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50-POUND THRUST ATTITUDE-CONTROL MOTORS

by

J. W. Shaw
Propulsion Development Department

ABSTRACT. The 50-pound thrust attitude-control motors are high performance liquid rocket engines capable of being operated in either pulsed or variable-thrust modes.

The motors are durable and versatile flightweight systems, weighing less than one pound. A vacuum-corrected specific impulse of 310 lb-sec/lb was achieved using nitrogen tetroxide and mixed hydrazine. Response of the motor from signal input to 90 percent of full thrust was 7 ms in both the pulse and variable-thrust modes. The motor was operated in a pulsing mode up to 100 cps and also in the variable-thrust mode with a repeatable thrust accuracy of five percent. A new variable-thrust actuation system was developed for which a patent has been applied.

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

May 1963

U. S. NAVAL ORDNANCE TEST STATION
AN ACTIVITY OF THE BUREAU OF NAVAL WEAPONS

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FOREWORD

The work reported herein was undertaken as an extension of previous variable-thrust motor development effort at the U. S. Naval Ordnance Test Station during Fiscal Year 1963.

This work was authorized by Task Assignment RMMP-24-080/216-1/F009-06-02.

This report was reviewed for technical accuracy by Daniel Meraz Jr. and Benjamin Glatt.

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NEGATIVE NUMBERS OF ILLUSTRATIONS

FIG. 1, LO81767; FIG. 2, LO74232; FIG. 3, LO81768; FIG. 4, LO72108; FIG. 5, LO77870; FIG. 6, 72844; FIG. 7, LO83150; FIG. 8, LO59948; FIG. 9, LO83149; FIG. 10, LO83148; FIG. 11-12, none; FIG. 13, LO72110; FIG. 14, LO81744; FIG. 15, LO81743; FIG. 19, LO83147; FIG. 20-31, none.

INTRODUCTION

The program was set down as a development project on small pulse and variable-thrust motors. Secondary emphasis was on the development of a motor adaptable for use with the Guided Flight Vehicle Program, which required a high response type motor.

The main attention in the development was toward an improved actuation system, better orifice sealing, and higher performance than previous small motor systems.

The control systems selected for comparison were the servovalve system, the solenoid valve hydraulic control system, and a direct solenoid pulsing system. Response of the system was to be as high as reasonably feasible, and a goal of a maximum allowable seat leakage rate of one cubic inch was determined as feasible.

The program investigated the following areas:

1. Flightweight combustion chambers
2. Improved injector design
3. Control systems applicable to small motors
4. Testing apparatus
5. Motor system

Figure 1 shows the 50-pound motor which was developed and tested.

COMBUSTION CHAMBER

The development of the combustion chamber consisted of two separate phases. One phase was a combustion chamber workhorse to be used with testing of the injectors; the other phase was the development of a flightweight combustion chamber.

The design of the chambers involved consideration of the following parameters:

A low chamber pressure of 100 psi was selected so that a small nozzle exit pressure could be obtained for higher nozzle performance without a large weight penalty; 100 psi is also high enough so that the theoretical C^* loss in the combustion process is negligible.

For high performance pulse motors, fast response is desirable if the loss of C^* efficiency is only a few percent. Thrust response time

FIG. 1. 50-Pound Pulse Motor.

is directly proportional to the L*, but as the L* decreases so does the C* efficiency. Response and C* efficiency are then dependent on the character of the mission to be accomplished. Chambers with L*'s of 8 and 40 were tested with this program.

The workhorse combustion chamber is a dependable long duration chamber with the same basic internal configuration as a flightweight combustion chamber. Water-cooled chambers as a workhorse type were useful in gaining data on propellant flow, control system performance, and thrust rise duration. But, because of high heat losses to the cooled walls (as much as 25 percent of C* was lost), uncooled chambers were used in the final testing. The uncooled chambers were inexpensive throwaway parts with a firing life of one minute.

Figure 2 shows a water-cooled chamber with its accompanying graphite insert for varying L*. Figure 3 shows the disassembled uncooled chamber with the 50-pound injector.

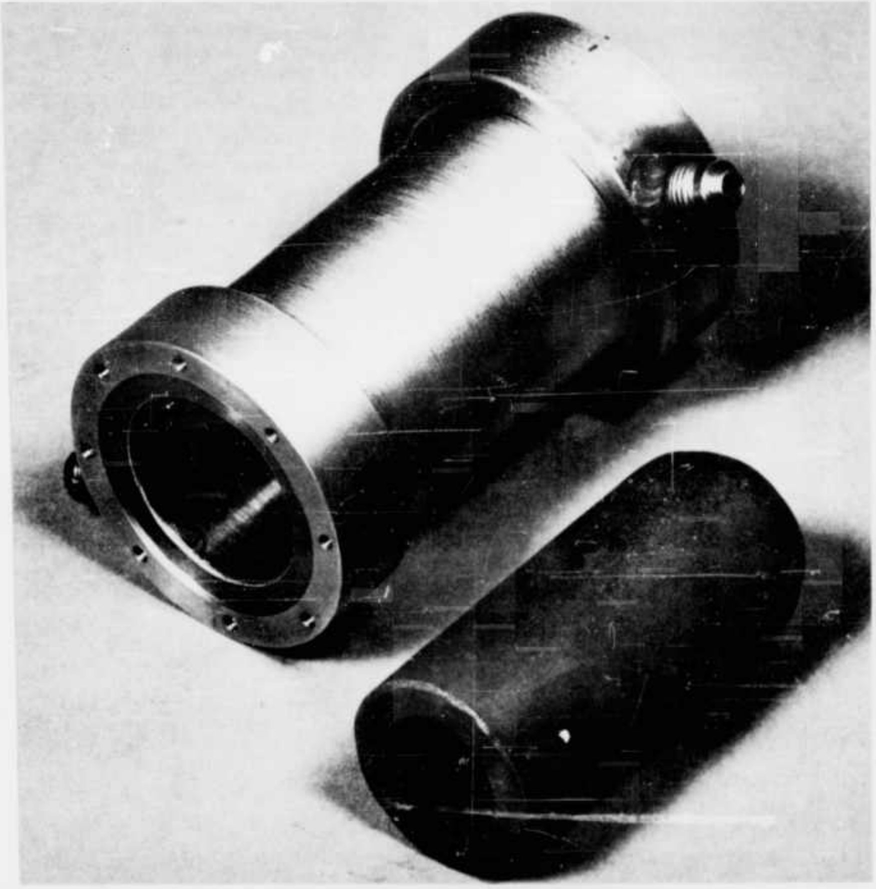


FIG. 2. Water-Cooled Chamber With Graphite Insert.

FIG. 3. Disassembled Uncooled Chamber and Injector.

The thrust rise time with a L* = 8 chamber was between 4 and 6 milliseconds (ms). The thrust rise time for the L* = 40 chamber was between 6 and 8 ms. C* values decreased between 1 and 5 percent from the L* = 40 chamber to the L* = 8 chamber. Data were taken under varying conditions and the C* values for the L* = 8 uncooled chambers were never under 90 percent of theoretical.

The flightweight chambers were constructed of Astrolete and fiberglass wrapping. Figure 4 shows the chamber attached to the 35-pound motor, which was a workhorse research motor. The weight of the chamber was approximately 6 ounces. Two ablative type chambers were fabricated and tested for 20 seconds at 35 pounds of altitude-corrected thrust under steady-state firing. On both tests the throat erosion was less than one percent. One chamber failed in the fiberglass wrapping (Fig. 5). This failure can be cured by wrapping the fiberglass at an angle to the centerline of the chamber. Similar chambers have been tested at NOTS at chamber pressures of 300 psi for 3 minutes.

Figure 6 shows a combination ablative-radiation type chamber designed for vacuum use with a 35-pound thrust motor.

All theoretical parameters were taken from Ref. 1.

INJECTOR

The 50-pound injector design (Fig. 7) is a continuance of previous variable-thrust development at NOTS. The initial variable-thrust injector development at NOTS is described in Ref. 2 - 3.

The NOTS variable-thrust concept of metering the propellants with a single moving part, called the pintle, was very practical when adapted to pulsing engines. The chief advantages were:

1. Close synchronization of the propellant metering
2. Extremely fast response feasibility of the pintle
3. Small propellant impingement length
4. Inherently good mixing of the propellants due to splash plate and direct impingement.

Previous NOTS injectors had several weak points that were overcome in the development of the 50-pound motors. These weak points are described in the following paragraphs.

FIG. 4. Flightweight Combustion Chamber With 35-Pound Injector.

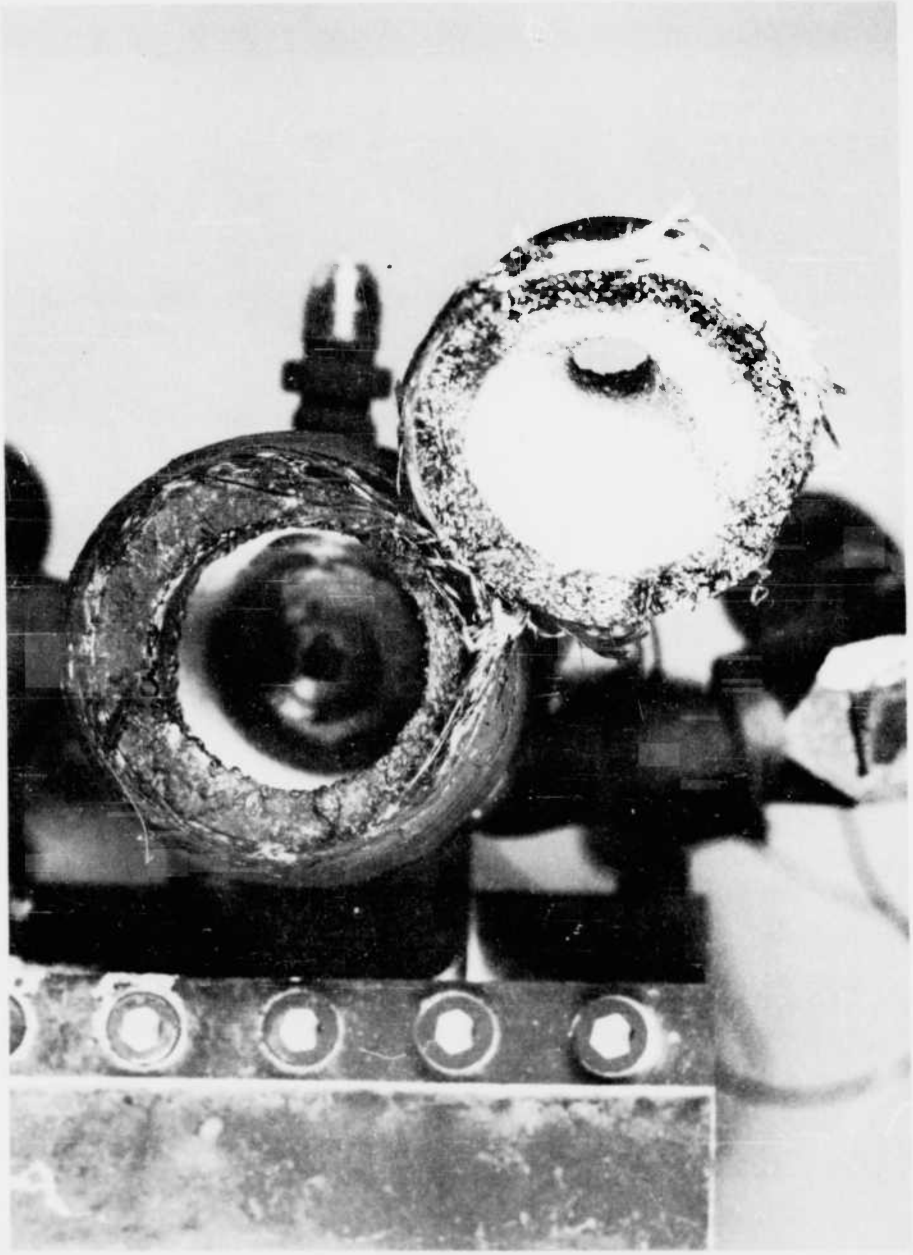


FIG. 5. Failure of Flightweight Chamber in Fiberglass Wrapping.

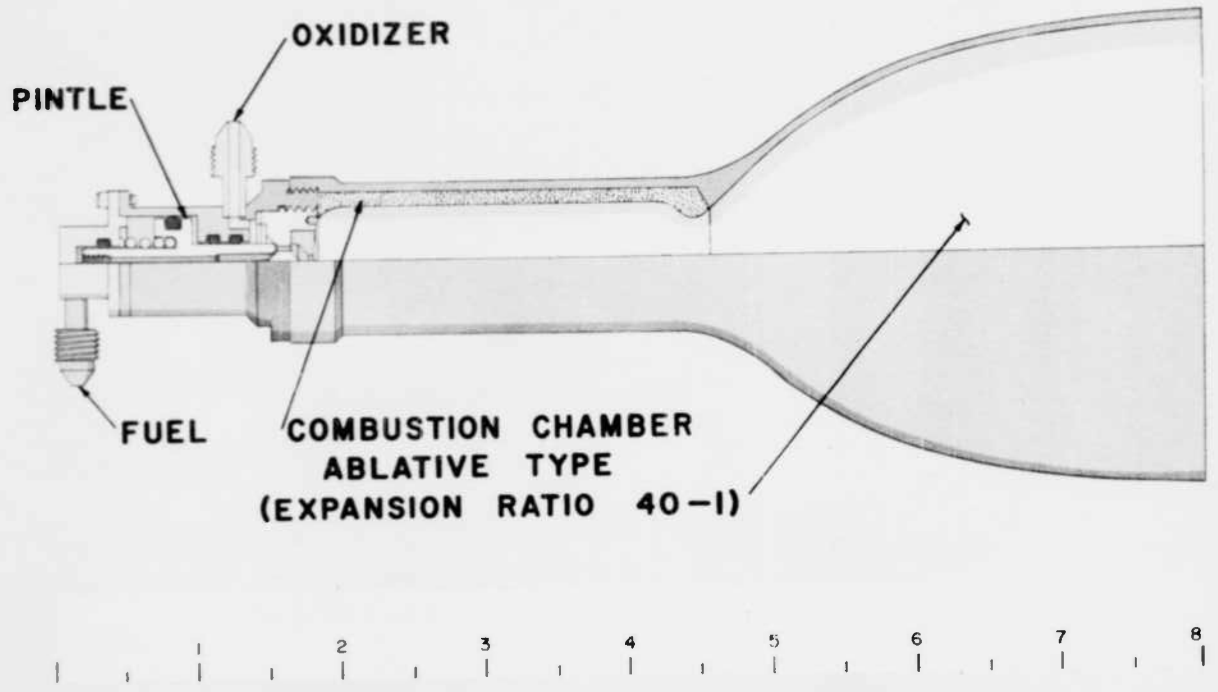


FIG. 6. Combination Ablative-Radiation Type Chamber for Vacuum Use With 35-Pound Motor.

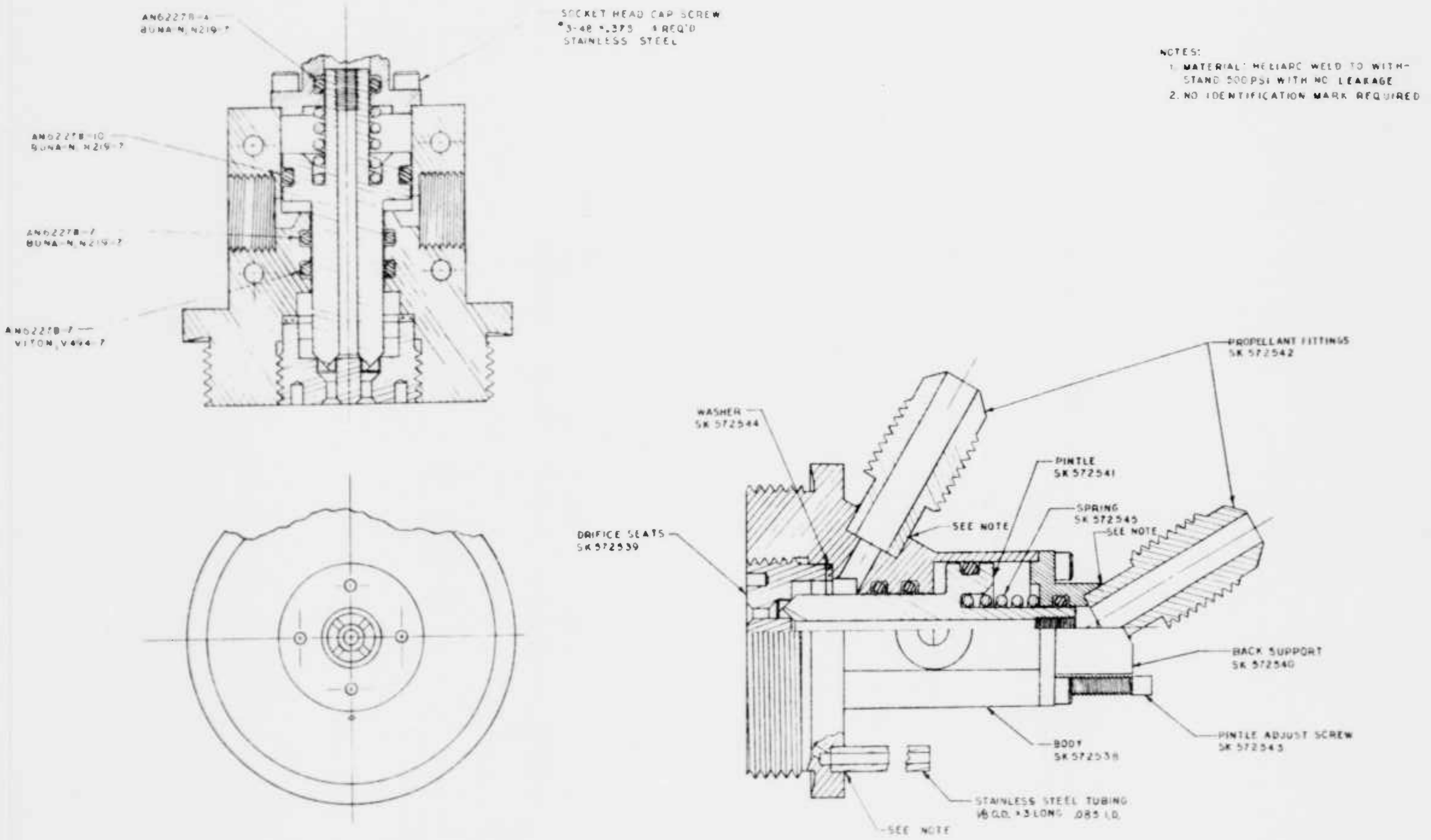
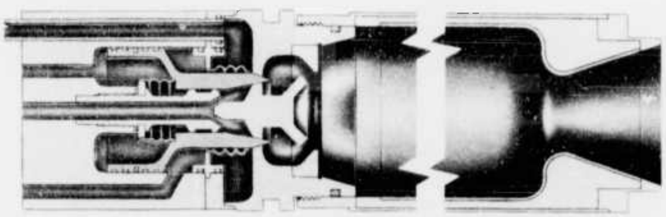


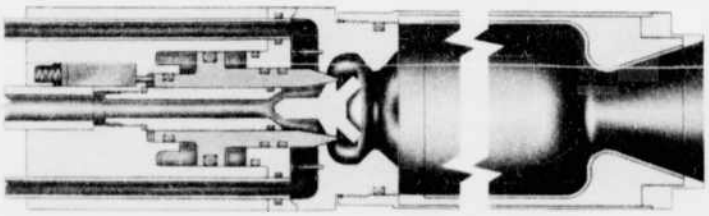
FIG. 7. 50-Pound Injector Assembly.

All of the previous variable-thrust injectors used conical seats as shown in Fig. 8. The conical surface orifice design inherently, because of its geometry, gave varying O/F ratios with relation to pintle position. The closed injector leakage rate was also excessively high, sometimes being as high as 20 percent of the maximum flow. Also, these two characteristics were very susceptible to small particle contamination in the system.



(a)

BELLOWS SEAL DESIGN



(b)

O-RING SEAL DESIGN

FIG. 8. NOTS Variable-Thrust Injector.

The core piece was a long shaft which threaded into the back of the injector and gave numerous alignment and adjustment problems. Most of the injectors as a whole were complicated to assemble.

In the development of the 50-pound injector (Fig. 7), a comparison of the conical seat design arrangement was made with a ribbon type seat. In the ribbon seat design the following characteristics were incorporated (see Fig. 9-10 for detailed design).

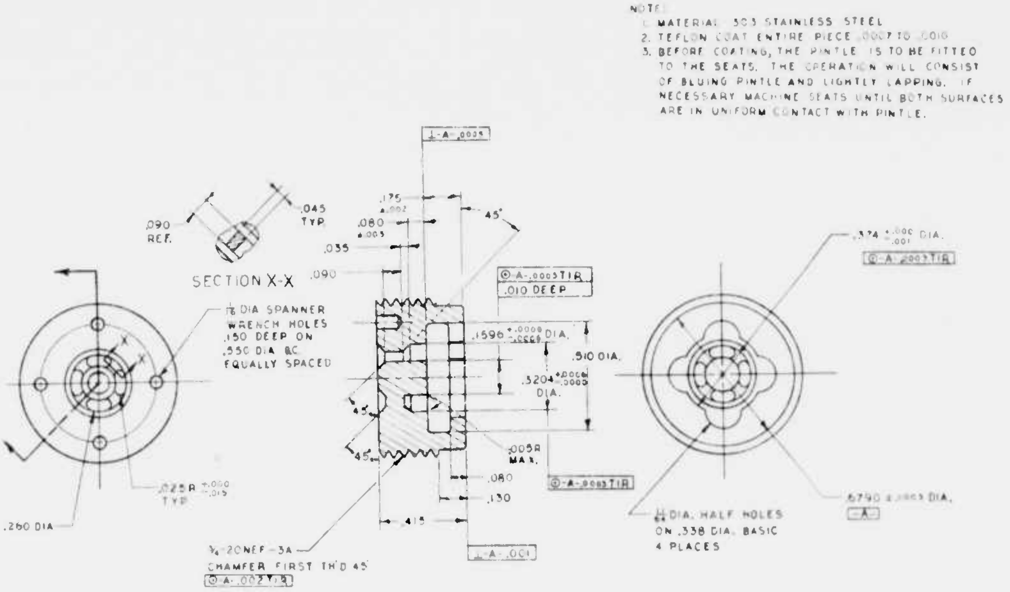

NOTE:
1. MATERIAL 303 STAINLESS STEEL
2. TEFLON COAT ENTIRE PIECE .0007 TO .0010
3. BEFORE COATING, THE PINTLE IS TO BE FITTED TO THE SEATS. THE OPERATION WILL CONSIST OF BLUING PINTLE AND LIGHTLY LAPPING. IF NECESSARY MACHINE SEATS UNTIL BOTH SURFACES ARE IN UNIFORM CONTACT WITH PINTLE.

FIG. 9. 50-Pound Motor Seat.

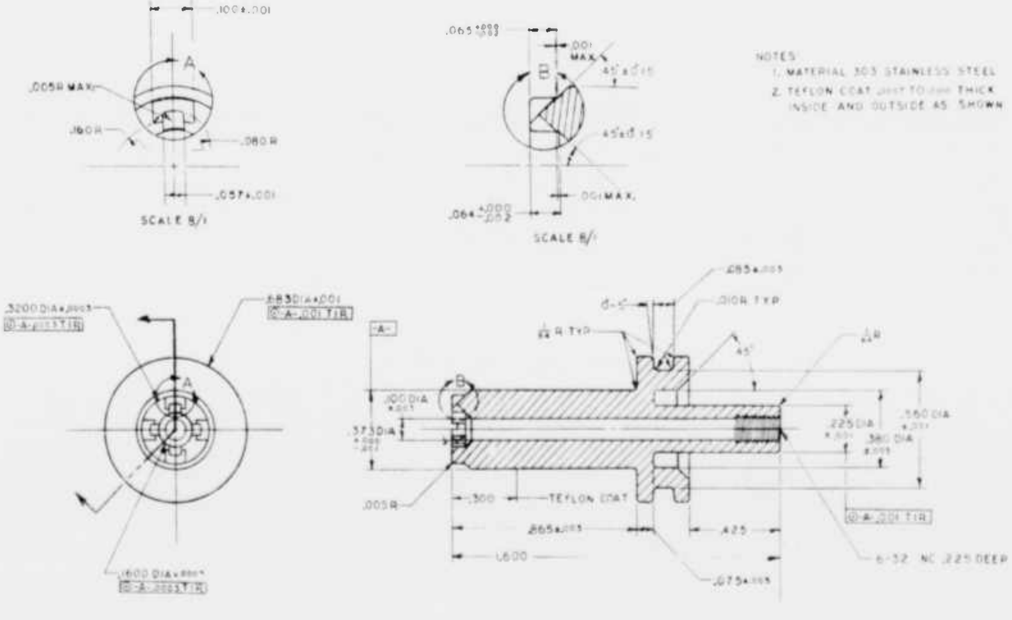

NOTES:
1. MATERIAL 303 STAINLESS STEEL
2. TEFLON COAT [illegible] TO [illegible] THICK INSIDE AND OUTSIDE AS SHOWN

FIG. 10. 50-Pound Motor Pintle.

1. The seat configuration was a 45-degree surface against a sharp edged corner, which is considered to be optimum for sealing by industrial valve manufacturers for metal to metal seats.

2. The fluid control orifice design inherently gives a linear relation between flow area and pintle position for maintaining the correct O/F ratio. The control orifices also tend to have a square shape which allows for greater particle passage.

3. The core piece of the 50-pound injector was directly machined to the outer seat and held in place by four thin spokes. This arrangement eliminated the alignment, adjustment, and assembly problems of previous core pieces.

4. The spokes were designed to allow the core to seat first and then bend to allow the outer orifice to seat. The spokes were designed and test proven to give a strain of 2, 500 lb/in or 1. 25 pounds of seating force for 0. 0005 in. of typical movement.

The ribbon type seat proved to be a considerable improvement over the conical seats. With the ribbon type seat there was no apparent seat leakage when an air pressure differential of 50 psi was applied. Wearability of the ribbon seat also proved superior to the conical, and the ribbon injector can pass contamination particles ten times larger in diameter. Propellant flow data versus pintle position for the ribbon injector are given on Fig. 11.

With the conical seats, the basic geometry greatly restricts the size flexibility of the design. This was not a factor in the design of the ribbon injector.

Both "O" ring seals and bellows have been used successfully in previous NOTS injectors (Fig. 8). "O" ring seals were used in the 50-pound motor for easier on-station construction and for ease of assembly. The 50-pound motor could be redesigned to employ bellows seals, if the mission to be accomplished required the injector to be filled with propellants or to be under extreme vacuum conditions for long periods of time.

In the initial stages of developing airtight seats, gold plating and Teflon coating of the pintle were tried. Both processes provided exceptionally good sealing material under static conditions, but once the injector is operated the gold or Teflon erodes off so they have little sealing effect. The gold or Teflon coatings could be used for airtight static seals before initial firing or to keep the metallic seats from vacuum welding together under prolonged space conditions.

Data sheet in Appendix A shows the parameters of the 50-pound injector.

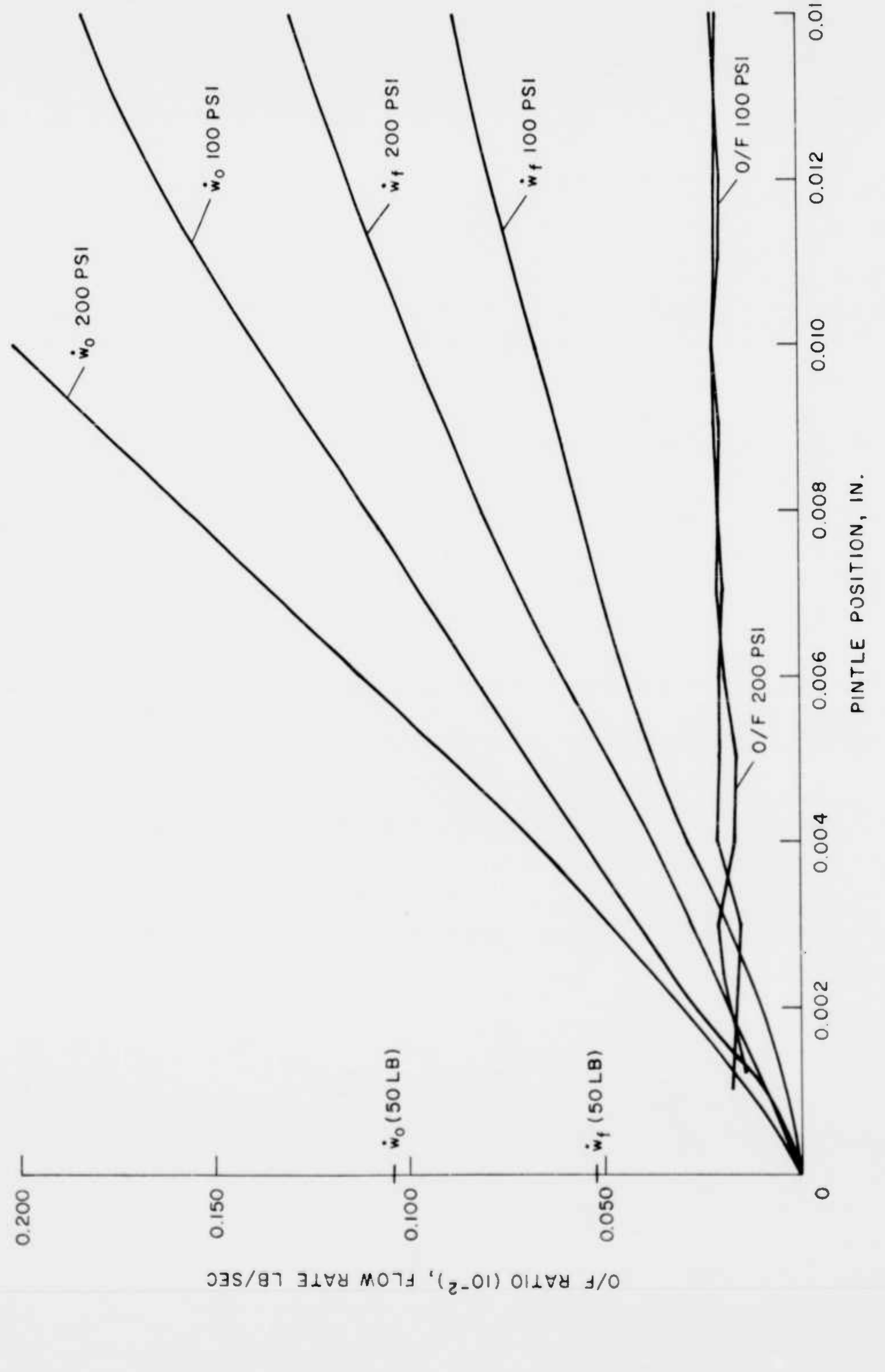


FIG. 11. Ribbon Seat Propellant Flow Data Vs Pintle Position.

ACTUATION SYSTEMS

The actuation systems for the 50-pound motor are divided into two divisions: the variable-thrust system and the pulsing system.

VARIABLE-THRUST SYSTEM

Variable-thrust motors have been operated at NOTS using the servovalve control system described in Ref. 1. All of these motors had a maximum thrust output of over 1,000 pounds. As a result, the quiescent flow of a servovalve was not a prohibiting factor in the actuation system. But, for a 50-pound variable-thrust motor, the quiescent flow of a servovalve is approximately equal to one-half the propellant flow used by the injector at full thrust. Also, the servovalve requires a high supply pressure of over 1,000 psi. Since fuel line pressure is normally used as the hydraulic source, only about 200 psi is available for the 50-pound motor actuation.

These factors made the use of a servovalve very impractical. As a result, the solenoid valve hydraulic control system for which a patent has been applied was developed. The solenoid valve hydraulic control system is shown in Fig. 12.

The pintle is hydraulically positioned by a pair of solenoid valves connected to the sides of the pintle piston cavity. Hydraulic fluid is metered into the cavity by one of the valves and out by the other. The amount of pintle displacement is determined by the length of time the valve is on.

The response of the pintle is dependent on the following:

1. Action time of the valve from first error signal
2. Rate of fluid flow through the valve
3. Sampling rate of servo system

The fluid in the cavity is acted upon by a closing spring force. Since the pintle travel is small, the spring essentially keeps a constant pressure of 100 psi in the cavity. Therefore, a constant pressure of 100 psi is across the valves when a 200 psi supply pressure is used. This allows for a constant hydraulic gain as far as pressure drop or pintle position is concerned. This is important in keeping the resolution constant.

In the system development, a linear position transducer attached to the pintle was used to close the servo circuit loop. Chamber pressure and thrust have been used for feedback on previous larger motors and could be used on the 50-pound motor.

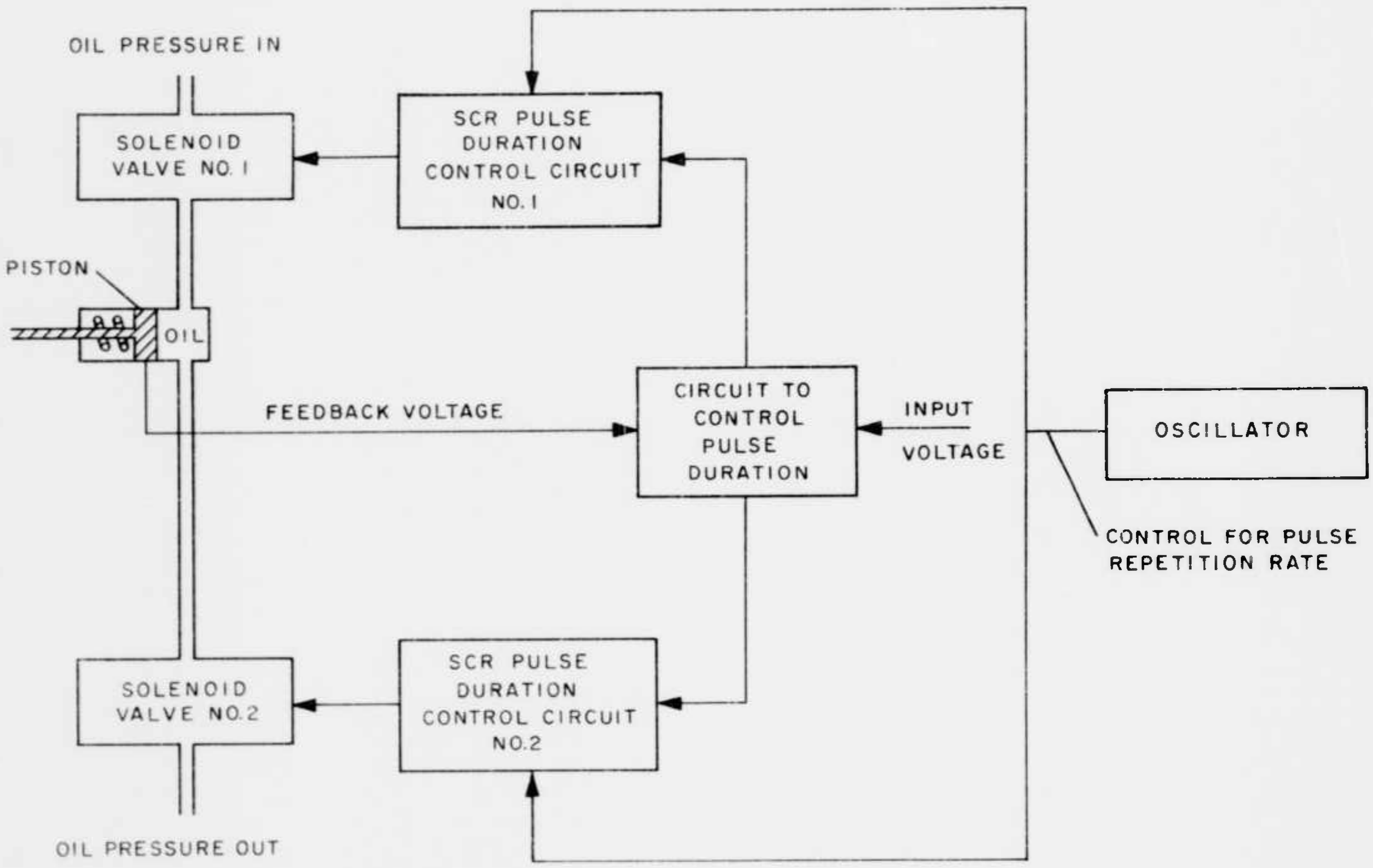


FIG. 12. Solenoid Valve Actuating System.

The solenoid valve control circuit is fully operational and reliable. This circuit is described in Appendix B, and, although it is thought to be considerably less expensive to construct than the servovalve circuitry, a second circuitry was developed and proved feasible for operating the solenoid valve control system. This second circuitry is described in Appendix C and has the following features:

1. Fewer and less expensive parts
2. Considerably smaller size
3. Higher performance feasibility.

The solenoid valves used are coaxial AF77C-43 off-the-shelf valves manufactured by the Eckel Valve Company. These valves are inexpensive (approximately 60 dollars each), lightweight (approximately one ounce), and possess the fast-operating characteristic needed. Improved valve characteristics, such as greater equivalent orifice area, larger coils, and greater reliability, can be obtained if specially ordered from the factory.

The basic operation of the hydraulic control system is to be able to move the pintle fast if the error signal is large, and also give a high position resolution.

To obtain this type of operation, a variable hydraulic gain was built into the system. For small movements of the pintle, the valve to be used is dithered by a variable length pulse. The length of the pulse is determined by the error signal. The dithering of the valve lets only a small amount of control fluid flow for small position changes. As the pulse width or error signal increases, the valves will open fully. A characteristic of the solenoid valve is that once the valve is fully open it will stay open until the magnetic field completely collapses. The magnetic field for this certain valve usually takes one millisecond to collapse after the current to the solenoid is shut off. As a result, the valve stays full on for a period of at least one millisecond longer than when dithered. This causes a considerable change in hydraulic gain for little change in error signal. When operating the motor, the pintle can be moved a full stroke with one high gain 2-ms pulse or controlled within five percent of its 0.010-inch full stroke by dithering of the valves. A characteristic of the system is that it uses only enough fluid to move the pintle and then only when opening the pintle. In comparison, the solenoid valve control system uses one-third of an ounce of control fluid per five minutes of one cycle per second (cps) sine wave operation whereas a servovalve uses a minimum of 20 pounds of fluid in just quiescent flow per five minutes of operation.

In the actual operation of this system, it was found that a sampling rate of 250 samples per second was the optimum value to be used. Therefore, the valves "see" a 250-cps sharp leading edge signal at all times. When there is no error signal, the pulse width is just small enough for the valves not to react. When a small error signal is present, the pulse width is increased slightly and the appropriate valve dithers at 250 cps. If the error signal is large, the pulse width continues to increase and the valve opens fully.

In a general comparison with the servovalve, the solenoid valve actuation system proved greatly superior. It proved to be easier to operate and have a higher reliability, besides fitting the particular needs of the 50-pound variable thrust motor, having higher performance, and being considerably cheaper. The 0-35 pound variable-demand liquid propellant gas generator and its accompanying servovalve were used as a comparison and are shown in Fig. 13.

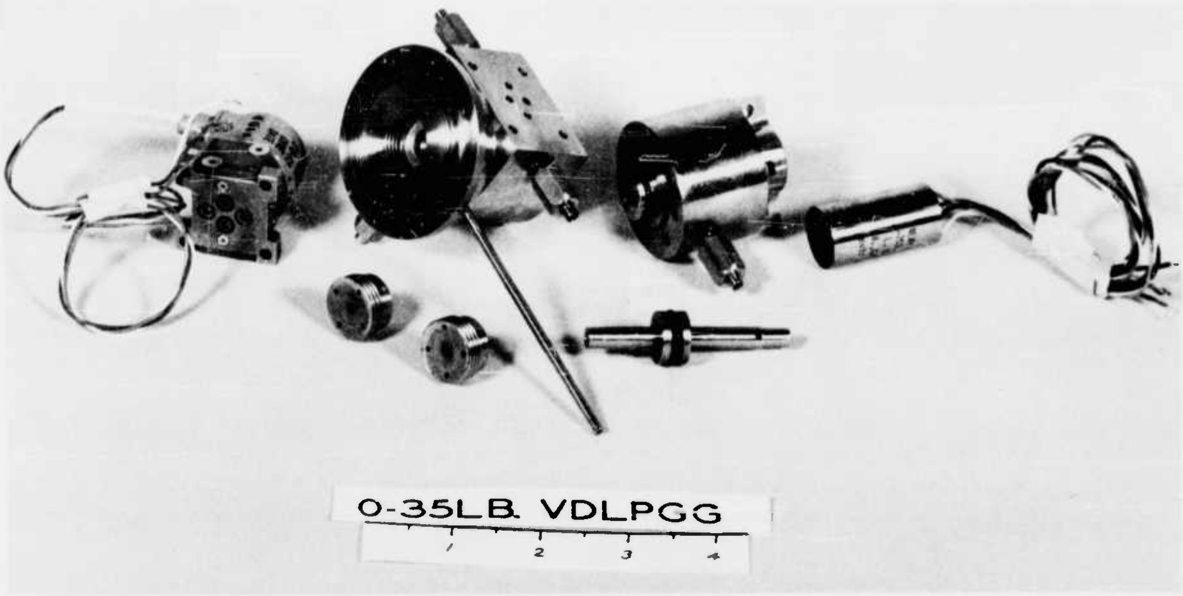


FIG. 13. 0-35-Pound Variable-Demand Liquid Propellant Gas Generator.

PULSE SYSTEM

The pulse motor actuation system developed along two lines. One system operated similarly to the variable-thrust system, but operated full stroke. The other system used a solenoid directly attached to the pintle. It was started late in the program and work done to date has just proved feasibility.

A fast response pulse motor feasibility was realized in the development of the variable-thrust control system, when response times of less than 5 ms became practical. Since this is faster than any existing pulse motor system, a circuitry was developed to prove feasibility. This circuitry is described in Appendix D.

The operation consists of firing the motor with a square wave signal input, the duration of firing time being a function of the square wave signal duration. The inlet solenoid valve pulses once and opens the pintle fully when the circuitry "sees" the leading edge of the square wave. The outlet valve pulses once and closes the pintle when the circuitry "sees" the trailing edge of the input square wave. In this manner the motor was operated up to 125 cps as shown in Fig. 14. Figure 15 shows the system operating at 40 cps. The top trace is the input signal and the lower trace is the output from the pintle displacement transducer. The oscilloscope time scale is 2 ms per centimeter. The figures show that the response to full pintle travel from signal input is approximately 4 ms. In actual operation the propellant would start to flow after 2 ms from signal input.

The use of a solenoid to directly operate the pintle was tried unsuccessfully at NOTS on previous programs. Figure 16 shows the 10-pound thrust motor concept (Ref. 2). This concept was considered impractical because of power and weight requirements.

In developing the solenoid valves for the variable-thrust system, it was found that careful electromagnetic design practice could make the idea of a solenoid-operated pintle more practical.

The solenoid-operated pintle system required a solenoid to operate a 0.1-pound pintle against a 25-pound return spring in a time of 1 to 2 ms over a 0.010-inch stroke. The above performance requirements were thought to be feasible and competitive to the hydraulic actuation system.

Using a power limitation of 28 watts (28 volts, 1 amp), calculations showed that a traverse time of 2 ms was feasible with a 50-pound force solenoid. The weight of the solenoid would be about one-half pound.

A workhorse solenoid case was fabricated with coils that could easily be changed. Brief tests of the solenoid were run with a dummy, spring-loaded pintle under poor conditions, where such "constants" as stroke, spring force, and piston alignment were unreliable. The solenoid as designed proved to provide at least full stroke actuation of the pintle in 3 ms from command initiation. The closing time was approximately 3 ms also. This test proved that using a solenoid to operate the pintle in a pulsing mode at speeds less than 3 ms was very feasible. Figure 17 shows the response test results.

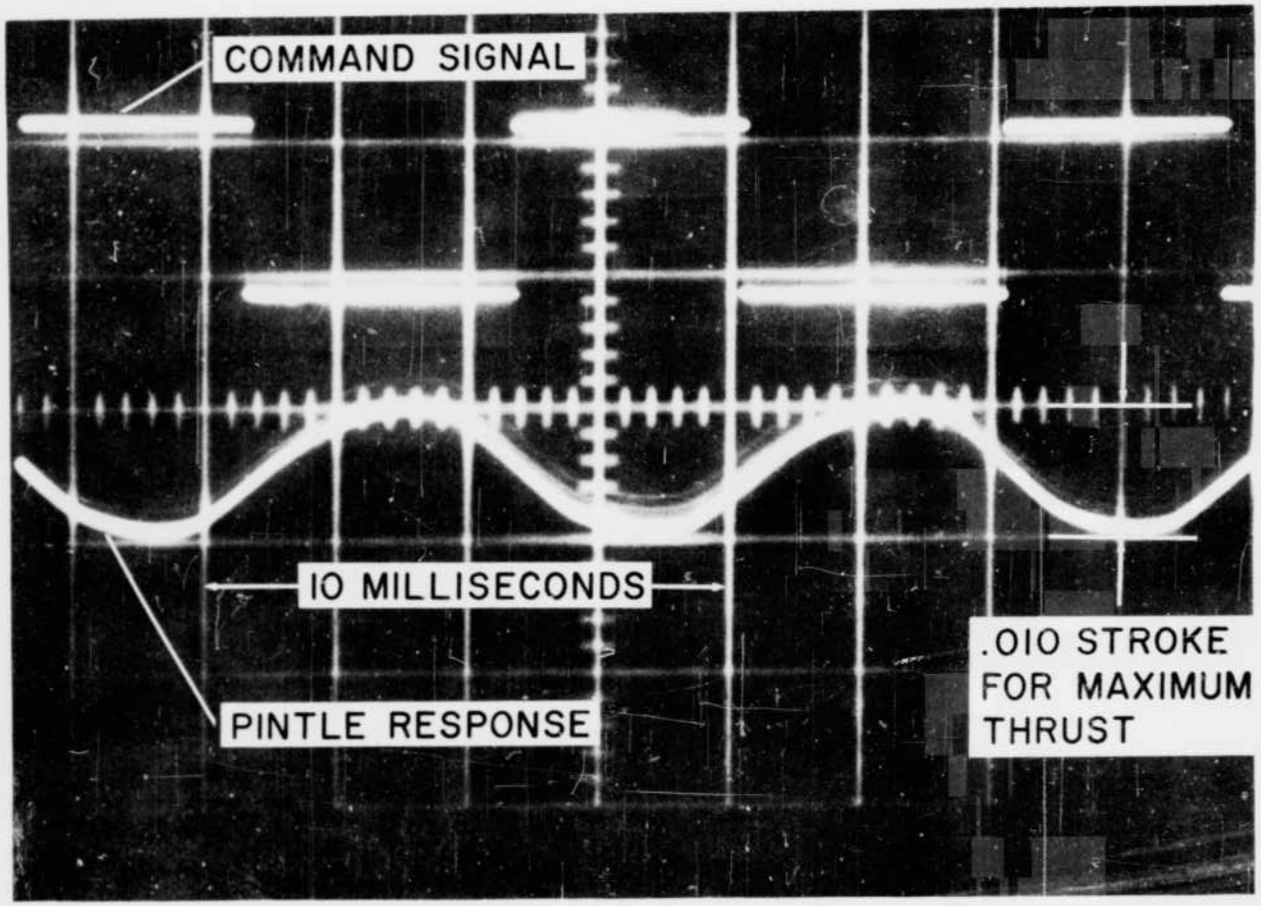


FIG. 14. 125-cps Operation.

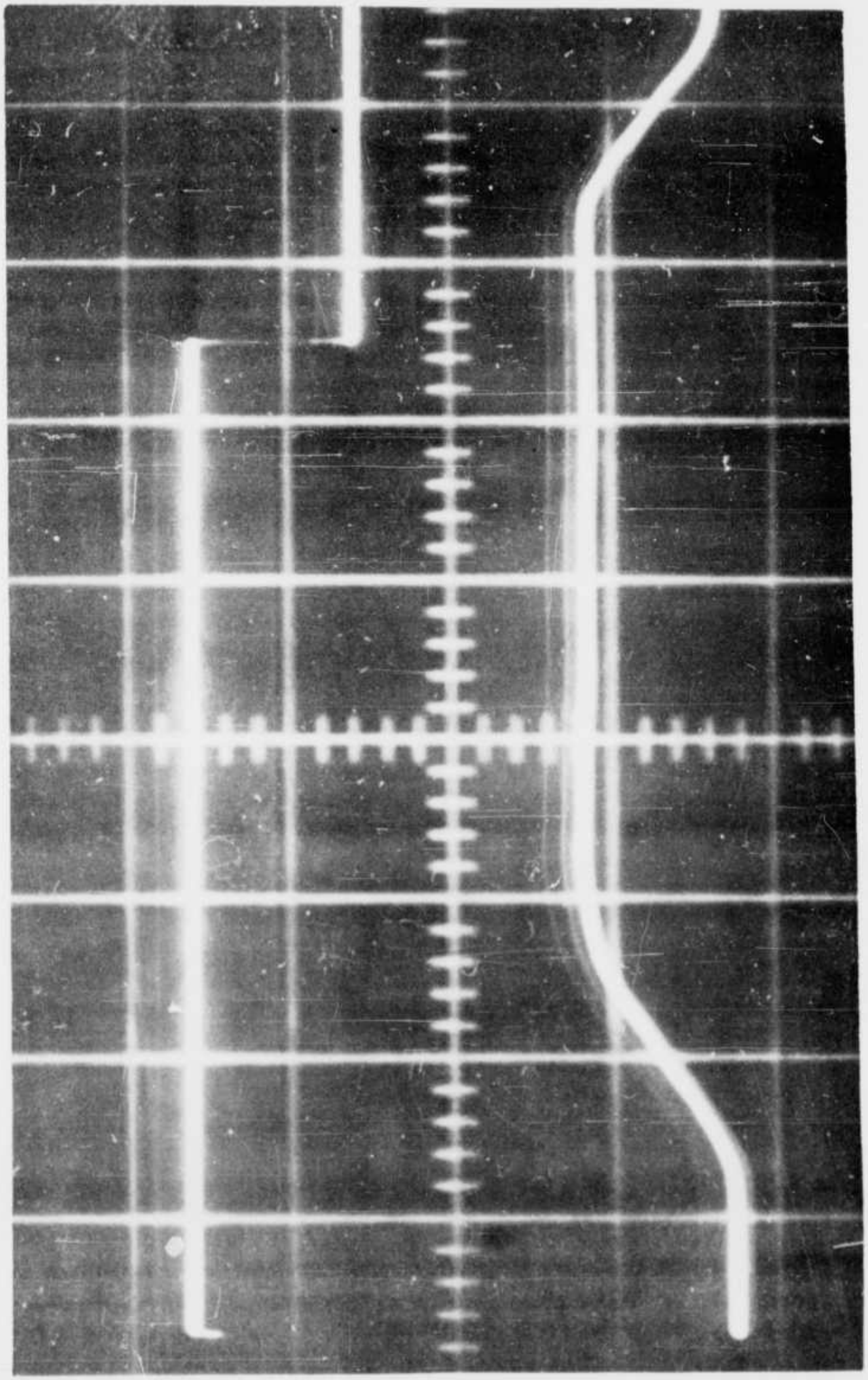


FIG. 15. 40-cps Operation.

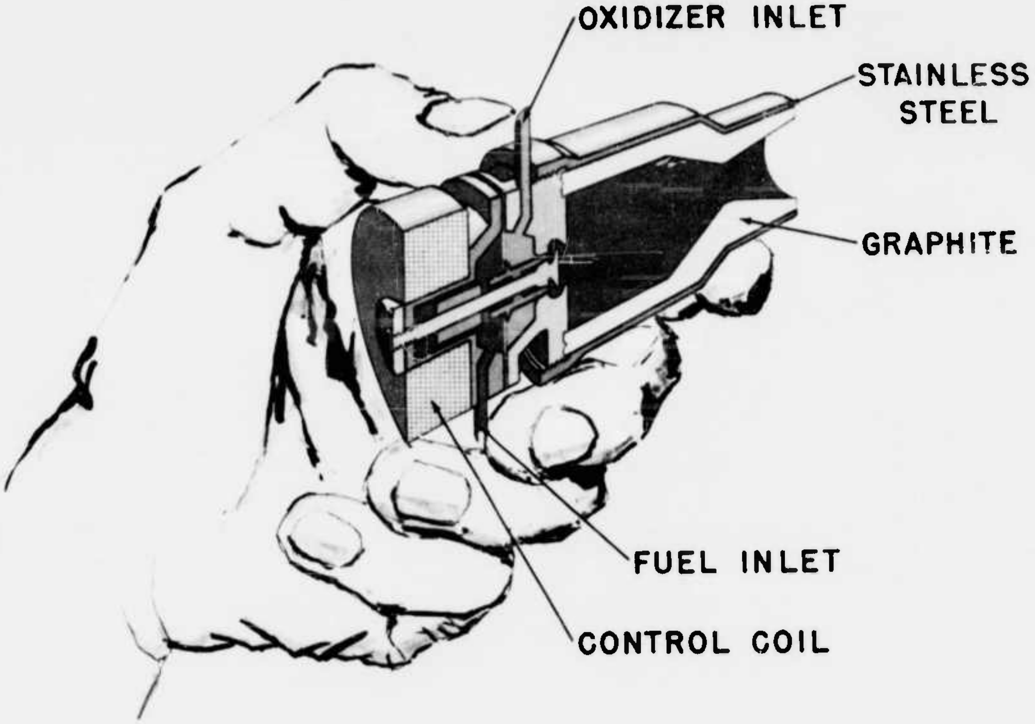


FIG. 16. 10-Pound Variable-Thrust Motor.

TEST APPARATUS

All firings were performed at building C at Area R, using a self-contained (except for instrumentation) portable test stand, including propellant tanks and all valving (Fig. 18). Operation was carried out from behind a barricade 20 feet away. A flexure-type thrust mount was used and 10-micron filters were placed in the propellant lines. Potter turbine flowmeters were used for all of the tests. During some of the tests, Standard Control strain gage meters were placed in series with the potters. The response of the strain gage meter was approximately 5 milliseconds and also had a wider flow range than the turbine type. It was found, however, that the propellants affected the strain gage, which became inoperable after one 10-second test.

A hot firing of the motor is shown in Fig. 19. Appendix E gives a typical data point from the test data. Because of the short number of firing tests run on the motor to date, exact performance of the motor cannot be claimed.

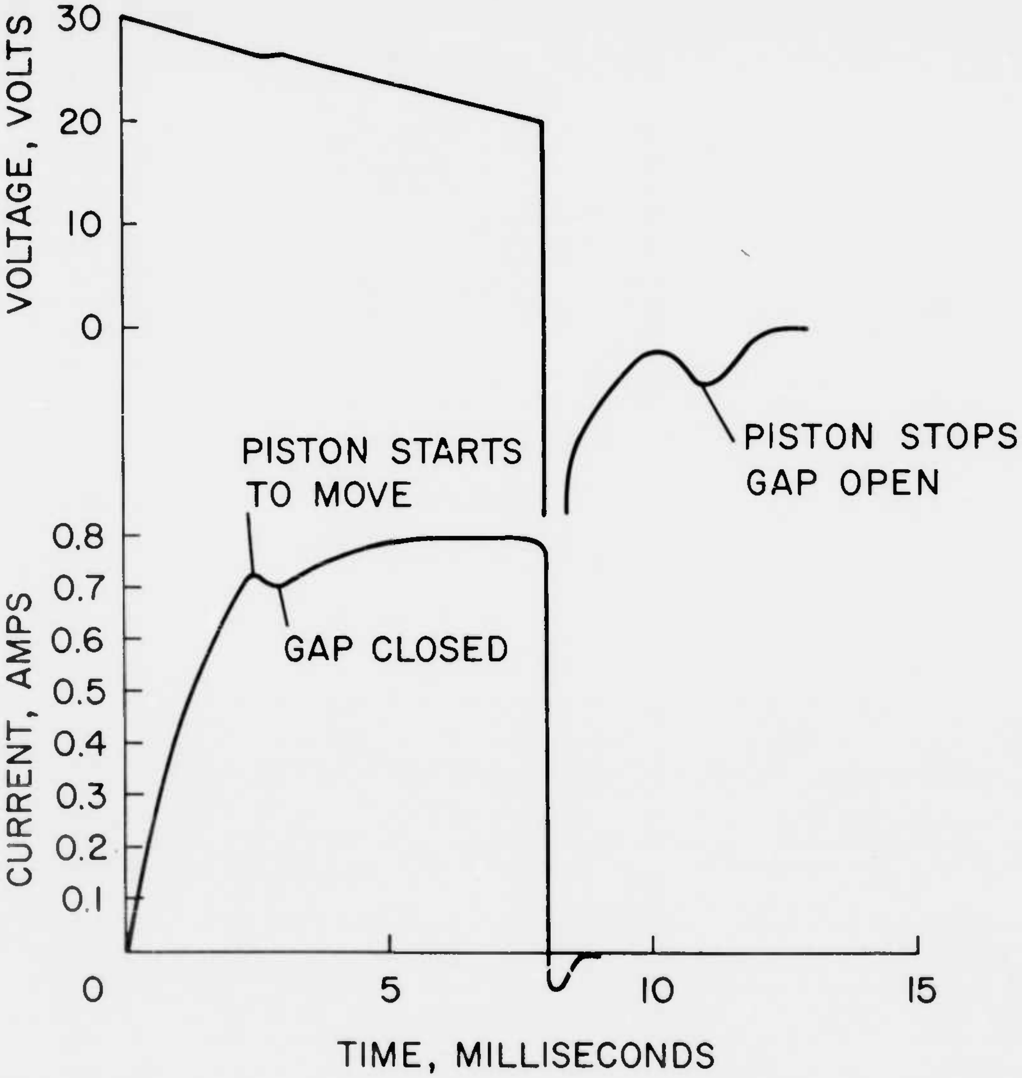


FIG. 17. Response Test Results.

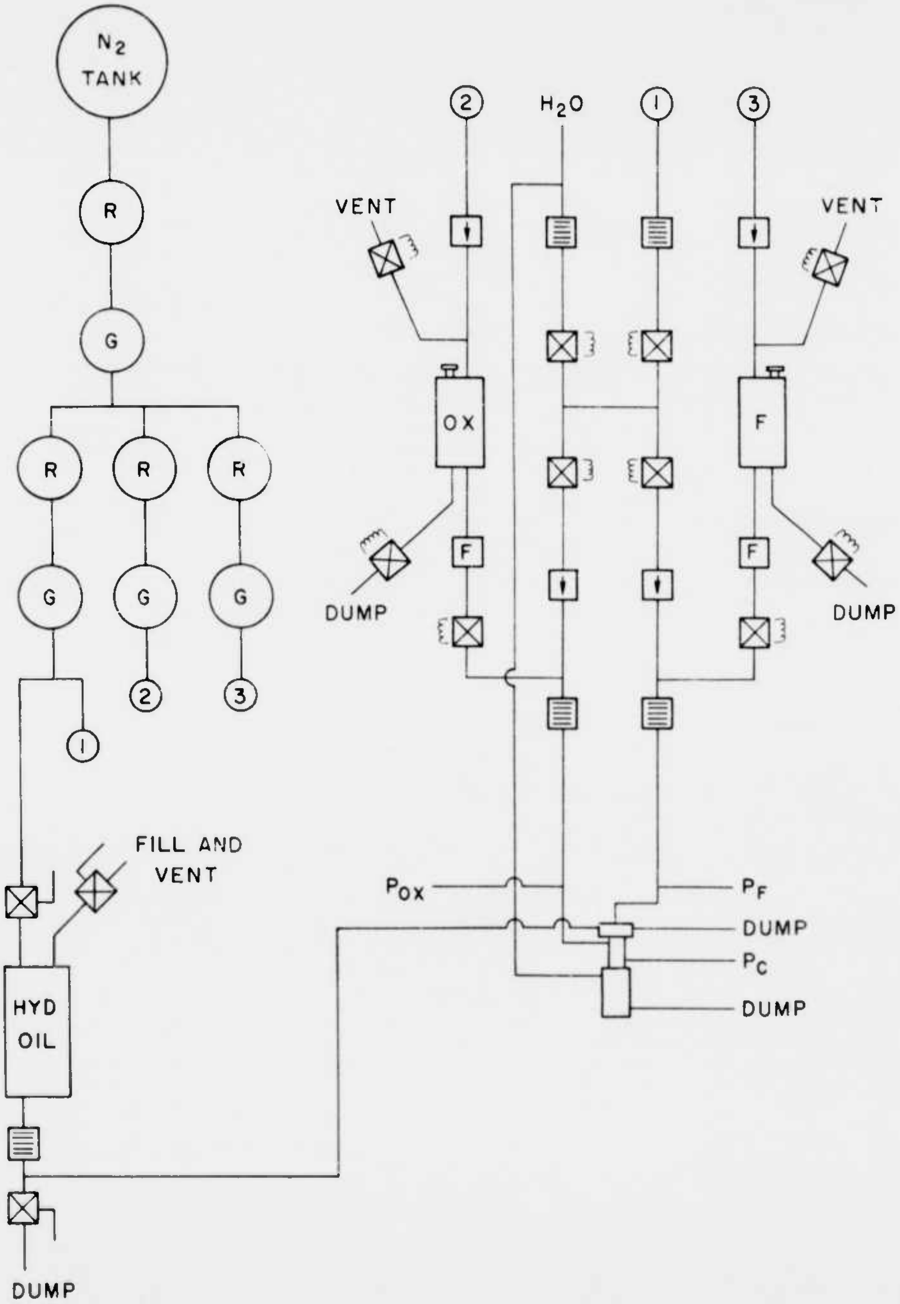


FIG. 18. Portable Test Stand, Plumbing Layout.

FIG. 19. Hot Firing of Motor.

The test stand proved to be very dependable and easily adapted to different tests.

The following instrumentation parameters were recorded on an oscillograph during the static tests:

1.	Oxidizer flow rate	1/8-inch turbine flowmeter
2.	Oxidizer flow rate	1/8-inch turbine flowmeter
3.	Fuel flow rate	1/8-inch turbine flowmeter
4.	Fuel flow rate	1/8-inch turbine flowmeter
5.	Command signal	0-5 volts output
6.	Feedback signal	0-5 volts output
7.	Filtered thrust-above 200 cps	0-50 lb force ring
8.	Unfiltered thrust	0-50 lb force ring
9.	Oxidizer line pressure	0-500 psi pressure transducer
10.	Fuel line pressure	0-500 psi pressure transducer
11.	Chamber pressure	0-200 psi pressure transducer

MOTOR SYSTEM

The 50-pound motor system possesses many characteristics which can be used for various missions. It has high response characteristics which are needed to control the attitude of rotating space platforms. It also has smooth and precise thrust control needed for attitude control of non-rotating missiles and vehicles.

The hydraulic system as used until now exhausts the used control fluid to the atmosphere or to a reservoir. In actual operation it is proposed that the control fluid be exhausted back to the fuel line as shown in Fig. 20.

CONCLUSIONS

The 50-pound motor system proved to be a high performance liquid rocket engine capable of being operated in either pulsed or variable-thrust modes.

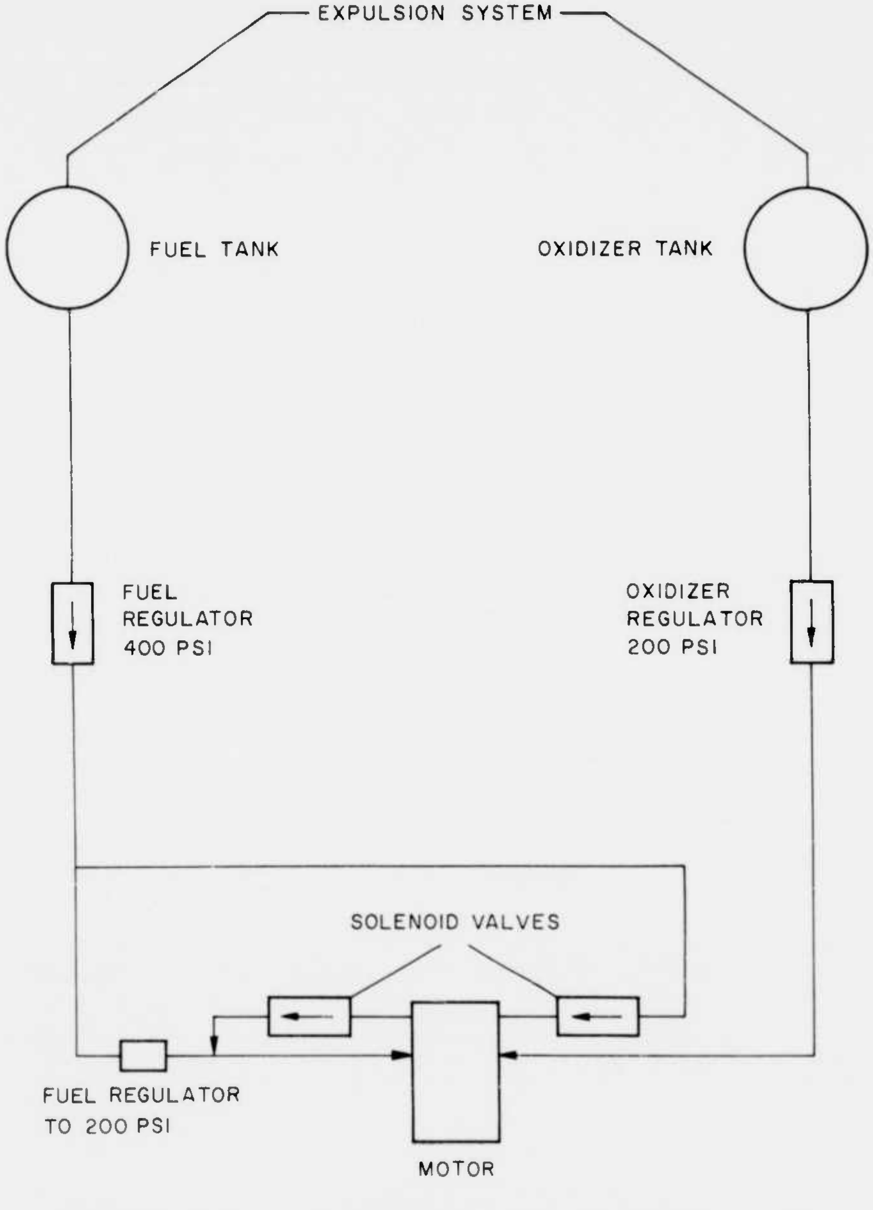


FIG. 20. Proposed Propellant Flow Schematic.

From the work done on this program and other related programs, the flightweight combustion chamber should pose no problems for firing times up to five minutes.

The injector can be considered fully developed and operational. The areas that could be worked on are bellows design, aluminum construction, and ease of fabrication. The propellant flow characteristics and orifice sealing for the injector are considered adequate for any small motor needs.

As the control systems stand, they are more than adequate for small motor needs. The main problem in higher response performance motors now is the propellant ignition characteristics.

In developing the variable-thrust actuation systems, it has become very apparent that the actuation system is competitive to the servovalve system for any application.

The actuation system proved to be very low in cost with only its reliability to be fully proved.

In the case of pulse operation, it is suggested that both the solenoid valve system and direct solenoid system be considered when choosing the actuation system. Both have certain advantages with relation to weight, power requirements, response, and propellant feed system.

Although brief high performance tests were run, the system should be tested further to confirm present results.

Appendix A

DATA SHEET - VARIABLE-THRUST MOTOR

Project Name: 50-lb pulse motor

Max. Thrust Level: 50-lb alt. and 30-lb s.l.

Propellants Used: N_2O_4 and 50% UDMH & 50% N_2H_4

I_{sp} Theoretical: 333 sec (alt.)
198 sec (s.l.)

I_{sp} Expected: 320 sec (alt)
188 sec (s.l.)

INJECTOR PARAMETERS

$\dot{W}$ Total: 0.156 lb/sec

Orifice Pressure Drop: 100 psi

Pintle Travel: 0.010

O/F Ratio: 2.00

Materials Used: SS 303, Viton, Buna-N, Teflon

Control System: Hyd. solenoid valve pulse system

Weight of Injector Approx.: 12 oz.

Pintle Actuation Area: 0.25 in.^{2}

Max. Ox. Orifice Area: 0.00274 in.^{2}

Max. Fuel Orifice Area: 0.00160 in.^{2}

Ox. Orifice C_d: 0.60 (ribbon)
0.75 (conical)

Fuel Orifice C_d: 0.65 (ribbon)
0.95 (conical)

CHAMBER PARAMETERS

Chamber Designed Thrust: 30-lb sea level

Expansion Ratio: 1.77/1

Characteristic Length: 6 in.

Design Chamber Pressure: 100 psi

Thrust Coefficient (C_f): 1.10 (s.l.)

Firing Time Expected: 1 min. water cooled

Material Used: Stainless steel and copper

Injector Assembly Drawing No.: SK572536

Appendix B

VARIABLE-THRUST CIRCUIT

INTRODUCTION

This section covers the electronic circuits which control the opening of the valves. The circuit includes two operational amplifiers regulating the pulse lengths of two similar voltage-controlled delay multivibrators (DMV's). These DMV's operate the pulse driving circuits which open the solenoid valves. A block diagram of the circuit is shown in Fig. 21.

INPUT CIRCUIT

The electronic circuits are controlled by two input voltages. One voltage, varying between 0 and +5 volts, controls the position of the pintle. The other voltage, which consists of a 0 to -5 volt feedback signal, indicates the pintle's present position. The difference between these voltages determines the distance and direction which the pintle must move in order to achieve the control position. The amplitude of this voltage is used to control the pulse duration of the solenoid valves, and the polarity determines which valve must open in order to move the pintle in the proper direction.

The input circuit is shown in Fig. 22. It consists of two operational amplifiers each controlling the pulse width of a voltage-controlled DMV.

A George Philbrick Researches, Inc. solid state, differential operational amplifier, type P2, is being used in the input circuit. A resumé of the specifications follows:

Gain, open loop	40, 000 minimum
Input admittance	600 micromicrofarad
Input current (25°C)	5×10^{-11} amp, maximum
Drift referred to input at 20 - 45°C	5 mv, maximum, typically 0. 1 mv over an 8-hour period at constant temperature
Maximum peak output swing for linear operation	±10 v, 1. 0 microamp (typical)
Power requirements	±15 vdc, 11 ma, maximum

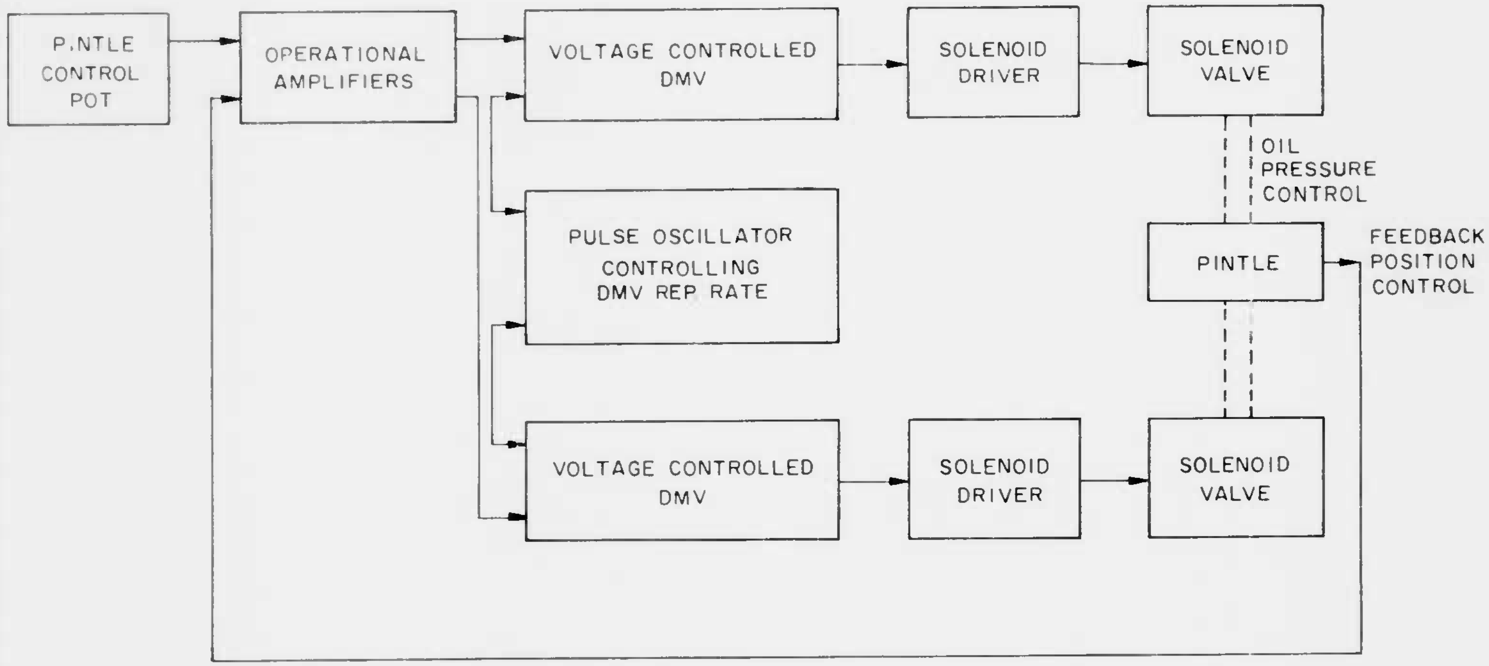


FIG. 21. Block Diagram of Variable-Thrust Motor Control Circuit.

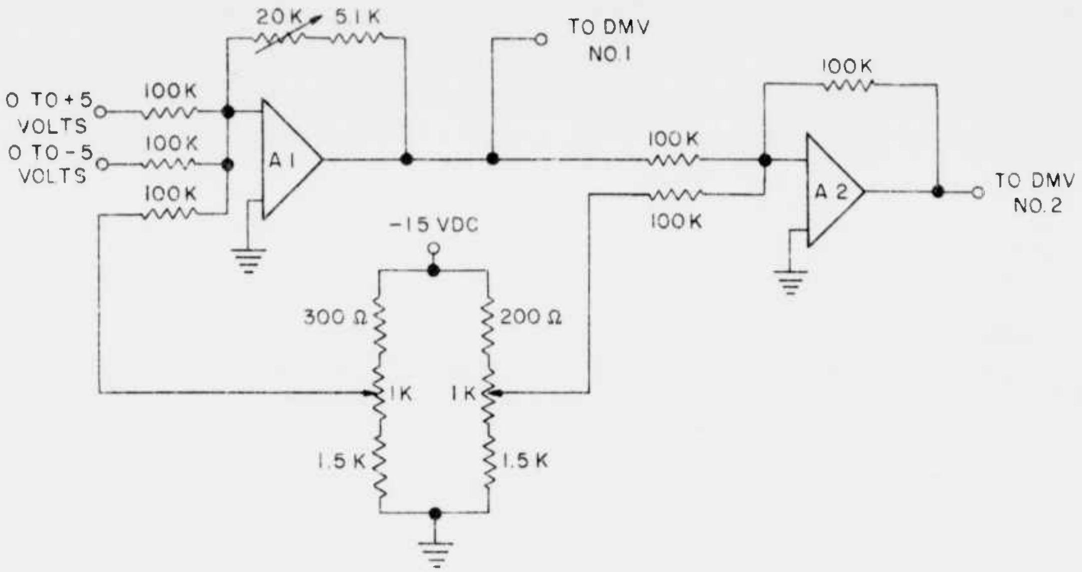


FIG. 22. Input Operational Amplifier Circuit.

Following is a list of the pin connections for the amplifier.

Pin 1 = + input

Pin 2 = - input

Pin 3 = -15 vdc

Pin 4 = common (ground)

Pin 5 = +15 vdc

Pin 6 = output.

The input is truly floating in respect to ground while the output is 180 degrees out of phase in respect to the input.

As will be shown later in the report, the DMV's operate with input voltages between 1.1 and 2.1 volts. Thus the amplifiers must adjust the ±5 volt input for this swing.

When the difference voltage is between 0 and -5 volts, the output of the first amplifier, A_1, is adjusted so that it will vary between +1.1 and +2.1 volts. This will then control the pulse duration of one DMV. If the voltage difference is positive, the amplifier output is less than 1.1 volts and the DMV is shut off.

The output of A_1 is next fed into a second amplifier which acts as a phase inverter. A_2 takes the signal which is below +1.1 volts, inverts and biases it such that the output is above +1.1 volts. Thus a positive 0 to 5 volt difference voltage comes out of A_1 as a negative going +1.1 to +0.1 volts. This is inverted and biases in A_2, so that the output is +1.1 to +2.1 volts which is enough to control the pulse duration of the second DMV. (It can be seen that the output of A_2 will be less than 1.1 volts, cutting off the DMV, if the input to A_1 is negative.) Thus a negative input to A_1 controls one DMV and a positive input controls the other DMV.

DELAY MULTIVIBRATOR

The voltage-controlled DMV is similar to a standard emitter coupled DMV except the base of the normally off transistor is connected to a DC voltage for pulse duration control. Figure 23 shows the DMV circuit.

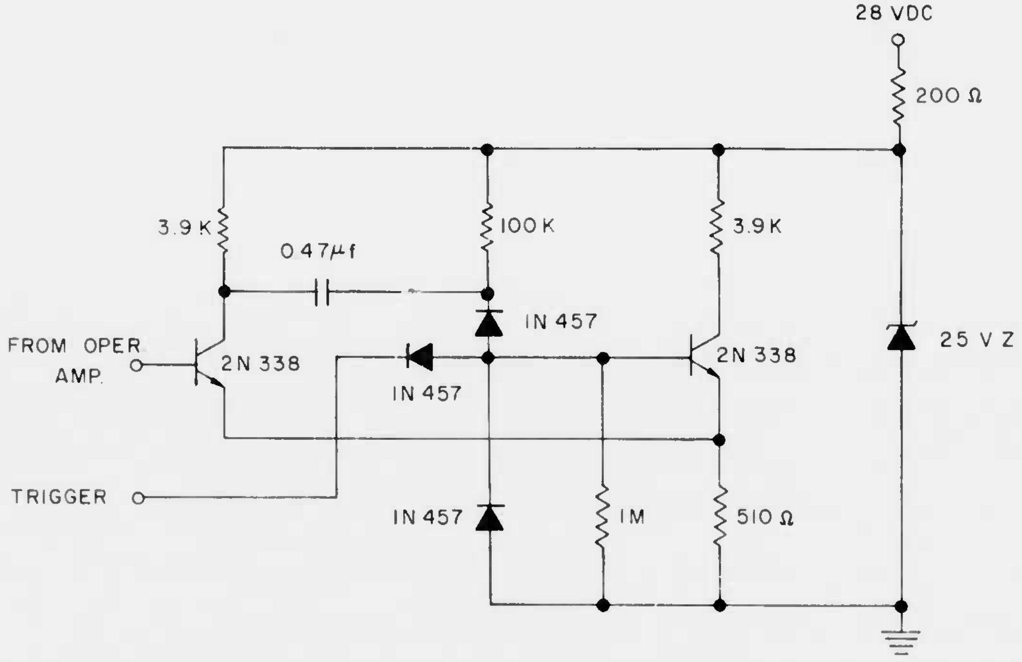


FIG. 23. Voltage Controlled Delay Multivibrator.

Using the components shown in Fig. 23, the output pulse can be varied from less than 0.5 ms to 15 ms, with a period of 20 ms (50 cps repetition rate) by varying the control voltage from 1.1 volts to 2.1 volts. This circuit also provides a zener regulated B^+ of 25 volts in order to help eliminate pulse width variations due to supply voltage fluctuations.

In order to assure uniform pintle movement in either direction, the pulse duration of both DMV's should be within one percent of each other over the operating range. Two DMV's were checked by adjusting their pulse durations so that they would both be equal to 15 ms for equal control voltages. As the control voltage was reduced, the pulse durations decreased, but at different rates. By the time the pulses were reduced to about 2 ms duration, a difference between pulse durations of over 5 percent was noted between the two DMV's.

Since pulse widths are dependent upon the gain of the first transistor, collector to base feedback was tried. This improved the pulse variation by 2 percent; however, this was not enough. Another way of controlling a transistor's gain would be to vary its unbypassed emitter resistor. In one DMV the emitter remained fixed and in the other a 250-ohm variable resistor was placed in the emitter as shown in Fig. 24. This adjustment allowed the DMV pulse durations to be equalized at a 15-ms duration. Upon reducing the pulse lengths to 0.5 ms, the variation between pulse durations remained well within 1 percent.

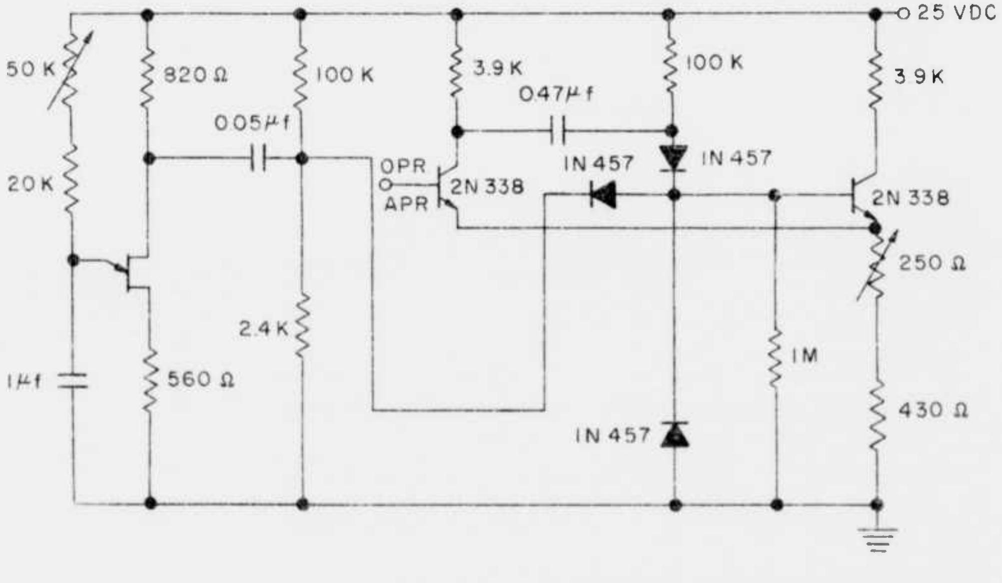


FIG. 24. 50-cps Oscillator and Emitter Adjusted DMV.

In addition to a pulse duration circuit, a pulse repetition rate circuit is also necessary. This is accomplished with the unijunction RC oscillator shown in Fig. 24. The oscillator provides a 3-volt negative pulse with a repetition rate which is variable between 50 and 500 cps for turning on the DMV's. In addition, the circuit provides output biasing resistors which set the trigger voltage at a level compatible with the DMV's trigger circuit.

SOLENOID VALVE DRIVER STAGE

The solenoid valves used to test the electronic circuits were designed to operate at 28 volts and 1 ampere. Using this voltage, the valves opened fully in 4.5 ms and closed in 8 ms, for a total valve time of 12.5 ms. This was much too slow to give good control resolution, so faster valves were required. The response time of the fast valves (3 ms to fully open) was still not adequate, so a special circuit was designed to help improve the situation. Since the fast valves were similar electrically to the slower ones, it was decided to check out the circuits with the slow valves; therefore, reference throughout this report is made with respect to the 12.5 ms valves.

One way of speeding up the response of the valves would be to initially apply a high voltage pulse across the coil during the time that the valve was opening. Also, if the current through the valve coil was reduced just before it was turned off, then the valve would close more quickly. As a temporary step, the circuit in Fig. 25 was built.

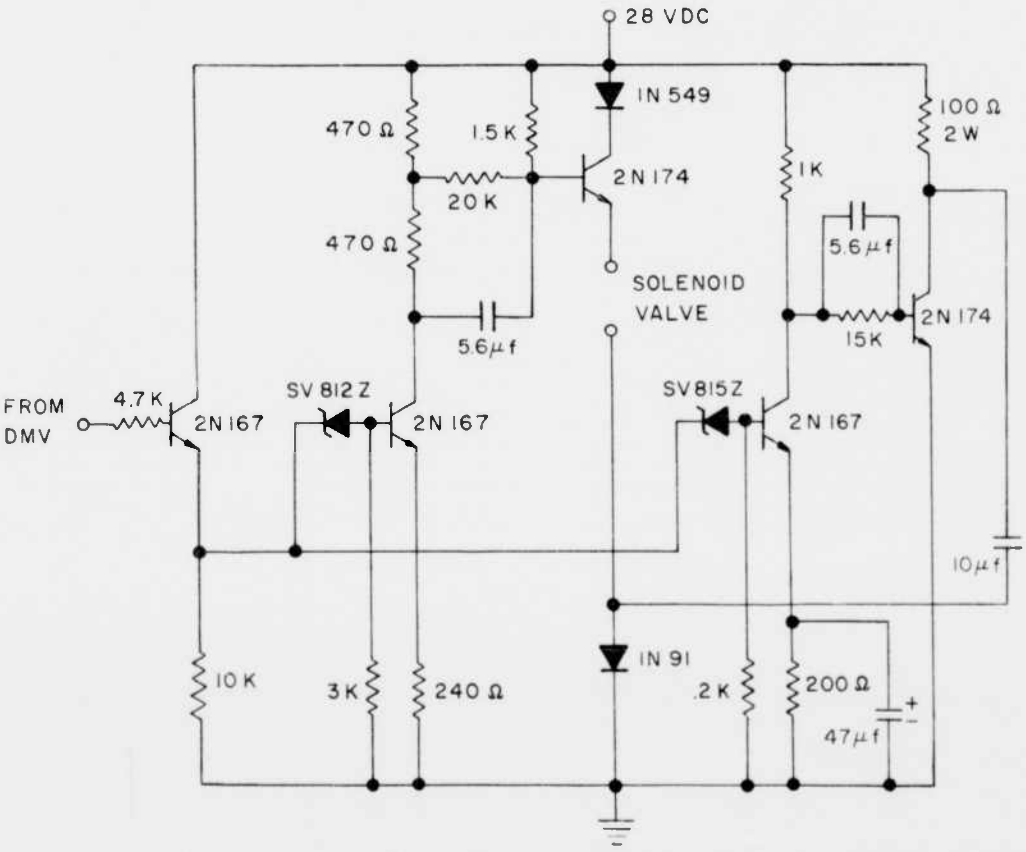


FIG. 25. Solenoid Driver Circuit.

This circuit consists of two parts. The lower circuit turns on the valve and holds it on while the upper circuit forms a negative pulse which is applied to the low side of the coil. This pulse lasts only during the time that the valve is opening.

Looking at Fig. 25, the first transistor acts as an impedance matching device to keep the driver circuit from loading the DMVs. The amplitude of the DMV pulse is about 20 volts. It is reduced to about 10 volts by the 12-volt zener in the base of Q_2. The zener is used to eliminate a one- to two-volt pulse occurring in the output of the off DMV. This pulse is caused by the on DMV and could falsely trigger the off driver. The 10-volt pulse from the zener easily turns Q_2 on and off. When Q_2 is turned on, its collector drops in voltage, thus turning Q_3 hard on through capacitor C. After the valve is fully opened (about 5 ms), the capacitor is discharged and Q_3 remains slightly on through its 10K base resistor. Limiting the current of Q_3 in this way reduces the current through the coil allowing the valve to close 3 ms sooner. Of course there is a practical limit to reducing this current. It must be large enough to force the valve to remain open even when the valve is being jarred by motor vibration. Until some vibration tests can be run, the current will not be further reduced.

In order to turn Q_3 off, it was found necessary to reduce the emitter voltage to 0.5 volt less than B^+. A diode was used since its voltage drop would be nearly constant for the current variations used in this circuit.

The pulsing circuit consists of a zener diode which reduces the pulse amplitude as it did in the lower part of the circuit. This pulse turns on Q_4 producing a negative 28-volt pulse. This negative going pulse is partially differentiated and fed into a current amplifier Q_5. The output of Q_5, still negative, is differentiated into a 1 ms, 20-volt pulse. The diode in the collector leg of Q_3 in Fig. 25 turns off when the negative pulse appears so that the voltage appearing across the coil, when the DMV is turned on, is +28 volts and -20 volts for a total of 48 volts. After 4 ms this voltage has decreased so that only the holding current keeps the valve on.

With this arrangement the opening time of the slow valve was reduced to 3 ms and the closing time was reduced to 5 ms. Applying this technique to the faster valves resulted in less than a 4-ms response time in going through a fully open to fully closed cycle.

CONCLUSIONS

A temporary motor control circuit (Fig. 26), following the design in this report, has been built. The circuit includes: (1) the input operational amplifiers which control the voltage-controlled DMV's,

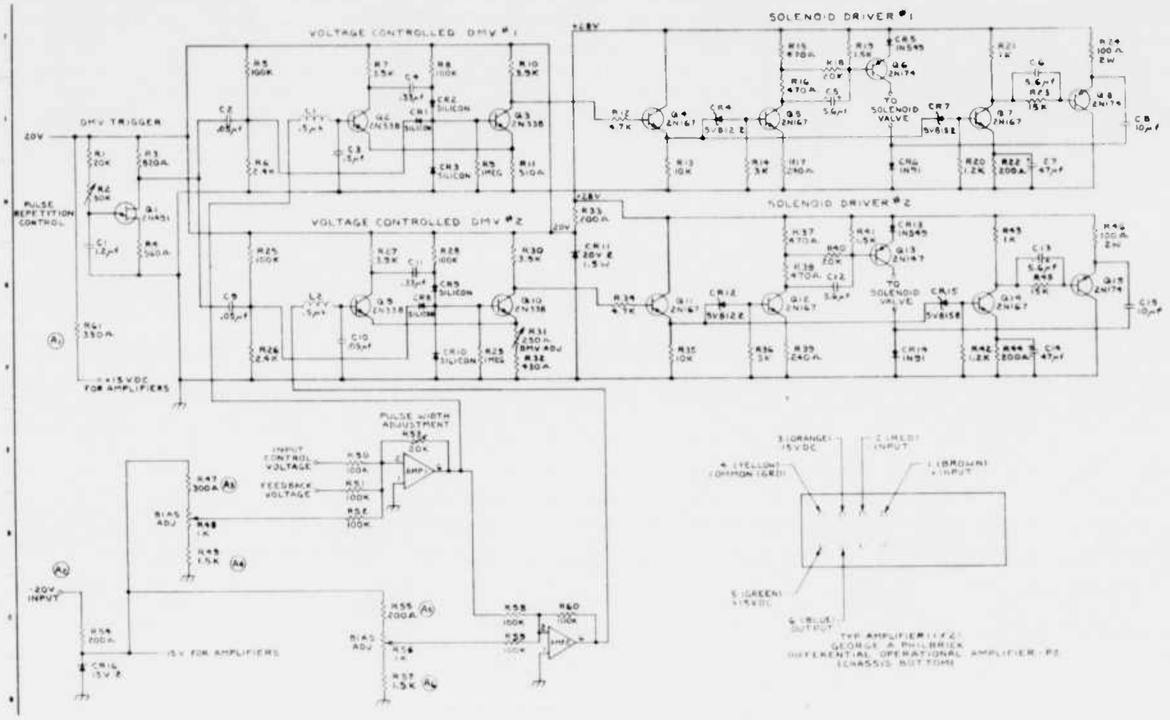


FIG. 26. Temporary Motor Control Circuit.

(2) the two DMV's with a pulse length adjustment, and (3) the two valve driver stages. This circuit has satisfactorily controlled two solenoid valves under oil pressure and successfully controlled a variable-thrust motor.

Future designs of this circuit will include a power supply, elimination of unnecessary components, and perhaps a method of applying a greater voltage across the coil using the same B+ supply.

Appendix C

VARIABLE-THRUST CIRCUITRY NO. 2

INTRODUCTION

In order to increase the response of the servo control system, the repetition rate of the solenoid valves has to be increased. In the original circuit, a 20-volt pulse was used in conjunction with the 28-volt supply to improve the opening time of the valves. In the present circuit, a silicon control rectifier (SCR) applies a 116-volt pulse across the valve to open it, after which the voltage is reduced to less than 16 volts for the remainder of the pulse. This low voltage is enough to keep the valve open, yet it allows the valve to close quickly after the current is turned off.

This section covers the circuit descriptions and the operation of the SCR control system. Figure 27 is a schematic of Circuit No. 2.

CIRCUITRY

The response of a solenoid valve can be improved by applying a high voltage across its terminals, thus increasing the rate of flow of current in the valve coil. Since silicon control rectifiers have the ability to conveniently handle these higher voltages and currents, they were used in these circuits. The pulse duration circuit shown in Fig. 28 consists of a modification of a delay multivibrator suggested by Solid State Products Inc.[1] The pulse repetition rate is set by the oscillator at input C. This pulse turns SCR-2 "ON", thus applying 116 volts across the valve. The minus 100 volts is also applied to the anode of SCR-1 through condenser C-1. As C-1 charges through R-1, the trigger potential of SCR-1, which is determined by R-1, CR-1, and R-5, also rises. When this trigger reaches a sufficiently positive voltage, the control rectifier turns on, thus producing a negative pulse which is coupled to point D through C-1. This negative pulse, which is produced by the discharging of capacitor C-2 through R-1, turns SCR-2 off. As the discharge current decreases, the current in the rectifier drops below its holding current and SCR-1 turns off. In this manner the 116 volts is applied to the solenoid for 0.4 ms at which time the valve is fully open. One millisecond later SCR-1 turns off so this part of the circuit remains off until the arrival of the next oscillator pulse.

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[1] Solid State Products Inc., Applications and Circuit. Design Notes. Salem, Massachusetts. Solid State Products, March 1962 (Bulletin D420-02)

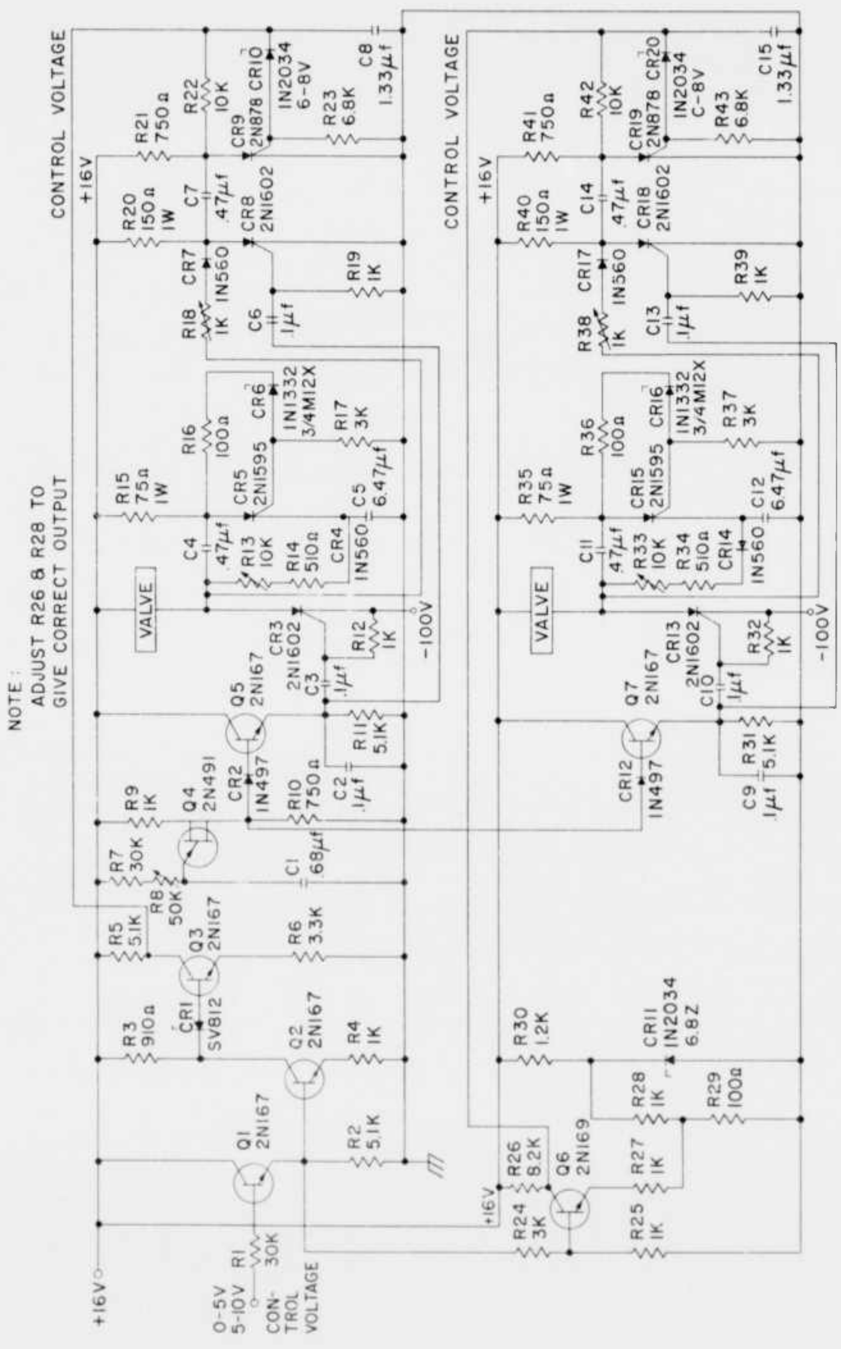


FIG. 27. Pulse Duration Control Circuit No. 2 Schematic.

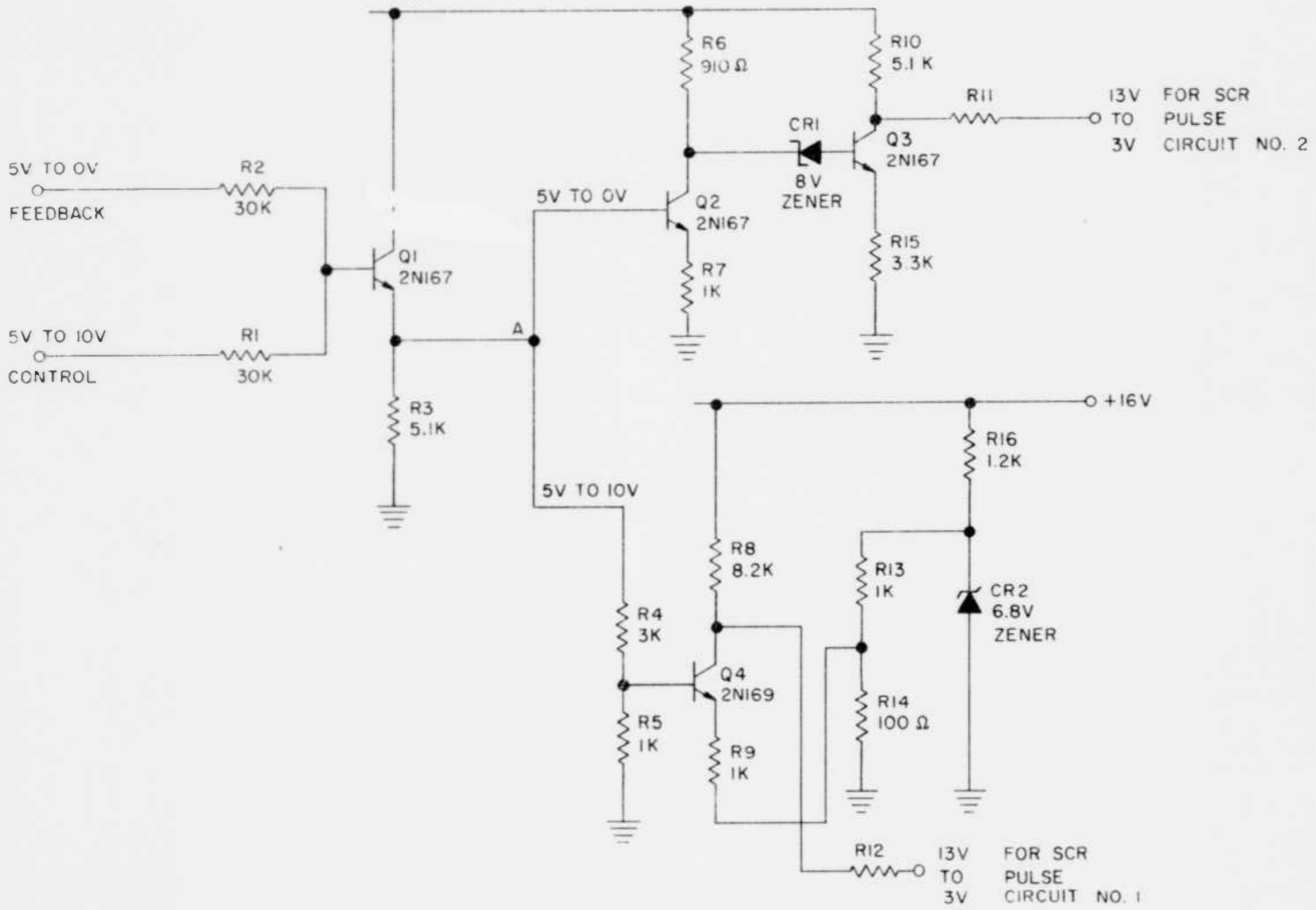


FIG. 28. Circuit to Control Pulse Duration.

It is also necessary to control the duration of time that the valve remains open. SCR's 3 and 4 are used to hold the valve open for this period. The same oscillator pulse which turns on SCR-2 also turns on SCR-3. This causes the capacitor C-5 to drop the anode voltage on SCR-4, thus turning it off. SCR-3 draws its holding current through R-2 during the time that the 116 volts are applied to the valve. When this voltage is turned off, current flows through diode D-1, R-3, and SCR-3 so that less than 16 volts is across the valve. Resistor R-3 is used to limit the current flow in the valve so the valve just stays open, thus the valve will close more quickly when the current is cut off.

When SCR-4 is turned off, capacitor C-6 begins to charge at a rate determined by the voltage from the pulse duration control circuit. This variation in charging time determines the period during which SCR-4 remains off. When the trigger of SCR-4 charges to a voltage more positive than that at the cathode, the rectifier will turn on; this in turn will shut off SCR-3 and the valve will close. This full-open period for the valve can be varied from 0.5 to 5 ms by a control voltage change from 13 volts to 3 volts. By limiting the current flow through the valve with R-3, the valve closing time is reduced to less than 2 ms. Thus the shortest response of the valve in going from fully open to fully closed is slightly over 2 ms compared with the 4.0 ms obtained by using the previous all-transistor circuit and 6 ms using the valve manufacturers' recommended voltage of 28 volts.

The circuit which controls the voltage to the valves is shown in Fig. 29. This circuit averages the feedback voltage from the piston with the control voltage by means of R-2 and R-1. When the piston is in the control position, the average voltage is 5 volts. The voltage then goes through amplifiers Q_2 and Q_3 if it is below 5 volts. The output from Q_3 is a voltage which is between 13 and 3 volts for an input to Q_2 of 5 volts to 0 volts. Likewise a 5- to 10-volt signal will produce a 13- to 3-volt output from Q_4 while leaving Q_3 cut off and its output at 13 volts. Thus the error voltage developed in the averaging resistors will cause the proper valve to open and will control the length of time that it remains open.

These circuits can improve the response of a solenoid valve, which means that a higher pulse repetition rate can be used. This faster pulse rate enables the system to have a better control resolution.

CONCLUSIONS AND RECOMMENDATIONS

These circuits have demonstrated that better response can be obtained from solenoid valves by using high voltage, short duration pulses.

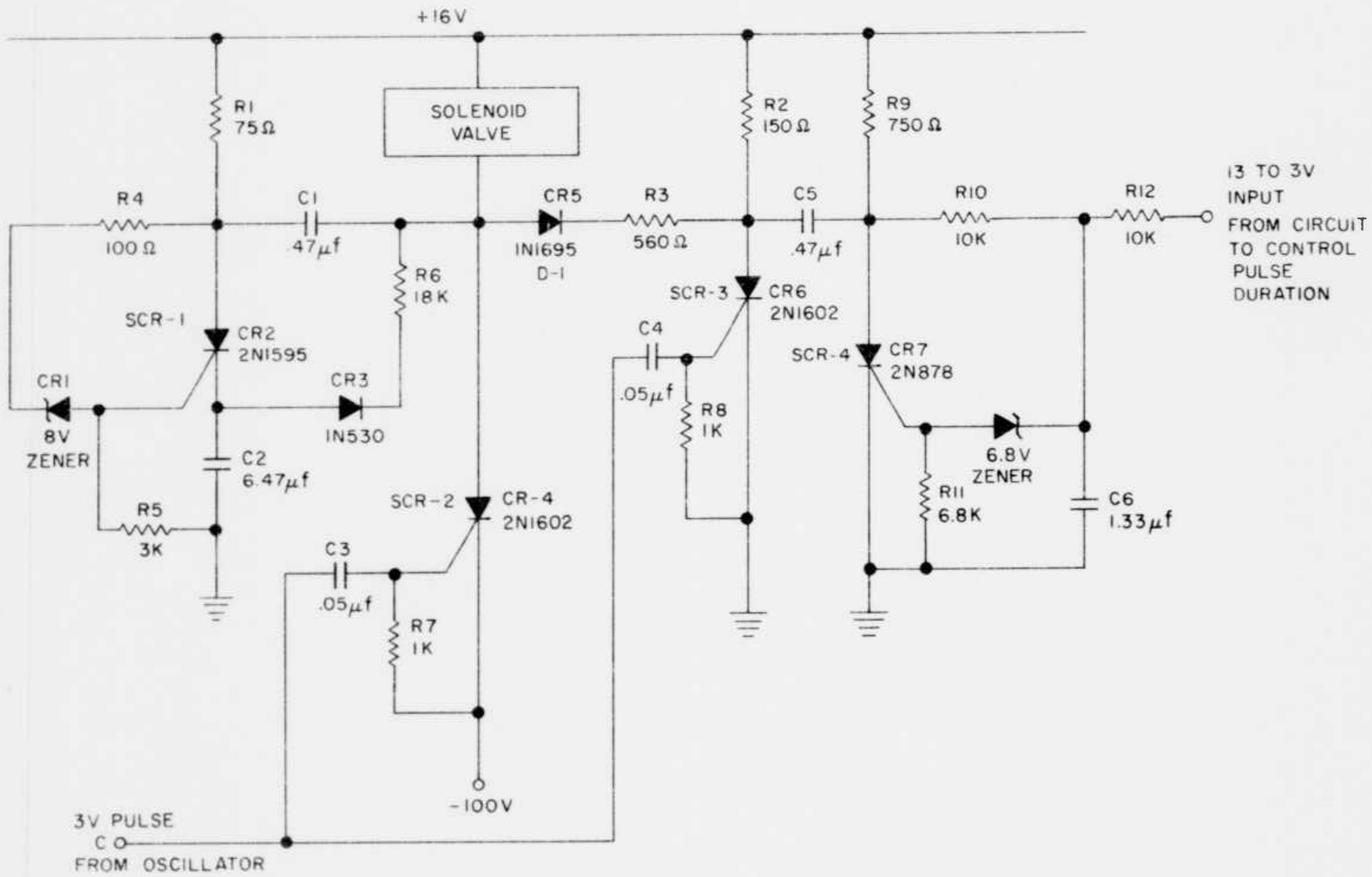


FIG. 29. Silicon Control Rectifier Control Circuit.

The circuit showed that the response of a solenoid valve can be as short as 2 ms and can be increased to 6 ms by adjusting the duration of the pulse which operates the valves. These response characteristics allow the pulse repetition rate to be increased to nearly 500 cps, thus providing improved control resolution for the system. By inspecting the circuit diagram, it can easily be seen that the components are small and inexpensive. This would allow for smaller, less expensive packaging than previous systems.

Appendix D

PULSE MOTOR CIRCUITRY

INTRODUCTION

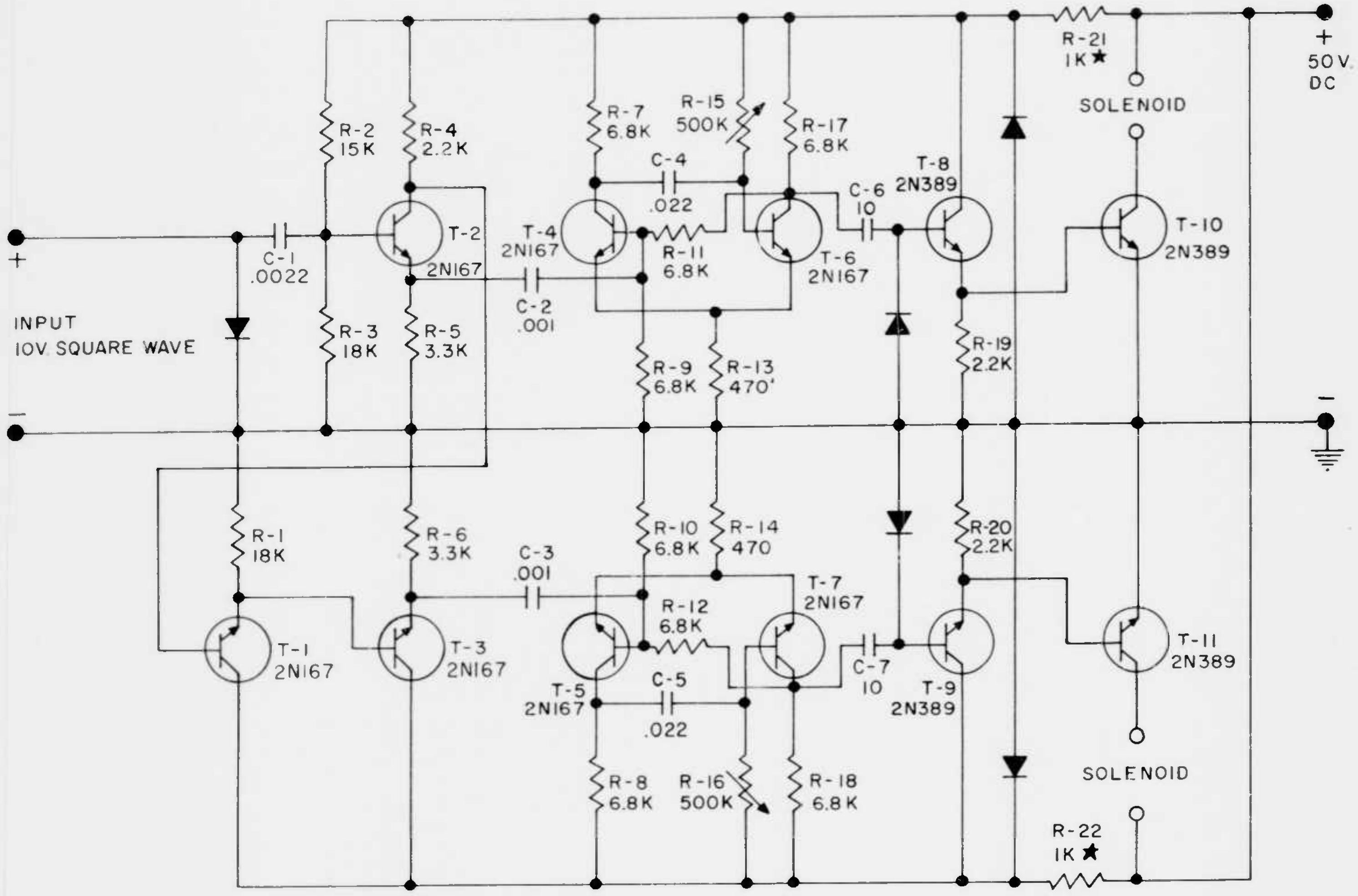
It was foreseen that the pulse motor would be turned on when an appropriate error signal is fed to the circuitry, and then turned off when that error signal stops. Therefore, the function of the circuitry is to pulse the opening solenoid valve when an error signal is seen and to pulse the closing valve when it stops.

A method of varying the pulse width was built into the circuitry for initial test operation until the optimum pulse width was determined.

CIRCUITRY

The error signal is first differentiated by C-1 (Fig. 30), then passed on to transistor, T-2, where it is phase splitted. The signal from the emitter is then fed into DMV no. 1 (Fig. 31), which has a variable resistor on the base of the transistor, T-6, to vary the width of the pulses. The pulses are then fed into the driver circuit which allows a corresponding current to flow through the driver transistor to the output transistor. A solenoid is placed in the collector of the output transistor, so that when the pulse from the driver circuit is fed into the output circuit the output transistor will conduct current. This current must come through the solenoid, causing the valve to open when the transistor conducts and to close when the transistor is shut off.

The signal from the collector of the phase splitter, T-2, must be fed to another phase splitting transistor to convert the negative square wave trailing edge to a positive signal for operating DMV no. 2. Solenoid valve no. 2 is actuated as was solenoid valve no. 1.



ALL RESISTORS 1/4 WATT EXCEPT ★ 1 WATT
ALL CAPACITORS IN MICROFARADS AT 50V.

FIG. 30. Schematic of Pulse Duration Control Circuit.

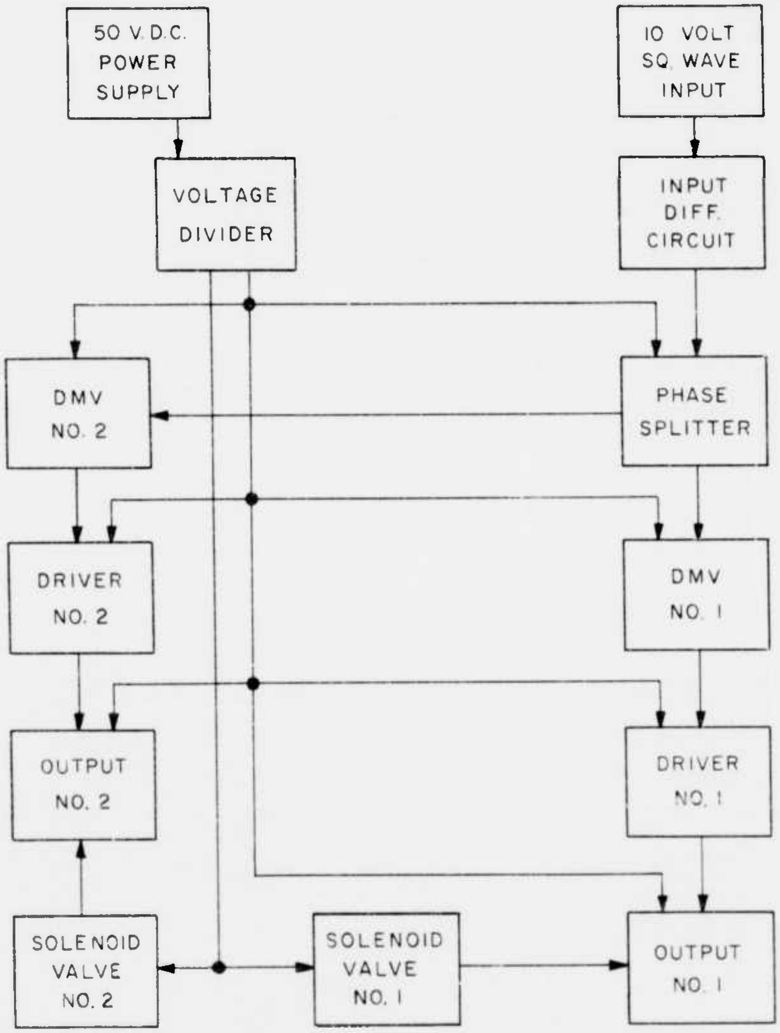


FIG. 31. Block Diagram of Pulse Motor Circuitry.

Appendix E

TYPICAL VARIABLE-THRUST DATA POINT

Firing number STR 630, LC 687 DATA POINT NO. 3

Thrust = 20.5 lb

Chamber pressure = 90.7 psia

$\dot{\omega}_o$ = 125 cps (Potter flow meter - 0.000581 correction factor)

$\dot{\omega}_f$ = 125 cps (Potter flow meter - 0.000284 correction factor)

$\dot{\omega}_o = 125\ (0.000581) = 0.0727$ lb/sec

$\therefore$ O/F ratio = 2.04

$\dot{\omega}_f = 125\ (0.000284) = 0.0355$ lb/sec

$\dot{\omega}_{total} = 0.1082$ lb/sec

$C^* = \frac{PAg}{\dot{\omega}}$ $\qquad A = 0.20\ \text{in.}^2$

$$C^* = \frac{90.7\ (0.20)\ (32.2)}{0.1082} = 5{,}380\ \text{ft/sec}$$

$$I_{sp} = \frac{20.5}{0.1082} = 189\ \text{sec}$$

T_{alt} $\qquad T = C_F P A_T$ $\qquad C_{F_{alt}} = 1.85$

$$T = 1.85\ (90.7)\ (0.20) = 33.6\ \text{lb}$$

$I_{sp}alt$ $\qquad I_{sp} = \frac{T_{alt}}{\dot{\omega}_{total}}$

$$I_{sp} = \frac{33.6}{0.1082} = 310\ \text{sec}$$

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1. The Marquardt Corporation. Controllable Liquid Rocket Program, Marquardt Report S-173, Van Nuys, Calif., 3 December 1960.

2. U. S. Naval Ordnance Test Station. Design and Testing of a 0-10 lb Variable-Thrust Rocket Motor, by R. F. Dettling. China Lake, Calif., NOTS, January 1962. (NAVWEPS Report 7803, NOTS TP 2799), CONFIDENTIAL.

3. ------. Development of the Liquid Propellant Variable-Thrust Sustainer Motor for Automet Missile A, by D. H. Strietzel and others. China Lake, Calif., NOTS, November 1961. (NAVWEPS Report 7789, NOTS TP 2782), CONFIDENTIAL.

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ABSTRACT CARD

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50-Pound Thrust Attitude-Control Motors, by J. W. Shaw. China Lake, Calif., NOTS, May 1963. 48 pp. (NAVWEPS Report 8118, NOTS TP 3206), UNCLASSIFIED.

ABSTRACT. The 50-pound thrust attitude-control motors are high performance liquid rocket engines capable of being operated in either pulsed or variable-thrust modes.

The motors are durable and versatile flight-weight systems, weighing less than one pound. A vacuum corrected specific impulse of 310 lb-sec/lb

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was achieved using nitrogen tetroxide and mixed hydrazine. Response of the motor from signal input to 90 percent of full thrust was 7 ms in both the pulse and variable-thrust modes. The motor was operated in a pulsing mode up to 100 cps and also in the variable-thrust mode with a repeatable thrust accuracy of five percent. A new variable-thrust actuation system was developed for which a patent has been applied.

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