17. USE OF COMPUTER MODELING TO INVESTIGATE A DYNAMIC INTERACTION PROBLEM IN THE SKYLAB TACS QUAD-VALVE PACKAGE

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SUMMARY

This paper describes a valve opening-response problem encountered during development of a control valve for the Skylab thruster attitude control system (TACS). The problem involved effects of dynamic interaction among valves in the quad-redundant valve package. Also described is a detailed computer simulation of the quad-valve package that was very helpful in resolving the problem.

ACKNOWLEDGMENT

INTRODUCTION

The Skylab thruster attitude control system was a cold-gas blowdown system using nitrogen as the propellant. Flow to each of the six thrusters was controlled by a quad-redundant valve package, as illustrated by the schematic in Figure 1. A sketch of the Skylab showing the location of the TACS control valves and other components is shown in Figure 2.

The TACS control valve had to be designed to meet a unique combination of requirements that included very low leakage, high flow rates, a wide range of operating pressures and temperatures, capability to operate down to zero pressure, quick response for both opening and closing, limited current draw, and capability to withstand launch vibration loads. The allowable leakage for the valve had to be consistent with the nine-month duration of the Skylab mission and was set at 2 sccm. Since the TACS was a blowdown system, and since it was desirable that all the loaded gas be usable, the valve was required to operate with inlet pressures ranging from O n/m^2 to 2.2×10^4 n/m^2 (0 to 3200 psia). A wide range of operating temperatures -66° to +93° C (-150° to +200° F) was also encountered as a result of the Skylab's solar-inertial attitude, since three of the TACS thrusters were mounted on the solar side of the vehicle

and the other three were on the antisolar side. An opening response requirement of 46 ms was established for compatibility with the control system.

This combination of requirements precluded use of any off-the-shelf valve and led to the design shown in Figure 3. The valve was a pilot-operated solenoid type constructed of stainless steel with integral mounting provisions. A small pilot valve, integral and coaxial with the main poppet, was used to control pressure forces for opening and closing. The pilot poppet and main poppet were linked so that energizing the solenoid coil would create opening forces sufficient for full opening of both poppets at low pressure. In the closed condition, both poppets were pressure-unbalanced closed to assure leak-tight sealing.

Development of this valve was a difficult task, but the process led to some rare insights into operation of this type of component.

VALVE INTERACTION PROBLEM

During development testing, it was found that when four valves were operated in the quad (series-parallel) setup, the opening response of the downstream valves was very erratic, sometimes to the point of not opening at all. The same behavior was observed with two valves in series, but not in single-valve operation.

Figure 4 shows data on valve current and valve outlet pressure (thruster chamber pressure) for an abnormal series-valve opening case. Normal opening data are also shown for comparison. It can be seen that in the abnormal case, the pilot valve opened normally and the main poppet started to open, but then closed. The downstream valve would usually (but not always) open within 100 ms, but since the Skylab control-system computers sent out 50 ms pulses, this delayed opening was unacceptable.

The opening anomaly occurred in about one quarter of the pulses, with the frequency of occurrence varying from one set of valves to another. The frequency appeared to be independent of whether one or both legs of a quad-valve package were operating, but the problem disappeared completely when the upstream valves were held open and the downstream valves were cycled individually. The anomaly was also strongly dependent on pressure, being more prevalent at higher inlet pressures.

The investigation of the erratic opening problem included extensive valve testing under a variety of operating conditions and a detailed examination of several of the valves that exhibited the anomaly. Also, since the problem appeared to involve interactions between the upstream and downstream valves for which no qualitative explanation was evident, it was decided to prepare a computer model of the quad-valve package that would be capable of simulating the motion of all three moving parts in each valve.

COMPUTER MODEL

A block diagram of the TACS valve digital computer model is shown in Figure 5. The model simulated the electrical, mechanical, pneumatic, and body forces on the moving parts (Figure 6) of each valve. The gas-flow model is shown in Figure 7.

The subscripts of the model variables were chosen so that each valve could be modeled to conform to a unique set of design parameters. This permitted investigation of the effects of variations in orifice size, solenoid air gap, piston stroke, etc. from valve to valve.

Real-gas properties were considered using a special subroutine based on Reference 1 to determine the effect of the changing thermodynamic properties on flow rate and compressibility. In regions near the critical point, the real-gas flow rate and compressibility differed from a perfect gas by more than 40 percent.

The nonlinear effects of electromagnetic iron losses, back EMF, and hysteresis were also included in the electrical portion of the model. An electromagnetic circuit algorithm based on methods from Reference 2 was included. The mechanical portion of the model took into account the effects of external acceleration loads as well as sliding friction forces on the motion of the valve parts.

A modified backward-difference extrapolation integration technique was used for all the state variables in the system. A digital algorithm that monitored the mechanical motion of the three valve parts was used to keep these parts within the specified design travel limits for each valve. When a specified travel limit was reached, the program integration was recycled to compute a collision using a specified coefficient of restitution.

RESULTS OF VALVE INVESTIGATION

The valve investigation disclosed two possible causes of the abnormal behavior described above. Testing showed that a small amount of leakage past the lip seal (Figure 6) existed in all valves. It was hypothesized that the pressure surge from opening of the upstream valve caused a cocking of the poppet that could increase this leakage to the point where drainage of the volume behind the main poppet would be too slow to permit immediate opening.

The second possible cause was bending of the small flange attached to the plunger (Figure 8). Disassembly of the valves that exhibited problems showed the downstream valve flange to be bent in all cases. The bent flange would interfere with valve opening, both by reducing pilot valve flow area and by leaving the flow passage through the main poppet open. It was believed that the flanges became bent as a result of a testing procedure in which the downstream valves were held open while the upstream valves were cycled. Under

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this condition, the pressure surge from upstream valve opening would push the main poppet against the flange. This situation could be relieved by adding a stop to prevent the main poppet from contacting the bottom of the flange with the plunger at maximum travel.

Further testing of the valves revealed that the problem could be alleviated by delaying the opening of the upstream valve relative to the downstream valve by 5 to 10 ms. This phenomenon also defied qualitative explanation.

COMPUTER MODEL RESULTS

The computer model was refined until it could accurately predict normal valve operation, as illustrated in Figure 9. It was then used to investigate the effects of lip-seal leakage and bent flanges on valve operation. The model verified that both of these mechanisms could lead to the anomalous behavior observed in tests. Figures 10 and 11 show computer results for single-valve (upstream valve held open) and series-valve operation for a case in which the downstream valve had flange bent back by 0.0203 cm (0.008 inch). Single-valve operation is shown to be normal, but the series-valve results are similar to the data in Figure 4. Figure 12 shows the results of adding a 10-ms delay in upstream valve opening for the case covered by Figure 11. The model predicted that this would allow the downstream valve to open normally.

The data on pneumatic and electrical forces obtained from the computer model provided an apparent explanation for a valve that would not open properly in the series case but functioned normally in the single- and delayed-upstream-valve cases. In the series case, the upstream valve would open first as a result of having a smaller pressure differential across it. This would cause a pressure surge against the downstream main poppet that would push it open before the solenoid current buildup could provide enough force to compress the button spring at the top of the solenoid plunger. The surge on the main poppet would push it away from the plunger flange, thus opening the inlet to the volume upstream of the pilot and concurrently closing the pilot poppet. When this occurred, the pressure inside the volume upstream of the pilot would increase rapidly. The main poppet would then close, and the draining of the volume behind it would be recycled, but this time from the high surge pressure rather than from the initial pressure level. The lip-seal leakage, or the inability to open the pilot fully due to the bent flange, would then delay or prevent main-poppet opening.

In the single-valve and delayed-upstream cases, the simulations showed that the solenoid force would build up to a level where the plunger could complete its movement before the main poppet could move away from it, thus avoiding a pressure buildup in the volume upstream of the pilot that could push the main poppet closed.

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RESOLUTION OF THE PROBLEM

Because of pressing schedules, it was decided to incorporate remedies for both potential problem mechanisms into the valve and also to add a timer to delay upstream-valve opening. A redundant seal was added at the point of suspected lip-seal leakage, and the computer model was used to optimize a poppet stop that would prevent bending of the flange (see Figure 13). Because of tolerance buildup, it was necessary to restrict main-poppet movement severely to assure that the poppet would not contact the flange. This caused concern that the pressure drop across the valve would increase excessively, but the computer model showed that excessive pressure drop would not occur because the main poppet had been only about half open at steady state without the poppet stop (see Figure 14).

After incorporation of these changes, no additional response problems were encountered, and the TACS performed perfectly throughout the 9-month Skylab mission.

CONCLUDING REMARKS

This effort proved the value of detailed computer models in dealing with complex component development problems. The model described here was also useful in resolving a later valve-test problem (in which an upstream valve was damaged by backflow when another thruster was cycled) and in providing flight-performance predictions.

REFERENCES

1. Johnson, A. C., "Real Gas Effects in Critical Flow through Nozzles, and Thermodynamic Properties of Nitrogen and Helium at Pressures to 300×10^5 Newtons/Square Meter," NASA SP-3046, U. S. Government Printing Office, 1968.

2. Rotors, H. C., Electromagnetic Devices, Wiley, New York, 1941.
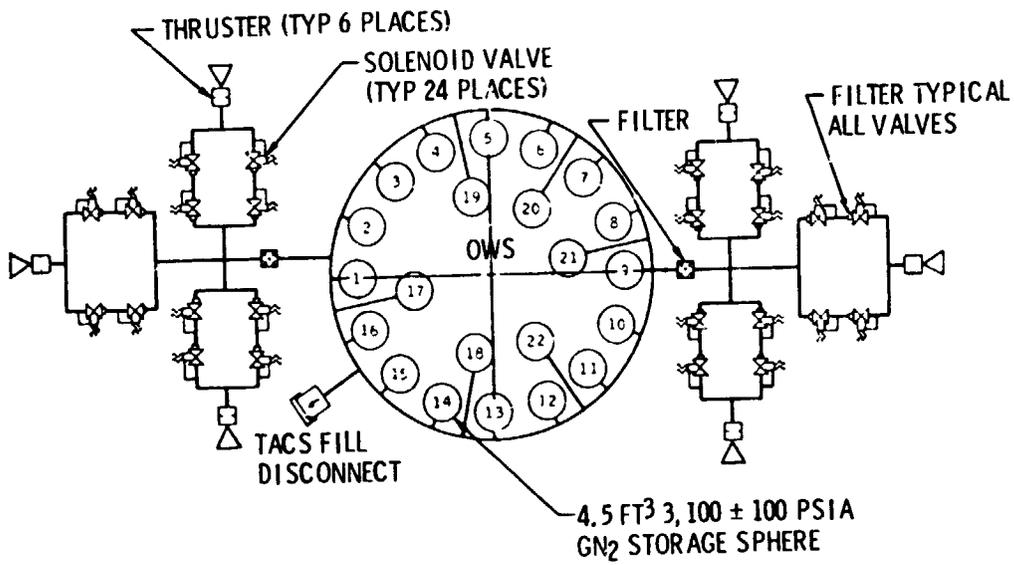
Figure 1. TACS Schematic
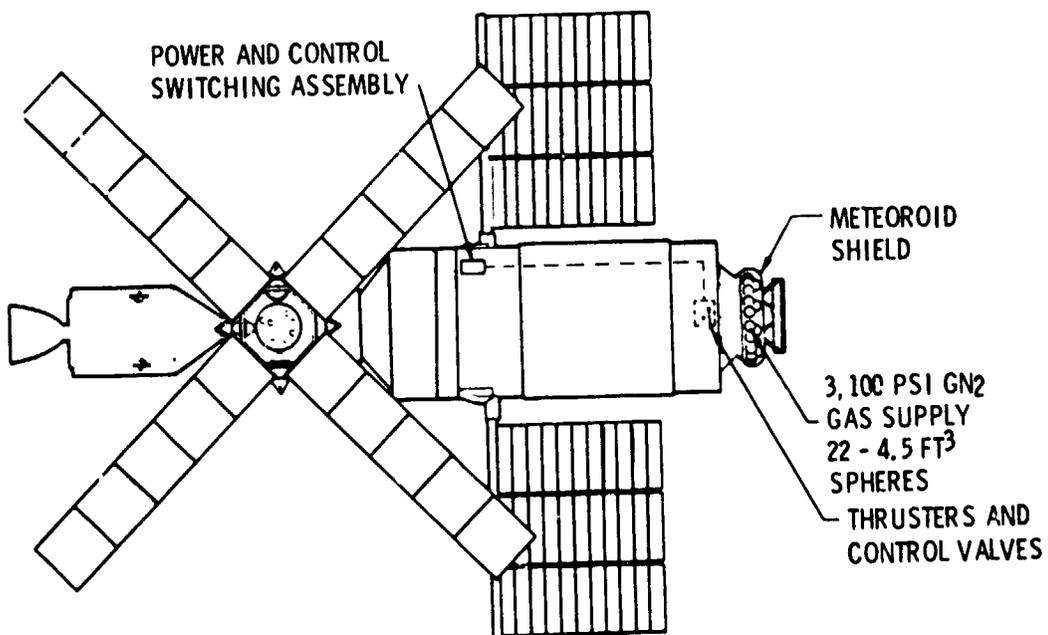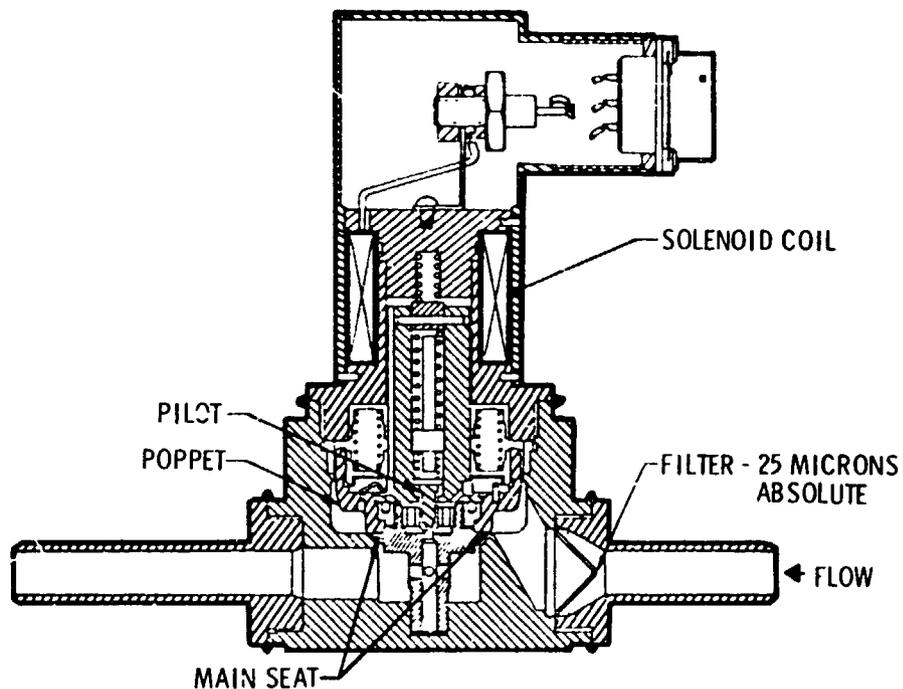

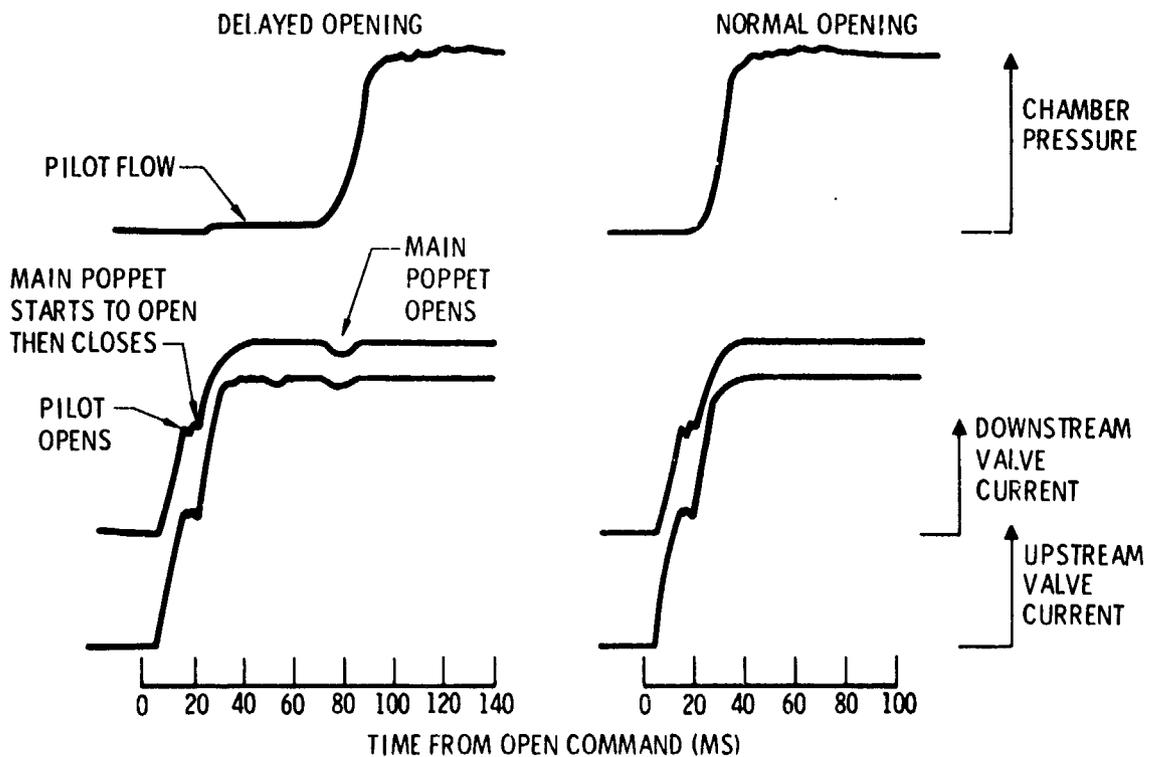Figure 2. TACS Component Locations

Figure 3. TACS Control Valve

TIME FROM OPEN COMMAND (MS)

Figure 4. Valve Response Problem

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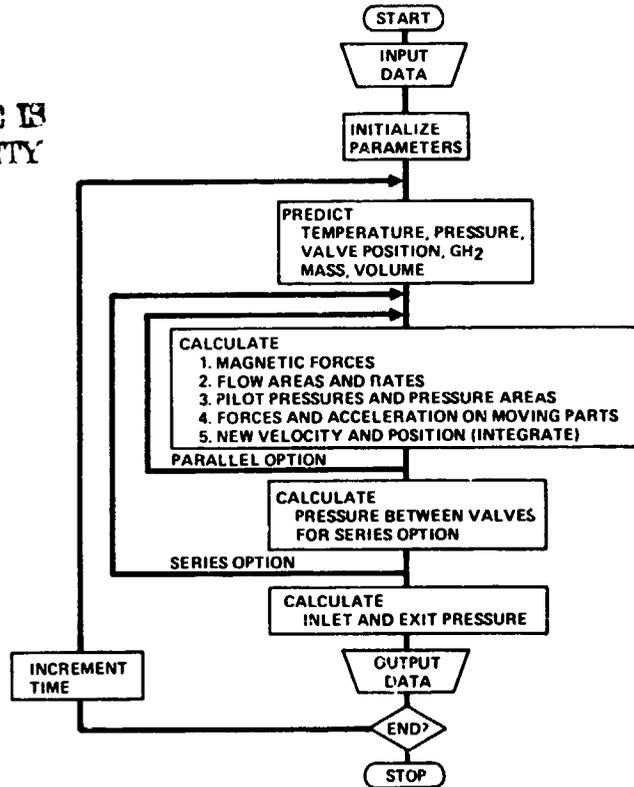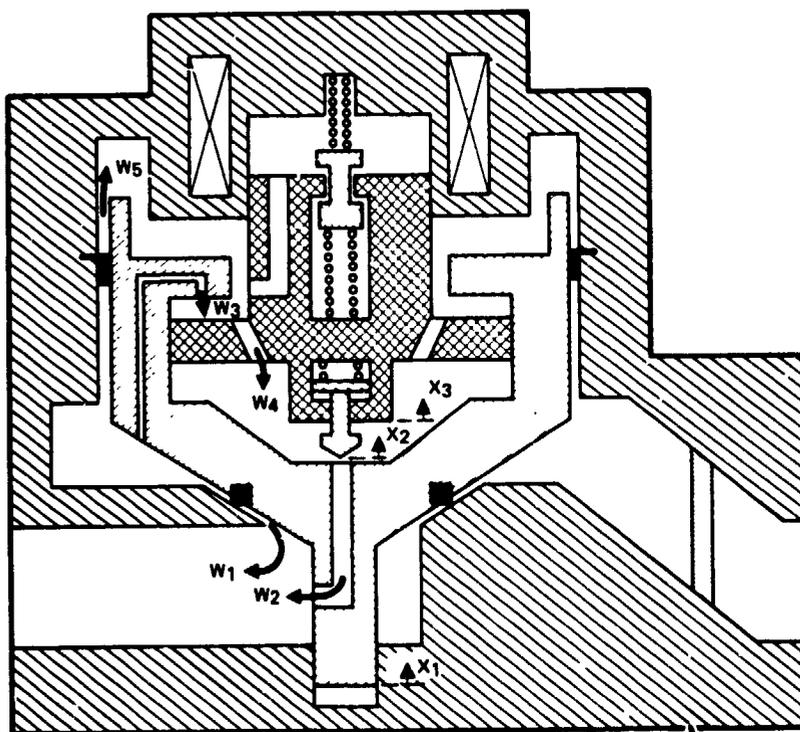
Figure 5. Valve Program Flow Diagram

X₁ = MAIN POPPET MOTION
X₂ = PILOT POPPET MOTION
X₃ = PLUNGER MOTION

W₁ = MAIN FLOW
W₂ = PILOT FLOW
W₃ = FLOW THROUGH MAIN POPPET ORIFICE
W₄ = FLOW THROUGH PLUNGER ORIFICES
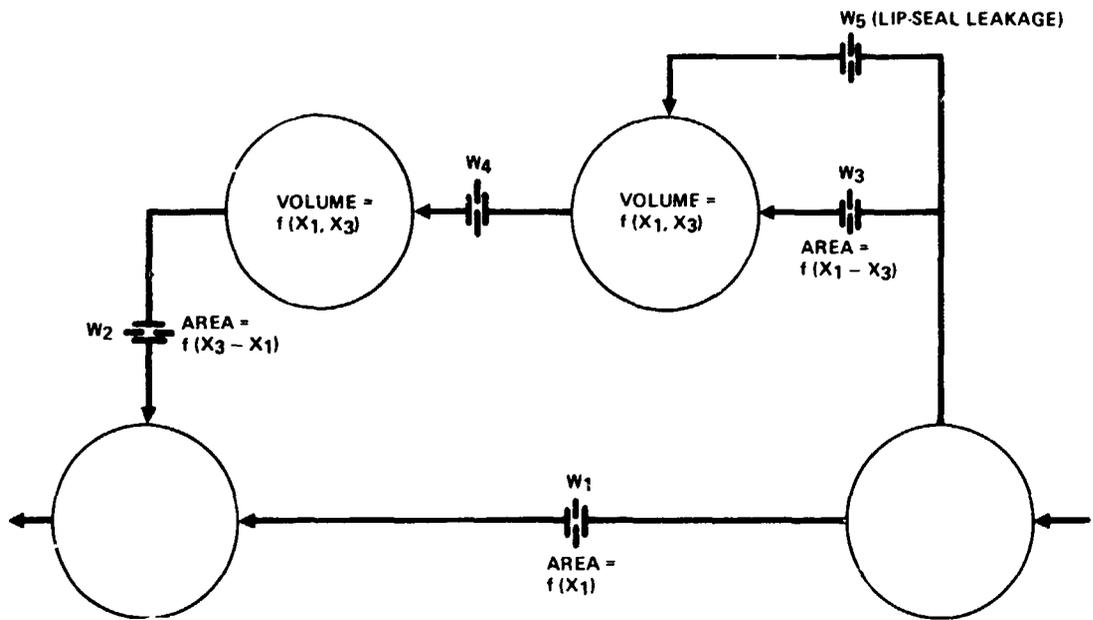W₅ = LIP-SEAL LEAKAGE

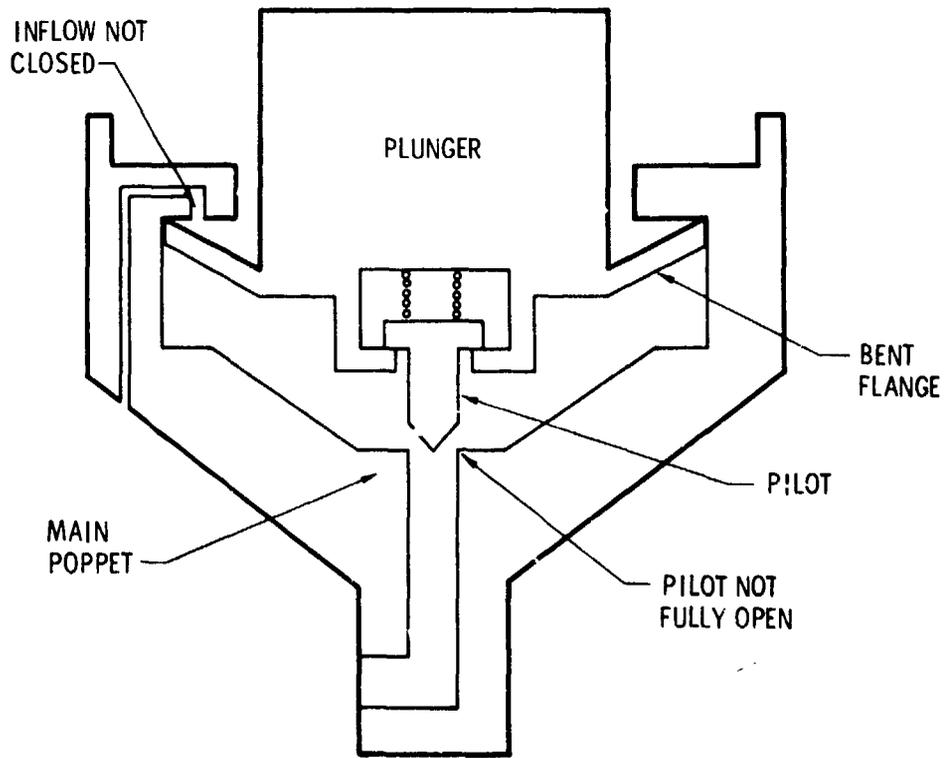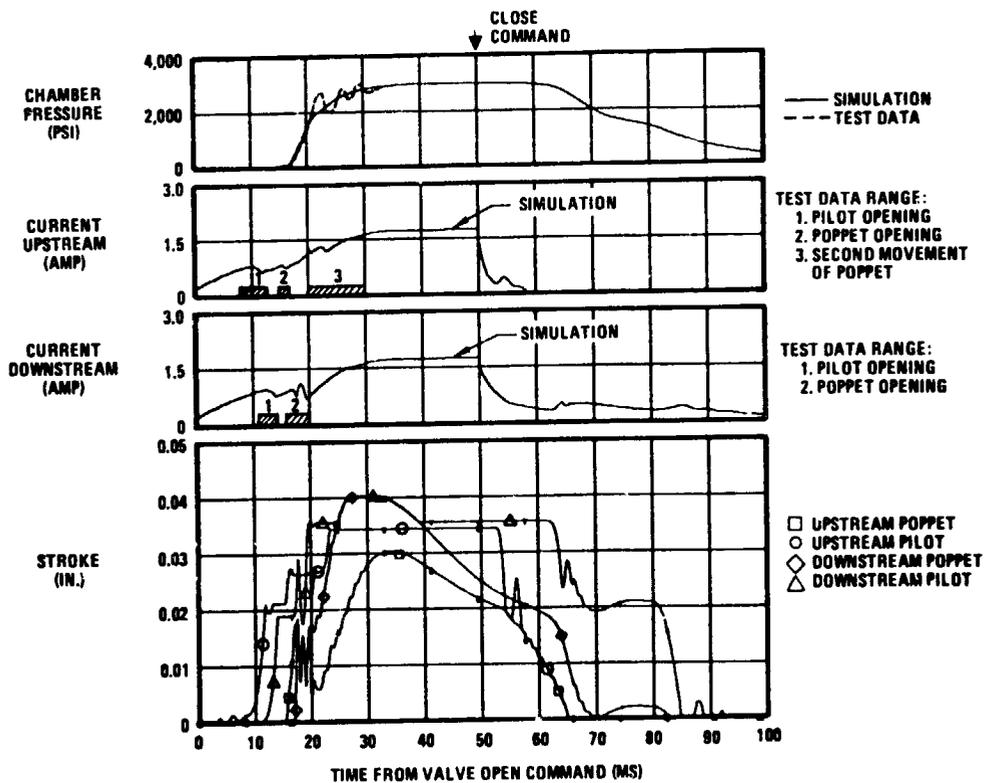Figure 6. Valve Schematic

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Figure 7. Valve Gas-Flow Model

Figure 8. Effects of Bent Flange

Figure 9. Simulation of Normal Quad-Valve Operation
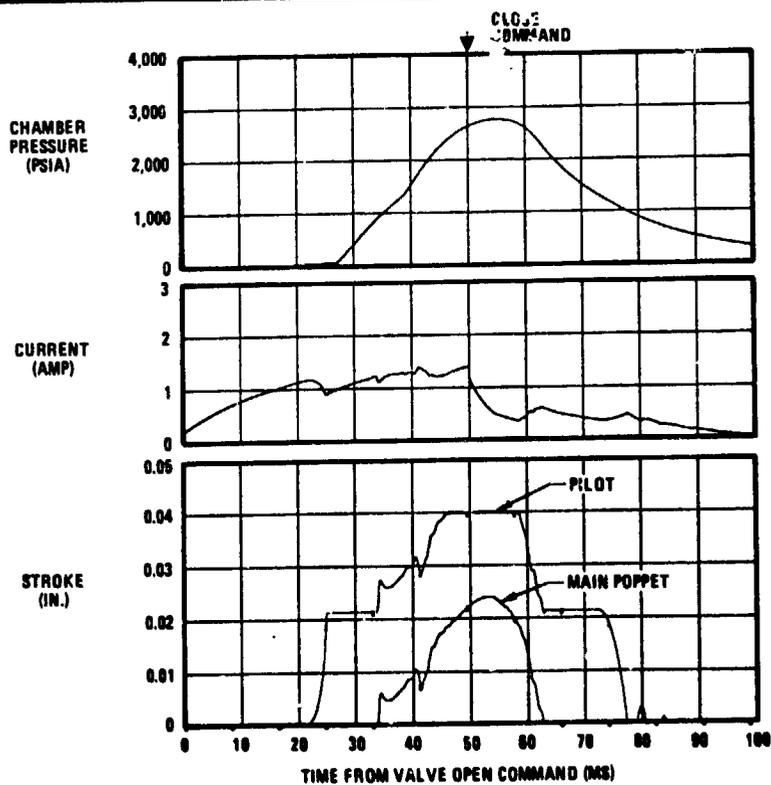
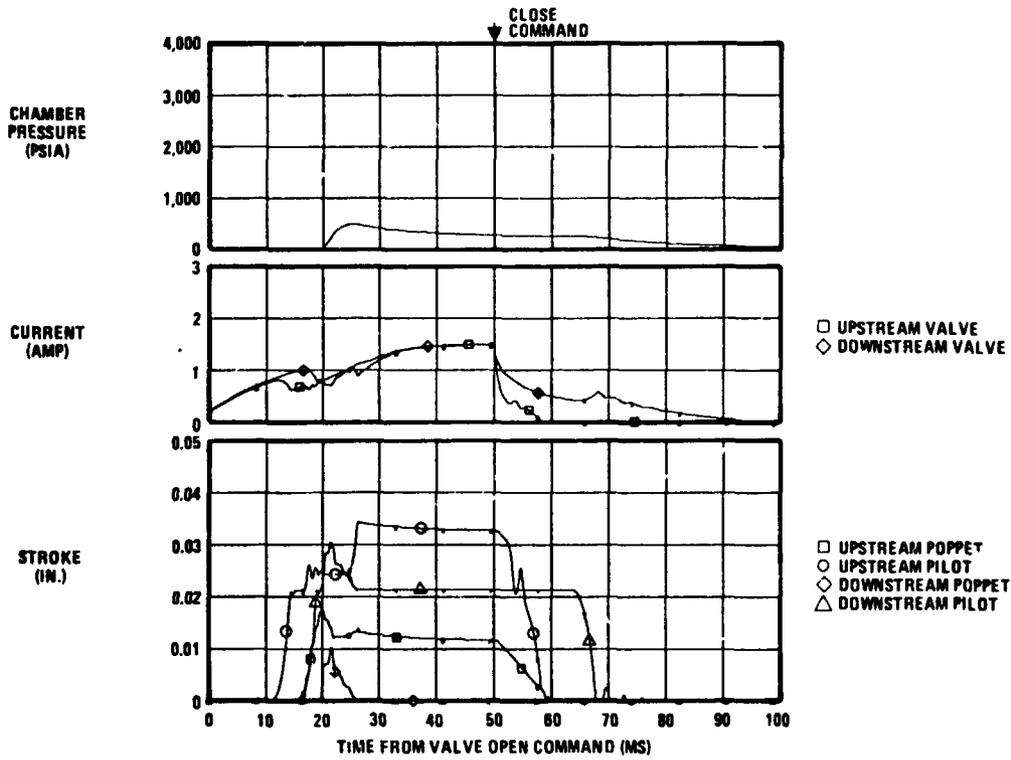**Figure 10. Simulation of Single-Valve Operation with Bent Flange**

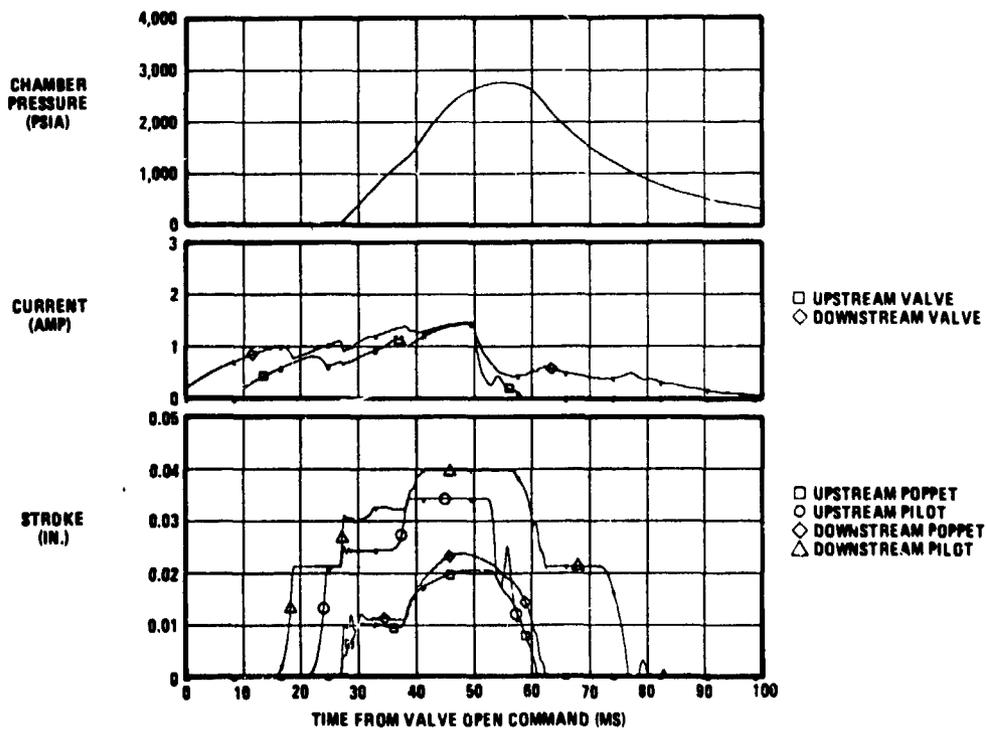Figure 11. Simulation of Dual-Valve Operation with Bent Flange in Downstream Valve

Figure 12. Simulation of Dual-Valve Operation with Bent Flange in Downstream Valve
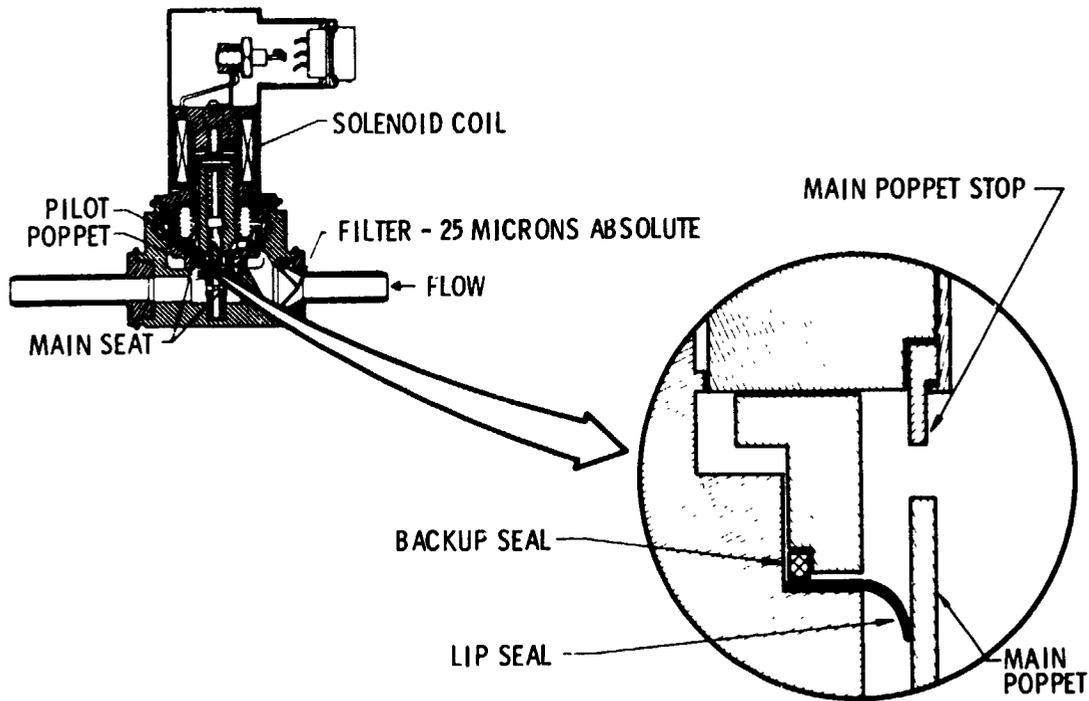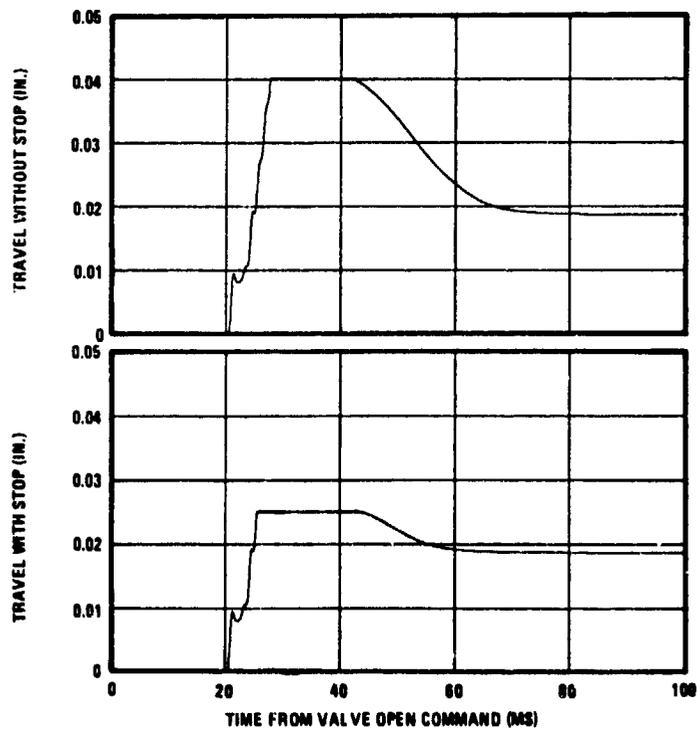and Delay of Upstream Valve Opening

Figure 13. Valve Modifications

Figure 14. Main Poppet Travel With and Without Poppet Stop