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THE DEVELOPMENT OF SERVOVALVES WITH IMPROVED RELIABILITY FOR SPACE VEHICLES

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ABSTRACT

Considerations for improvement in the reliability of the Saturn engine gimbal servosystems are briefly covered. The Saturn I servovalves operate with increased electrical input power. The Saturn V vehicle stages will use mechanical feedback actuators with increased electrical input power, larger orifices and nozzle sizes, larger torque motor wire size, and greater spool driving forces.

Further considerations for improvement in system reliability led to the development of servovalves with improved reliability. The primary objective was to develop servovalves that have a higher reliability factor by increasing electrical input power and minimizing sensitivity to fluid contamination. Two different approaches were taken; in the first approach, a conventional two stage, double nozzle flapper electrohydraulic servovalve with mechanical feedback from the spool position was used. Methods for optimizing the characteristics effecting the reliability are shown and the test results are given for the optimized functional model. In addition to being built for use on an electrical feedback actuator, the valve was modified to show that it was designed with sufficient power for its operation on a mechanical feedback actuator. The second approach is also a two stage mechanical feedback servovalve; however, the hydraulic amplifier in this case is of the jet pipe receiver design. The study began with a theoretical analysis of the conventional state-of-the-art servovalves and selection of the jet pipe as offering the greatest potential for high reliability. The study then progressed to a series of test fixtures and breadboard hardware to evaluate the optimized design, which through further development resulted in a functional model. The functional model characteristics are presented.

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INTRODUCTION

The commitment to a manned lunar landing in this decade did not provide a great deal of development time to make a significant improvement in the reliability of state-of-the-art hydraulic servosystem components. The space vehicle designers, therefore, expeditiously explored every means to achieve maximum reliability since the lives of the Apollo astronauts, the tremendous cost of each vehicle, and the prestige of the nation were at stake.

The redundant feature of clustered engines in the Saturn first and second stages, with an independent hydraulic system for each gimbaled engine, was the first step toward achieving the goal of maximum reliability. With a failure of one engine or the control of one engine, satisfactory vehicle control can still be maintained by the proper sizing of the engine swivel range.

Redundancy Considerations

To further improve the reliability of the Saturn V vehicle, redundancy of the hydraulic gimbal system was considered. However, it was realized that the premature and careless use of redundant design could result in little or no improvement in reliability but could actually degrade reliability.

Saturn will have limited redundant implementation in the control system electronics (control computer). Triple modular redundancy is used for those portions of the control computer that have a long mission use time (i.e., in excess of 10 minutes). This specifically includes the electronics for the spatial attitude control system during S-IVB coast and for the gimbal control of the single engine of the S-IVB stage which is restarted after coast.

Limited redundant design of the hydraulic servovalve compatible with the S-IVB electronics is being investigated. Further implementation of redundant design is not feasible. The increased weight penalty of further implementation would result in too great a loss of payload. The complexity of the redundant system would also present additional checkout complexities. All the adverse side effects and trade-off penalties were considered. The redundant feature of the clustered engine stages and the other considerations mentioned did not justify the development of a more redundant hydraulic gimbal system.

To further improve the reliability of the servosystem, the Marshall Space Flight Center directed its effort to optimizing the reliability of critical components Preferably, any possible failure should be eliminated by improved design, and the utilization of redundancy techniques should only be considered when necessary to obtain the required reliability.

Statistics show that the most unreliable components in the actuator are the feedback potentiometer and the servovalve. Futile attempts were made to develop a more reliable electrical feedback transducer. The dc wirewound potentiometer gave way to the conductive plastic potentiometer. The pure ac linear variable differential transformer, the dc to dc linear variable differential transformer, and other types of potentiometers were investigated.

Mechanical Feedback Actuation

The successful development and use of a mechanical feedback system by the Martin Marietta Corp. and Moog Servocontrols, Inc., prompted an evaluation of electrical versus mechanical feedback actuators. Studies showed that a significant improvement in reliability could be obtained with the use of mechanical feedback actuators. Their use in other programs verifies their dependability. With the mechanical feedback actuator, the number of electrical wires could be reduced (a change from 6 to 2) by eliminating the feedback transducer wiring. Since the actuator and the control computer are remote from each other in the vehicle, the number of solder joints and connections at each interface could be reduced approximately 67 percent. The feedback amplifiers and the summing network in the control computer could be eliminated. The potentiometer power supplies could also be eliminated. The potentiometer itself, which is sensitive to shock, vibration, wear, and moisture, could be eliminated. The mechanical feedback design also provides the fail-safe feature of actuator centering in event of an electrical failure.

The results of the evaluation were conclusive and the choice of the mechanical feedback system was made for the S-II, S-IVB, and S-IC Saturn stages. The potentiometer was eliminated from the system.

Servovalve Improvement

The other critical component in the actuator was the servovalve. MSFC had already taken steps on Saturn I to improve the reliability of this component. The electrical input power had been raised to 225 percent (i.e., 8 to 12 mA into 1000-ohm coils). Rigid fluid-contamination control procedures were established with SAE-ASTM maximum levels verified by the ARP-598 procedure. Control and certification of the servoactuator filter were also required from the vendor on each actuator. To further improve the servovalve, MSFC initiated studies for the development of a servovalve of improved reliability. These studies were to consider present day servosystem capability and to improve reliability through the use of more input power, weight, and larger envelope and by reducing the servovalve's complexity and sensitivity to contaminants.

SERVOVALVE STUDY

History and Background

The present state-of-the-art servovalves are at least in part influenced by concepts and design evaluation which were established more than a decade ago. Some of these concepts which today are still propagated in valve designs are:

1. Small size and weight - Early applications placed extreme emphasis on minimum size and weight. Relative importance of these parameters is now giving way to the preference for higher reliability with the application of the large manned space boosters.

2. Low electrical input power - A "standard" of 0.032 watts of control power (i.e., 8 mA differential current with 1000-ohm coils) was established because of its compatibility with the early tube-type amplifiers.

3. Minimum leakage - This requirement is an effect of attempts to maintain small size and weight. Better assessments of current state of the art coupled with the significant reliability advantages of higher valve leakage are recommended.

4. Maximum frequency response - To achieve this requirement, the servovalve is designed with extensive reliability compromises. Paradoxically, only the isolated and very special control systems require a wide bandwidth.

Contemporary Servovalve Designs

Current servovalve designs utilize concepts and techniques that perpetuate this emphasis on minimum size and weight. Industry standards on input power continue as an outgrowth of early vacuum tube capability and do not take full advantage of transistorized circuit technology.

In addition to these important physical restrictions influencing servovalve design, the performance parameters of total leakage and frequency response, if specified beyond reasonable limits, also require a compromise with reliability.

These four requirements have influenced servovalve design and development and have dictated the use of the following:

1. Small nozzles and orifices.
2. Circuitous, sometimes blind, and occasionally plugged, fluid passages.
3. Minimum size high precision parts.
4. Reduced factors for safety and minimum mechanical integrity.
5. Small diameter coil wire.
6. Ten micron nominal fluid filtration.
7. Minimum spool diameters.
8. Two-stage configuration.

Higher Reliability Concepts

Concern of the aerospace industry and MSFC for improving reliability of servovalves led to reassessing the present state of the art of this critical control component and soliciting proposals from industry for a study program. Complete design freedom was encouraged and it was recommended that industry attempt to optimize servovalve reliability by using increased input power and minimizing the servovalve's sensitivity to contaminated fluids. All other areas were left unspecified and were considered of secondary importance to that of improving reliability.

Two study and development contracts were awarded in June 1963. A summary of each program follows.

THE MOOG SERVOCONTROLS STUDY AND DESIGN

The purpose of the development study undertaken by Moog was to investigate the improvements that might be gained in the standard Moog Type 30 servovalve by increasing the electrical signal input power. The essential improvement being sought was increased reliability, although other trade-offs involving performance, size, and weight were considered.

Improvement Areas

The criterion for improved servovalve reliability was based upon the following valve parameters: (1) contamination tolerance of the first stage, (2) spool driving force gradient, (3) ultimate spool driving force, and (4) coil wire size. The first three parameters relate to valve performance, should there be dirt or debris in the hydraulic fluid or built into the valve. The last parameter is a measure of coil reliability, apart from coil design considerations. Each of these parameters provides a qualitative assessment of valve reliability. No attempt was made to determine the degree of reliability improvement associated with each parameter.

To focus attention on the primary purpose of the study program, a number of valve design parameters were selected and fixed. These included the second stage spool and sleeve configuration and the torque motor coil resistance. Valves chosen were representative of Saturn I hardware with rated flow: 1260 cm^3/s (20 gpm) at 2070 N/cm^2 (3000 psi); resistance: 1000 ohms per coil.

Sizing Valve Parameters

Next, the question of electrical input power was attacked by considering the use of four progressively larger torque motors for the valve size selected (Fig. 1). The smallest torque motor is that actually used in the first stage of Saturn I. This has a useful output of 0.04 m-N (0.36 in-lbs) at 12 mA differential.* The three larger torque motors have full torque outputs of 0.2 m-N (1.75 in-lbs), 0.5 m-N (4.5 in-lbs), and 1.2 m-N (10.5 in-lbs), respectively.

The servovalve performance obtained with each torque motor is intimately associated with other first stage parameters. In fact, the first three criteria selected for assessing valve reliability can vary widely with any one torque motor by variation of nozzle size, spacing, flapper moment arm, inlet orifice size, etc. Therefore an analytical investigation of 12 valve configurations utilizing the four different torque motors was carried out. Following this, the most attractive configuration for each torque motor was actually built and tested to verify the analytical predictions.

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* Normally this valve would be rated at 8 mA differential signal input, which is a signal input power of 32 mW. It was recognized prior to the Moog study program that improvements could be obtained by additional electrical signal power, so in Saturn I this was increased to 72 mW.

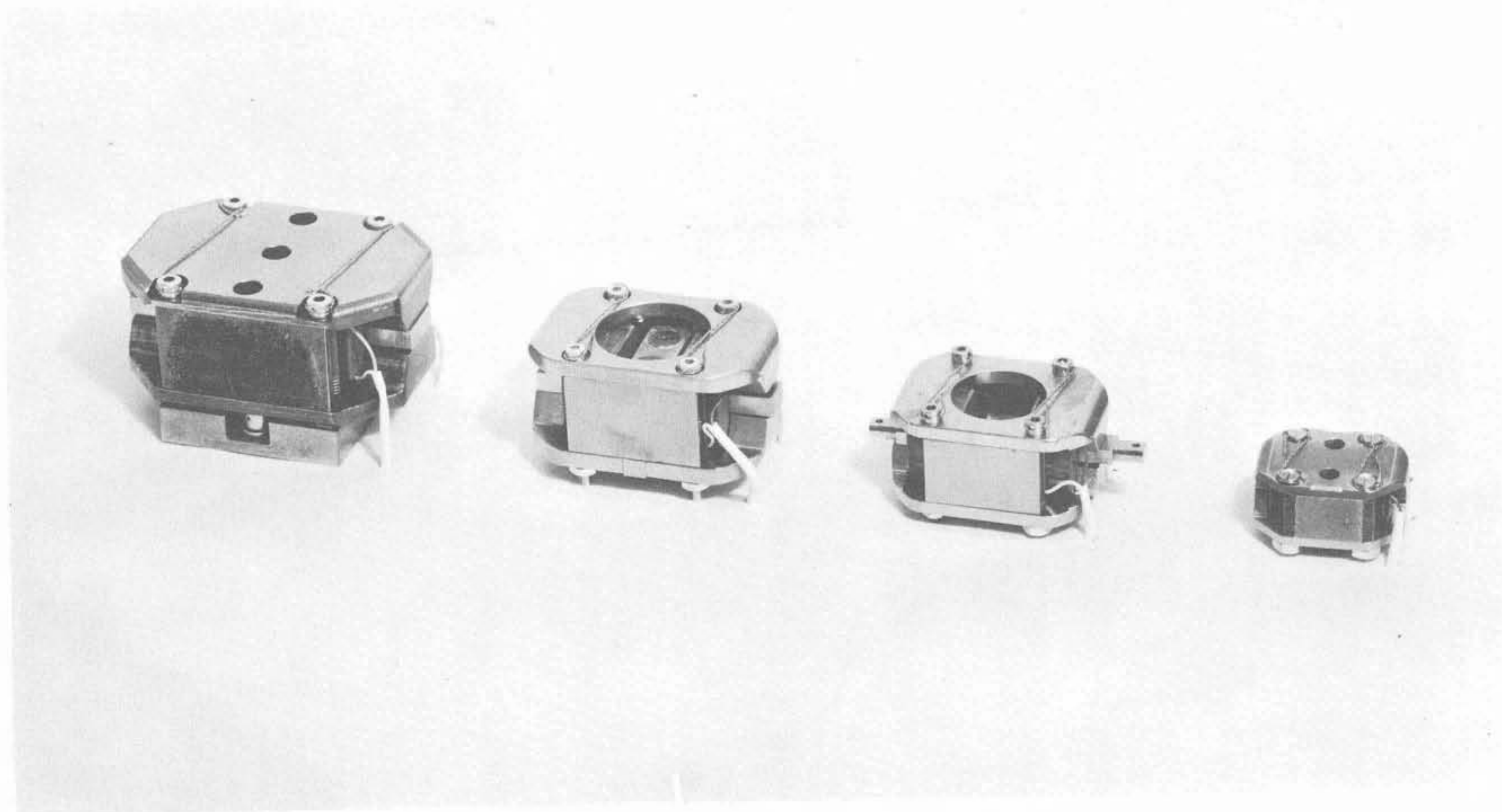


Figure 1. Moog Torque Motors.

Selection of first stage parameters started by presuming that 670 N (150 lbs) ultimate spool driving force was adequate. So, rather than select parameters that yielded still higher levels of ultimate force, those which favored spool driving force gradient and increased micron capacity of the first stage were pursued. Here, use of larger torque motors permits larger flapper moment arms. These give higher internal valve loop gain and also allow wider nozzle spacing without deterioration of the first stage pressure gain.

Performance Improvement and Consequences

The resulting improvements in servovalve performance obtained through the use of larger torque motors are shown in Figure 2. The plotted data are for the configurations selected for each torque motor. Actually, the 1.2 m-N (10.5 in-lb) torque motor exceeds that which is usable on the valve size selected (for reasons which will be discussed later), so the configuration built for these tests was derated to 0.8 m-N (7.1 in-lbs).

The consequences of using progressively larger torque motors are summarized in Figure 3. Envelope and weight are not sufficiently large for concern in Saturn application. Input signal power, even at the 1 watt level, is not enough to cause serious limitation. Likewise, first stage leakage, even with the largest torque motor, is still reasonable compared to second stage null leakage.

The important limitation is the reduction of the first stage natural frequency (associated with the larger armature inertia of the big torque motors), coupled with the increase in valve loop gain. These concurrent trends lead to valve instability, and so establish the practical upper limit for torque motor size which can be used with any given second stage. For the valve used in this study, the 1.2 m-N (10.5 in-lb) configuration is above this upper limit.

The optimum configuration selected was the next smaller torque motor 0.5 m-N (4.5 in-lbs), which is shown on the valve in Figure 4. Comparing the performance of this valve to that of the valve used in Saturn S-1 shows:

- first stage micron capacity increased from 65 to 150 microns

- spool driving force gradient doubled

- valve internal loop gain tripled

- coil wire size increased 50 percent (AWG 44 to AWG 40)

The wire size information given relates to a 1000-ohm coil.

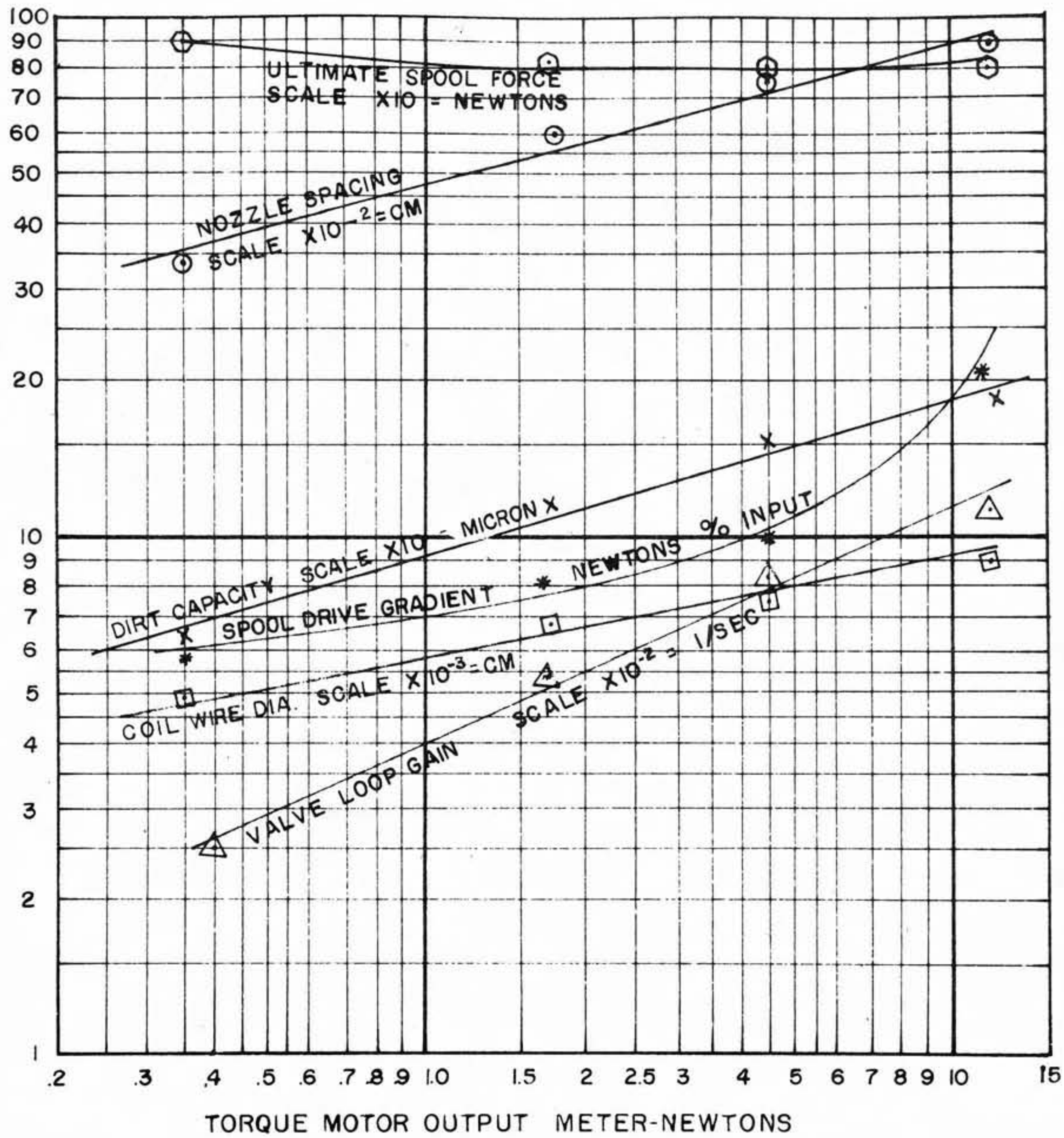


Figure 2. Performance Improvements with Large Torque Motors.

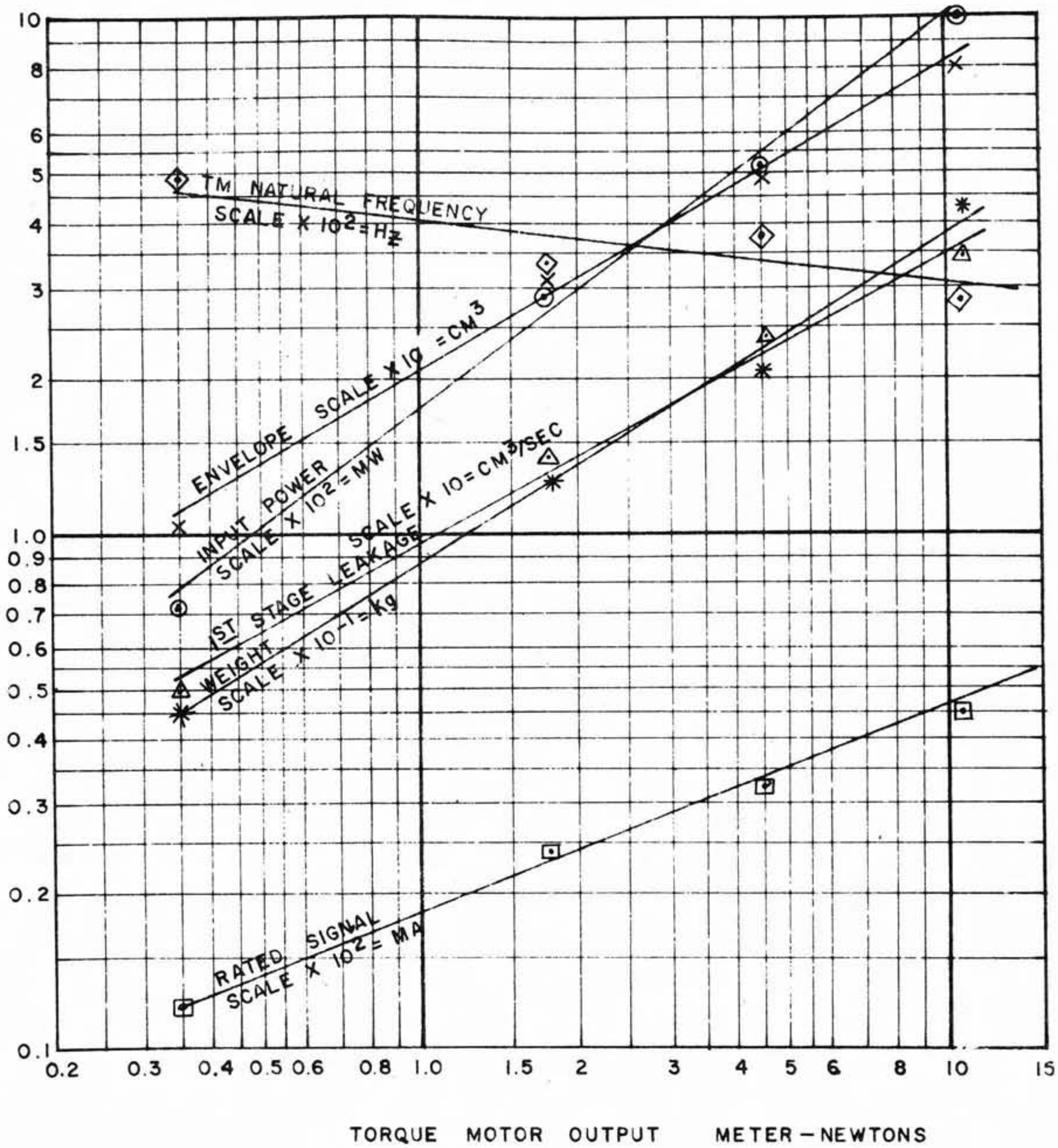


Figure 3. Penalties Imposed by Large Torque Motors.

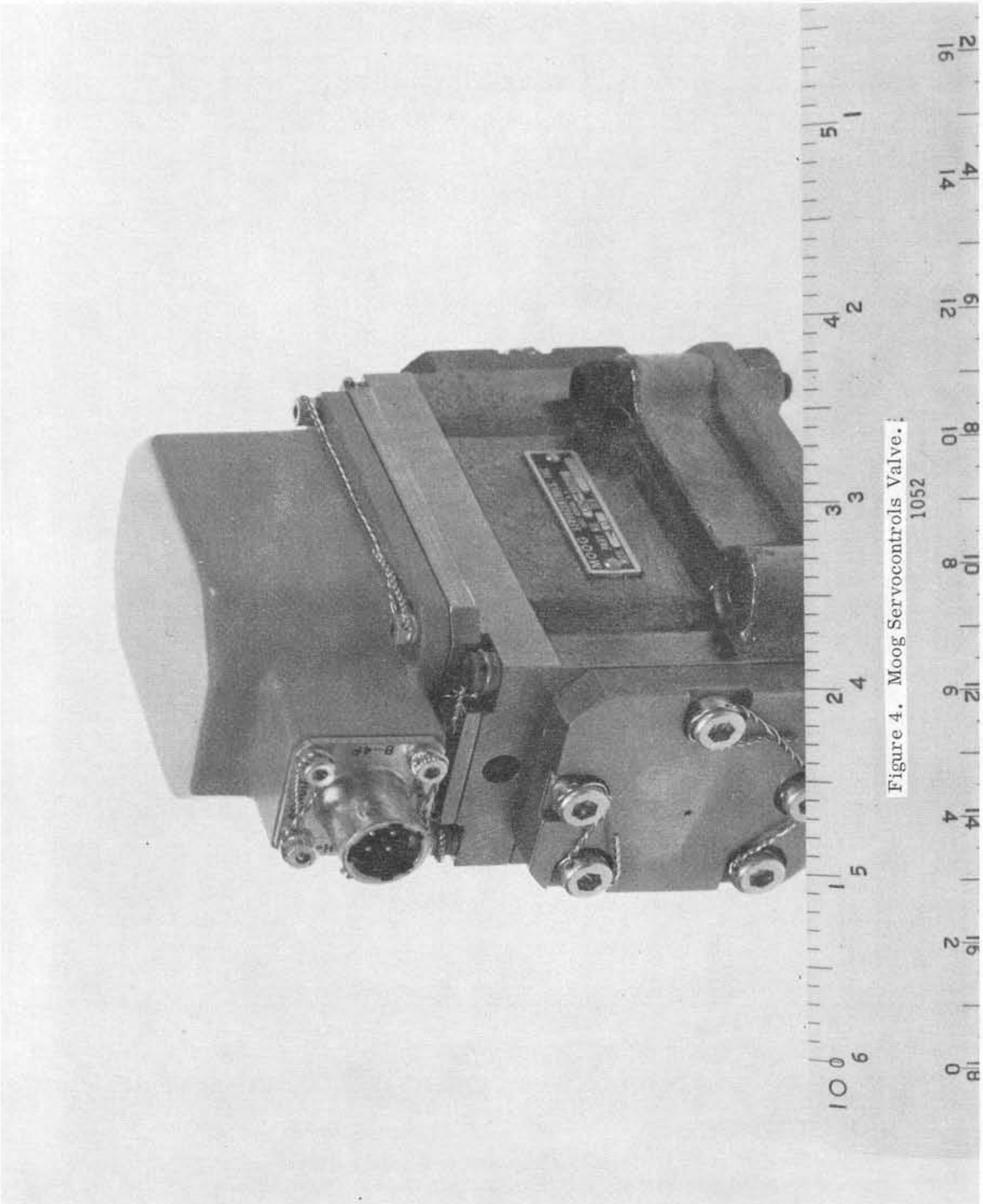


Figure 4. Moog Servocontrols Valve.

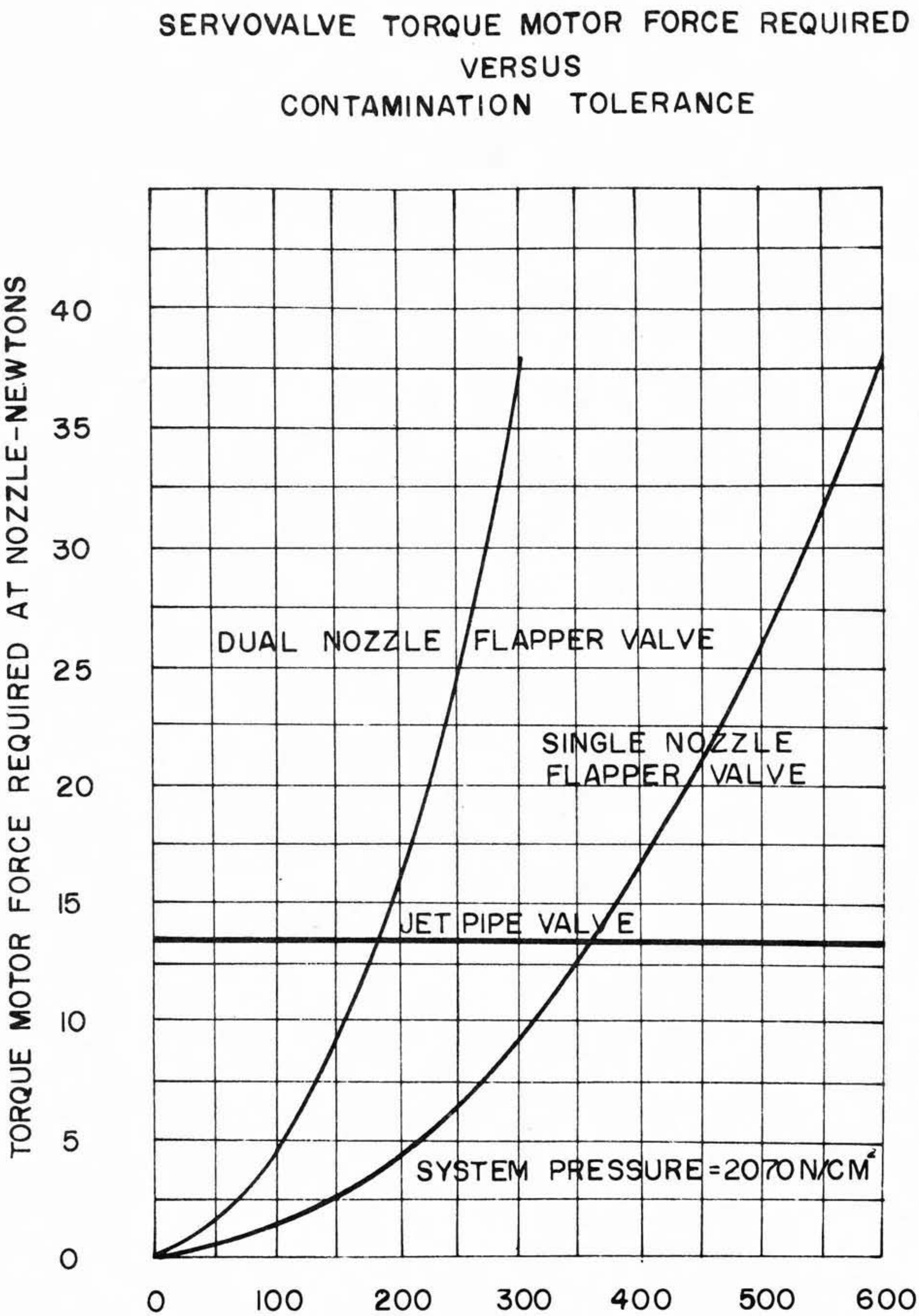


Figure 5. Torque Motor Force Output Versus Contamination Tolerance for Three Valve Configurations.

(d) Relatively large degree of engineering and manufacturing experience and know-how.

2. Single Nozzle Flapper

(a) Dissymmetry in design results in most centershift with temperature and pressure.

(b) Half area second stage spool driving forces by approximately 50 percent.

(c) Improved first stage dirt tolerance over double nozzle flapper type.

3. Jet Pipe

(a) Highest first stage dirt tolerance.

(b) Lowest relative first stage fluid power consumption.

(c) Lowest equivalent electrical input power resulting from omission of nozzle flow reaction forces.

(d) Double the power transfer efficiency between first and second stage (Fig. 6).

(e) Relatively limited degree of engineering study, analysis, and manufacturing experience even though concept was first patented in 1889.

These factors and related analyses resulted in the selection of the jet pipe concept as offering the greatest potential for increasing servovalve reliability. The significant disadvantage of this configuration concerning the present difficulty in precise engineering analysis and parametric study was fully appreciated and acknowledged at the inception of the program.

Program Plan

In the specification and design review, a reassessment by MSFC of the critical design areas and objectives led to a mutual agreement that contamination sensitivity was one of the major factors contributing to servovalve reliability: however, it would be unwise to sacrifice all other considerations simply to provide,

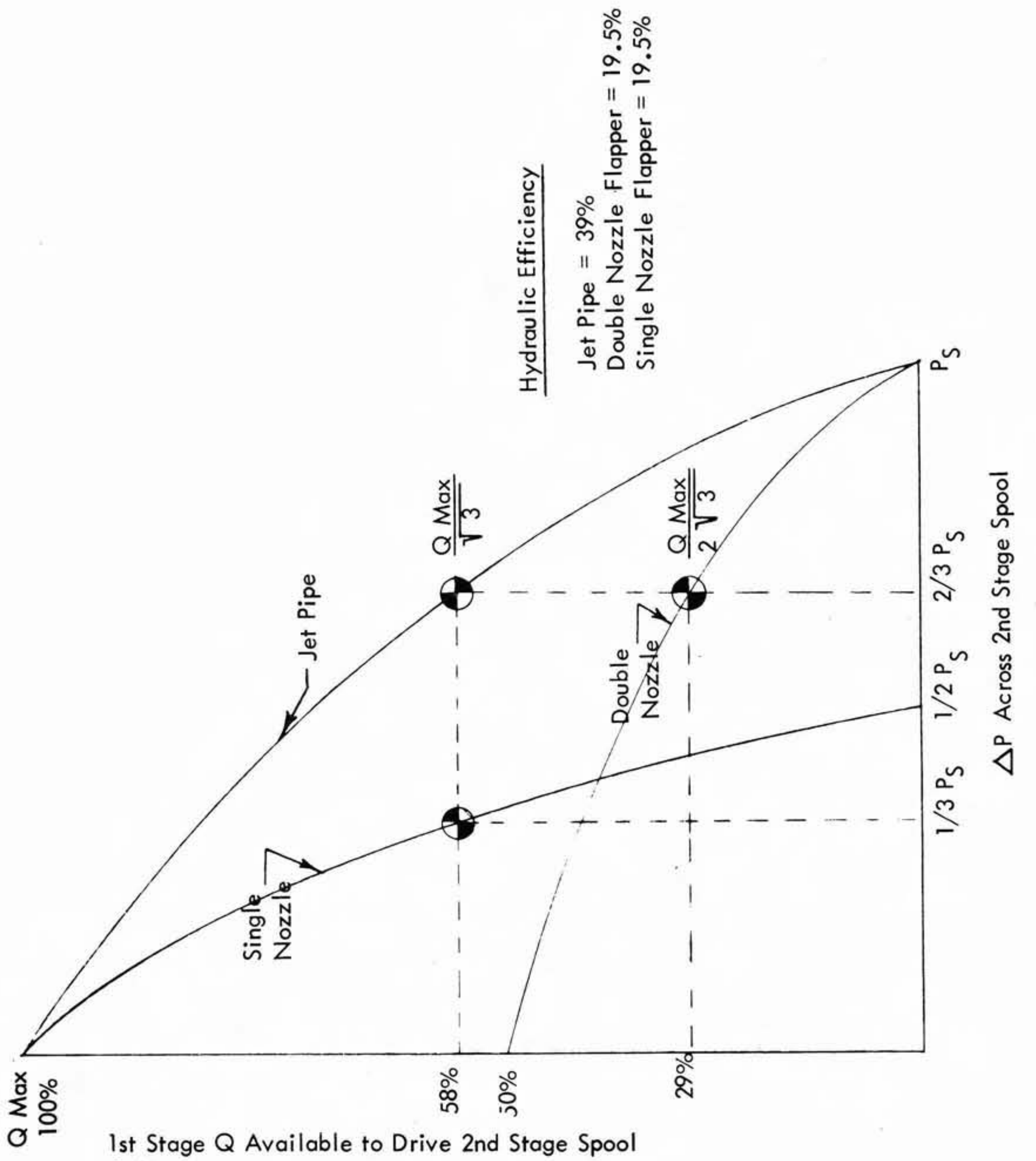


FIGURE 6

Figure 6. Hydraulic Power Transfer Efficiency Curves for Double Nozzle Flapper, Single Nozzle Flapper, and Jet Pipe Valves.

for example, 1000 micron dirt capability. It was agreed that significant improvements in valve susceptibility to dirt could be incorporated within the design and still permit investigation of a servovalve which could have reasonable total leakage, comparative dynamic response, and, in addition, lead to the development of a unit that could be used with the present state-of-the-art guidance and fluid power systems.

The following general specifications were established:

Contamination Tolerance	450 microns
System Pressure	2070 N/cm^2 (3000 psi)
Rated Flow	1160 cm^2/s (18.5 gpm)
Pressure Gain	6900 $N/cm^2/mA$ (10,000 psi/ma)
Hysteresis	3%
Response (90° phase lag)	100 Hz
Flow Linearity	5%
Quiescent Leakage	38 cm^3/s (0.6 gpm)

Design Considerations

1. Fluid Barrier Design and Evaluation

Four types of fluid barriers were evaluated with the following results:

(a) Diaphragm - Flexure stiffness was found to be excessive because of dual necessity to accommodate a fluctuating differential pressure across the fluid barrier without centershift and a diaphragm design having a fluid carrying web section.

(b) Single-Ended Flexure Tube - Exhibited significant advantages; however, other overriding difficulties in packaging the fluid supply tube cancelled its use.

(c) Torsion Tube - Necessity to cantilever the jet pipe and nozzle outboard of the torque motor would require a larger first stage. Flow reaction forces tended to alter the nozzle-receiver gap and generate pressure centershift problems.

(d) Double-Ended Flexure Tube - This concept was selected as superior and best suited to the overall design. This design facilitated mass balancing, provided a predictable spring pivot, and eliminated armature translation within the air gaps. The tube design minimized centershift with changes in supply pressure and eliminated the need for additional spring members. It is the only part under flexure.

2. Nozzle and Receiver Design and Analysis

One of the major design objectives of this study was to use full system pressure in the fluid amplifier stage of the servovalve. The final design required no pressure-dropping orifices and no first stage drain orifice, and therefore uses and controls the full energy potential of the hydraulic system in which it operates.

The most restrictive orifice in the hydraulic amplifier stage of the servovalve is the 450 micron (0.018 in) diameter exhaust nozzle.

The design and development of the nozzle and receiver geometry involved the following efforts.

(a) Study, mathematical analysis, and verification through actual breadboard testing of the theories and fluid phenomena were described in MIT report number 8090-8 entitled "Basic Research and Development in Fluid Power Control for the USAF." This previous study established a number of the more basic interrelationships between nozzle-to-receiver diameter, nozzle-diameter-to-nozzle-receiver spacing, and flow and pressure transfer characteristics.

(b) Actual flow and pressure transfer efficiencies between first and second stage were measured and improved with design progress until both exceeded 90 percent. These efficiencies were significantly higher than previous data indicated.

(c) Jet exhaust nozzle flow coefficient was optimized so that minimum flow and maximum nozzle diameter could be used with appropriate benefit to valve leakage and dirt tolerance.

(d) Square receivers were investigated and ultimately selected.

It was noted that as the exhaust jet traversed through its midposition from one round receiver to the other, a pronounced change in flow gain occurred. This gain decrease occurred as a result of the web section between the receivers. Selection of square receivers with a hardened tool steel minimum thickness web separating them not only increased hydraulic power transfer efficiencies and reduced instabilities of fluid splash back but also permitted a continuous gain through null (Fig. 7). A significant improvement in ease and simplicity of manufacture also resulted.

3. Torque Motor Design and Analysis

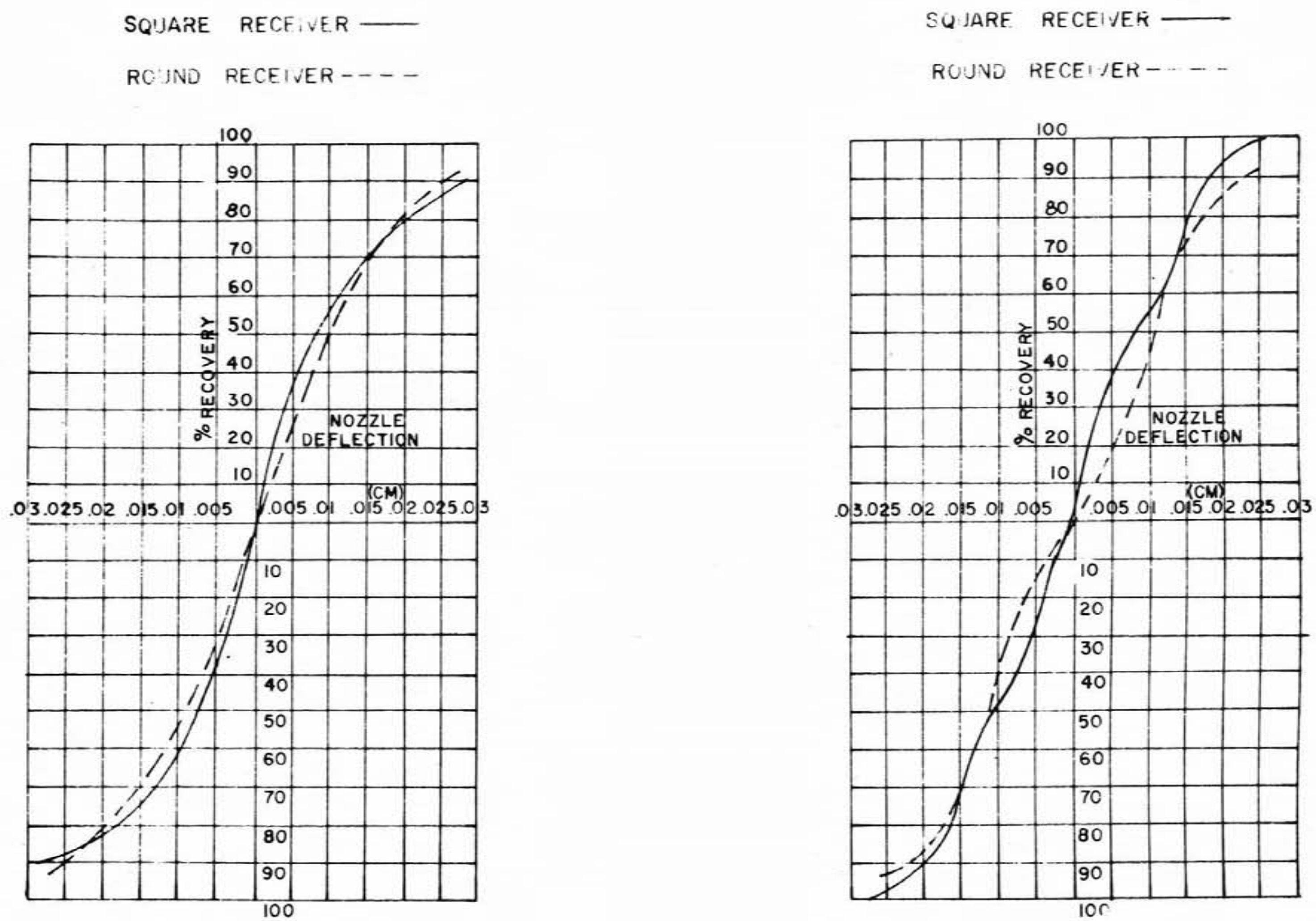
Many factors were considered in the design of the torque motor to increase its reliability.

Electrical reliability was improved by selecting large coil wire. Number 36 AWG wire was chosen as having over 6 times the cross-sectional area and twice the insulation thickness of conventional number 44 AWG wire.

Torque motor output was developed to overcome the uncancelled restoring torque of the flexure member at a signal ratio corresponding to an internal loop gain of approximately 7. Design of the flexure member itself was governed by the required swing of the nozzle and the distance from pivot to nozzle face. Sufficient safety factors were incorporated to provide proof strength and reliable fatigue life to the flexure member.

A spool stroke length of 0.045 cm (0.018 inches) was used to preserve a 450 micron dirt tolerance. The valve employed mechanical feedback and produced full nozzle deflections with a maximum of 20 percent rated input current for improved first stage pressure gain (spool driving force gradient) and flow gain characteristics.

The final torque motor produced 350 m-N (3.1 in-lb) useful output torque and used all of the 0.25 watts available power aboard Saturn (50 mA x 100 ohms effective resistance). Useful output torque developed by a jet pipe servovalve is fully available to slew the exhaust nozzle. In a nozzle flapper configuration, the major portion of useful output torque is used opposing the hydraulic centering forces of the fixed nozzles. Because of time limitations, theoretical evaluations concerning optimum input power level were not possible, however, this 0.25 watts was believed to be entirely adequate.



PRESSURE RECOVERY COMPARISON

FLOW RECOVERY COMPARISON

Figure 7. Pressure and Flow Gain Curves Comparing Square and Round Receivers.

The optimum level of input power to a servovalve depends to a great degree on the configuration and geometry of the gimbaling system. A nozzle flapper type servovalve having large area nozzles for maximum dirt tolerance requires higher output torque to operate against the substantial hydraulic centering forces. Additionally, if the servovalve is used with a mechanical feedback actuator, rated current input must be increased a minimum of 4 or 5 times to maintain a desirable gain relationship and equivalent system resolution. The power necessary to operate this particular servovalve with a mechanical feedback actuator would increase from 0.25 watts to 4 or 5 watts.

4. Slide Valve Design and Analysis

Certain data indicate that the second stage of a servovalve is less reliable than the first. Failure analyses suggest that the first stage of a servovalve is mainly susceptible to large particles which plug nozzles and orifices; whereas most second stage failures are caused by small particles and silting. To be complete, any servovalve reliability improvement study should consider both stages.

Study of various types of spool profiles led to the selection of four designs for comparative evaluation; the multigroove, Cadillac Gage Co. standard, narrow land, and tapered spool types as indicated in Figure 8.

Each of these four spools had some analytical data in support of its superiority; therefore, some of each were fabricated and run simultaneously on a contamination life cycle test to monitor actual performance. Except for profile, all parameters remained constant.

Force-versus-displacement tests and subsequent tests within the servovalve showed that actual dimensional variations during fabrication completely submerged any significant performance differences between spool designs. Limitations in time prevented further investigation and the spool with the best dimensional control (i.e., straightness or rainbow, taper, roundness, etc.) was selected.

A 1.27 cm (0.5 inch) diameter spool was ultimately chosen which produced in excess of 2230 N (500 pounds) spool breakout force. (This compares with breakout forces of approximately 290 N (65 pounds) and 1180 N (265 pounds) for valves with 0.475 cm (3/16 inch) and 0.95 cm (3/8 inch) spools, respectively).

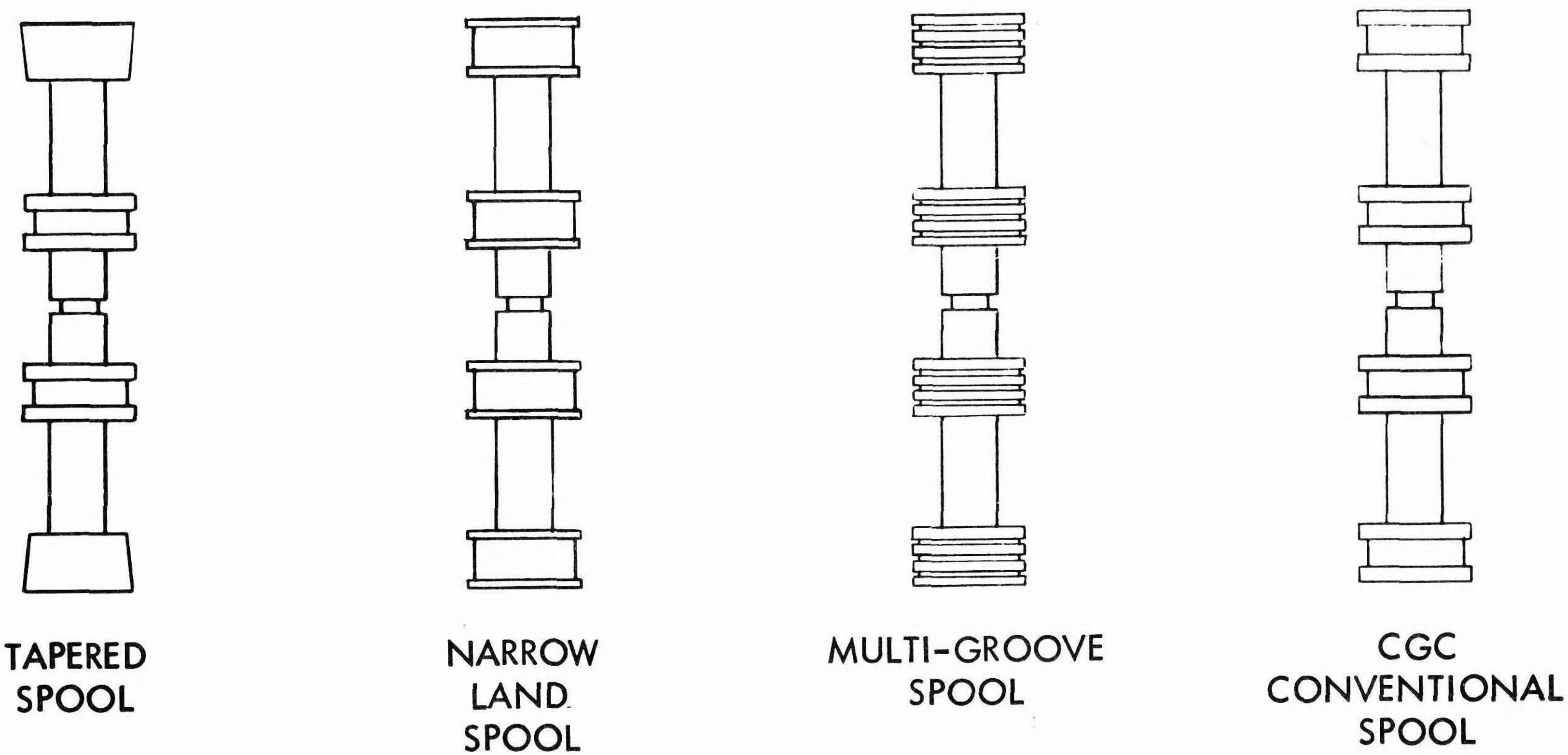


Figure 8. Four Spool Profiles Tested.

Spool driving force gradient, or first stage pressure gain, was considered a significant factor for improving reliability of a servovalve. A pressure gain of 124 $N/cm^2/mA$ (180 psi/mA) with the 50 mA torque motor was developed. Smaller signal versions of this design would produce correspondingly higher pressure gains.

The sleeve was centerlocked within the valve body to eliminate asymmetrical growth and centershift with temperature. Fluid cavities were conservatively designed to provide linear flow without saturation over the full operating range.

5. Mechanical Feedback Design and Development

Initially, instabilities of the servovalve were prevalent. These instabilities were aggravated by many factors, some of which were: (1) use of full 2070 N/cm^2 (3000 psi) system pressure in the first stage, (2) low first stage damping, and (3) fluid splash back caused by inadequate design and quality of nozzle and receivers. The mechanical feedback linkage was an additional contributor because feedback force, as generated by spool displacement, was transmitted through this linkage to the jet pipe. Of necessity, the linkage was offset from the centerline of the jet nozzle exhaust converting this force to a torque which created a fluctuating wind-up of the jet pipe and additional instabilities.

A tandem or dual feedback linkage assembly was developed which offered a solution to this problem. Some of the apparent advantages were (1) redundancy of feedback; (2) tandem contact between feedback assembly and spool, which minimized spool side loading and reduced second stage friction; (3) reduced importance for close tolerance fit between ball and groove; and (4) reduced feedback bending stresses through use of smaller diameter wire.

6. General Design Concepts

Since the emphasis of this study program was on improving servovalve reliability and investigating alternatives for achieving this goal, no effort was placed on minimizing envelope or packaging considerations (Fig. 9). To the contrary, the "breadboard" functional model valve was designed sufficiently large and with additional parts and adjustments to facilitate changes and ease of disassembly and test.

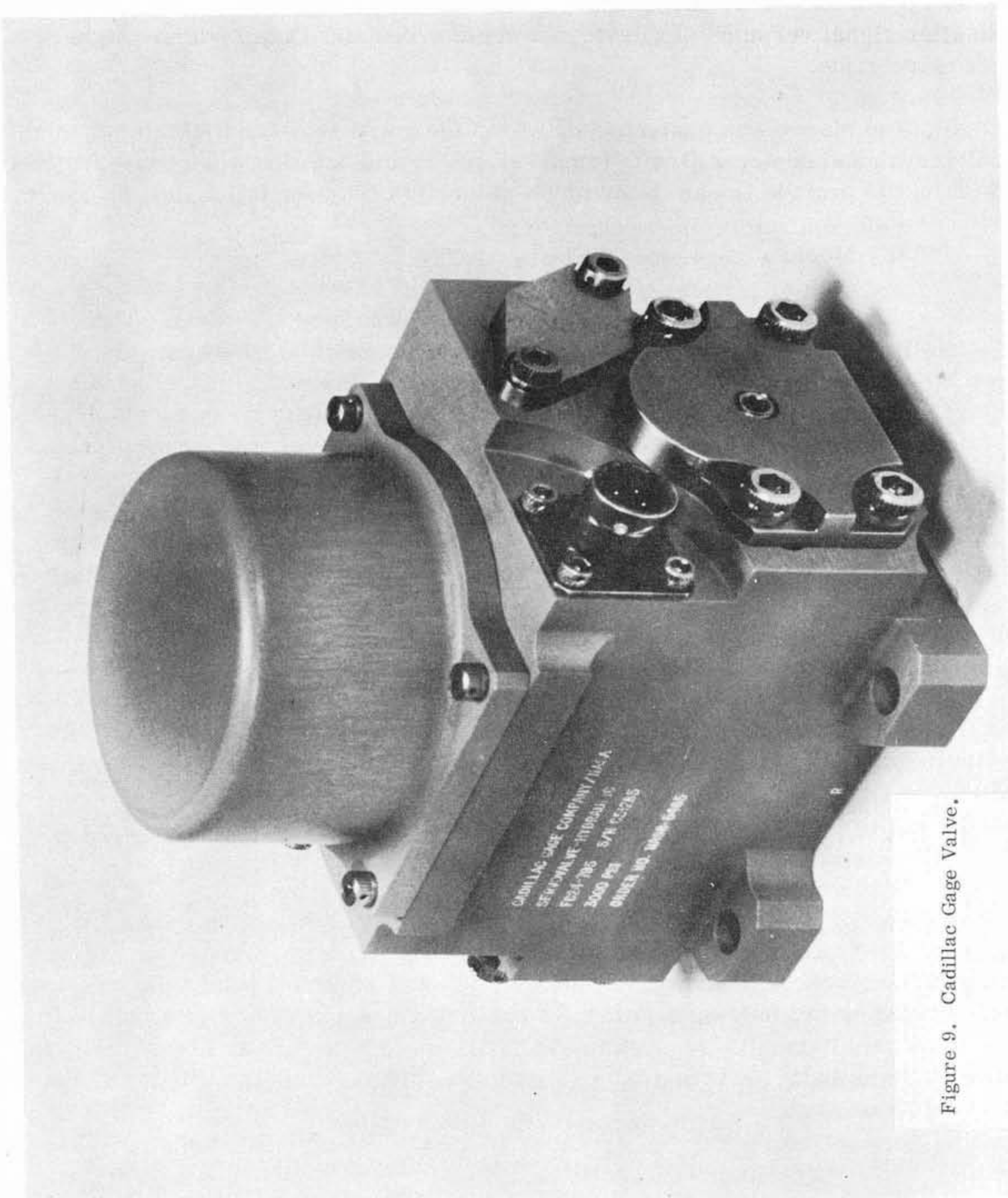


Figure 9. Cadillac Gage Valve.

Design Summary

A tabulation of the more significant design features and actual performance data is as follows (Fig. 10):

Higher electrical input power (0.25 watts).

A 450 micron contamination tolerance.

No orifices upstream of the jet nozzle.

Full flow filtration.

Double-ended flexure tube.

No mechanical connection between supply tube and jet pipe.

Square receivers.

Centerlocked sleeve for minimum temperature centershift.

Tandem mechanical feedback.

Dry, hermetically sealed torque motor.

A 1.27 cm (0.5 inch) diameter spool for high breakout forces.

No blind fluid passages.

Large coil wire for electrical reliability

The following performance data were recorded on the functional model servovalve:

Actual Performance Data	MSFC/OGC VALVE
Threshold	0.4%
Pressure Centershift	0.6%/690 N/cm^2 (1000 psi)
Temperature Centershift	1%/38°C (100°F)

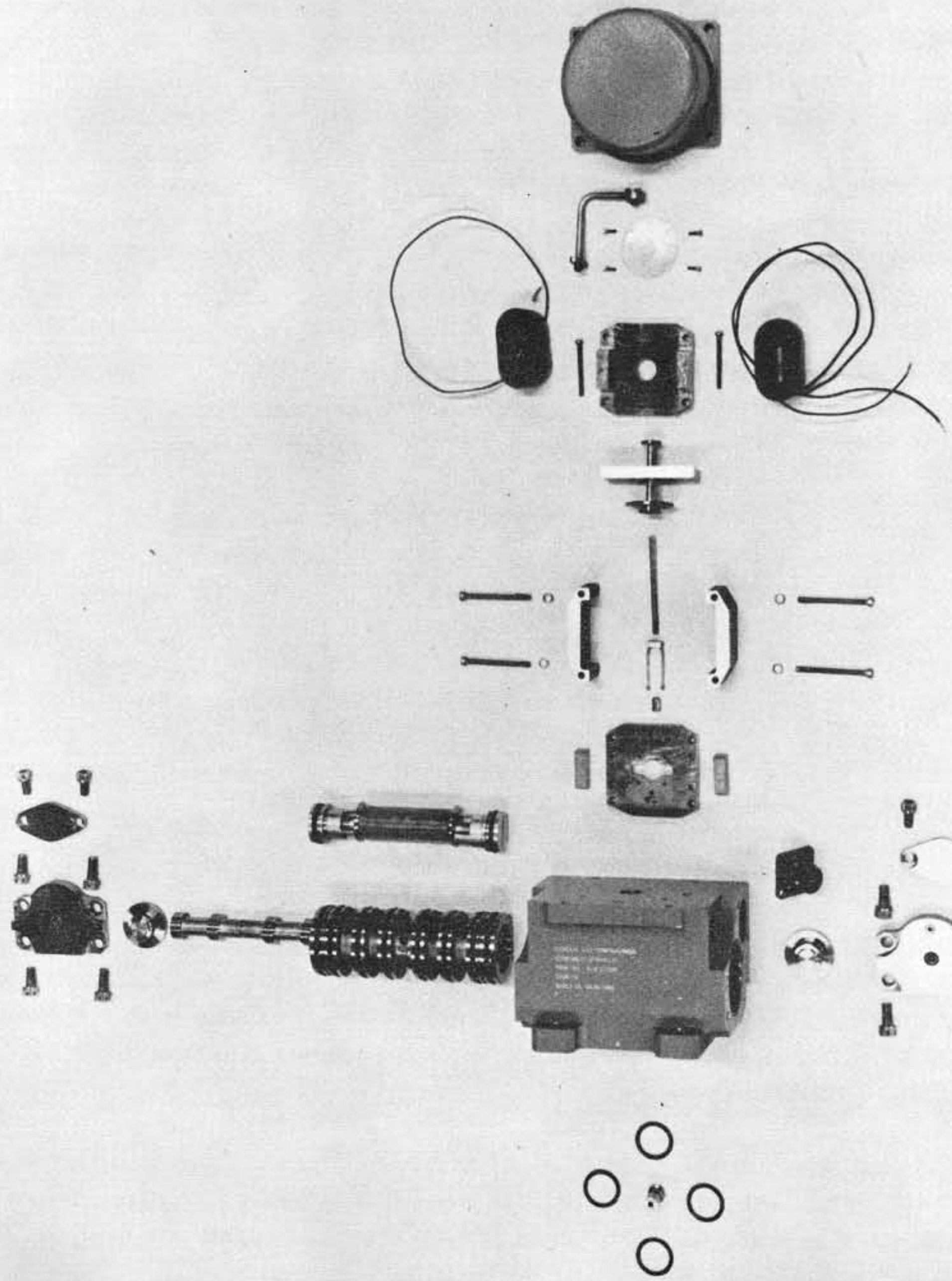


Figure 10. Exploded View of Cadillac Gage Valve.

Hysteresis	2.5%
Response (90° phase lag)	90 Hz
Flow Symmetry	5%
Flow Linearity	5%
Quiescent Leakage	4%

During assembly and testing of the servovalve, no precautions were taken to assure cleanliness of the unit, its component parts, or the hydraulic test stand on which it was developed. The valve ran for an estimated minimum of 100 hours without any filtration. Fluid samples contained the following contaminants:

10-50 micron range	100,000 particles
50-100 micron range	300 particles
greater than 100 micron range	44 fibers
	18 plastic particles
	17 metallic particles

Note: Particle counts made in accordance with ARP-598a.

CONCLUSIONS

Each of the valve studies has resulted in an improvement in servovalve reliability. Some of the improvements of the Moog development have been incorporated into the Saturn systems and others are being considered. However, additional trade-off design studies and performance tests must be made before any further changes are made.

Additional studies and development are required with the Cadillac Gage jet pipe servovalve before a complete assessment and flight hardware implementation can be made. A phase II program is expected to expand our knowledge in this area.

In Saturn flight hardware, the replacement of the potentiometer with the more reliable mechanical feedback mechanism and the improvement in the design of the servovalve have resulted in actuator reliability which exceeds that required of the actuator in the reliability budget.

To guarantee the quality and improve the reliability of all Saturn vehicle components, MSFC has implemented a strict surveillance and traceability program. The NASA Quality Control NPC 200 documents are the medium used to establish the quality programs which insure that the NASA space systems, launch vehicles, spacecraft, and the associated ground support equipment achieve the required reliability for a successful mission.

The NASA Reliability Program Provisions for Space System Contractors (NPC 250-1) was established as a guide for designing reliability into space systems. The NASA programs cannot tolerate an approach in which there is relatively high risk in first design attempts and where the necessary reliability is only achieved in later design. The NASA programs with only small quantity production must have the required reliability in the first as well as all later designs.

With the use of reliability prediction models, designers can re-evaluate and determine where to improve their designs. These models should be used more to find and improve the low reliability areas of a design.

The many component tests, system checkouts, and vehicle simulated flight tests, and a critical review of the results obtained, have eliminated many malfunctions in flight. Every effort made to assure quality and improve reliability in the Saturn vehicle is an effort to insure a manned lunar landing in this decade.

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