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APOLLO EXPERIENCE REPORT -
GUIDANCE AND CONTROL SYSTEMS:
CSM SERVICE PROPULSION SYSTEM
GIMBAL ACTUATORS

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16. Abstract The service propulsion system gimbal actuators of the Apollo command and service module were developed, modified, and qualified between February 1962 and April 1968. The successful development of these actuators, as part of the Apollo Program, was the result of extensive testing, retesting, and modification of the initial design. Successful completion of each mission without anomalies attributable to the actuators indicates that the particular configuration (modification) in use was adequate for the flight profile imposed.					
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APOLLO EXPERIENCE REPORT
GUIDANCE AND CONTROL SYSTEMS:
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SUMMARY

In February 1962, the decision was reached to use a service propulsion system engine that would be gimbaled at the engine throat. This concept selection meant that some type of gimbal actuator was required to provide thrust vector control. After completion of a trade-off study of types of actuators, the electromechanical concept was chosen over the electrohydraulic or hydraulic blowdown concepts as the means of servoactuator control of the engine thrust vector.

Design and development of adequate lunar mission hardware proved to be a difficult undertaking. Use of the electromechanical actuator design selected in lieu of the more conventional hydraulic actuators for engine gimbaling dictated advancement in magnetic-particle clutch design. Throughout development and qualification programs, the magnetic-particle clutch design continued to be the major problem area.

The vendor for the service propulsion system actuators produced several experimental hardware designs before settling on the design later to be known as the Mod O configuration. The basic design did not change appreciably after the Mod O configuration was completed. Actuators of the Mod O, Mod I, Mod II, and Mod IIA configurations were qualified during the Apollo Program. Each configuration was qualified for the flight profile imposed. All configurations were used at some stage of the Apollo Program, but only the Mod IIA was qualified for a manned lunar mission.

The greatest single factor requiring changes from the Mod O and Mod I designs was overheating of the magnetic-particle clutches, which limited the force gain of the clutch and, hence, the maximum rate capability. Additional problems with the clutches and changes to the position transducer were the primary reasons for adopting the Mod IIA configuration. Successful completion of each mission without anomalies attributable to the actuators indicates that the particular configuration in use was adequate for the flight profile imposed.

INTRODUCTION

The development of the service propulsion system (SPS) gimbal actuators was begun in 1962. It was decided that the SPS engine would be positioned by electromechanical actuators as a result of a trade-off study of electromechanical versus two types of hydraulic systems. Improvements to the state of the art for electromechanical actuators were required to meet the lunar mission objectives. This report describes the evolution of the Apollo SPS gimbal actuators from the description in the first statement of work through qualification of hardware for the lunar landing. Particular attention is given to problems encountered.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Syst me International d'Unit s (SI). The SI units are written first, and the original units are written parenthetically thereafter.

ACTUATOR CONCEPTS

The basic concept for the SPS actuators was to provide thrust vector control (TVC) for the gimballed SPS engine for all firing modes. A representative actuator configuration is shown in figure 1. In February 1962, it was decided that the SPS engine would be gimballed at the engine throat and that some type of gimbal actuator would be required. At about the same time, the prime contractor made a trade-off study of three types of gimbal system actuators: electromechanical, electrohydraulic, and hydraulic blowdown. The basic system requirements considered during the trade-off study were performance, power requirements, system weight, maintenance and service, system compactness, reliability, and growth. Table I presents a summary of the trade-off factors, and table II lists the basic system requirements.

The electromechanical actuators concept was selected in July 1962 on the basis of the trade-off factors. The electromechanical actuator was noted to be self-contained, whereas the use of hydraulic actuators would have required the addition of a hydraulic system (viz., hydraulic power supply, lines, valves, etc.) or a high-pressure gas system. The electromechanical actuator was heavier than the hydraulic actuators; but, when the required hydraulic systems were added, the electromechanical system showed a weight advantage. The electromechanical actuator was considered more efficient with less total power used. Checkout and maintenance were considered simpler for the electromechanical actuator. Leaks and fluid contamination are detrimental to the operation of hydraulic systems, and no such system had been operated in space at the time the studies were made.

The original specifications, based on engineering judgment, were established without knowing exactly what would be needed for control-system stability. It was recognized that refinement of specifications might be necessary as knowledge of total vehicle requirements increased. Specific changes — and the rationale for these changes — are shown where configuration changes are described.

TABLE I. - SYSTEM EVALUATION TRADE-OFF FACTORS

Factor	Hydraulic blowdown system	Electrohydraulic system	Electromechanical system
Advantages	Simplicity Few parts No motor Established reliability values Compatible with Apollo concept Compatible with space environment	Lightweight Established reliability values Choice of power source allowed	Lightweight Compact Self-contained Efficient Less total power Stiffer system Simpler checkout and maintenance Common power source No piping, valves
Disadvantages	Possible leaks Not self-contained Fluid contamination High-pressure system (fabricated) Several servovalves Additional onboard fluid capacity High weight for equivalent reliability Low stiffness	Possible leaks Not self-contained Fluid contamination Additional onboard fluid capacity Low pump and motor reliability Servicing and storage Several components Moving parts Low efficiency Low stiffness	Slightly higher peak power demand Hermetic seal required
Weight, kg (lb)	^a 18.1 to 20.4 (40 to 45)	^a 18.1 to 20.4 (40 to 45)	22.6 to 26.3 (50 to 58)
Reliability	0.999978	0.999966	0.999981

^aHydraulic fluids and associated piping and valving not included.

TABLE II. - BASIC SYSTEM REQUIREMENTS

Gimbal deflection, δ , deg	± 10
Deflection rate, $\dot{\delta}$, rad/sec	$\pm .35$
Acceleration rate, $\ddot{\delta}$, rad/sec ²	± 3.5
Reliability	0.99996
Power requirements	Minimal

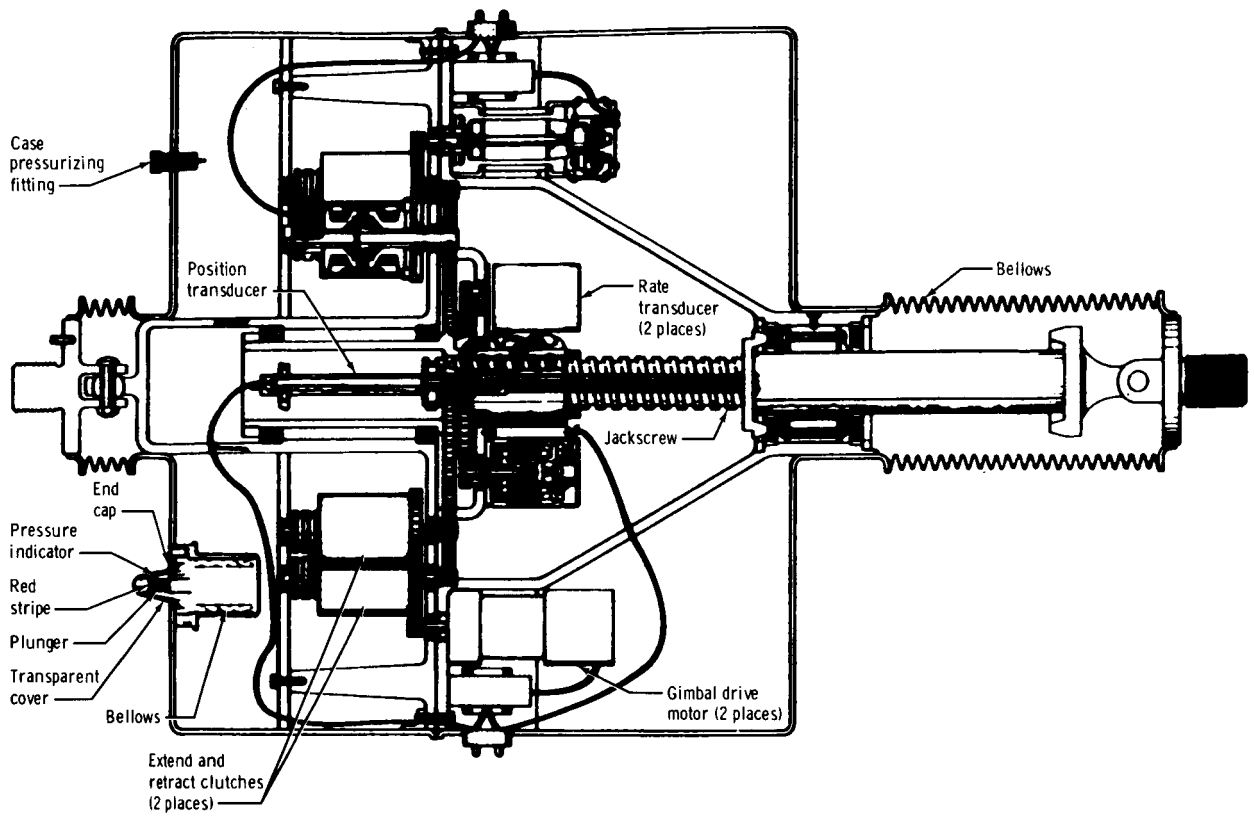


Figure 1.- Electromechanical gimbal actuator for the SPS.

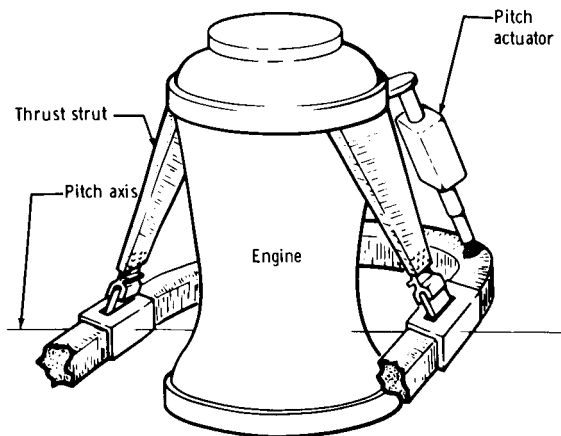


Figure 2.- Engine mount for the SPS.

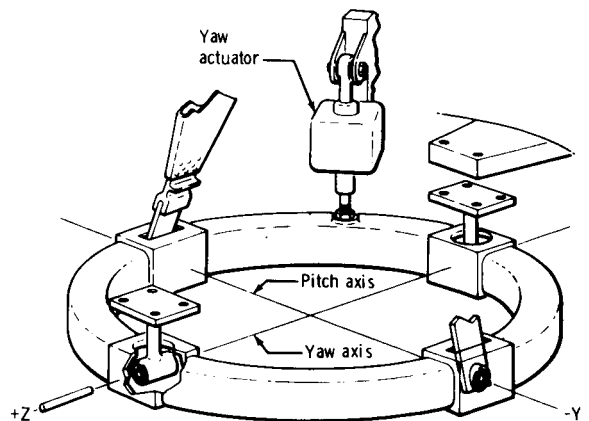


Figure 3.- Gimbal mount for the SPS.

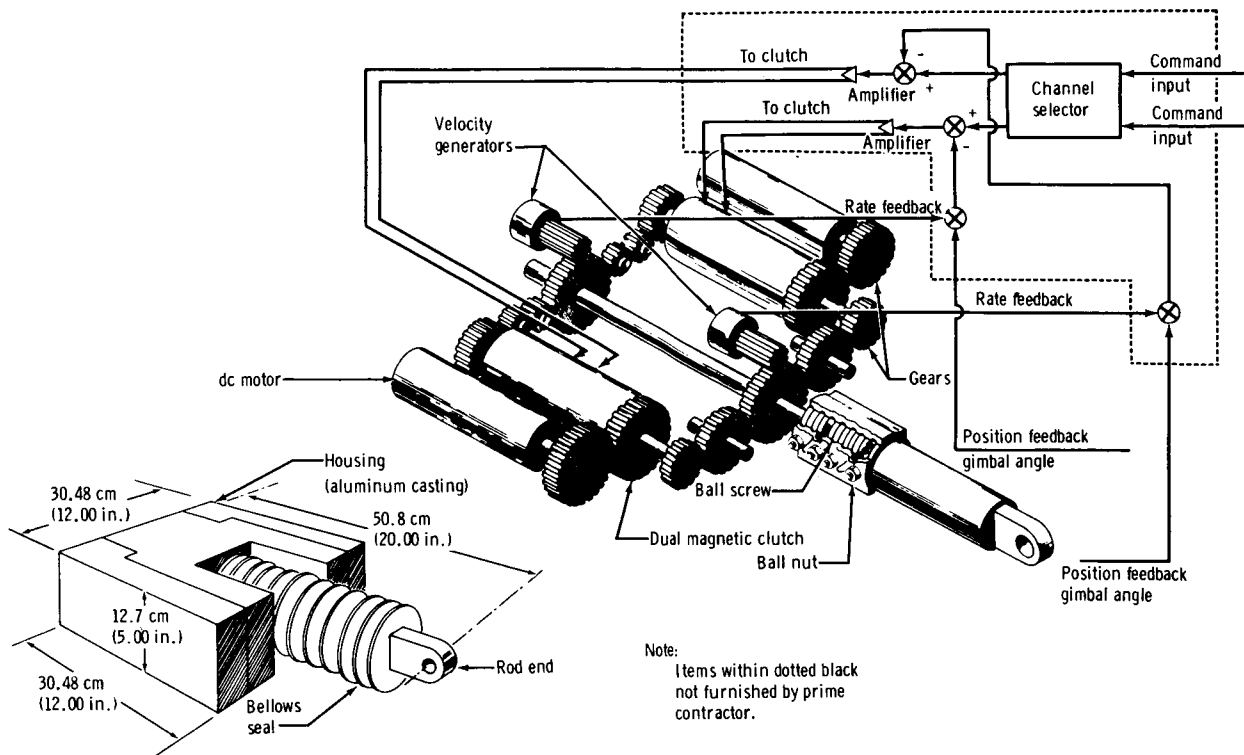


Figure 4.- Gimbal actuator concept.

DESIGN

In April 1962, a contract for supplying the SPS engine (including actuators and gimbal system) was awarded. The engine mount and gimbal mount are depicted in figures 2 and 3, respectively. The SPS engine contractor initially awarded the actuator contract to a vendor in July 1962. Structural integrity verification was begun in December 1962 with the completion of the first breadboard units. Figure 4 presents a pictorial representation of the actuator concept as of August 1962, and table III lists the actuator design requirements as of the same date. The position feedback was to have been provided by a gimbal angle transducer located in the gimbal assembly. By November 1962, the position feedback was included internal to the actuator via a linear variable differential transformer. Four linear position transducer channels were included in one package, and three separate velocity transducers were included in the original specification. By September 1963, several changes had been made in the specifications. The changes included using only three position transducer channels and two rate transducers. Two position and two rate transducers were used to provide redundancy. The third position transducer provided display information. Table IV shows the changed actuator requirements as of November 1963 and the basis for each change. The earliest design parameters were selected on the basis of engineering judgment. Detailed investigations were made of the parameters, and additional parameters were

TABLE III. - ACTUATOR DESIGN REQUIREMENTS AS OF AUGUST 1962

Acceleration, rad/sec ²	3.5
Angular rate, rad/sec	0.35
Chamber excursion, deg	± 10
Actuator weight, kg (lb)	9.5 to 10.5 (21 to 23)
Power requirement:	
Peak power, W	1200
Continuous duty power, W	700
Normal operating power, W	550
Force output requirement:	
Peak force output, N (lbf)	5783 (1300)
Continuous duty force, N (lbf)	3114 (700)
Normal operating force, N (lbf)	2447 (550)

TABLE IV. - GIMBAL ACTUATOR REQUIREMENTS AS OF NOVEMBER 1963

Parameter	Value	Basis of requirement
Travel:		
Pitch, deg	± 6	Vehicle center-of-gravity excursion plus authority
Yaw, deg	± 8.5	Vehicle center-of-gravity excursion plus authority
Rate, rad/sec	0.3	Stability of autopilot
Acceleration, rad/sec ²	3.0	--
Force, N (lbf)	6672 (1500)	Acceleration reaction resulting from vehicle angular acceleration thrust misalignment

added when the procurement specification was written. Consideration was given to such items as vehicle center-of-gravity excursions, autopilot stability, thrust misalignment, and maximum force requirements caused by vehicle angular acceleration. Hardware state-of-the-art knowledge and experience played an important part in actuator development because virtually all previous actuators of this size had been hydraulic or electrohydraulic and had not needed the redundancy and reliability required of these units. Weight and power consumption were also important considerations from the beginning of this development.

Implementation of design parameters was begun in June 1962 when the vendor began building breadboard units. During the period from July 1962 to July 1964, the vendor supplied the following actuators.

<u>Number of sets</u>	<u>Design</u>	<u>Performance</u>
2	A	Breadboard - high hysteresis
4	B	Low power
4	C	Low response
7	D	Poor quality control and poor job performance

Initially, despite failure of the vendor to meet all specifications, it was thought that design deficiencies could be eliminated. The vendor moved his operations from one plant to another early in the development of these actuators and, from that time on, was not able to provide quality control in accordance with Apollo Program requirements. As a consequence, the SPS engine contractor elected to choose a new vendor as an alternate source, and a contract to this effect was initiated on October 9, 1963.

Breadboard testing was begun by the new vendor in December 1963, and the first breadboard units were delivered to the SPS engine contractor in January 1964. The new vendor's design was considered complete at this time. As in the case of the initial vendor, the first units did not meet the specifications as defined. The first 11 sets were low in strength, stiffness, and rate of travel. Three sets of the second design were built, and all were below specification requirements for rate. Units built as a third design were later referred to as Mod O actuators with the advent of a redesign to be known as Mod I. The basic design did not change appreciably after the Mod O configuration was completed.

DEVELOPMENT

A great amount of testing was performed in an effort to formulate a final design for the SPS actuators. All units built by the initial vendor were built to specifications predating the Mod O configuration. The third generation of the new vendor's design became known as the Mod O configuration in March 1965. At that time, it was determined that the Mod O specifications could not be met and that, if use of the electromechanical actuator were to continue, design requirements would have to be relaxed. The

most significant problem was the inability of the actuator to meet rate-of-travel requirements. The testing of the Mod O flight configuration (May to June 1965) disclosed the following actuator problems.

1. Brush failures resulting from a brush-bounce problem
2. Rod-end bearing failures
3. Excessive gear wear caused by a metallurgical (hardness) problem
4. Clutch failures resulting from overheating
5. Inadequate performance
6. Position transducer failures caused by misalignment

In April 1965, a new procurement specification for Mod I actuators was prepared that reflected the limits of performance believed to be attainable at that time. This specification reduced the actuator rate requirement with a 2891-newton (650-pound) sideload from the Mod O value of 0.30 rad/sec to the Mod I value of 0.227 rad/sec. Program management chose to remove the abort requirement in the stabilization and control system (SCS) change-in-velocity (ΔV) mode to ease the specification requirements. In addition, the Mod I design provided for the five following hardware changes.

1. Hardened bull-gears using the same material with a nitriding process
2. Clutch brush improvements and a retainer
3. A clutch bearing insert
4. Precision rod-end bearings
5. A modified valve cap for actuator pressurization

The greatest single factor making it necessary to change from both the Mod O and the Mod I configurations was overheating of the magnetic-particle clutches, which limited the force gain and hence the maximum rate capability. In going from Mod O to Mod I, consideration was given to providing a liquid-fluorinated-hydrocarbon cooling system to keep the clutches cool under load; however, this system was not added. Force gain reading for the actuators was reduced to 13.34 ± 4.45 N/mA (3.0 ± 1.0 lbf/mA); and, as stated previously, the abort requirement in the SCS ΔV mode was eliminated. Clutch heating over the period of required operation and under the specified loads continued to be a problem with the Mod I design; consequently, an intensive study was initiated in December 1965 to determine if it were possible to reduce further the rate requirements for TVC. The hardware changes recommended for a Mod II configuration were as follows.

1. Reduced clutch speed, requiring new gear sizing and component respacing (new housing)
2. Position transducer redundancy
3. Thrust bearing improvements
4. A high-temperature clutch
 - a. A metal container
 - b. Glass-impregnated redundant seals
 - c. A stronger bearing housing

The primary change was a reduction in maximum rate from 0.227 to 0.10 rad/sec. It was determined by simulation and by a better knowledge of the SCS/reaction control system (RCS)/SPS interrelationships that large signal stability of the SCS could be reduced. Initial offsets in engine rate and attitude were determined to be much smaller than originally anticipated. The RCS was able to keep rates down to a minimum and c.g. locations were predicted with greater accuracy; hence, the startup transients supported a decrease in actuator rate.

Once the Mod II configuration was built and tested, it appeared that a design had been achieved which was satisfactory for TVC; however, qualification testing demonstrated the need for additional improvement in the clutch design. Qualification testing disclosed some erratic behavior in ramp rate response in certain clutch assemblies. Investigation showed that the drag cups or rotors of these clutches became warped during use; the warpage was believed to cause the clutches to bind intermittently during operation. This defect caused out-of-tolerance conditions during ramp rate response tests. No clutch failed because of this anomalous condition; however, it was believed to be serious enough to merit further design changes. The clutch rotor was modified to a slotted configuration that prevented the rotor warpage that had occurred previously in Mod II configurations. The position transducer assembly was modified by removal of one transducer slug, separation of the remaining two slugs with a T-bar arrangement, and changes in the shear pins of the feedback arm. These changes were deemed necessary to prevent loss of position feedback by loss of more than one channel of the actuator. One position transducer was connected to each actuator channel. Displays were driven by the active actuator channel. The configuration incorporating the clutch modification and position transducer changes was known as the Mod IIA.

QUALIFICATION HARDWARE

Research and development testing of the Mod O configuration was completed in September and October 1965; a month later, hardware qualification of Mod O actuators for the Apollo AS-201 mission (spacecraft 009) was completed. A formal qualification report was not issued for this configuration; however, certification test requirements were satisfied, as far as actuators were concerned, by the issuance and acceptance of

the engineering analysis report dated November 24, 1965. The actuators were qualified specifically for the Apollo AS-201 unmanned suborbital mission.

Research and development testing of the Mod I design was completed in January 1966, and qualification tests were begun. Actuator qualification was completed in May 1966. Block I SPS engine qualification was completed in March 1966. The actuator data from engine firings at Arnold Engineering Development Center, Tullahoma, Tennessee, became a part of the actuator qualification documented in June 1967; the data fulfilled the certification test requirement for Block I. After several delays caused by research and development testing, qualification testing of the Mod II actuator was completed in the first half of 1967.

The Mod IIA qualification program was begun in November 1967 and was completed in April 1968. During this period, a penalty qualification program was run to verify low-temperature tests using corrected procedures. In addition, an augmented test program was initiated in June 1968 to increase confidence in the hardware for all manned flights. This test program demonstrated that the hardware was capable of longer life and could operate in a more severe environment than was required in the original specification.

FLIGHT HARDWARE

The development and qualification of flight hardware led to many changes from the original plans for flight hardware. On several occasions, actuators were removed from flight vehicles at the prime contractor facility or at the NASA John F. Kennedy Space Center because of some malfunction or reasonable doubt of flightworthiness. These removals usually led to the substitution of upgraded hardware such as Mod I for Mod O and Mod II for Mod I. The following hardware configurations were used on the Apollo flights indicated.

<u>Flight</u>	<u>Spacecraft</u>	<u>Actuator</u>
AS-201 (unmanned)	009	Mod O
AS-202 (unmanned)	011	Mod I
AS-501 (unmanned)	017	Mod II
Apollo 6 (unmanned)	020	Mod II
Apollo 7 and subsequent (all manned)	101 and subsequent	Mod IIA

FLIGHT HISTORY

The SPS gimbal actuators were used in all Apollo flights beginning with spacecraft 009. No anomalies were observed in the operation of the gimbal actuators

or in the TVC that could be attributed to faulty operation of the actuators. Actuator configurations earlier than the Mod IIA configuration were not qualified for a manned lunar mission. The certification test requirements for each mission were met by the available hardware. Successful completion of each mission without anomalies attributable to the actuators indicates that the particular actuator configuration in use was adequate for the flight profile imposed.

CONCLUDING REMARKS

When Apollo Program managers decided to use a service propulsion system engine gimballed at the engine throat, the requirement for some type of gimbal actuator to provide thrust vector control came into being. Early trade-off studies indicated that an electromechanical design was superior to the more conventional electrohydraulic and hydraulic blowdown systems. The electromechanical system was chosen on the bases of weight, compactness, power efficiency, system stiffness, ease of maintenance and servicing, and dependency on a common power source.

Design and development of electromechanical actuator hardware qualified for manned lunar missions proved to be more difficult than originally envisioned. One actuator vendor-subcontractor delivered 17 unacceptable sets of four different designs before the engine contractor elected to choose a new vendor as an alternate source for the actuator. The second vendor delivered 14 unacceptable sets of two different designs before a third design (to become known as the Mod O configuration) was found to be satisfactory. Three more designs (Mod I, II, and IIA) followed as the state-of-the-art improved, hardware requirements were changed, and total vehicle needs were more precisely defined. Although the Mod O, I, and II configurations were not qualifiable for manned flight, they were adequate for the missions for which they were used. Extensive testing, retesting, and modification of the Mod O configuration were required to produce the actuator used for Apollo 7 and subsequent missions.

Numerous minor modifications to parts design and materials were made in the course of achieving the basic Mod O configuration. However, it became evident that design specifications could not be met using an electromechanical actuator unless certain requirements were relaxed. The most significant problem was the inability of the actuator to meet rate-of-travel requirements, primarily because the magnetic-particle clutches overheated when maximum control current was applied. While work to improve clutch performance continued, system requirements were reviewed to determine their validity. As a result, it was ascertained that the maximum rate and load capabilities required of the actuator were unnecessarily stringent. Some requirements were relaxed and qualification of hardware suitable for manned rating was completed.

An augmented test program conducted to increase confidence in the man-rated hardware demonstrated that the actuators could operate for a longer period in a more severe environment than required in the specifications. The useful life of the actuators was shown to be sufficient for the long-duration Skylab flights.

No anomalies attributable to actuator malfunction were experienced during 4 un-manned and 11 manned Apollo missions, demonstrating that the various configurations used were adequate for the flight profile imposed.

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