NASA Technical Memorandum 80093

Cyclic Tests of P-Bulb End-Seal Designs for a Shuttle-Type Wing-Elevon Cove Membrane Seal

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SUMMARY

Shuttle-type entry vehicles require a seal in the spanwise cove between the wing and elevon to prevent ingestion of aerodynamically heated gases. A silicone-rubber membrane seal has been incorporated into the Shuttle base-line design and provides an absolute seal along the wing span; however, the ends cannot be rigidly attached without significant twisting and stretching of the membrane. Consequently, the end closure is the most critical part of the design. A P-bulb end seal which is molded into the membrane has been identified as the best design approach.

Four P-bulb end-seal designs were tested at room temperature in a cyclic end-seal test apparatus. Test results show that the end seals have the durability required for a 100-mission life (neglecting possible elevated-temperature effects) and 3 of the 4 P-bulbs provide an adequate seal against a 7.0-kPa air-pressure differential. Antifriction material attached to the P-bulb rub surface reduced friction slightly but could degrade the sealing effectiveness. A flat rub surface molded into the P-bulb discouraged wrinkling and rolling and thereby reduced leakage. However, the P-bulbs lacked resilience, as indicated by increased leakage when P-bulb compression was reduced. The best P-bulb concept tested included an antifriction interface bonded to a flat surface molded into the P-bulb.

INTRODUCTION

Shuttle-type entry vehicles require various aerothermal barriers and seals to protect primary structures, internal equipment, and payloads. For example, the wing-elevon cove of the Shuttle orbiter is a critical area because the differential pressure across the wing promotes ingestion of aerodynamically heated gases into the cove on the lower surface between the wing and control surfaces, as illustrated in figure 1. Therefore, the cove must be sealed to prevent these hot gases from penetrating and degrading the vehicle structure. Wind-tunnel investigations have been conducted to define the aerothermal load to the cove (ref. 1) and the allowable gap in the rub seal where gas leakage would occur (ref. 2).

The rub-seal design, shown in the left inset of figure 1, is an early Shuttle base-line design. It consists of a spring-loaded wiper used to maintain contact between the seal and the rub tube at the hinge line. However, concern that adequate seal contact could not be maintained because of close fabrication tolerance requirements as well as anticipated structural deformations due to aerodynamic loads and differential thermal expansion resulted in development of alternate designs (ref. 3). The membrane-seal design (center inset), which is the most promising concept identified in reference 3, consists of a silicone-rubber membrane reinforced with Nomex[1] fire-resistant nylon fabric to form a positive seal between the wing and the elevon along the spanwise cove. A form of the membrane seal has been incorporated into the Shuttle base-line design as the redundant rub/membrane-seal design (right inset).

The membrane seal provides a positive seal along the wing span; however, the ends of the membrane cannot be rigidly attached without significant twisting and stretching of the membrane, which could lead to early failure. Consequently, the end seal becomes the most critical part of this seal design. The end closure must maintain contact (i.e., provide a seal) with an end plate while accommodating elevon deflection and differential growth between the wing and elevon. A P-bulb end-seal design which is molded into the membrane was identified in reference 3 as the best design approach. The P-bulb must adequately restrict leakage under the flight differential pressure at various degrees of P-bulb compression. Also, the P-bulb must be durable, since the elevons of a multimission vehicle are actuated many times during flight maneuvers and checkouts. Four P-bulb end-seal designs, which were developed from the design study of reference 3, were fabricated and tested at room temperature in a cyclic end-seal test apparatus to determine seal performance and durability. The test results are reported herein.

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SYMBOLS

F_f	friction force, N
l	length of P-bulb, $l = 0.424$ m
$\dot{m}_d$	leakage mass-flow rate for decreasing P-bulb compression, g/s
$\dot{m}_i$	leakage mass-flow rate for increasing P-bulb compression, g/s
t	time, s
δ	length of P-bulb compression (see fig. 2), m

[1]Nomex: Registered trademark of E. I. du Pont de Nemours & Co., Inc.

MEMBRANE-SEAL DESIGN

The membrane seal, illustrated in figure 2, is attached to the wing and elevon structures continuously along the cove span. Attachment of one side of the membrane along the elevon hinge line allows the membrane to rotate without stretching, thereby increasing seal life. A P-bulb end seal in contact with an end plate is also shown in figure 2. The P-bulb, which is installed in a partially compressed position, expands or compresses farther from this position to accommodate the structural deformation from aerodynamic loads and differential thermal expansion. This expansion and compression of the P-bulb is illustrated by the two sketches in figure 2. In the upper sketch, the P-bulb is shown touching the end plate but uncompressed. As shown in the lower sketch, the P-bulb is designed to fold inward as it is compressed. The oval cross section of the P-bulb was selected because it has less rubber bulk to fold when compressed than a circular cross section. The ends of the membrane are stiffened with embedded metal battens to assist in maintaining proper P-bulb contact with the end plate.

The rub friction between the end plate and the P-bulb was an additional design consideration, since friction can cause seal wear and therefore decrease seal durability. Two antifriction techniques were incorporated into the designs tested: (1) a dry, lubricative coating on the end plates and (2) fabric attached to the P-bulb rub surface. Additional design details for the membrane-seal design are presented in reference 3.

TESTS

Specimens

The four P-bulb end-seal test specimens are shown in figure 3. The specimens are made of silicone rubber and the membrane is reinforced with Nomex fibers and steel battens. The basic P-bulb cross section is oval, 1.91 cm long and 1.27 cm wide. Specimen 1 is plain, but the other three specimens have antifriction material attached to the rub surface of the P-bulb. The antifriction material is an elastic fabric composed of cloth-covered elastic cords. Cotton cloth was used for the test specimens because of its availability; however, other cloth material such as Nomex should offer greater durability. Specimen 2 (fig. 3(b)) has the antifriction material bonded to the curved rub surface in a "wraparound" manner. Specimen 3 has a narrow strip of antifriction material bonded to a flat rub surface. Specimen 4 has a large-diameter cord of antifriction material bonded on each side of the P-bulb rub surface. Pretest photographs of each specimen installed on the test apparatus are shown in figure 4. The test seal and the extension loop required to fit the test apparatus are shown in figure 4(a). In figures 4(b), 4(c), and 4(d), the texture of each of the antifriction materials is indicated by the appearance of the P-bulb rub surface which contacts the end plates.

Apparatus

A cyclic end-seal test apparatus was designed to hold a membrane seal 1.04 m long that could also fit an existing wind-tunnel test fixture. (See ref. 1.) The membrane covers an open side of a plenum with a volume of about 10 000 cm^3. (See fig. 5.) The P-bulb extends around the periphery of the plenum and presses against the end plates. When the plenum is pressurized with air, leakage at the end seals can be monitored with a flow meter in the supply line to the plenum. Figure 6 shows the entire apparatus, including the motor and drive linkage used to rotate the plenum about its pivot points. This causes the membrane end seals to rub against the end plates. The aluminum end plates were coated with Tufram,[2] a dry lubricant proposed for the Shuttle end plates. The end plates can be adjusted to compress the P-bulb to represent various structural translations.

The rotation of the end seal in the test apparatus is illustrated in figure 7. The shaded profile indicates the end-seal position at the rotational midpoint and the dashed lines indicate the position at the rotational extremes. Rotation from one extreme to the other results in the seal rubbing along an arc 10 cm in length. This rotation, with the end seal fixed around the end of the plenum, differs from the true seal movement produced by actuating the elevon. However, the rotation of this cyclic test is substantially greater than the design application for which one edge of the seal is fixed at the hinge line.

Procedure

The test sequence, shown in table I, consisted of determining the static rub friction, seal durability, and seal leakage for each end-seal specimen at room temperature. Initially, the force required to overcome the static rub friction was determined for each P-bulb at various compression lengths δ by measuring the force required to rotate the P-bulb end seals from the midpoint position (fig. 7). Next, the durability tests were performed by rotating the end seal at a rate of 0.05 cycle per second with the plenum pressure maintained at 7.0 kPa. This pressure is about twice the maximum pressure differential expected across the shuttle wing during the entry heating pulse (ref. 2). Only one end of the specimen was tested at a time, with the opposite end sealed by attaching the end plate to the plenum. The right end was tested for 1000 cycles at P-bulb δ values of 0.00, 0.32, 0.64, and 0.96 cm for a total of 4000 cycles. (See table I.) The left end was tested for at least 8000 cycles at $\delta = 0.64$ cm. Although leakage was monitored during the durability tests, special leakage measurements were made later to determine the seal effectiveness. The leakage was measured for values of δ from 0.00 to a maximum of 0.96 cm (increasing δ) then back to 0.00 (decreasing δ). Each δ setting was held for at least 18 cycles to establish stable leakage conditions.

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[2]Tufram: Registered trademark of General Magnaplate Corporation.

RESULTS AND DISCUSSION

Deformations

In contrast to the design expectations of reference 3, the outer walls of the oval P-bulbs did not fold inward when compressed. (See fig. 2 for expected compression.) Each P-bulb specimen is shown in figure 8 with the P-bulbs compressed against the end plates (δ = 0.64 cm). The P-bulb outer walls are folded outward rather than inward. This type of folding combined with the rub friction between the P-bulb and the end plate causes wrinkling and rolling of the P-bulb, especially in specimens 1 and 2 for which the contact surfaces were initially curved. A more stable compressed condition was evident for the other two specimens because they have flat contact surfaces. The P-bulbs were designed for a compression of 1.4 cm but were not tested at δ values greater than 0.96 cm because of the extreme P-bulb distortion produced by the wrinkling and rolling of the P-bulb.

Friction

The purpose of the antifriction interface material bonded to the P-bulbs was to reduce the rub friction between the P-bulb and the end plate. The force required to overcome static friction between the P-bulb and the end plate for various P-bulb compressions was measured to assess the effectiveness of the antifriction devices. This friction force F_f per unit length of P-bulb l as a function of δ is plotted in figure 9. For all designs, the force increased linearly with δ for values up to 0.64, and the magnitudes of the forces were about equal. Specimen 2, with the wraparound antifriction device, had the least friction. For $\delta = 0.96$, the friction force of specimens 1 and 4 was substantially higher than that of the other two specimens, probably because of increased rubber contact.

The friction caused some of the P-bulbs to roll. However, a reduction in P-bulb rolling occurred in some instances as the P-bulb was cycled, an indication that the friction force had decreased. In these instances, a thin film which formed on the P-bulb seal, possibly dirt, caused the reduced friction and subsequent decrease in the rolling motion. However, the end plates, which were coated with Tufram, remained clean in all tests. When it became necessary to clean the rubber seals with a solvent, the rubber became tacky and rub friction increased. Therefore, the use of cleaning solvents or other fluids near the seal must be carefully controlled to avoid rubber compatibility problems that could drastically change the friction coefficient. In general, antifriction material used on the P-bulbs had a minimal effect on friction reduction in these tests.

Leakage

The P-bulb seal leakage was minimal for most of the durability tests; therefore, leakage data were not recorded continually. After the durability tests of all specimens, it was discovered that the instrument, which indicated unmeasurable leakage, was not reliable. Therefore, special leakage data were obtained over a range of P-bulb δ values from 0.00 to 0.96 cm. The leakage flow rates $\dot{m}_i$ plotted in figure 10 were obtained at the midpoint position of the 18th cycle of each test as δ was increased incrementally from 0.00 to 0.96. The leakage was excessive for $\delta = 0.00$ as might be expected. In all cases, leakage was reduced substantially with increased δ. As previously discussed, the tendency for the P-bulb to roll increased with increasing δ. The leakage increased substantially for specimens 1 and 2 when the P-bulb began to roll. A slight increase in leakage occurred for specimen 4, but the leakage for specimen 3 essentially decreased monotonically with increasing δ. This good performance resulted because the flat rub surface of this design maintained good contact over the entire range of δ. The high leakage of specimen 2 was caused primarily by flow through the porous fabric used as the antifriction interface. Specimen 3, which had similar interface material, performed significantly better than specimen 2 because the interface material had a finer mesh and was impregnated with rubber adhesive, thereby eliminating the flow through the fabric.

Based on the test results of reference 2, in which the allowable spanwise gap for the rub seal was determined to be 0.6 mm, and assuming a span between end seals of about 1.0 m, the allowable leakage at each end seal of the Shuttle was estimated to be about 0.4 g/s. For $\delta > 0.3$ cm, specimens 1, 3, and 4 maintained a leakage rate below the estimated allowable leakage rate, as shown in figure 10. In fact, the leakage rate for specimen 3 is less than 13 percent of the allowable leakage rate for $\delta > 0.1$ cm, and therefore specimen 3 is obviously the best of the four designs tested.

Different leakage rate results, however, were obtained when δ was decreased from the maximum compression of 0.96 cm to lower values rather than increased as in the previous tests. (See table I.) When δ was instantaneously reduced, greater leakage occurred at each position, indicating a lack of P-bulb resilience. The ratio of the leakage rate measured when δ was being decreased to the leakage rate measured when δ was being increased is shown in figure 11 for a typical value of $\delta = 0.11$. The ratio is plotted as function of time t after compression was decreased from 0.32 cm to 0.11 cm. When the end plates were retracted to reduce δ, P-bulb hysteresis allowed increased leakage to occur. As the test continued for a duration of 360 s (18 cycles) with $\delta = 0.11$ cm, the seal partially recovered, but the leakage did not reach the level obtained earlier $\left(\dot{m}_d/\dot{m}_i = 1\right)$ when δ was increasing. All the P-bulbs tested lacked resilience. As shown in figure 11, specimen 2 was the most resilient, but resilience is not the only consideration for design effectiveness. As indicated earlier in figure 10, specimen 2 allowed the greatest leakage. Specimen 3 still must be considered the preferred design in spite of poor resilience, because of its overall seal effectiveness. (See fig. 10.)

Although the present tests were conducted at room temperature, the silicone rubber of which the membrane seal is molded has a working temperature much greater than the Shuttle wing-elevon cove design temperature of 450 K, which is dictated by the aluminum structure. Reference 3 suggests insulative coatings of the membrane where greater temperatures are expected. However, the results of references 1 and 2 indicate that the Shuttle cove temperature should be below 450 K if the seal is effective, and will remain near ambient temperature during the critical Shuttle-entry heat pulse. If substantial leakage occurs around the P-bulb end seal, however, local heating from direct hot-gas flow impingement could produce catastrophic seal failure. Therefore, it is important in any application of the P-bulb design that continual P-bulb to end-plate contact be insured to minimize leakage.

Durability

All the P-bulb seals demonstrated good durability. In some cases the P-bulbs wrinkled and rolled badly for as many as 8000 test cycles (estimated to be the equivalent of at least 100 Shuttle missions), but did not suffer any serious damage. The antifriction interface experienced very little wear, as indicated in the posttest photographs of the right end seal shown in figure 12. These photographs were taken after the 4000 test cycles at the various P-bulb compression settings and were typical of both ends of the test specimens. The greatest wear occurred on the double-cord interface (specimen 4), as shown by the arrow in figure 12(d). The cord tore loose from its adhesive where the center line of the cord rubbed tangentially to the rotation of the apparatus. The failure occurred at the maximum compression of 0.96 cm near the end of the 4000 cycles. The tear was probably caused by shear produced from differing frictional forces on the cord and the adjacent rubber. There was no other substantial wear apparent. Since the rubbing motion of the present test apparatus is more severe than that expected for flight vehicles, it is believed that all the end-seal designs tested at room temperature showed durability sufficient for a 100-mission life requirement (neglecting possible elevated-temperature effects).

CONCLUDING REMARKS

Four P-bulb end-seal designs for a Shuttle-type wing-elevon cove membrane seal were tested at room temperature in a cyclic end-seal test apparatus. Test results show that all the P-bulb end seals have the durability required for a 100-mission life (neglecting possible elevated-temperature effects) and 3 of the 4 end seals provide an adequate seal against a 7.0-kPa air-pressure differential. Antifriction material attached to the P-bulb rub surface reduced friction slightly but could degrade the sealing effectiveness. A flat rub surface molded into the P-bulb discouraged wrinkling and rolling of the P-bulb and thereby reduced leakage to as much as 13 percent of the estimated allowable leakage of the Shuttle wing-elevon cove. However, the P-bulbs lack resilience as indicated by increased leakage when P-bulb compression was reduced. The best P-bulb design tested included an antifriction interface bonded to a flat surface molded into the P-bulb.

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2. Scott, C. D.; Murray, L. P.; and Milhoan, J. D.: Shuttle Elevon Cove Aerodynamic Heating by Internal Flow. AIAA Paper 77-757, June 1977.

3. Varisco, A.: Design and Fabrication of Elevon Cove Thermal Protection Systems for Aerospace Vehicles. NASA CR-159055, 1979.

TABLE I.- TEST SEQUENCE

End	δ, cm	Cycles	Compression
Static rub friction			
Right	0.00	---	---
	.32	---	---
	.64	---	---
	.96	---	---
Seal durability			
Right	0.00	1000	---
	.32		---
	.64		---
	.96		---
Left	.64	8000	---
Seal leakage			
Right	0.00	18	Increasing
	.11		
	.21		
	.32		
	.42		
	.53		
	.64		Decreasing
	.74		
	.85		
	.96		
	.64		
	.32		
	.11		
	0		

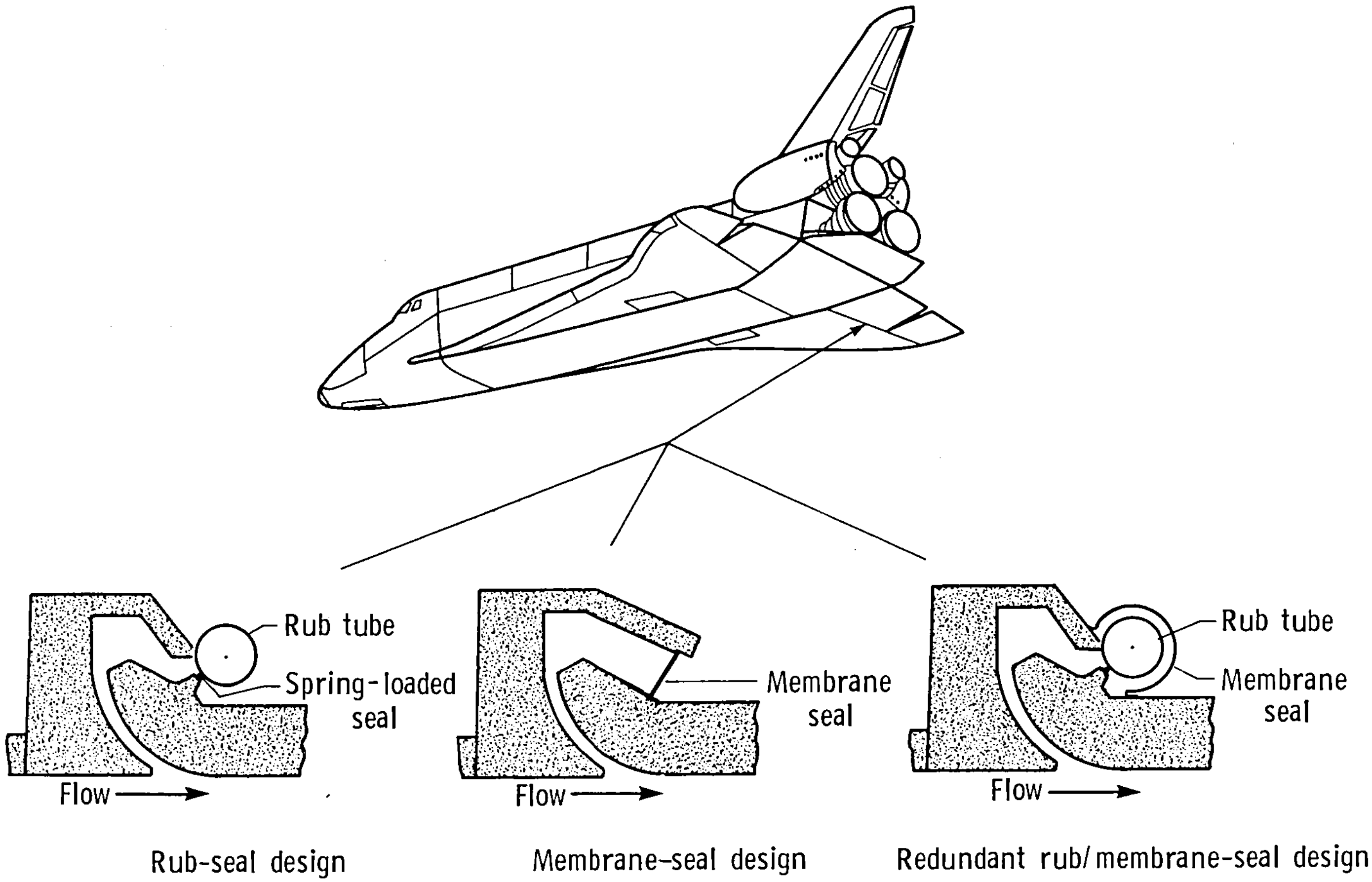


Figure 1.- Shuttle orbiter with various wing-elevon cove seal designs.

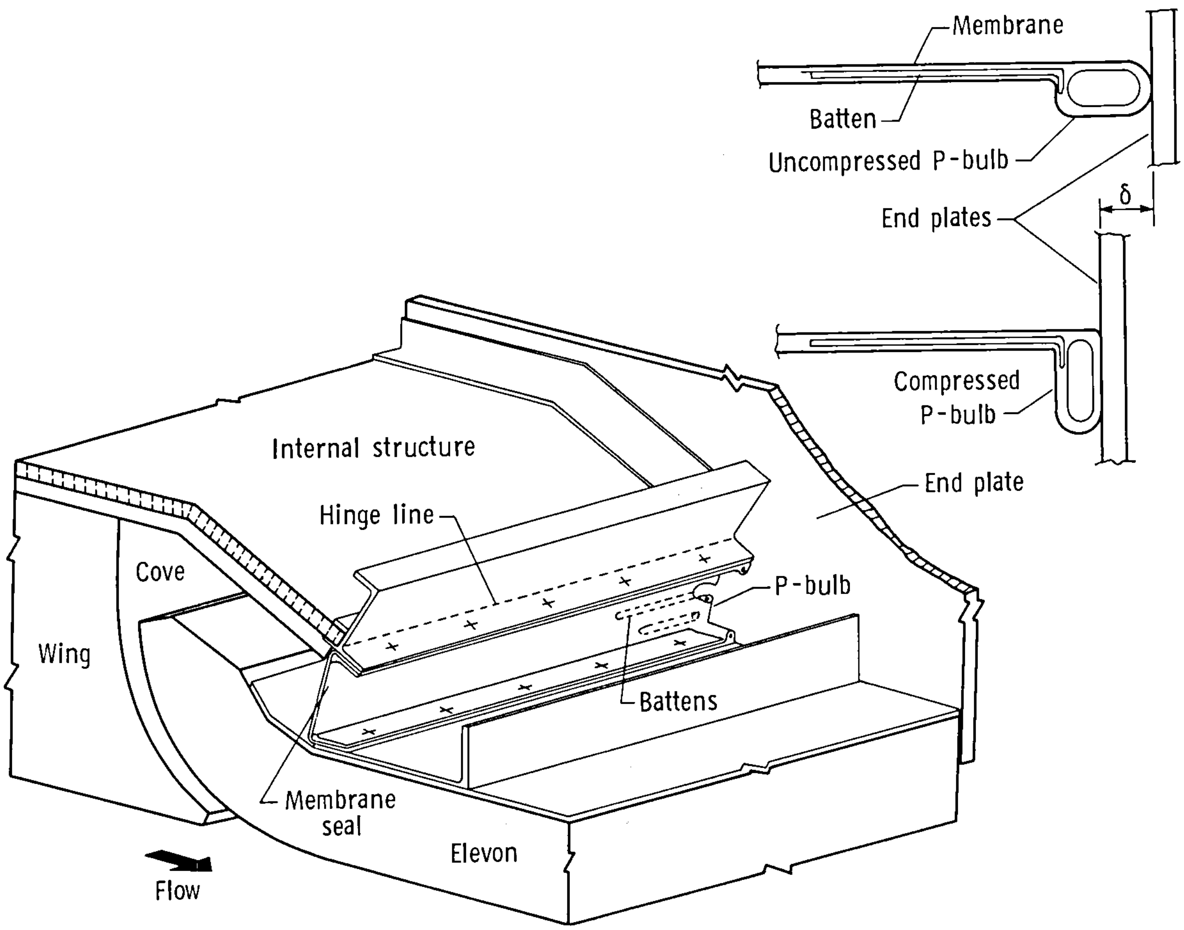
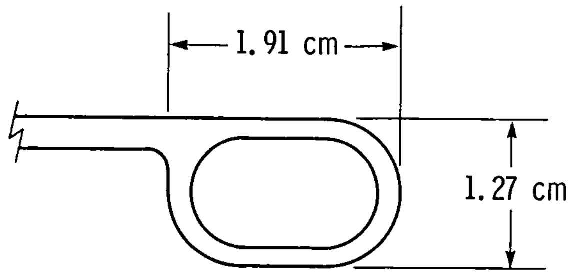
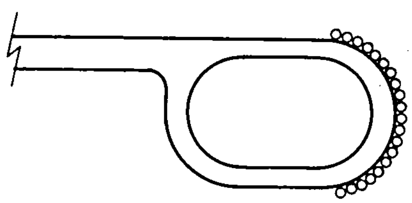


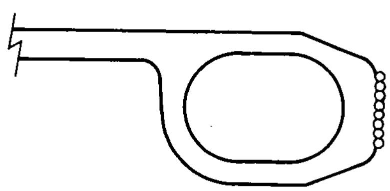
Figure 2.- Membrane-seal design.



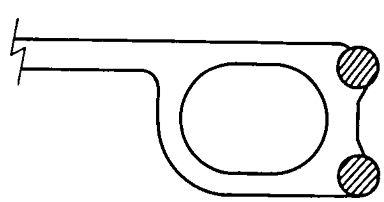
(a) Specimen 1 (plain).



(b) Specimen 2 (wraparound).

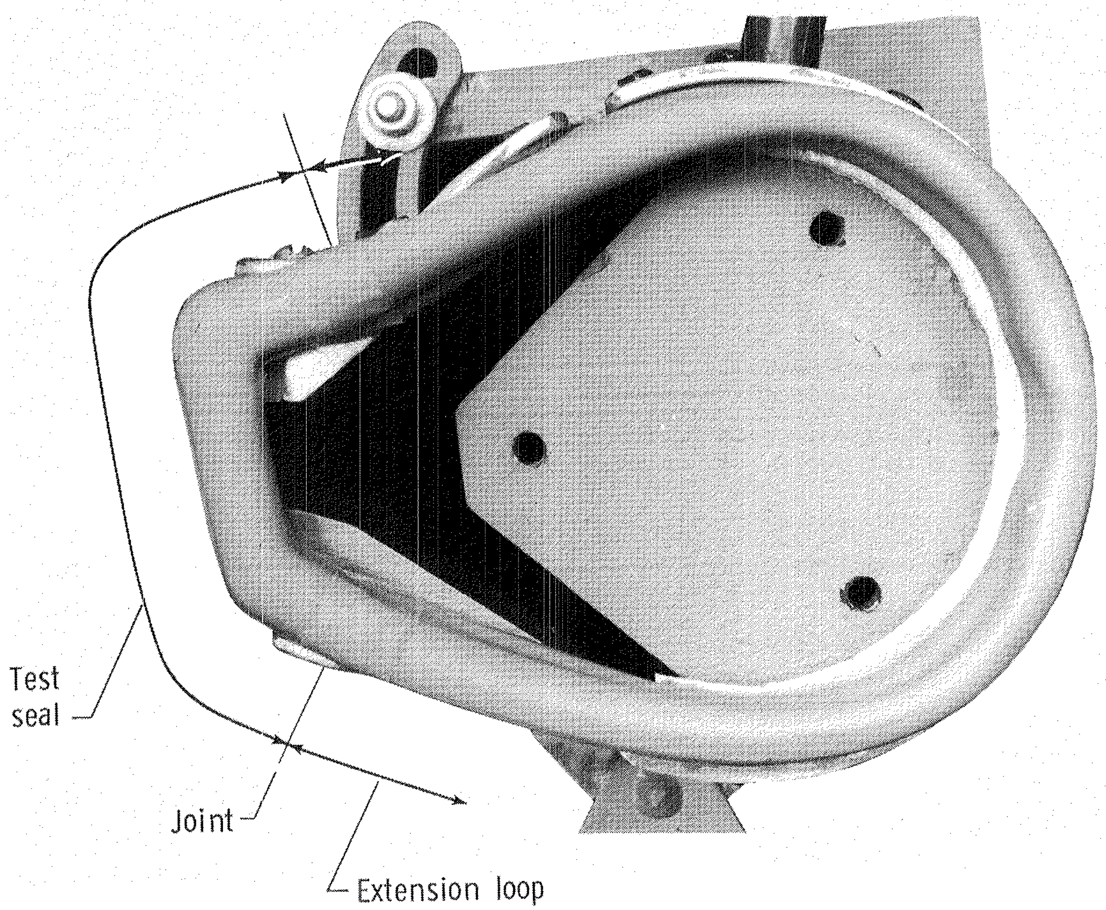


(c) Specimen 3 (flat).



(d) Specimen 4 (double cord).

Figure 3.- Cross sections of P-bulb end-seal specimens with various antifriction attachments.



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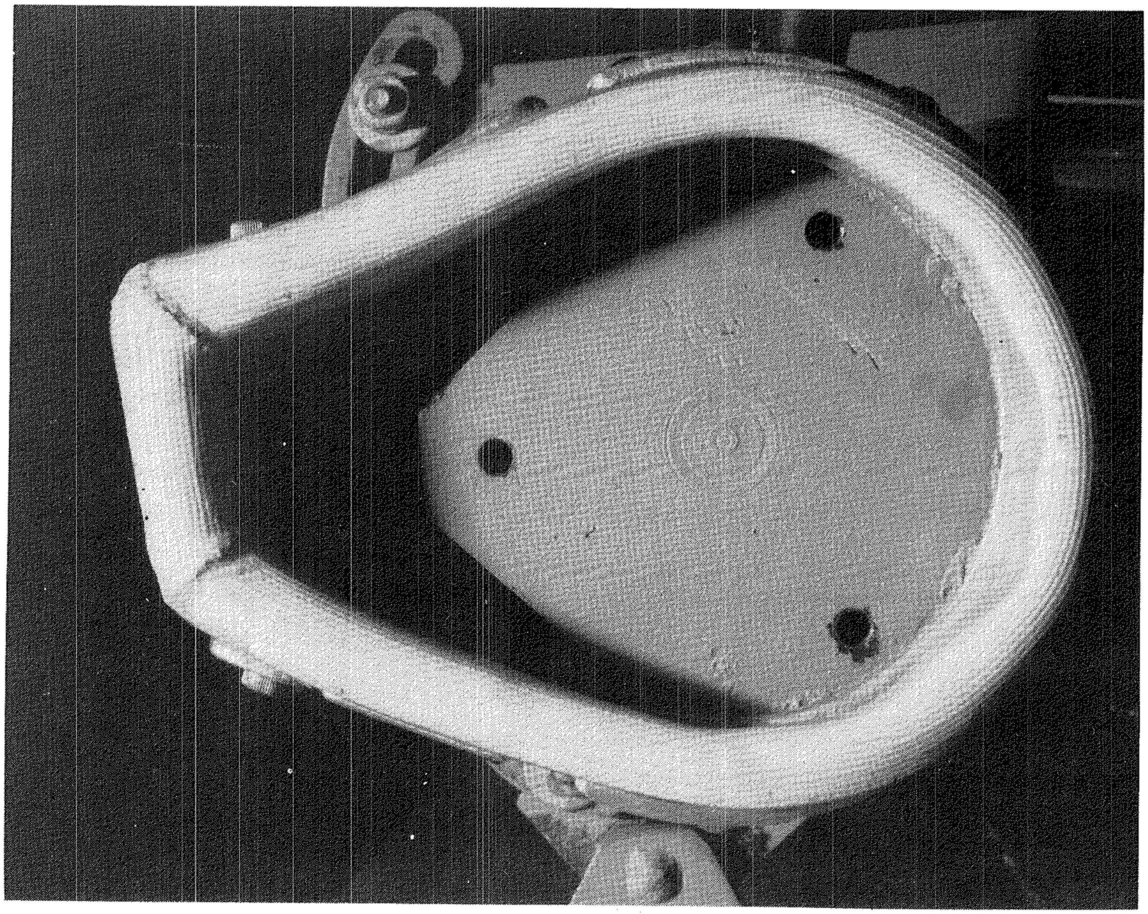
(a) Specimen 1 (plain).

Figure 4.- P-bulb end seals in the cyclic end-seal test apparatus.



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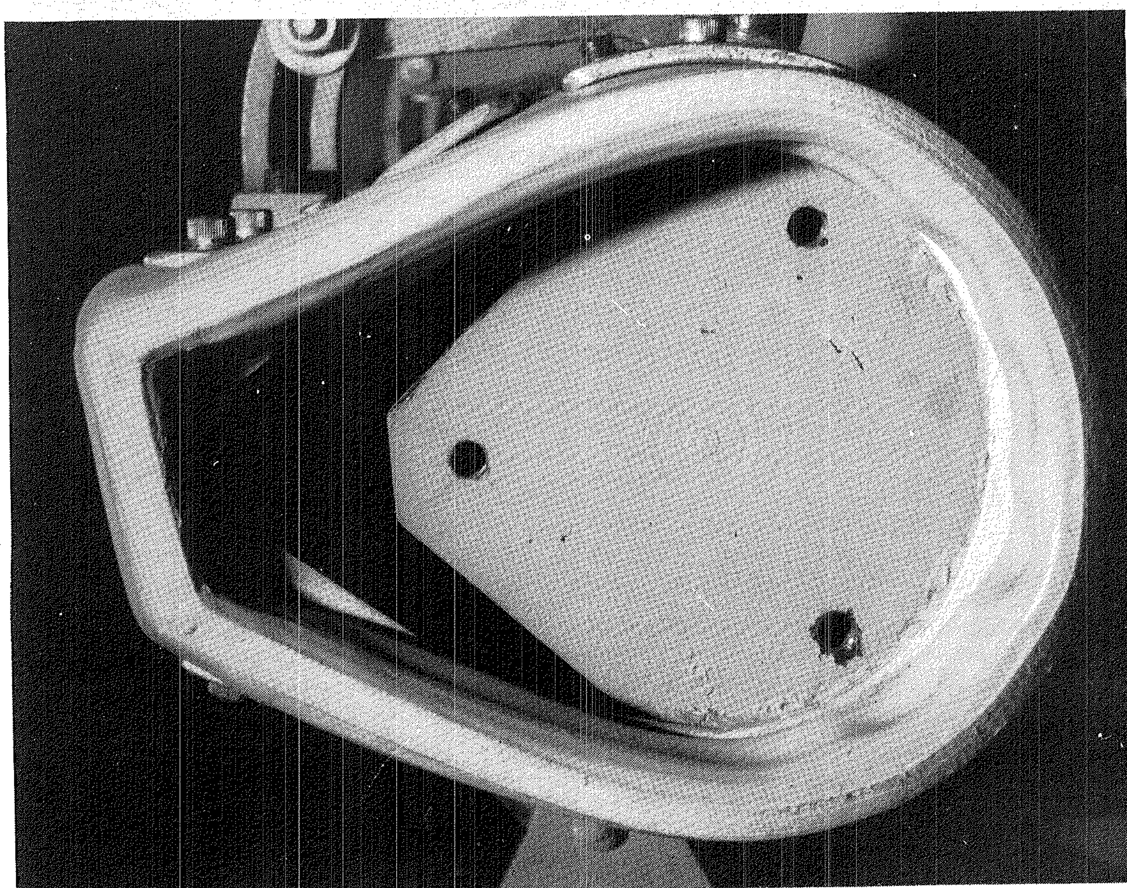
(b) Specimen 2 (wraparound).

Figure 4.- Continued.



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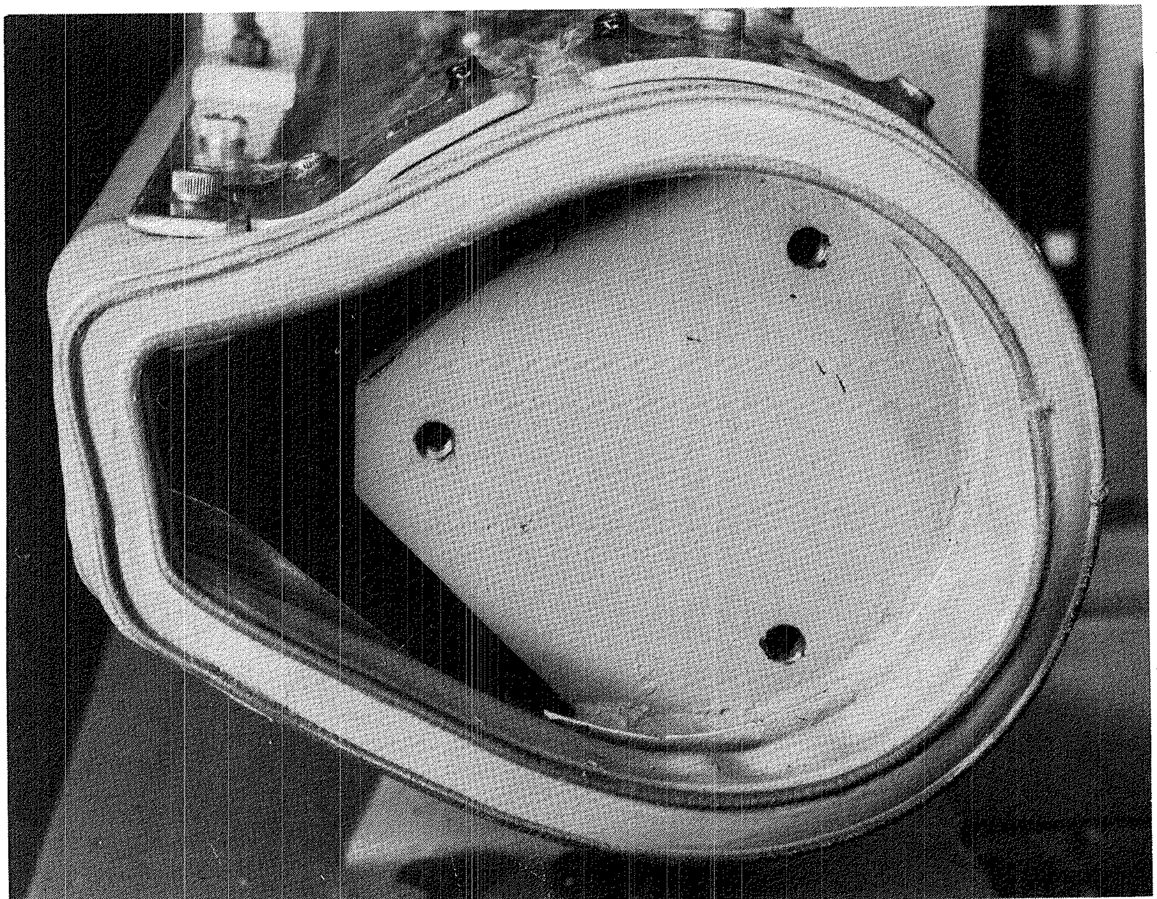
(c) Specimen 3 (flat).

Figure 4.- Continued.



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(d) Specimen 4 (double cord).

Figure 4.- Concluded.

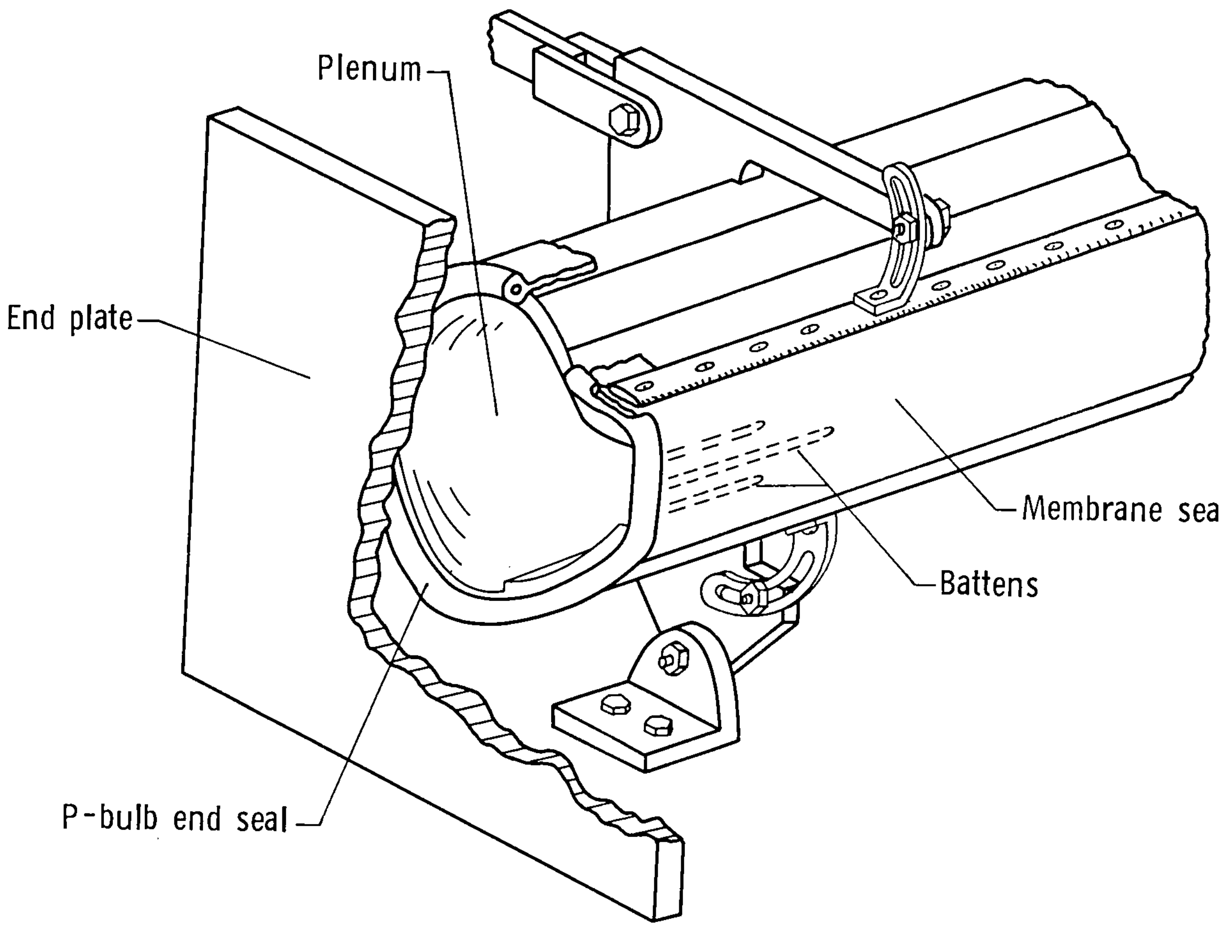

Figure 5.- Cyclic end-seal test apparatus – conceptual sketch.

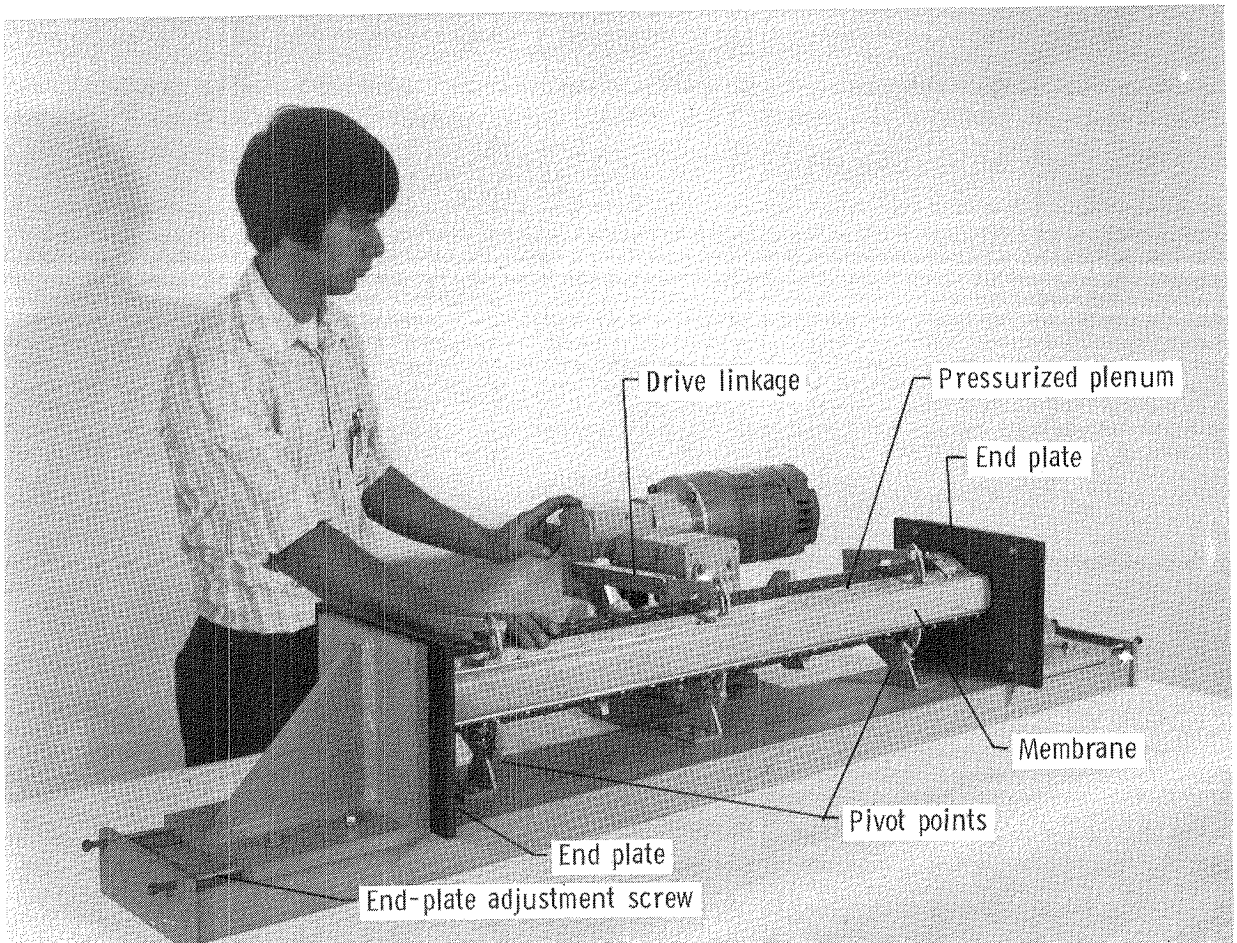

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Figure 6.- Cyclic end-seal test apparatus.

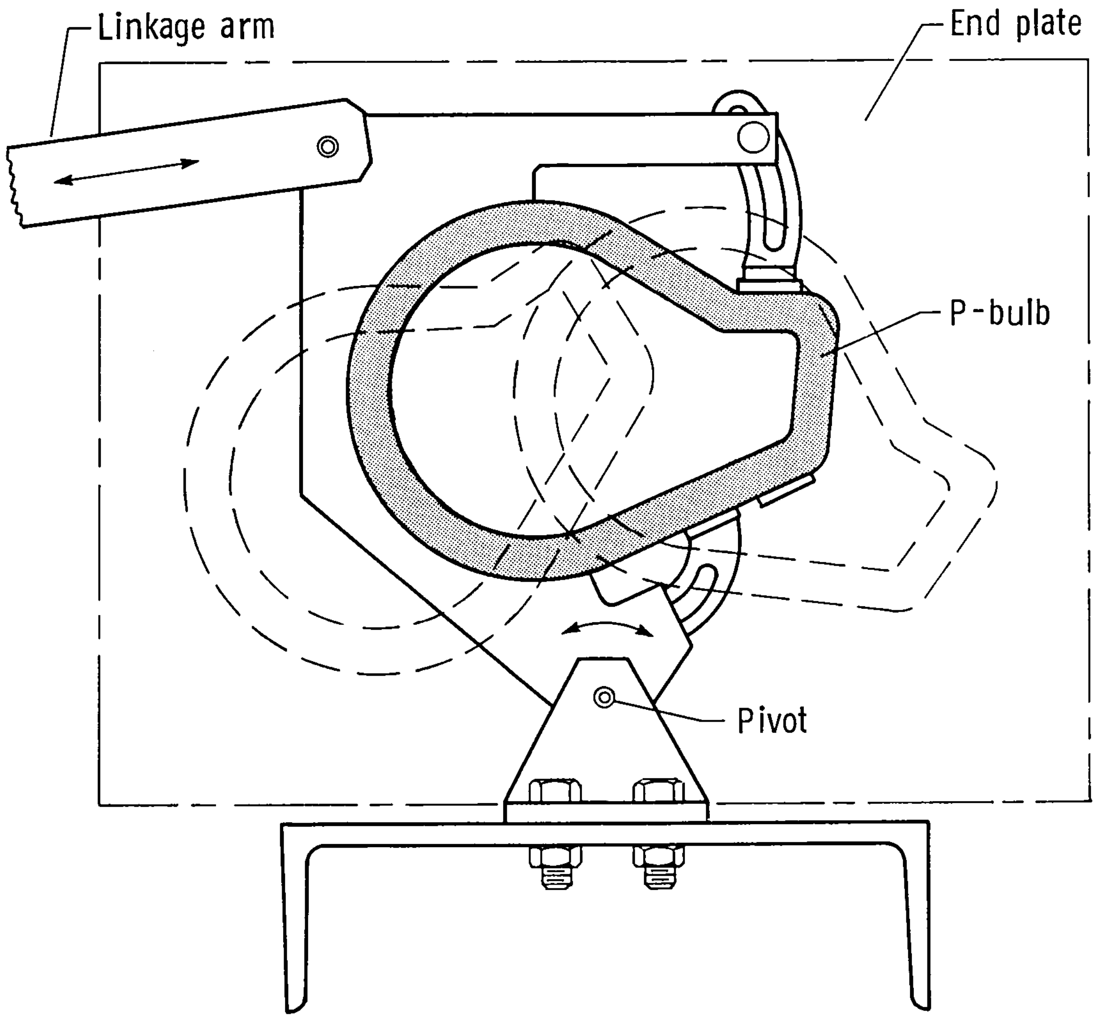
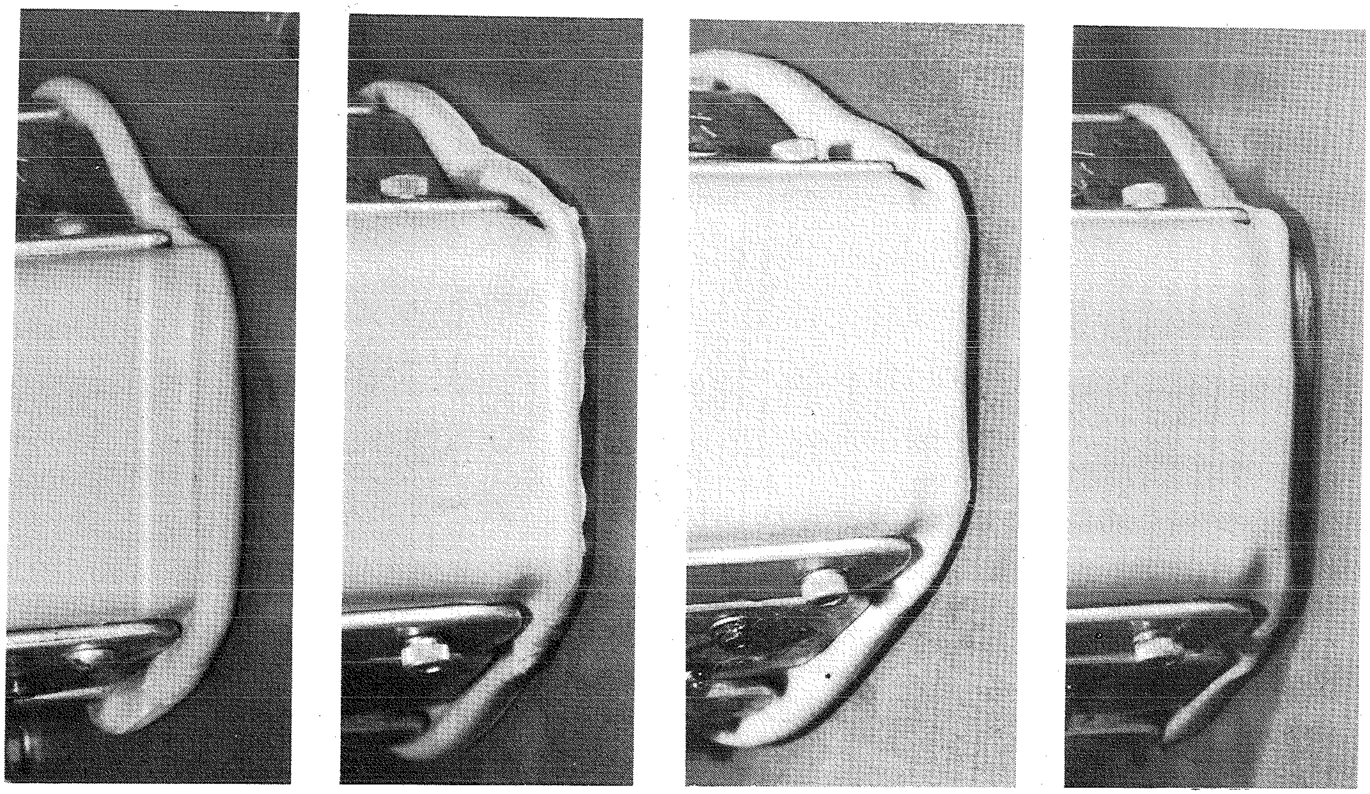


Figure 7.- Three rotational positions of an end seal during a cyclic test.



(a) Specimen 1 (plain).

(b) Specimen 2 (wraparound).

(c) Specimen 3 (flat).

(d) Specimen 4 (double cord).

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Figure 8.- P-bulb end seals pressed against end plate with 0.64-cm compression.

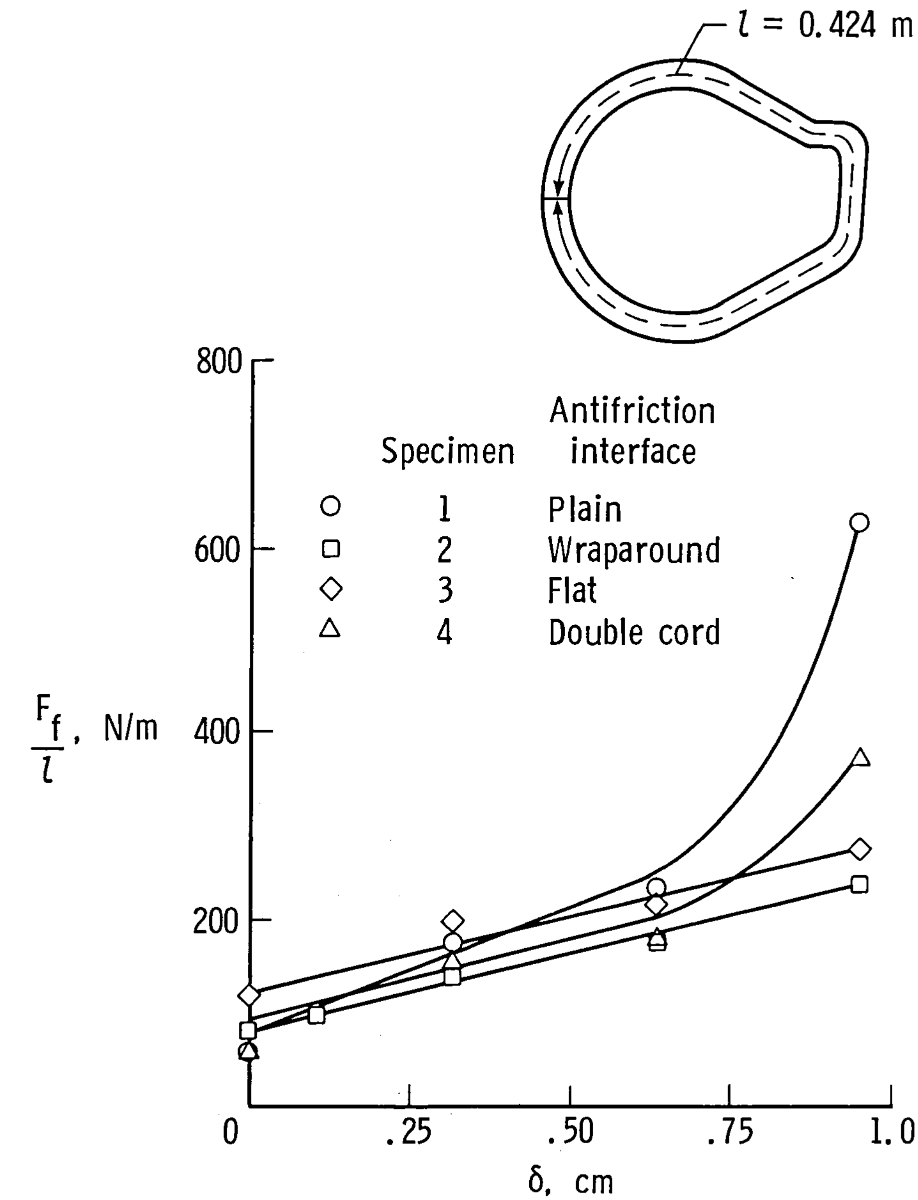


Figure 9.- Variation of rub friction force per unit length with P-bulb compression for various P-bulb designs.

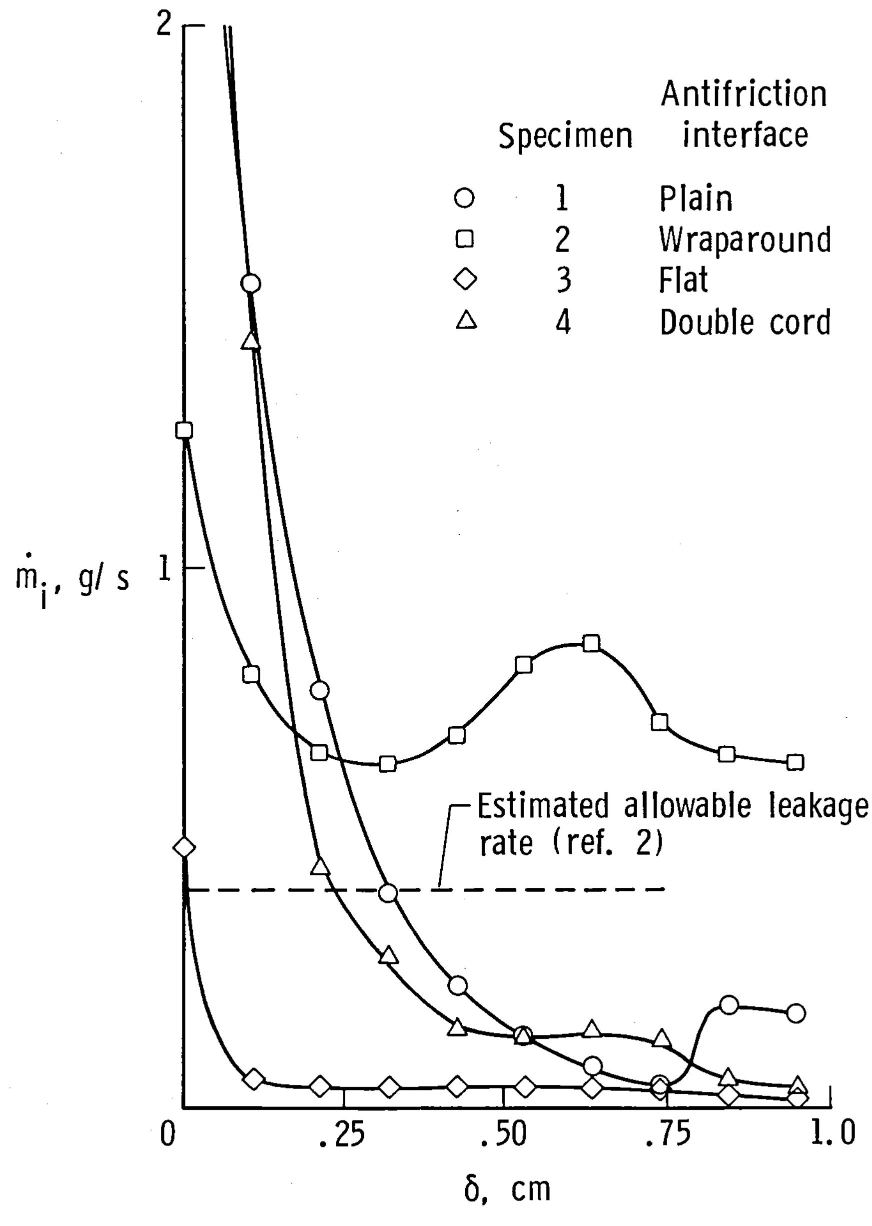


Figure 10.- Leakage around end seals at various compression lengths.

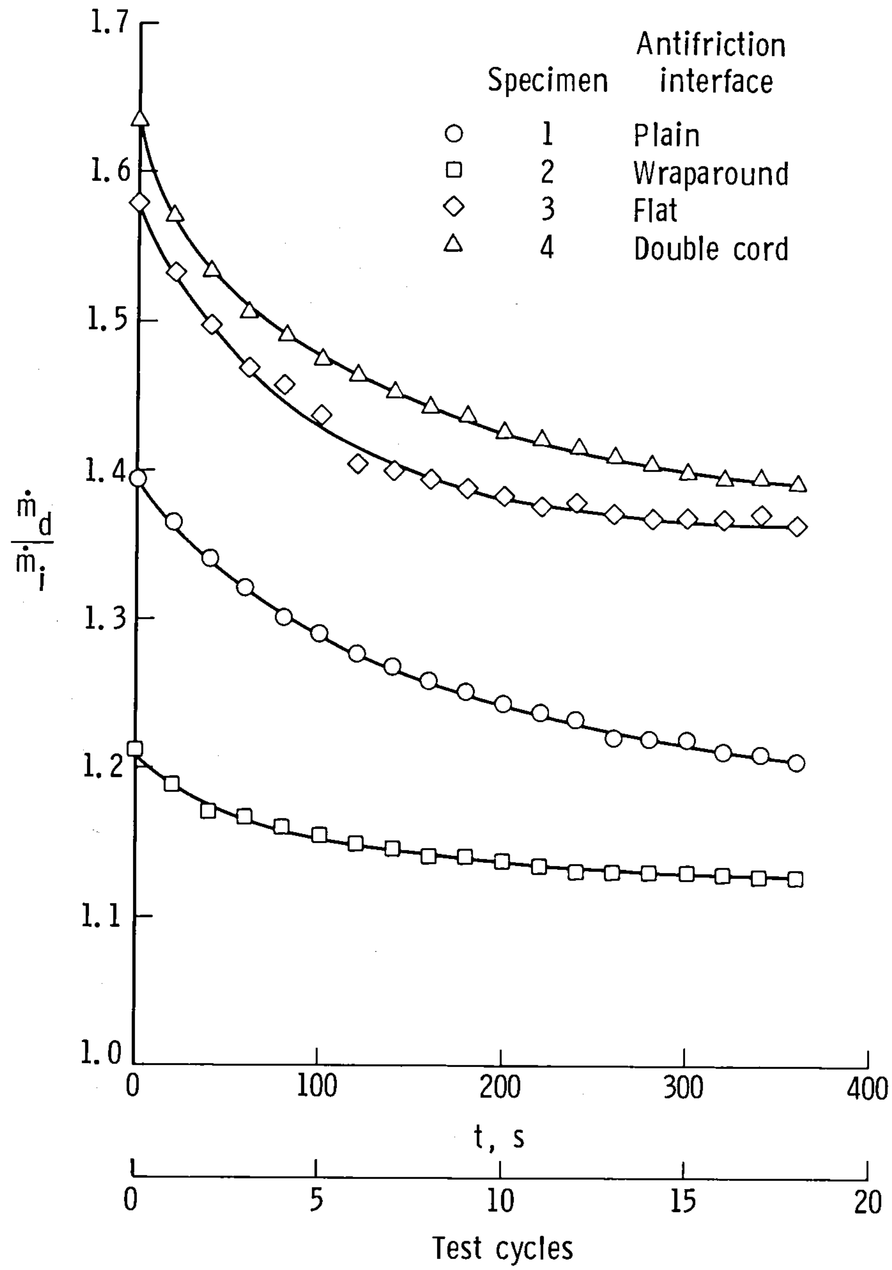
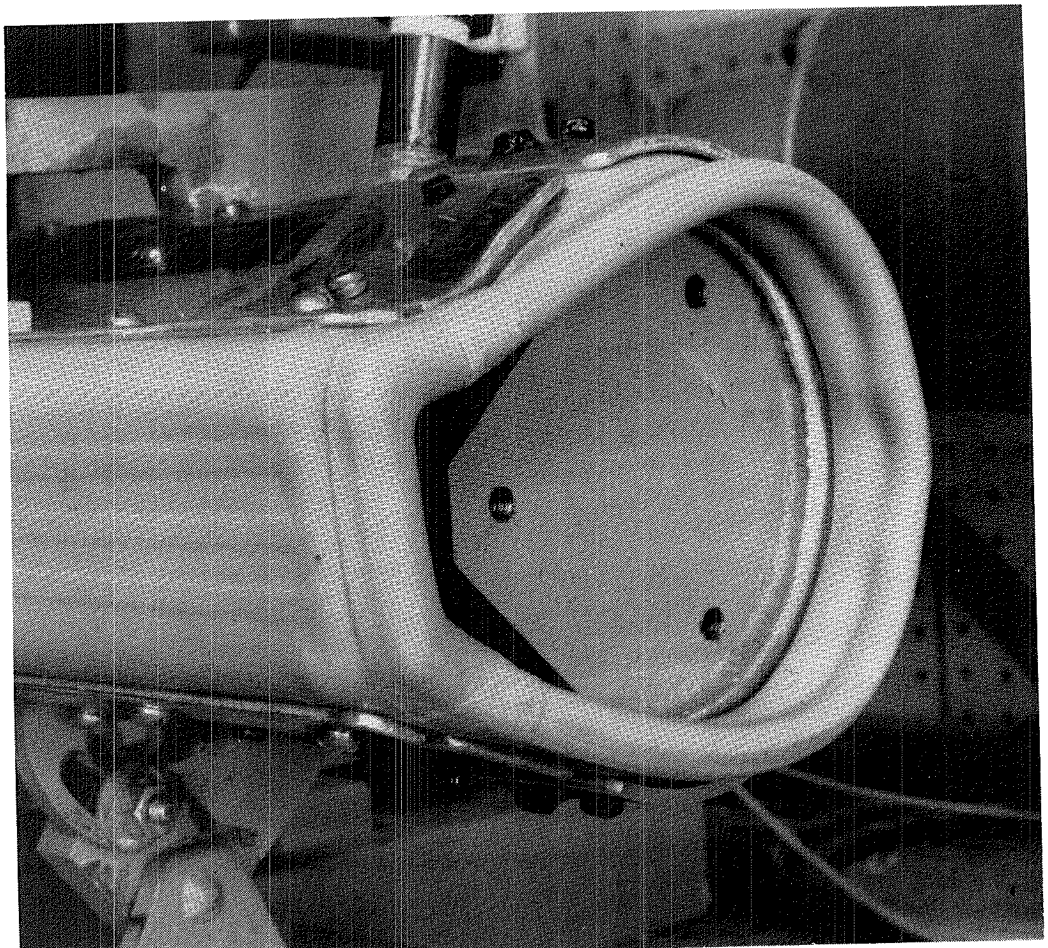


Figure 11.- Leakage measurements indicating P-bulb resilience (δ instantaneously reduced from 0.32 to 0.11 at $t = 0$).



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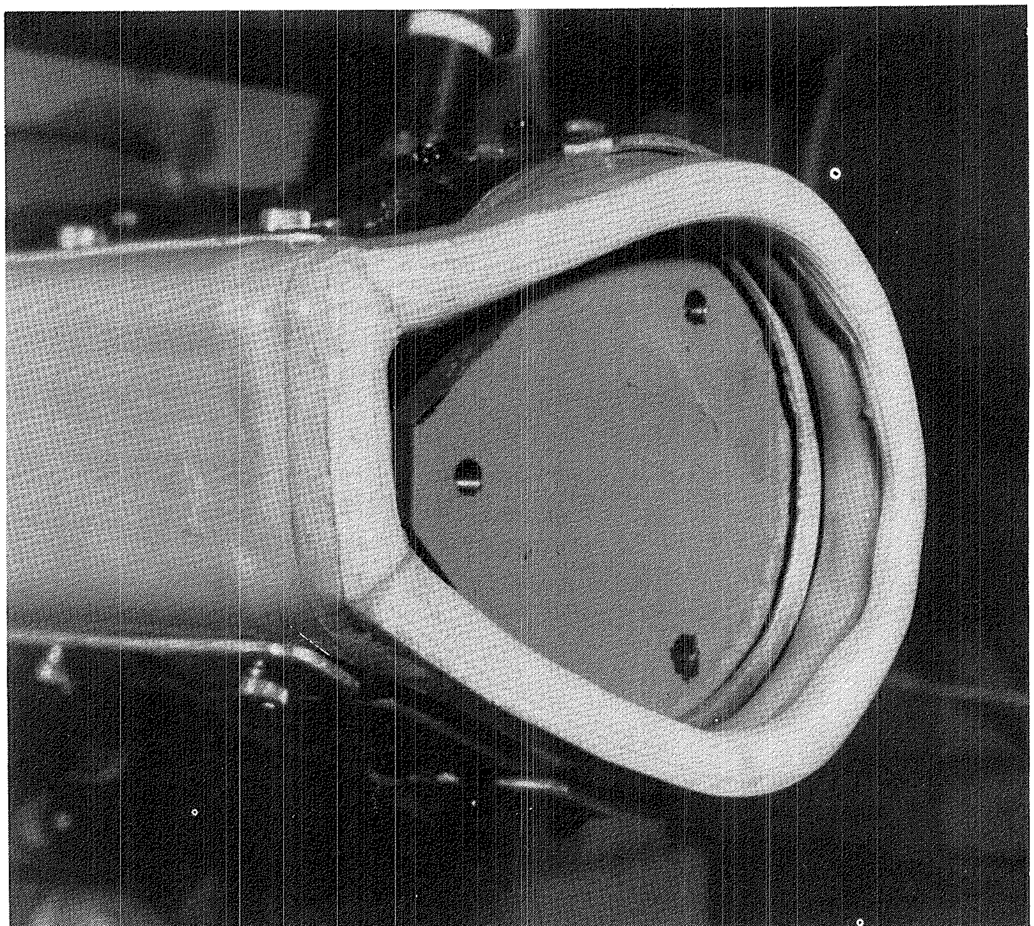
(a) Specimen 1 (plain).

Figure 12.- Posttest condition of P-bulb concepts tested in the cyclic end-seal test apparatus.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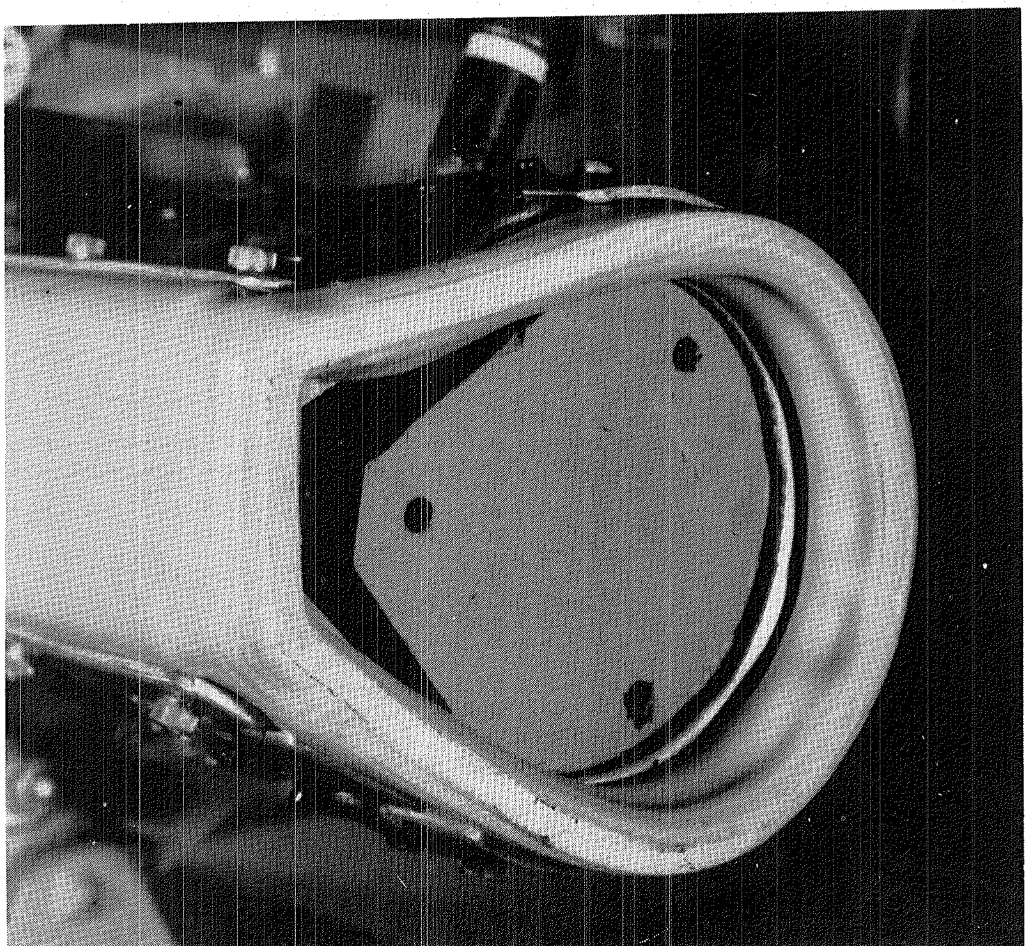
(b) Specimen 2 (wraparound).

Figure 12.- Continued.



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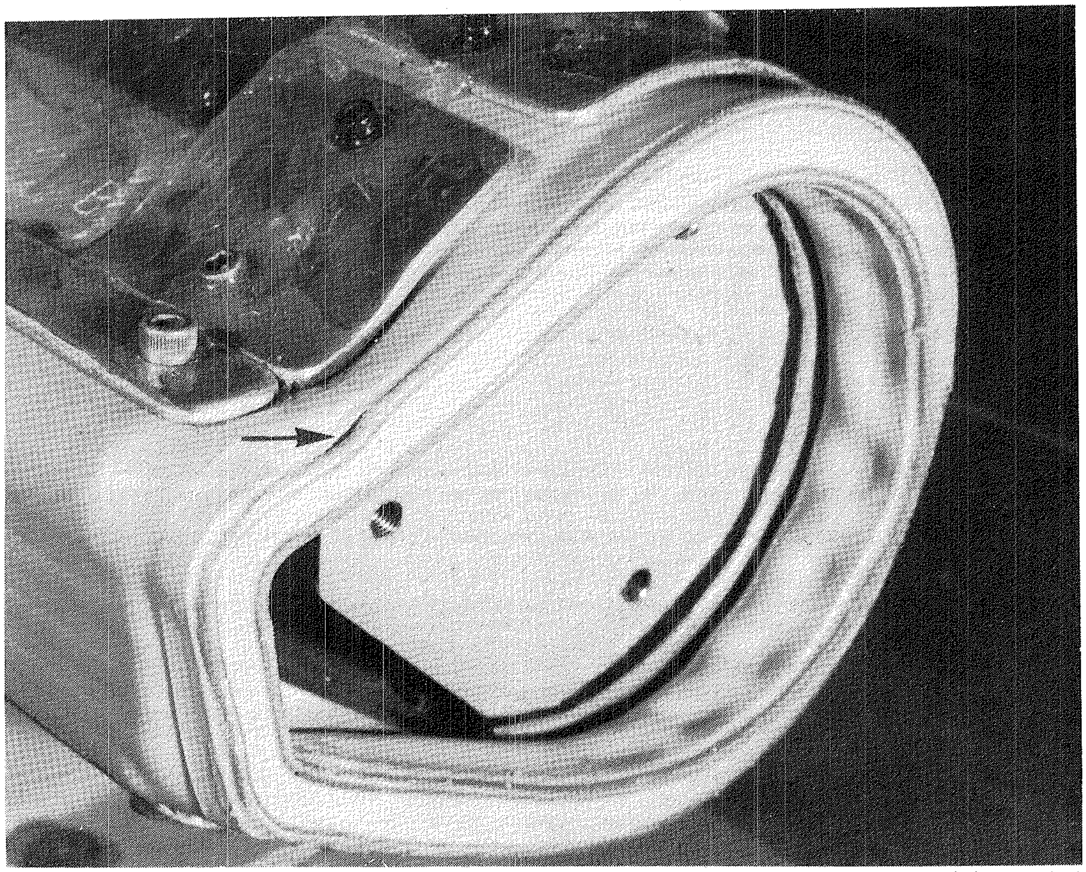
(c) Specimen 3 (flat).

Figure 12.- Continued.



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(d) Specimen 4 (double cord).

Figure 12.- Concluded.

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16. Abstract

Shuttle-type entry vehicles require a seal in the spanwise cove between the wing and elevon to prevent ingestion of aerodynamically heated gases. Four P-bulb end-seal designs were tested at room temperature in a cyclic end-seal test apparatus. Test results show that all the P-bulb end seals have the durability required for a 100-mission life (neglecting possible elevated-temperature effects) and 3 of the 4 P-bulbs provide an adequate seal against a 7.0-kPa air-pressure differential. Antifriction material attached to the P-bulb rub surface reduced friction slightly but could degrade the sealing effectiveness. A flat rub surface molded into the P-bulb discouraged wrinkling and rolling and thereby reduced leakage. However, the P-bulbs lacked resilience, as indicated by increased leakage when P-bulb compression was reduced. The best P-bulb design tested included an antifriction interface bonded to a flat surface molded into the P-bulb.

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