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TESTING OF MOLDED HIGH TEMPERATURE PLASTIC ACTUATOR ROD SEALS FOR USE IN ADVANCED AIRCRAFT HYDRAULIC SYSTEMS

by A. W. Waterman, R. L. Huxford, and W. G. Nelson

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16. Abstract

Molded high temperature plastic first- and second-stage rod seal elements, furnished by NASA, were evaluated in seal assemblies to determine performance characteristics. These characteristics were compared with the performance of machined seal elements, evaluated during the NAS3-14317, NAS3-16733 and NAS3-16744 contracts. The 6.35 cm (2.5 in.) second-stage Chevron seal assembly was tested using molded Chevrons fabricated from five molding materials. Impulse screening tests conducted over a range of 311°K (100°F) to 478°K (400°F) revealed thermal setting deficiencies in the aromatic polyimide molding materials. Seal elements fabricated from aromatic copolyester materials structurally failed during impulse cycle calibration. Endurance testing of 3.85×10^6 cycles at 450°K (350°F) using MIL-H-83283 fluid showed poorer seal performance with the unfilled aromatic polyimide material than had been attained with seals machined from Vespel SP-21 material. The 6.35 cm (2.5 in.) first-stage step-cut compression loaded seal ring fabricated from copolyester injection molding material failed structurally during impulse cycle calibration.

Molding of complex shape rod seals was shown to be a potentially controllable technique, but additional molding material property testing is recommended to obtain data for better control of dimensions in the finished parts and before conducting further seal tests using molded elements.

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TESTING OF MOLDED HIGH TEMPERATURE PLASTIC ACTUATOR ROD SEALS FOR USE IN ADVANCED AIRCRAFT HYDRAULIC SYSTEMS

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1.0 SUMMARY

The objectives of the program conducted under NASA contract NAS3-18529 were to evaluate two classes of high temperature plastics (molded as first- and second-stage rod seals) for application in advanced aircraft hydraulic systems, and to compare molded seal performance to that of machined seals developed during the NAS3-14317 contract. These objectives were accomplished by conducting tests on the 6.35 cm (2.5 in.) Chevron seal to determine molded-element structural integrity during 200,000 applications of pressure impulse cycling and material wear during 3.85×10^6 cycles of endurance actuation.

Both classes of plastics, molded as second-stage Chevron element seals, showed poor dimensional control quality in comparison to machined Chevrons. The unfilled aromatic polyimide molding material was preferred over similar materials having either 10 percent molybdenum disulfide or 10 percent graphite fillers, based on impulse screening evaluations. The best performance of a molded seal, as measured by leakage during impulse testing, was 22.1 cc in comparison to 1.75 cc for a machined seal. The major cause of poor molded seal performance was thermal setting of this aromatic polyimide molding material attributed to curing at too low a temperature. Thermal setting also caused poor seal performance during endurance testing of Chevrons made from the unfilled aromatic polymide. An average performance of 484 cycles per drop of leakage for molded seals was measured during short stroke endurance testing, accounting for 3.75×10^5 cycles, as compared to 224,659 cycles per drop for machined seals.

Chevron seals, molded from the second class of plastic (an aromatic copolyester), had better geometric adherence to design specifications, but failed structurally during impulse cycle calibration. A first stage seal, injection molded from the aromatic copolyester, also failed.

The tests indicated that seal performance is closely related to the impact and fatigue strength of the molded material. In order to achieve the success with molded seals that has been achieved with machined seals (NAS3-14317, NAS3-16733 and NAS3-16744 contracts), materials with equivalent strength will be needed. If such characteristics are not available in moldable materials, the seal design should be altered for adaptation of the best moldable material. More extensive property testing and further refinement of molding techniques are recommended before fabricating additional molded seals for performance evaluation of advanced airplane or space vehicle hydraulic system applications. Machined seals, fabricated to the NAS3-14317 design and proven successful over a wide operational range, should be tested toward assessing their applicability to single-stage installations with high seal differential pressure requirements.

2.0 INTRODUCTION

The development of advanced aircraft and space hydraulic systems requires consideration of new materials and design concepts. The higher fluid temperatures identified with these hydraulic systems preclude the use of many heretofore conventional seal design practices. The universal application of the elastomer to all hydraulic sealing applications is a thing of the past. The elastomers used in conjunction with polytetrafluoroethylene (PTFE) seal components will still have specific design applications, but critical dynamic sealing requirements will require new materials capable of long life at high fluid temperatures.

The material properties of several high temperature plastics are acceptable for the entire range of type III hydraulic system temperatures as well as for considerably higher temperatures, making these materials prime candidates for experimental seal research for advanced aircraft and space applications. NASA initiated research that was instrumental in the development of the new machine fabricated Chevron and K-section seal concepts using polyimides in exploratory tests to determine sealing characteristics under various operating environments. These efforts were conducted under the NAS3-14317, NAS3-16733, and NAS3-16744 contracts (references 1-3). Experimental investigations with these seals to date have emphasized the stable strength properties of machinable polyimides and satisfactory seal performance at high temperatures over long durations during thermal cycling and during exposure to hard vacuum.

The program reported herein is a continuation of the above-mentioned seal development programs. It was intended to verify first- and second-stage rod seal performance using molded seal elements and compare this performance with that of the machined elements previously evaluated. Impulse screening tests of 200,000 cycles were conducted on seal elements fabricated from candidate molding compounds and the seals with the best performance were further evaluated by endurance testing of 3.85×10^6 cycles at $450^\circ K$ ($350^\circ F$) in a hydraulic system using MIL-H-83283 fluid.

3.0 SEAL EVALUATION TESTS

The objective of this program was to determine whether high temperature plastic seals could be manufactured by molding to provide similar performance characteristics as had previously been demonstrated with machined polyimide seals under contracts NAS3-14217, NAS3-16733, and NAS3-16744 (references 1-3). A total of five second-stage seal sets and one first-stage seal set supplied by NASA and fabricated from 5 molding materials were inspected for drawing conformance and subjected to impulse tests similar to those performed on machined seals. Following an analysis of impulse test results, preferable seals were tested for wear during endurance cycling.

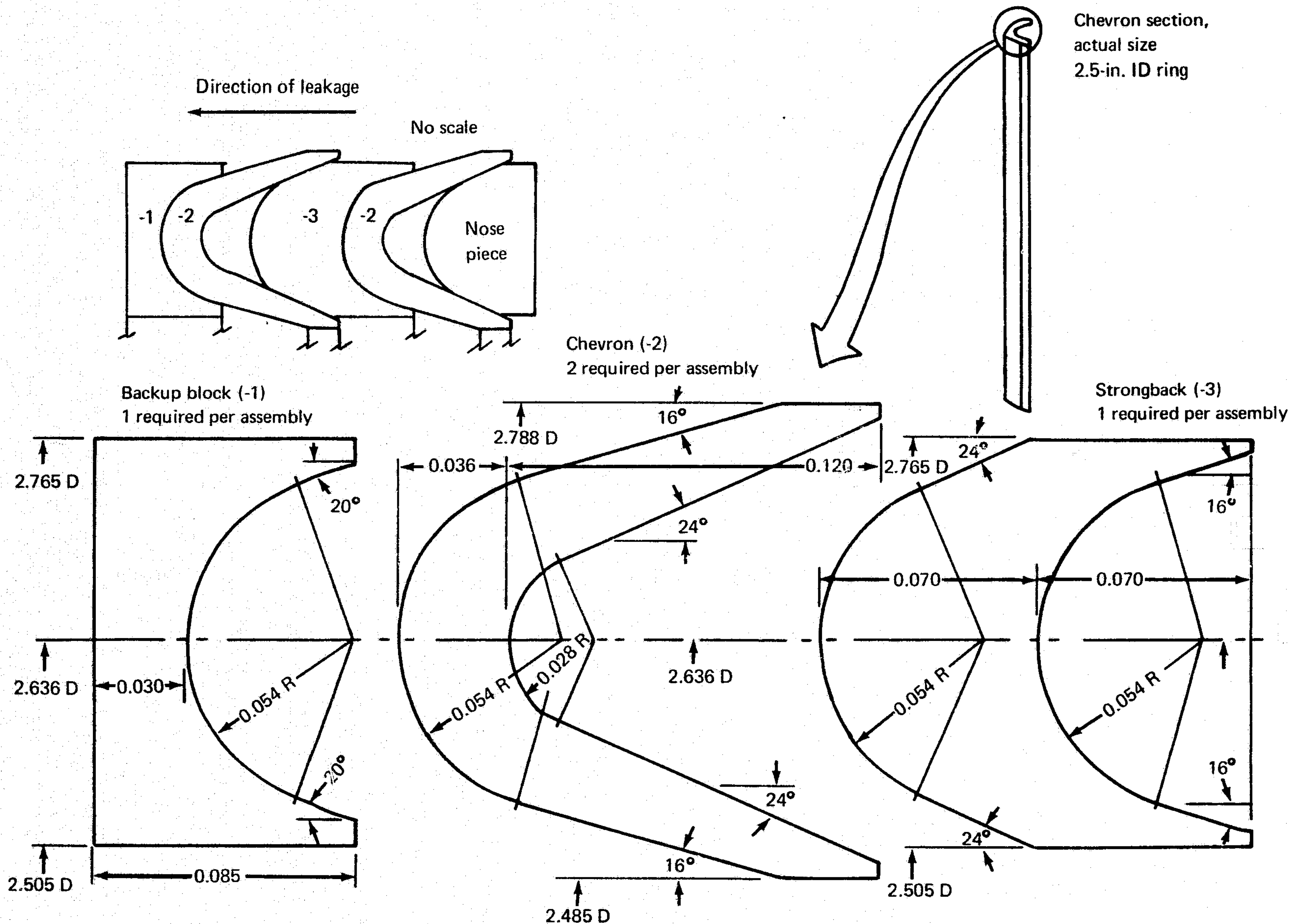
Inspections were performed to determine if dimensional tolerances and structural integrity could be maintained during the molding process. The inspections also provided a means by which part selection was made for testing and a baseline established for evaluating the effects of impulse and endurance testing. Impulse tests were used to evaluate the structural integrity of the molded seals at various test temperatures under impact loading. These tests served as a basis for screening candidate seals to select one second-stage seal for endurance testing. The endurance test was conducted to evaluate the performance of the selected seal to the accelerated life cycle requirements representative for a high performance aircraft actuator.

3.1 SEAL CONFIGURATIONS

The second-stage seals received for test were of the 6.35 cm (2.5 in.) Chevron configuration (Boeing drawing 64-14048) as designed under NASA contract NAS3-14317 (see figure 1). The Chevron elements of the seal, part 2, were the only pieces fabricated by molding, these being the parts that perform the actual sealing function. The remaining parts needed to complete the seal assembly (parts 1 and 3 detailed in figure 1 and a nose piece to fill out the gland upstream of the upstream Chevron) were machined parts retained for use from the NAS3-14317 contract.

The first-stage seal was the two-piece Boeing standard split-ring step-cut configuration per BACS11AM (see appendix A) used in all previous testing under contracts NAS3-14317, NAS3-16733, and NAS3-16744. Only the inner ring of the two-piece seal was molded. The outer ring was the standard spring-ring used to load the inner-ring.

Aromatic polyimide and aromatic copolyester materials were the two classes of high temperature resistant plastics used to mold the seals for test evaluations. The molding was completed under separate contract by the NASA Project Manager, with finished seals delivered to Boeing for inspection and test. The material class, composition, and molding process used to fabricate test seal elements was as follows:



All dimensions in inches: No SI conversion was made on dimensioned parts

Figure 1.—Second-Stage Rod Seal Assembly—2.5-in. I.D. Chevron Application

Seal Element	Material Class	Filler	Molding Process
Chevron (Second-Stage)	Aromatic Polyimide	None	Compression
	Aromatic Polyimide	10% MoS_2	Compression
	Aromatic Polyimide	10% graphite	Compression
	Aromatic Copolyester	None	Compression
	Aromatic Copolyester	None	Injection
Sealing ring (First-Stage)	Aromatic Copolyester	None	Injection

All of the Chevron second-stage seal elements made from the aromatic polyimide were compression molded and finished by touchup machining on the sealing surfaces. The compression molded Chevron made from the aromatic copolyester was molded in the shape of a rectangular cross-section toroid and then machined to the seal element shape as shown on figure 1. Fabrication of the sealing ring of the first-stage assembly was accomplished by injection molding of aromatic copolyester and required no subsequent machining. A minimum of hand sanding was needed to remove excess material in the mold riser areas.

3.2 SEAL INSPECTIONS

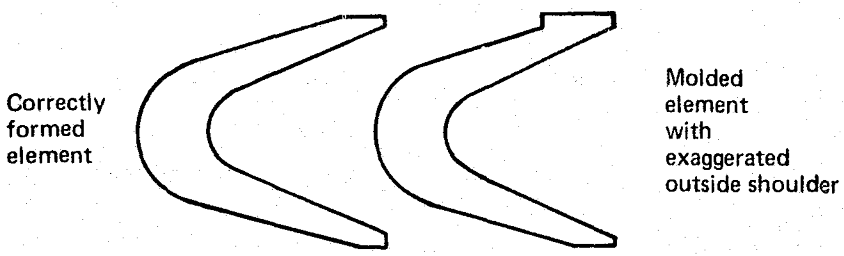
All molded sealing elements delivered to Boeing by NASA were thoroughly inspected both dimensionally and visually. The purpose of the dimensional inspection was to ascertain the accuracy achieved during the molding process to control critical dimensions and to select the best parts for evaluation testing.

The most critical dimensions for the second-stage Chevron elements were the inside and outside diameters. Accurate control of these dimensions was necessary to insure sealing at the rod surface at high temperature and sealing at the gland surface at low temperature. A nominal design dimension of 7.0810 cm (2.7878 in.) for the outside diameter provides a 0.00254 cm (0.001 in.) interference fit between the freestate seal and the nominal gland at 228°K (-50°F). The 6.3129 cm (2.4854 in.) nominal inside diameter provides a 0.00254 cm (0.001 in.) interference fit between the free-state seal and the nominal rod at 450°K (350°F). Because these dimensions were the specifications for design of the machined sealing elements they were used as a reference for comparison of the molded parts.

Complete dimensional inspections of the molded first-stage step-cut rings could not be accurately conducted against drawing tolerances without the fabrication mandrel used for establishing ring acceptance following step-cut machining by the manufacturer (see appendix A). A substitute method was employed to obtain inside diameter measurements, using the seal assembly with the spring-ring in place to provide a uniform compression of the step-cut ring. The measurements for diameters at two perpendicular locations were obtained both before and after segments of test to determine wear as the result of testing. Visual inspections of both the first- and second-stage molded elements before and after testing were obtained to provide data for the evaluation of performance during testing. Rejection of elements during the pretest inspection was based on an absence of material uniformity, discontinuity in the sealing edges, or a lack of general quality in seal construction which might reduce sealing performance or structural integrity.

3.2.1 INSPECTION RESULTS – AROMATIC POLYIMIDES

In general, the molding construction and cross-sectional profiles for all second-stage Chevron elements fabricated from the three aromatic polyimides were identical. The geometric shapes of the molded Chevron elements all exhibited one significant deviation from the design specification (figure 1). This deviation is shown in exaggerated illustration below and shows an obvious shoulder at the sealing surface of the outer leg of each Chevron.



The factors most affecting the selection of the molded elements to be tested were the magnitude of edge irregularities and material nonhomogeneity. Chevrons made from all three material candidates exhibited various types of outside and inside sealing edge imperfections. These included nicks, gouges, irregularities in edge shape, and tooling marks. Material nonhomogeneity was very prevalent on the Chevron elements using filler materials. Most of the MoS_2 and graphite filled elements showed uneven flow of the fillers throughout. The unfilled elements, in contrast, showed excellent material uniformity with only a few instances of slight discoloration.

Dimensional analysis showed the molded Chevron elements to have reasonable adherence to drawing inside and outside diameter dimensions considering these parts to be the first production using a new mold. The presence of a shoulder on the outside leg of the Chevron indicated that molding shrinkage was more than anticipated. Thus, the extent of cleanup machining to form the sealing edge on the outside leg had to be limited to preserve acceptable outside diameter dimensions, leaving the shoulder.

The six Chevron elements fabricated from the unfilled polyimide material showed the best conformance to drawing diameters with an average deviation of 0.0036 cm (0.0014 in.) undersize on the I.D. and 0.0015 cm (0.0006 in.) undersize on the O.D. dimensions compared to the drawing reference (figure 1). The eight Chevron elements made of polyimide + 10% MoS_2 filler showed an average deviation of 0.0022 cm (0.0009 in.) undersized I.D. and 0.0074 cm (0.0029 in.) undersized O.D.. The eight elements made of polyimide + 10% graphite filler showed a deviation of 0.0015 cm (0.0006 in.) and 0.0112 cm (0.0044 in.) undersized dimensions for the I.D. and O.D. respectively. Table 1 shows the dimensions for each of the individual elements inspected.

Table 1.—Dimension Inspection Summary for Chevrons of Aromatic Polyimide

Inside Diameters

Procurement drawing dimension = 6.3129 cm ±.0025 = 2.4854 in. ±.0010

		Unfilled						Filled with 10% MoS_2								Filled with 10% Graphite							
Chevron Element		(14)	(15)	16	[17]	18	[19]	3	(4)	5	6	(7)	8a	9	10	1	(2)	(3)	4	5	6	7	8
Max. measurement	cm	6.309	6.309	6.309	6.309	6.309	6.309	6.312	6.312	6.312	6.312	6.314	6.312	6.314	6.309	▷2	6.312	6.314	▷2	6.312	6.312	▷2	▷2
	in.	2.484	2.484	2.484	2.484	2.484	2.484	2.485	2.485	2.485	2.485	2.486	2.485	2.486	2.484		2.485	2.486		2.485	2.485		
Min. measurement	cm	6.309	6.309	6.309	6.309	6.309	6.309	6.312	6.312	6.307	6.309	6.309	6.307	6.307	6.309	▷2	6.309	6.312	▷2	6.312	6.309	▷2	▷2
	in.	2.484	2.484	2.484	2.484	2.484	2.484	2.485	2.485	2.483	2.484	2.484	2.483	2.483	2.484		2.484	2.485		2.485	2.484		
Avg. measurement	cm	6.3090	6.3090	6.3090	6.3090	6.3090	6.3090	6.3120	6.3120	6.3090	6.3110	6.3120	6.3090	6.3110	6.3090	▷2	6.3110	6.3130	▷2	6.312	6.3110	▷2	▷2
	in.	2.4840	2.4840	2.4840	2.4840	2.4840	2.4840	2.4850	2.4850	2.4840	2.4845	2.4850	2.4840	2.4845	2.4840		2.4845	2.4855		2.4850	2.4845		
▷1 Deviation from Drawing	cm	-.0036	-.0036	-.0036	-.0036	-.0036	-.0036	-.0010	-.0010	-.0036	-.0023	-.0010	-.0036	-.0023	-.0036	▷2	-.0023	+.0003	▷2	-.0010	-.0023	▷2	▷2
	in.	-.0014	-.0014	-.0014	-.0014	-.0014	-.0014	-.0004	-.0004	-.0014	-.0009	-.0004	-.0014	-.0009	-.0014		-.0009	+.0001		-.0004	-.0009		

Outside Diameters

Procurement drawing dimension = 7.0810 cm ±.0025 = 2.7878 in. ±.0010

		Unfilled						Filled with 10% MoS_2								Filled with 10% Graphite							
Chevron Element		(14)	(15)	16	[17]	18	[19]	3	(4)	5	6	(7)	8a	9	10	1	(2)	(3)	4	5	6	7	8
Max. measurement	cm	7.079	7.076	7.079	7.082	7.084	7.087	7.074	7.074	7.079	7.076	7.082	7.074	7.076	7.071	7.048	7.084	7.082	7.059	7.082	7.084	▷2	7.069
	in.	2.787	2.786	2.787	2.788	2.789	2.790	2.785	2.785	2.787	2.786	2.788	2.785	2.786	2.784	2.775	2.789	2.788	2.779	2.788	2.7[illegible]		2.783
Min. measurement	cm	7.076	7.076	7.076	7.079	7.079	7.079	7.066	7.074	7.071	7.071	7.079	7.069	7.071	7.069	7.038	7.082	7.076	7.056	7.079	7.082	▷2	7.061
	in.	2.786	2.786	2.786	2.787	2.787	2.787	2.782	2.785	2.784	2.784	2.787	2.783	2.784	2.783	2.771	2.788	2.786	2.778	2.787	2.788		2.780
Avg. measurement	cm	7.0777	7.0760	7.0777	7.0803	7.0820	7.0827	7.0701	7.0740	7.0752	7.0740	7.0803	7.0710	7.0740	7.0701	7.0434	7.0827	7.0790	7.0574	7.0803	7.0827	▷2	7.0650
	in.	2.7865	2.7860	2.7865	2.7875	2.7880	2.7885	2.7835	2.7850	2.7855	2.7850	2.7875	2.7840	2.7850	2.7835	2.7730	2.7885	2.7870	2.7785	2.7875	2.7885		2.7815
▷1 Deviation from drawing	cm	-.0033	-.0046	-.0033	-.0008	+.0005	+.0018	-.0109	-.0071	-.0058	-.0071	-.0008	-.0097	-.0071	-.0109	-.0376	+.0018	-.0020	-.0236	-.0008	+.0018	▷2	-.0160
	in.	-.0013	-.0018	-.0013	-.0003	+.0002	+.0007	-.0043	-.0028	-.0023	-.0028	-.0003	-.0038	-.0028	-.0043	-.0148	+.0007	-.0008	-.0093	-.0003	+.0007		-.0063

▷1 Average measured dimension minus nominal drawing dimension

(x) Seals selected for impulse testing

[x] Seals selected for endurance testing

▷2 Seal rejected based on edge quality — no dimension recorded

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3.2.2 INSPECTION RESULTS – AROMATIC COPOLYESTER MATERIALS

The visual differences between Chevron elements made by injection molding of the copolyester compound and elements machined from compression molded blanks of the copolyester material were very apparent. These differences were not directly comparable because final fabrication using the injection molding compound was by molding, while final fabrication using the compression molding material was by machining.

Only two Chevron elements of the eight machined from blanks made out of the compression molded copolyester showed any faults which were cause for rejection. These faults consisted of one notch in the sealing edge of the outside leg of element #5 and one fracture on the sealing edge of the outside leg of element #8. Element #8 also showed discoloration and splatches on most of the surface.

All Chevron elements made by injection molding of the copolyester material had major and minor faults. Eight of the ten elements were immediately rejected because of visible fractures through the Chevron leg cross-section profile. Figure 2 is a photograph of a typical crack and shows its proximity to the molding riser position at the inside apex of the Chevron cross-section. All visible cracks identified in initial inspection were at similar locations with respect to the molding riser positions. This type of crack and its location indicates that failure was probably caused by stress-relieving during cooling after removing the finished part from the mold. This showed that the molding material had marginal strength in the finished cross-section. In addition to the stress factures, all injection molded Chevrons showed some type of imperfection on a sealing edge, nonhomogeneity in the material, evidence of mold parting lines and riser positions, and some imperfections resulting from touchup machining.

The appearance of the first-stage injection molded inner ring made from copolyester material showed the same nonuniformity similar to the injection molded Chevron elements. Parting line and molding riser positions could be identified. There were no visible structural crack or sealing-edge imperfections.

Dimensional inspections indicated rather poor adherence to drawing dimension specifications for all second-stage Chevron elements made of the copolyester materials. The average deviation from drawing dimensions for ten Chevron elements made of the compression molding copolyester material was 0.0102 cm (0.0040 in.) oversize on the inside diameter and 0.0053 cm (0.0021 in.) oversize on the outside diameter. These dimensions imply overstressing of the outer leg and a reduction in sealing capability at the rod under elevated temperatures.

The average deviation from drawing dimensions for ten Chevron elements made of the injection molding copolyester material was 0.0127 cm (0.0050 in.) oversize on the outside diameter and 0.0196 cm (0.0077 in.) undersize on the inside diameter. These dimensions imply an overstressing of both the inner and outer legs of the Chevrons. Table 2 shows the dimensions for each of the individual elements inspected.

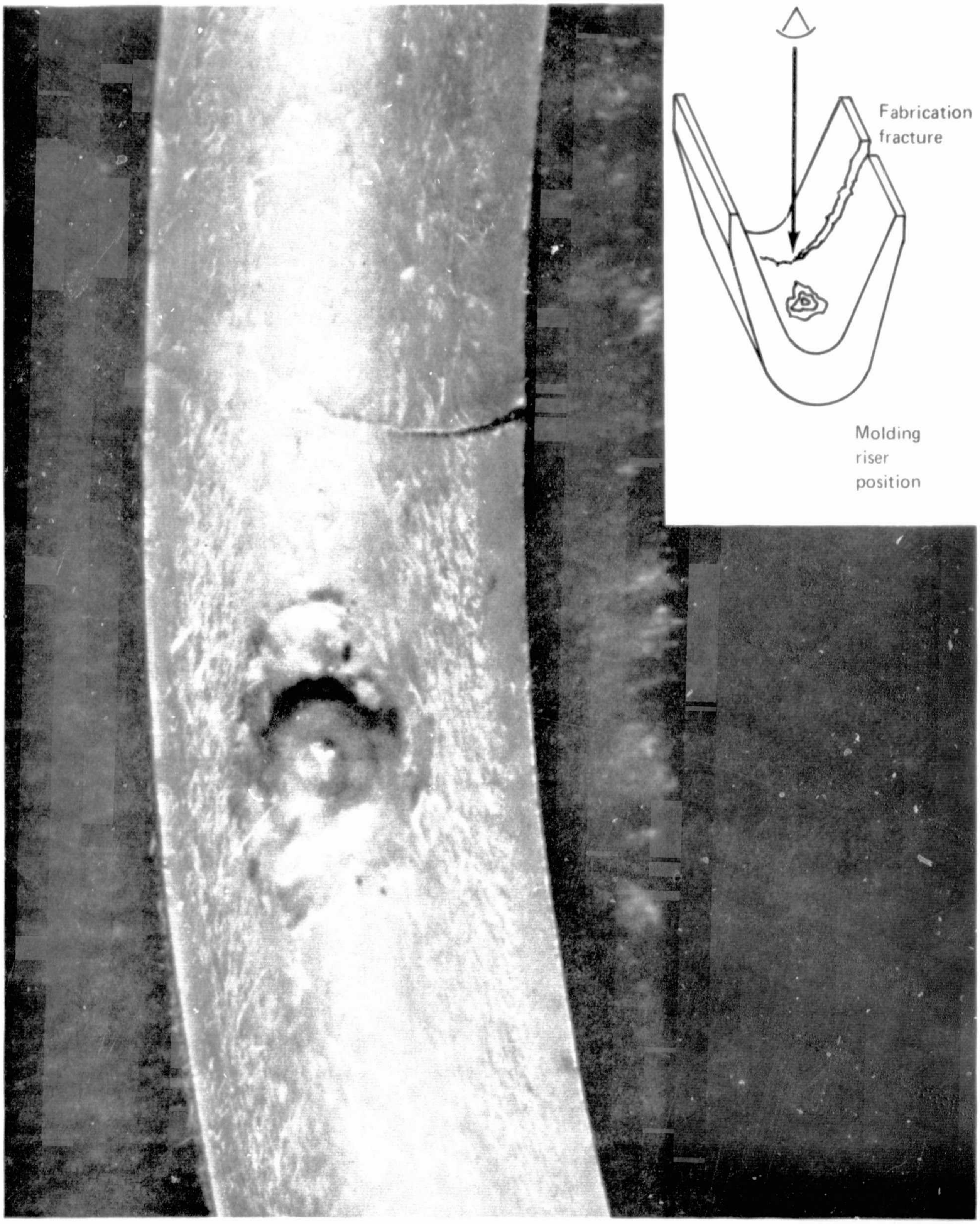


Figure 2.—Initial Inspection – Chevron of Injection Molded Copolyester

Table 2.—Dimension Inspection Summary for Chevrons of Aromatic Copolyester

Inside Diameters

Procurement drawing dimensions = 6.3129 ± .0025 cm = 2.4854 ± .0010 in.

		Compression Molded Elements								Injection Molded Elements									
Chevron Element		1	2	3	4	5	6	7	8	1	2 ▷2	3 ▷2	4	5 ▷2	6 ▷2	7 ▷2	8 ▷2	9 ▷2	10 ▷2
Max. measurement	cm	6.327	6.327	6.322	6.322	6.309	6.325	6.327	6.330	6.332	6.340	6.340	6.332	6.337	6.337	6.330	6.330	6.327	6.335
	in.	2.491	2.491	2.489	2.489	2.484	2.490	2.491	2.492	2.493	2.496	2.496	2.493	2.495	2.495	2.492	2.492	2.491	2.494
Min. measurement	cm	6.322	6.322	6.320	6.317	6.317	6.322	6.322	6.327	6.304	6.314	6.317	6.317	6.317	6.320	6.314	6.317	6.314	6.317
	in.	2.489	2.489	2.488	2.487	2.487	2.489	2.489	2.491	2.482	2.486	2.487	2.487	2.487	2.488	2.486	2.487	2.486	2.487
Avg. measurement	cm	6.3246	6.3241	6.3216	6.3195	6.3190	6.3228	6.3254	6.3279	6.3236	6.3292	6.3284	6.3266	6.3304	6.3297	6.3216	6.3228	6.3216	6.3283
	in.	2.4900	2.4898	2.4888	2.4880	2.4878	2.4893	2.4903	2.4913	2.4896	2.4918	2.4915	2.4908	2.4923	2.4920	2.4888	2.4893	2.4888	2.4895
▷1 Deviation from Drawing	cm	+.0117	+.0112	+.0086	+.0066	+.0061	+.0099	+.0125	+.0150	+.0107	+.0163	+.0155	+.0137	+.0175	+.0168	+.0086	+.0099	+.0086	+.0104
	in.	+.0046	+.0044	+.0034	+.0026	+.0024	+.0039	+.0049	+.0059	+.0042	+.0064	+.0061	+.0054	+.0069	+.0066	+.0034	+.0039	+.0034	+.0041

Outside Diameters

Procurement drawing dimension = 7.081 ± .0025 cm = 2.7878 ± .0010 in.

		Compression Molded Elements								Injection Molded Elements									
Chevron Element		1	2	3	4	5	6	7	8	1	2 ▷2	3 ▷2	4	5 ▷2	6 ▷2	7 ▷2	8 ▷2	9 ▷2	10 ▷2
Max. measurement	cm	7.089	7.092	7.087	7.089	7.089	7.084	7.082	7.104	7.080	7.076	7.074	7.0650	7.069	7.071	7.069	7.069	7.059	7.069
	in.	2.791	2.792	2.790	2.791	2.791	2.789	2.788	2.797	2.7875	2.786	2.785	2.7815	2.783	2.784	2.783	2.783	2.779	2.783
Min. measurement	cm	7.082	7.084	7.079	7.084	7.084	7.082	7.076	7.097	7.0472	7.043	7.046	7.0599	7.043	7.043	7.043	7.051	7.046	7.061
	in.	2.788	2.789	2.787	2.789	2.789	2.788	2.786	2.794	2.7745	2.773	2.774	2.7795	2.773	2.773	2.773	2.776	2.774	2.780
Avg. measurement	cm	7.0848	7.0784	7.0828	7.0861	7.0784	7.0828	7.0784	7.1001	7.0648	7.0645	7.0645	7.0622	7.0594	7.0599	7.0587	7.0455	7.0543	7.0658
	in.	2.7893	2.7903	2.7885	2.7898	2.7903	2.7885	2.7870	2.7953	2.7814	2.7813	2.7813	2.7804	2.7793	2.7795	2.7790	2.7738	2.7773	2.7818
▷1 Deviation from Drawing	cm	+.0038	+.0064	+.0018	+.0051	+.0064	+.0018	-.0020	+.0191	-.0163	-.0165	-.0165	-.0188	-.0216	-.0211	-.0224	-.0206	-.0267	-.0155
	in.	+.0015	+.0025	+.0007	+.0020	+.0025	+.0007	-.0008	+.0075	-.0064	-.0065	-.0065	-.0074	-.0085	-.0083	-.0088	-.0081	-.0105	-.0061

▷1 Average measured dimension minus nominal drawing dimension

(x) Seals selected for impulse testing

[x] Seals selected for endurance testing

▷2 Rejected due to fracture in element as received

The results of dimensional inspections of the first-stage molded rings are shown on table 3. This was not an inspection for drawing conformance but was accomplished to provide a baseline for measuring wear on the inner sealing ring during testing. The average variation in diameter measurements made on the ten elements received was 0.0089 cm (0.0035 in.).

3.2.3 TEST ELEMENT SELECTION

The selection of molded Chevron elements for impulse and endurance testing was accomplished by segregating groups of elements, made from each candidate material, which exhibited the closest overall adherence to drawing dimensions. Within each of these groups, four Chevron elements were selected which had the best sealing-edge surfaces, overall preferable construction, and best material and geometric uniformity. Two of the four elements from each material group were assigned for use in the seal assembly for impulse testing and two were reserved for potential use in endurance testing. Of the two elements selected for each seal assembly, the element showing the best overall quality was placed in the upstream position of the seal assembly (see figure 1). The Chevron elements selected for test are identified on tables 1 and 2 showing the results of dimensional inspections leading to their selection.

There were no significant differences between the ten first-stage elements available for testing. Selection of an element for test use, as indicated on table 3, was based on general appearance and uniformity of the material in the finished elements.

3.3 IMPULSE SCREENING TESTS

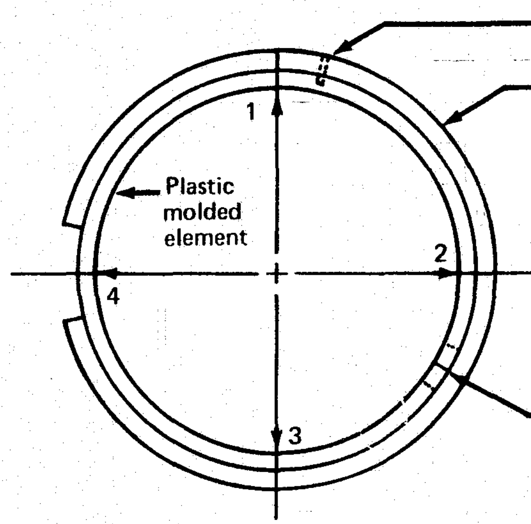
Pressure impulse tests were accomplished to compare the structural impact resistance of the molded sealing elements to that of the machined sealing elements previously tested under the NAS3-14317 contract (see reference 1). The impulse requirements imposed during the tests were the same as those imposed during the NAS3-14317 contract tests on the machined seal assemblies, i.e., 200,000 cycles of the waveform shown on figure 3 as applicable for either the first- or second-stage seal. These cycles were imposed in the following sequence to evaluate the seals for a high performance application with a simulated life cycle of temperature.

Impulse Cycles	Temperature	
	$^{\circ}K$	$^{\circ}F$
40,000	311	100
115,000	408	275
40,000	450	350
5,000	478	400

3.3.1 TEST ARTICLES

Each article to be tested by impulse cycling consisted of a single second-stage Chevron seal assembly or a first-stage seal installed in a housing to retain the seal in a manner duplicating an aircraft installation. Existing hardware was used to the greatest extent possible to provide the necessary housings as illustrated in figure 4. Only one seal was tested in a single housing

Table 3.—Dimension Inspection Summary for First Stage Molded Rings



I.D. Measurement Positions	Units	Seal Element Number 1	2	3	4	5	6	7	8	9	10
1-3	cm	6.289	6.287	6.281	6.281	6.289	6.292	6.287	6.289	6.289	6.284
	in.	2.476	2.475	2.473	2.473	2.476	2.477	2.475	2.476	2.476	2.474
2-4	cm	6.299	6.297	6.297	6.304	6.304	6.304	6.304	6.297	6.297	6.304
	in.	2.480	2.479	2.479	2.482	2.482	2.482	2.482	2.479	2.479	2.482

* Seal selected for impulse testing

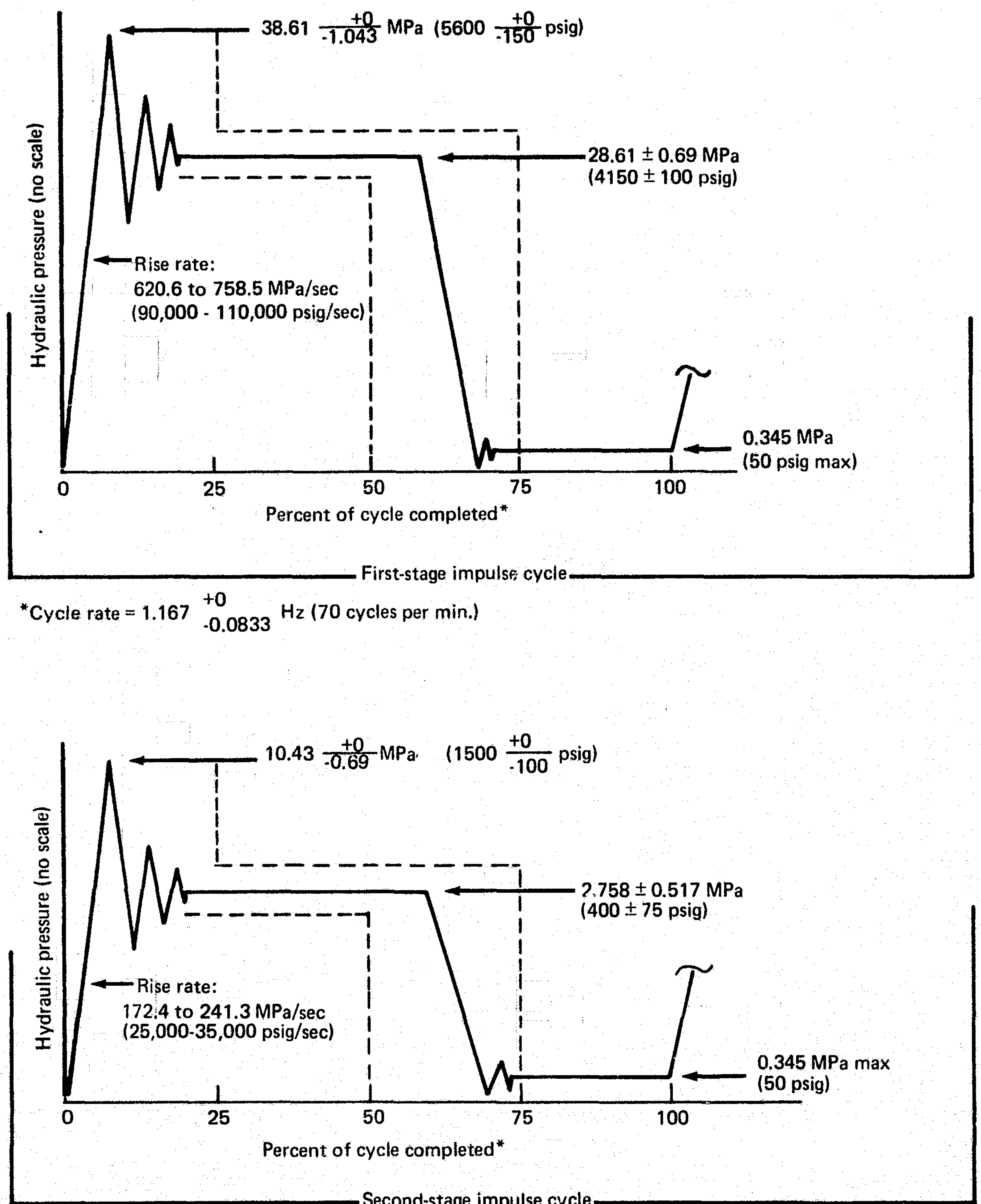


Figure 3.—Impulse Cycle

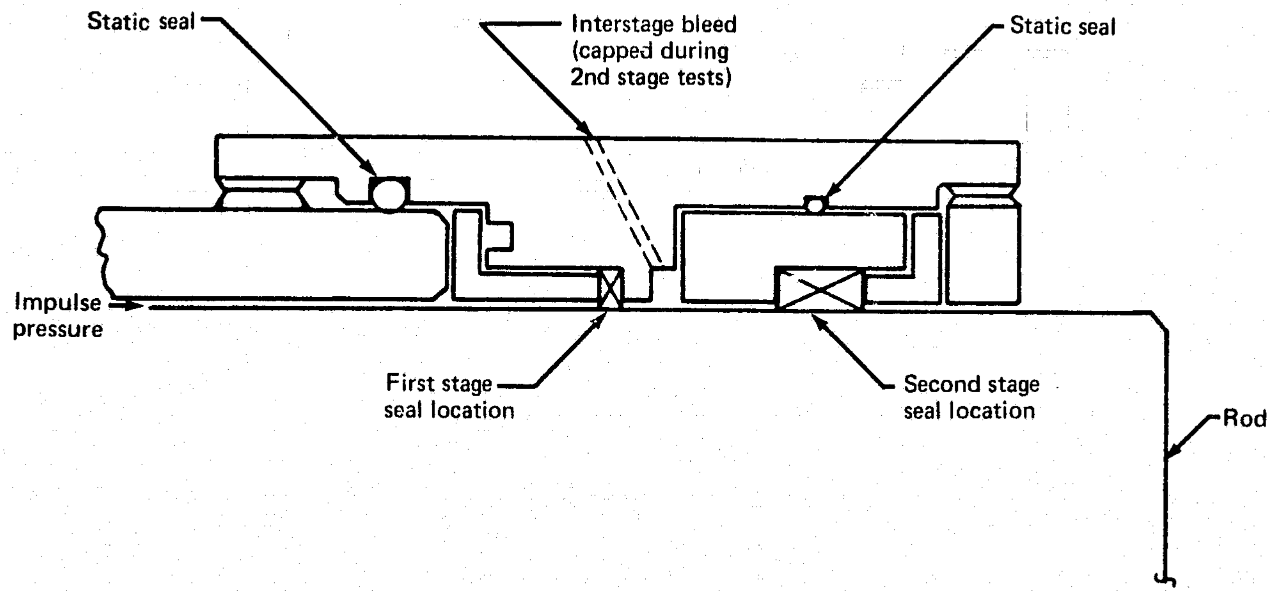


Figure 4.—Seal Installation Impulse Test

end. Thus, when a second-stage configuration was to be tested, the first-stage gland was left empty. When the first-stage seal was tested, a Boeing seal was installed in the second-stage gland only to allow collection of leakage and was not considered to be under test.

Each second-stage seal assembly consisted of one of the pairs of molded Chevrons, fabricated from one material compound and identified for test on tables 1 and 2, combined with the machine fabricated parts necessary to complete an assembly as shown in figure 1. The first-stage seal consisted of the molded inner ring identified on table 3 combined with its matching steel compression ring to form the BACS11AM configuration seal (appendix A).

Testing was accomplished using the same impulse test procedures and equipment employed for previous machined seal testing. The test system description and operating sequence are described in appendix B.

3.3.2 IMPULSE TEST RESULTS

Performance of the impulse test seal assemblies was determined by evaluating each test assembly for the following:

a. Sealing performance: measured by comparing pretest and posttest static leakage checks and by comparing dynamic leakage variation during testing.

b. Seal integrity: measured by comparing pretest and posttest visual inspections.

c. Seal deformation and permanent set: measured by comparing pretest and posttest dimensional inspections.

3.3.3 SECOND-STAGE SEALS

The sealing performance of the molded Chevrons, as determined by leakage measurements made before, during, and after impulse testing is shown on table 4. None of the seals tested demonstrated performance comparable to the machined seals. The 6.35 cm (2.5 in.) Chevron machined seal assembly had a total leakage of 1.75 cc during the 200,000 cycles of impulse testing conducted under the NAS3-14317 contract. By comparison, the best assembly using molded elements was with the aromatic polyimide + 10% graphite Chevrons which exhibited 22.1 cc total leakage during the 200,000 impulse cycles. The Chevrons made of the aromatic copolyester materials structurally failed during impulse cycle calibration, therefore leakage performance could not be measured.

Comparison of the pre- and posttest static leakage checks with the data on leakage variation that occurred during the impulse cycling did not show a consistent explanation for seal performance. The unfilled and MoS_2 filled Chevrons showed essentially no variation in static leakage during the test. This result tended to indicate that these seals expanded away from the rod as temperature increased due to the coefficient of thermal expansion of molded polyimide being approximately three times greater than the coefficient of thermal expansion for steel.

The graphite-filled Chevrons showed no ability to control leakage after the impulse test, but leakage increase during impulse testing was not significantly different than with the unfilled or MoS_2 filled materials. This performance implied that some thermal setting occurred at an elevated temperature and resulted in a permanent gap between the sealing edges of the Chevrons and either the gland or the rod.

The post-impulse test visual inspections of the Chevrons made from the aromatic polyimide series of materials revealed surface cracks on both the unfilled and MoS_2 filled elements. The upstream and downstream Chevrons made of the unfilled material both showed slight surface cracking on the outside of the apex curvature. The MoS_2 filled Chevrons had circumferential surface cracks around the entire outside sealing edge of the upstream element and slight cracking at the apex section of the downstream element. By comparison, the graphite filled elements showed no evidence of cracking and it was concluded that these parts had yielded plastically under stress to produce the high leakage condition noted in the posttest static leakage check.

Attempts to impulse test the second-stage Chevron seals made from the aromatic copolyester materials were terminated because of the excessive leakage of the seals during calibration of the impulse test. This leakage resulted from fracture of the upstream and downstream elements made of the compression molded material as shown in figures 5 and 6, cracking of the upstream element made of the injection molded material as shown in figure 7, and compressive deformation of the downstream element made of the injection molded material as shown in figure 8.

Table 4.—Leakage Data for Second Stage Impulse Test

Test Condition Static Leak Check	Aromatic Polyimide						Aromatic Copolyester			
	Unfilled		Filled With 10% MoS_2		Filled With 10% Graphite		Compression Molded		Injection Molded	
	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test
Proof pressure = 10.43 MPa (1500 psig) at 450°K (350°F) for 300 sec. (5 min.)							0 cc/min.	**	0 cc/min.	**
Proof pressure = 10.43 MPa (1500 psig) at 297°K (75°F) for 300 sec. (5 min.)	0 cc/min.	0 cc/min.	0.13 cc/min.	0.09 cc/min.	0 cc/min.	*				
Proof pressure = 10.43 MPa (1500 psig) at 228°K (-50°F) for 300 sec (5 min.)							0 cc/min.	**	0.4 cc/min.	**
Test condition dynamic leakage										
40,000 cycles at 311°K (100°F) of figure 3 profile	5.0×10^{-8} M^3 (1 drop) per 8,000 cycles		<5.0×10^{-8} M^3 (1 drop) per 40,000 cycles		5.0×10^{-8} M^3 (1 drop) per 11,000 cycles		Seals failed at initiation of cycle calibration			
11,500 cycles at 408°K (275°F) of figure 3 profile	5.0×10^{-8} M^3 (1 drop) per 528 cycles		5.0×10^{-8} M^3 (1 drop) per 344 cycles		5.0×10^{-8} M^3 (1 drop) per 523 cycles					
40,000 cycles at 450°K (350°F) of figure 3 profile	5.0×10^{-8} M^3 (1 drop) per 200 cycles		5.0×10^{-8} M^3 (1 drop) per 129 cycles		5.0×10^{-8} M^3 (1 drop) per 244 cycles					
5,000 cycles at 478°K (400°F) of figure 3 profile	5.0×10^{-8} M^3 (1 drop) per 125 cycles		5.0×10^{-8} M^3 (1 drop) per 50 cycles		5.0×10^{-8} M^3 (1 drop) per 93 cycles					

Allowable leakage during impulse was 5.0×10^{-8} M^3 (1 drop) per 900 seconds (15 min.) or an equivalent of 1050 cycles
Poorest performance of machined seals was 1 drop/4368 cycles (reference #1)
*Could not hold 10.43 MPa (1500 psig) pressure — 1.379 MPa (200 psig) leakage was 8.3 cc/min.
**Seal failed to complete test

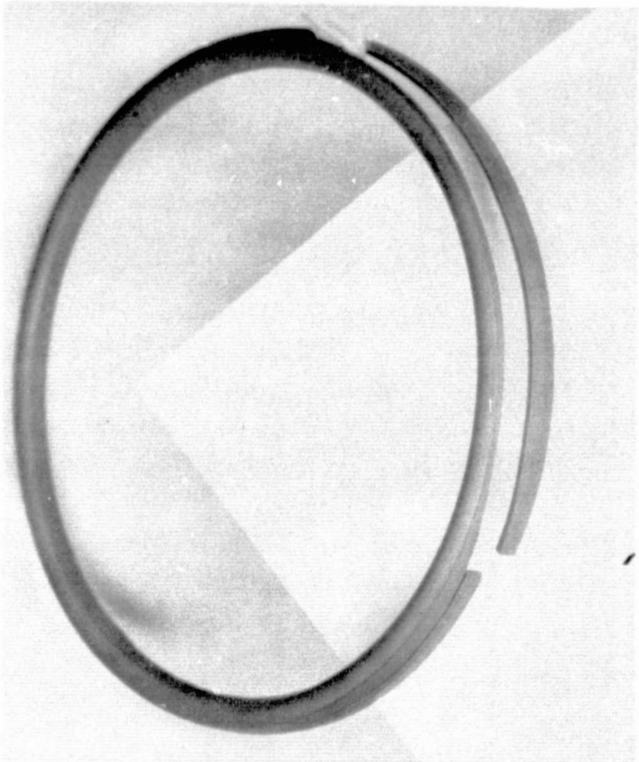


Figure 5.—Second-Stage Upstream Element Fracture—Compression Molded Copolyester

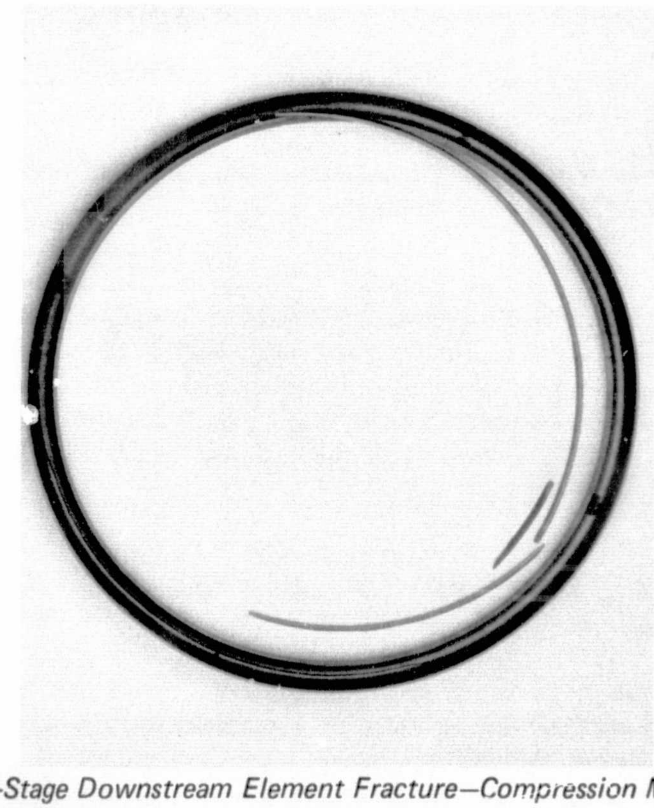


Figure 6.—Second-Stage Downstream Element Fracture—Compression Molded Copolyester

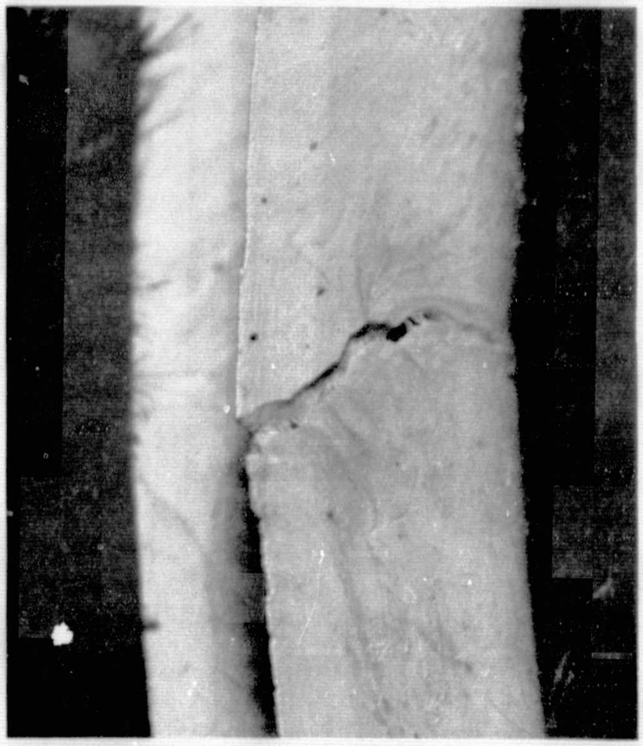


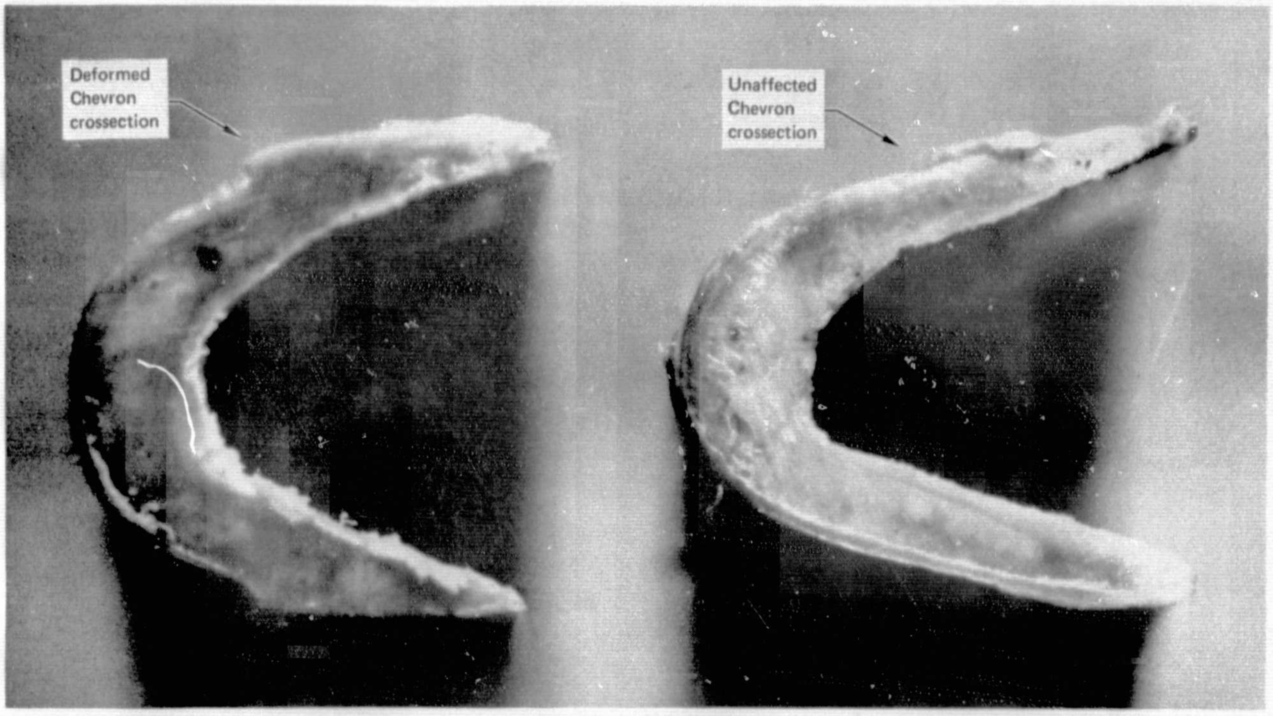
Figure 7.—Second-Stage Upstream Element Fracture—Injection Molded Copolyester

Failure of the Chevron elements made of the compression molded copolyester material was due to the lack of material impact strength as evidenced by the fractures around the entire circumference of the sealing elements. (See figures 5 and 6.) Data indicated that the impulse profile (figure 3) was not exceeded and there were no pressures in excess of the test specification.

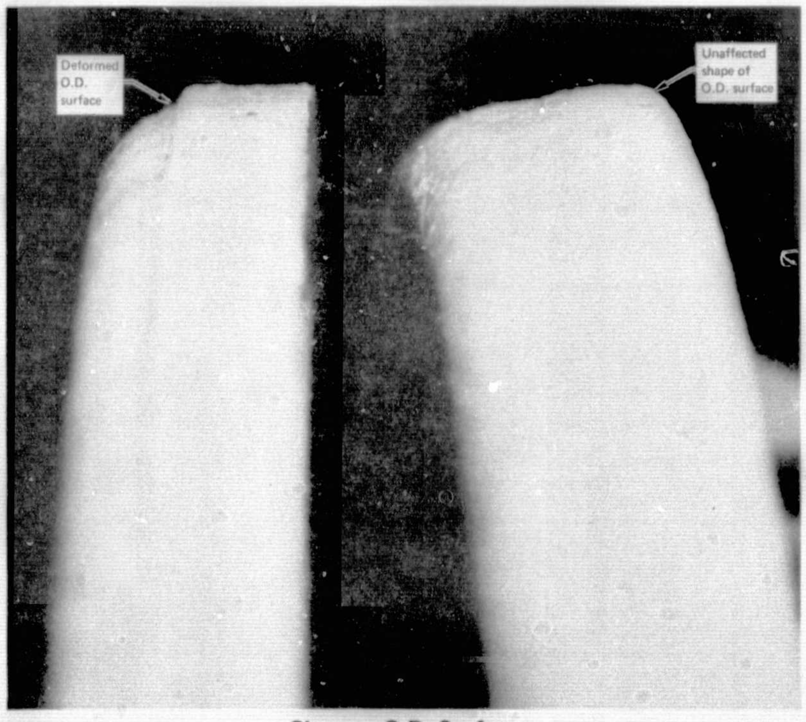
It was concluded that the initiation of failure of the Chevron elements made of the injection molded copolyester material occurred as a result of pressurization during the static leakage checks, since there was some seal leakage evidenced during the low temperature static leakage check of the seal (see table 4). Pressure caused the plastic deformation as shown on figure 8 and forced the downstream Chevron sealing legs to conform to the shape of the backup block (Part 1, figure 1) reducing the flexibility in the Chevron leg and causing it to have a greater susceptibility to leakage.

Dimensional inspections of the Chevrons made of the aromatic polyimide series of materials that completed impulse tests all showed evidence of shrinkage averaging 0.0071 cm (0.0195 in.) on the outside diameter.

Data for each individual Chevron is presented on table 5 with the largest change in dimension being a reduction of 0.0635 cm (0.025 in.) in the outside diameter of one of the graphite-filled Chevrons. These dimensional changes are consistent with the large postinspection static test leakage obtained with the seal using graphite-filled Chevrons. The evidence of shrinkage supports the conclusion that thermal setting had occurred during impulse testing of Chevrons made of the aromatic polyimide series of materials.



Chevron Crossections



Chevron O.D. Surface

Figure 8.—Second-Stage Downstream Element Deformation—Injection Molded Copolyester

Table 5.—Post Impulse Test Inspection Results

		Aromatic Polyimide Materials					
		Unfilled		Filled with 10% MoS_2		Filled with 10% Graphite	
		Downstream #15	Upstream #14	Downstream #7	Upstream #4	Downstream #2	Upstream #3
Average Pre-test I.D.	cm	6.3094	6.3094	6.3119	6.3119	6.3106	6.3132
	in.	2.4840	2.4840	2.4850	2.4845	2.4845	2.4855
Average Post-test I.D.	cm	6.3056	6.3005	6.3056	6.3119	6.3017	6.2992
	in.	2.4825	2.4805	2.4825	2.4850	2.4810	2.4800
Average I.D. change	cm	-.0038	-.0089	.0064	–	.0089	.0140
	in.	-.0015	-.0035	-.0025	–	-.0035	-.0055
Average Pre-test O.D.	cm	7.0764	7.07777	7.0803	7.0739	7.0828	7.0790
	in.	2.7860	2.7865	2.7875	2.7850	2.7885	2.7870
Average Post-test O.D.	cm	7.0371	7.0295	7.0193	7.0333	7.0193	7.0345
	in.	2.7705	2.7675	2.7635	2.7690	2.7635	2.7695
Average O.D. change	cm	-.0394	-.0483	-.0610	-.0406	-.0635	-.0445
	in.	-.0155	-.0190	-.02450	-.0160	-.0250	-.0175

3.3.4 FIRST-STAGE SEALS

The only molded first-stage elements fabricated were made of injection molded aromatic copolyester material. The one element selected for impulse testing (see table 3) failed during impulse cycle calibration. Figures 9 and 10 show the conditions of this failure and that it demonstrates insufficient material impact strength for the application. Figure 9 shows that plastic flowing occurred under the 38.61 MPa (5600 psig) first-stage peak impulse pressure. Figure 10 shows the evidence of the extrusion of the molded material into the sealing gap as a result of the application of first-stage pressure.

3.3.5 SEAL SELECTION FOR ENDURANCE TESTING

One of the objectives of conducting impulse tests was to screen candidate materials to determine the preferable material for seals that would be used for endurance testing. The successful completion of impulse testing of the aromatic polyimide series of materials showed the unfilled polyimide to exhibit the least amount of thermal setting, better resistance to surface cracking, and superior homogeneity compared with either the MoS_2 or graphite-filled materials. Thus, second-stage Chevron sealing elements made of unfilled polyimide material were selected for use during endurance testing.

Endurance testing using either the first-stage or second-stage seals with aromatic copolyester elements was not conducted due to the nature of the failures of these elements during impulse testing. A cast-iron first-stage seal of the BACS11AM configuration (appendix A) was selected for use in the test actuator during endurance testing to meet the requirements of the test configuration, but was not considered under test for performance evaluation.

3.4 ENDURANCE TEST

The objective of endurance testing was to establish whether acceptable wear life was attainable from high performance aircraft hydraulic rod seals having molded polyimide elements. A second objective was to compare the wear life of molded seal element configurations that satisfactorily passed the impuse tests to the life demonstrated by machine seals evaluated during previous research contracts.

The requirements imposed during the endurance test were identical to those established for similar testing conducted on machined seals. The test duration was established at 3.85×10^6 cycles of actuation at 450°K (350°F) with the major portion (3.75×10^6 cycles) conducted under short stroke (2 percent) operation. Appendix C describes the details of the test system and operational sequence.

3.4.1 TEST ARTICLES

The seal under evaluation in the endurance test actuator consisted of a second-stage Chevron assembly (figure 1) with the Chevron elements selected per table 1 and made of the unfilled aromatic polyimide material. Because no molded first-stage seal was acceptable for endurance testing, a first-stage per the BACS11AM configuration, made of cast iron, was installed in the seal module to complete the two-stage installation. The first-stage seal was not considered under test even though data was obtained on its performance.

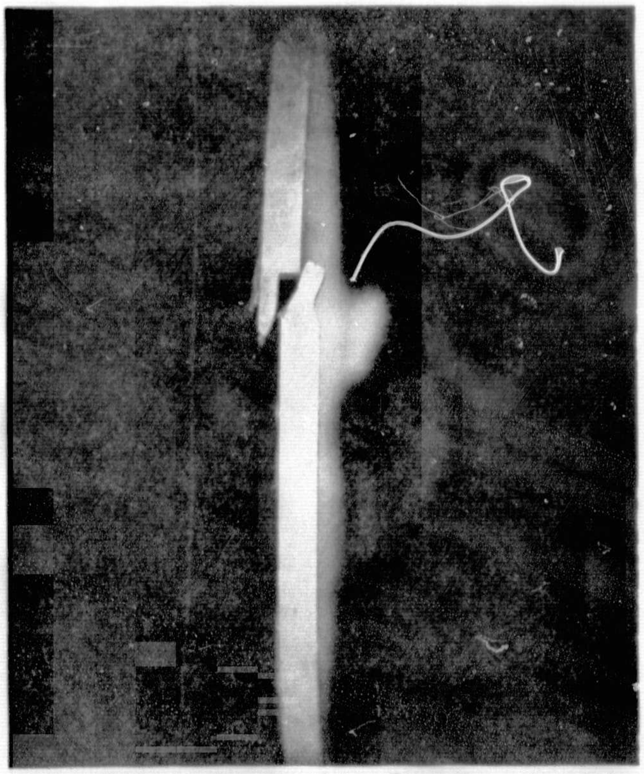


Figure 9.—First-Stage Step Cut Deformation Resulting From Impulse—Injection Molded Copolyester

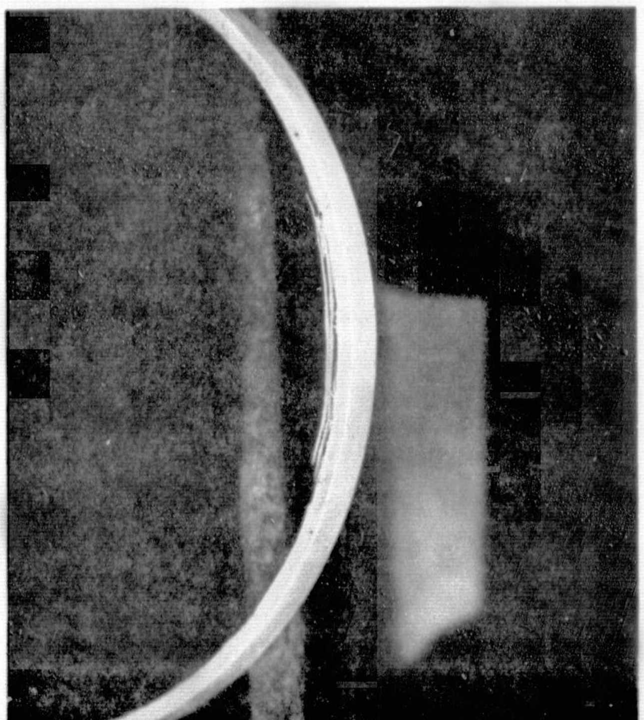


Figure 10.—First-Stage Element Extrusion Resulting from Impulse—Injection Molded Copolyester

3.4.2 ENDURANCE TEST RESULTS

The performance of the second-stage seal tested for endurance life was determined by evaluating the following:

a. Sealing performance: measured by periodic sampling for seal leakage during endurance cycling.

b. Seal wear: evaluated by the change in leakage rates obtained at various test times and by an examination of the seal elements after the test.

3.4.2.1 Second-Stage Seal

The 3.85 x 10^6 cycles of endurance testing were successfully completed using the second-stage seal assembly with molded Chevron elements. No leakage was evidenced during the static leakage tests at room temperature and 1.379 MPa (200 psig), which were conducted for 15 minutes both before and after the endurance test. The sealing performance of the molded elements, determined by leakage measurements made during endurance testing at 450°K (350°F), is shown on table 6. This performance shows an average of 484 actuation cycles per drop of leakage for short stroke performance (2 percent) and 114 actuation cycles per drop of leakage during long stroke testing (summation of 25, 50, and 100 percent stroke data). The original Chevron seal design criteria for leakage acceptance during endurance testing was 12.5 cycles/drop which was met by the molded Chevron elements.

The performance of the molded elements was compared to the performance of machined elements previously evaluated. The results in the table below show that molded elements exhibit much poorer performance than the machined elements.

	Short Stroke act. cycles/drop	Long Stroke act. cycles/drop
Average Performance with Molded Chevron Elements	484	114
Average Performance with Machined K-Section Elements*	224659	2717

*Data summarized from References 1 and 2

It is important to note, however, that the machined seals tested in the 6.35 cm (2.5 in.) size were of the "K" section configuration (see references 1-3), not the Chevron configuration. The machined seals were fabricated in the "K" section configuration because the stress analysis for that section was more critical than for the Chevron section (see reference 1). Based on that analysis, a Chevron section of equivalent material should show better performance than a "K" section.

The change in sealing performance during endurance testing was evaluated by comparing the progressive variation in leakage rates during each segment of stroking condition in the cycling sequence. Although leakage rates were sometimes erratic, the average rate for each condition of the cycling sequence gave an indication of the overall sealing performance (see table 6). Sealing performance during the first 20 percent of testing (Run 1) accumulating

Table 6.—Second Stage Leakage During Endurance Testing of Unfilled Aromatic Polyimide Seals

Cycles Per Test Run	Actuator Stroke Condition	Accumulated Cycles Per Drop of Leakage									
		Run 1		Run 2		Run 3		Run 4		Run 5	
		Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
7.50×10^5	2%	>691 [1]	75	467	81	>615	125	224	30	425 [2]	27
0.05×10^5	25%	112	112	201	201	236	236	47	47	24	24
0.10×10^5	50%	132	120	52	38	62	62	>189	176	78	2
0.05×10^5	100%	96	77	>108	43	>171	>171	>141	>141	56	2

[1] Median value = 300 cycles/drop

[2] Median value = 80 cycles/drop

7.7×10^5 cycles, was particularly significant. During this testing segment, sealing performance was affected by thermal setting and shrinkage of the molded polyimide material with the greatest change evidenced during the short stroke (2 percent) condition of the cycling sequence.

During the short stroke condition of testing in Run 1, the average performance was 691 cycles per drop of leakage. This value, however, does not express the change occurring during the run. During the initial 200,000 cycles of Run 1, all the data entries indicated seal performance better than 1,500 cycles per drop. During the remaining 570,000 cycles performance was between 250 and 300 cycles per drop. This change in the sealing characteristic was attributed to thermal setting and aging of the polyimide seal material. Because there was a wide variation in leakage between the early and later portions of Run 1 testing, the median performance of 300 cycles per drop is considered more representative than the average of 691 cycles per drop as shown in table 6 for the short stroke cycling condition. During the other cycling conditions, 25 percent, 50 percent, and 100 percent stroke leakage data showed much less variation; therefore, average performance was considered more significant.

Wear had the principle effect on seal performance during the last four runs of the endurance test. Posttest visual inspections indicated considerable wear on the inside diameters of both the upstream and downstream Chevron element. Figures 11 and 12 show the results of these inspections.

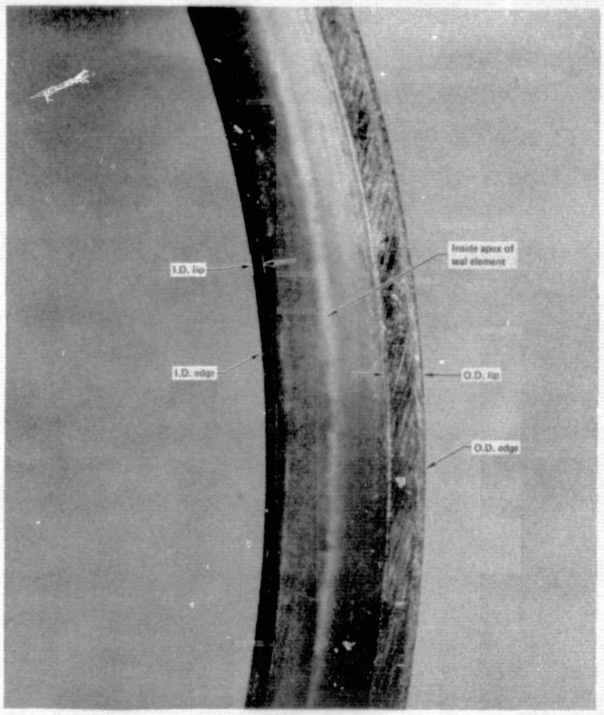
Testing experience has shown that polyimide material wear does not necessarily occur uniformly with test duration; therefore, the random appearance of the seal leakage data in table 6 was not considered unusual. Seal performance as measured by leakage improved through the first three runs as a function of wear with the exception of the effect of thermal setting during Run 1. Wear during this segment of testing resulted in polishing and the reduction of uneven surface contact on the sealing surfaces. Wear during the 4th and 5th runs resulted in material removal over the full contact surface of the Chevron element causing reduced contact pressure and increased leakage.

The analysis of second-stage seal performance during Run 5 showed an unusual distribution. A few measurements indicated no leakage causing the average performance value of 425 cycles per drop to not be truly representative of the trend in seal performance. A better representation of performance during Run 5 is the median value of 80 actuation cycles per drop of second-stage seal leakage.

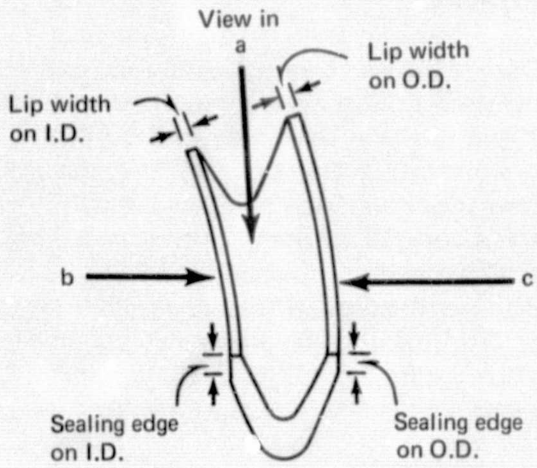
3.4.2.2 First-Stage Seal

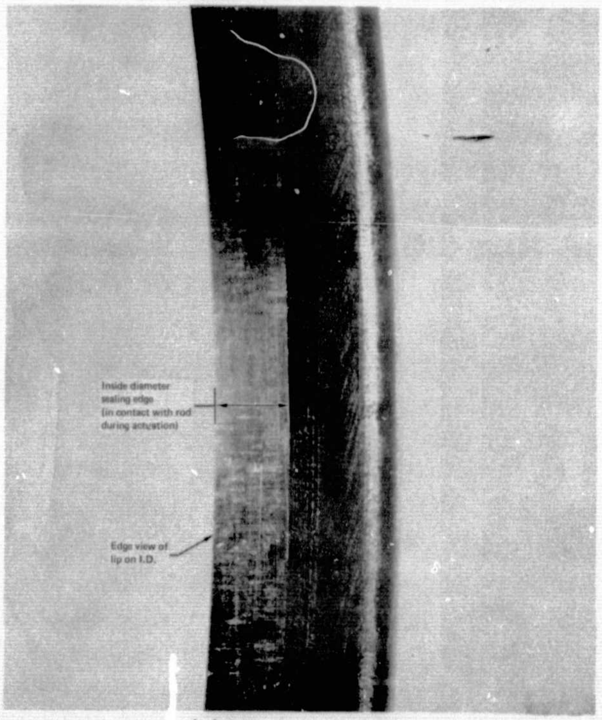
A cast-iron BACS11AM seal per appendix A was installed in the endurance test actuator because a molded first stage seal was not available. This was the same configuration as that used during the NAS3-16733 and NAS3-16744 testing reported in references 2 and 3.

First-stage leakage measurements were discontinued during Run 1 of endurance testing because measurement of this leakage resulted in pressure bleed-down of the interstage cavity. This pressure bleed-down affected the ability to maintain sealing of the second-stage

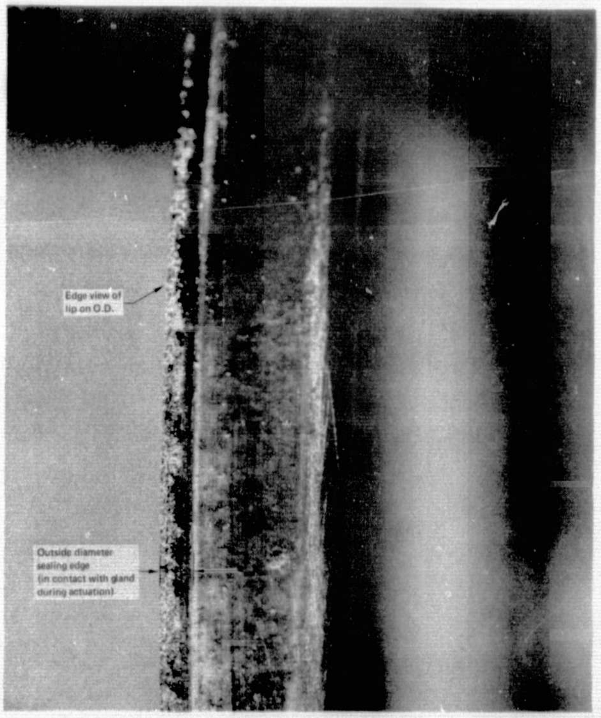


(a) Lip Variation



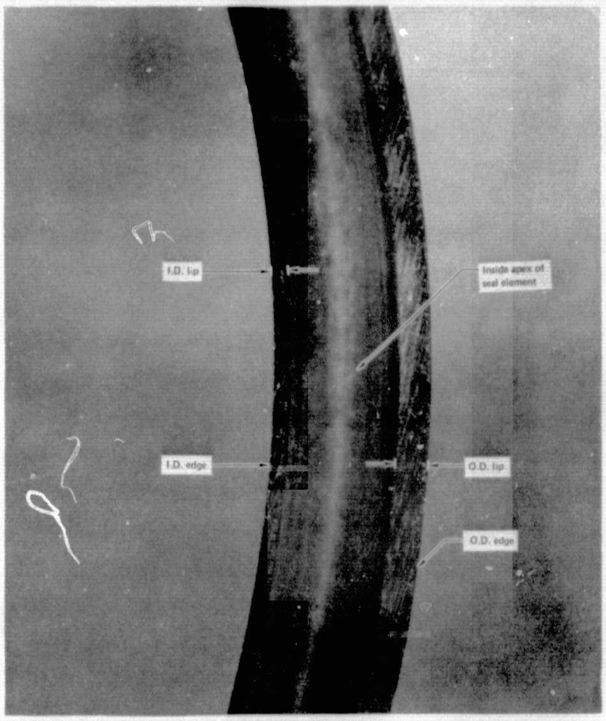


(b) I.D. Sealing Edge

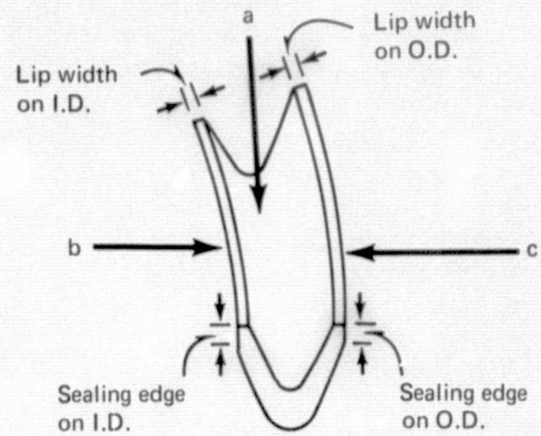


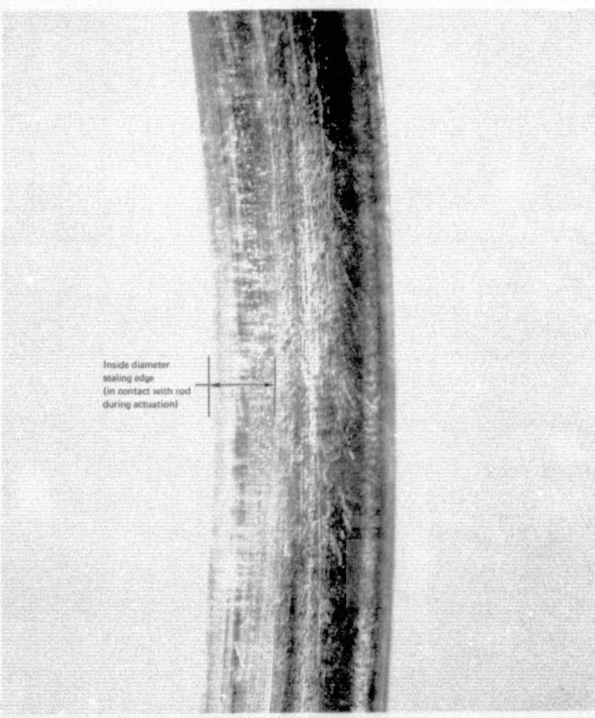
(c) O.D. Sealing Edge

Figure 11.—Post Endurance Test Inspection—Downstream Molded Aromatic Polyimide Second-Stage Chevron

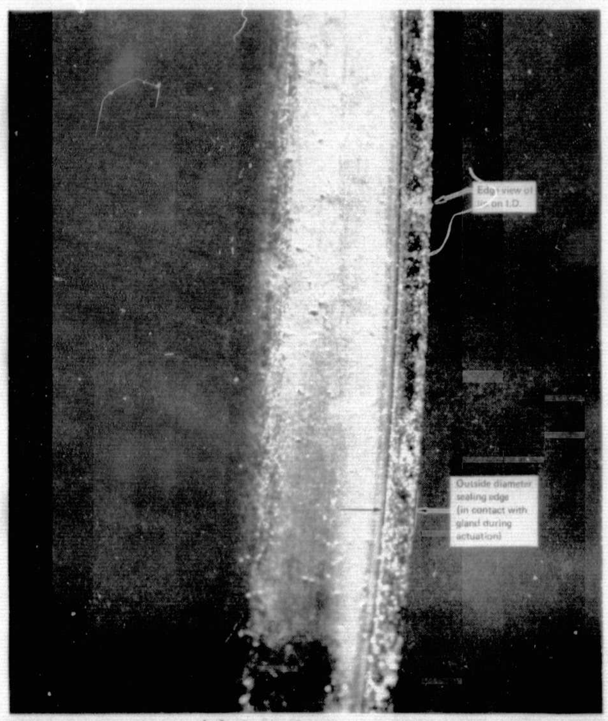


(a) Lip Variation





(b) I.D. Sealing Edge



(c) O.D. Sealing Edge

Figure 12.—Post Endurance Test Inspection—Upstream Molded Aromatic Polyimide Second-Stage Chevron

molded aromatic polyimide Chevron elements, indiating that interstage pressure was needed to load the molded Chevrons. During testing in Run 4 of the endurance sequence, leakage passing by the first-stage seal was shown to be inadequate to maintain the interstage pressure at 1.379 MPa (200 psig) due to the increased leakage by the second-stage seal. During subsequent testing the interstage cavity was externally pressurized to 1.379 MPa (200 psig) to maintain second-stage seal pressure loading.

4.0 DISCUSSION OF RESULTS

The results of testing molded, high-temperature, plastic seals has shown some reduced performance due to one or more molding material properties as compared to the properties of DuPont Vespel SP 21 and Vespel SP1 used to fabricate the second- and first-stage machined seals respectively (see reference 1). The most significant molding material weaknesses were as follows:

a. *Thermal setting of the aromatic polyimide materials* led to continued shrinkage of molded sealing elements at elevated temperatures. To reduce these effects, the curing of these materials prior to completing seal fabrication by molding must be conducted at a temperature in excess of the hottest application temperature. The time required at the curing temperature to prevent further shrinkage needs to be determined by the material supplier.

   A similar procedure for curing was adopted during fabrication of the machined seals under the NAS3-14317 program reported in reference 1. The DuPont Vespel SP-21 material was baked at 533°K (500°F) for 7200 sec (2 hrs.) prior to machining the seals.

b. *The weakness of the aromatic copolyester materials to impluse loading* was considered no different than that exhibited by many materials used in structural applications. The ability of these materials to resist impact loading is considerably different than the material resistance to steadily applied tensile loads. Because impact data is not as readily available as tensile load data, it is difficult to assess the effects of impact at the time material selections are made. If impact data is not available, sufficient testing should be conducted to indicate acceptability before selecting a material for seal element fabrication.

c. *The aromatic copolyester for compression molding was not directly usable* for molding the complex geometric shape of the Chevron cross-section. The necessity for extensive machining to finish and shape the molded blank defeats the objective of producing a lower cost seal by molding.

d. *An improvement is needed in the ability to control dimensions* of the finished molded seal element by properly configuring the mold. The elements made of both classes of high-temperature plastics showed considerable variation in the dimensions of the finished products. Such variations would not be acceptable for production procurement. Rejection rates due to edge imperfections and cracks were excessive and molding techniques need to be explored to reduce these rejection rates.

5.0 CONCLUSIONS

The molded second-stage rod seals, made of the aromatic polyimide material without fillers, completed both the impulse screening test and the endurance test. Performance was not acceptable as an alternate to the same configuration machined seal made from Vespel SP-21 material. The deficiency of these molded seals appears related to material thermal setting. Corrective action of this deficiency may be possible by molding at higher temperatures to insure that the delivered seals shrink to a minimum size before use in an application.

The aromatic copolyester molded second-stage rod seals showed a definite improvement in the uniformity of geometric shape, made possible by improved molding. The copolyester materials used in fabrication were selected based on anticipated improvement in their thermal setting characteristics as compared to the polyimide materials. Data to verify that there was less thermal setting with these materials was not obtained due to the early structural failures of the seal elements due to low material-impact strength. Further evaluation of the copolyester molding materials for seals requiring good impact strength is not recommended.

The first-stage seals made from the injection molded copolyester material could not be fully evaluated due to yielding of the material by pressure impulse loading. In comparison to a seal machined from Vespel SP-1 material to the same configuration, the Vespel material had adequate impact strength, but less than desirable wear life. Due to the structural failure of the molded seal, no wear data on this material was obtained. The injection molded copolyester material is not recommended for further use in fabricating first-stage molded rod seals.

Although the performance of the molded Chevron seals did not compare favorably with that of the machined polyimide seals as reported in references 1-3, test results showed where improvements were most needed.

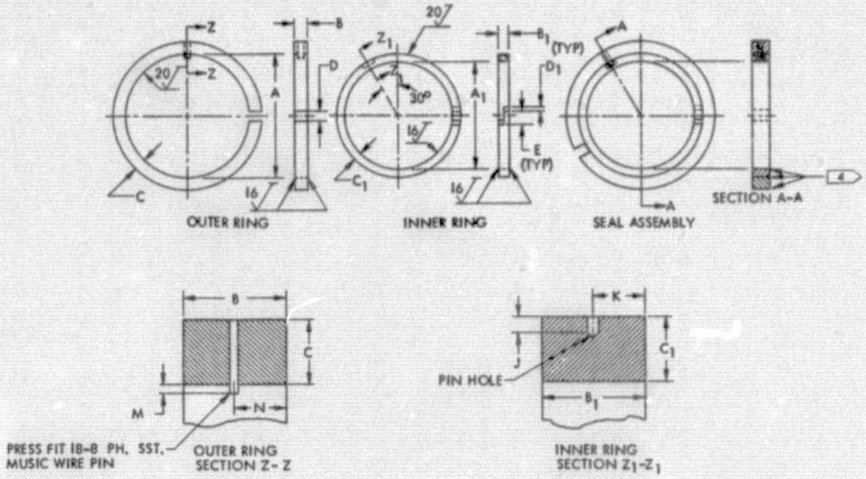
The manufacturers of seal molds must be given more complete data on the properties of the molding materials they use so that molds can be fabricated that will yield seal elements having better dimensional conformity to design specifications. It is therefore commended that some standard material tests be performed on such selections prior to fabricating finished seal parts to insure that the desired properties are available in the selected materials.

The success of the machined seals developed under the NAS3-14317, NAS3-16733 and NAS3-16744 contracts has been due to tailoring the seal design to the impact and fatigue strength of the material used in seal fabrication. To achieve the same success with molded seals, the impulse and fatigue strength of the molding materials in the finished molded form must be equivalent to the machining material, DuPont SP-21, used for the original design. If such molding materials are not available, the design for the molded seal must be altered to accommodate the properties of the molding materials with the most suitable properties. More extensive property testing of materials and further refinement of molding procedures is recommended to establish material/design compatibility before further performance testing of molded seals for advanced airplane and space vehicle hydraulic system applications.

The exemplary performance of the machined second-stage seals made of Vespel SP-21 polyimide material demonstrates that these seals are usable in applications with more stringent requirements than have been examined by the testing conducted under the NAS3-14317, NAS3-16733, and NAS3-16744 programs. It is therefore recommended that the machined second-stage Chevron and/or "K" section seal assemblies be evaluated for single-stage sealing applications with the objective of satisfying advanced airplane and space vehicle hydraulic system rod seal requirements.

APPENDIX A

SEAL ASSEMBLY, ROD, METALLIC
BOEING STANDARD BACS11AM



TOLERANCES: ±.005 UNLESS OTHERWISE SPECIFIED

BOEING STD. NO. BACS11AM	KOPPERS PART NUMBER	OUTER RING A	OUTER RING B ±.0005	OUTER RING C	OUTER RING D 2	OUTER RING D 2 TOL	INNER RING A1	INNER RING B1 ±.0005	INNER RING C1	INNER RING D1 1	INNER RING D1 1 TOL	E +.030 -.000	J +.005 -.000	K	M	N ±.001	PIN DIA	PIN HOLE	D 3
112	56695	.538		.023-.027	.115		.496		.019-.023										.047-.077
113	56698	.600		.023-.027	.115		.558		.019-.023										.047-.077
114	56701	.667		.025-.029	.115	-.000	.621		.021-.025	.020	+.005	.074							.047-.077
115	56704	.729		.025-.029	.115	+.020	.683		.021-.025		-.000				NO PIN				.047-.077
116	56707	.792		.027-.031	.125		.746		.021-.025										.052-.082
211	56710	.854		.027-.031	.125		.808		.021-.025										.052-.082
212	56713	.917		.028-.032	.135		.871	.0610	.028-.033										.060-.090
213	56716	.979	.0620	.028-.032	.135		.933		.028-.033										.060-.090
214	56719	1.041		.030-.035	.135		.996		.028-.033										.060-.090
216	56722	1.172		.035-.040	.150		1.121		.028-.033			.105	.013		.009				.062-.102
218	56725	1.303		.040-.045	.170		1.246		.028-.033	.035				.0295	.012				.072-.112
220	56728	1.434		.045-.050	.185		1.371		.029-.034					.0325		.031	.015	.025	.080-.120
222	56731	1.565		.048-.053	.200		1.496		.032-.037										.087-.127
326	56734	1.698		.053-.058	.220		1.621		.036-.041										.092-.142
327	56737	1.829		.057-.062	.240		1.746		.039-.044	.040		.136							.102-.152
328	56740	1.955		.057-.067	.255		1.871		.041-.047		+.015				.012				.110-.160
329	56743	2.080		.057-.067	.255		1.996		.041-.047		.000		.018		.017				.110-.160
330	56746	2.217		.067-.077	.295		2.121		.043-.053					.0445					.130-.180
331	56749	2.342	.0920	.067-.077	.295		2.246	.0910	.043-.053	.050				.0475		.046	.020	.035	.130-.180
332	56752	2.479		.074-.084	.320		2.371		.049-.059										.142-.192
333	56755	2.614		.078-.088	.320	-.000	2.496		.054-.064			.167							.142-.192
334	56758	2.741		.084-.094	.360	+.030	2.621		.055-.065										.157-.217
335	56761	2.874		.088-.098	.375		2.746		.059-.069	.055									.165-.225
336	56764	2.999		.088-.098	.375		2.871		.059-.069										.165-.225
337	56767	3.135		.097-.107	.415		2.995		.065-.075						.015				.185-.245
338	56770	3.260		.097-.107	.415		3.120		.065-.075				.022		.020		.025	.040	.180-.250
339	56773	3.397		.106-.116	.450		3.245		.071-.081										.197-.267
340	56776	3.522		.106-.116	.450		3.370		.071-.081										.197-.267
341	56779	3.659		.115-.125	.485		3.495		.077-.087										.215-.285
342	56782	3.784	.1235	.115-.125	.485		3.620	.1225	.077-.087		+.020	.190		.0600					.215-.285
343	56785	3.923		.123-.133	.520		3.745		.084-.094		-.000			.0630		.0615			.232-.302
344	56788	4.048		.123-.133	.520		3.870		.084-.094	.060									.232-.302
345	56791	4.185		.133-.143	.560		3.995		.090-.100										.242-.332
347	56794	4.447		.141-.151	.590		4.245		.096-.106										.257-.347
349	56797	4.709		.150-.160	.625		4.495		.102-.112				.037		.030				.275-.365
427	56800	4.972		.159-.169	.660		4.744		.109-.119		+.030				.035				.277-.397
429	56803	5.234		.168-.178	.710		4.994		.115-.125		-.000	.220					.030	.052	.302-.422
431	56806	5.484		.168-.178	.710		5.244		.115-.125										.302-.422
433	56809	5.748		.181-.191	.765	-.000	5.494		.122-.132										.332-.452
435	56812	5.998		.181-.191	.765	+.040	5.744		.122-.132										.332-.452

DATE 18 MAR 70 REV.

1	— —	2	— —
LIST OF ACTIVE SHEETS			

CODE IDENT NO. 81205

BAC S11AM SH 1 OF 2

SEAL ASSEMBLY, ROD, METALLIC

BAC S11AM SH 1 OF 2

PAGE 60.15.6.8.1

1. END CLEARANCE OF EACH RING TO BE MEASURED IN A GUAGE OF "A_1" ±.0005 DIAMETER.
2. END CLEARANCE OF EACH RING TO BE MEASURED IN A GUAGE OF "A" ±.0005 DIAMETER.
3. TENSION CONTROLLED BY OUTER RING GAP, RING IN FREE STATE.
4. I.D. EDGES OF INNER RING MAY HAVE A RADIUS OF .003 MAX FOR SIZES THROUGH BACS11AM345. SIZES LARGER THAN 345 MAY HAVE A RADIUS OF .005 MAX. O.D. EDGES OF OUTER RING MAY HAVE A RADIUS OF .015 MAX. INNER RING O.D. AND OUTER RING I.D. EDGES SHALL BE SHARP. ALL EDGES SHALL BE FREE OF BURRS.

MATERIAL: INNER: KOPPERS K-6E, ALLOY GREY IRON PER AMS 7310 EXCEPT CHROMIUM AND MOLYBDENUM ALLOYING ELEMENTS ADDED.
OUTER: 17-4PH CRES PER AMS 5643 OR AMS 5398, HARDNESS - R_c30-40.
PIN: 18-8 CRES PER AMS 5688.

FINISH: INNER RING ONLY. PARCO LUBRITE NUMBER 2 PER BAC5810, CLASS 1. THE RING SHALL THEN BE IMMEDIATELY IMMERSED IN HYDRAULIC FLUID WHICH MEETS THE REQUIREMENTS OF BMS3-10 AND PACKAGED WHILE DRIPPING WET WITH FLUID.

SURFACE ROUGHNESS: 63 RHR PER USAS B46.1 UNLESS OTHERWISE SPECIFIED. ROUGHNESS TO BE MEASURED PRIOR TO PARCO LUBRITE TREATMENT.

MARKING: EACH PACKAGE SHALL BE MARKED WITH THE SUPPLIER'S NAME, TRADEMARK OR CODE NUMBER, THE SUPPLIER'S PART NUMBER, AND THE BOEING STANDARD NUMBER.

CLEANING: PER KOPPERS COMPANY SPECIFICATION E-3803 TITLED "CLEANING AND PACKAGING PARTS TO BE USED IN PRECISION SEAL APPLICATIONS." CHLORINATED SOLVENT SHALL NOT BE USED IN THE CLEANING PROCESS.

PACKAGING: RING SETS CONSISTING OF AN OUTER AND INNER RING IN MATCHED SETS SHALL BE INDIVIDUALLY PACKAGED IN A HEAT SEALED POLYETHYLENE BAG. THE BAG SHALL THEN BE PLACED IN RIGID OR SEMI-RIGID BOXES.

INSPECTION: 100% INSPECTION BY THE MANUFACTURER. ASSEMBLY TO BE 100% LIGHT TIGHT BETWEEN INNER RING AND GAGE IN A GAGE OF "A_1" ±.0005 DIAMETER, AND 100% LIGHT TIGHT BETWEEN INNER AND OUTER RINGS FOR A DISTANCE EXTENDING 20° EITHER SIDE OF INNER RING STEP JOINT. LIGHT WHICH CAN BE PRESSED OUT WITH A RADIAL FORCE NOT EXCEEDING 5 LBS/INCH OF RING DIAMETER SHALL NOT BE CAUSE FOR REJECTION. EACH ASSEMBLY SHALL BE INSTALLED IN A TEST FIXTURE WITH A ROD FINISH OF 8 RHR AND A DIAMETER EQUAL TO THE MINIMUM ALLOWABLE PER MIL-G-5514, TABLE I, COLUMN "B". THE FOLLOWING TESTS SHALL BE CONDUCTED: MAXIMUM STATIC LEAKAGE USING MIL-F-7024, TYPE II AT ROOM TEMPERATURE AT 750 AND 4000 PSI SHALL NOT EXCEED 10 CC/MIN UP TO 2.500 INCH ROD DIAMETER, 25 CC/MINUTE FOR RODS 2.501 TO 5.000 INCH AND 50 CC/MINUTE FOR RODS OVER 5.000 INCH DIAMETER.

PROCUREMENT: KOPPERS COMPANY INCORPORATED, METAL PRODUCTS DIVISION, BUSH AND HAMBURG, BALTIMORE, MARYLAND 21203 (CODE IDENT NO. 75370)

THE SUPPLIERS LISTED AND THEIR AUTHORIZED DISTRIBUTORS ARE THE ONLY APPROVED SOURCES FOR THE ABOVE QUALIFIED PRODUCTS. CHANGES IN PRODUCT DESIGN OR QUALITY WITHOUT PRIOR BOEING APPROVAL MAY RESULT IN SUPPLIER DISQUALIFICATION. SUPPLIERS OF COMPETITIVE PRODUCTS MAY APPLY TO A MATERIEL DEPARTMENT OF THE BOEING COMPANY FOR QUALIFICATION.

USAGE AND APPLICATION INFORMATION

THESE SEAL RINGS ARE INTENDED AS ROD SEAL RINGS IN HYDRAULIC ACTUATORS WITH FLUID PER BMS 3-10 AT OPERATING TEMPERATURES OF 350° WITH EXCURSIONS TO 500°F. THESE SEALS TO BE USED WITH GROOVES PER BACD2040. THESE SEALS ARE NOT INTENDED FOR ZERO LEAKAGE APPLICATIONS.

DATE 18 MAR 70 REV.

SEE PREFACE FOR GENERAL USAGE NOTES.

APPENDIX B

PRESSURE IMPULSE TEST, SYSTEM DESCRIPTION AND OPERATING SEQUENCE

TEST SYSTEM DESCRIPTION

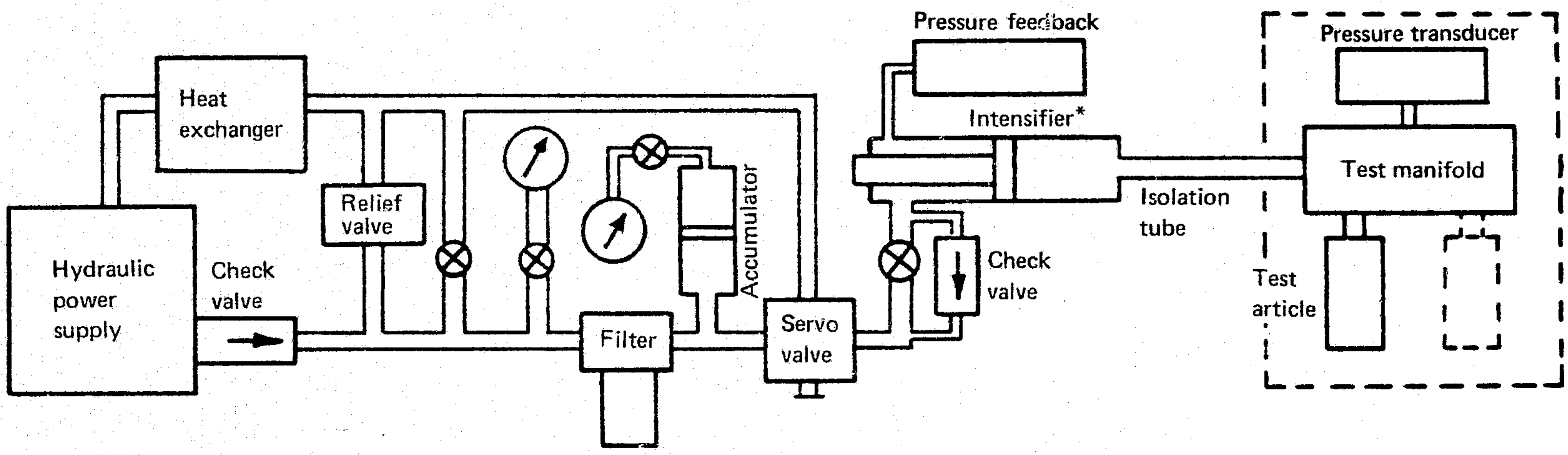
TEST OPERATION COMPONENTS

The hydraulic system shown schematically in figure 13 describes the test rig used for impulse testing. This is an existing rig developed primarily for testing of tubing, fittings, and hoses. It consists of the following major components:

Hydraulic power supply	Denison 8-gpm pump unit
Hydraulic relief valve	Denison
Hydraulic filter	Purolator, T type (25 micron absolute)
Servovalve block	Boeing laboratory equipment (SK11-96025)
Intensifier (3 to 1 area ratio)	Boeing laboratory equipment
Heat exchanger	Harrison, water cooled
Accumulator	Hydrodyne, $3.785 \times 10^{3}\ m^{3}$ (1 gal), 68.94 MPa (10,000 psig)
Isolation Tube	0.013 m (1/2 in.) O.D. for first-stage test 0.0064 m (1/4 in.) O.D. for second-stage test

The hydraulic power supply consists of a $5.047 \times 10^{-4} m^{3}/sec$ (8 gpm) 34.42 MPa (5000 psig) variable-displacement pump with reservoir. A high-pressure, piston-type accumulator is located in the supply line just upstream of the servovalve manifold to provide peak flow requirements beyond the maximum dynamic response of the pump. Ports within the servovalve block are oversized to reduce pressure drop. For tests requiring pressure rise rates below 1033 MPa/sec (150,000 psig/sec), a 3 to 1 intensifier is placed between the servovalve and the test manifold. This allows the pump and servo to be operated well within their working pressure range while impulsing the test article at rather high pressure peaks.

For this series of tests reported, the fluid on the servo side of the intensifier was MIL-H-5606 and the fluid on the test article side of the intensifier was MIL-H-83282 (reference 4). The test article temperature was provided by placing the seal retaining housing in an environmental enclosure and controlling the ambient temperature within this enclosure. Because the fluid in the test article was almost dead-ended, no preheating of the supply fluid was required. The test chamber was positioned approximately 152.4 cm (60 in.) from the intensifier and connected by a suitable section of hydraulic tubing. This tube was used to isolate the test article temperature from the intensifier.



*Shown for 2nd stage test operation, direction reversed for 1st stage tests

Figure 13.—Impulse Test Setup Schematic

CONTROL CIRCUIT AND INSTRUMENTATION

The control system for impulsing was based on an electrohydraulic, closed-loop, pressure-control servo system. Components of this system were arranged as shown in figure 14. The control actuating device was the four-way, pressure-control servovalve with one cylinder port blocked. The servo controller was a Boeing-built controller with an adjustable servo loop gain from unity to a multiplication of one hundred. The controller output stage was a voltage driver which also provided damping for the servo-valve.

The servovalve was driven by two superimposed square waves of variable amplitude and period. The basic wave provided a signal corresponding to the desired working, or plateau, pressure level. The second wave with the same leading edge, greater amplitude, and a shorter duration was superimposed to provide the overshoot pressure peak. The shape of the overshoot peak pressure wave was varied between a single damped wave to that of a nearly zero damped oscillatory wave by varying the controller loop gain. Additional fine adjustment of wave shape, rate of pressure rise, and pressure level was made by varying the servovalve input wave shape, hydraulic supply pressure, pressure loss in the supply line to the intensifier, and the test article volume. A Boeing-built, fail-safe panel provided for system shutdown at loss of 10% of the peak pressure for one cycle or loss of 3 percent to 5 percent for several cycles.

DATA

A data system was used to determine that proper adjustment had been made to the control system for the specific impulse profile. Cycle programmer output and servovalve current were used as reference control information. Output from a data system transducer, mounted on the test specimen manifold, provided a dynamic impulse pressure trace for visual monitoring. Oven temperatures were controlled automatically and monitored on a vertical temperature indicator. Instrumentation data accuracy is reported in appendix D.

INPULSE TEST PERFORMANCE SEQUENCE

TEST ARTICLE ASSEMBLY

Test articles were assembled for six individual impulse tests which were conducted in the following order:

a. Second-stage 6.35 cm (2.5 in.) Chevrons of unfilled aromatic polyimide.

b. Second-stage 6.35 cm (2.5 in.) Chevrons of aromatic polyimide with 10% MoS_2 filler.

c. Second-stage 6.35 cm (2.5 in.) Chevrons of aromatic polyimide with 10% graphite filler.

d. Second-stage 6.35 cm (2.5 in.) Compression molded Chevrons of aromatic copolyester.

e. Second-stage 6.35 cm (2.5 in.) Injection molded Chevrons of aromatic copolyester.

f. First-stage 6.35 cm (2.5 in.) Injection molded step-cut of aromatic copolyester.

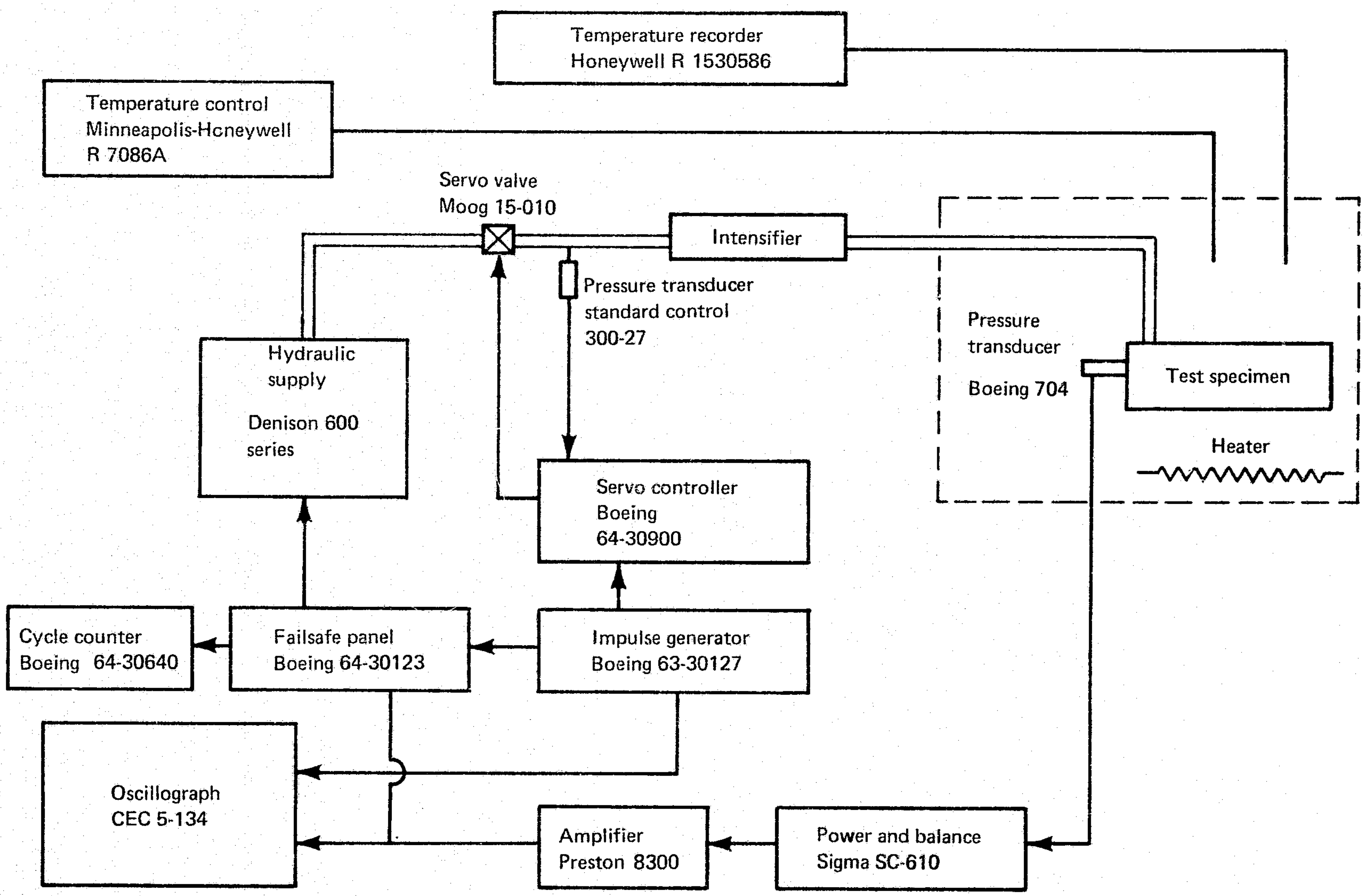


Figure 14.—Impulse Test Instrumentation Block Diagram

Seals were installed by wetting the seal and gland surfaces with hydraulic fluid and using finger pressure to position the individual parts on the rod. The seal housing bushing was then used to push the seal assembly into its proper position in the gland. No sticking or binding was encountered during installation.

TEST OPERATION

After the test article and data transducer were installed on the test manifold, a system pressure of 0.689 MPa (100 psig) was applied to the intensifier and test article to allow air to be bled from the system. Full system pressure was thereafter applied and the servo controller used to manually vary pressure from zero to maximum to check for system leaks and control system stability.

Proof pressure tests were conducted on the second-stage seal assemblies to establish pre-impulse test leakage performance of the test articles. These tests were conducted by statically pressurizing the seals to 10.43 MPa (1500 psig) for 300 sec. (5 min.). The test was conducted at 297°K (75°F) with seals made of the aromatic polyimide series of materials and at both 450°K (350°F) and 228°K (-50°F) with seals made of the aromatic copolyester materials. The proof pressure test of the first-stage seal was conducted at 38.61 MPa (5600 psig) for 300 sec. (5 min.) at both 450°K (350°F) and 228°K (-50°F).

The test data system was calibrated and the pressure impulse profile set to the requirements of figure 3 by:

a. Adjusting the cycle programmer offset control to place the pressure plateau at the correct level.

b. Opening the programmer's leading edge width control just far enough to obtain desired peak pressure.

c. Adjusting the power supply pressure as necessary to obtain the correct peak pressure amplitude.

d. Adjusting the servo controller gain to shape the overshoot wave to the desired profile.

Recordings were made to determine pressure rise, which was calculated as follows:

P = peak pressure in psig

$\Delta 1$ = time at 10% P (sec)

$\Delta 2$ = time at 90% P (sec)

Rate of rise in MPa/sec (psig/sec) = $(0.9P - 0.1P)/(\Delta 2 - \Delta 1)$. This is the straight line slope of the pressure-time trace.

The 3-to-1 intensifier used to boost peak pressure during first-stage seal testing was reversed and used as a deboost cylinder for the low-pressure impulse test of the second-stage seals. In addition, the accumulator precharge was adjusted and the isolation tube size reduced to provide added correction to obtain the lower rate of rise for testing second-stage seals.

Heater controls were adjusted to maintain seal housing temperatures at the level prescribed for each segment of the impulse test. During testing, leakage was measured by collection in burettes or by visual monitoring where leakage was only an infrequent drop.

POSTTEST INSPECTION

The seals that completed impulse tests were examined for structural damage, cracking of the seal material, and contact surface polishing. The above were not considered as conditions of seal failure unless the leakage during the test was greater than the allowable. The inspection was performed by unaided visual observation to make a qualitative description of the seal, supplemented by observations using a microscope.

APPENDIX C

ENDURANCE TEST, SYSTEM DESCRIPTION AND OPERATING SEQUENCE

TEST SYSTEM DESCRIPTION

The endurance test installation, shown in figure 15, is an existing rig developed primarily for testing linear actuator seals. The installation consists of a load system, the hydraulic power supply with its associated plumbing, and the control electronics. The major power and loading components are as follows:

Oven-dispatch, model 203

High-temperature power supply—Auto Controls Laboratory, Inc., model 4586

Load fixture—Boeing laboratory equipment

Filter—microporous (25 micron absolute)

Relief valve—Vickers C-175-F

Servovalve block—Boeing laboratory equipment

Accumulator—Hydrodyne 68.95 MPa (10,000 psig)

The load system consisted of a torsion bar capable of providing resisting torque for the actuator. The torque bar length was adjusted to provide a torsional load such as to require full system pressure of 27.58 MPa (4000 psig) at full actuator stroke. The force from the actuator was reacted to the torsion bar through a lever arm and bearing assembly to simulate a flight control surface hinge point. Self-aligning bearings were used for the actuator head-end and rod-end connection points. No additional side load other than bearing friction was applied. The mounting base of the load system and the actuator was installed in a test oven. This installation is shown in figure 16. Due to its size, the torsion bar extended through the back of the oven and was supported externally at the extreme end by a pedestal.

Hydraulic power was supplied by a 1.262 x $10^{-3}m^3$/sec (20 gpm) Auto Controls Laboratory high-temperature power supply. This unit is complete with all pressure and temperature controls. It supplied MIL-H-83282 (reference 4) hydraulic fluid at 27.58 MPa (4000 psig) and at the required test temperature. The 9.464 x $10^{-3}m^3$ (2.5 gal) accumulator was located in the supply line between the power supply and the test rig. In addition to filtration within the power supply; a 25-micron-absolute filter was located in the supply line downstream of the accumulator. The cavity between the first- and second-stage seals in the test actuator was vented to return through a relief valve to maintain second-stage seal pressure at 1.379 MPa (200 psig). Additional check and isolation valves allowed measurement of first-stage leakage without interrupting actuator cycling during testing.

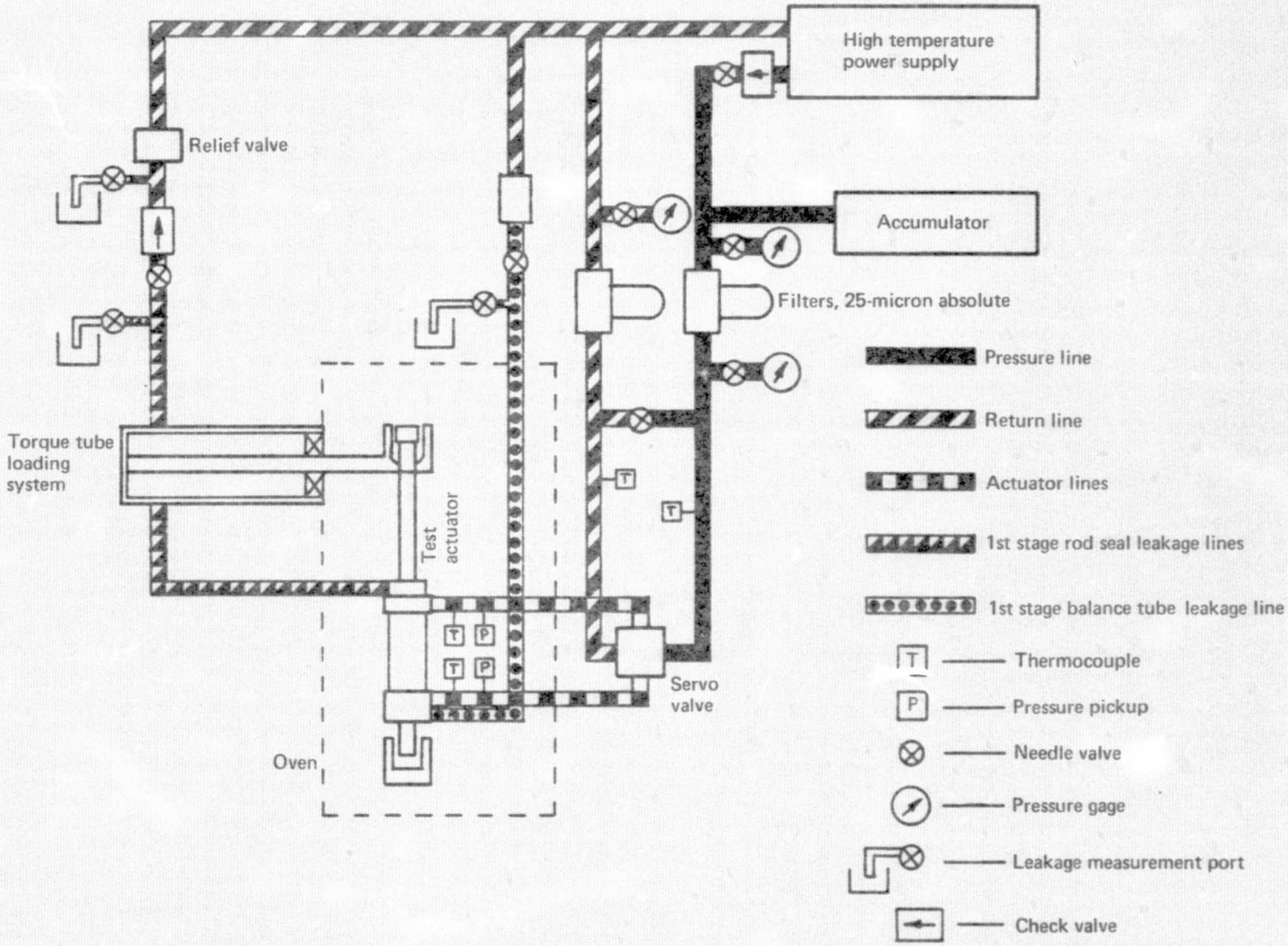


Figure 15.—Hydraulic Installation Schematic, Endurance Test

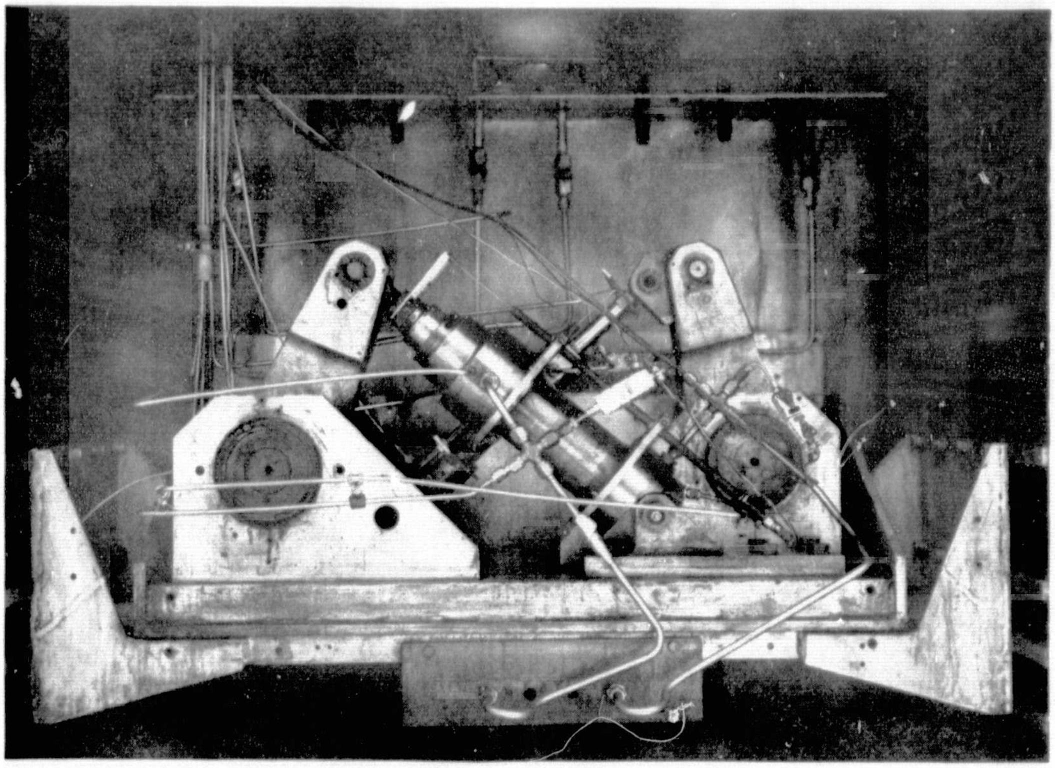


Figure 16.—Actuator Installation, Endurance Test

CONTROL ELECTRONICS

The control of test operation cycling was provided by a closed-loop electrohydraulic flow control loop incorporating position feedback.

Components were arranged as shown in figure 17. The electrical loop consisted of the feedback transducer (LVDT), carrier amplifier, Boeing standard controller, and servovalve, with the total loop completed mechanically through the fluid-powered actuator rod. The servocontroller was driven with a function generator providing a sinusoidal cycle at the required period. The actuator stroke amplitude and position were set at the servocontroller command for the flow control servovalve.

Actuator head- and rod-end cylinder pressures were measured and recorded on a direct-write oscillograph. The actuator position was also recorded on the oscillograph and monitored during test to ensure that proper position and stroke amplitude were maintained.

Oven ambient, oil, and component temperatures were recorded on a stamping-type temperature recorder.

Instrumentation and recorded data accuracies are reported in appendix D.

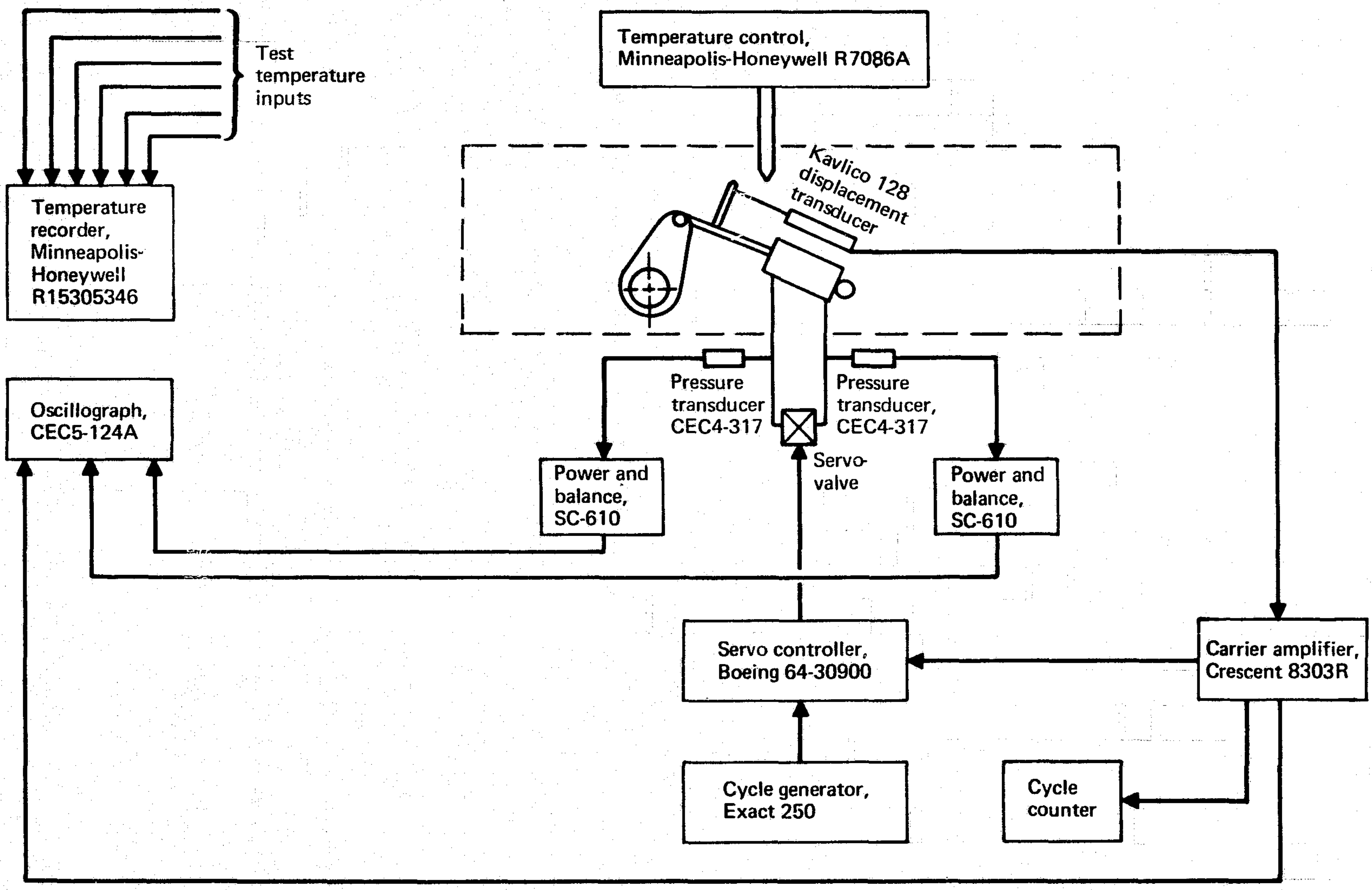


Figure 17.—Electrohydraulic Control Loop, Endurance Test

ENDURANCE TEST PERFORMANCE SEQUENCE

TEST ARTICLE ASSEMBLY

The first- and second-stage seals to be tested were assembled into the seal module of the test actuator shown in figure 18. This module was specifically designed during the NAS3-14317 program to hold the test seals for evaluation during endurance testing. The actuator was then assembled and manually inspected for binding. A proof pressure test was then conducted and preendurance test leakage rates established for the seals at room temperature.

TEST OPERATION

After the test actuator and data transducers were installed in the loading fixture, a reservoir pressure of 0.344 MPa (50 psig) was applied and air was bled from the hydraulic system. A room temperature checkout was conducted, starting with a system pressure of 6.894 MPa (1000 psig) and increased in incremental steps to working pressure while cycling. Testing was performed in the sequence defined in the table below and test conditions were established by adjusting:

a. The hydraulic power supply to test temperature and 27.58 MPa (4000 psig) nominal working pressure

b. The oven controls to maintain the test temperature for the mass of the actuators and fixture

c. The function generator to the cycle rate required by the test schedule

d. The servocontroller to provide the desired actuator neutral cycling point and percent of rod stroke

e. The interstage relief valve to maintain 1.379 MPa (200 psig)

ENDURANCE TEST SEQUENCE

Sequence number	Cycles	% load and stroke (see notes 4 and 5)	Maximum cycle rate, Hz	Actuator temperature	
				$^{\circ}$K	$^{\circ}$F
1	7.5×10^5	2	6	450	350
2	5 000	25	0.83	450	350
3	10 000	50	0.67	450	350
4	5 000	100	0.56	450	350

Notes:

1) All cycles are to be run around actuator midstroke position.
2) A portion of the cycles from sequences 2, 3, and 4 are to be randomly interspersed during performance of sequence 1.
3) Testing spectrum is to consist of five consecutive runs in the sequence shown, i.e., 1, 2, 3, 4, 1, 2, 3, 4, 1, 2...with the sum of sequences 1+2+3+4 equalling one run.
4) 6.35 cm (2.5 in.) actuator: 100% stroke = 7.62 cm (3.0 in.) 100% load = 88.964 N (20 000 lbf)

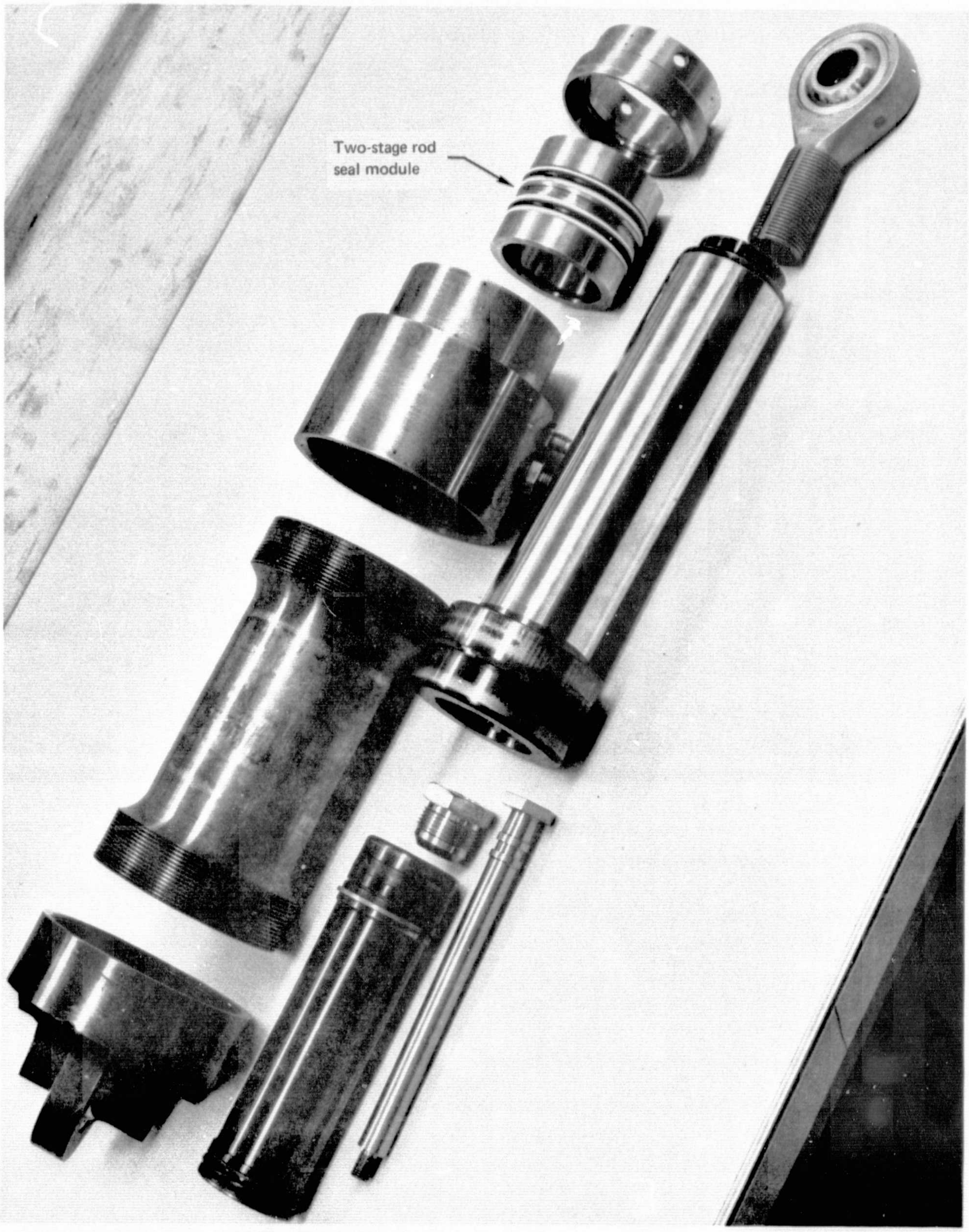


Figure 18.— 6.35 cm (2.5 in.) Endurance Test Actuator

During testing, first-stage leakage was measured by its collection in burettes. The second-stage leakage was measured by visual observation.

POSTTEST INSPECTION

The seals that completed endurance tests were examined for structural damage, cracking of the seal material, contact surface polishing, and unusual wear. This was conducted by unaided visual observation supplemented by observations using a microscope.

APPENDIX D

INSTRUMENTATION CALIBRATION AND DATA ACCURACY

Test instrumentation equipment calibrations are traceable through the Boeing flight test calibration laboratory to the National Bureau of Standards. Strain gage, bridge-type transducers were calibrated to determine nonlinearity, hysteresis, and R-shunt calibration transfer values. Position transducers were end-to-end calibrated in place by a calibrated scale/visual technique.

Pressure

Transducer accuracy within	±0.75% full scale
Power and balance/conditioning within	±0.1% full scale
Oscillograph accuracy within	±2.0% full scale
Pressure measuring system accuracy (RSS) within	±2.1% full scale

Displacement

Transducer accuracy within	±0.1% full scale
Signal conditioning within	±0.2% full scale
Oscillograph accuracy within	±2.0% full scale
Displacement measuring system accuracy (RSS) within	±2.0% full scale

Temperature

Thermocouple accuracy within	$\pm 1.11^{\circ}$ K($\pm 2^{\circ}$F)
Temperature recorder within	$\pm 2.2^{\circ}$ K($\pm 4.5^{\circ}$F)
Temperature measuring system accuracy (RSS) within	$\pm 2.5^{\circ}$ K($\pm 4.0^{\circ}$F)

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