NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-866

Motor-Driven Mechanisms for Space Flight Applications

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A scanning mechanism was employed on the *Mariner II* spacecraft to orient the radiometer experiment. A similar device was used to orient the television camera on *Mariner IV*. These mechanisms were designed to withstand the launch-vehicle boost environment, long storage (109 days for *Mariner II* and 228 days for *Mariner IV*) in the space environment, and operation at planet encounter.

Author

I. INTRODUCTION

Mariner II was launched on August 27, 1962, and encountered Venus on December 14, 1962. *Mariner IV* was launched on November 28, 1964, and encountered Mars on July 14, 1965. Aboard each spacecraft was a science package which required planet orientation in order to gather information. *Mariner II* carried a radiometer experiment which measured the surface temperature of Venus and details concerning its atmosphere. A television camera was carried aboard *Mariner IV*. Since the exact position of a spacecraft relative to a planet at encounter could not be determined prior to launch, both spacecraft required a drive mechanism to scan the science experiments and seek the planet. This Report discusses the system requirements, design, fabrication, test, and in-flight performance of these mechanisms.

Although the two missions were extremely dissimilar, the requirements for the scan mechanisms for both *Mariner II* and *IV* were alike in many respects.

II. *MARINER II* SCAN MECHANISM

A. System Requirements

Prior to the Venus encounter, the *Mariner II* scan mechanism was required to scan at a rate of 1 deg/sec over an included angle of 120 deg for planet acquisition. During this mode of operation, the control was open-loop from the scan logic. As the radiometer sensed the limb of the planet, a second mode of operation was initiated. In this mode, the *Mariner II* scan actuator was the drive unit in a closed-loop system receiving its commands from the radiometer through the scan-logic system. Figure 1 is a block diagram of the closed-loop system. After planet acquisition, the scan-logic system was required to switch the scan mechanism to a slow rate of 1/10 deg/sec and to restrict the scan to cover only the planet's surface while temperature measurements were being made.

The scan mechanism was required to operate on no more than 2 w of 400-cps, 26-v, square-wave, single-phase power and to weigh no more than 3 lb. The test conditions to which the scan mechanism was submitted are listed in sequence below:

Vibration

24 min { 1–3 cps with ±3 in. amplitude; 3–40 cps at 3 *g*'s acceleration }

6 sec at 15-*g*-rms noise

3 min at 10-*g*-rms noise

6 min at { 4.5-*g*-rms noise; 4.5-*g* sinusoid }

6 sec at 15-*g*-rms noise

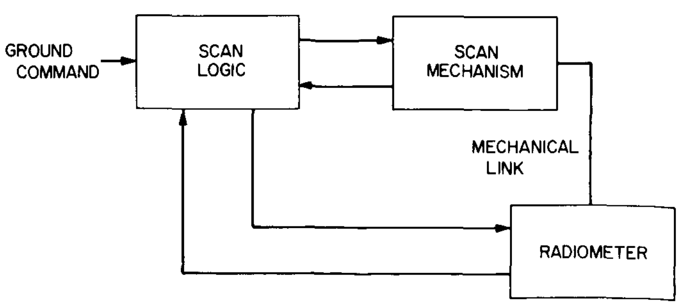

Fig. 1. Block diagram of sensing-and-control system for *Mariner II* scan mechanism

Shock

Two 200-*g* shocks of 0.5–1.5 msec duration

Vacuum Temperature

4 hr at −10°C; 12 days at +65°C } with pressure of 10^{-4} mm Hg

In addition to the environmental conditions, the materials to be used were to be nonmagnetic where possible.

B. Actuator Design

Since the *Mariner II* mission required two scan speeds for the radiometer experiment, and since it was very undesirable to attempt to shift gears to attain the two speeds, the unit was designed using two motors. These motors were Size 8, 400-cps, 26-v, hysteresis synchronous motors with integral gearheads. The motors operated at 12,000 rpm and delivered a rated torque (at the output of the integral gearhead) of 4 in.-oz at 8.19 rpm. In order to obtain the two scan speeds from a common output shaft, the *Mariner II* actuator employed a differential as shown in Fig. 2. The two speeds could, therefore, be obtained without disrupting the drive train.

Additional gearing was used to obtain the 1/10- and 1-deg/sec speeds from the 8.19/rpm motor gearhead. To eliminate any possibility of vacuum welding in the gearing, No. 303 stainless-steel pinions were mated with No. 2024 aluminum gears. All of the aluminum gears of the aluminum stainless-steel running pairs were lubricated with electrofilm 4396. Because of the short time

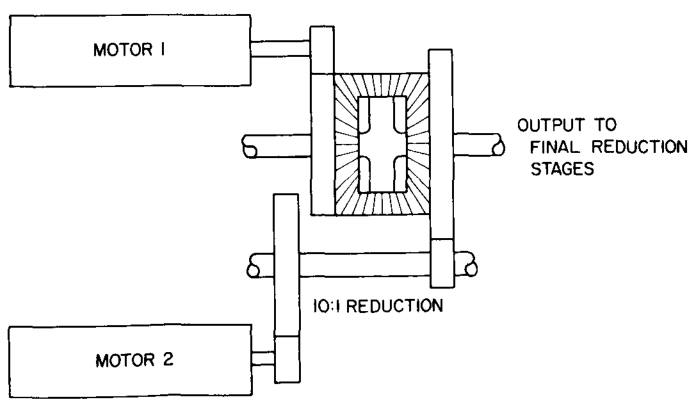

Fig. 2. Differential for *Mariner II* scan mechanism

allotted to fabrication of the *Mariner II* actuator, it was desirable to use standard catalog gears with slight modifications as necessary for mounting.

Ball bearings were used throughout the scan mechanism to support the rotating members. All bearings external to the integral gearhead were fabricated with phenolic separators which were vacuum-impregnated with General Electric F-50 silicone oil. Phenolic separators could not be employed in the integral gearheads because of size restrictions. Silicone oil F-50 was applied to the bearings and gears in the integral gearheads. Although the gearheads were not sealed, the leak paths were greatly restricted by a pair of shielded bearings at the output ends and by the motors at the input ends. The low vapor pressure of the F-50 silicone oil (10^{-6} mm Hg) assured lubrication if the evaporation mean free path was reasonably restricted.

In order to protect the mechanism during handling and testing, the output torque of the *Mariner II* unit was limited to 20 in.-lb by a slip clutch in the final stage of the reduction gearing. The clutch consisted of an aluminum plate sandwiched between two discs of bone fiber which in turn were clamped between two No. 303 stainless-steel plates. A Belleville spring was used to load the stock of plates and control the slip torque. In order to avoid any torque change as a result of oil contamination after assembly, the bone-fiber discs were impregnated with F-50 silicone oil.

The 120-deg planet search scan was controlled by hermetically sealed switches each located 60 deg from the center scan position. These switches were actuated by a lever attached directly to the scan-mechanism output shaft, thus eliminating any backlash error. Since the switches were sealed, they were capable of operation in high vacuum without any possibility of welding of the switch contacts.

The angular position of the scan-mechanism output shaft and, thus, the aiming angle of the radiometer were indicated by a potentiometer attached directly to the upper end of the output shaft. The potentiometer was a single-turn unit employing a resistive film deposited on a ceramic disc for survival in the space environment. The bearings were lubricated with F-50 silicone oil, as were the other bearings in the unit.

A hermetically sealed, glass-header-type electrical connector was mounted in the base of the mechanism housing. The interconnecting wiring internal to the unit was No. 22 teflon insulated cable.

Even though each component internal to the scan mechanism was capable of operation in a high-vacuum space environment, the housing was sealed and pressurized as an additional safety feature. The scan-mechanism cover and electrical connector were sealed with Viton A O-rings, using conventional static seal techniques. The output shaft was sealed by two O-rings spaced approximately 5/16 in. apart with an oil reservoir between them. This reservoir was filled with F-50 silicone through an external tap, after the unit was assembled (see Fig. 3).

Since the *Mariner II* scan mechanism was situated on the Sun side and since conductive heat paths to the spacecraft were limited, the exposed surfaces were used to establish a heat balance. The top surface, which was exposed to the Sun, was coated with a white silicone paint. The sides and bottom of the aluminum housing were polished to a mirror brightness. To aid in distributing heat to the outer surfaces of the housing, the internal surface of the cover was anodized black. A conventional automobile-tire filler valve was used to pressurize the unit with dry air. This was sealed with a special cap prior to flight. Dry air was used instead of nitrogen as an added safety margin. As oxide coatings wear off during operation, they grow back quite rapidly, even in reduced-pressure atmospheres, if oxygen is present. A nitrogen atmosphere could possibly enhance the opportunity for cold welding, should the flight unit lose pressure.

A problem did arise, as a result of pressurizing the scan mechanism, which limited the initial internal pressure to 19 psia, rather than 2 atm as was the early intent. The limit switches, which were the only hermetically sealed miniature switches available at the time of the *Mariner II*

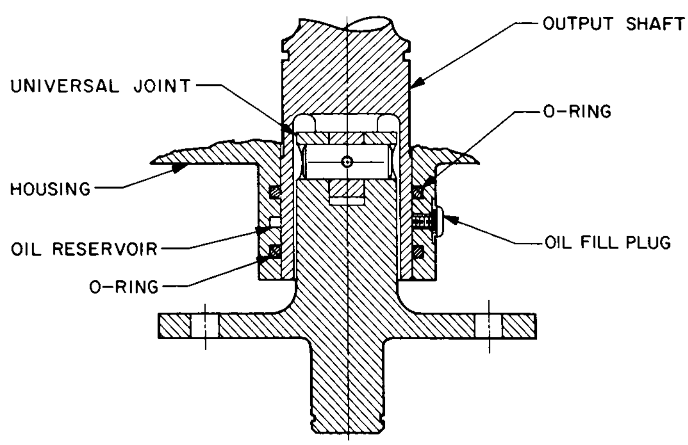

Fig. 3. Output-shaft seal and universal joint for *Mariner II* scan mechanism

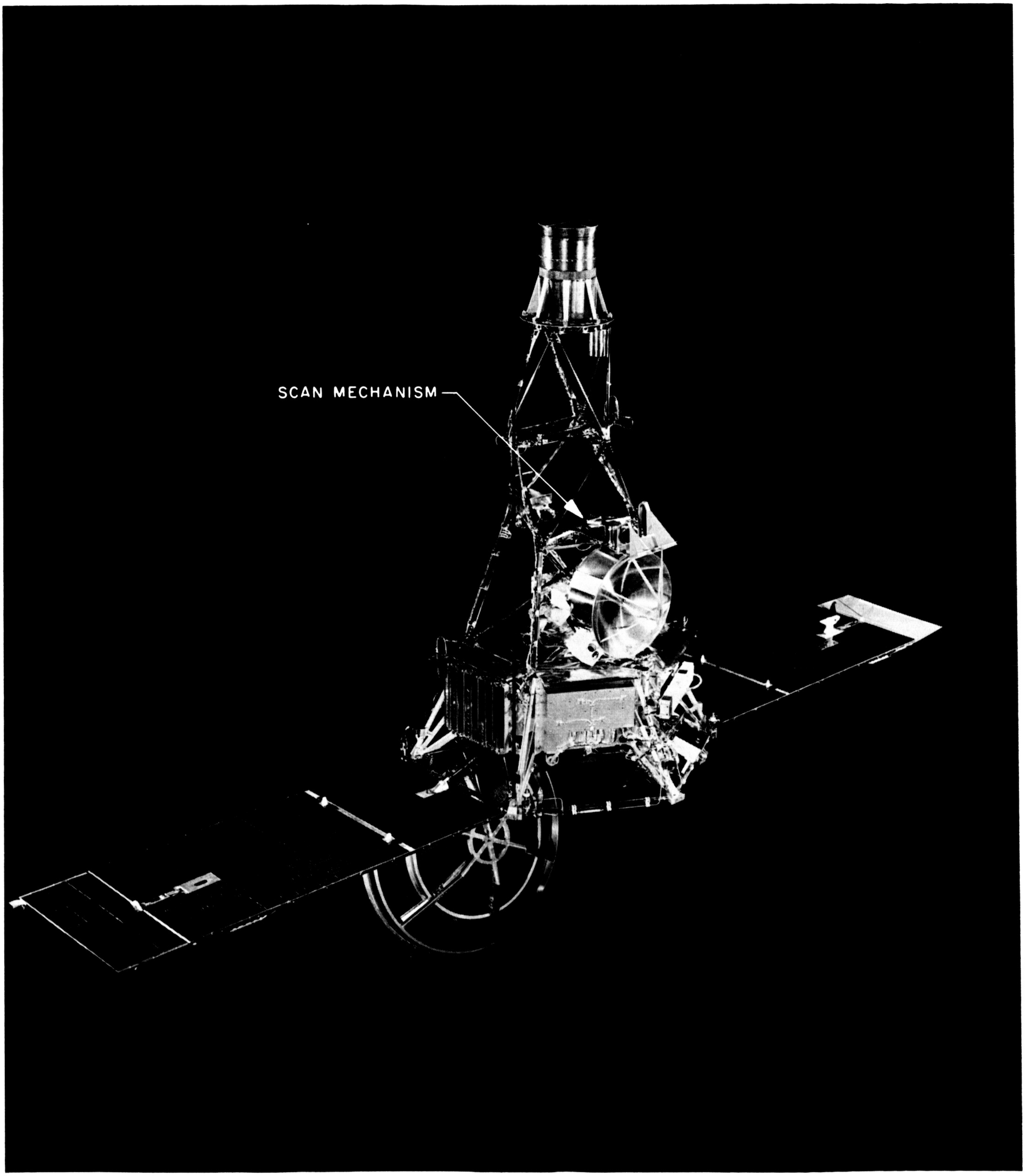

Fig. 4. Scan mechanism mounted on *Mariner II* spacecraft

fabrication, were found to be pressure-sensitive. However, the resulting pressure limitation did not degrade the system in any way other than reducing the margin of safety.

To avoid excessive bearing loadings at the output shaft as a result of misalignments, the output shaft employed an integral universal joint (see Fig. 3). The universal joint also permitted the structure, tò which the scan mechanism was mounted, to deflect during launch boost without damage to the unit.

In the initial concept of the radiometer-scan system, the scan mechanism was mounted on the top of the basic structure of the *Mariner II* spacecraft. The radiometer was to be supported above the scan mechanism by the output shaft. Because of spacecraft conceptual design changes, the scan mechanism was finally mounted on the spacecraft superstructure above the radiometer (see Fig. 4). The radiometer base was supported by a bearing on the basic spacecraft structure.

By the time of the scan-system configuration change, the design of the scan mechanism had proceeded quite far. It was a right-angle drive unit which derived much of its rigidity from the cover. Considering the final configuration, this may not have been an optimum design. However, the design was judged adequate because of time restrictions and was completed as originally conceived. The final configuration of the *Mariner II* scan mechanism is shown in Fig. 5.

C. Special Tests

During the design and preflight periods there was insufficient time to conduct extensive life testing on com-

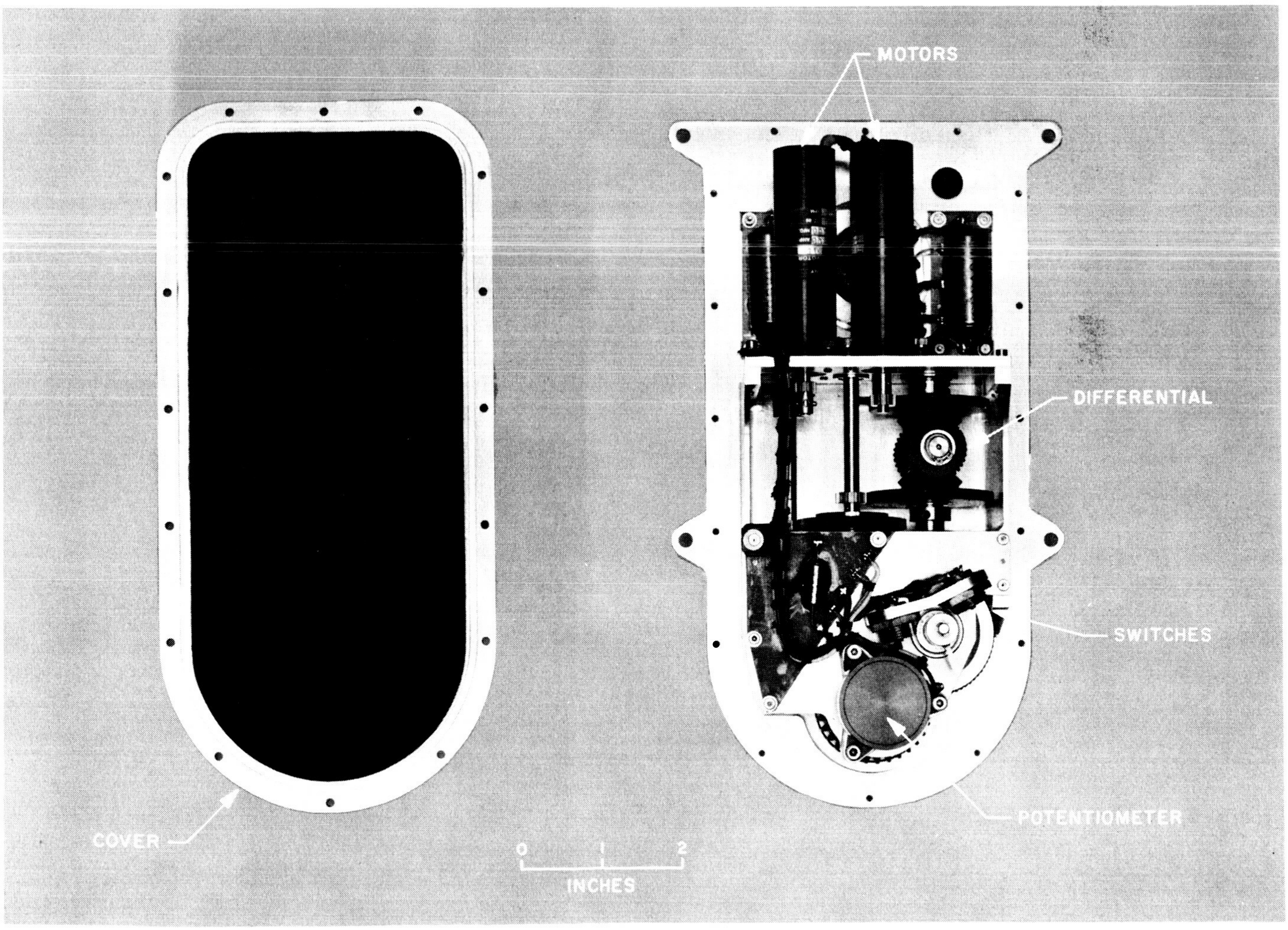

Fig. 5. Final configuration of *Mariner II* scan mechanism

ponents other than the tests conducted on the assembled actuator. After launch, a test was conducted to determine the life expectancy under space environments of a motor such as those used in the *Mariner II* scan mechanism. For this test the motor and integral gearhead bearings (steel separators) were lubricated with F-50 silicone oil. The motor was mounted on a temperature-controlled plate and installed in a vacuum chamber operating at 10^{-6} mm Hg. The temperature-controlled plate was heated to 120°F to speed the lubricant evaporation. The motor was driven with rated 400-cps power continuously with the motor reversing direction every 5 min. This test continued for 6 months with no operational degradation in the motor. The test was terminated to make the vacuum facility available for other component testing.

D. Flight Performance

Following 112 days of exposure to space environment, the *Mariner II* spacecraft encountered Venus and the radiometer experiment was switched on by ground command. The scan mechanism began scanning immediately. However, it did not scan at the 1-deg/sec rate specified for the planet search mode. Because of an anomaly in the radiometer, the scan logic circuit was commanded to operate the scan mechanism at the slower scan speed of 1/10 deg/sec. The scan unit operated properly, although at the slower speed, for 7½ hr. During the sequence of making radiometer measurements on Venus, the radiometer scanned off the limb of the planet and commanded the faster 1-deg/sec scan for several minutes. This command, although not an intended function, did give an indication that the scan mechanism was capable of operation in both modes. In spite of the anomalies in the control circuitry, the radiometer experiment was a success and there were no indications of degradation in the scan mechanism. Since there were no means of measuring the internal pressure or temperature of the scan unit on the *Mariner II* flight, it is not known what conditions were imposed on the mechanism. Therefore, it is not known how conservative a design was actually achieved.

III. *MARINER IV* SCAN MECHANISM

A. System Requirements

The *Mariner IV* scan actuator was the drive unit which aimed the television camera at the planet Mars. This unit received its command from the planet sensors through the scan-logic system when operating as a closed-loop system. Figure 6 is a block diagram of the system.

Approximately 7 hr prior to Mars encounter, the *Mariner IV* scan mechanism was required to cause a platform containing the two planet sensors and the television camera to scan through an angle of ±90 deg at a rate of 0.5 deg/sec. During this mode of operation the scan actuator and scan logic operated as an open-loop system. As the first sensor (the wide-angle sensor) acquired the planet, the scan mechanism was commanded by the scan logic to stop the search scan and was switched into the closed-loop mode of operation, keeping the sensor centered on the planet. Upon planet acquisition by the second planet sensor (the narrow-angle Mars gate), the television camera was activated and the picture-taking sequence was to begin.

The power allocation for the *Mariner IV* scan mechanization was the same as that for the *Mariner II*, 2 w of 400-cps, 26-v, square-wave power. Whenever possible, the same nonmagnetic material requirement was enforced as that for *Mariner II*.

The *Mariner IV* scan actuator was also submitted to the boost environment of the *Atlas–Agena* and the thermal vacuum environment of outer space. The test requirements were revised somewhat from those of the *Mariner II* program and are as follows:

Vibration

2–35 cps at 1.3 *g*'s acceleration

35–48 cps at 3 *g*'s acceleration

48–500 cps at 5 *g*'s acceleration

14 sec of 14-*g*-rms noise at beginning of complex wave

600 sec of 5-*g*-rms noise plus { 2 *g* rms sinusoid, 15–40 cps; 9 *g* rms sinusoid, 40–250 cps; 4.5 *g* rms sinusoid, 250–2000 cps }

18 sec of 14-*g*-rms noise at conclusion of test

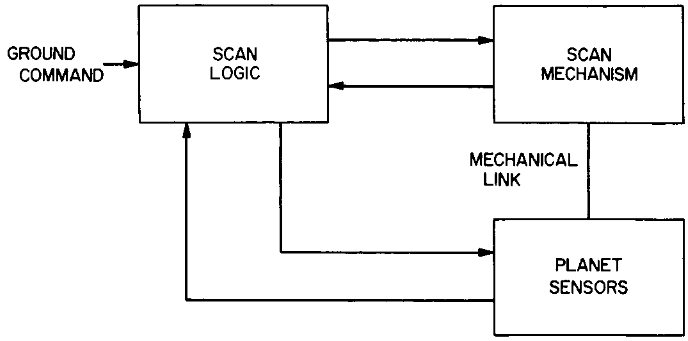

Fig. 6. Block diagram of sensing-and-control system for *Mariner IV* scan mechanism

Shock

Five 200-*g* shocks of 0.5–1.5 msec duration

Vacuum Temperature

4 hr at −10°C } with pressure of 10^{-4} mm Hg or
12 days at +75°C } less

B. Actuator Design

Since only one scan speed was required for the *Mariner IV* mission, a single motor was used. This Size-8, hysteresis synchronous motor operated at 8,000 rpm, rather than at 12,000 rpm as did the motors used on the *Mariner II* unit. The slower motor was preferable in that bearing life is a function of rotational speed.

An integral gearhead was also employed on the *Mariner IV* unit. However, the gearhead was Size 11, thus permitting the use of phenolic separator bearings in its construction.

The output torque of the motor and integral gearhead was rated at 16 in.-oz at 8.19 rpm. A greater torque capability was possible from the *Mariner IV* drive motor due to the increased size and torque capacity of the integral gearhead.

A longer fabrication period was allotted to the *Mariner IV* scan mechanism, permitting the method of gear fabrication to differ from that of *Mariner II*. Since a No. 2024 aluminum gear was always used in a running pair with a No. 303 stainless-steel pinion as described in the *Mariner II* discussion, it was desirable to fabricate the pinion integral with the shaft to minimize concentricity error accumulation. A series of tests on dry film lubricants, conducted prior to the *Mariner IV* fabrication, indicated that No. 303 stainless-steel gears which have been electroless nickel-plated, operating with No. 2024 aluminum gears which have been hard-anodized, gave wear lives, under heavy loading, which exceeded the lives of dry film lubricants. As an added safety feature, electrofilm 4396 dry film lubrication was applied following plating and anodizing.

Phenolic separator bearings, vacuum-impregnated with F-50 silicone oil, were used throughout the *Mariner IV* actuator. To assure that each bearing was manufactured correctly, torque traces were required with each bearing.

The output torque of the *Mariner IV* scan mechanism was limited by a clutch to 40 in.-lb to protect the unit during handling and testing. The clutch used in the *Mariner II* unit was adequate; however, it exhibited a characteristic which is quite common in this type of device: a higher break-away than running torque. A different type of clutch was employed in the *Mariner IV* scan mechanism in an attempt to minimize the break-away torque. The clutch was cam-operated and was not solely dependent upon the break-away and running friction coefficients of the clutch surfaces. The clutch was designed with conical clutch plates, with the outer plate being the gear-driven element (see Fig. 7).

When the clutch was slipping, the outer plate was free to rotate about the output shaft. The inner clutch plate was spring-loaded against the outer clutch plate and transmitted the torque from the outer driven plate to the shaft through the cam. The cam consisted of three ⅛-in. aluminum oxide balls caged in detents. Aluminum oxide was used to eliminate any chance of vacuum welding. The upper halves of the detents were machined into the bottom of the inner clutch plate and the lower halves were machined into the ramp plate attached to the output shaft. When there was no torque being transmitted, the balls were free in their detents. As torque was applied, the detent ramp plate on the output shaft attempted to rotate with respect to the inner clutch plate, thus transmitting the torque through the balls. When the resisting load reached 40 in.-lb, the balls attempted to cam out of the detents, thus compressing the Belleville springs, loading the inner clutch plate, separating the clutch plates, and disrupting the drive train. The primary difference between the cam clutch and the conventional slip clutch is that the break-away force to be overcome on the cam clutch prior to slipping is a vertical friction force on the cone surfaces. In the case of the conventional plate clutch, the forces depend on the static and dynamic friction coefficients of the materials.

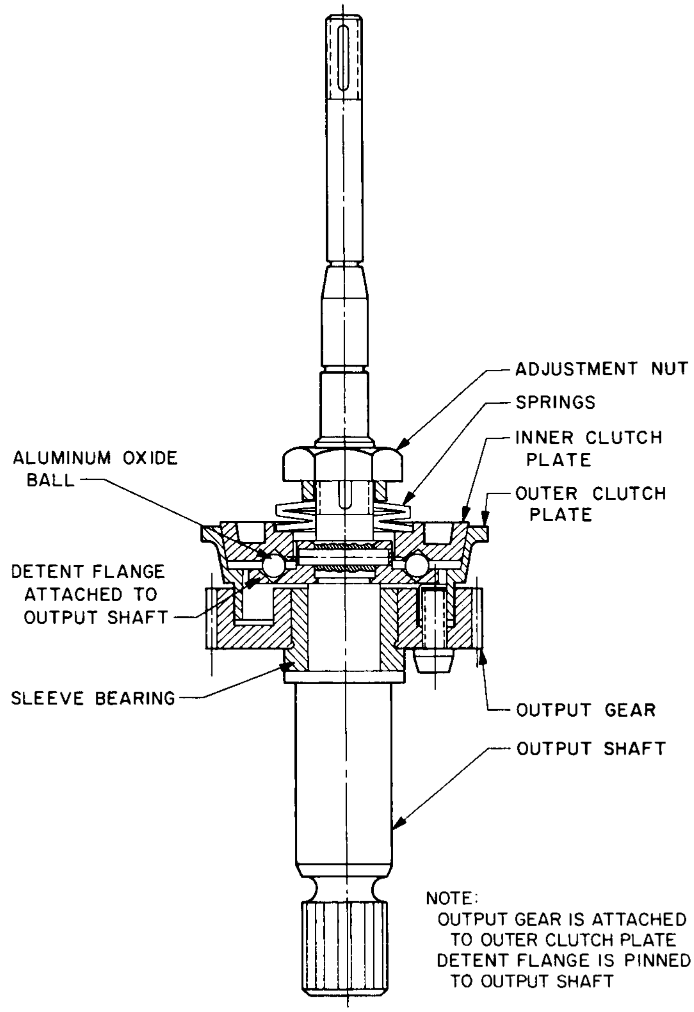

Fig. 7. Clutch assembly for *Mariner IV* scan mechanism

Flat plates would have, perhaps, been a better design for the cam clutch since no vertical force would have been present. However, the amount of torque transmission required and the size limitations made the cone clutch necessary. Due to the high loading on the clutch surfaces, they were fabricated from No. 303 stainless steel with the outer surface electroless nickel-plated and the inner surface chrome-plated. The difference in break-away and running torque for the cam clutch operating normally at 40 in.-lb was typically 1 in.-lb. A test conducted to determine clutch surface life characteristics indicated a decrease of 1 in.-lb of transmitted torque after 24 hr of continuous slipping.

To indicate the aiming direction of the television camera, a potentiometer (the same as was used on *Mariner II*) was coupled to the output shaft of the scan mechanism. A single stage of antibacklash gearing was used to increase the ±90° output shaft rotation to a potentiometer rotation of ±170° for larger voltage deviations per degree. Any discrepancies introduced by the stage of gearing were accounted for by an accurate calibration plot of angle and voltage correlations.

In the time period between the *Mariner II* and *Mariner IV* fabrications, different types of miniature, hermetically sealed switches became available. The switches selected for the *Mariner IV* scan mechanism were not affected by external pressures. Four limit switches were used in the *Mariner IV* scan unit to provide a redundant switch at each limit.

The sealing method used on the *Mariner IV* was the same as that used on the *Mariner II* unit. It was possible, however, to monitor the scan-mechanism internal pressure and internal temperature at Mars encounter on the *Mariner IV* unit.

The final configuration of the *Mariner IV* scan actuator was also a result of an earlier requirement. The original concept placed the scan unit inside a 3-in.-diam tube and made it an integral part of the platform which supported the television camera and planet sensors. A later requirement separated the two components and placed the scan actuator atop the spacecraft primary structure (see Fig. 8). The design had been completed at the time of the change; therefore, the unit retained its cylindrical shape (see Figs. 9 and 10).

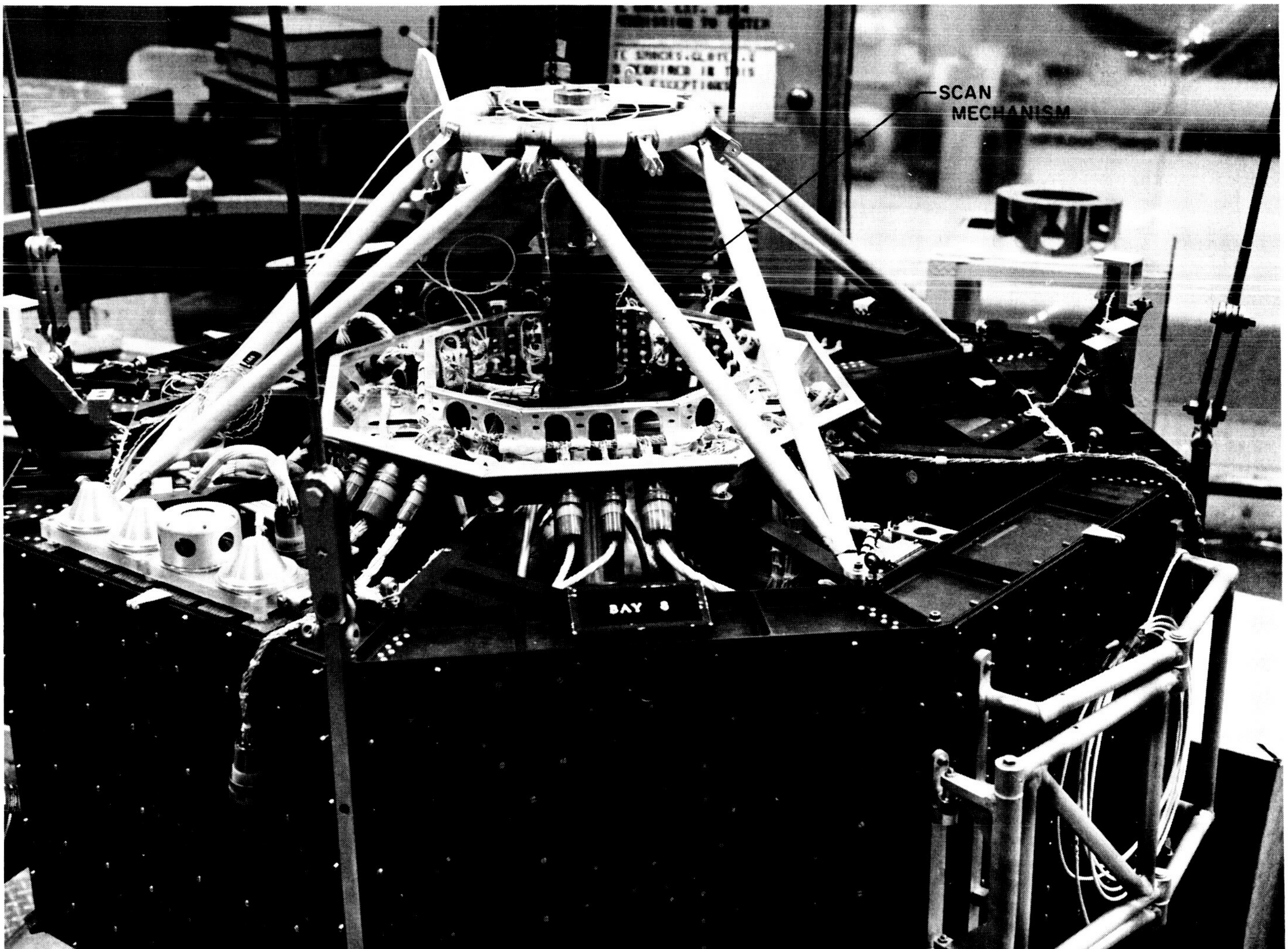

Fig. 8. Scan mechanism mounted on partially assembled *Mariner IV* spacecraft

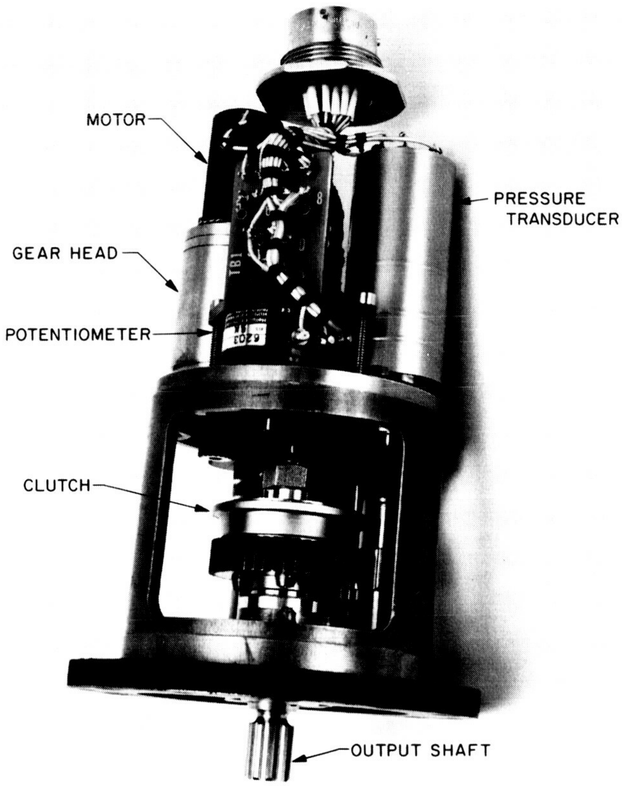

Fig. 9. *Mariner IV* scan unit with cover removed

Fig. 10. *Mariner IV* scan mechanism with cover installed

C. *Special Tests*

A vacuum-temperature life test was conducted on the *Mariner IV* scan actuator to further assure the unit's reliability. The test was conducted in a vacuum chamber with a temperature-controlled shroud surrounding the unit. The pressure was maintained at 10^{-4} mm Hg or less and the shroud temperature was regulated at 130°F. Since a vacuum could not be created which would be as severe as that encountered in flight, the test was made more imposing on the scan unit by removing the air pressure plug from the actuator housing. This would simulate a seal failure or meteorite damage.

The actuator was operated 14 hr each day for a total of 1220 hr of running time. At the conclusion of the test, the scan mechanism was operating normally. Disassembly of the unit disclosed a small amount of dry lubricant worn from the gears; however, no metal had been removed.

D. *Flight Performance*

The original intended mode of operation for the science-platform scan actuator was an automatic, preprogrammed sequence with command override capabilities. Approximately 9 hr prior to closest approach to Mars, a stored command was to initiate the planet search scan. As the planet came into the view of the wide-angle planet sensor, the search scan would cease. At this time the scan actuator would have become the drive unit in a closed-loop system which would keep the planet centered in the wide-angle sensor's view. This mode of operation would have continued until the planet came into view of the narrow-angle Mars gate sensor. The scan would then have been disabled and the television picture-taking sequence would have begun.

The automatic, planet search sequence was not employed however, because of optimum television-camera look-angle and other system considerations. Instead, a command sequence was used to preposition the television camera at a desired clock angle prior to a planet encounter. The search scan was commanded prior to the normal occurrence time for the stored command. At this time the scan actuator performed its ±90-deg search scan. The scan data was observed for approximately 14 scans to ascertain if the operation was normal and to determine the scan period. This information was used to predict the real time for transmitting a command to disable the scan at the desired clock angle.

The clock angle desired for optimum television camera coverage was 179.43 deg. Since the absence of gravity influences scan-actuator coastdown time, the television camera was actually positioned at a 178.69-deg clock angle. Degradation of the television pictures as a result of the 0.74-deg displacement was estimated to be approximately 3%.

Throughout the search scan, the actuator operated at a constant speed with no apparent degradation due to the space environment. The scan period was somewhat less than the nominal 12 min with an average scan period of 11 min, 53.2 sec. This deviation can be explained by tolerances in the original limit-switch positioning, by effects of the absence of gravity, and by a small amount of wear of the dry lubrication used on the switching cam.

The actuator housing was pressurized with dry air to 30 psia at its time of assembly. At launch the pressure was indicated at 29.5 psia. During an in-flight check 75 days after launch, the scan actuator was exercised and the actuator housing pressure was measured to be 28.8 psia. At encounter the pressure had decreased to 26.6 psia. Conventional O-ring and quad-ring seals were used in the actuator. Leakage was probably a combination of seal leakage and porosity in the magnesium actuator housing. The internal temperature of the actuator increased from 50 to 58°F during its 162-min encounter operation.

IV. CONCLUSIONS AND RECOMMENDATIONS

One significant conclusion which can be drawn from the successful operation of the scan mechanisms on the Venus and Mars missions is that conventional design techniques are effective if consideration is given to material selection. Although careful screening is important, standard catalog bearings are adequate. Components which may be subject to cold welding, such as switches, are readily available with hermetic seals. Aircraft-type electric motors are adequate if sufficient quality control is exercised. Complex hermetic sealing of the entire mechanism is not necessary for flight durations such as those experienced on the Venus and Mars missions. The fabrication problems experienced in devising a truly hermetically sealed drive far outweigh the risks of small pressure losses through conventional O-ring seals.

An ingredient which is of prime importance to the successful flight operation of a mechanism is meticulous, patient, devoted care on the part of the assembly and test technicians. This is a consideration which cannot be enforced by a blueprint or specification. However, it may be the most important one in obtaining mechanism reliability.