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DEVELOPMENT OF A ROTARY FLUID TRANSFER COUPLING AND SUPPORT MECHANISM FOR SPACE STATION

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ABSTRACT

A design has been developed for a rotary fluid coupling to transfer coolant fluids (primarily anhydrous ammonia) across rotating joints of the Space Station. Development testing using three conceptual designs yielded data which were used to establish the design of a multipass fluid coupling capable of handling three fluid circuits. In addition, a mechanism to support the fluid coupling and allow an astronaut to replace the coupling quickly and easily has been designed.

INTRODUCTION

A permanent manned Space Station, as currently envisioned, will be gravity gradient stabilized and incorporate rotating solar arrays and thermal radiator panels. The rotation of the solar arrays and radiators will provide much more efficient thermal and power systems, thereby reducing overall size, weight, and cost of the systems.

The rotation requirement calls for the development of structural, fluid, and electrical systems to provide for the transfer of loads, thermal control fluids (heat), and power across the rotation joints. As part of the advance development effort, an investigation was begun which would lead to the design of a rotary fluid coupling which allows 360° rotation and meet the severe design requirements of the Space Station.

The primary objectives of the development program were to demonstrate the design feasibility and to evaluate the particular design concepts proposed for a 360° continuous rotation joint. These objectives included the identification of manufacturing or assembly methods, identification of candidate materials and investigation of compatibility, selection of seals, determination of leakage rates, determination of drive power requirements, and lifetime assessment.

A set of design requirements was assembled based on the expected mission of the Space Station. Included in this set was a lifetime goal of 20 years of continuous rotation in orbit with little or no maintenance. The design rotation rate was one revolution per orbit period, or about 0.01 RPM.

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Anhydrous ammonia was the proposed coolant fluid, operating between saturated liquid and saturated vapor phases. As a goal, the leakage allowed from the rotary coupling was set at 454 g/yr (one pound per year), or .018 std.cc/sec. The flowrates of ammonia through the coupling were based on a total Space Station heat rejection capability of about 300 kilowatts (for two couplings). At the start of the investigation, the heat rejection was distributed among three separate fluid circuits as described in Table 1. Based on these flowrates, the coupling was to be sized to have a pressure drop of not more than 6.895 KPa (1 psi) for any circuit through the coupling.

Three conceptual designs for rotary couplings were investigated. An engineering model of each concept was designed and fabricated. Testing of each unit was then accomplished in an ammonia flow test facility which simulated the Space Station thermal bus. Based upon the results of the testing, an engineering prototype unit was designed and fabricated.

In addition to the rotary coupling designs, a support mechanism was designed which allows an astronaut to replace the fluid coupling quickly and easily. The objective was to design a device which allows essentially hands-off installation or removal of a coupling.

ROTARY COUPLING CONCEPTS

As mentioned, three concepts for rotary fluid couplings were evaluated. The evaluation was done in more of a serial fashion than in parallel so that results from previous testing and design experience could be factored into each design.

Each design included a shaft which rotated inside a stationary outer housing. The shaft contained flow passages which ran parallel to the rotating axis of the shaft, and then turned 90° out to annular passages between the outer diameter of the shaft and the inner diameter of the housing. Each of the annular passages was isolated by the use of various types of fluid seals. Each concept approached the problem of sealing in a slightly different manner.

Concept 1

The initial approach taken to designing the rotary fluid coupling is shown in figures 1 and 2. This design, called Concept 1, was fabricated of 316 stainless steel. A rotary shaft, which contained the seal glands, seals, and machined flow passages rotated inside of a mating smoothbore housing. The maximum internal diameter of the housing was 15.54 cm (6.12 in). The flow passage diameters were 1.27 cm (.50 in) for liquid and 2.54 cm (1.0 in) for gas. Four point contact bearings were used at each end of the shaft, exterior to the seals.

The interior surfaces of the housing were polished to a 2-4 microinch finish and then plated with electroless nickel to provide a very smooth, hard surface for the seals. The exterior surfaces of the shaft were also plated with the nickel. Some previous compatibility testing with ammonia had indicated that either the electroless nickel or chrome plating would be acceptable with anhydrous ammonia. The electroless nickel does not hold up well at all, however, when exposed to ammonium hydroxide. This was a concern due to the great affinity which ammonia has for water. The chrome plating, while not exhibiting this problem, would have been difficult to polish on the surfaces requiring the "super" finishes.

The seals selected for evaluation in this unit were rotary shaft seals sized for .32 cm (1/8 in) glands and were similar in cross-section to that shown in figure 3. The material for the seals was a compound of teflon with 15 percent graphite to improve wear properties. A metal spring located in the seal provides the initial pressure on the surfaces of the shaft and housing necessary for sealing. Pressure on the interior surfaces from the fluid increases the contact force to improve sealing.

During assembly of Concept 1 it became evident that the seals could not be stretched over the shaft without incurring permanent inelastic deformation in the seals. This resulted in some initial looseness of the seals in the glands. When the shaft was inserted in the housing, however, the seals were forced back to a tight fit with the shaft by the tolerances between the shaft and housing.

<u>Concept 2</u>

To improve on the basic Concept 1 design, a second design was proposed as shown in figure 4. This Concept 2 hardware was designed for testing purposes to have no flow passages in the shaft. Instead, ports were provided in the housing to allow ammonia to be pumped through the unit while the shaft rotated. The seal glands for this unit were located in the housing. The housing and shaft were fabricated of 6061-T6 aluminum alloy. Previous testing with ammonia heat pipes had shown that this alloy could withstand long term exposure to the ammonia. The housing was sulfuric acid anodized, but the shaft was coated with a proprietary coating of the General Magnaplate Corporation designated as "Magnaplate HCR." This coating applies a tough teflon film to the surface which improves the hardness and frictional properties.

The seals in this unit were similar in cross-sectional appearance to the seals used in Concept 1. The seals used in Concept 2, however, were sized for .64 cm (1/4 in) glands. The seal material selected for investigation was virgin TFE teflon. Historically, teflon rubbing on teflon does not hold up well, but the design of this unit appeared to warrant further evaluation of this combination.

The assembly of Concept 2 was much simpler and easier than Concept 1. The seals slipped into the internal glands with only slight hand manipulation. No permanent distortion of the seals was observed and the seals fit snugly into the housing. The installation of the shaft into the housing was done on a horizontal boring mill.

Concept 3

Concept 3, shown in figure 5, was designed to use mechanical face seals as the primary seals. To accomplish this, the housing was designed as a segmented unit. The shaft diameter was reduced to 7.62 cm (3.0 in) to accommodate commercially available seal designs. The sizes of the flow passages, however, remained the same as those used in Concept 1. The housing and shaft were fabricated of 6061-T6 aluminum alloy, as was Concept 2. The shaft was also coated using the Magnaplate HCR and the housing was sulfuric acid anodized.

The mechanical face seals used rotating rings of grade P-8290 carbon graphite from Pure Carbon Company. The mating rings were grade PS-9242 reaction bonded silicon carbide. Each ring was lapped to a flatness of 1-3 Helium light bands. The bellows and O-rings on the seal were fabricated of ethylene propylene.

Rotary shaft seals were used as backup seals in the design. These seals provided additional restriction for any leakage which would escape past the mechanical seals. Also, these seals would prevent the "rubber" parts of the mechanical seals from being exposed to a pressure in the range of the vapor pressure in the space environment. Ultrahigh molecular weight polyethylene was selected as the material for these secondary seals.

TESTING AND RESULTS

An ammonia flow test facility was designed and built to provide the range of flow and rotation rates required to simulate the Space Station coolant system. This system, shown in figure 6, was designed primarily to operate with liquid anhydrous ammonia. Flow rates from 0 to 0.167 l/s (0 to 2.65 gal/min) could be selected. A motor/gear drive provided rotation rates through the drive shaft of from 0.01 rpm to 1.00 rpm with an output torque of 667 N-m (5900 in-lb) available over the entire range. The temperature of the fluid within the system could be controlled from -37°C to +32°C (-35°F to 90 °F) using a separate temperature controlled liquid bath and heat exchanger.

Each unit was installed and tested in the ammonia flow facility until leakage of ammonia past the seals reached an unacceptable level or the target number of revolutions of the rotary coupling (116,800) were exceeded. The pressure within the test facility flow circuit was maintained between 786 KPa gage and 869 KPa gage (114 psig and 126 psig). This was controlled by maintaining the system temperature at 21 to 24 °C (70 to

75°F). The rotation rate was set at 1.0 rpm. This rate was somewhat arbitrary; however, the objective was to accelerate the test without modifying the performance of the seals.

Concept 1

The Concept 1 unit was tested through 31,560 revolutions before the test was stopped because of excessive leakage. The leakage past the primary seals was checked before rotation was started on unit, and it was found to be very high (95 scc/sec). The unit was rotated without ammonia for a period of one week to see if the seals would "seat." The leakage was checked with ammonia at that time and the leakage rate had dropped to .073 scc NH_3/sec. Although this rate exceeded the design goal, the decision was made to begin testing. The drive torque varied between 21.5 and 29.9 N-m (190 and 265 in-lb) during testing. The leakage past the primary seals ranged from .046 cc/sec to 1.65 cc/sec. Finally, after the unit had been driven through 31,560 revolutions (526 test hours) the leakage jumped to 50 scc NH_3/sec. The test was stopped at this point and the unit was pulled out of the test facility for inspection. While no specific cause for the leakage increase could be identified, several things were found which would contribute to the problem. First, considerable wear was noted on the seals. Residue from the seal wear was evident in the housing. Second, a bluish crystalline residue was also found in the housing. Analysis of the residue showed it to be primarily nickel. Apparently, the electroless nickel reacted with the trace ammonia vapor escaping past the seals and the water vapor from the air to form a salt compound. The presence of the residue in the housing could have contributed to the leakage failure; however, the leakage from this unit never achieved the desired goal.

Concept 2

The Concept 2 test unit accumulated 11,070 revolutions before it was removed from testing because of excessive leakage. The breakout torque for Concept 2 was 44.06 N-m (390 in-lb) at the start of testing. The running torque varied during testing from 20.79 to 23.73 N-m (184 to 210 in-lb). The leakage ranged from 2.6 to 20 scc NH_3/sec. This leakage also exceeded the design goal, but testing was continued to evaluate the long term performance of the unit. The leakage jumped sharply when the unit completed approximately 11,070 revolutions (184.5 hours). When the failure occurred, the leakage was high enough to cause significant ice formation on the unit, and attempts to measure the leakage would have put personnel at risk. When the unit was removed from the test facility and disassembled, a large amount of seal wear residue was found inside the housing. No other significant damage to the seals could be found other than the general uniform wear at the sliding interface. This would tend to confirm the undesirable performance of teflon rubbing on teflon. The surfaces of the housing and shaft were found to be virtually unaffected by the testing.

Concept 3

After 131,788 revolutions, the Concept 3 test was stopped. All performance goals for the unit had been exceeded, and examination of the unit was necessary to determine whether any design changes were required.

The unit was tested in the same manner as the other units except for the rotation rates. The initial rate was raised to 1.5 rpm. At 45,374 revolutions into the test, the test facility drive gear motor failed. A pump drive was quickly adapted, but this drive could only be controlled down to 3 rpm. Therefore, the remainder of the test was accomplished at this rate. The measured leakage from the test unit ranged between 1.9×10^{-6} and 2.0×10^{-5} scc NH_3/sec over the entire test. The torque value at breakout was 39.54 N-m (350 in-lb). The running torque was about 33.90 N-m (300 in-lb).

Disassembly of the unit revealed several latent problems. First, there was some corrosion of the shaft inboard of the outside set of secondary seals. Further in, where the ammonia concentration would have been higher, there was no corrosion. This led to the hypothesis that the corrosion was caused by ammonium hydroxide formed by the combination of ammonia vapor and water vapor from the air surrounding the test unit. A small test coupon of aluminum which had been coated with the Magnaplate HCR coating was exposed to ammonium hydroxide in an attempt to duplicate the type of corrosion found on the shaft. The coupon corroded in a similar fashion to the shaft. The second problem identified was due to the design of the silicon carbide mating rings in the mechanical face seals. The design did not include a retainer for the rings other than the spring force behind the rotating rings. When the system pressure was released, trapped gas between the primary and secondary seals caused the mating rings to act as pneumatic pistons to compress the springs. Movement of the mating rings allowed the rings to jam and prevented them from returning to their correct positions.

MULTIPASS COUPLING DESIGN

Based on the results from the testing program a multipass fluid coupling was designed which contains three separate flow circuits for different temperatures, pressures, and flowrates. The design, shown in figure 7, utilizes the technology of the Concept 3 test hardware with several improvements. Retaining snap rings were added to prevent the silicon carbide rings from moving out of position at system vent-down. Flanges were added to the secondary seals to prevent the possibility that the seals could slide at the wrong surface. New flange clamp rings were required to position and hold the seals using this approach. Metallic static seals were chosen to replace elastomeric o-rings between segments of the housing.

Currently, plans call for building one multipass coupling which will be evaluated in comparison testing with units built by other Space Station contractors.

SUPPORT MECHANISM DESIGN

As part of the total design of a rotary fluid coupling, in-orbit removal and replacement techniques were considered. In support of this effort, a conceptual design was created for a mechanism which would allow an astronaut to make a rotary coupling change quickly and easily.

The mechanism is illustrated in figure 8. The rotary coupling will be located in the center between two movable sealing plates. The fluid lines in and out of the rotary coupling will terminate at flanges on each end of the coupling. The movable sealing plates can be moved toward the coupling by a motor drive and lead screw. When the sealing plate reaches the correct position, mechanical stops will restrain the plate from advancing farther. A slide latch will be released at this point allowing the lead screw to continue to advance a drive collar which will serve as a hinge point for four latching jaws. The latching jaws will be driven inside of the flange on the rotary coupling and rotate out to grab a clamping lip on the coupling flange. The jaws will then apply a clamping force which will pull the coupling flange against the sealing plate. Some of the steps in this process are shown in figure 9.

Bellows will be used behind the sealing plate to allow the necessary movement of the plate relative to fixed hardware. The free position of the bellows will be about .32 cm (.125 in) away from the stopped position of the sealing plate. This will cause .32 cm (.125) stretch and 1.27 cm (.50 in) compression in the bellows over the entire movement.

Some development testing was performed to evaluate the capabilities of the static seals which would be required at the interface for each of the fluid lines. Shown in figure 10 is the design for a typical seal assembly. Figure 11 shows a cross-sectional view of the seal which was selected for this application. During testing, mating parts of the seal assembly were driven together using a load testing machine. The leakage external to the assembly was tested using helium gas at 862 KPa gage (125) psig internal to the assembly. A helium leak detector with a sensitivity of 1×10^{-10} scc He/sec could not detect leakage, even after bagging the unit for 24 hours.

The clamping load required between a coupling flange and a sealing plate is approximately 4448 N (1000 lbs) for each fluid line which must be sealed at the interface. Of this number, 3825 N (860 lbs) are due to the compression of the static seals.

CONCLUSIONS

The development program for a rotary fluid transfer coupling for Space Station identified a unit design (Concept 3) which exceeded the testing requirements that had been established. The design used mechanical face seals as the primary seals, with secondary rotary shaft seals of ultrahigh molecular weight polyethylene. During testing, liquid anhydrous ammonia was flowed through the unit while the shaft was rotated for the equivalent of over 20 years of rotation life. The leakage external to the unit did not exceed 2.0×10^{-5} scc NH_3/sec throughout the test.

A prototype multipass fluid coupling design, which incorporates the Concept 3 test unit sealing principles, has been completed. This unit will accommodate up to three separate flow circuits operating at different temperatures, pressures, and flowrates. The design can be modified easily for more or fewer flow circuits as required.

A design has also been described for a mechanism which allows a rotary coupling to be removed or replaced in orbit. By actuating a motor drive, the mechanism will connect fluid lines to the rotary coupling, apply the necessary clamping forces, and mechanically link the coupling to the structure providing torque.

TABLE 1

Design Heat Rejection for Space Station

Circuit No.	Temperature, °C	Heat Rejection, KW	Ammonia Flowrates, Kg/hr
1	1.7	36	51.7
2	21	140.4	214.1
3	32	120	190.5

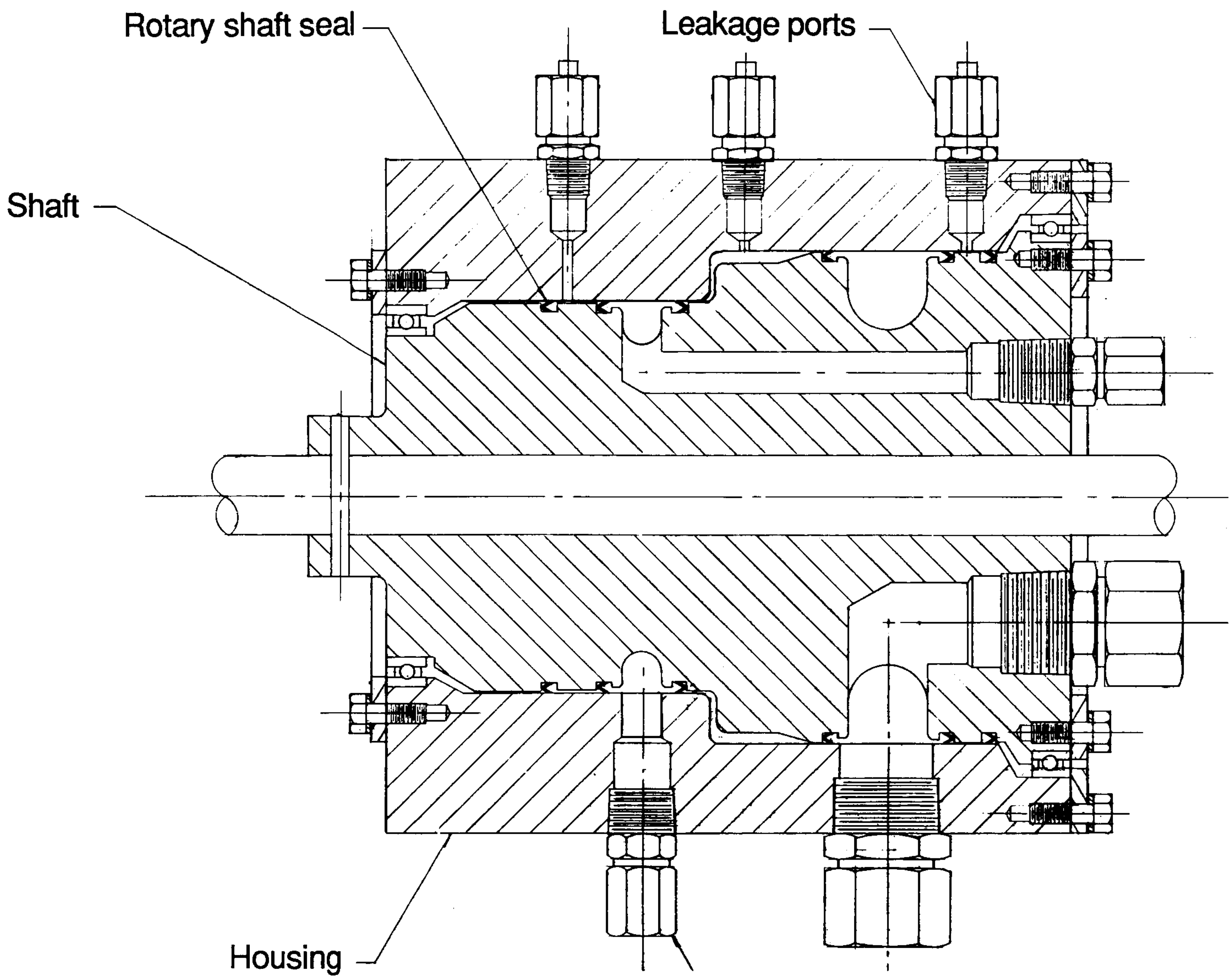


Figure 1. Concept 1 Rotary Coupling Design

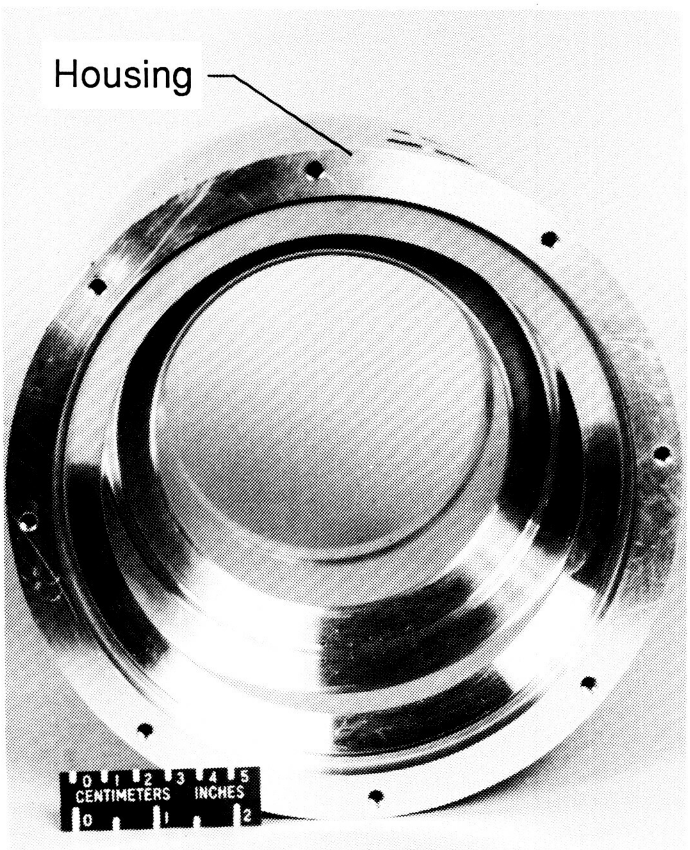


Figure 2. Concept 1 Test Hardware

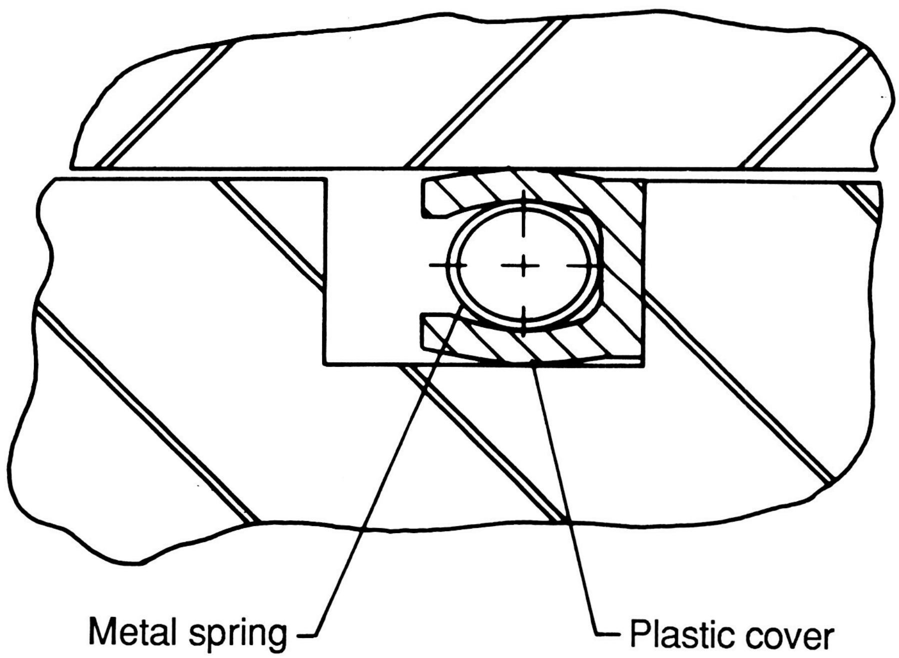


Figure 3. Typical Rotary Shaft Seal

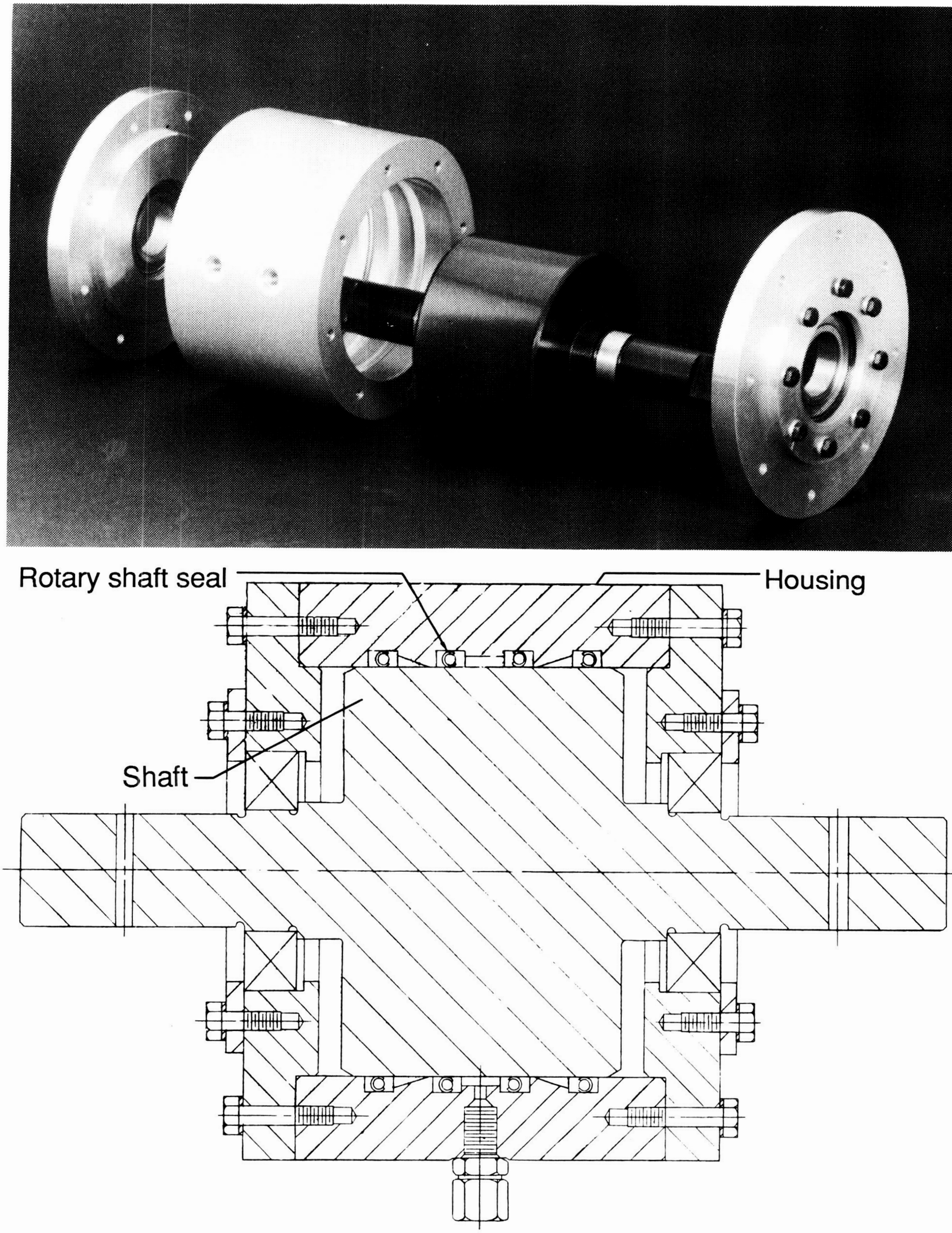
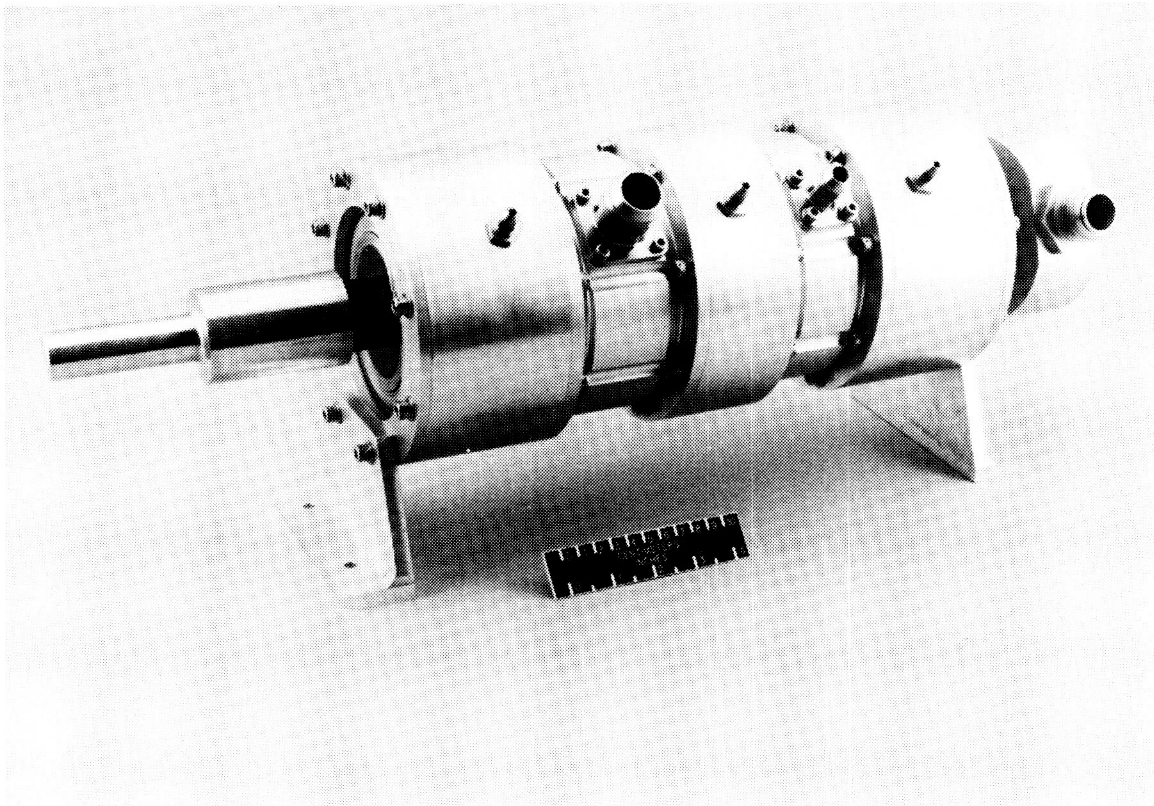


Figure 4. Concept 2 Rotary Coupling



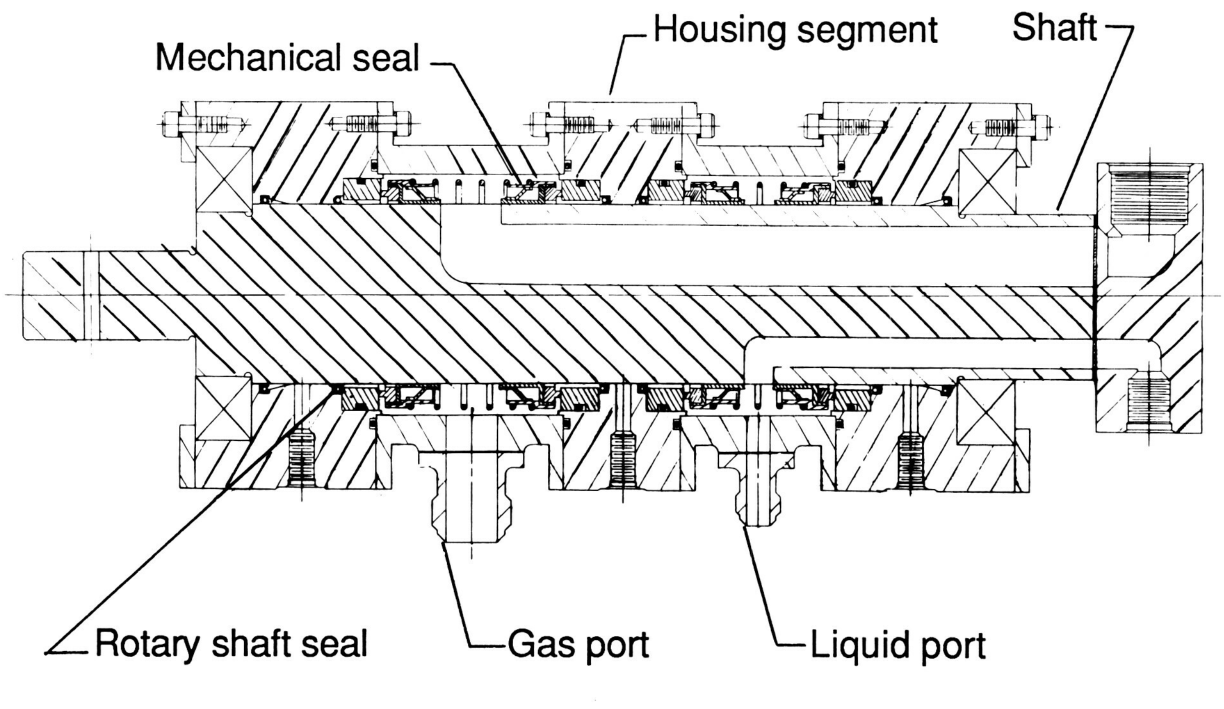


Figure 5. Concept 3 Rotary Coupling

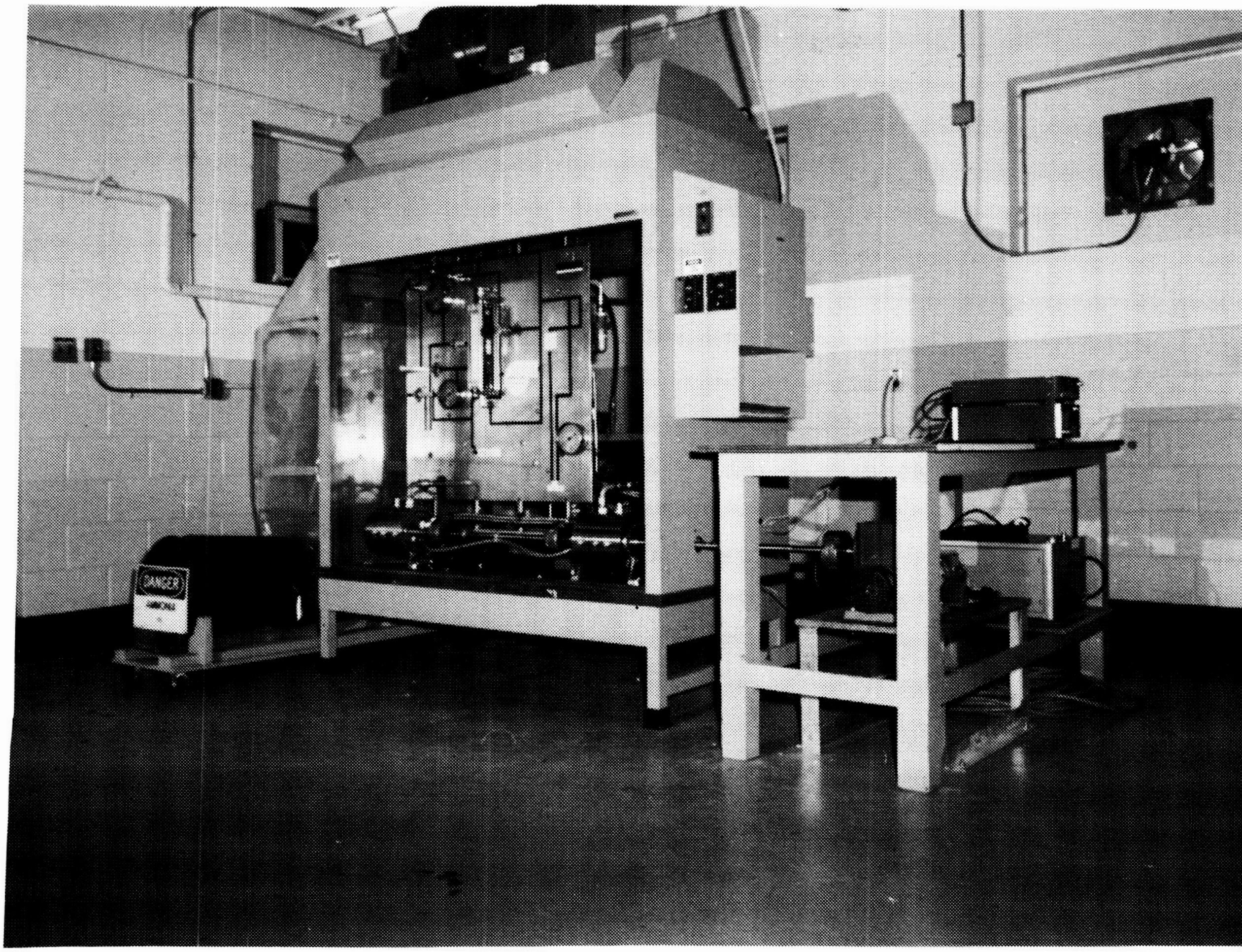


Figure 6. Ammonia Flow Test Facility

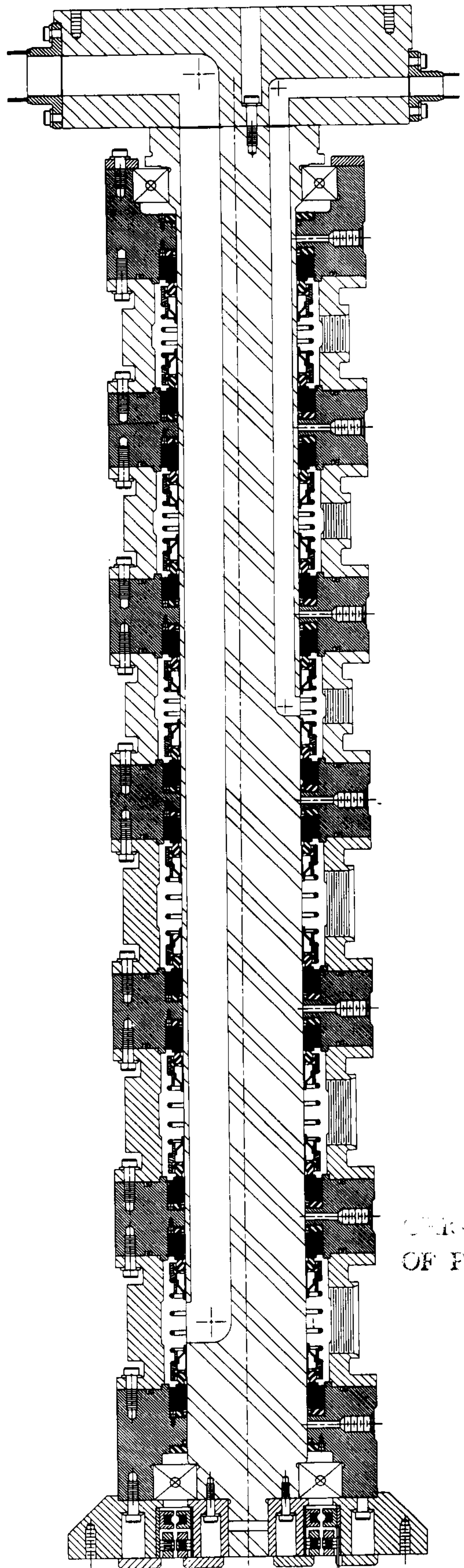


Figure 7. Expanded Concept 3 Design For Multiple Flow Passages

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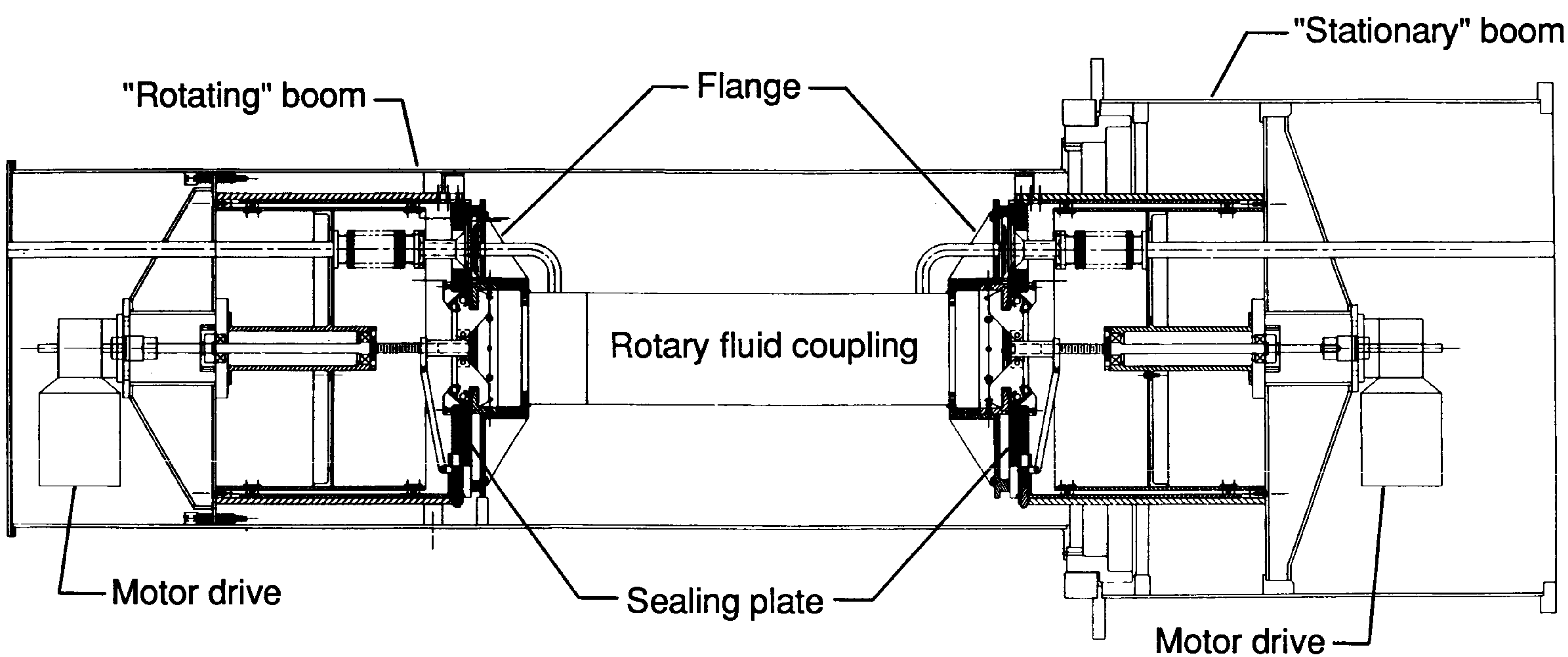

Figure 8. Support Mechanism For Rotary Coupling

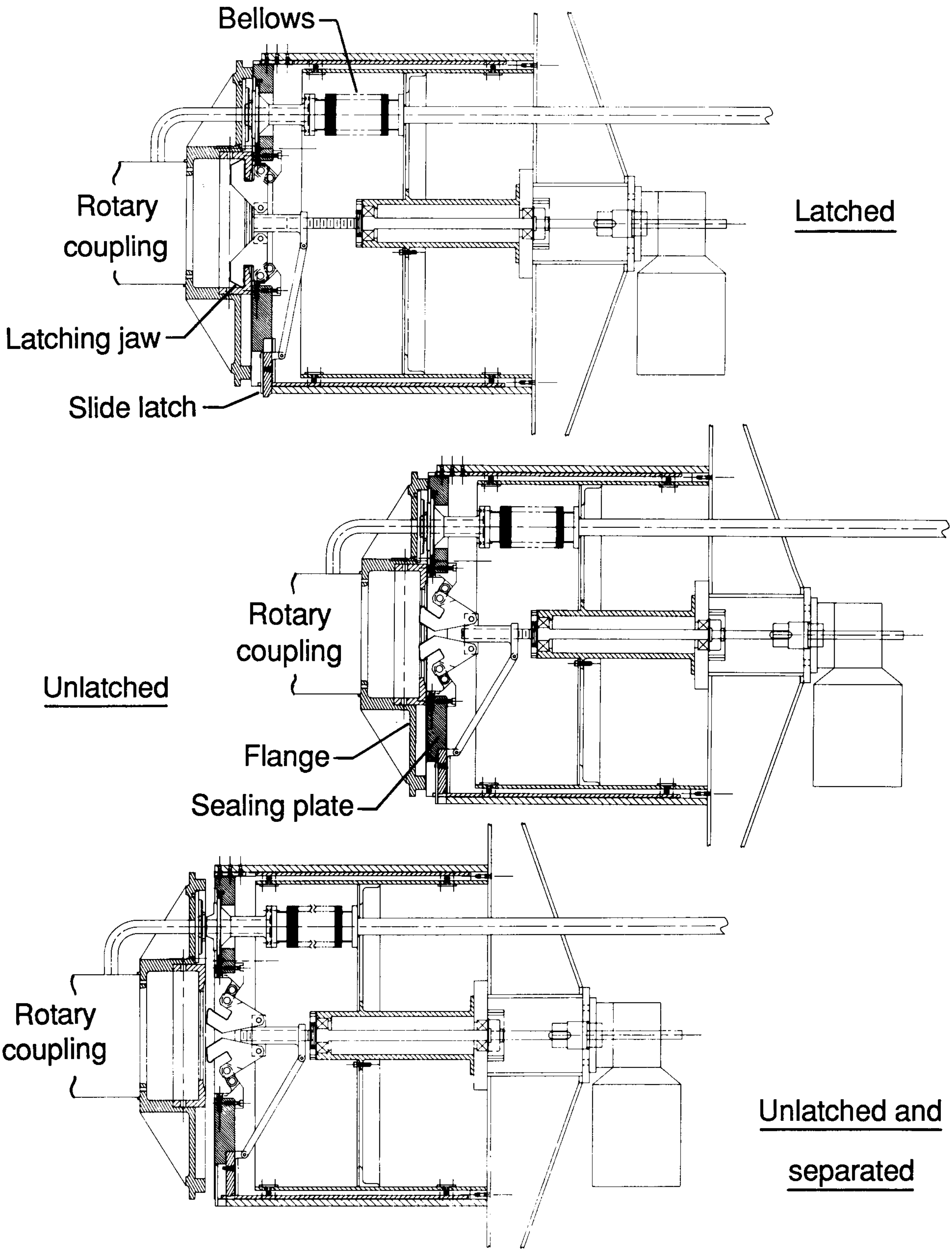

Figure 9. Latching Mechanism Movement

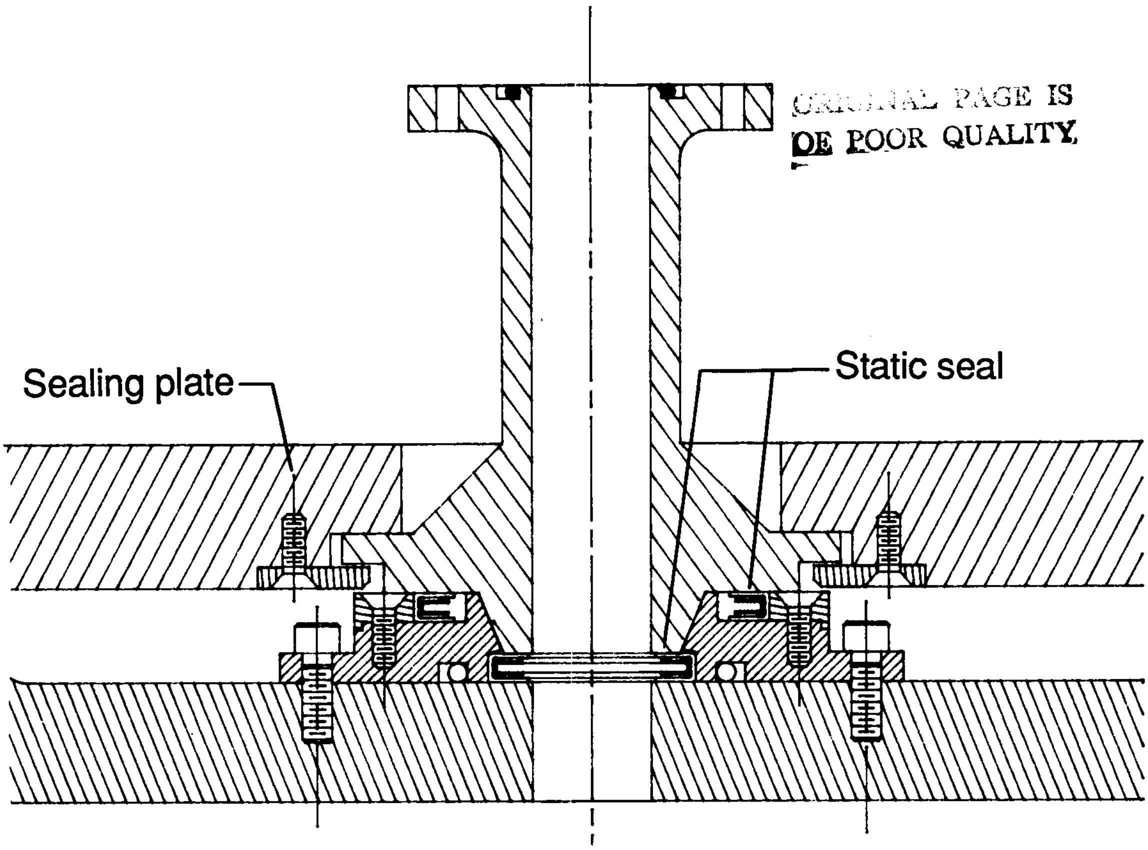

Figure 10. Seal Assembly

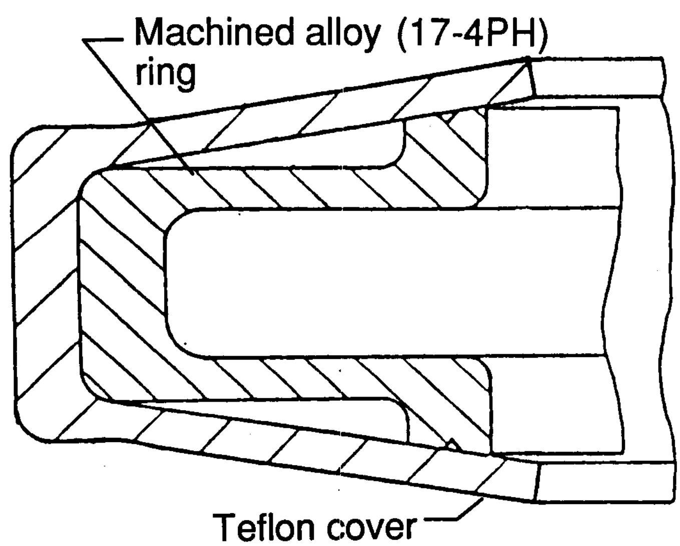

Figure 11. Static Seal