NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-691

Combined Effects of Hydrazine Exposure and Endurance Testing on Solenoid-Actuated Valve Performance
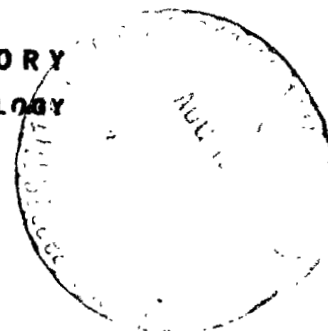
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CALIFORNIA INSTITUTE OF TECHNOLOGY

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16. Abstract

This article presents the results from a test program which was conducted to assess the capability of various solenoid-actuated valve design concepts to provide performance characteristics commensurate with long-duration (ten-year) missions to explore the outer planets. The valves were installed in a hydrazine flow test setup and periodically cycled during a nine-month test period under test conditions comparable to anticipated mission operating conditions. In situ valve performance was periodically determined, and leakage was continuously monitored.

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PREFACE

The work described in this report was performed by the Liquid Propulsion Section of the Propulsion Division at the Jet Propulsion Laboratory.

ABSTRACT

This article presents the results from a test program which was conducted to assess the capability of various solenoid-actuated valve design concepts to provide performance characteristics commensurate with long-duration (ten-year) missions to explore the outer planets. The valves were installed in a hydrazine flow test setup and periodically cycled during a nine-month test period under test conditions comparable to anticipated mission operating conditions. In situ valve performance was periodically determined, and leakage was continuously monitored.

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I. INTRODUCTION

The performance criteria and operating conditions specified for the propellant (hydrazine) control valves which would be used for missions to the outer planets are significantly more stringent than the requirements imposed on the control valves that were used for previous space missions. To accommodate the large number of valve actuations that are necessary to perform the anticipated spacecraft maneuvers, solenoid-actuated valves were selected for the baseline liquid propulsion feed systems. General requirements were formulated to eliminate identified deficiencies and potential problem areas associated with the use of solenoid-actuated valves for propellant control as follows:

(1)   Materials of construction: materials must be compatible with hydrazine, and those in the flow path should have a minimum catalytic effect on hydrazine composition. Titanium and aluminum are the most desirable materials for both corrosion resistance and minimum catalytic effect. Stainless steel (CRES) is satisfactory for corrosion resistance, but the evidenced decomposition of hydrazine by CRES samples limits usage to short-duration missions until such time as precise decomposition rates are established. The use of platings or coatings to protect a noncompatible base metal is unacceptable.

Materials must provide satisfactory performance during and after exposure to the radiation environments imposed by radioisotope thermal generators and to those encountered in outer space and during planetary flybys.

The amount of magnetic material should be minimized.

(2)   Propellant leakage: loss of propellant due to leakage across the valve seat must be minimized. The durability of a "hard," all-metal seat can be utilized to minimize environmental effects providing the susceptibility to particulate contamination can be tolerated or circumvented. A "soft" seat with a compatible elastomeric seal is acceptable if sufficiently durable. Designing for minimum leakage may involve two seats (one "hard" and one "soft") in series, with the "hard" seat at the thruster interface.

"Hard" seats made from tungsten carbide (WC) with 6% cobalt as the binder are satisfactory for corrosion resistance but evidenced decomposition of hydrazine limits usage of this material to short-duration missions until precise decomposition rates are established. Unalloyed WC and titanium carbide have potential for alternate "hard" seat materials.

"Soft" seats using TFE Teflon are satisfactory when properly designed to minimize "cold" flow effects. TFE is compatible with hydrazine and has no apparent catalytic effect on decomposition. TFE, a fluorocarbon, is more susceptible to radiation than most hydrocarbons. A new elastomer, designated AF-E-102 by the Air Force, seems to offer benefits similar to TFE with improved elasticity and resistance to "cold" flow but no long-term performance data is available. AF-E-102 is a hydrocarbon (Hystl-filled ethylene propylene terpolymer) which should be more radiation resistant than TFE.

(3) Contamination sensitivity: particle generation by abrasion from relative motion between surfaces in the propellant flow path must be avoided. Integral screens, filters, etc., should be incorporated to protect critical areas from any particulate contamination which might be introduced during installation, test, or operation. Cavities which can trap propellant and flushing fluid should be minimized.

(4) Dimensions: envelope and weight will be minimized. The internal ("dribble") volume downstream of the normally closed valve seats will be minimized.

(5) Hermetic seal: all external leak paths and coil cavities will be sealed by welding.

(6) Indicator: all latching valves will incorporate a position (opened and closed) indicator for remote monitoring.

(7) Magnetism: generated magnetic fields will be kept to the lowest level commensurate with required valve performance. Required permanent fields must remain constant or be predictable throughout the valve operational life.

Mission requirements for the Thermoelectric Outer Planet Spacecraft (TOPS) program necessitated two thruster sizes. One thruster with 111 N (25 lbf) output thrust was required for the Trajectory Correction Propulsion Subsystem (TCPS) to provide changes in spacecraft velocity. Sixteen small thrusters with 0.445 N (0.1 lbf) or less output thrust were required for the Attitude Propulsion Subsystem (APS) with eight each in two redundant branches. The baseline configurations for the APS and the TCPS incorporated two types of solenoid-actuated valves in the propellant feedlines; a normally closed (NC) valve for thruster operation and a latching valve for redundant shutoff of the propellant when thruster operation was not required. Some consideration was given to a plan which used the same valves for both thruster sizes, but this approach was abandoned in favor of using smaller APS valves to decrease weight and envelope.

TOPS valve requirements were sent to all known valve vendors to ascertain whether current valve technology could adequately provide the necessary capability. Vendor responses indicated that many existing valves could meet some of the requirements, but no valve was completely satis- factory for flight hardware. Some of the proposed valve designs did offer significant potential for upgrading to flight hardware and some incorporated design features that appeared to have sufficient design margin to justify an attempt to extend operating limits. Representative valves which incorporated desirable design features were obtained for evaluation.

As the result of the industry search, JPL was faced with the need to evaluate a multitude of promising solenoid-actuated valve designs whose only common feature was the operating voltage (28 Vdc nominal). All of the valves could withstand exposure to hydrazine. The designs ranged from those intended specifically for hydrazine control to those that had been used to control gaseous nitrogen (GN_2) for "cold"-gas, attitude-control jets. The objective of the evaluation program was to determine the potential of can- didate valve designs to provide the required performance during long-duration (10 years) missions to the outer planets.

Emphasis was placed on the testing of smaller valves similar to those which could be used on the APS. Experience has shown that smaller valves present the more difficult design problems and that solutions to these problems are usually applicable to larger valve designs. Two other factors were considered in the decision to test the smaller valves.

(1)   Considerable test and flight data for valves in the size range that
      would be needed for the TCPS are available from previous space-
      craft programs. Verification of documented performance and
      extensions to verified operating limits are planned during testing
      by JPL on other flight programs, during TCPS thruster testing,
      and during long-term hydrazine exposure tests.

(2)   Restricting the hydrazine flow rates to the APS range of
      2.5×10^{-4} kg/s (5.5×10^{-4} lbm/sec) would permit the size of
      the flow test setup to be reduced and the resultant compact,
      portable unit could be moved to any desired test area. The flow
      metering was accomplished by a Lee Viscojet, P/N 38VL5,
      which provides the APS flow rate at a pressure drop of approxi-
      mately 2.2×10^6 N/m^2 (300 psid).

A schematic diagram of the hydrazine flow test setup is shown in
Figure 1. The physical arrangement of the setup components is shown in
Figure 2. The test section is shown in Fig. 3. The control panel for the
manual valves is shown in Fig. 4.

The electrical control bench is shown in Fig. 5. The solen   control
box was used to manually switch the latching valves and to monitor valve
position indicators. The recycling timer was used to cycle the latching
valves. The third box is an electronic pulser which was used to cycle the
NC valves.

A schematic diagram of the solenoid control box is shown in Fig. 6.
The mercury switch and oscilloscope connect points were used to determine
opening and closing responses for both latching and normally closed valves.
The integral suppression diodes were used to limit the back EMF when the
latching valve actuation coils were de-energized. Suppression circuits for
the NC valves (Fig. 7) were installed across the external jacks.

The flow test setup was designed and fabricated at JPL. After proof
pressure and leakage tests, the setup was installed in Pit G, a JPL hazard-

ous test facility, where it was inspected and certified by the Propulsion Section safety coordinator. The setup was filled with a solution of 50% hydrazine and 50% water and allowed to passivate for 48 hours. After passivation, the setup was drained and vacuum dried. The setup was then loaded with hydrazine per MIL-P-26536 by filling the catch tank and then transferring the hydrazine to the high-pressure run tank.

II. DISCUSSION AND RESULTS

The test program was conducted per the requirements of Ref. 1. Valves which were tested during the program are listed in Table 1. The results of performance evaluation tests prior to hydrazine exposure were presented in Refs. 2 to 4. Due to the press of time, two valves were cycled without verifying pretest performance. The Marquardt valve, P/N X28051, was delivered late in the program with documented performance during acceptance testing at Marquardt. The Parker valve, P/N 5696050, also was not available until late in the program, due to extended operation during thruster testing. Omission of the pretest performance evaluation allowed the valves to complete the endurance (cycle) test prior to the conclusion of the program.

The photograph of the test section (Fig. 3) was taken at one point early in the program. The number and kinds of valves being tested varied during the program as valves either became available and were added to the setup or testing was completed and the valves were removed. The 15-μm absolute-rated filter, Vacco P/N SI-81847-2, and the Viscojet were not changed during the program. During the test program, a total of six N' and two latching valves were exposed to hydrazine. Exposure durations varied, but all normally closed valves accumulated the maximum number of programmed cycles (250, 000). Exposure durations and the number of cycles for the two latching valves were not related. Both latching valves exceeded normal TOPS operating requirements (2, 000 cycles) with one valve accumulating the maximum number of programmed cycles (25, 000). A summary of exposure durations and accumulated cycles by valve part number is shown in Table 1.

A test plan, which minimized manpower requirements by the utilization of test equipment and operators on a "when available" basis, was established as follows:

(1) Initial test goals of 100,000 cycles for NC valves and 2,000 cycles for the latching valves would be accrued at a rate of approximately 10,000 cycles per week for the NC valves and 200 cycles per week for the latching valves.

(2) The valves would be cycled and response measured with a tank pressure of 2.2×10^6 N/m^2 (300 psig) and a supply voltage of 28 Vdc.

(3) Supply tank pressure during storage periods between cycling would be initially "locked-up" at 1.4×10^6 N/m^2 (200 psig) by closing the manual valve in the pressurization line. Regulated pressure upstream of the valve was then vented to local ambient. Tank pressure was monitored two or three times per day to check for pressure variations between cycle increments.

(4) After completion of the initial goals in June 1971, a decision was made to extend the testing to Dec. 31, 1971, or until the NC valves had accumulated 250,000 cycles.

Valve cycling started on April 6, 1971, and the valves were cycled for three increments before response-measuring equipment and an operator were available to measure opening and closing response. The first signature traces were recorded on April 30, 1971. A dual-beam oscilloscope and a Polaroid camera were used to simultaneously record the transient voltages across the 1-Ω resistor (current trace) and across the solenoid coil (voltage trace) (Fig. 7). Valve opening and closing responses were determined from interpretations of the oscillograph traces as shown in Figs. 7 and 8. A chronological tabulation of measured valve responses is shown in Table 2. Representative traces for opening and closing at the inception and conclusion of the endurance testing are shown in Figs. 9 through 16.

With the exception of the slight increase in opening time for the Carleton latching valve, the recorded responses did not indicate any problems with

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valve performance. The opening response for the Carleton valve increased
from 9.0 ms after 2500 cycles to 10.5 ms after 2700 cycles. These
responses were measured on the same day--before and after being cycled
200 times. Valve performance was monitored for two additional cycle
increments (approximately three weeks), and the opening response appeared
to remain somewhat slower than that demonstrated before accumulating the
2700 cycles. Since the valve had accumulated more than the 2000 cycles
originally programmed, a decision was made to terminate testing of this
valve and use it as a hydrazine shutoff valve in a small thruster test setup.
This usage will provide additional long-term hydrazine exposure data with
only occasional cycling when thrusters are tested. Performance under these
test conditions will be monitored for further eviden.? of degradation.

Two other variances are shown in Table 2. The response values titled
"Pretest" were taken from data accumulated during performance evaluation
testing. These responses were measured with different test conditions and
are included for reference only. The pretest data represents valve response
with 30 Vdc supply voltage, 2.76×10^6 N/in^2 (400 psig) inlet pressure,
and rated (or greater) flows. The consistency of test results should be
determined by comparison of all subsequent data with that recorded on
April 30, 1971. The second anomaly appears in the opening responses for
the Hydraulic Research, Rocketdyne, and Moog valves after 250,000 cycles.
As shown in Table 2, the responses for all valves appear faster than previous
measurements. Close scrutiny of the signature traces indicates that the test
voltage (28 Vdc) was correct, but all valves actuated at current levels which
were lower than previous actuations. Whereas the test logbook does not
indicate a test deviation, the only explanation for the anomaly must involve
test pressure, and an assumption is made that the valve responses were
inadvertently measured at storage pressure, 1.38×10^6 N/m^2 (200 psig),
rather than the specified test pressure of 2.2×10^6 N/m^2 (300 psig).

Hydrazine leakage past the valve seats was not quantitatively measured
during the exposure tests, but a qualitative estimate of "zero" leakage can
be inferred by the constant pressure observed in the supply tank during
storage periods between cycle increments. A pressure loss in the "locked-
up" supply tank would have indicated a leak either past the valve seats or in

the setup plumbing. Since the observed pressures were constant throughout the storage periods, the amount of hydrazine and GN_2 leakage was insignificant. This premise was validated when post-test GN_2 leakage tests failed to detect any internal leakage (less than one scc/hour).

One aspect of the leakage measurements was unexpected. The "hard" seat Hydraulic Research valve had leaked as much as 100 scc of GN_2 per hour prior to hydrazine testing. Liquid leakage at this gas leak rate should not be excessive, so the valve was tested to evaluate the "hard" seat performance capability and to determine equivalent hydrazine leakage. Since the in situ leak detection methods indicated "zero" hydrazine leakage, post-test gas leakage testing was carefully conducted to establish an estimation of allowable gas leakage for a hydrazine valve. The estimation could not be determined, since the post-test leakage measurements indicated that the valve seat was "bubble-tight." The Hydraulic Research valve had accumulated approximately 60,000 cycles during testing with GN_2 by the Spacecraft Control Section prior to being transferred to the Liquid Propulsion Section. Testing by the Spacecraft Control Section had been terminated due to excessive gas leakage of the valve. The evidenced pretest gas leakage was probably due to entrapped or generated particulate contamination which was subsequently either flushed from the seat contact area or dissolved by the hydrazine. Disassembly of the test valve and an identical valve which has only seen GN_2 flow is programmed to further investigate this problem with the "hard" seat concept.

Periodic in situ "blowdown" tests were conducted to ascertain that the valves would still flow hydrazine when opened. With the Viscojet controlling the flow, a decrease in valve seat area could not be detected until the flow area was almost closed. During a hydrazine exposure test at Edwards Test Station, the ethylene propylene rubber (EPR) seal (Parker E-515-8 Compound), in a Wright valve, P/N 15548; S/N 024, swelled sufficiently to prevent any flow through the valve when the armature was actuated. This degree of swelling was not detected during two "blowdown" tests at Pit G; however, the Wright valve P/N 15548; S/N 022, which was tested with an EPR seal, did show a reduced flow rate during post-test performance evaluation. The flow at a differential pressure of 6.89×10^4

N/m^2 (10 psid) had dropped from a pretest value of 1.77×10^{-3} to 4.05×10^{-4} kg/s (3.9×10^{-3} to 8.9×10^{-4} lbm/s) of water or, conversely, the pressure drop at a flowrate of 1.77×10^{-3} kg/s (3.9×10^{-3} lbm/s) of water had increased from 6.89×10^4 to 3.65×10^5 N/m^2 (10 to 53 psid). This cnange in flow area was not evidenced by any of the other valves, including the second Wright valve, S/N 023, which had been modified prior to testing by replacing the EPR seat seal with a seal of "new" Teflon (duPont fluoroelastomer LRV-448).

The evidenced decreases in flow area indicate that EPR should not be used in any seat seal application that involves flow metering of hydrazine. EPR material would be suitable for static applications (O-rings, etc.) when hydrazine decomposition is not a problem. Swelling of the EPR O-rings in the Viscojet may have closed a small bypass leakage path in the housing. The post-test Viscojet calibration indicated a flow rate approximately 7% lower than pretest values. Disassembly of the Viscojet is programmed to inspect internal conditions. The O-ring swelling premise, if validated, will explain variances in the date on similar Viscojets. The Space Division of North American Rockwell Corp. found that a similar Viscojet housing must be torqued to 1.0 m-kg (80 in.-lb) to eliminate bypass leakage and obtain a minimum flow rate. The final calibration for 38VL5 Viscojets by North American Rockwell Corp. also showed flow values that were approximately 7% lower than the JPL pretest calibration. Leakage attributable to inadequate installation torque will not affect flight units, since all bypass flow will ᵇe eliminated by welding the Viscojet capsule into an installation boss. EPR O-rings are used in the present housing for convenience of inspection and cleaning test hardware during evaluation of flow-metering capability.

The first four response measurements (Table 1) for the Marquardt latching valve were made with the integral suppression diodes (Fig. 6) in the circuit. When the traces of Figs. 16 and 17 are compared, the effect from shunting the mutually coupled second coil with a suppression diode when the operating coil is being energized is apparent. Response is slower, and more power is required to actuate the valve. Since this effect was not apparent during testing of the Carleton valve, which also has two coils, an investigation was conducted to determine why the valves reacted differently. The primary difference was traced to the direction of the coil windings. The

coils for the Carleton valve are pre-wound and then inserted in the housing. Routing of the coil lead wires through a common passage requires one coil to be inverted which reverses the winding direction. The Marquardt valve coils are wound on a common bobbin and both are wound in the same direction. A secondary difference can be attributed to the magnetic efficiency (coupling coefficient) which is quite poor in the Carleton design.

Two other dual-coil solenoid valves were studied during the investigation of coil coupling. The shunting effect of the suppression diodes was apparent on both the National Waterlift valve, P/N 3780000 and the Marquardt valve, P/N X22700. These valves had dual coils which were both wound in the same direction; but the coils of the Marquardt valve were pre-wound and the direction could be reversed to verify the difference in coupling due to coil winding direction.

The investigation showed that the effect could be eliminated if a zener diode with a breakdown voltage rating higher than the induced EMF was installed in series with the suppression diode (Fig. 7). If the zener-clipped EMF is higher than allowable, the suppression circuit on the inactive coil must be lifted while the operating coil is being energized.

III. CONCLUSIONS

The flow test setup allows many small propellant feed system components to be simultaneously evaluated at a comparatively low cost. The successful completion of the test program verifies a premise that any component which contains compatible materials will give satisfactory performance in a hydrazine system if protected from external influences. This statement does not include the potential catalytic decomposition of the hydrazine, since this test was not designed to detect small pressure increases over long periods of time. Observation of the storage pressure over periods as long as one month did not disclose significant pressure increases, even though changes as small as 1.38×10^4 N/m^2 (2 psi) could have been detected.

Satisfactory performance for all components indicates that the design requirements which were used as screening criteria are valid for selection of hydrazine feed system components.

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3.   Hagler, R., Solenoid-Actuated Valve Performance Evaluation Tests, IOM 384FS-71-317, March 12, 1971 (JPL internal document).

4.   Hagler, R., Solenoid-Actuated Valve Performance Evaluation Tests, IOM 384FS-71-839, Oct. 6, 1971 (JPL internal document).

Table 1. Solenoid-actuated valve hydrazine exposure/endurance test

Vendor part number	Type	Line, cm (in.)	Date installed	Exposure duration, wk	Cycles	Seat
Carleton 2217-07-2-1	Mechanical latching	0.635 (1/4)	4-2-71	26	3,100	Soft TFE Teflon
Hydraulic Research 39006000	NC	0.635 (1/4)[a]	4-2-71	41	250,000	Hard WC
Marquardt X28051	Magnetic latching	0.318 (1/8)	10-4-71	10	25,000	Soft AF-E-102
Moog 010-58723-1	NC	0.318 (1/8)	12-16-71	5	250,000	Soft TFE Teflon
Parker 5696050	NC	0.635 (1/4)[a]	12-16-71	5	250,000	Soft TFE Teflon
Rocketdyne 409402	NC	0.475 (3/16)	10-4-71	10	250,000	Soft FEP Teflon
Wright 15548	NC	0.318 (1/8)	4-2-71	41	250,000	Soft EPR
Wright 15548 (modified)	NC	0.318 (1/8)	4-2-71	41	250,000	Soft new Teflon

[a]Tested with MS 33656-4 fittings. Flow capability is more consistent with MS 33656-2 size.

Table 2. Signature trace data

Date	Cycles	Wright S/N 22		Wright S/N 23		Hydraulic Research		Carleton	
		Open, ms	Close, ms	Open, ms	Close, ms	Open, ms	Close, ms	Open, ms	Close, ms
1-15-71	Pre-test	6.0	6.0	5.0	11.0	10.0	4.0	8.0	6.0
4-30-71	30,000 700	5.0	7.0	4.5	12.0	6.0	4.0	9.0	6.0
5-6-71	40,000 900	5.0	7.0	4.5	12.0	6.0	4.0	9.0	6.0
5-14-71	50,000 1,100	5.0	7.0	4.5	12.0	6.0	4.0	9.0	6.0
5-17-71	60,000 1,300	5.0	7.0	4.5	12.0	6.0	4.0	9.0	6.0
5-26-71	70,000 1,500	5.0	7.0	4.5	13.0	5.5	4.0	9.0	5.5
6-3-71	80,000 1,700	5.0	7.0	4.5	12.0	5.5	4.0	8.5	6.0
6-9-71	90,000 1,900	5.0	7.0	5.0	12.5	5.5	4.0	9.0	5.5
6-15-71	100,000 2,100	5.0	7.0	4.5	12.0	5.5	4.0	8.5	5.5
7-12-71	110,000 2,300	5.0	7.0	4.5	12.5	6.0	4.0	9.5	6.0
8-6-71	120,000 2,500	5.0	7.0	4.5	12.0	6.0	4.0	9.0	6.0
8-6-71	130,000 2,700	5.5	7.0	4.5	12.5	6.5	4.0	10.5	6.0
8-13-71	140,000 2,900	5.5	7.0	4.5	12.0	6.0	4.0	10.0	6.0
9-1-71	150,000 3,100[a]	5.5	7.0	4.5	12.5	5.5	4.0	10.0	6.0
9-10-71	160,000	5.5	7.0	4.5	12.0	5.5	4.0		

Table 2 contd

Date	Cycles	Wright S/N 22		Wright S/N 23		Hydraulic Research		Rocketdyne		Moog		Parker		TMC	
		Open, ms	Close, ms	Open, ms	Close, ms	Open, ms	Close, ms	Open, ms	Close, ms	Open, ms	Close, ms	Open, ms	Close, ms	Open, ms	Close, ms
10-20-71	170,000 2,500[b]	5.5	7.0	4.5	12.5	5.0	4.0							2.9	2.7
10-21-71	5,000[b] 7,500[b] 10,000[b]													2.9 2.9 2.8	2.7 2.7 2.7
10-25-71	25,000							NG	NG						
10-26-71	50,000							NG	NG						
10-28-71	75,000 10,000							4.0	4.6					2.2	1.9
11-9-71	100,000							4.2	4.5						
12-10-71	25,000									3.6	2.2	6.0	7.2		
12-13-71	50,000									3.7	2.3	6.0	7.2		
12-15-71	75,000									3.7	2.2	6.0	7.4		
12-16-71	100,000									3.6	2.3	6.0	7.4		
1-6-72	170,000[a] 25,000[a]							4.3	4.6	3.7	2.3	6.0	7.6	2.3	2.1
1-11-72	250,000[a]	5.5	6.8	4.6	11.4	4.5	4.0	3.5	4.6	3.3	2.3	6.0	7.4		
1-14-72	250,000[a]														

[a] Test terminated.
[b] Response influenced by suppression circuit.
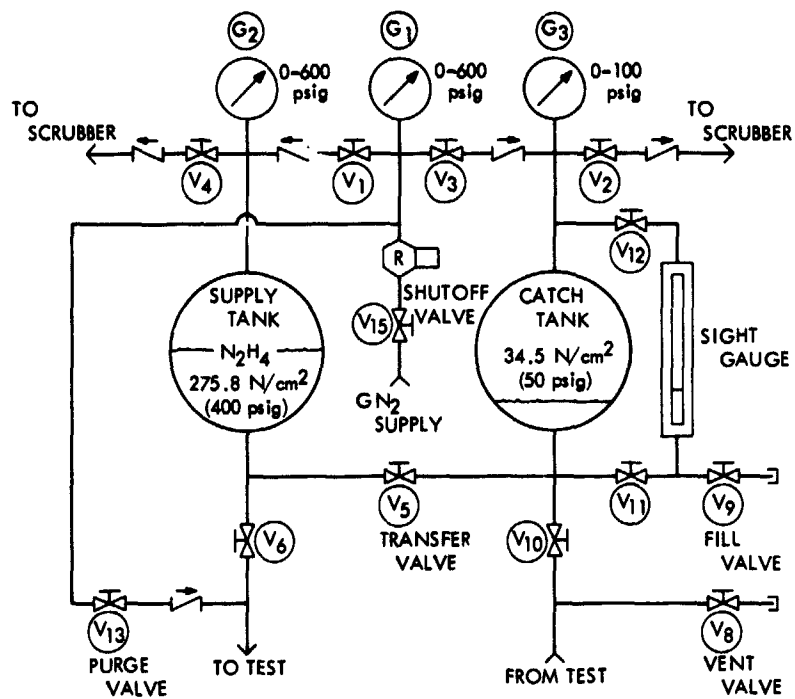
Fig. 1. Hydrazine flow test setup schematic
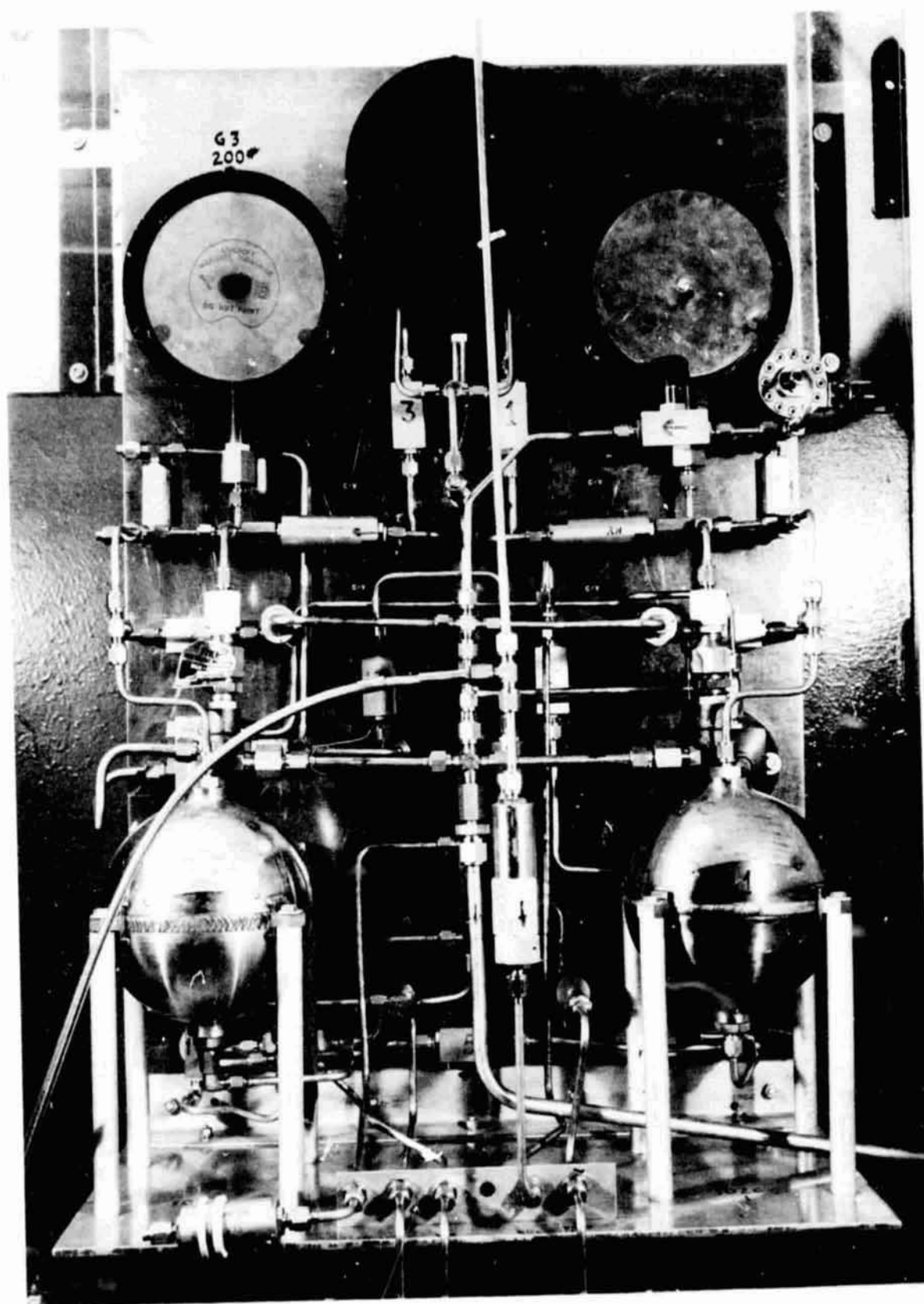
Fig. 2. Flow test setup
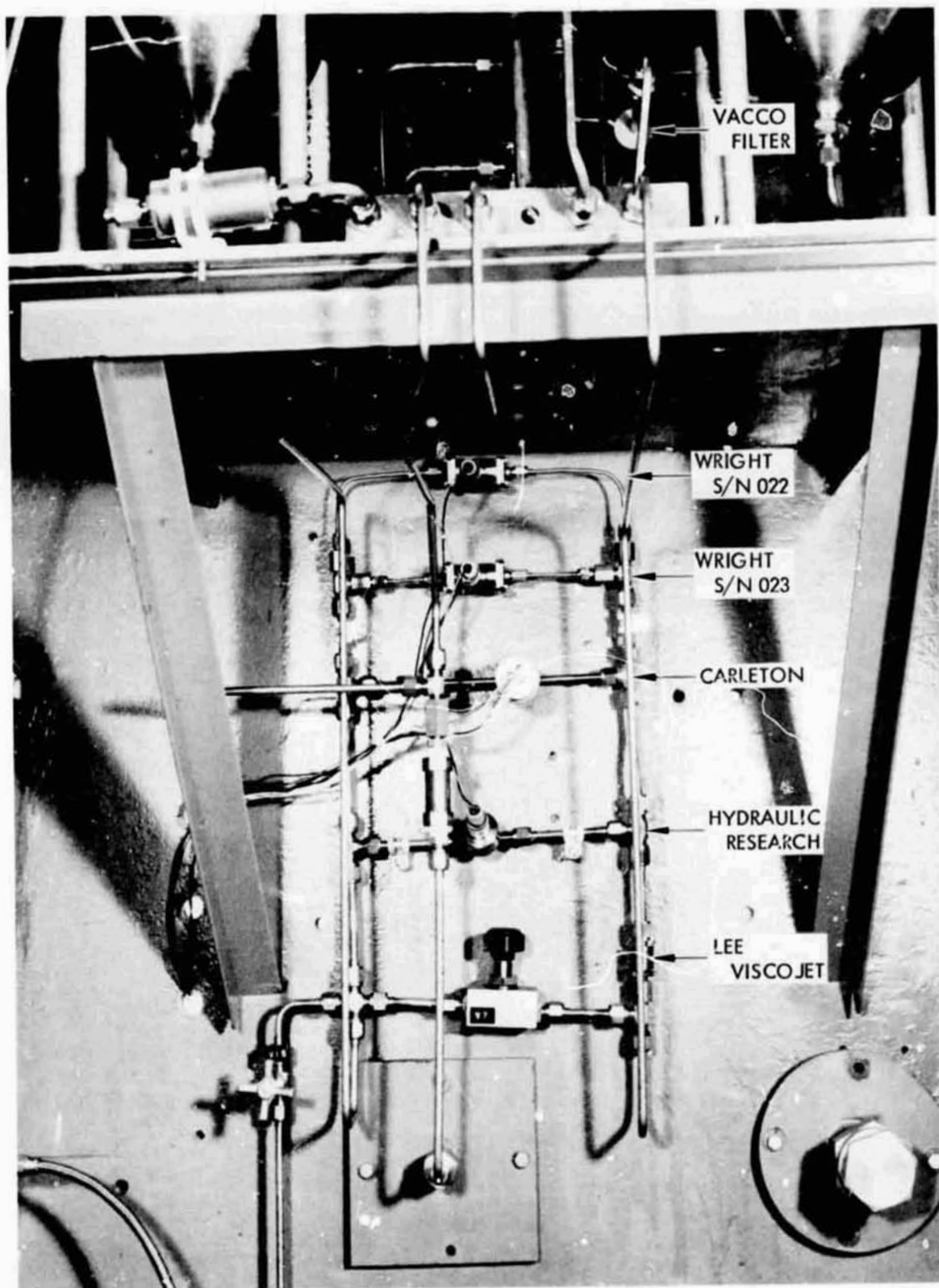
Fig. 3. Flow test components
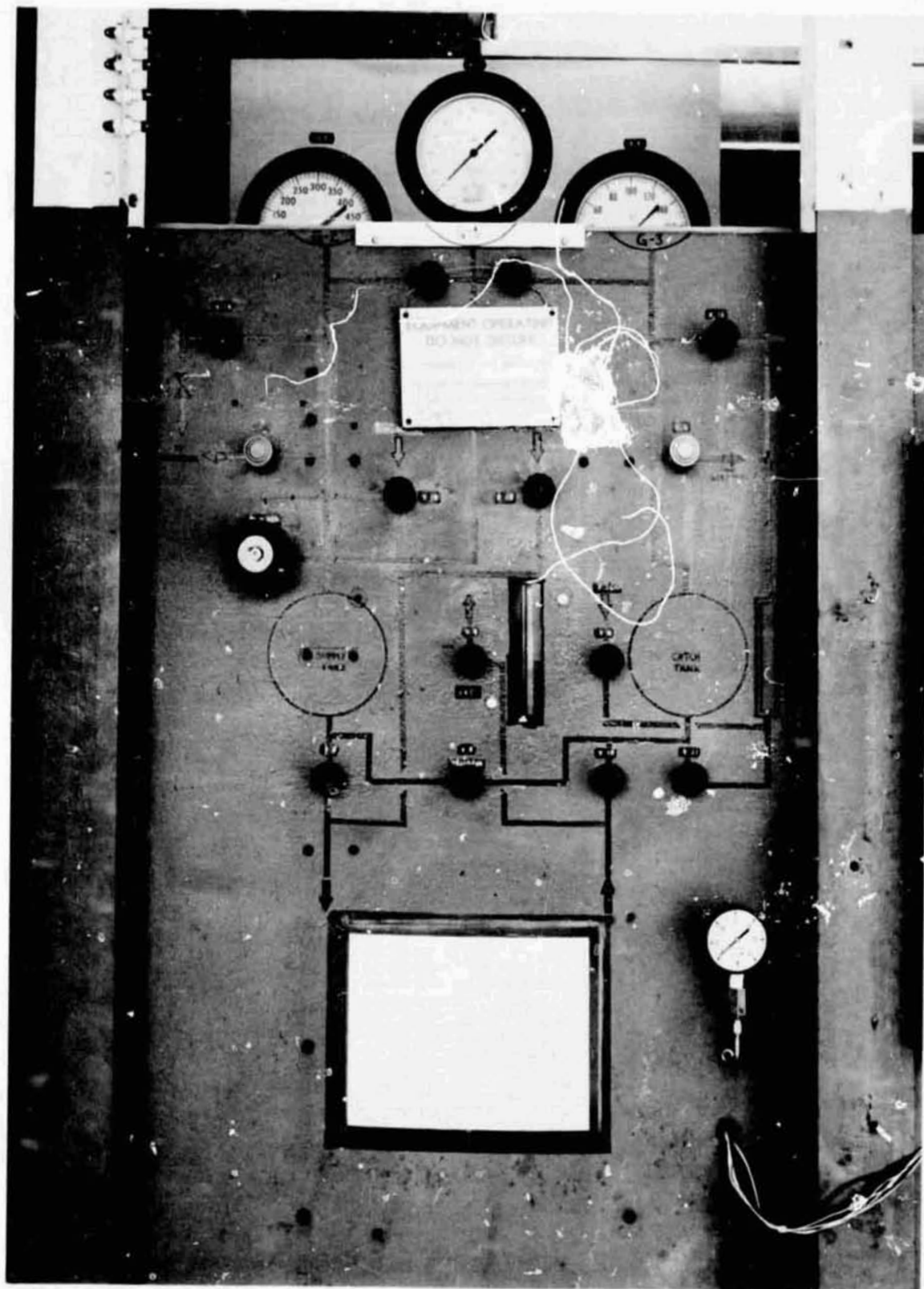
Fig. 4. Flow test control valves
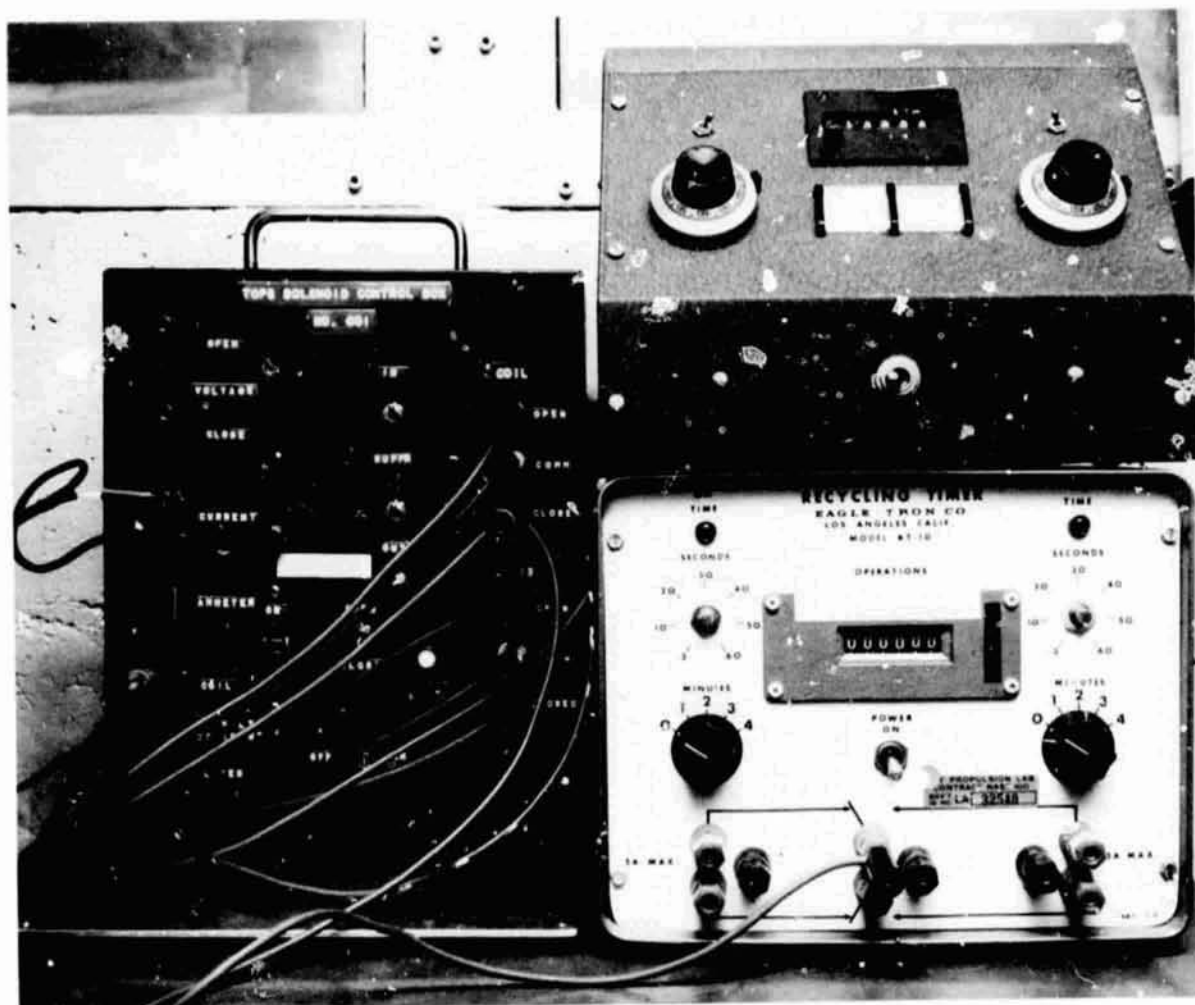
Fig. 5. Flow test electrical controls
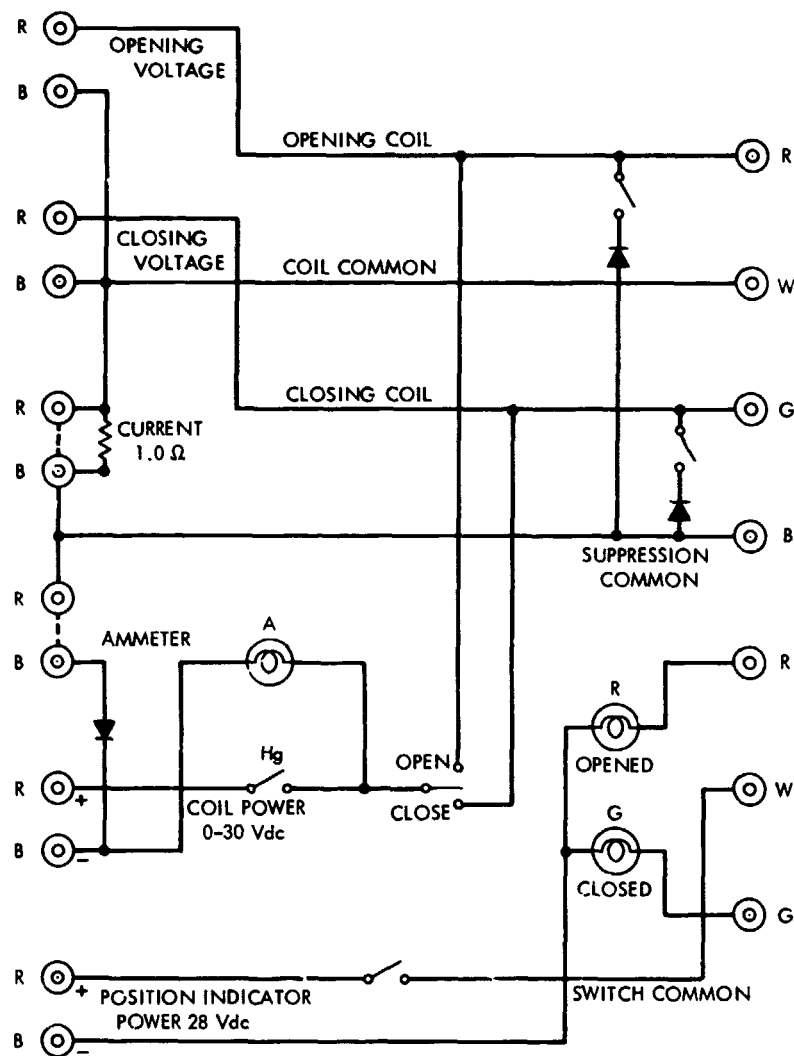
Fig. 6. TOPS bistable solenoid control box

(a) POWER SUPPLY CIRCUIT
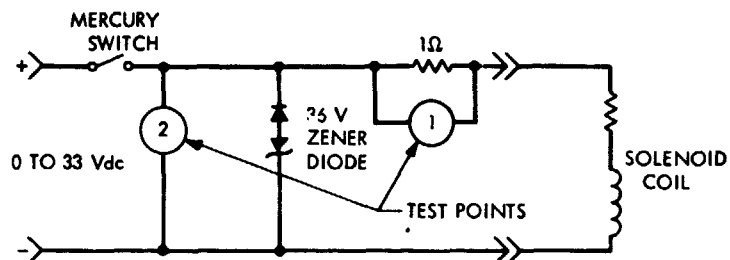
(b) OPENING TRACE (TEST POINT 1)
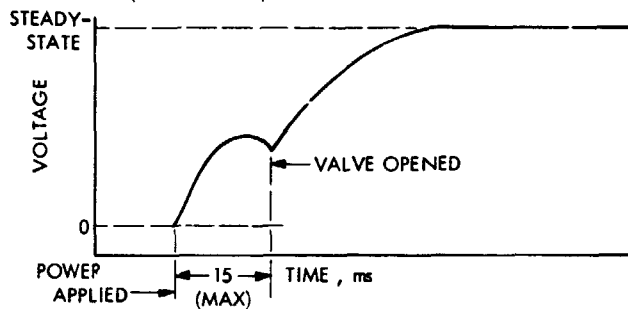
(c) CLOSING TRACE (TEST POINT 2)
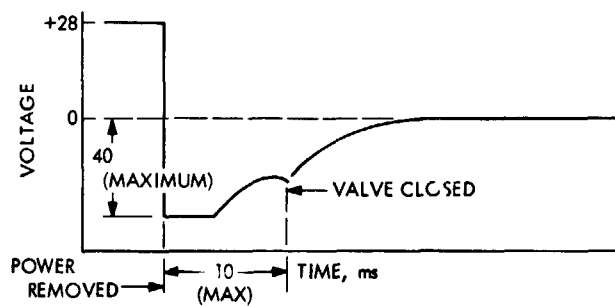
Fig. 7. Normally closed valve performance
determination

(a) POWER SUPPLY CIRCUIT
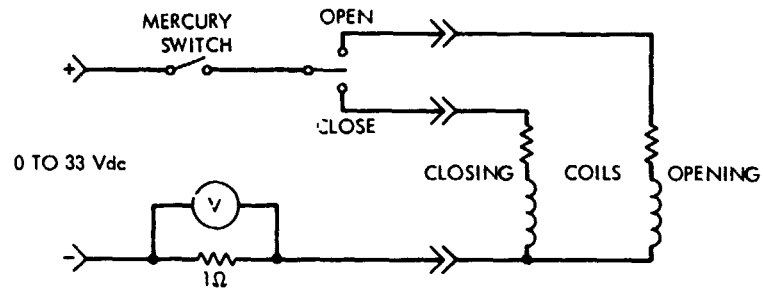
(b) OPENING TRACE (TEST POINT V)
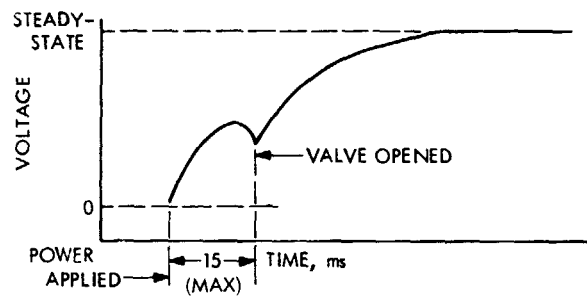
(c) CLOSING TRACE (TEST POINT V)
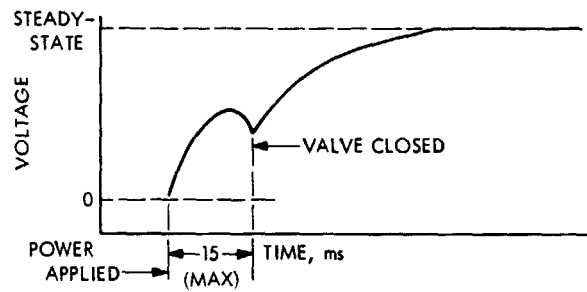
Fig. 8. Latching valve performance
determination
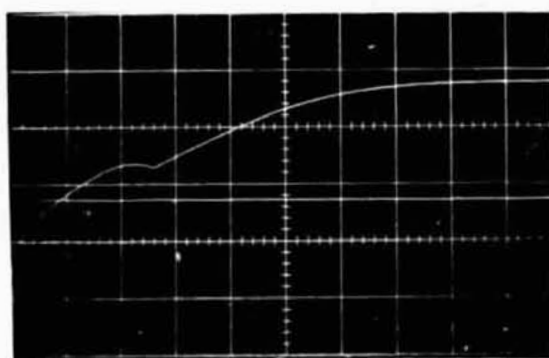
OPEN
30,000 CYCLES
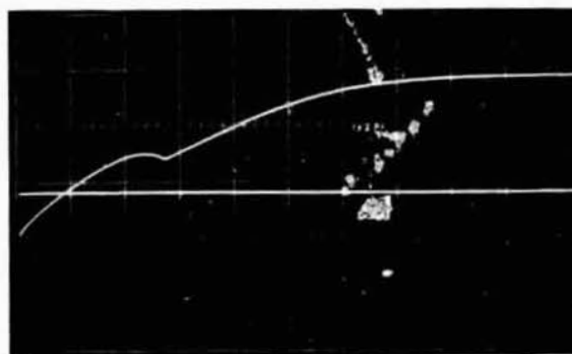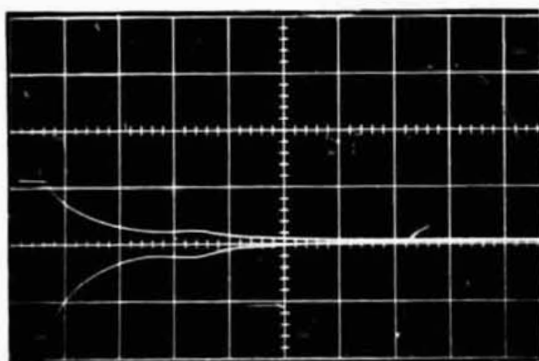
OPEN
250,000 CYCLES
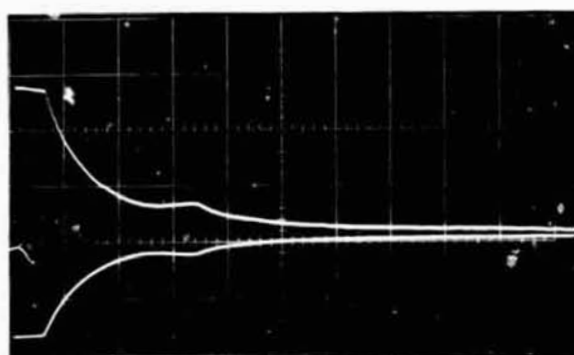
CLOSE
30,000 CYCLES

CLOSE
250,000 CYCLES

1 cm = 2 ms

Fig. 9. Wright valve S/N 022 response

OPEN
30,000 CYCLES

OPEN
250,000 CYCLES

CLOSE
30,000 CYCLES

CLOSE
250,000 CYCLES
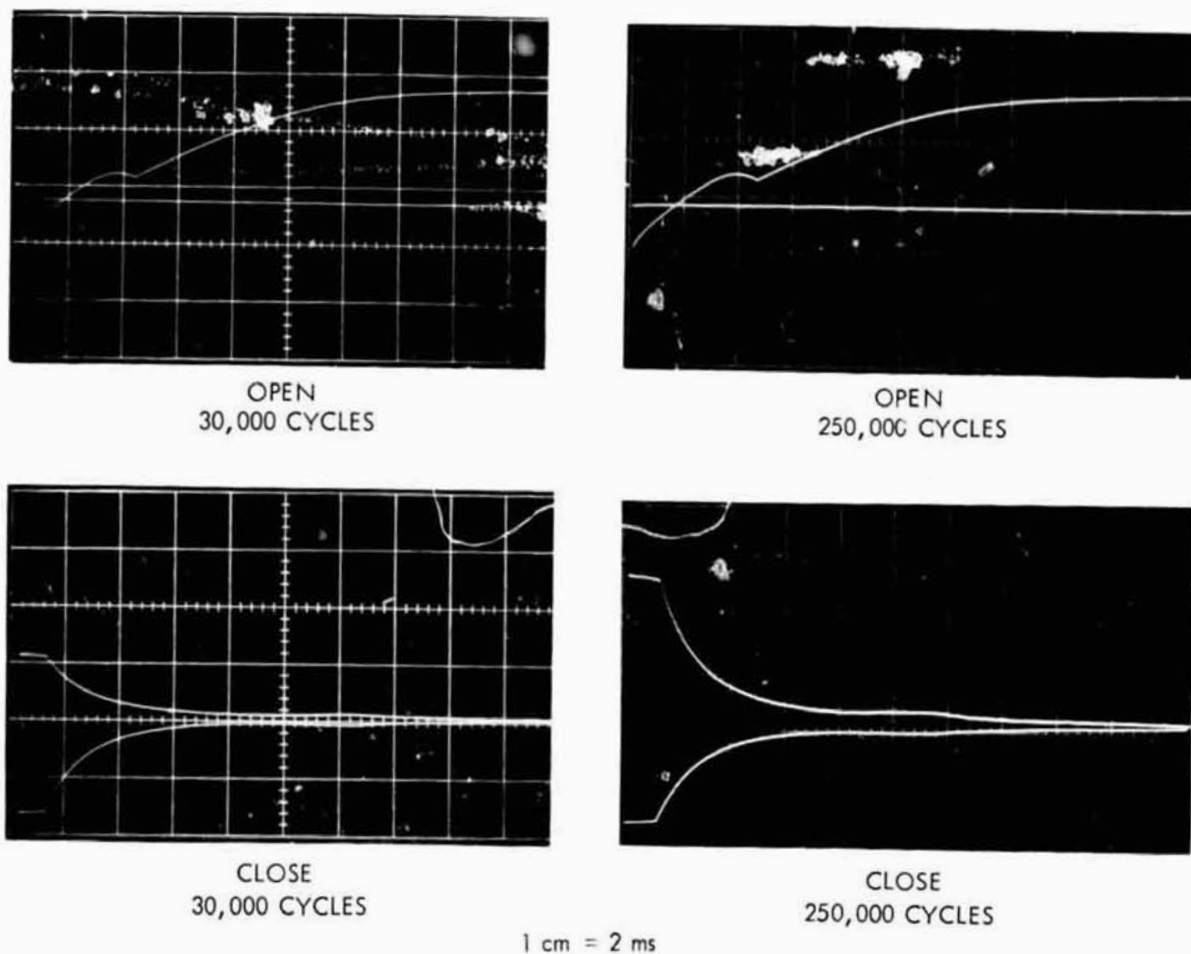
1 cm = 2 ms

Fig. 10.   Wright valve S/N 023 response

24
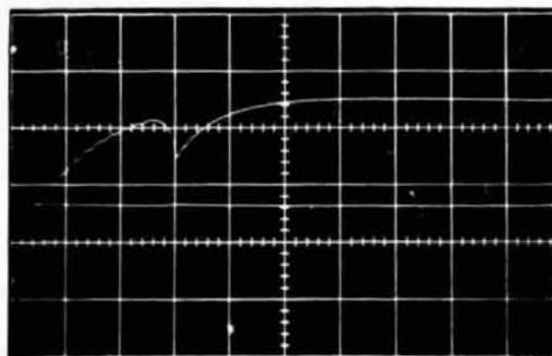
OPEN 30,000 CYCLES
1 cm = 2 ms
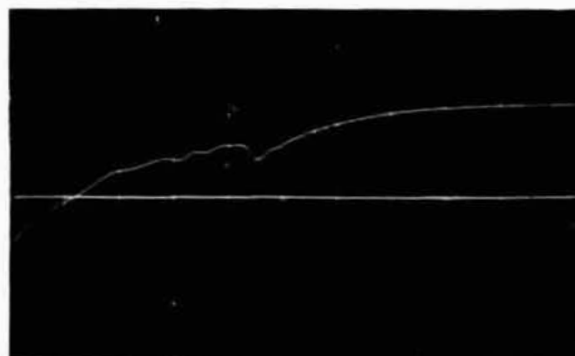
OPEN 250,000 CYCLES
1 cm = 1 ms
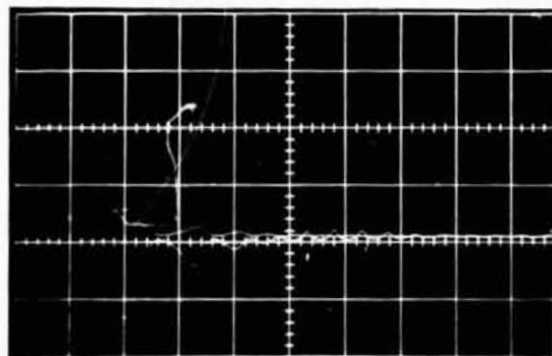
CLOSE 30,000 CYCLES
1 cm = 1 ms
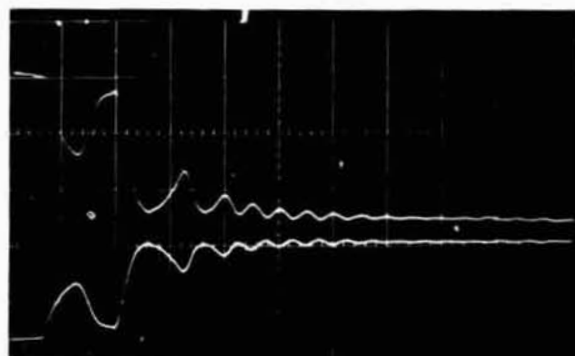
CLOSE 250,000 CYCLES
1 cm = 1 ms

Fig. 11. Hydraulic Research valve response
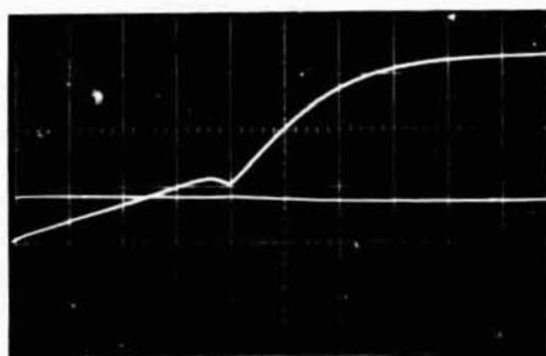
OPEN
75,000 CYCLES
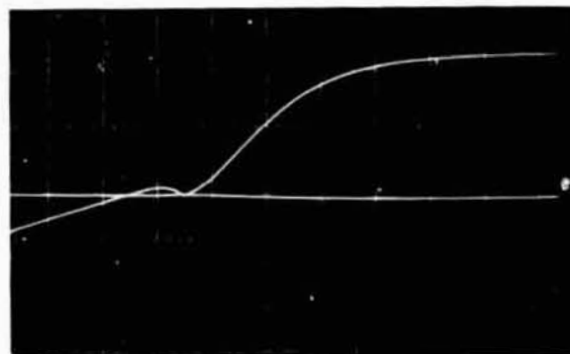
OPEN
250,000 CYCLES
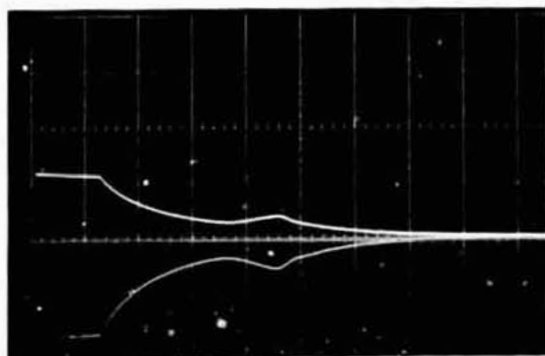
CLOSE
75,000 CYCLES
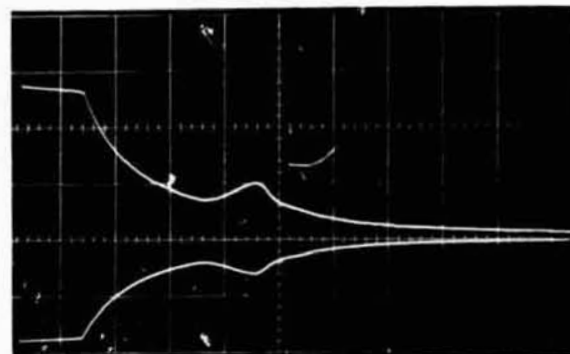
CLOSE
250,000 CYCLES

1 cm = 1 ms

Fig. 12. Rocketdyne valve response

OPEN
25,000 CYCLES

OPEN
250,000 CYCLES

CLOSE
25,000 CYCLES

CLOSE
250,000 CYCLES
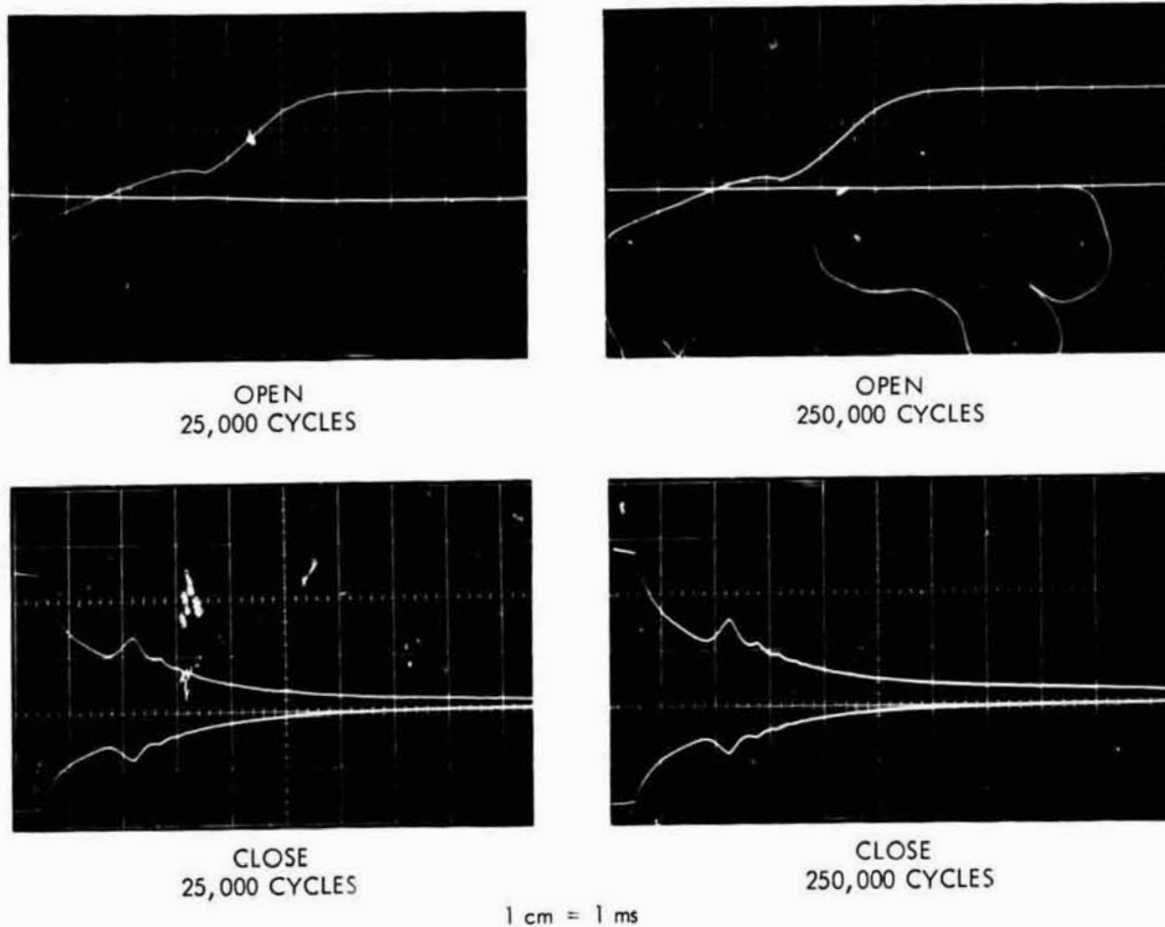
1 cm = 1 ms

Fig. 13. Moog valve response
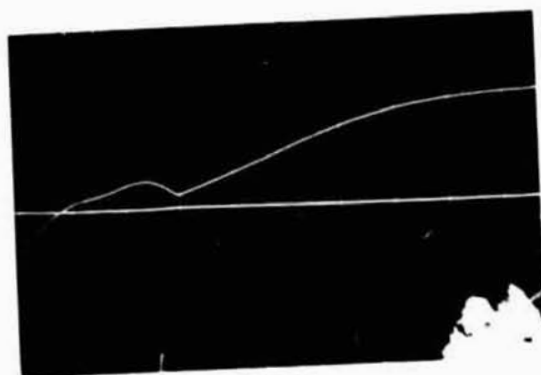
OPEN 25,000 CYCLES
1 cm = 2 ms
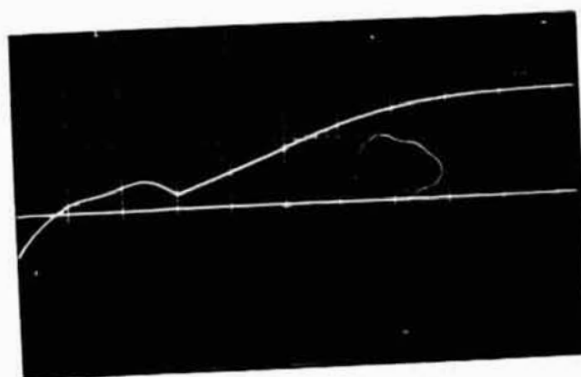
OPEN 250,000 CYCLES
1 cm = 2 ms
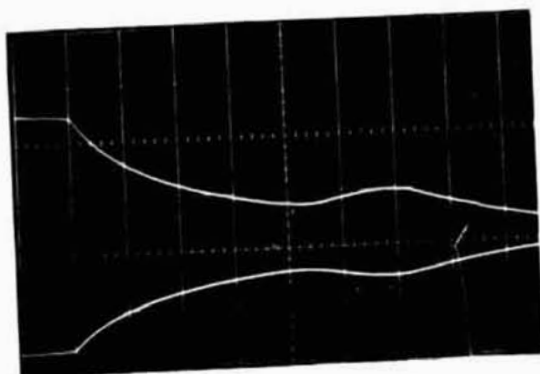
CLOSE 25,000 CYCLES
1 cm = 1 ms
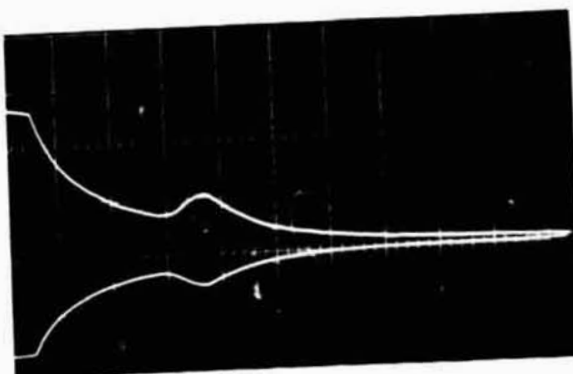
CLOSE 250,000 CYCLES
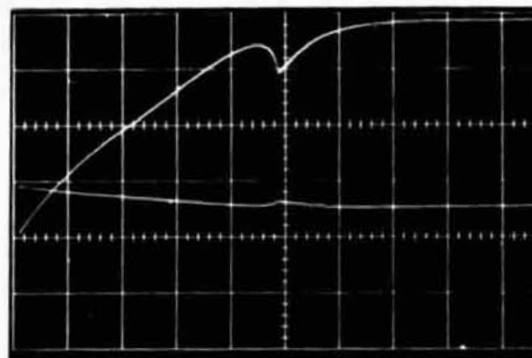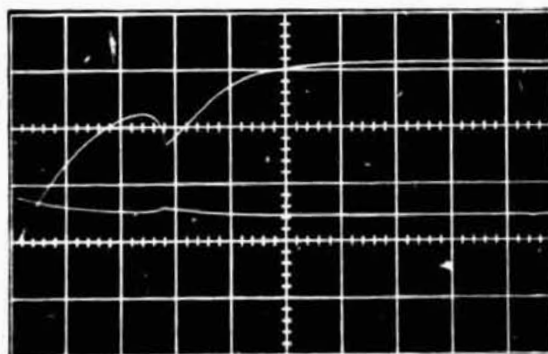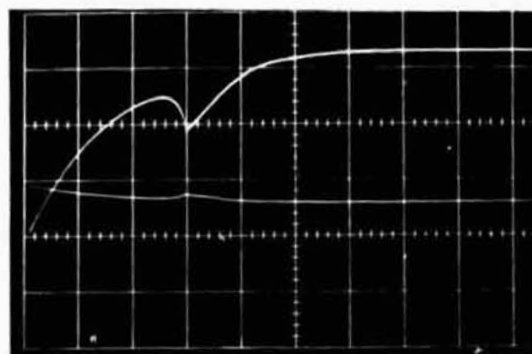1 cm = 2 ms

Fig. 14. Parker valve response
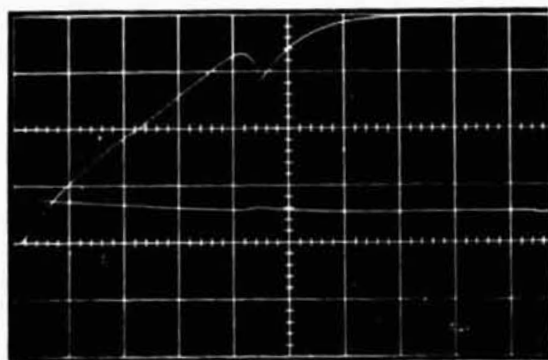
OPEN
700 CYCLES

OPEN
3100 CYCLES

CLOSE
700 CYCLES

CLOSE
3100 CYCLES

1 cm = 2 ms
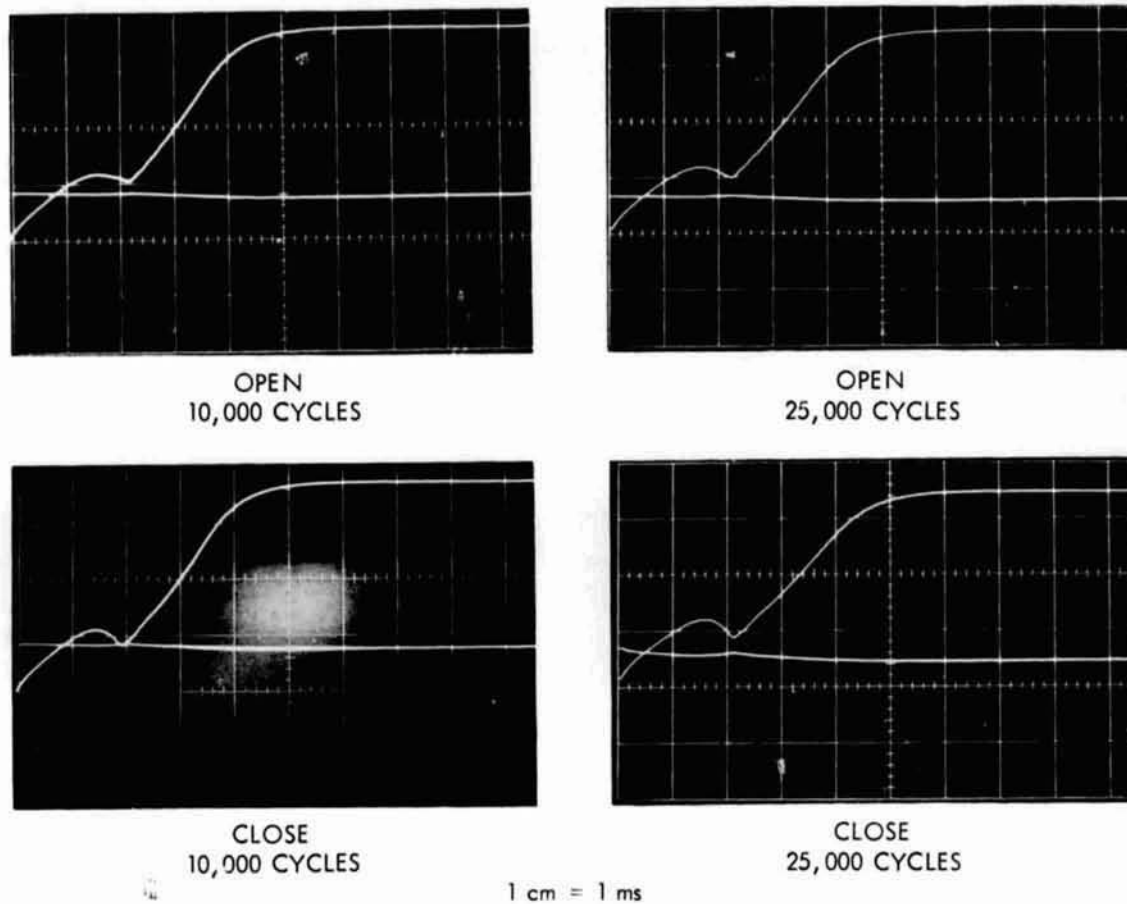
Fig. 15. Carleton latching valve response

OPEN
10,000 CYCLES

OPEN
25,000 CYCLES

CLOSE
10,000 CYCLES

CLOSE
25,000 CYCLES

1 cm = 1 ms

Fig. 16. Marquardt latching valve response (normal)
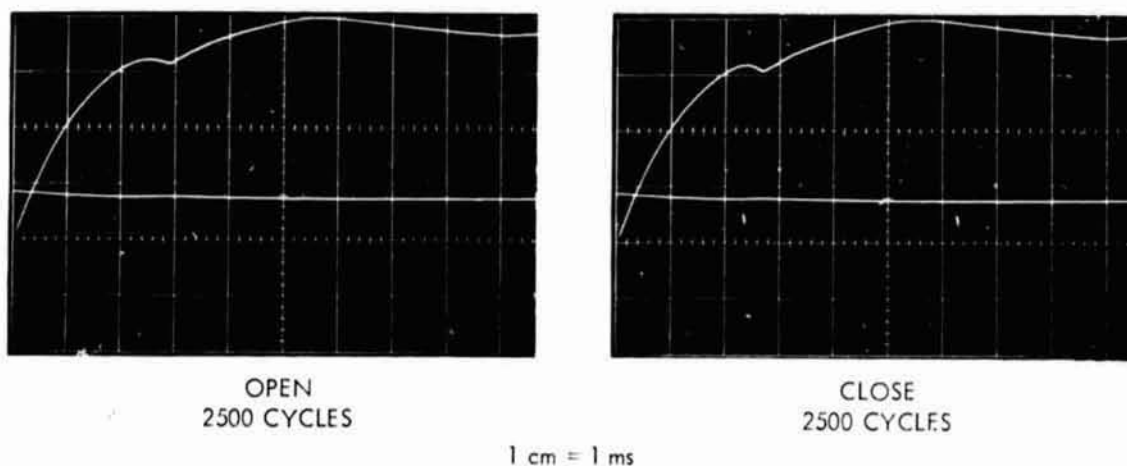

OPEN
2500 CYCLES

CLOSE
2500 CYCLES

1 cm = 1 ms

Fig. 17. Marquardt latching valve response (diode influenced)