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### EVALUATION OF A SMALL PULSE MOTOR SUITABLE FOR ATTITUDE CONTROL

by

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**ABSTRACT.** Several 5-pound thrust bipropellant pulse-rocket motors suitable for attitude-control systems were evaluated. The motor consisted of two fast-acting solenoid valves, for injection of propellants, mounted on a radiation-cooled combustion chamber.

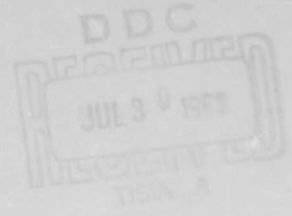
Using the hypergolic-propellant combination of red fuming nitric acid and unsymmetrical dimethylhydrazine, thrust pulses of 10 milliseconds were obtained without thrust attenuation on an L\* 50 unit. Steady-state and pulse-performance tests are discussed as well as pulse-operation-response tests.



U. S. NAVAL ORDNANCE TEST STATION

China Lake, California

April 1963



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FOREWORD

This report covers the evaluation of a series of bipropellant pulse motors suitable for use in attitude control systems.

The evaluation was made during Fiscal Year 1962 under Task Assignment RT70-43-001/216-1/F019-03-002.

This report was reviewed for technical accuracy by E. Yim and T. Seufert and is transmitted for information only, representing information at the working level which is subject to modification or withdrawal.

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NEGATIVE NUMBERS OF ILLUSTRATIONS

FIG. 1, LO82684; FIG. 2, LO82683; FIG. 3-6, none; FIG. 7  
 LO69091; FIG. 8-15, none.

## INTRODUCTION

A series of tests was performed at the United States Naval Ordnance Test Station (NOTS) during Fiscal Year 1962 on a small bipropellant pulse-rocket motor. This motor, which is suitable for use in attitude-control systems, was designed and constructed by the TAPCO Group of Thompson Ramo Wooldridge Company. Designed thrust for the motor is five pounds at sea level or 7.3 pounds when expanded 20:1.

The general specifications for the characteristics of the motor which were to be met ultimately are as follows:

1. Thrust - 5 pounds
2. Pulse width - 11 milliseconds
3. Pulse rate - minimum 20 pulses-per-second with equal off periods.
4. Current - 1 amp at 24 volts
5. Propellant - unsymmetrical dimethylhydrazine (UDMH) and inhibited red fuming nitric acid (IRFNA)
6. Expansion ratio - sea-level optimum
7. Chamber pressure - 50 pounds-per-square-inch gage (psig)
8. Valve leakage - 1.0 cubic centimeter-per-minute maximum
9. Duration - 5 minutes at full cyclic rate

All but specifications 2 and 3 were met with the first motor. In order to meet these specifications, TAPCO made modifications from motor to motor incorporating several recommendations made by NOTS. The last motors that were delivered adequately met the specifications set forth.

Five motors were fired in the evaluation tests. The characteristic combustion chamber length ( $L^*$ ) varied from 50 to 100 inches. Four of the motors tested were designed for sea-level work while a fifth was equipped for altitude firing. Table 1 lists the physical characteristics of the motors. Figure 1 shows six pulse motors; however, only motors 1 through 5 were tested.

## DESCRIPTION

Components of the 5-pound TAPCO pulse motor shown in Fig. 2 are two fast-acting solenoid valves for control of the propellant and the motor body which includes expansion cone and combustion chamber. All of the internal surfaces of the stainless steel motor are protected by a thick layer of zirconium oxide. This type of construction provides for radiant cooling of the motor. The two small axial solenoid

TABLE 1. Motor Physical Characteristics

Motor	L*	Expansion ratio ( $\epsilon$ )	Remarks
1	100	1.36:1	Designed for static test work only
2	77.5	1.36:1	Flightweight motor
3	70	20:1	Flightweight motor
4	70	1.36:1	Similar to above, except expansion cone has been shortened
5	50	1.36:1	Flightweight motor
6	50	20:1	Similar to above, except motor has a long expansion cone and was not tested

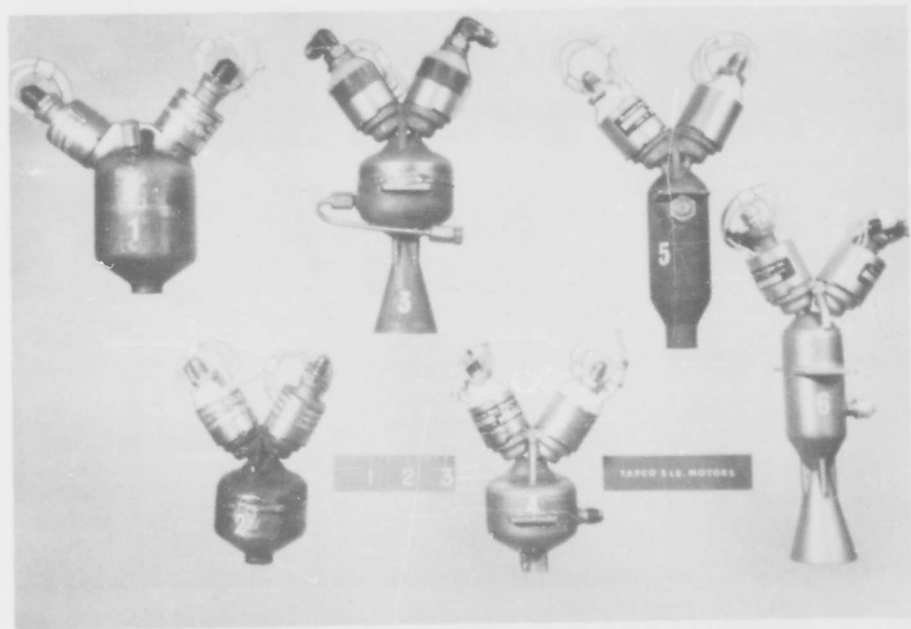


FIG. 1. View of Six TAPCO Pulse Motors.



FIG. 2. View of Disassembled TAPCO Pulse Motor.

valves are the principal parts. These valves meter the flow of propellant to the two orifices which are machined into the head end of the combustion chamber. The orifices are located so that direct impingement of the propellants takes place on the combustion chamber axis with the horizontal momentum of the propellant nullified.

The solenoids are rated for 24 volts at 1 amp; however, they will operate at about one-half that voltage. Each pair of solenoid valves was electrically matched to minimize the time difference between the two valves. This time difference is important when considering valve-opening times with regard to propellant utilization and ignition delays. It was found that, while the difference in valve-opening times was on the order of 1 to 0.3 millisecond, the oxidizer valve always opened before the fuel valve. This slight oxidizer lead produces smooth combustion and eliminates hard starts.

## THEORETICAL PERFORMANCE CHARACTERISTICS

The propellants to be used for the pulse motor were inhibited red fuming nitric acid (IRFNA) and unsymmetrical dimethylhydrazine (UDMH). Reagent-grade IRFNA with 20% nitrogen dioxide ( $\text{NO}_2$ ) was inhibited by the addition of reagent-grade aqueous hydrogen fluoride (HF). This oxidizer combination was used for all tests (instead of military standard IRFNA) in order to reduce contamination and minimize scale deposits in the valve passageways. The injector was designed for an oxidizer-to-fuel (O/F) ratio of 2.1. With an expansion ratio of 1.36, five pounds of thrust would be produced at a chamber pressure of approximately 50 psig. At sea level the thrust coefficient is 1.04, and at a 20:1 expansion ratio, it is 1.71.

Theoretical shifting specific impulse ( $I_{sp}$ ) for the propellants is 177 lb-sec/lb at an O/F ratio of 2.3 when expanded from 65 to 14.7 psia. When expanded from 65 to 0.32 psia, equivalent to a 20:1 expansion ratio, the maximum shifting  $I_{sp}$  is 295 lb-sec/lb at an O/F ratio of 3.0. Characteristic exhaust velocities ( $C^*$ ) are 5,400 and 5,550 ft/sec, respectively. These values were obtained through the use of a propellant-performance program on an electronic computer. A plot of O/F ratio versus shifting and frozen  $I_{sp}$ ,  $C^*$ , and combustion temperature is shown in Fig. 3 for a pressure ratio of 4.4:1, and in Fig. 4 for a pressure ratio of 200:1.

## CONTROL SYSTEMS

Two different control systems were used for actuating the solenoid-injector valves. One system uses a mechanical switch and the other an electronic trigger. Figure 5 is a circuit diagram of the mechanical-timing system. The 24 volts necessary to actuate the solenoids is controlled by a micro switch which is in turn tripped by a variable motor-driven cam. Pulse frequency and pulse duration were controlled by a change in motor speed or cam size. This method was found not to be completely satisfactory because of switch noise and the finite time required to trip the switch; therefore, it was replaced by an electronic trigger shown in Fig. 6. This trigger consists of a Schmidt trigger for frequency control, a flip flop, and a solenoid driver for pulse width control. It was found that the electronic-control scheme noticeably reduced valve delays.

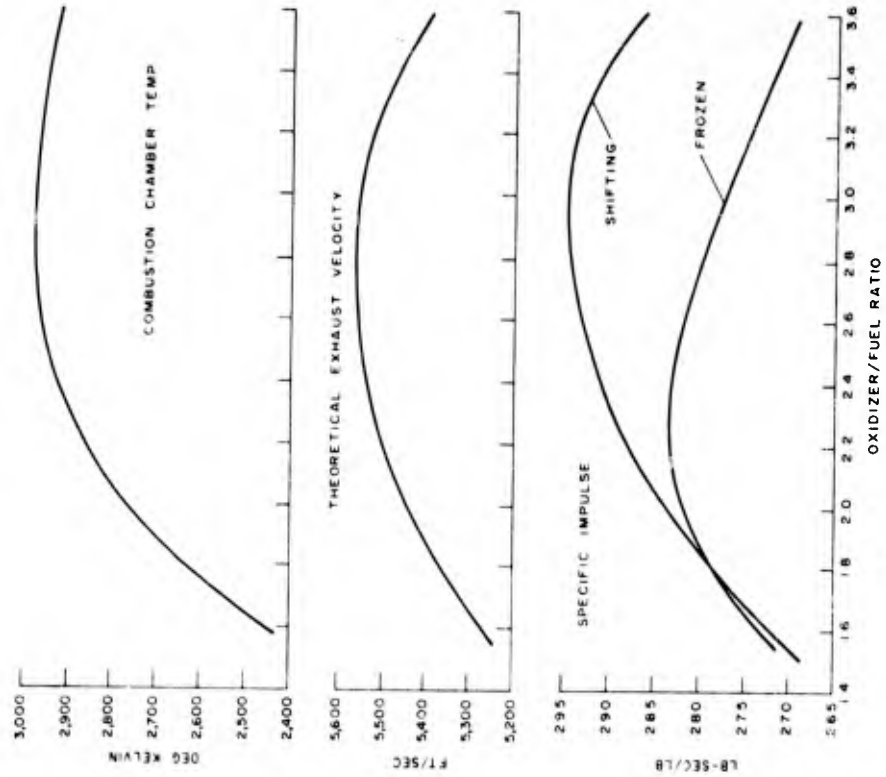


FIG. 4. Performance of IRFNA (20% NO<sub>2</sub>) and UDMH Expanded from 65 to 0.32 psia.

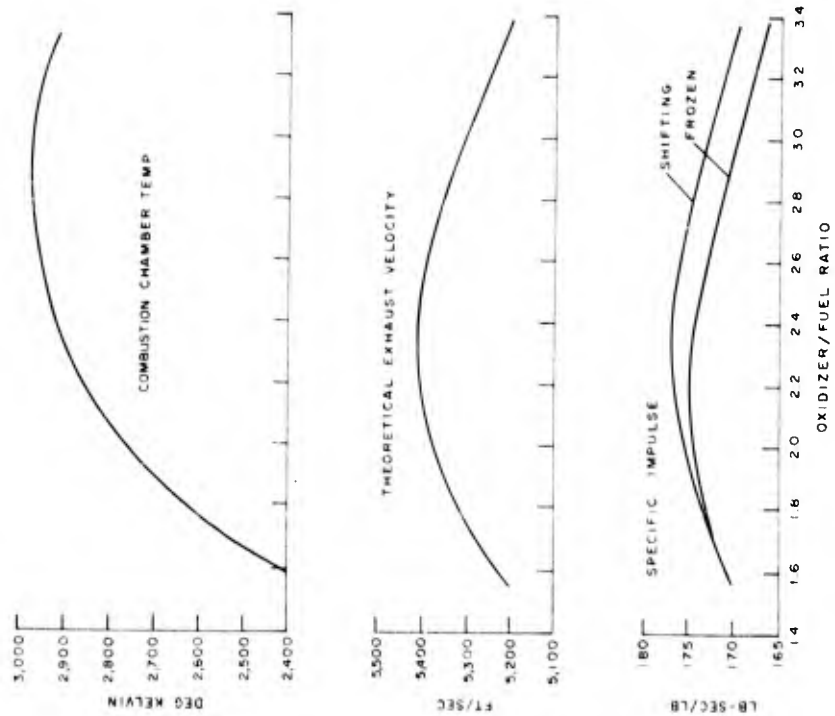


FIG. 3. Performance of IRFNA (20% NO<sub>2</sub>) and UDMH Expanded from 65 to 14.7 psia.

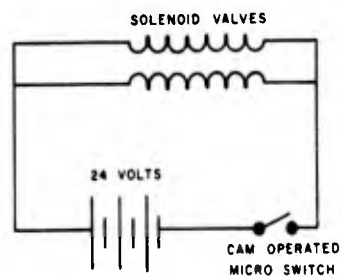


FIG. 5. Mechanical Control Circuit.

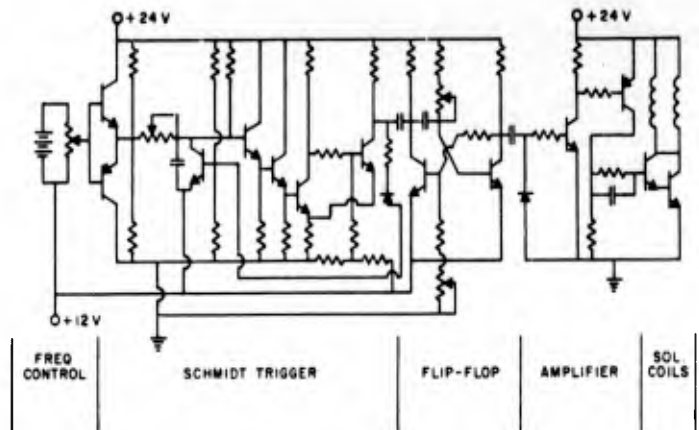


FIG. 6. Electronic Control Circuit.

### TESTS

Motors 1, 4 and 5 were tested under sea-level conditions while motors 2 and 3 were tested in a vacuum tank. Three basic types of tests were performed with these motors: (1) steady-state performance, (2) pulse-operation response, and (3) pulse-operation performance. Pulse-operation response was made at both sea-level and altitude conditions while the other two types were made under sea-level conditions only.

Values measured were chamber pressure, fuel and oxidizer line pressures, thrust, combustion chamber wall temperature, oxidizer and fuel flow rates, solenoid voltage and currents. A list of the measuring equipment used can be found in Appendix A.

The transducer used to measure chamber pressure was coupled to the chamber with a short linkage (Fig. 7). This view shows the motor attached to the thrust mount which was used for the altitude response test. A similar set-up was used for the sea-level tests. Thrust was measured by attaching the motor directly to a load cell and then mounting the load cell in a vertical position on the test stand. Thin bent-aluminum tubes were used as propellant supply lines.

Flow measurements proved to be a problem area throughout the test series. Several types of meters were used with little data from any of them. Too much or too little flow occurred for the range of the transducer, or contaminants interfered with the transducer operation.

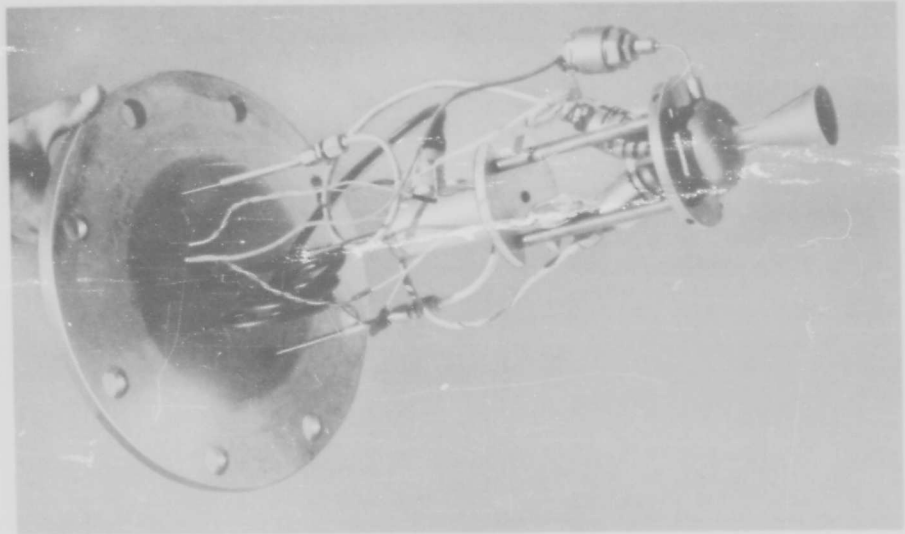


FIG. 7. 5-lb TAPCO Pulse Motor on Thrust Mount Used in Vacuum Tank Test.

## TEST RESULTS

### STEADY-STATE PERFORMANCE TESTS

Not as much emphasis was placed on the steady-state performance tests as on the pulse-operation-response tests. The experimental error of the data obtained is in the order of 10%. As has previously been mentioned the propellant combination used for all the tests was reagent-grade IRFNA containing 20%  $\text{NO}_2$  and UDMH. With these propellants, performance values listed in Table 2 were obtained for the L\* 70 and L\* 50 motors. For the L\* 70 motor a characteristic exhaust velocity ( $C^*$ ) of 4,480 ft/sec and an  $I_{sp}$  of 120 lb-sec/lb were recorded near the design O/F ratio. These values compared to the theoretical values for an O/F ratio of 2.2 are only 83% and 68% of the  $C^*$  and  $I_{sp}$  values, respectively. The most probable reason for low performance figures is the fact that the steady-state runs were for only three seconds; the combustion chamber probably did not reach equilibrium-temperature conditions at which point maximum performance can be expected.

TABLE 2. Steady-State Performance of 5-lb TAPCO Motor

$T_x$	$P_c$ , psig	$P_{ox}$ , psig	$P_{fuel}$ , psig	$W_{ox}$ , lb/sec	$W_{fuel}$ , lb/sec	O/F ratio	$C^*$ , ft/sec	$I_{sp}$ , lb-sec/lb
A. L* 70 motor								
5.1	62	115	158	0.0253	0.0181	1.4	4480	118
5.4	67	144	160	0.0288	0.0178	1.6	4510	116
4.7	55	111	113	0.0254	0.0143	1.8	4500	118
5.8	69	134	142	0.0321	0.0160	2.0	4480	120
B. L* 50 motor								
5.7	66	125	134	0.0303	0.0145	2.1	4630	127
5.4	59	134	128	0.0316	0.0126	2.5	4280	122
5.6	57	104	154	0.0233	0.0171	1.4	4383	139

For the L\* 50 motor at the design O/F,  $C^*$  and  $I_{sp}$  values of 4,630 ft/sec and 127 lb-sec/lb were 86% and 72% of the theoretical values, respectively.

A test of 310 seconds duration was run on motor 1 with several periods of off time to determine temperature rise and restart time. Thermocouples were spot welded to the injector boss and the outside of the combustion chamber to measure the temperature rise. Figure 8 is a plot of the results showing temperature rise and percent full thrust as a function of time. The combustion chamber wall reached 425°F after 46 seconds at which time the temperature trace was lost. After 100 seconds, during which the pulse width was 70 milliseconds with a 50 millisecond off period between pulses, the boss temperature reached 100°F. Following this first pulsing period, the motor was turned off for 15 seconds and then turned on for another 15-second pulse period. This pattern was repeated for the remainder of the test except for the last three pulsing periods when the pulse period width was changed to 50 milliseconds on and 25 milliseconds off.

Full-thrust pulses were not obtained on the initial pulse for any of the restarts. On the first restart it required nine pulses before full thrust was achieved. As the motor temperature increased, the time required to achieve full-thrust pulses on subsequent restarts also increased. For the last restart with a boss temperature of 185°F, 50 pulses were required. This delay in thrust buildup occurred because the propellants became vaporized by the warm metal around the injection ports and valve seats. After several pulses, the propellants cooled the injection area to the point where they were no longer

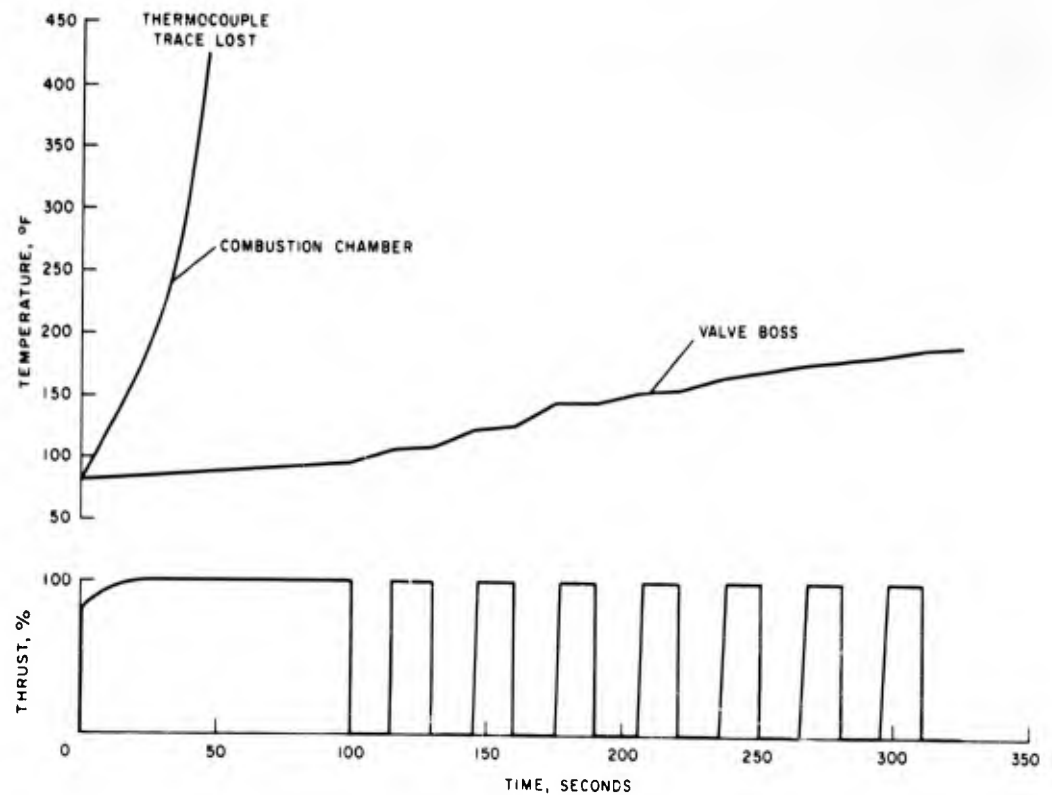


FIG. 8. Temperature Rise and Percent Full Thrust as a Function of Time for Motor 1.

vaporized before entering the combustion chamber and full-thrust pulses were then obtained.

During the off portions of the pulsing cycle, heat from the combustion chamber was transferred to the cool areas around the valves. By reducing the size of the injector bosses on the flightweight motors, the amount of heat soak back to the valve area was minimized, and the thrust buildup delay was greatly shortened.

Since this run was of long duration, equilibrium heat transfer rates were assumed for the motor. It was noted that the peak thrust-per-pulse slowly increased as the chamber temperature rose. An increase thrust of 15% was measured between 3 and 25 seconds of the first pulsing period; once the peak thrust was reached after 25 seconds, it remained constant except for the restart conditions mentioned previously. A similar performance increase could be expected whenever equilibrium conditions are reached with the radiation-cooled combustion chamber.

**PULSE OPERATION RESPONSE TESTS**

In evaluation of the pulse motor, the primary interest was in the response characteristics both under sea-level and vacuum conditions. Measurements of these characteristic times were obtained through the use of high-response transducers and galvanometers for measuring chamber pressure, thrust, and injector-valve voltage and current.

The following characteristic motor-response times were determined from the preceding measurements:

Valve delay	Time from voltage application to start of valve opening
Valve opening time	Time required for solenoid plunger to move full stroke
Valve closing time	Cessation of voltage to valve closing
Voltage pulse	Time from application to cessation of voltage
Thrust delay	Time from voltage application to initial rise of thrust
Chamber pressure delay	Time from voltage application to initial rise of chamber pressure
Thrust rise	Time from beginning of thrust rise to full thrust
Chamber pressure rise	Time from beginning of chamber pressure rise to full chamber pressure
Thrust decay	Time from start of thrust decay to no thrust
Chamber pressure decay	Time from start of chamber pressure decay to no chamber pressure
Thrust pulse	Total time thrust is produced
Chamber pressure pulse	Total time chamber pressure is produced
Thrust decay delay	Time from cessation of voltage pulse to start of thrust decay
Chamber pressure decay delay	Time from cessation of voltage pulse to start of chamber pressure decay

## VACUUM TANK TESTS

The vacuum-tank test objectives were to determine ignition delay times and to ascertain that there would be no ignition problem. Three pulsing series were run with the 77.5 L\* motor and two with the 70 L\*, 20:1 expansion ratio motor. No ignition problems were encountered on the initial pulse of any of the pulsing series or on any successive pulses, but there was an ignition delay.

Figure 9 is a copy of an oscillograph trace showing thrust, chamber pressure, fuel and oxidizer line pressures, and solenoid valve currents while the motor was firing in the vacuum tank. The oscillations on the thrust trace are the result of the characteristic stand frequency of approximately 160 cps.

No comparisons of thrust rises or decays should be made because the thrust measurement is greatly affected by the stand frequency characteristics.

By comparing the chamber-pressure trace with the valve currents, which show valve opening, the ignition delay can be found. The notch in the valve currents is the result of the solenoid plunger motion. A gradual increase in chamber pressure can be noted at the time the injector valves open. This gradual rise continues for 5 milliseconds at which time the chamber pressure begins to rise steeply. It is this change in slope of the pressure trace which indicates ignition. The ignition delay on the first three or four pulses was greater than succeeding or typical pulses. For all tests, an equivalent altitude of greater than 100,000 feet was maintained and greater than 125,000 feet in some instances.

Table 3 lists values for a typical pulse from each of the two motors fired as well as performance values. It will be noted that the ignition delay from the motor with the expansion ratio of 20:1 is approximately 1 millisecond greater than the motor with expansion ratio of 1:36:1. It is suspected that this delay was a function of the injector-orifices alignment. Thrust was nearly double for the motor expanded 20:1. This was the result of increased propellant-supply pressure and nearly optimum expansion conditions.

## SEA-LEVEL TESTS

Motor 1 with L\* 100 was tested using the mechanical control system. Typical values for the motor characteristics are shown in Table 4. For a voltage pulse of 15 milliseconds, the thrust pulse was 23 milliseconds which was the shortest full thrust obtainable. Only one pulsing series was made for measuring pulse characteristics with

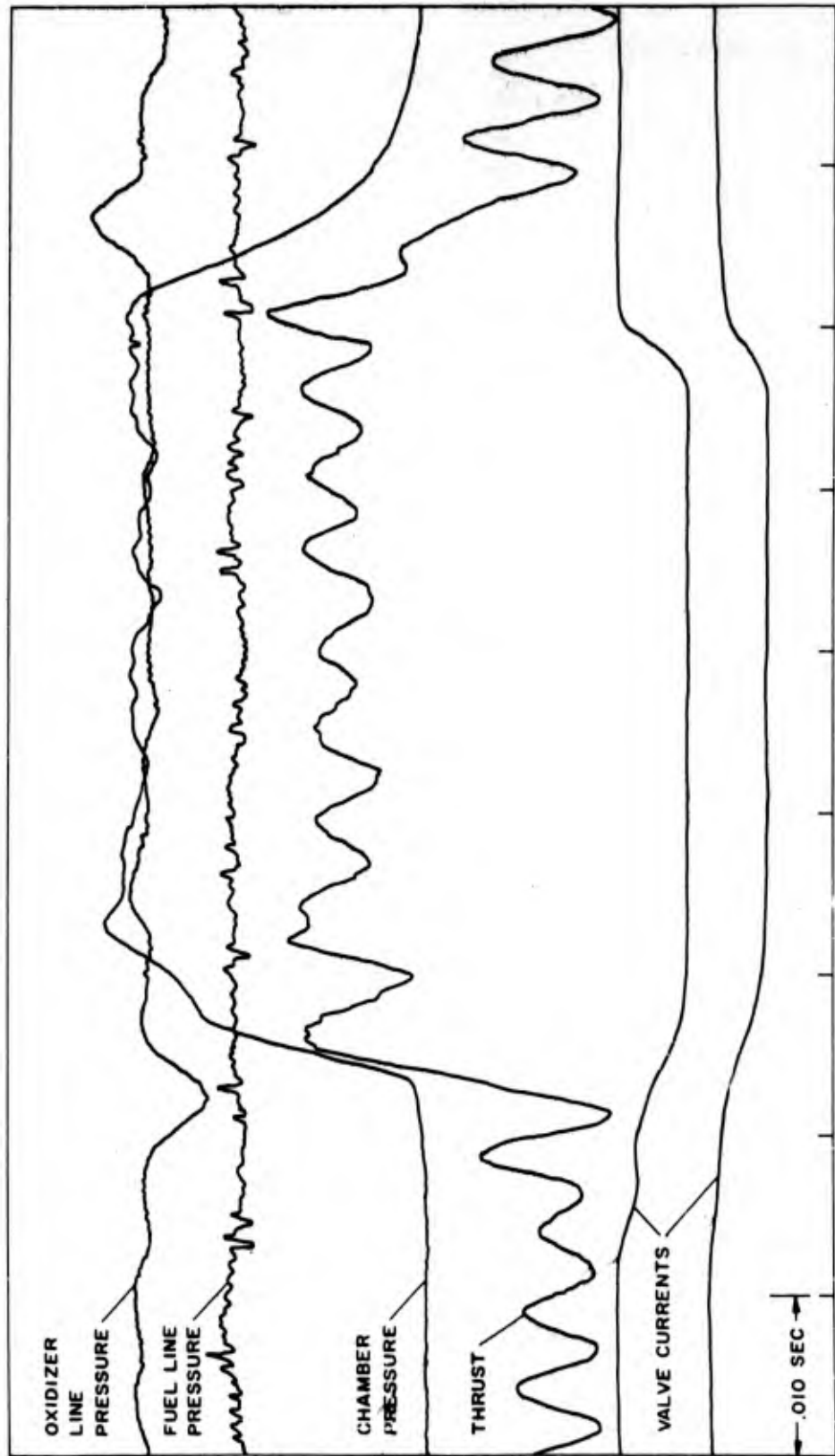


FIG. 9. Oscilloscope Trace From Vacuum Tank Test.

TABLE 3. Typical Pulse and Performance Values at Simulated Altitude

Action	Nozzle of 1.36:1 expansion, L*80	Nozzle of 20:1 expansion, L*70
Valve delay time, ms	5.0	5.5
Valve delay and opening time, ms	7.0	7.5
Thrust delay, ms	10.0	11.5
Thrust rise, ms	4.0	4.0
P <sub>c</sub> delay, ms	11.5	13.0
P <sub>c</sub> rise, ms	5.0	7.0
Valve closing time, ms	3.0	3.0
Thrust decay delay, ms	5.0	5.0
Thrust decay, ms	5.5	8.0
P <sub>c</sub> decay delay, ms	8.0	5.5
P <sub>c</sub> decay, ms	11.0	14.0
Performance:		
Thrust, lb	6.5	11.3
Thrust calculated from C <sub>f</sub> & measured P <sub>c</sub> , lb	6.6	11.5
P <sub>c</sub> , psia	62.0	86.0
P <sub>fuel</sub> line, psig	125.0	148.0
P <sub>ox</sub> line, psig	90.0	130.0
Equivalent altitude, ft x 10 <sup>3</sup>	115.0	110.0

this motor because instrumentation improvements were necessary and improved motors with smaller L\* became available for testing.

The motors with L\*'s of 70 and 50 were extensively tested for determination of pulse characteristics. Primary improvements made in instrumentation included the use of a higher response chamber-pressure gage and high-response galvanometers. Table 4 contains average pulse-characteristic values with 95% confidence limits for these two motors.

Using the electronic-control system the valve-delay time was reduced by 1.5 to 2 milliseconds, and the valve-opening time was reduced by slightly more than 1 millisecond. Slight differences in the valve delays and opening times like the differences between the L\* 70 and L\* 50 values are the result of slight variations in the solenoid valve construction. These differences are minimized at the time of manufacture by closely matching the electrical and mechanical properties of the valves.

TABLE 4. Typical Pulse, and Performance Values  
at Sea Level

Action	Nozzle of 1.36:1 ex- pansion, L* 100	Nozzle of 1.36:1 ex- pansion, L* 70	Nozzle of 1.36:1 ex- pansion, L* 50
Valve delay time, ms	4.5	3.9±0.2 4.1±0.2	3.6±0.2 3.8±0.2
Valve delay and opening time, ms	---	4.8±0.2 5.0±0.2	4.3±0.2 4.4±0.2
Thrust delay, ms	5.0	5.3±0.3	5.4±0.2
Thrust rise, ms	6.0	5.5±1.0	6.2±1.0
P <sub>c</sub> delay, ms	12.0	6.4±0.2	6.0±0.2
P <sub>c</sub> rise, ms	9.0	4.3±0.4	3.4±0.4
Valve closing time, ms	---	3.0±0.2	---
Thrust decay delay, ms	5.0	---	---
Thrust decay, ms	7.0	6.8±1.0	6.5±1.0
P <sub>c</sub> decay delay, ms	5.5	3.2±0.2	3.1±0.2
P <sub>c</sub> decay, ms	14.5	7.3±0.4	6.8±0.2
Performance:			
Thrust, lb	---	4.6	5.7
Thrust calculated from C <sub>f</sub> & measured P <sub>c</sub> , lb	4.6	5.1	6.0
P <sub>c</sub> , psia	55.0	62.0	73.0
P <sub>fuel</sub> line, psig	195.0	130.0	132.0
P <sub>ox</sub> line, psig	100.0	130.0	132.0
Altitude, ft x 10 <sup>3</sup>	2.0	2.0	2.0

As L\* is reduced, the time for pressure in the combustion chamber to buildup or decay is reduced. A reduction in L\* by 50%, maintaining the same pressure ratio conditions, should reduce the time by 50%. This fact was experimentally verified in that the chamber-pressure pulse-width reduction was slightly more than 50% from the L\* 100 to the L\* 50 motor.

When comparing the sea-level test of the L\* 70 motor with the test in vacuum of the L\* 77.5 motor with the chamber pressures nearly the same, it may be noted that the pressure rise takes approximately

the same time, but the decay takes longer in the vacuum test. These results are as theory predicts.

A difference in rise time between the two units fired in the vacuum test is a direct result of the difference in chamber pressure reached by each unit

By controlling the duration of the voltage pulse, the total impulse bit-per-pulse is controlled; therefore, the average impulse over a period of time can be varied. Tests were made to determine the relationship of the voltage pulse, thrust pulse as reflected by chamber pressure, and the maximum thrust-per-pulse. These tests consisted of slowly varying the voltage pulse between 3 and 15 milliseconds. A curve (Fig. 10) with the chamber-pressure pulse width plotted as a function of voltage pulse proves to be linear down to approximately 7 milliseconds. Below this point the pressure pulse shortens faster than the voltage pulse. A possible explanation of this phenomenon is that the fixed times for valve opening, ignition delay, and valve closing are the dominate factors comprising the pulse width.

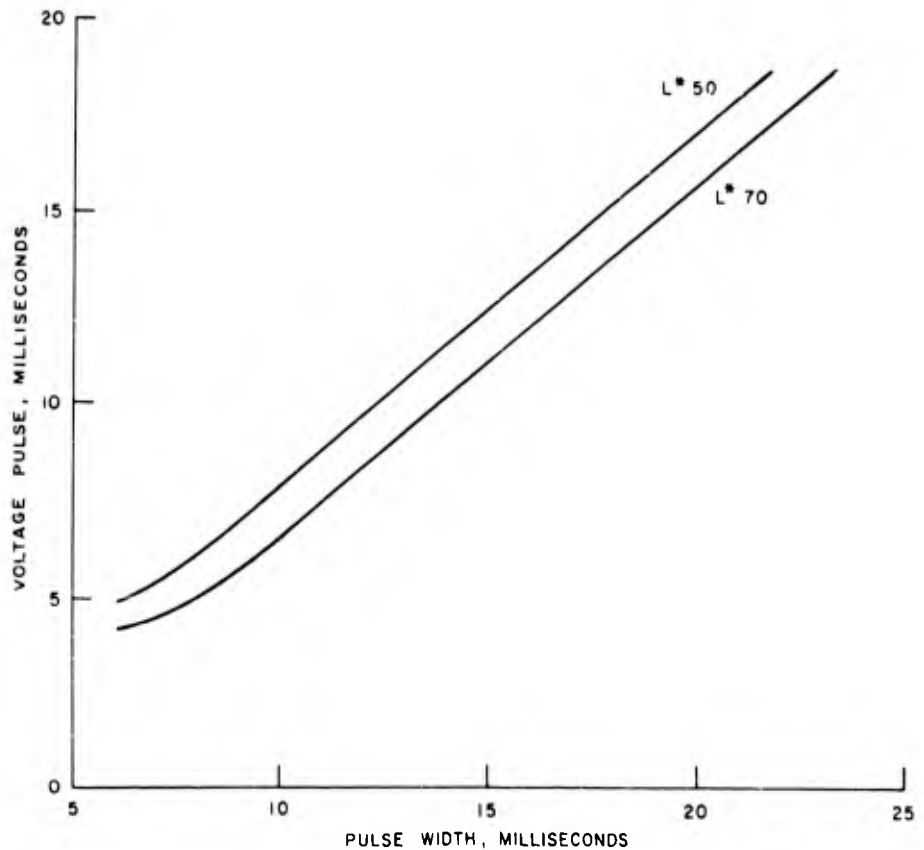


FIG. 10. Pulse Width Measured From Chamber Pressure Trace as a Function of Voltage Pulse.

The second factor determined by the tests was thrust attenuation as a function of the voltage pulse. For the attenuation measurements, the pressure trace was used because there was considerable overshoot in the thrust measurement. A plot of this attenuation is shown in Fig. 11. For the L\* 70 motor a voltage pulse of 8.5 milliseconds is required to achieve a full chamber-pressure pulse of 12 milliseconds, and for the L\* 50 motor a voltage pulse of 8 milliseconds is

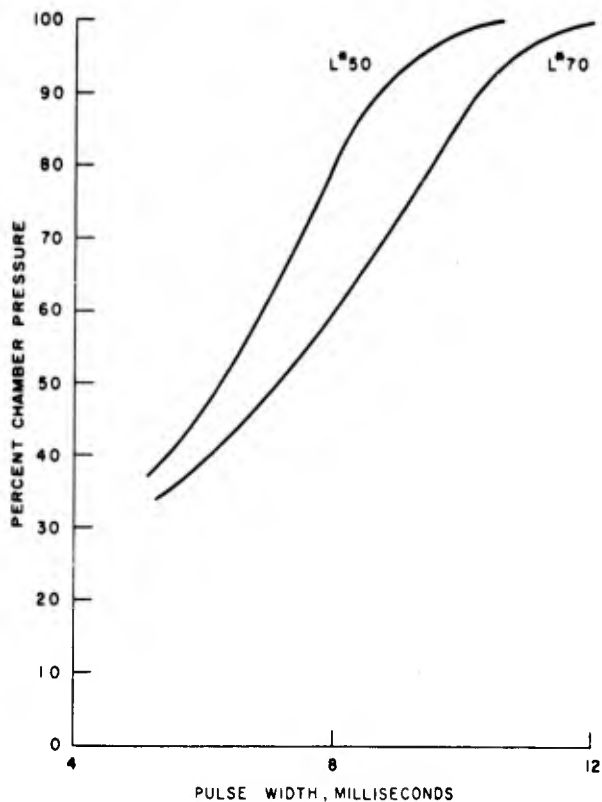


FIG. 11. Chamber Pressure Attenuation.

required to achieve a full chamber-pressure pulse of 10 milliseconds. When the voltage pulse is less than 4 milliseconds, the solenoid valves fail to open; therefore, no thrust is produced. Figure 12 shows the chamber pulse, valve currents, and voltage pulses as a function of time. It may be seen that as the voltage pulse is varied, the area under the chamber-pressure curve which can be related to the total pulse bit-per-pulse is varied. This is because the peak up to maximum pressure and duration of the pressure curve are changed.

In another pulsing series a determination of the maximum pulses-per-second was attempted using the L\* 50 motor. The pulsing frequency was slowly increased to the maximum frequency of the electronic

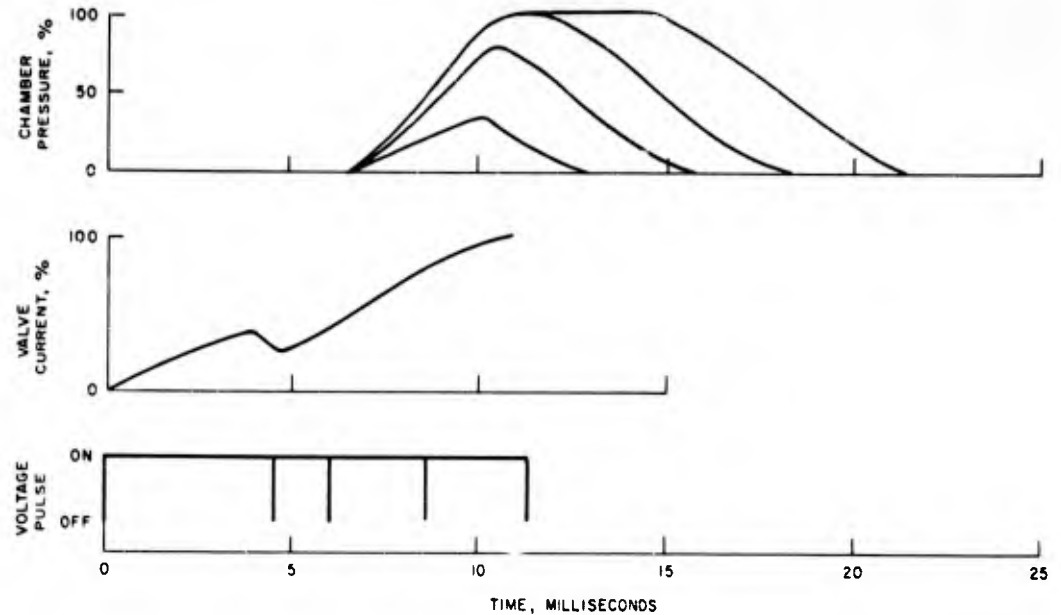


FIG. 12. Pressure Pulses, Valve Currents, and Voltage Pulse as a Function of Time.

control system which was between 69 and 70 pulses-per-second. At this rate, maximum thrust was still obtained with a voltage pulse of 8.5 milliseconds and a pulse width of 12.4 milliseconds. Since the limitation in frequency was the control system, higher pulse-per-second rates are possible with this motor. Figure 13 shows thrust chamber pressure, and valve currents from the oscillograph trace for the maximum pulsing rate attempted.

#### PULSING PERFORMANCE TESTS

Using the piston flow meters discussed in Appendix B, several pulsing tests were made to determine the average performance-per-pulse. The piston meter measured the total amount of propellant used over any one pulse. It was found, as would be expected, that the performance decreases as the pulse width is shortened. Figure 14 is a plot of  $C^*$  as a function of pulse width. For a pulse of 18.5 milliseconds, the  $C^*$  value was 2,660 ft/sec which is 60% of the measured steady-state value. What has been reported previously about the performance improvement, once the motor reaches equilibrium temperature conditions, holds true here because all of these tests were of short duration. Therefore, a performance increase in the order of 15% could be expected.

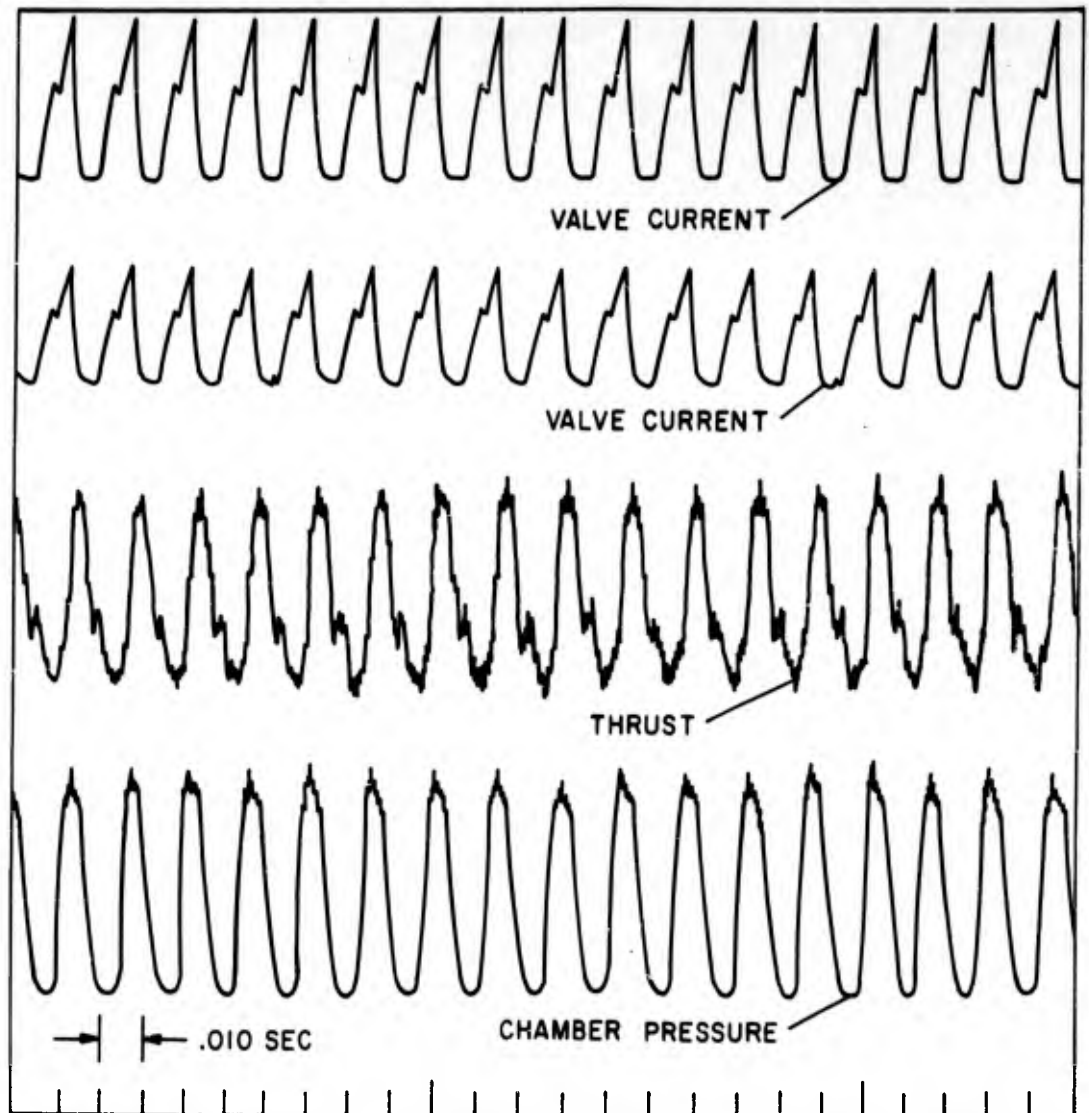


FIG. 13. Maximum Pulse Rate Oscillograph Trace.

### CONCLUSION

The L\* 50 motor met all of the design specifications. Full pulse widths of 10 milliseconds were obtained and a pulse rate with equal off time of greater than 40 pulses-per-second was obtained. Furthermore, discrete thrust pulses at a rate of 70 pulses-per-second were obtained. Duration of the motor was excellent with negligible throat erosion or combustion chamber deterioration. Slight deterioration of the valve pintles and seats was noted with a small increase in leakage rate and stickier valve action.

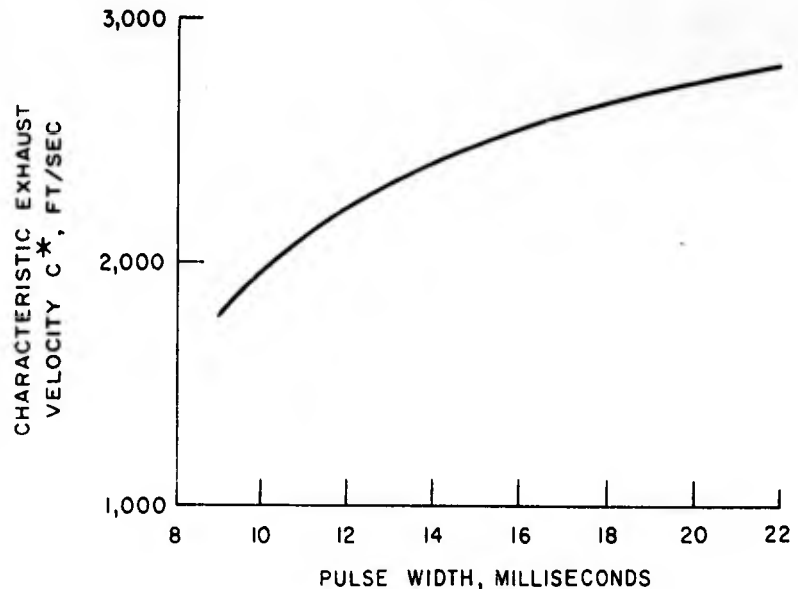


FIG. 14.  $C^*$  as a Function of Pulse Width.

For pulse motors of this type, several design criteria must be considered. Among these, the most important items are the combustion chamber  $L^*$ , combustion chamber pressure, valve sequencing, and propellant combinations.

As has been previously reported, the smaller the  $L^*$ , the shorter the thrust pulses; therefore, when short pulses are desired, one means of obtaining them is by reducing the  $L^*$ . However, in the radiation-cooled combustion chamber, as the  $L^*$  is reduced, the surface area available for radiating becomes smaller; consequently, design trade-offs are necessary. Isolation of the injector valves presents problems of keeping the valve temperature from exceeding the safe operating-temperature limit of the propellants. Also, as the  $L^*$  is decreased, performance usually decreases; therefore, to maintain the desired performance level, an efficient injector design becomes very important. In addition, the injector design is important when minimizing the pulse width since a minimum path is desired from the valve to the impingement point to reduce the propellant-transport time and the ignition delay.

With the  $L^* 50$  motor, a pulse rate of better than 100 pulses-per-second would have been achieved with but slight attenuation in thrust, if the electronic control system had been modified. By further reduction of  $L^*$ , the ultimate limitation on the pulsing rate for the small motors will be the speed of solenoid valves or some other control mechanism. Pulsing rates of 150 to 200 pulses-per-second with a full thrust pulse should be possible, and probably exceeded.

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When two solenoids are used for injection-valve control, it is extremely important to match their electrical properties as well as the mechanical properties of the valves. For most propellant combinations, it is desirable to have the oxidizer valve lead the fuel valve by a few tenths of a millisecond to avoid hard starts which create large overpressurizations in the combustion chamber.

Materials will play an important role in producing a usable pulse engine, and care must be taken to insure compatibility with the propellant combinations. Hypergolic-propellant combinations with extremely short ignition-delay times appear to be the most promising for bipropellant pulse-motor applications. Furthermore, in choosing a propellant combination for attitude-control systems, one must consider vacuum ignition and propellant storability.

## Appendix A

## INSTRUMENTATION

The following is a list of equipment used to measure pressures, thrust, voltages and currents, and flow rates:

## Pressure Transducers:

Wiancko, 0 - 500 psi, fuel-line pressure transducer  
Wiancko, 0 - 500 psi, oxidizer-line pressure transducer  
Wiancko, 0 - 500 psi, chamber-pressure transducer  
C. E. C., 0 - 100 psi, chamber-pressure transducer  
Drynesco, 0 - 500 psi, fuel- and oxidizer-line transducer

## Thrust transducers:

Wiancko,  $\pm 20$  lb transducer  
Statham,  $\pm 25$  lb transducer  
Alinco,  $\pm 50$  lb transducer

## Thermocouple:

Iron constantan

## Flow Meters:

Potter, 1/8-inch, turbine-type flow meter  
Standard Controls, 0 - 0.5 gpm, flow meter  
Piston-displacement type with G. L. Collins  
linear-position transducer  
Ramapo, Mk X, flow meter

## Appendix B

## PISTON DISPLACEMENT FLOW TRANSDUCER

A piston displacement flow transducer was designed and built for measurement of the total flow from a short-duration pulse. Figure 15 is an assembly showing the piston, inlets and outlets, and linear-position transducer. To charge the piston, the solenoid valve is opened and the propellant flows into the piston cavity, driving the piston to the left. The valve is closed and the hydraulic pressure is raised to  $4/3$ , the desired operating pressure. As the motor is fired, the piston displaces the propellant and the piston movement is measured by the linear-position transducer. To obtain the total flow used during a pulse, the initial and final positions of the piston are measured and multiplied by the area of the piston.

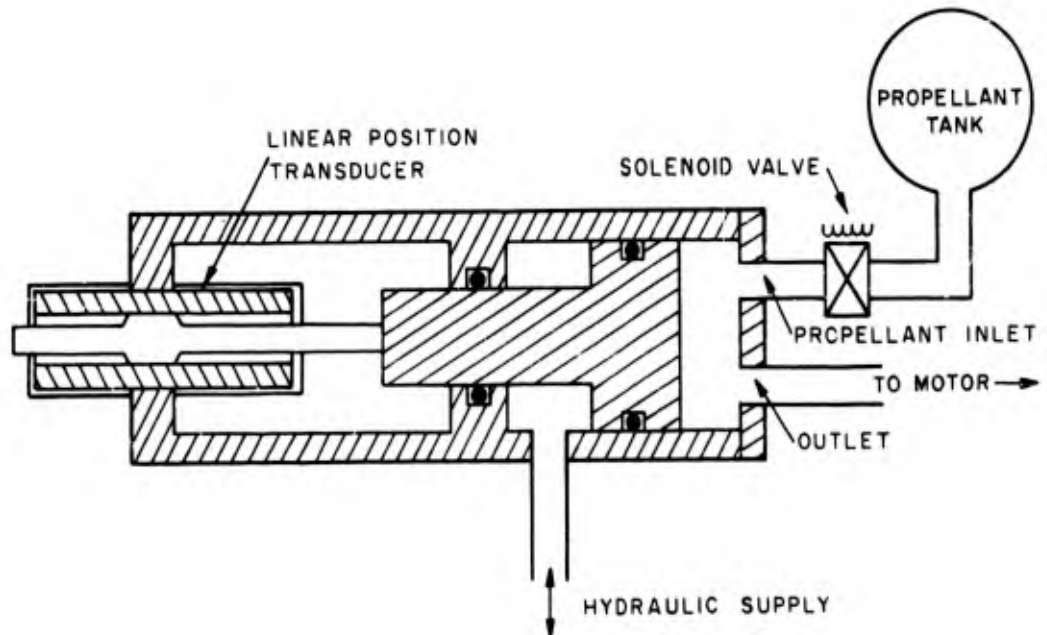


FIG. 15. Motor Assembly Showing Piston, Inlets and Outlets, and Linear-Position Transducer.

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