2 and, for the hot gas, C_2 = 0.185 °$R^{1/2}$/sec. Using 520°R as the cold gas temperature and 1960°R as the hot gas temperature, and solving for the ratio:

$$\frac{C_2/\sqrt{T_n}}{C_2/\sqrt{T_n}} = \frac{0.523/\sqrt{520}}{0.185/\sqrt{1960}} = 5.48$$

The resulting ratio, 5.48, was the approximate ratio of nitrogen weight flow to hot gas weight flow required to pressurize the system. The necessary nitrogen flows were calculated as follows:

For HOGG4, $\dot{w}_{sn1} = 2 \times 5.48 = 11.0$ lb/sec

For HOGG3, $\dot{w}_{sn2} = 0.3 \times 5.48 = 1.64$ lb/sec

From the above nitrogen flows and the hydrogen and oxygen flows stated previously, line sizes were calculated.

HOGG3 Layout

Figure 18 shows a layout of HOGG3 with a preliminary version of the associated vortex amplifier VA5. The arrangement is essentially as indicated in the schematic, Figure 17.

The oxygen injectors were perforated ceramic plugs. These were cemented in place and also were retained mechanically by threaded fasteners. A gasket was placed between the retainer and the oxygen injector to aid in minimizing leakage.

An automotive spark plug was used as an ignition source for HOGG3. The Champion N-14Y was selected because of its long reach.

The rear structure of the vortex amplifier button formed one of the combustion chamber faces, and was sealed by metallic "O" rings. The button was the highest temperature component in the system, since it received the direct impingement of the hot gas flow and was centrally located in the structure.

The HOGG3 gas generator as designed is shown disassembled and assembled in Figures 19 and 20, respectively.

HOGG4 Layout

Figure 21 shows the layout of the HOGG4 gas generator. This layout was completed later in the program, after considerable testing had been

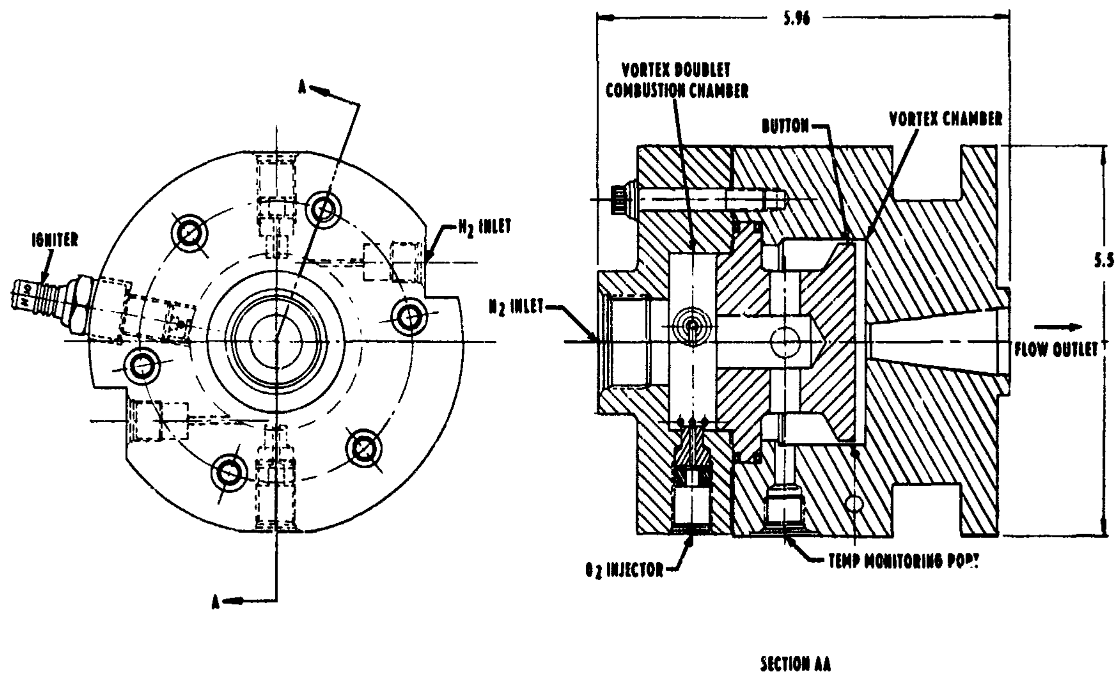


Figure 18 - HOGG3 Layout

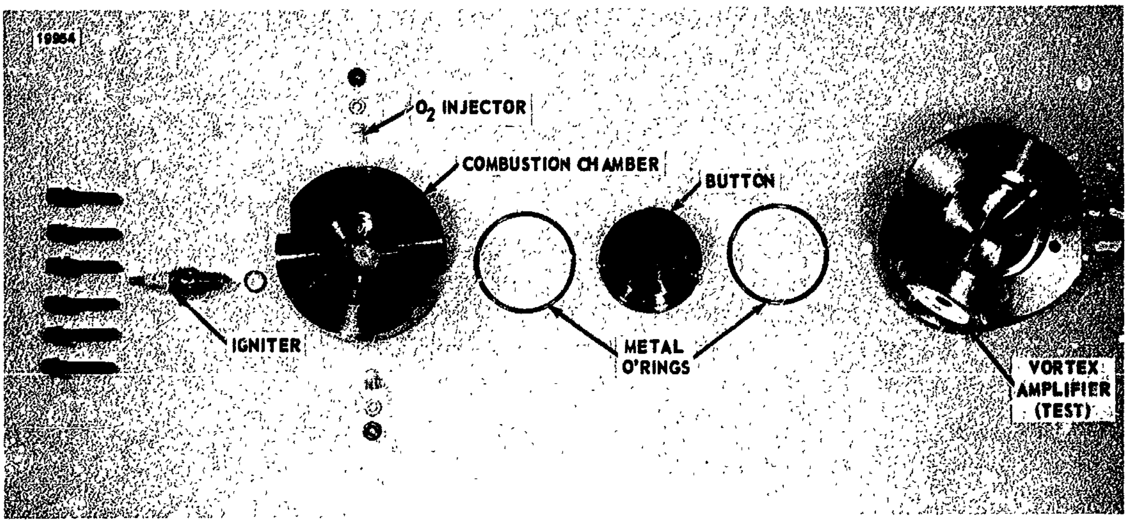


Figure 19 - HOGG3 Disassembled

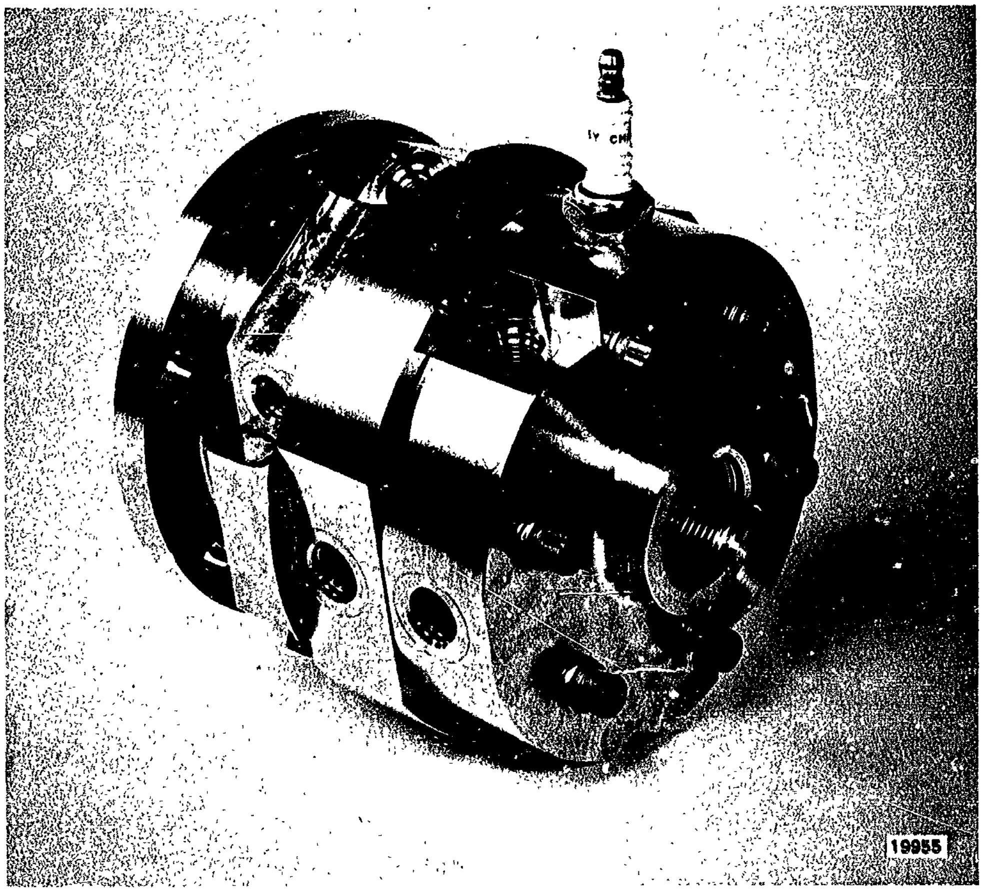


Figure 20 - HOGG3 Assembled

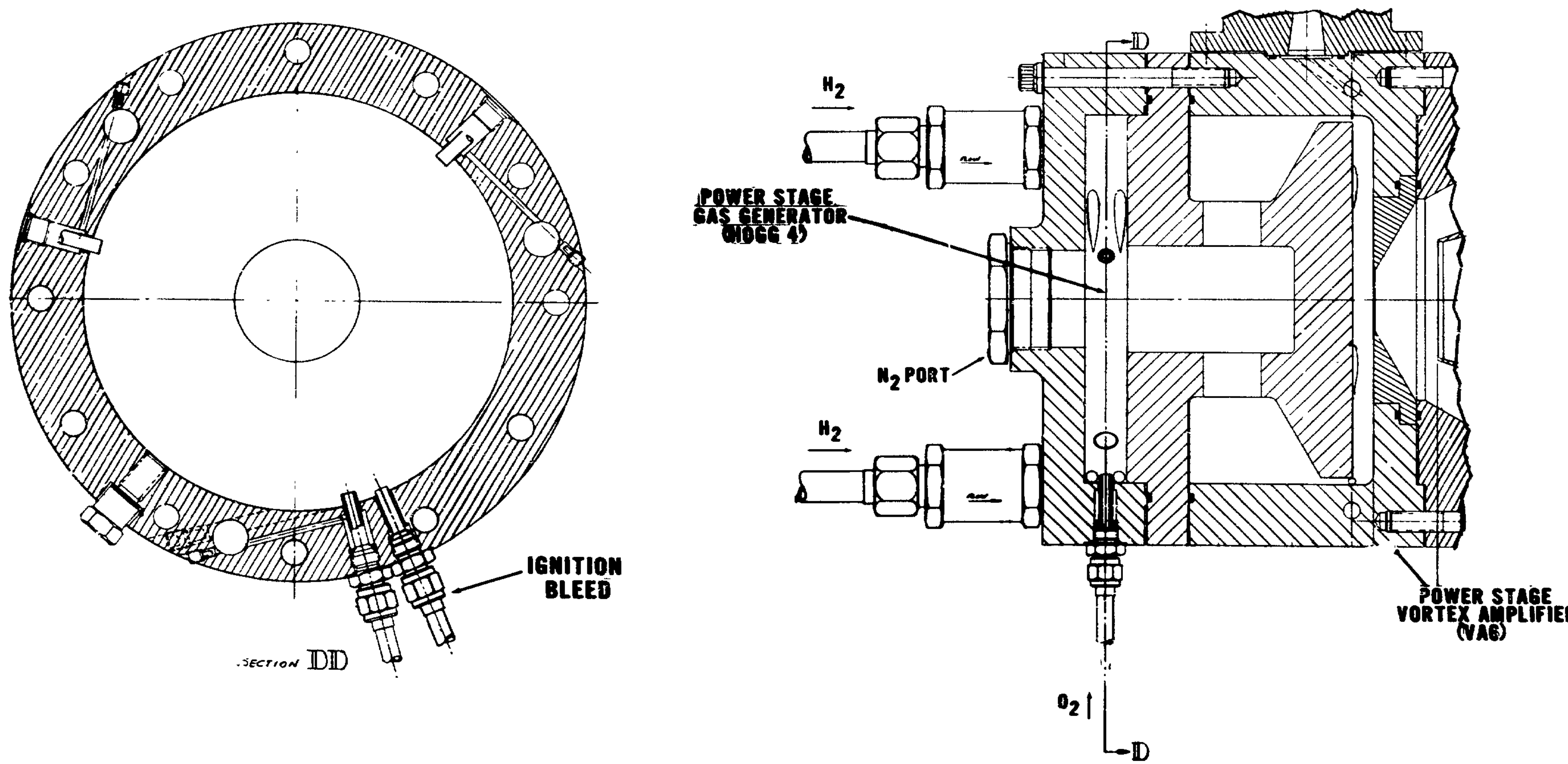


Figure 21 - HOGG4 Layout

accomplished on HOGG3. The oxygen injectors shown conform to Configuration III, which was the best injector configuration tested during testing of HOGG3.

MATERIALS SELECTIONS

Main Structure

A number of different metal alloys were considered for use in the vortex-doublet gas generators. These were of three classes: the 300 series stainless steels, high nickel alloys, and high cobalt alloys. References 2 through 5 were used as the source of data during the comparison. Table 9 gives the approximate chemical compositions of typical members of these classes. Table 10 presents physical properties of these same alloys, while Table 11 shows the mechanical properties at both room temperature and at the desired hot gas temperature of 1500°F. Finally, Figure 22 illustrates the 0.2% offset yield strength as a function of temperature.

The vortex amplifier could be constructed from 300 series stainless without fear of rupture. However, some difficulty had been experienced under the previous program with leakage because of thermal warping. The more compact nature of the new design tended to aggravate the tendency to thermal warp. Hence, it was concluded that a material with higher strength than 300 series stainless steel was required.

As can be seen from Figure 22, the 0.2% offset yield strengths of the alloys considered fall into four groupings across the temperature range from room temperature to 1500°F. The lowest grouping is that of the 300 series stainless steels. The next highest is that typified by such alloys as Haynes 25 and Hastelloy C. The curve for Inconel X-750 is higher than those for Haynes 25 and Hastelloy C for temperatures up to 1500°F. Finally, the highest yield strength for the various alloys considered at temperatures up to 1800°F is that possessed by Haynes R-41.

Inconel X-750 was selected as the material for both the gas generators and the vortex amplifiers. This alloy has excellent mechanical properties over an extremely wide range of temperatures. Its yield strength at 1500°F is higher than that of 300 series stainless steel at room temperature. It also has excellent oxidation resistance. In addition, the melting temperature is somewhat higher than that of the other superalloys considered. The machinability of Inconel X-750 is not as good as the 300 series stainless steels, but is better than most high-temperature alloys. Finally, Inconel X-750 is one of the oldest of the superalloys and has a well-established field of application. Hence, the material is more readily available than some of the other high-temperature materials.

The bolts fastening the gas generator to the vortex amplifier were constructed of A286 alloy. Bolts fabricared from this material are recommended for use at temperatures up to 1300°F. It was not

Table 9 - Approximate Chemical Compositions of Selected High-Temperature Alloys

Alloy	F_e	Ni	Co	Cr	Mo	W	C	Ti	Al	Mn	Others
304 L Stainless	68	10	-	19	-	-	0.03		-	2	Si 1
316 Stainless	67	12.5	-	17	2.5	-	0.08	-	-	2	Si 0.75
Inconel X-750	7	70	-	17	-	-	0.08	2.50	0.7	1.2	Cb + Ta 0.95
Haynes 25	3	10	50	20	-	15	0.10	-	-	[illegible]	
Hastelloy C	5	56	2.5	15.5	16	4	0.08	-	-	1.0	
Haynes R-41	2	53	11	19	10	-	-	3.2	1.5	-	0.007 B
TZM-1 Moly	-	-	-	-	99.5	-	-	0.5	-	-	0.09 Z

P-3317

Percentages are average of a range or maximum values, percentages in parentheses are by difference and include all residual elements.

Table 10 - Physical Properties of Selected High-Temperature Alloys

Alloy	Density lb/in³	Min. Melting Temp.	Specific Heat Btu/lb °F	Thermal Conductivity Btu-in/hr-ft² °F		Thermal Expansion μ-in/in °F*		
	(R.T.)	°F	(R.T.)	RT	1500	1000°F	1500°F	1600
304 L Stainless	0.29	2550	0.12	113	184	10.3		
316 Stainless	0.29	2550	0.12	113	184	10.3		
Inconel X-750	0.298	2540	0.103	83	159	8.1	9.1	
Haynes 25	0.330	2425	0.092	74	172	8.0		9.1
Hastelloy C	0.323	2310	0.092	67		6.6	8.1	
Haynes R-41	0.298	2385	0.108	87	168	6.7	8.5	
TZM-1 Moly	0.37	4650	0.066			3.2	3.3	

*Average value from room temperature to temperature indicated

P-3317

Table 11 - Typical Mechanical Properties of Selected High-Temperature Alloys (Bar and Sheet)

Alloy	Room Temp. Tensile Strength 1000 psi	Room Temp. 0.2% Offset Yield Strength 1000 psi	1500°F Tensile Strength 1000 psi	1500°F 0.2% Offset Yield Strength 1000 psi	1500°F Stress for Rupt. 1000 hrs. 1000 psi
304 L Stainless	83.5	34.0	21.0	12.0	4.0
316 Stainless	85.5	38.5	27.5	18.5	6.6
Inconel X-750	162	92.5	60.0	40.5	18.0
Haynes 25*	146	67	50	36	22
Hastelloy C*	121	58	70	40	16
Haynes R-41	206	154	130	110	17.5
TZM-1 Moly	132	100	95	80	

P-3317

*Sheet

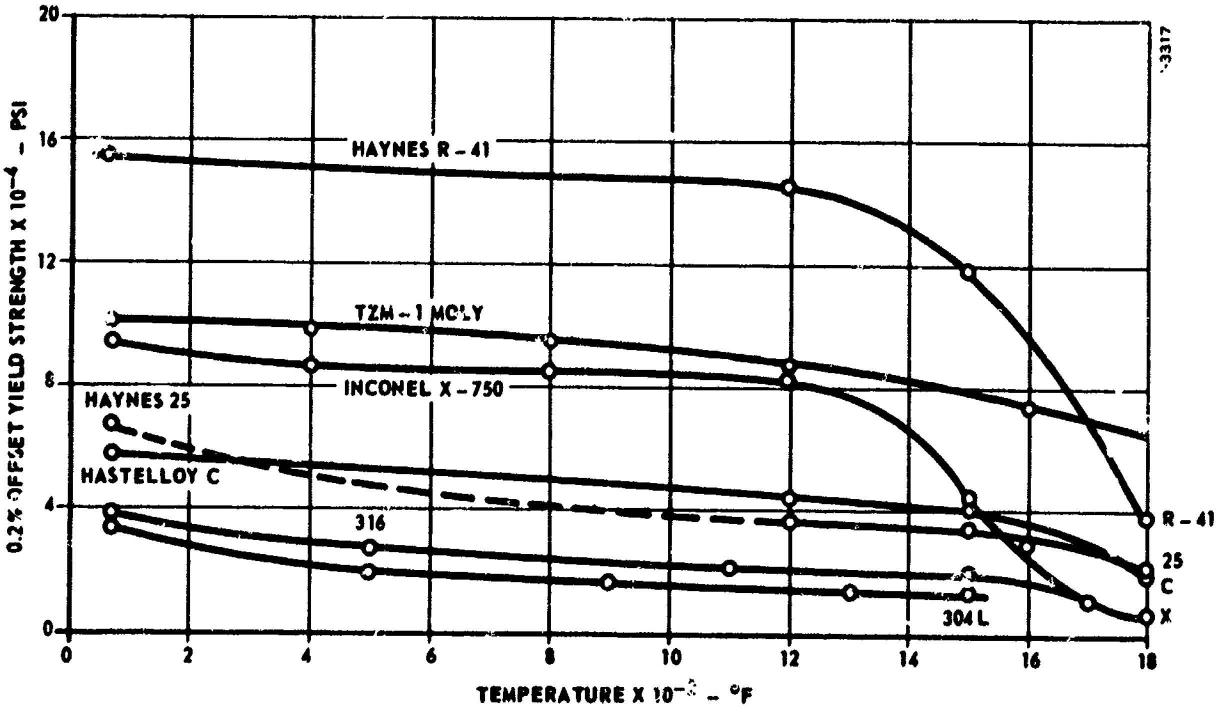


Figure 22 - 0.2% Offset Yield Strength of Selected Alloys as a Function of Temperature

considered likely that the bolts would ever reach this temperature in this application. The calculated bolt stress for HOGG3 is 11,000 psi, which is moderate for this material.

The seals were made from Inconel X-750. This choice was based on the same reasoning which led to the selection of this alloy for the housings and button. The seals had a tubular cross-section and were copper-plated, following recommended high-temperature seal practice.

Oxygen Injectors

Previous experience with hydrogen-oxygen gas generators at Bendix Research Laboratories had indicated that one of the more critical gas generator design parameters is the oxygen inlet velocity. The stoichiometric temperature of the hydrogen-oxygen reaction in the pressure range of the two gas generators is on the order of 6400°R. If the oxygen inlet velocity is too low, the reaction zone is close to the oxygen injector so that burning or melting of the injectors may easily result. The minimum velocity in HOGG3 is extremely low, and in HOGG4 it is zero since HOGG4 shuts off completely when the SITVC system output is zero. Therefore, materials such as stainless steel, copper, and ceramic oxides were considered for the injectors. It was concluded that the material and configuration of the injectors should be determined by experiment. It was necessary to develop an injector configuration and select a material that would overcome the effects of low velocity.

TASK 2 TESTING

The principal area that required devleopment in the vortex-doublet hydrogen-oxygen gas generator was the method of propellant injection. The combustion chamber design proved to be satisfactory, although some evidence of excessive temperature at the outlet hole was observed, Figure 23 (center body). Because of the extreme temperatures (6000°F) associated with the direct combustion of the hydrogen and oxygen propellants, it was necessary to design the injectors so that combustion took place within the center of the combustion chamber away from both walls and injectors. The configurations of the oxygen injectors and the materials from which they were made were extensively studied. Figure 24 shows four injection schemes that were test evaluated. The goal was to devleop an injector configuration that would allow the generator to be operated efficiently at all flow levels from maximum design flow to zero flow without damage to the generator or to the injectors. Configurations I and II were both initial design configurations. Configuration I had a protruding oxygen injector made from ceramic and a set of three equal hydrogen ports positioned off the tangent to intersect the oxygen port. Configuration II was like Configuration I, except that the oxygen injector did not protrude and the hydrogen ports were tangential. The first hot tests were used to determine the proper ignition procedure and to evaluate Configurations I and II. Both of these configurations proved to be inadequate. The major difficulty was that the oxygen injector and the gas generator wall just downstream of the oxygen injector in the direction of hydrogen flow were severely eroded (Figure 25). This damage was caused by the direct combustion of a portion of the hydrogen and oxygen against the metal surface. Melting or metal burning continued, until a small pocket was created which essentially allowed the gases to burn in the newly created free space. This effect was attributed to the fact that the flow from the center hydrogen port

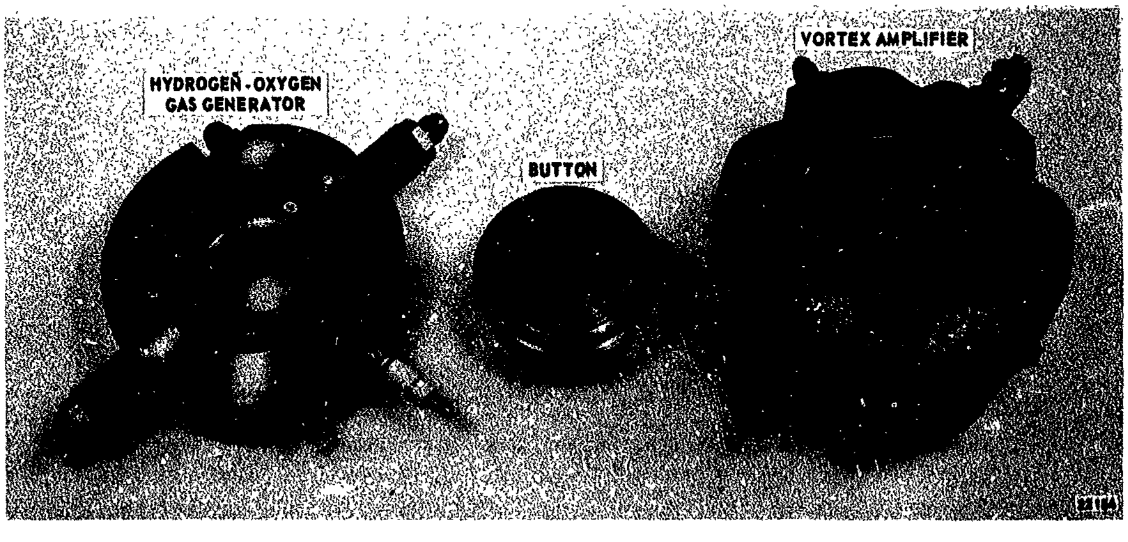


Figure 23 - HOGG3 Disassembled, with Vortex Amplifier

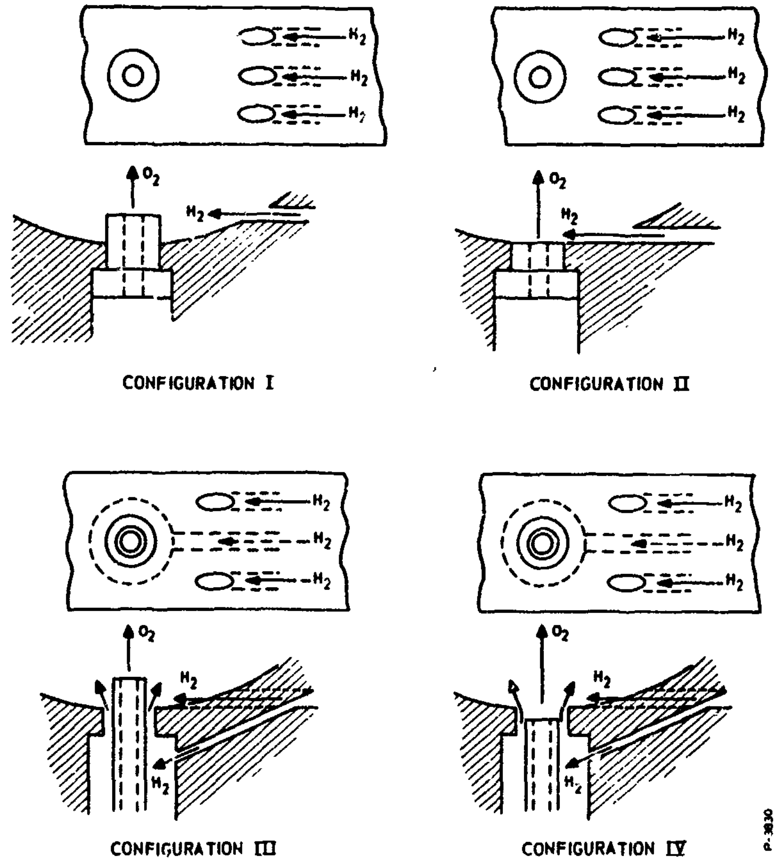


Figure 24 - Gas Generator Propellant Injector Schematics

directly intersected the oxygen flow stream, causing oxygen to contact the metal surfaces. At this point, some of the oxygen combined with some of the hydrogen at temperatures greatly in excess of the metal's melting point, producing a cavity in the chamber surface. By way of comparison, it is interesting to note here that direct impingement of propellants has been proven in the past to be a successful method of injection with the hypergolic liquid propellants. However, while these propellants undoubtedly have a fast reaction rate, the reaction rate of gaseous H_2 and O_2 is much faster because the propellants do not have to vaporize. Thus, with direct impingement, gaseous H_2 and O_2 begin to burn immediately near the outer wall while, with liquid propellants, there is a delay until the mixture has swirled inward slightly away from the wall.

Configuration III sought to correct this difficulty by plugging the center hydrogen port and by enlarging the two side ports. In addition, to provide further metal protection, a third hydrogen port surrounding the oxygen injector was installed. This concentric port provides

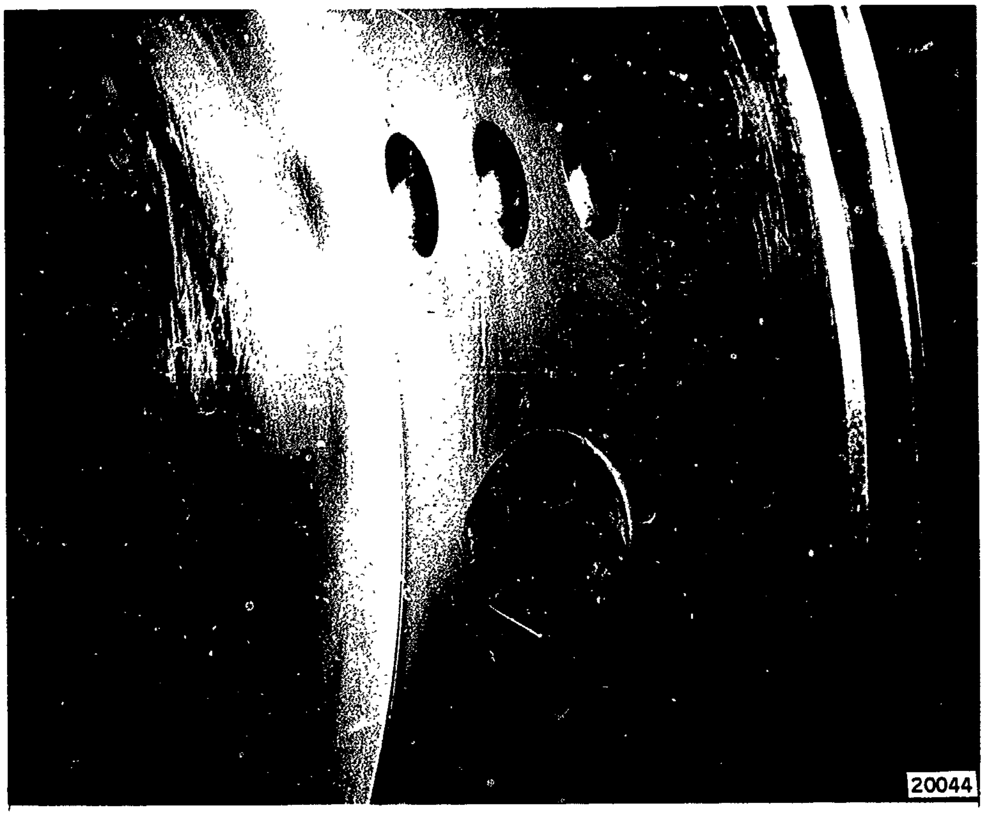


Figure 25 - Gas Generator Injector Damage (Configuration I)

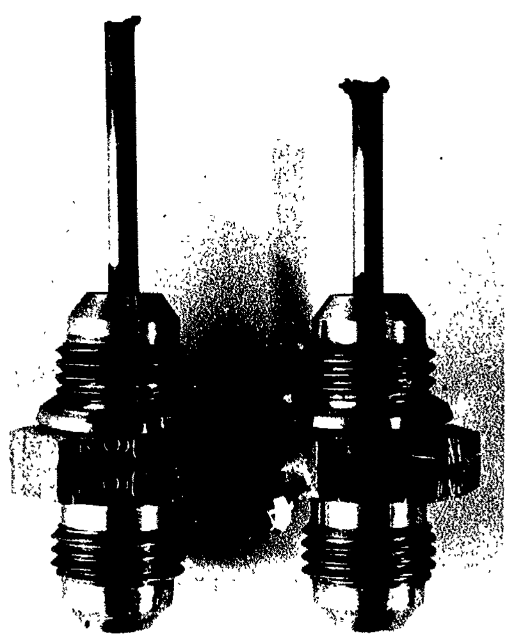


Figure 26 - Stainless Steel Injectors After Test

approximately 10% of the total hydrogen flow. The hydrogen "shield" surrounds the oxygen injector and protects both it and the downstream chamber walls from direct contact with oxygen. Also, without direct impingement of a tangential hydrogen jet, the oxygen jet itself is allowed to penetrate radially deeper into the combustion chamber before it contacts the general swirling flow from the combined doublets. In this way, the oxygen is allowed time to completely exit from its injector before any appreciable combustion takes place. Stainless steel tubes were tried in Configuration III first, but these were unreliable. Some lasted several tests but most were destroyed immediately. A pair of stainless steel injectors, after test, is shown in Figure 26. The longer injector is at approximately original length. Copper injectors were then tried in Configuration III and proved to be quite satisfactory. Copper has greater resistance to ignition in an oxidizing atmosphere when compared with stainless steel. It does have the disadvantage of a low melting point, but this is offset by its high specific heat and thermal conductivity.

These three innovations, namely the elimination of the center hydrogen port, the inclusion of an annular radial hydrogen port and the use of copper oxygen injectors, were the key design changes in achieving a successful vortex-doublet, hydrogen-oxygen gas generator. It was observed, however, that there was some slight erosion of the injector caused by particle impact on the side facing the swirling flow. To combat this not-too-serious problem, Configuration IV was designed, which uses a short oxygen injector that does not protrude into the combustion chamber.

This configuration was tested and it was observed that some downstream chamber wall burning did occur. This undoubtedly happened at deep throttling where the oxygen jet velocity decreased and allowed the flame front to approach the injector region. Configuration IV was considered dangerous for this reason, and it was concluded that Configuration III, the previous configuration, was the best that had been tested, and it was used as the basis for the HOGG4 power stage gas generator. Photographs of the final configuration after testing was completed are shown in Figures 27 and 28. The center hydrogen ports were plugged, as stated.

Evaluation of Configuration III with copper injectors was obtained through a series of tests ending with Test No. 3G-7B. These tests covered a period of 450 seconds in which many turndowns, shutoffs and restarts were accomplished at a mean gas temperature of 1500°F. In the final test, a turndown of 6 to 1 was achieved. The gas generator was subjected to three full-range flow modulations. A summary of the flows recorded in this test appears in Table 12.

<u>Test Facility and Procedure</u>

Figure 29 shows the HOGG gas generator on test. A breadboard vortex amplifier similar to VA5, the control stage vortex amplifier of

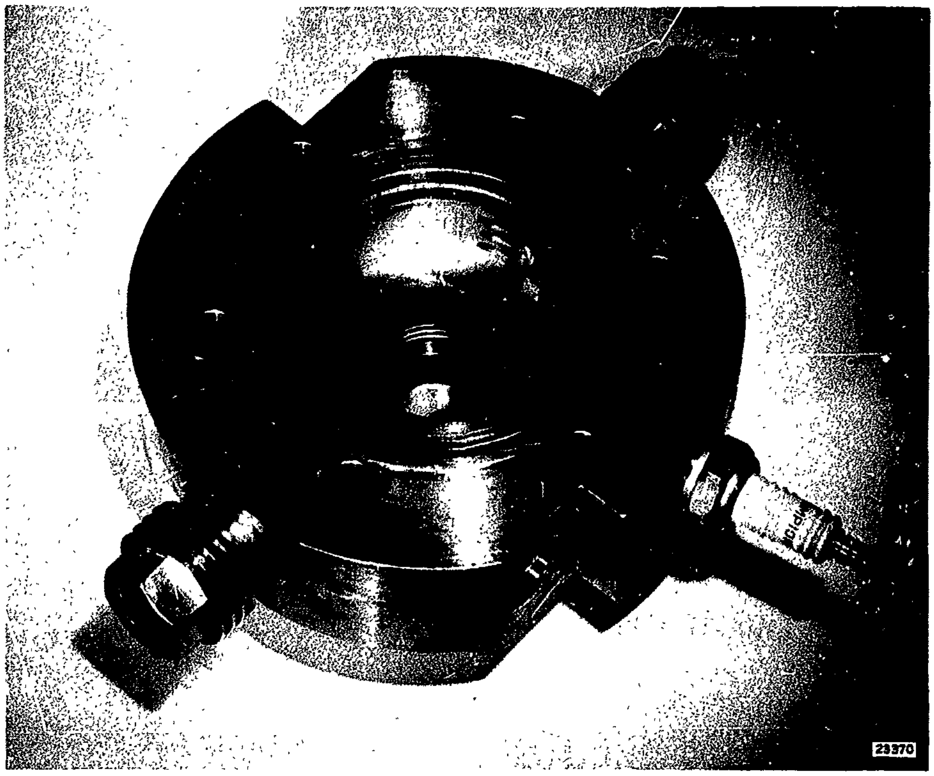


Figure 27 - Configuration III After Testing

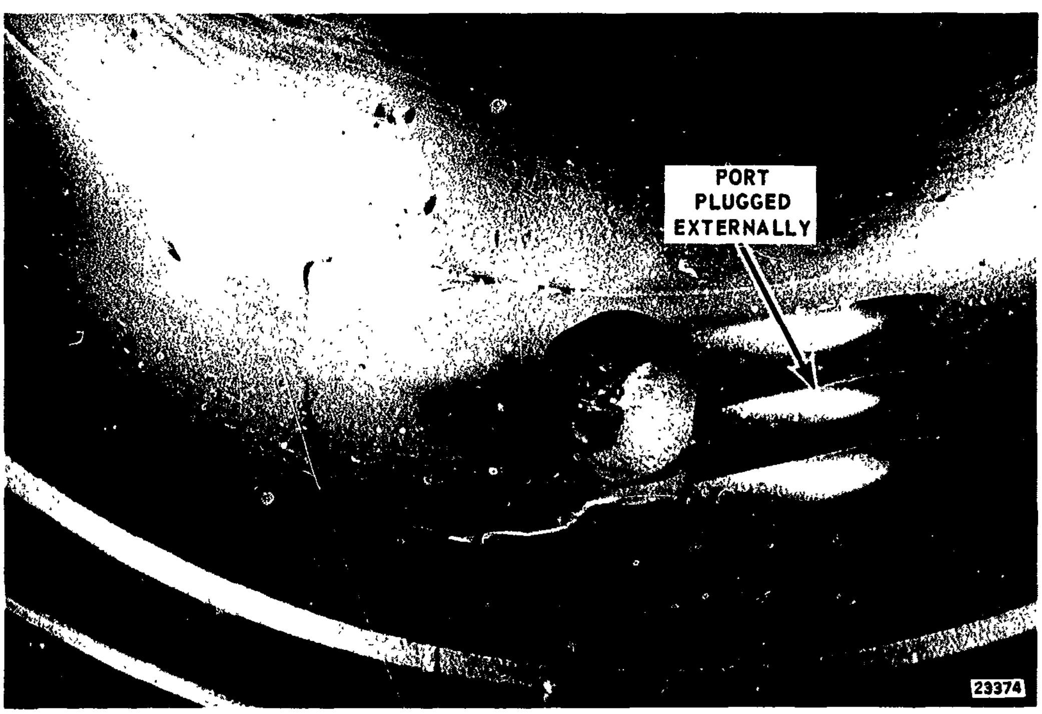


Figure 28 - Close-Up of Copper Injector After Testing
(Final Configuration)

Table 12 - Test No. 3G-7B Data Summary

Test Point	Chamber Pressure P_s psia	Pressure Drop Across O_2 Injector psid	O_2 Flow $\dot{w}$ lb/sec	H_2 Flow $\dot{w}_h$ lb/sec	Total Supply Flow $\dot{w}$, lb/sec	O/F Ratio	Supply Temp. T_s, °F	Flow Range* Max Flow / Min Flow
1	815	130	0.091	0.120	0.211	0.76	1440	1.59
2	818	0	0	0	0	-	640	Shutoff
3	835	5	0.024	0.049	0.073	0.50	1440	6.0
4	835	15	0.040	0.060	0.100	0.68	1580	3.6
5	835	50	0.069	0.085	0.154	0.81	1800	2.1
6	835	68	0.084	0.092	0.176	0.92	1900	1.7

P-4634

*Based on Oxygen Flow Range

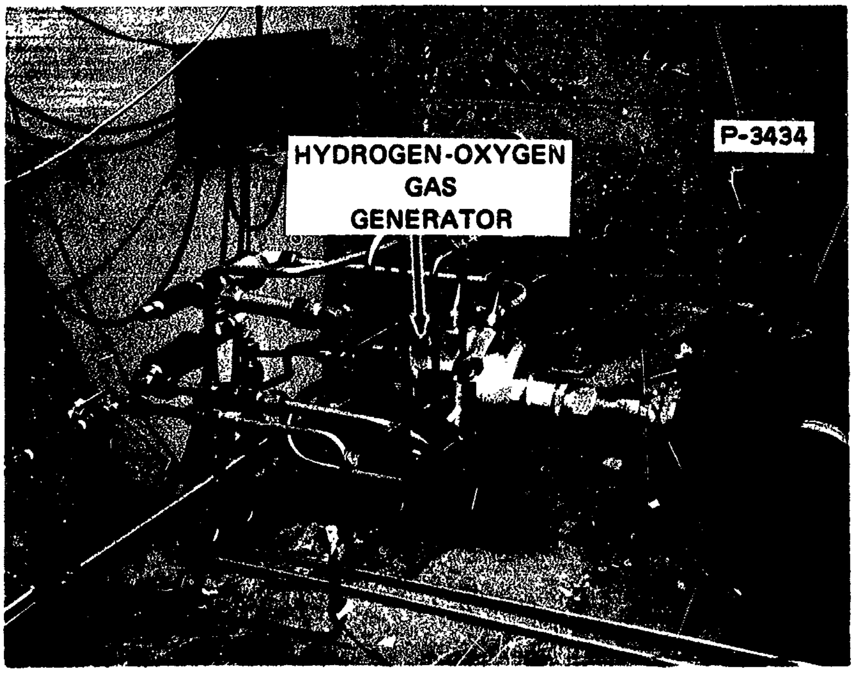


Figure 29 - HOGG3 Test Installation

Task 3, was used as the variable load. A simplified schematic of the test facility is shown in Figure 30. Hydrogen and oxygen stored in the gaseous state at high pressure were brought together in the gas generators through a system of pressure regulators. The O/F ratio was fixed by the propellant injector areas, as long as the hydrogen and oxygen inlet pressures were equal. Therefore, is was necessary to slave the propellant inlet pressures together, so that they remained equal.

Combustion chamber pressure was maintained by feedback to the hydrogen regulator and by comparison with its set dome pressure. The HOGG3 gas generator operated at a pressure of 800 psig. The outlet flow was regulated by varying the control flow to the vortex amplifier. Tests

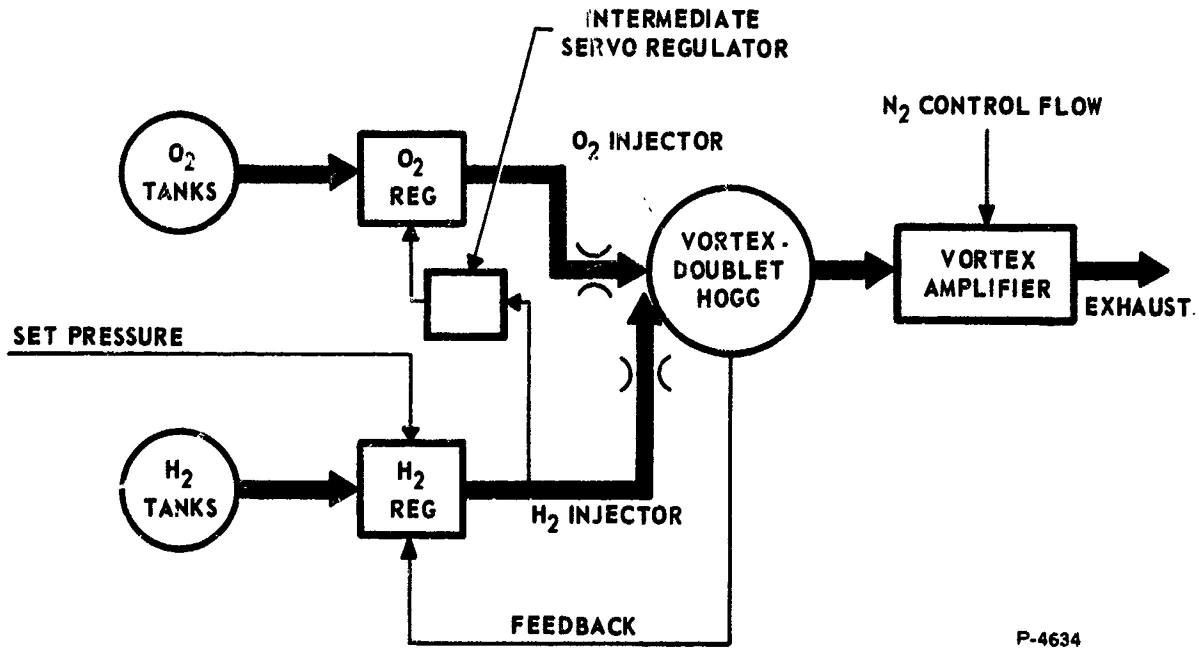


Figure 30 - Schematic of Hot Gas Test Facility - Task 2

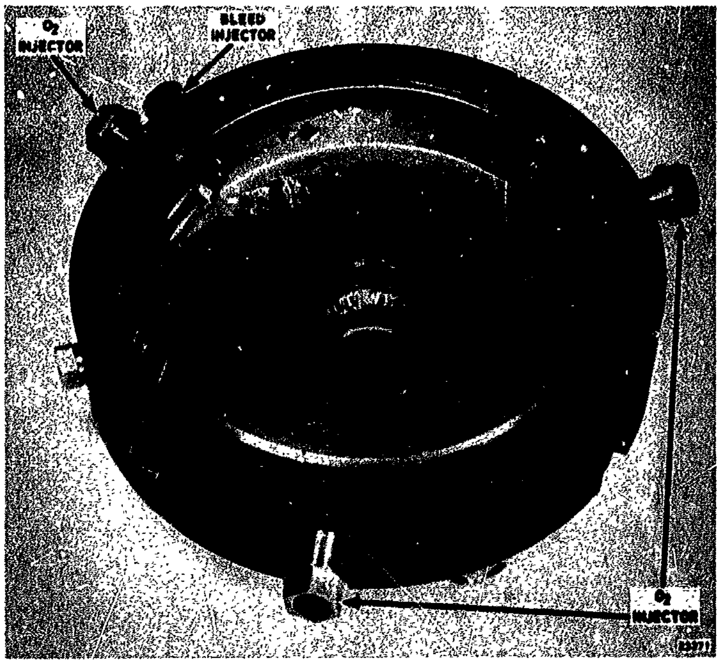


Figure 31 - HOGG4 Bleed Injector Configuration

were controlled from a remote firing panel which had provisions for starting, modulating, stopping and restarting the gas generators. All propellant flows were measured with calibrated orifices, located just upstream of the pressure regulators. The pressure and temperature of the hot gas, as well as many additional pressures, were recorded to provide a complete record of performance.

HOGG4 Testing

The basic chamber desing of HOGG4 developed in Task 3 proved to be satisfactory, as was proved previously in HOGG3. The oxygen injectors were made of copper and were designed like those of Configuration III, and these performed very well. The major development area was in achieving a reliable ignition. This gas generator is ignited from HOGG3 by bleeding gas through an external channel. The exact location of the bleed gas injector in the HOGG4 chamber proved to be critical.

The injector problem was solved by locating the ignition bleed injector just donwstream of one of the oxygen injectors, and angling it so that the oxygen and bleed gas streams intersected. This configuration is shown in Figure 31. The damaged areas in the combustion chamber were caused by earlier modifications.

The HOGG4 gas generator performed well; it produced gas at 1500°F at a flow rate of 2.0 lb/sec and could be modulated down to complete shutoff. Reignition occurred reliably when flow was demanded. This generator design is considered very satisfactory and its performance was good.

DEVELOPMENT OF FULL-SCALE SITVC SYSTEM
(TASK 3)

The objective of Task 3 was to design, build and test a complete single-axis STIVC system having no moving parts except in the pilot stage. The system comprises a power stage vortex amplifier rated at 2.0 lb/sec and integrated with the large vortex-doublet gas generator built in Task 2, a control stage vortex amplifier integrated with the smaller vortex-doublet gas generator of Task 2, and an electropneumatic pilot valve that provides the fluidic signal input to the control stage. In addition to demonstrating the operation of a practical SITVC system incorporating staged vortex amplifiers, it was intended to test the validity of scaling vortex amplifiers from one size to another. Therefore, the two vortex amplifiers for the full-scale system were designed by scaling up directly from the control stage and power stage amplifiers developed in Task 1.

In Task 2, development had been concentrated on HOGG3 (the gas generator for the control stage), and thereafter HOGG4 (the gas generator for the power stage) was designed and built using information from the HOGG3 development. Consequently, the development testing of HOGG4 and of the bleed line ignition method for this gas generator were included in the Task 3 program.

SUMMARY OF RESULTS

From the insight gained in the preceding two tasks, the Task 3 staged system was designed. The staging techniques developed in Task 1 were combined with the development of the pancake-shaped gas generator to design and build the Task 3, 2.0 lb/sec, hot gas system. The two new gas generators, one capable of supplying hot gas to the power stage and the other for the control stage, were integrated with their respective vortex amplifiers as shown in Figure 32. The control and power stages were integrated using internal manifolding.

Both cold and hot gas tests were performed on the system. The primary objective of the cold tests was to optimize the system performance. Since the system was a direct scale-up of the Task 1 unit, the majority of the design parameters had been set. The cold gas tests served to verify these parameters and to determine the optimum receiver position.

The final result of the cold gas tests was a close approximation of the final performance obtained on the Task 1 staged system. Turndowns of greater than 8 to 1 with approximately 100% initial flow recovery were accomplished, indicating gains in excess of 200. (By comparison, total flow modulations of 6 to 1 were demonstrated with both cold and hot gas on the Task 1 system.)

The initial hot gas test involved the development of the hot gas bleed method of ignition for the power stage gas generator. However,

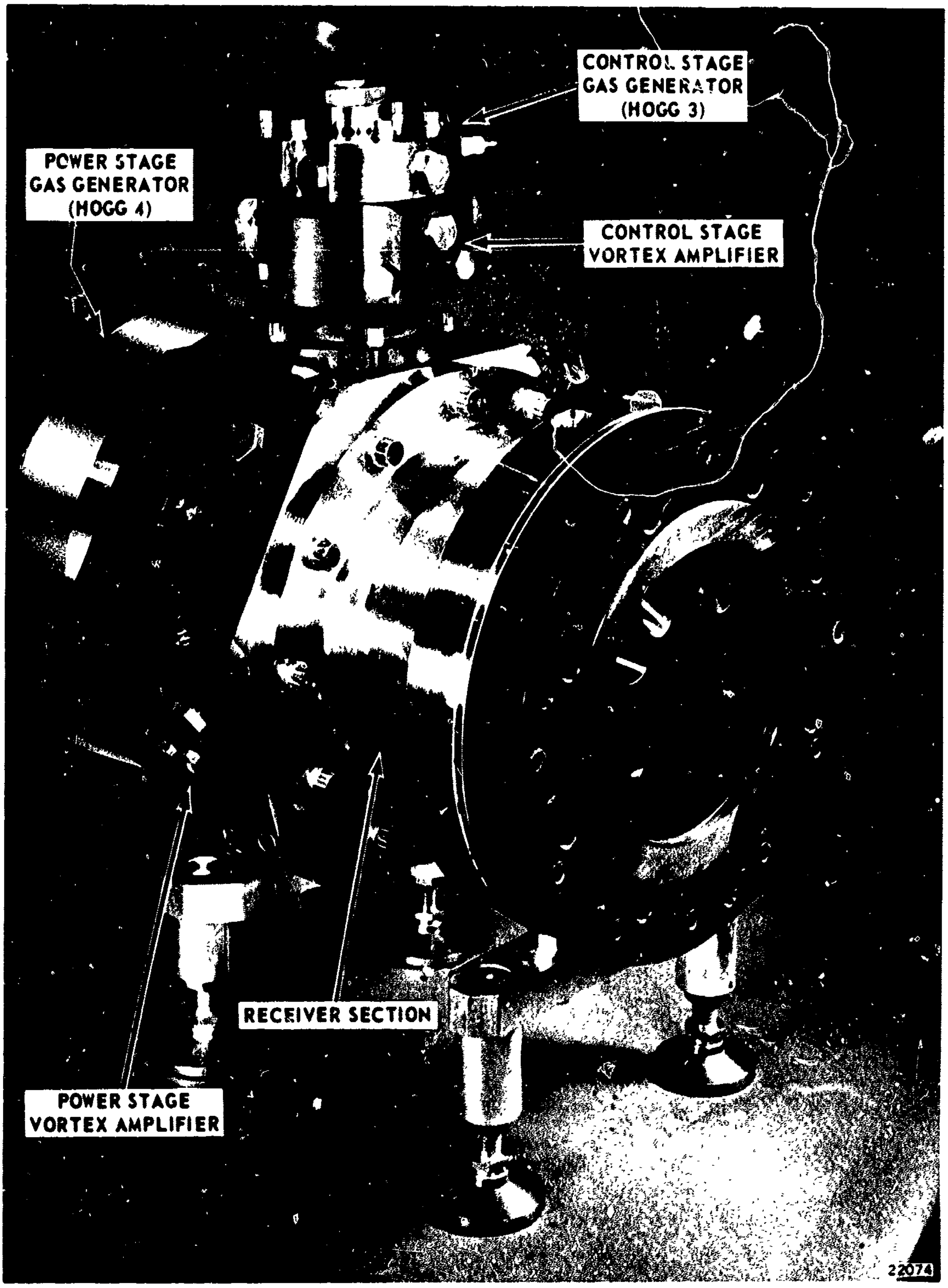


Figure 32 - Integrated Vortex Amplifiers and Gas Generators

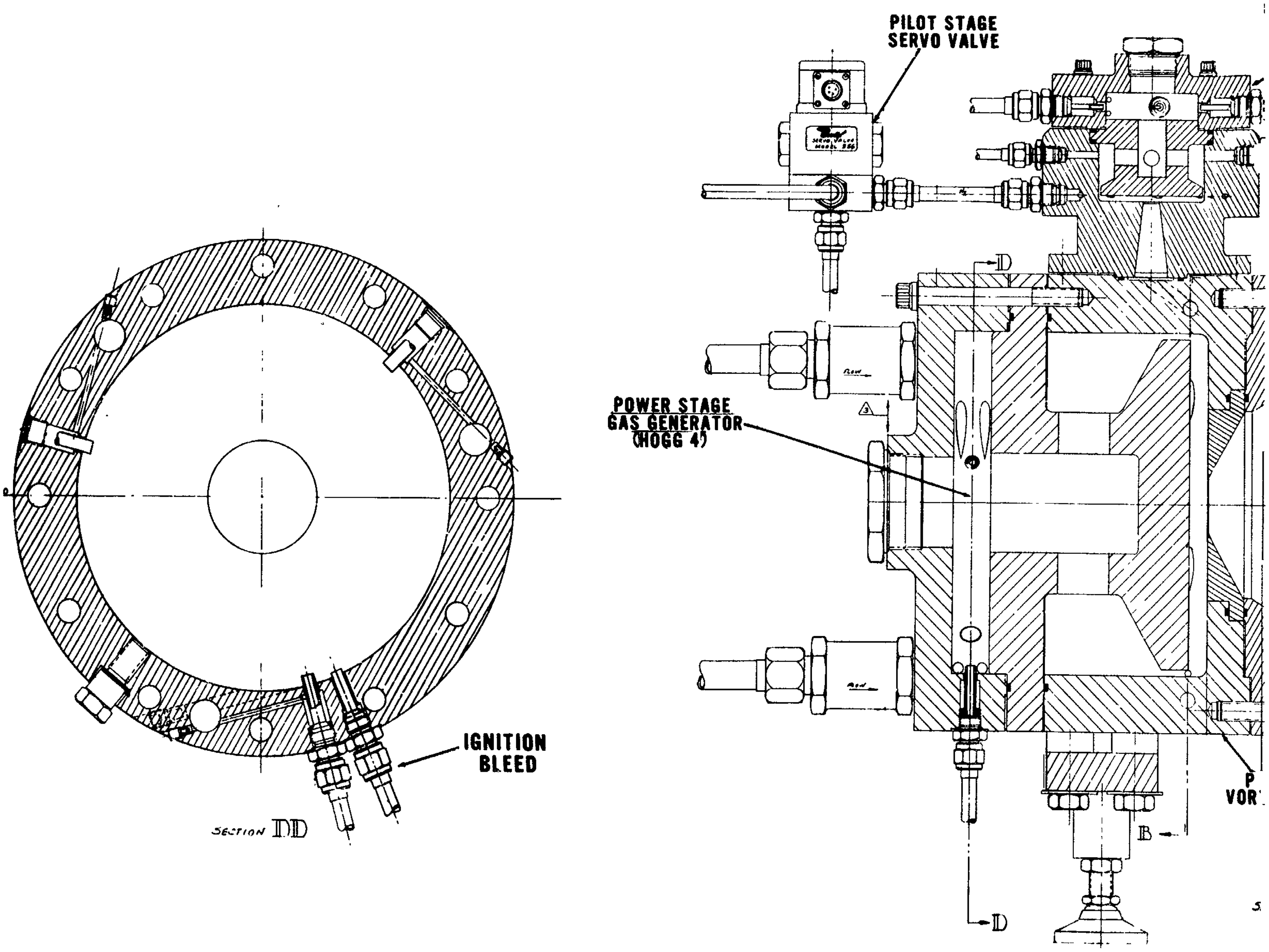
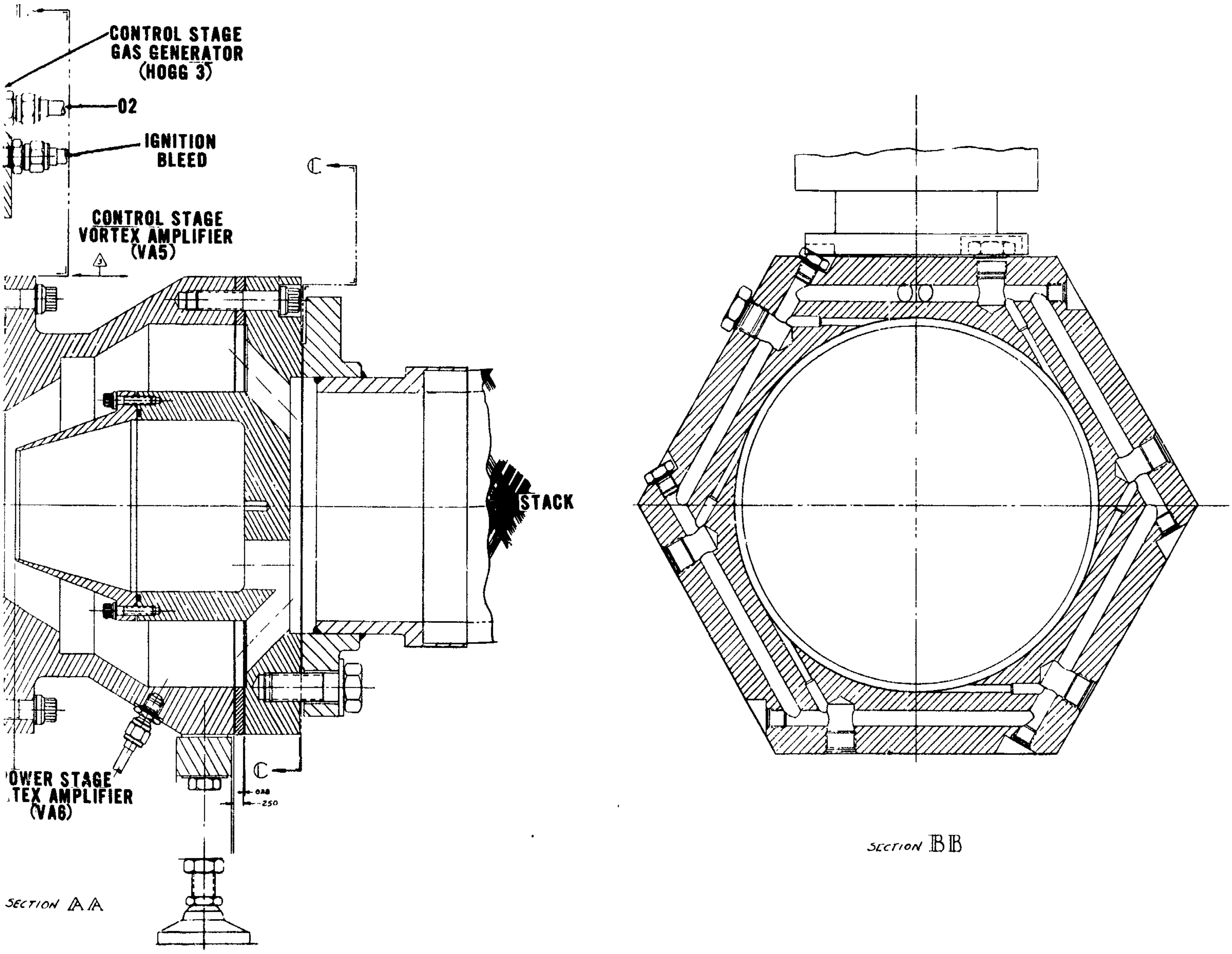


Figure 33 - Task 3 Two-Stage



e Vortex Amplifier Assembly

because of hardware damage sustained in preliminary hot gas testing, no successful staged hot tests were accomplished in Task 3. In the 21 minutes of hot gas testing on this system, none of the results obtained approached those demonstrated in the cold gas test. The test procedure required that the control stage gas generator be started first. During the time interval required for establishing the proper control stage operation prior to starting the power stage gas generator, the power-stage control manifold structure was subjected to thermal stresses by the hot control gas flowing through the internal passages. (These passages are shown in Section BB of Figure 33, the overall layout of the Task 3 system.) This hot gas produced localized expansions which caused metal cracks to occur between the internal passages and the internal wall of the chamber. This internal cracking allowed control flow from the control stage to leak into the power stage without contributing to swirl, thus severely degrading performance.

Internal hot gas manifolding was used in this project as a means of achieving a degree of compactness. The results have shown this type of design to be impractical. Since this program was primarily for development of vortex amplifier and gas generator technology, sophisticated high-temperature structural design was not included. Inconel X-750 and a massive structure were used as insurance against thermal damage but were inadequate in the face of temporary overtemperatures and localized expansions imposed by the starting procedure. It is apparent that future designs of this size, operating on gases at this temperature, must employ structures and materials specifically selected to withstand thermal effects. A composite design involving a refractory liner surrounded by insulating material is indicated.

In the initial Task 2 hot gas tests, the power stage ignition problem was solved by the proper location of the ignition gas bleed. However, during Task 3 the body section containing the control channels had been damaged beyond repair. The remaining Task 3 hot gas test only resulted in proving this fact after several attempts were made to repair the damaged walls with various welding techniques. The results of the Task 3 hot gas tests are summarized in Table 13.

The results of the cold gas tests of the full-scale system, when compared with the test results of the quarter-scale system in Task 1, show that the staged system and its components scale very well. This offers the possibility of saving time and cost by permitting a system to be analyzed and its performance to be established by using a smaller unit. Then a full-size system can be designed and built in its final configuration without extensive preliminary testing and modification.

SYSTEM DESIGN

The Task 3, 2.0 lb/sec, hot gas staged system was designed from the parametric data and insight obtained from the 0.5 lb/sec hot gas Task 1 staged system and previous development programs. The individual staged vortex amplifiers include integrated gas generators and are linked together

Table 13 - Results of Task 3 Hot Gas Tests

Test No.	Date	Power Stage	Control Stage	Gas	Purpose of Test	Test Results	Performance and Action
4	9-20 1966	VA6	VA5	H_2-O_2	HOGG3 Ignition and turndown with electro-pneumatic pilot stage	Ignition and partial turndown accomplished; pilot stage flow capacity too small. No damage.	HOGG3 Gas Temp. = 1635°F HOGG3 Duration = 80 sec Partial Turndown
5	9-20	VA6	VA5	H_2-O_2	Ignition of HOGG4 from HOGG3	HOGG4 ignition not accomplished because of thermocouple failure in automatic shutoff circuit.	HOGG3 Gas Temp. = 1635°F HOGG3 Duration = 60 sec Partial Turndown Skin temp. thermocouple replaced with gas temp. thermocouples.
6	9-21	VA6	VA5	H_2-O_2	Ignition of HOGG4 from HOGG3	HOGG4 ignition not accomplished because of external leak and resulting fire. Test manually terminated.	HOGG3 Gas Temp. = 1835°F HOGG3 Duration = 43 sec Full Flow Installed new seals.
7	9-21	VA6	VA5	H_2-O_2	Ignition of HOGG4 from HOGG3	HOGG4 ignition not accomplished because of damaged hydrogen pressure regulator. No damage to gas generators.	HOGG3 Gas Temp. = 1800°F HOGG3 Duration = 48 sec Approx. full turndown due to low pressure level. Replaced regulator diaphragm and installed check valves.
8	9-23	VA6	VA5	H_2-O_2	Ignition of HOGG4 from HOGG3	HOGG4 ignition not accomplished because control stage turndown limited by pilot stage capacity.	HOGG3 Gas Temp. = 1635°F HOGG3 Duration = 37 sec Partial Turndown Electropneumatic servovalve replaced by high capacity pressure regulator.
9	9-23	VA6	VA5	H_2-O_2	Ignition of HOGG4 from HOGG3	HOGG4 ignition not accomplished because of improper O/F ratio due to characteristic of gas regulation system.	HOGG3 Gas Temp. = 1635°F HOGG3 Duration = 87 sec HOGG3 turndown sufficient to start HOGG4 flows. Reset regulation characteristics and relocated hot gas ignition bleed. Ignition problems on HOGG4 have been solved.
10	9-30	VA6	VA5	H_2-O_2	Initial Task 3 hot gas test	HOGG4 ignition accomplished but hardware was damaged by excessive oxygen at start.	HOGG3 Gas Temp. = 1600°F HOGG4 Gas Temp. = — Test Duration = 40 sec Repaired damaged areas, relocated ignition bleed and decreased HOGG4 oxygen port area. Some vortex amplifier performance data obtained at less than full flow.
11	10-10	VA6	VA5	N_2	Leak Test	VA6 control port body leaked both internally and externally from control pressure channeling.	Repaired cracked areas by welding.
12	10-21	VA6	VA5	H_2-O_2	Task 3 performance static test	HOGG4 gas generator ignition accomplished. Flow test accomplished on HOGG4 gas generator. No generator damage.	Test duration = 92 sec Turndown not accomplished because of internal control flow leakage. Cracked areas reopened and were rewelded.
13	10-31	VA6	VA5	H_2-O_2	Task 3 performance static test	HOGG4 gas generator ignition accomplished. Test terminated because of massive external leaks.	Some performance data obtained at full flow. Test duration = 110 sec HOGG4 Gas Temp. = 1185°F Flow = 2.06 lb/sec (max) Internal cracks repaired by welding. Electropneumatic servovalve installed with bypass orifice for use in dynamic test.
14	11-23	VA6	VA5	H_2-O_2	Task 3 performance static and dynamic test	HOGG4 ignition not accomplished. Control stage modulated six (6) times.	Test data indicated massive internal leakage with resulting poor performance. Test duration = 330 sec HOGG3 Gas Temp. = 1550°F
15	12-5	VA6	VA5	H_2-O_2	Task 3 static and dynamic performance test.	HOGG4 gas generator ignition accomplished. No external leaks. Static and dynamic tests were accomplished.	Test data indicated massive internal leakage with resulting poor performance. Test Duration = 330 sec HOGG3 Gas Temp. = 1550°F Hardware not repairable.

Task 2 HOGG4 tests completed.
Task 3 tests concluded because of damaged hardware. Total Time 1247 sec

P-4634

in a series arrangement. The main philosophy used in the design was to build a unit capable of proving the feasibility of the staged vortex amplifier concept for SITVC application without attempting to design a lightweight system.

An objective of the basic design was to eliminate all possible areas where leaks could occur. Thus the control and power stage vortex amplifiers were stages in series by means of internal manifolding. The same internal manifold technique was employed in designing a pilot flow manifold in the control stage.

Power Stage

The power stage is designed for a flow rate of 2.0 lb/sec of H_2-O_2 at a supply pressure of 400 psig and a temperature of 1500°F. The vortex chamber outlet orifice is the principal parameter which determines the flow capacity of the vortex amplifier. From the orifice weight flow equation the outlet diameter was established at 1.500 inches.

From past experience, the vortex chamber diameter and chamber length are related to the outlet diameter by given ratios. The chamber diameter is 6 times the diameter of the outlet orifice, while the chamber length is one-third the outlet orifice diameter. Using these two ratios helps insure stability and good performance of the vortex amplifier. From these ratios the chamber diameter was established at 9.00 inches, and the chamber length at 0.500 inch.

The vortex chamber button diameter was sized to provide an annular area equal to 3 times the outlet orifice area. This is considered to be the optimum size to assure, on the one hand, that incoming supply flow is unrestricted and, on the other, that all of the supply flow interacts with the control flow. The button diameter thus was calculated to be 8.62 inches. The button length was selected at 0.750 inch, which is one-half of the outlet orifice diameter.

The receiver design was developed during Task 1. This development established the receiver diameter as 1.9 times the outlet orifice diameter; the optimum receiver position was determined to be at an axial distance equal to the outlet orifice diameter. Thus, the receiver diameter for the full-scale amplifier was calculated as 2.85 inches, and the receiver was located 1.5 inches from the outlet orifice plate.

The vortex supply flow is modulated by the output flow of the control stage. Six ports were provided in the power stage amplifier to inject this flow into the vortex chamber. The ports are equally spaced and tangent to the vortex chamber diameter. They lie on a plane common with the face of the button. By dividing the maximum flow of the control stage by a factor of six and by assuming a maximum inlet control pressure of 600 psig, the diameter of each control port was calculated to be 0.176 inch. Thus, the total injection area was 0.146 in^2, which would achieve an 8-to-1 turndown of the power stage.

To simulate the secondary injection load, an orifice was placed at the outlet of the receiver. At a flow recovery of 90% of the total flow, the maximum receiver pressure was 25% of the supply pressure. With these facts, the load orifice area was established at 5.92 in^2.

A summary of the preceding design parameters is shown in Table 14.

Table 14 - Task 3 Power Stage Vortex Amplifier Final Design Parameters

Outlet Orifice Diameter	D_{o1} = 1.500 in.
Chamber Diameter (D_1/D_{o1} = 6)	D_1 = 9.00 in.
Chamber Length (D_{o1}/L_1 = 3)	L_1 = 0.500 in.
Button Diameter	D_{B1} = 8.62 in.
Button Length (D_o/L_{B1} = 2)	L_{B1} = 0.750 in.
Control Port Diameter (6 Ports)	D_{c1} = 0.176 in.
Receiver Diameter (D_r/D_{o1} = 1.9)	D_r = 2.85 in.
Receiver Position (D_{o1}/X_r = 1)	X_r = 1.50 in.

Control Stage

The control stage is a smaller version of the power stage. The flow requirement is H_2-O_2 gas at 1500°F and a flow rate of 0.325 lb/sec. This flow rate represents an arbitrary increase of 30% over the theoretical control flow that is necessary to obtain an 8-to-1 turndown of the power stage. The Task 1 development demonstrated that, for a high-gain system, the control stage must have excess capacity. This allows a biasing flow point to be established that is in the partially turned-down, high flow gain region of the control stage. For the 0.325 lb/sec hot gas flow rate and a supply pressure of 800 psig, the outlet orifice diameter was calculated to be 0.445 inch.

The same ratios that were used to determine the power stage design parameters also apply to the control stage design parameters. The only exception to this is the chamber diameter, which was rounded off to 2.875 inches. This yields a chamber-to-outlet diameter ratio of 6.46. This increase was adopted to provide flexibility in the design of the control stage. In the event that the 30% margin in outlet flow was not sufficient to allow the control stage to modulate in its high-gain region, the outlet area could be increased as much as 20% without jeopardizing the stability of the control stage.

These and all the remaining design parameters of the control stage are shown in Table 15.

Table 15 - Task 3 Control Stage Vortex Amplifier Final Design Parameters

Outlet Orifice Diameter	D_{o2} = 0.445 in.
Chamber Diameter (D_2/D_{o2} = 6.46)	D_2 = 2.875 in.
Chamber Length (D_{o2}/L_2 = 3)	L_2 = 0.148 in.
Button Diameter	D_{B2} = 2.770 in.
Button Length (D_{o2}/L_{B2} = 2)	L_{B2} = 0.222 in.
Control Port Diameter (6 Ports)	D_{c2} = 0.050 in.

Materials

The material study that was accomplished for the Task 2 design also applies to the Task 3 system. All hot gas components of the control stage and power stage were fabricated from Inconel X-750. The only exceptions to this were the power stage outlet orifice plate and the receiver, which were manufactured from molybdenum alloy TZM-1. This material had already been used successfully in this application in the previous test program and in Task 1. It has excellent high-temperature properties. Past experience has shown that components made from this material retain their dimensions and sharp edges during hot gas testing.

SYSTEM TESTING AND EVALUATION

The Task 3 system was initially tested with cold gas to evaluate the design and the system performance. Although the system is designed for hot gas, preliminary cold gas testing has in the past proven to be a valid procedure in evaluating a system. Close correlation between hot and cold gas performance was obtained in testing the 0.5 lb/sec Task 1 system.

All of the cold and hot gas tests were conducted in the same facility. The facility has provision for operating with either inert gas or propellant gases. All testing is accomplished from a remote control panel with all pressures and temperatures electronically instrumented. This test installation allows convenient variation of flows and pressures and provides adequate instrumentation to obtain the data necessary to evaluate the system and component characteristics.

A block diagram of the facility is shown in Figure 34. The actual system and control panel are shown in Figures 35 and 36.

In the initial evaluation of the system, three cold gas tests were accomplished. The first test performance was entirely satisfactory. Then

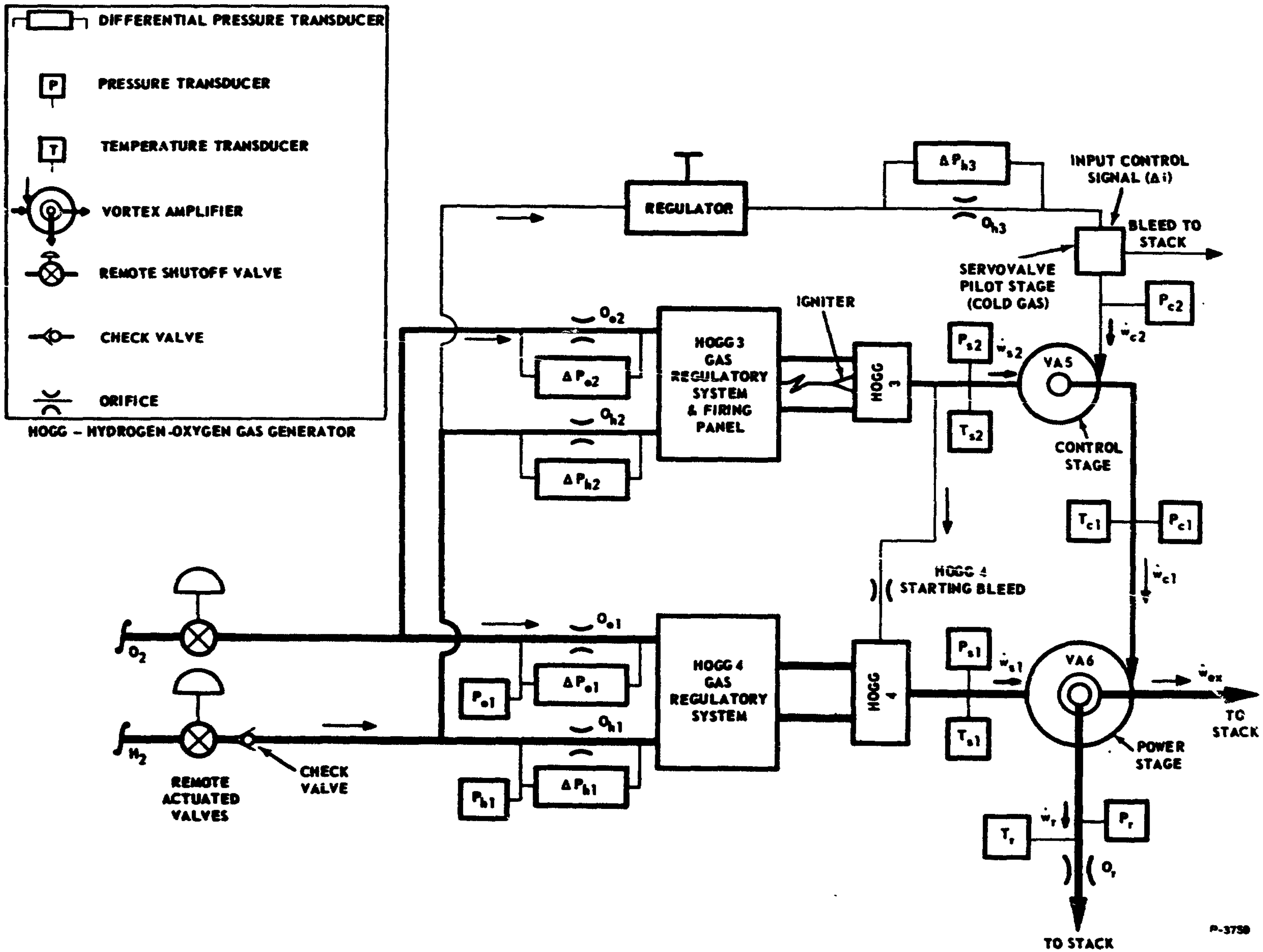


Figure 34 - Task 3 Hot Gas Test Schematic

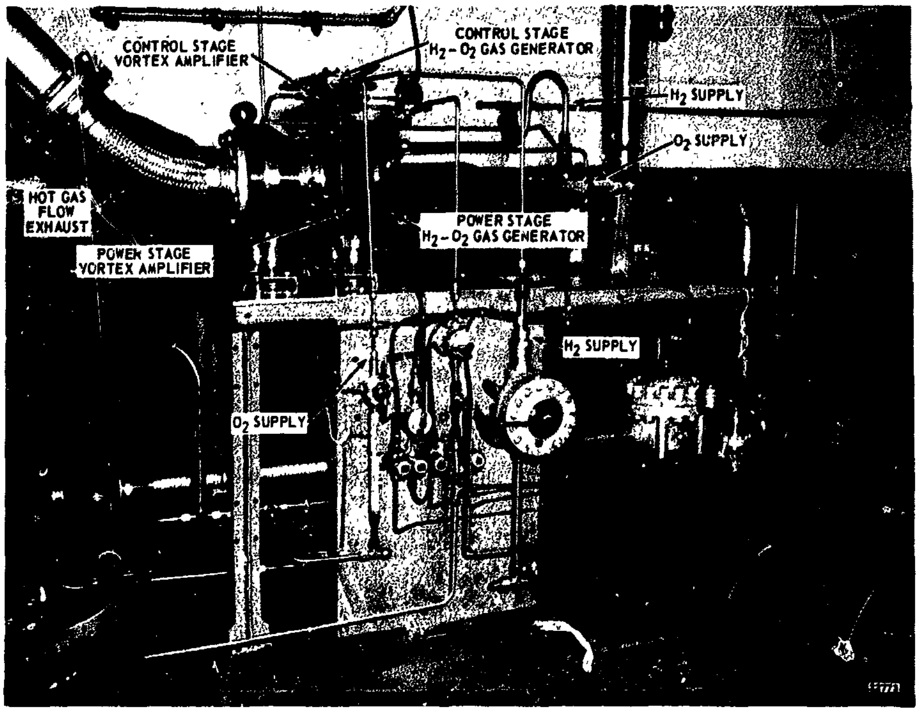


Figure 35 - Task 3 Hot Gas Test Facility

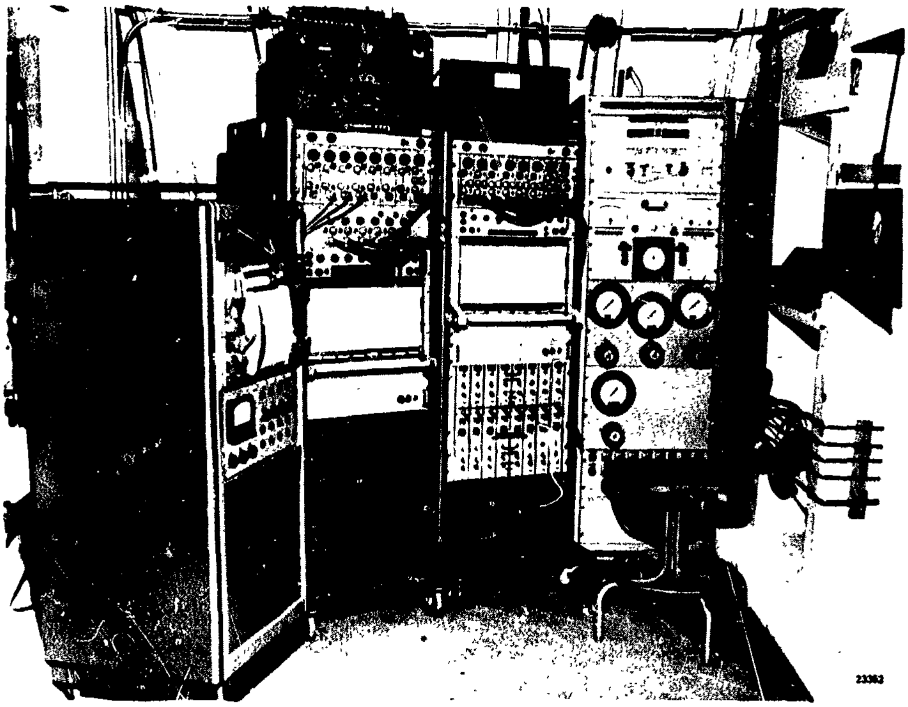


Figure 36 - Task 3 Hot Gas Test Control Panel

Table 16 - Task 3 Performance Summary

Test No.	Date	Power Stage	Control Stage	Gas	Purpose of Test	Test Results	Initial Flow Recovery %	Flow Recovery @ Bias Point %	Final Point P_{c2}/P_{s1}	Bias Point P_{c2}/P_{s1}	Total Flow Turndown	Pressure Recovery P_r/P_{s1} %	Receiver Flow At Shutoff %	Power Stage Flow Gain $\dot{w}_r/\Delta\dot{w}_{c1}$ (K_p)	Control Stage Flow Gain $\Delta\dot{w}_{c1}/\Delta\dot{w}_{c2}$ (K_c)	Overall Flow Gain $\dot{w}_p/\Delta\dot{w}_{c2}$ (K_pK_c)
1	8-15 1966	VA6	VA5	N_2	Initial test on Task 3 staged vortex ampl End point evaluation for shutoff potential.	Performance good.	100	—	2.20	—	7.4	22.5	0	8.4	33.1	278
2	8-25	VA6	VA5	N_2	Full range test evaluation of the design configuration.	Performance good. Specified goals met or exceeded.	97.5	90 (Selected)	2.14	2.42	8.9	23.2	0	8.7	24.6	214
3	8-25	VA6	VA5	N_2	Evaluation of receiver position. (Cold Gas Tests Completed)	Receiver performance inferior to that of Test No. 2. Overall performance degraded by change in operating mode with receiver location change.	99.0	90 (Selected)	2.03	2.32	8.3	22.2	0	12.2	14.2	174

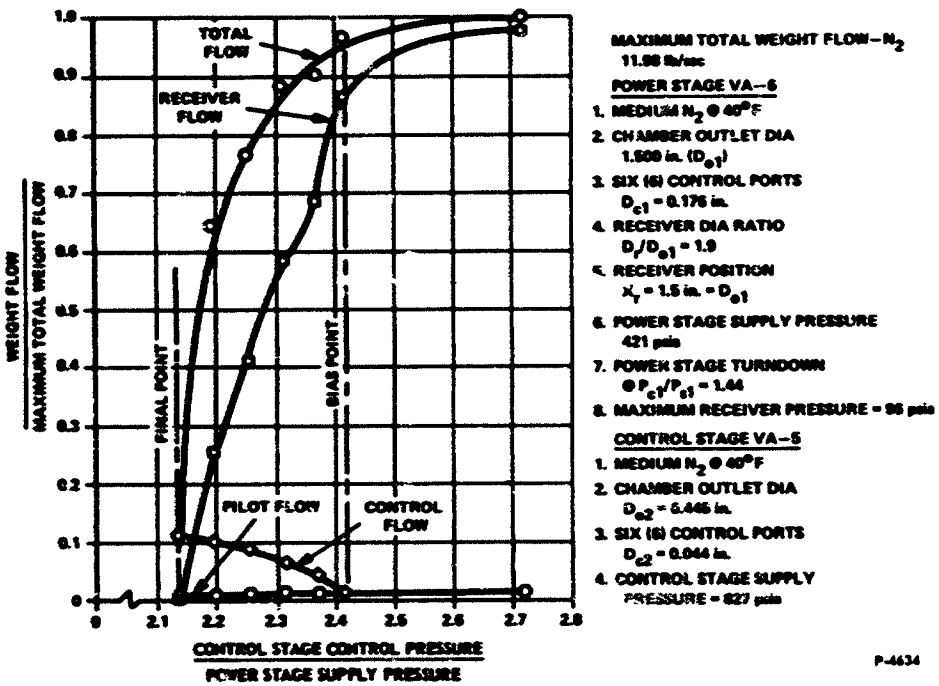


Figure 37 - Task 3 Cold Gas Test No. 2 Performance Curves

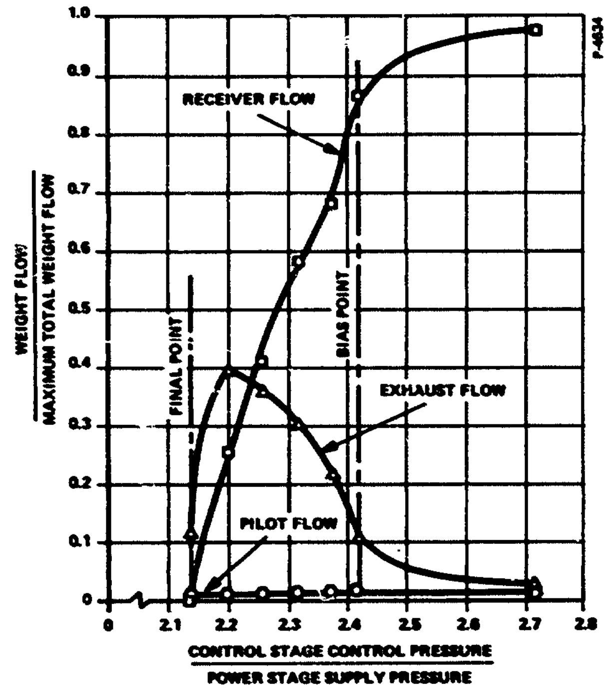


Figure 38 - Task 3 Cold Gas Test No. 2 SITVC Performance Curves

two additional cold gas tests were run to verify the optimum receiver position and the overall test results. The system design produced the required performance, and the design position of the receiver was experimentally verified to be the optimum position.

The best system performance was produced when the ratio of receiver location to outlet diameter was unity. This axial location determined the operating region of the system and resulted in accomplishing all of the goals. From the selected bias point receiver recovery of 90% to complete shutoff, an overall gain of 214 was realized in Test No. 2. In this test as in the other two cold tests, initial flow recoveries of approximately 100% were obtained. This performance is summarized in Table 16, which contains the performance summary for all of the cold gas tests. Figures 37 and 38 show the performance of Test No. 2 plotted in the conventional method and in SITVC format.

Hot tests were conducted principally to demonstrate the integrated staged unit when simulating a single-axis secondary injection thrust vector control system. Since the system design involved two integrated gas generators, hot testing depended on ignition of both gas generators. Ignition of the control stage gas generator is accomplished by an oxygen-

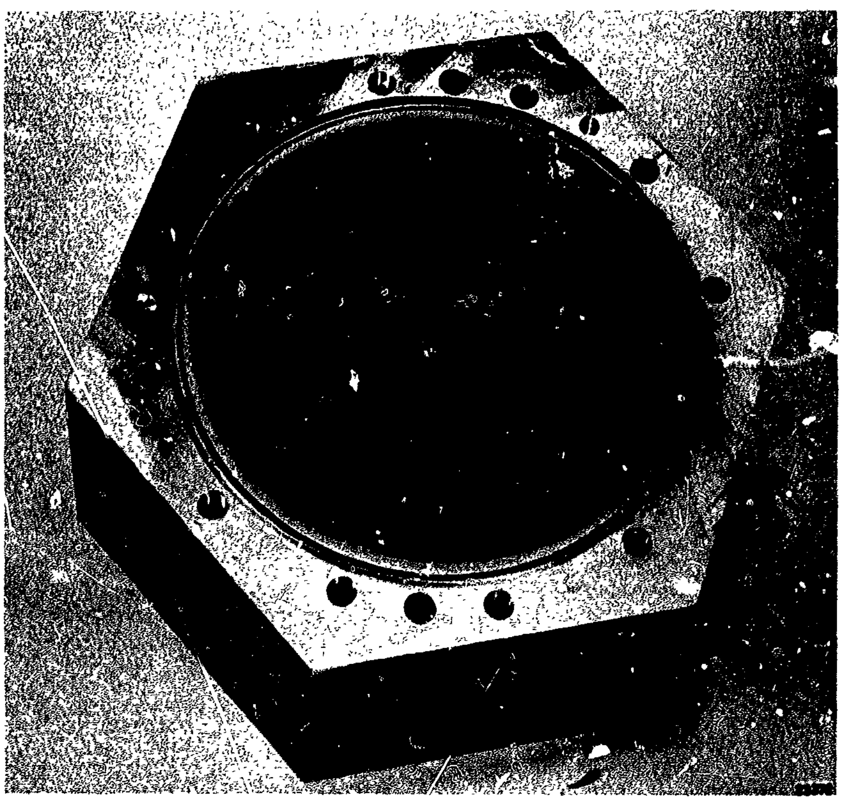


Figure 39 - Task 3 Power Stage Vortex Amplifier Showing Repair Welds in Chamber

rich start with the energy source supplied by a spark plug. The power stage gas generator is ignited by a hot gas bleed from the control stage gas generator. In the process of developing the hot gas injection scheme, a propellant system failure exposed the power stage to a temperature in excess of 2500°F, caused by an oxygen-rich hot gas flow. This damaged the power stage vortex amplifier wall and set up a transient temperature gradient in the vortex chamber. The temperature gradient developed thermal stresses which caused the metal to crack. These cracks degraded the vortex characteristic of the power stage by allowing control flow to communicate with the supply flow through the axial cracks in the supply plenum region upstream of the vortex chamber.

Several attempts were made to repair the damaged areas in order to complete the hot gas testing on the system. Various welding techniques were used to close the surface cracks that were in communication with the control flow internal manifold. The openings were sealed, but, as hot testing continued, new cracks developed and, as a result, no successful hot staged test was accomplished. Figure 39 shows the power stage vortex chamber with the welded areas.

Although a complete system test was not accomplished, the 21 minutes of hot gas testing did result in a successful method of igniting the power stage with a hot gas bleed and in demonstrating the capabilities of the vortex-doublet gas generator. Full flow and full turndowns were accomplished on both the power stage gas generator and the control stage gas generator without damage.

PRECEDING PAGE BLANK NOT FILMED.

RECOMMENDATIONS

HIGH-TEMPERATURE FLIGHTWEIGHT DESIGN

The interior configuration of the vortex amplifier and gas generator has largely been established by the present contract. It is recommended that these designs should now be refined to reduce weight and size and to enable the devices to withstand severe thermal transients. Preliminary investigations have indicated the feasibility of incorporating the control stage vortex amplifier inside the power stage with a great improvement in profile and a large weight reduction. In other investigations (Reference 6) the use of composite structures which include thin concentric shells of refractory material, insulation and structural metal has been proved and should be investigated for this application. A materials study and a transient thermal stress analysis would show how to minimize thermal stresses and how best to design structures to withstand thermal stresses. The goal would be to achieve a flightweight vortex amplifier system capable of integration with a rocket engine for thrust vector control.

ENGINE BLEED

The use of gas generators to supply the vortex amplifiers is recognized as an independent source of hot gas. A more logical method would be to obtain the hot gas directly from the engine by tapping the chamber or nozzle. This would save weight by eliminating one or both gas generators, separate regulators and ignition systems. It is recommended that engine bleed be studied because it appears to be a logical and simple way to obtain hot gas for secondary injection thrust vector control.

BASIC DEVELOPMENT

The vortex amplifier has not been developed to its full potential. One of the principal areas that require investigation is the region just downstream of the vortex chamber exit where the receiver is located. The present contract resulted in the achievement of a configuration that met the specified performance. However, little is known about the effects of loading, scaling, geometry and pressure effects. It is recommended that this area be investigated with a comprehensive program of analysis and experimentation to define and normalize the flow in this region. Once normalized parameters are established, they can be applied to design the receiver and output section to fulfill any specification requirement.

PRECEDING PAGE BLANK NOT FILMED.

APPENDIX A

EXPERIMENTAL DEVELOPMENT OF LARGE DIAMETER RECEIVER

In an effort to better understand the flow field of the gases emerging from the vortex chamber, a series of short experiments were performed. Two operating conditions were studied, one in which the gas is unswirled and the supply flow is unrestricted, and the second in which the vortex chamber is in maximum swirl and minimum flow is exiting.

The emerging gas is relatively unconed in the first condition, and the outer boundary of flow can be defined as shown in Figure A-1. All of the gas emerging from the vortex chamber is contained within this boundary. It is coned slightly because of the normal flare of a free jet and also because the control stage is admitting a minimum amount of control flow. This boundary was established by experimenting with three receiver sizes with diameter ratios of D_r/D_o = 1.1, 1.2 and 1.3. These receivers were axially positioned to give the best flow recovery.

The best flow recovery achieved was in the range of 90 to 94%. The receiver in all cases was loaded with the same fixed orifice simulating the secondary injection nozzle. Pressure recoveries of 25% were achieved. The location of the theoretical 100% flow recovery point was approximated by scaling up the receiver size on an area basis to improve the recovery from the actual value up to 100%. The assumption was made that the recovery was proportional to the entrance area of the receiver. This was done for the three receivers. A linear relationship was indicated, starting at the orifice edge and extending out at a half angle of 22 degrees relative to the centerline.

A second test series was performed to define the inside boundary of the hollow cone of gas under the maximum swirl and turndown condition. Using the same series of receivers as were used for the previous test series, the inner boundary of the cone was determined as shown in Figure A-2 by positioning the receivers axially to obtain minimum receiver flow. This data established the inner boundary at a half angle of 41 degrees. The inside of the cone is a stagnant area, with no flow under the maximum swirl condition.

Superimposing these two flow conditions, as shown in Figure A-3, revealed that there is a region (region "A") in which receivers can be sized and positioned to achieve 100% flow recovery and complete flow shutoff. On the basis of the tests performed with receiver diameter ratios of 1.1, 1.2 and 1.3, it was determined that the minimum receiver size that will fulfill this condition has a diameter ratio of D_r/D_o = 1.7 at a relative axial position of 0.86 D_o. This is the cricital location, since the inner and outer boundary curves cross at this point. Receivers located in region "A" beyond this critical point at higher maximum ratios

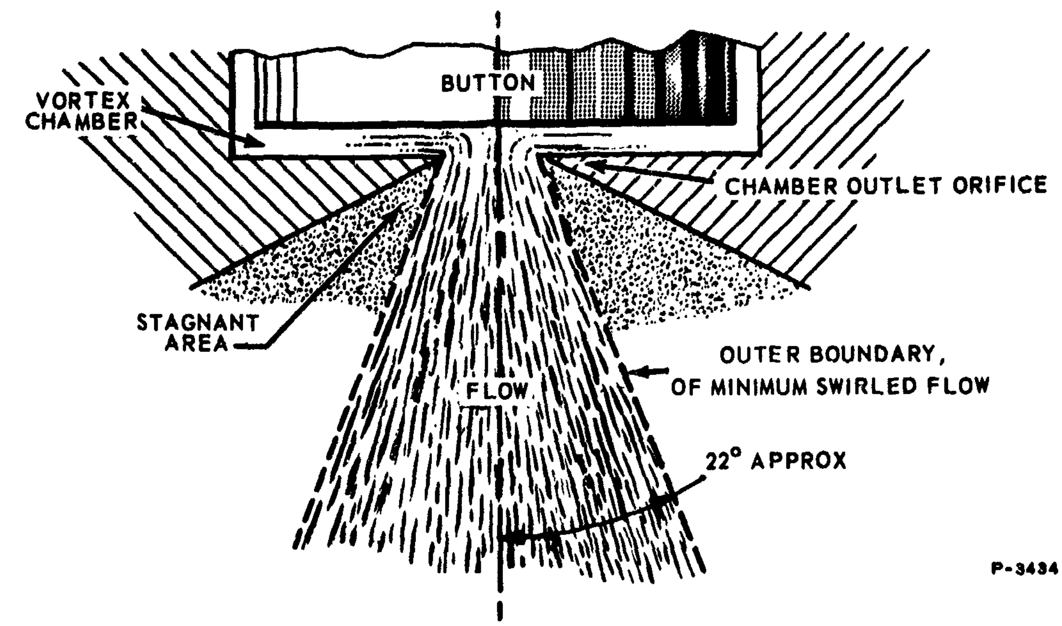


Figure A-1 - Emerging Gas at Maximum Flow Conditions

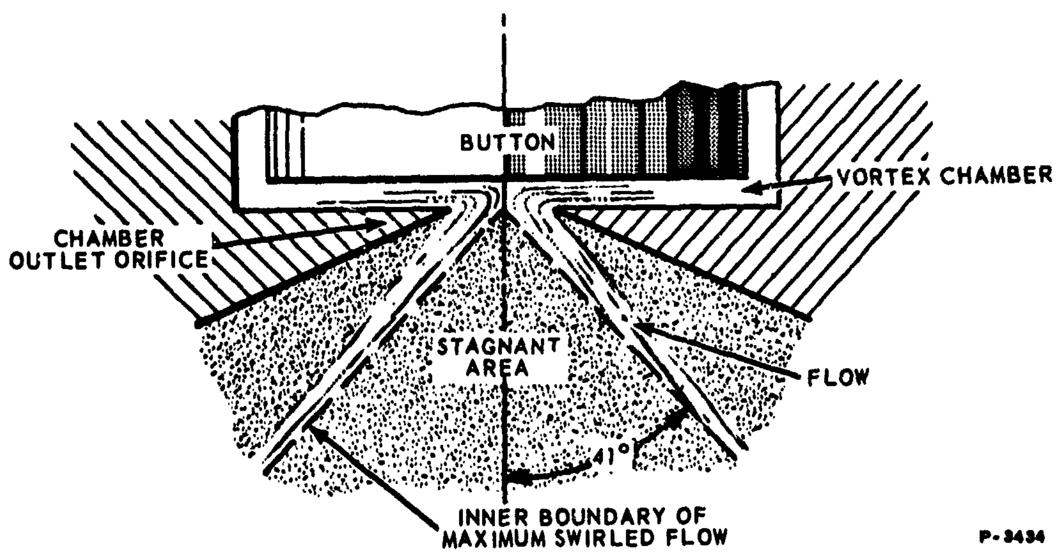


Figure A-2 - Emerging Gas at Minimum Flow Conditions

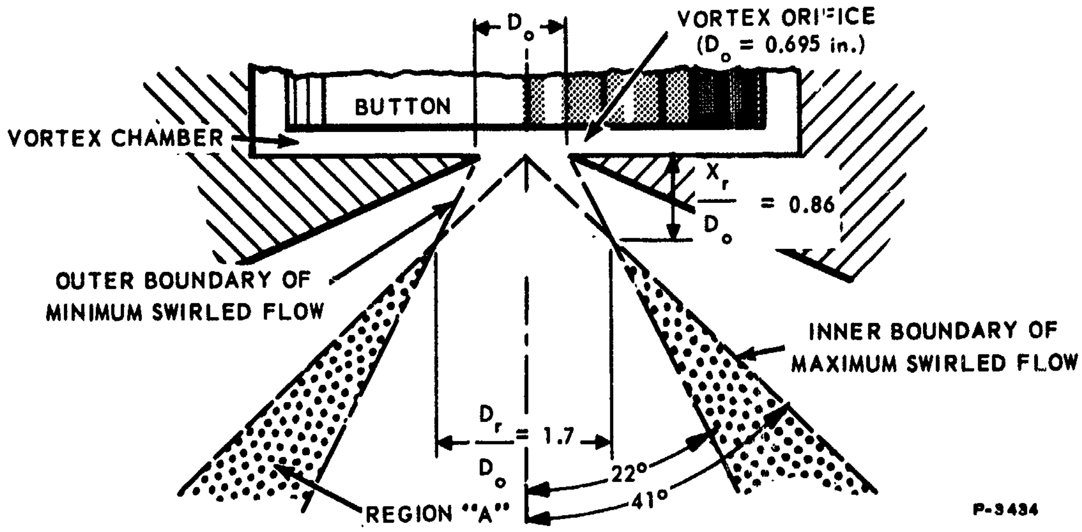


Figure A-3 - Composite Sketch of Cone Boundaries for Maximum and Minimum Flow Conditions

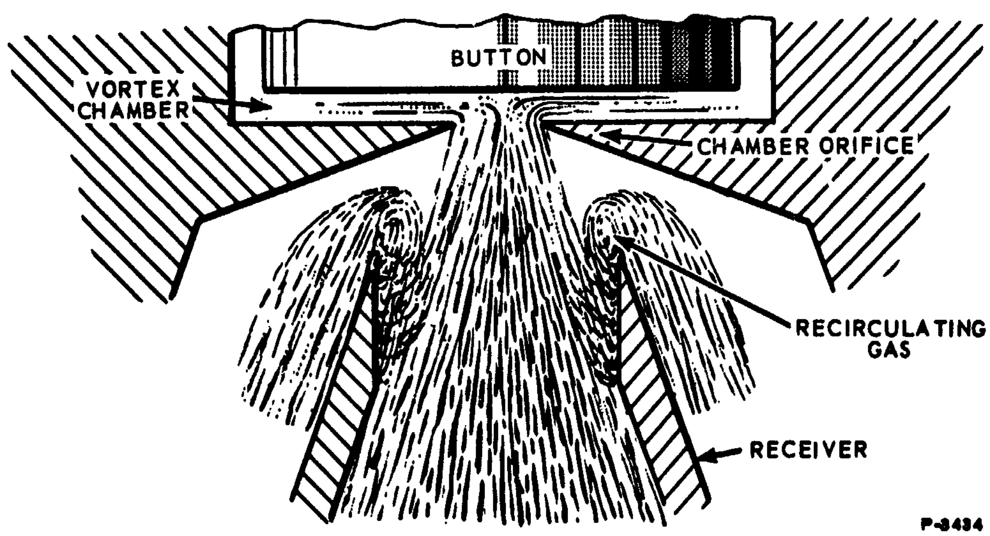


Figure A-4 - Receiver Flow Recirculation at Maximum Flow Conditions and larger axial spacings will allow a theoretical maximum flow recovery of 100% and, with maximum swirl, complete flow shutoff. Receivers located other than in region "A" can achieve either 100% maximum flow recovery or zero minimum flow, but never both conditions for a given receiver size and spacing.

A series of larger diameter receivers, D_r/D_o = 1.6, 1.7 and 1.9, were tested to supplement the previous data. The results were found to generally support the foregoing conclusions. Complete flow shutoff was obtained; however, it was found that flow recoveries greater than 94% could not be achieved. This is attributed to the fact that recirculation occurs in the larger receiver sizes. The phenomenon is shown in Figure A-4. Some of the gas flow entering the receiver reverses direction and escapes. This flow reversal is the direct result of receiver pressure loading caused by the downstream load orifice that simulates the secondary injection nozzle required for a thrust vector control system application. Lowering the maximum receiver pressure by increasing the size of receiver flow load orifice would tend to lessen the recirculation and improve total flow recovery.

Since the maximum size receiver tested had a D_r/D_o ratio of 1.9, the effect of using very large receivers at excessive distances was not investigated. It is to be presumed that region "A" does not extend indefinitely and, if the receiver is located too far away, the jet will have dispersed so that high flow recovery is impossible.

APPENDIX B

REFERENCES

1. Kasselmann, J. T., All-Fluid Amplifier Development for Liquid Rocket Secondary Injection Thrust Vector Control, Monthly Technical Report, Bendix Research Laboratories Report 3083, 17 August 1965.

2. Comparative Properties of Haynes High Temperature Alloys, Haynes Stellite Company, June 1962.

3. Steels for Elevated Temperature Service, United States Steel Corporation, 1961.

4. Handbook of Huntington Alloys, Huntington Alloy Products Division, The International Nickel Company, 1963.

5. "Materials Selector Issue," Materials in Design Engineering, Vol. 60 n5, Mid-October 1964.

6. Keranen, T. W., and Blatter, A., Research and Development of the Vortex Valve Principle and its Application to a Hot Gas (5500°F) Secondary Injection Thrust Vector Control System, Bendix Research Laboratories Final Report 4227 - Phase I, September 1967.

PRECEDING PAGE BLANK NOT FILMED.

APPENDIX C

Glossary of Symbols and Subscripts

Symbols

A	- Area, in^2
C_d	- Flow Discharge Coefficient
C_2	- Thermodynamic Gas Constant, $°R^{1/2}/sec$
D	- Diameter, in.
F	- Fuel
f_1	- Orifice Flow Function
g	- Gravitational Acceleration, in/sec^2
H_2	- Hydrogen Gas
H_2-O_2	- Specified Hot Gas
HOGG3	- Task 2 Control Stage Gas Generator
HOGG4	- Task 2 Power Stage Gas Generator
k	- Ratio of Specific Heats
L	- Length
L^*	- Characteristic Length
M	- Molecular Weight
N_2	- Nitrogen Gas
O	- Oxidizer
O_2	- Oxygen Gas
P	- Pressure, psi
R	- Gas Constant, in/°R
R^*	- Universal Gas Constant, in-lb/lb-mole-°R
T	- Temperature, °R
V	- Volume, in^3; Velocity, in/sec
VA2	- Task 1 Power Stage Vortex Amplifier
VA4M2	- Task 1 Control Stage Vortex Amplifier
VA5	- Task 3 Control Stage Vortex Amplifier
VA6	- Task 3 Power Stage Vortex Amplifier
$\dot{w}$	- Weight Flow, lb/sec
X	- Spacing, in.

Subscripts

1	- power stage
2	- control stage
a	- ambient
ann	- annulus
B	- button
b	- bias
bl	- bleed
c	- control
d	- discharge, downstream
ex	- exhaust
g	- generator
h	- hot, hydrogen
i	- inlet
max	- maximum
n	- nitrogen
o	- outlet, oxygen
p	- power
r	- receiver
s	- supply
t	- total
u	- upstream