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NASA Contractor Report 159055

Design and Fabrication of Elevon Cove Thermal Protection Systems For Aerospace Vehicles

Angelo Varisco
Albin Borysewiez
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GRUMMAN AEROSPACE CORPORATION
Bethpage, N.Y. 11714

CONTRACT NAS 1-14112
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16. Abstract

A design study was undertaken to develop and fabricate a flightweight, effective, reuseable seal for use along the elevon cove of shuttle-type reentry and hypersonic cruise vehicles. The development work included in this report deals primarily with membrane seals, both metallic and non-metallic. This type of seal spans the cove gap between the wing and elevon, and does not depend on spring tension to maintain contact along a flexing wing span. Technical requirements and criteria were generally derived from the space shuttle and utilized for seal design.

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FOREWORD

This report represents the work that was performed between April 1976 and July 1977 under Contract NAS 1-14112. The program described herein was performed by the Grumman Aerospace Corporation for the National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia. Technical direction of the contract was performed by Mr. W. D. Deveikis and Mr. L. R. Hunt of the Thermal Structures Branch, Structures and Dynamics Division.

The program was managed by A. Varisco under cognizance of Advanced Development Systems engineering. Major contributions were made by A. Borysewiez, Design; W. Wolter, Structural Temperatures; and E. Leszak, Manufacturing.

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Section 1

INTRODUCTION AND SUMMARY

1.1 INTRODUCTION AND SUMMARY

A design study was undertaken to develop and fabricate a flightweight, effective, reusable seal for use along the elevon cove of shuttle-type reentry and hypersonic cruise vehicles. A critical design requirement was that the seal had to protect the internal structure of the elevon against ingress of hot boundry-layer gases up to 1367 K (2000° F) at pressure ratios across the seal greater than two. Proof of concept would be demonstrated using an existing cove seal test apparatus to expose the seal to effects of the aerothermal environment produced in the Langley 8-foot, high-temperature structures tunnel. This facility is a large blowdown wind tunnel that operates at a nominal Mach number of 7 and uses methane-air products of combustion as a test medium. The cove seal test apparatus, shown in figure 1-1, consists of a fixed wing-cove housing, a rotatable elevon, and aerodynamic fences at the side walls to channel the upstream flow across the cove entrance. The development work included in this report deals primarily with membrane seals, both metallic and non-metallic. This type of seal spans the cove gap between the wing and elevon and does not depend on spring tension to maintain contact along a flexing wing span. Technical requirements and criteria were generally derived from the space shuttle and utilized for seal design guidelines.

Three metallic cove seal configurations, formed as the letters "W", "S", and "C", were analyzed for structural capability. In this application the membrane is subjected to at least seven types of loading, with some occurring simultaneously. Results from the analysis indicated that the most severe stresses occurred under seal rotational bending and differential elevon/wing expansion. The calculated rotational bending stresses were significantly beyond the yield limits of the material which implies that fatigue failure would eventually occur. The calculations also showed substantial deformation of the seal beyond the limits of the material under differential expansion. Moreover, a working model of a wing-elevon juncture with a René 41 membrane seal clearly demonstrated yelding at both limits of rotational travel and thus, confirmed the analytical implication that metallic membranes are not applicable for use as cove seal. The non-metallic seals were grouped into two categories called non-stretch and stretch concepts. The non-stretch concept uses a non-metallic membrane configured as a "C" with adequate length so that stretching is not required during elevon rotation and deflection. This concept offers two important advantages: first, the membrane can be fabricated with a Nomex cloth reinforcement which will significantly increase tear strength; and second, a thermal blanket can be bonded directly to the membrane and thereby provide a more predictable thermal barrier. However, to maintain the

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Note: Use of commercial products or names of manufacturers in this report does not constitute official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

required shape, metal battens must be molded within the rubber at suitable intervals. The metal battens suffer from all the disadvantages of metallic membranes, such as high bending stresses during rotation and extremely higher shear stresses due to differential wing/elevon expansion. The shear deformation is especially serious because the battens could twist and tear and thus cause membrane failure. Efforts to reduce the fixity of each batten and to minimize the stresses were unsuccessful. Therefore, this concept was eliminated from further study. For the stretch concept, a high-temperature silicone rubber membrane was slightly stretched between the wing and elevon. The primary advantage of this concept is its ability to accept any conceivable structural deformation between the wing and elevon without leakage. Since no metal is used in the basic seal, all stresses due to rotation or shear deformation are eliminated. A thermal blanket that would permit stretching can be added to increase the temperature capability of the seal. The stretch concept was retained for further study.

Although the membrane seal offers high potential for use as a cove seal, the ends of the membrane must also be sealed against chordwise walls such as at wing stubs. Therefore, two design concepts were developed for sealing the ends of the membrane against end plates in the cove seal test apparatus but which would also be applicable in a flight vehicle. The first employs a Nomex high-density-pile carpet wiper pad in each end plate. The ends of the membrane contain internally molded thin metal battens which provide edge stiffness for wiping against the carpet. However, the disadvantages of this design concept are that some leakage of air can occur through the fibers, and cyclic life can be reduced from shredding of the fibers during seal rotation. The second design concept employs an integrally molded "P" shaped bulb in each end of the membrane. Metal battens are also used to support and maintain the

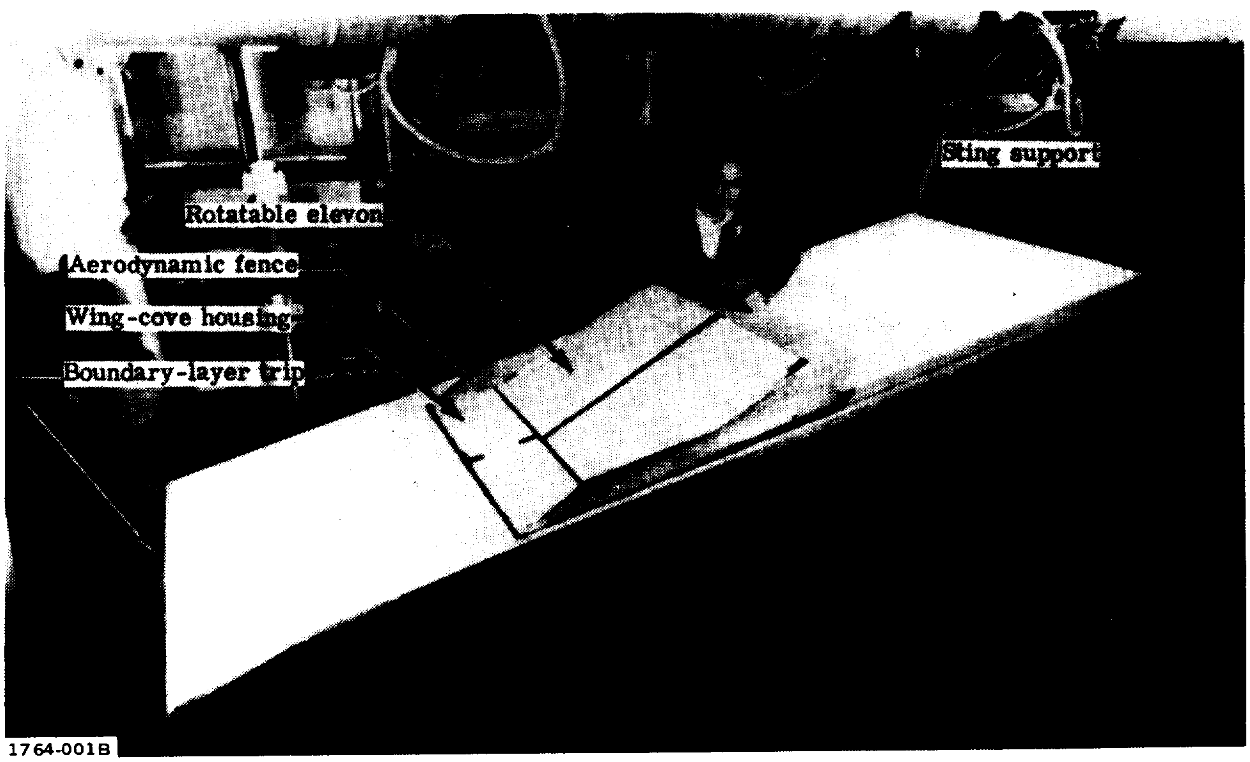

Figure 1-1. – Langley, cove seal test apparatus.

bulb against the end plate. The bulb is designed with adequate diameter so that end sealing is maintained during relative motion between the elevon and end plate. This concept requires a low-friction interface, which was accomplished by applying a ceramic dry film lube on the end plate. After considering advantages and disadvantages of the various seal design concepts and analyzing their structural integrity, the stretch curtain design concept with an integrally molded "P" bulb end seal was selected for the test seal. Four seals were designed and fabricated, each using the stretch curtain membrane, with four different "P" bulb configurations. One seal employed a plain "P" bulb. The other three employed modified "P" bulbs with three different knitelastic polyester (Spandex) treads on the contact surface of the "P" bulbs to enhance end sealing and to reduce friction between the seal and the end plate.

1.2 SYMBOLS AND UNITS

Although calculations were made in U.S. Customary Units, they are presented in this report in the International System of Units (SI) also. Factors relating to the two systems are given in reference 1-1. Symbols throughout this report are defined as they are introduced.

The appropriate quantities for the SI units used in this report are:

Quantity	Unit	SI Symbol
length	meter	m
force	newton	N
pressure	pascal	Pa
mass	kilogram	kg
temperature	kelvin	K

Abbreviations for the following prefixes have been employed for multiples of units in this report:

Prefix	Multiplication Factor	Abbreviation
centi	10^{-2}	c
milli	10^{-3}	m
kilo	10^{3}	k
mega	10^{6}	M
giga	10^{9}	G

1.3 REFERENCE

1-1 "Metric Practice Guide, E380-2 American Society Testing and Materials," June 1972.

Section 2

DESIGN CRITERIA

2.1 THERMAL CONDITIONS

Although the elevon cove temperatures for the shuttle orbiter have not yet been determined, a 450 K (350° F) temperature limit was initially assumed as a seal design requirement. However, the possibility of spanwise flow could raise cove temperatures in excess of 450 K (350° F). Additional effort would be required to estimate the effects of spanwise flow. Therefore, to account for spanwise flow, a 533 K (500° F) temperature limit was arbitarily established as a seal design goal.

The current space shuttle orbiter is expected to experience the following temperatures and pressures on the wing:

Mission Phase	Temperature K (° F) Min	Max	Ultimate Pressure (1) kPa (psi)
Pre-launch	267 (20)	339 (150)	----------
Ascent	267 (20)	339 (150)	-29.4 (-4.2) + 19.6 (+2.8)
On-orbit	172 (-150)	353 (175)	----------
Post heating	172 (-150)	(2)	-17.5 (-2.5) + 23.8 (+3.4)
Ferry/horizontal flight	219 (-65)	339 (150)	----------

(1) 1.4 times limit pressure

(2) 533 K (500°F) seal design goal

2.2 MECHANICAL CONDITIONS

The primary requirement of an elevon seal is that it must accept any conceivable structural and thermal displacement between the wing and elevon without leakage. Therefore, it was required to know the amount of displacement a typical seal would be required to accomodate, and then these data could be used as a design starting point from which additional criteria could be developed. Since an extensive amount of load/deflection data exists for the shuttle wing, these data were used in the Rockwell International, ASKA finite element analysis, post processing program. In this program, the wing and elevon are idealized into many nodes, and displacements are determined for all the node points under many conditions.

Figure 2-1 illustrates the nodes which were selected in the study. Node 164 is located on the wing lower skin, between the inboard and outboard elevons. Node 96 is

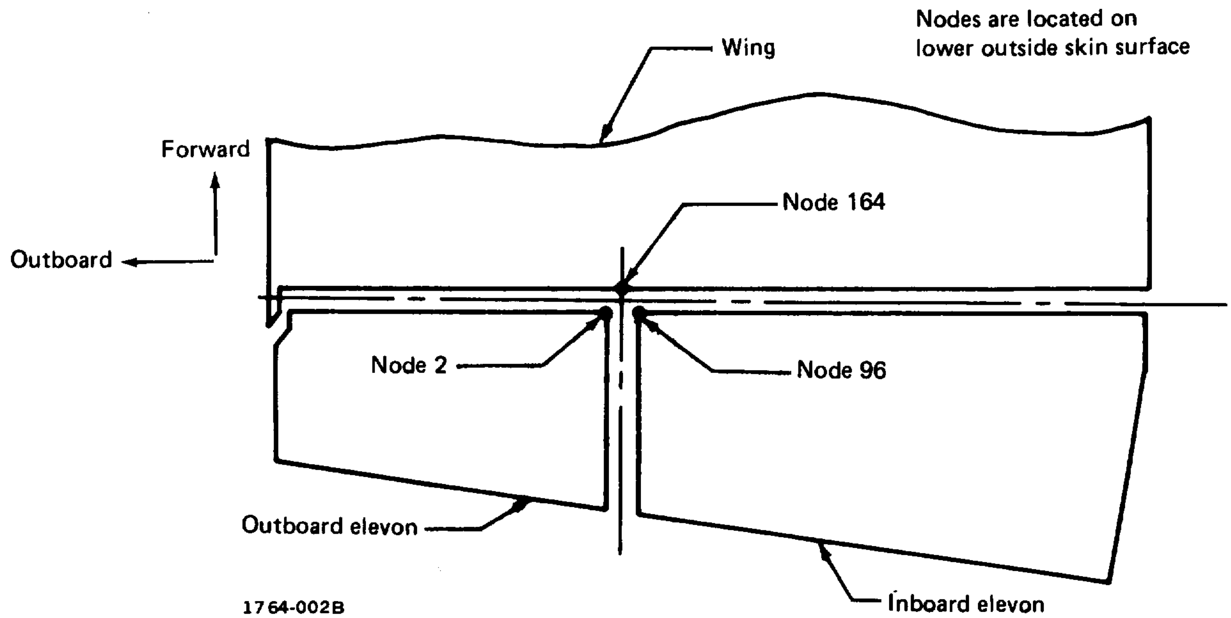

Figure 2-1. – LH shuttle wing/elevon configuration and node point locations.

located on the inboard elevon lower skin at the outboard corner. Node 2 is located on the outboard elevon lower skin at the inboard corner.

For the present study, data from reference 2-1 were used. Twelve reentry conditions determined by Rockwell and Grumman to be critical for the wing and elevon were checked, and these are listed in table 2-1 as items 1 through 12. These conditions produce displacements resulting from mechanical and thermal loads. In addition, the post heating conditions were searched and selected for maximum displacements. These are listed as items 13 and 14 of table 2-1. Although seal leakage may be permissible for conditions 13 and 14, it was considered important to know the largest displacements that would be encountered as design information.

Mechanical and thermal displacements for nodes 2, 96, and 164 are listed in table 2-2. A positive sign indicates outboard movement of the node, and a negative sign indicates inboard movement. All nodal displacements are spanwise only. No vertical or fore and aft displacements were considered. These values indicate that the largest displacements occurred in the inboard elevon (node 96) for the post heating conditions 13 and 14.

The net spanwise relative displacements between the wing stub and inboard and outboard elevons are listed in table 2-3. These were determined by properly combining the mechanical and thermal displacements in table 2-2. The column headed "Comb" (combined) in table 2-3 lists either a "C" (for end-seal compression) or an "E" (for end-seal extension) after each value. A "C" displacement indicates a net reduction of the space between the elevon and the wing stub side wall; whereas, an "E" displacement indicates an increase in that space. Maximum displacements for reentry and post heating conditions are listed in table 2-4. No extension of the space between the inboard elevon and wing stub is indicated at reentry, but substantial spanwise displacements occur during post heating. The largest displacement in the compression direction is 0.68 cm (0.267 in.) and 1.05 cm (0.414 in.) in the extension direction for a total excursion of 1.73 cm (0.68 in.). The spanwise compression must be accommodated in designing an end seal; otherwise, excessive seal compression and crushing would result. However, if the spanwise extension were to be accommodated, a larger end seal bulb diameter would be required, which would significantly reduce end-seal flexibility. Since this larger extension occurs during post heating, seal integrity would not be affected if a small gap were allowed between the end seal and stub wall by using a smaller end seal bulb diameter.

Table 2-1. – Critical wing elevon loading conditions.

Item	SF76 Data (1) Load Group	Reentry Condition	
1	G21R0585	Tail Sun, Reentry - 1.0G Maneuver, Mach = 8.0	
2	G21R0586	Tail Sun, Reentry -1.0G Maneuver, Mach = 10.0	
3	G21R0587	Same as 2 Except Entry Angle	
4	G21R0588	Same as 2 Except Entry Angle and Gross wt	
5	G21R0589	Same as 2 Except Entry Angle	
6	G09R0590	Tail Sun, Reentry, Sym Maneuver, Mach = 10.0	
7	R09R1300	Mission 3 Reentry, Sym Maneuver, Mach = 10.0	
8	G21R0591	Mission 3 Reentry, 1.0G Maneuver, Mach = 8.0	
9	G21R0592	Mission 3 Reentry, -1.0G Maneuver, Mach = 10.0	
10	G21R0593	Same as 9 Except Entry Angle	
11	G21R0594	Same as 9 Except Entry Angle and Gross wt	
12	G21R0595	Same as 9 Except Entry Angle	
13	G3AR0001	(2) TAEM Yaw Maneuver	Post Heating Conditions
14	G3AR0011	(2) TAEM Yaw Maneuver	

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Items 1 through 6 are mechanical and cold thermal conditions combined.
Items 7 through 12 are mechanical and hot thermal conditions combined.
Item 13 produces maximum end seal compression.
Item 14 produces maximum end seal extension.
(1) See reference 2-1.
(2) Terminal area energy management

Table 2-2. — Mechanical and thermal node displacements.

Item	SF76 Data Load Group	Wing Stub Node 164 cm (in.)	Inboard Elevon Node 96 cm (in.)	Outboard Elevon Node 2 cm (in.)	Wing Stub Node 164 cm (in.)	Inboard Elevon Node 96 cm (in.)	Outboard Elevon Node 2 cm (in.)
1	G21R0585	+0.051 +(0.020)	+0.163 +(0.064)	+0.099 +(0.039)	-0.328 -(0.129)	-0.150 -(0.059)	-0.051 -(0.020)
2	G21R0586	+0.058 +(0.023)	+0.15 +(0.059)	+0.127 +(0.050)			
3	G21R0587	+0.06 +(0.024)	+0.137 +(0.054)	+0.157 +(0.062)			
4	G21R0588	+0.066 +(0.026)	+0.016 +(0.063)	+0.198 +(0.078)			
5	G21R0589	-0.325 -(0.128)	-0.297 -(0.117)	-0.447 -(0.176)			
6	G09R0590	-0.16 -(0.063)	-0.328 -(0.129)	-0.315 -(0.124)	-0.328 -(0.129)	-0.150 -(0.059)	-0.051 -(0.020)
7	R09R1300	-0.16 -(0.063)	-0.328 -(0.129)	-0.315 -(0.124)	+1.22 +(0.480)	+1.45 +(0.571)	+1.173 +(0.462)
8	G21R0591	+0.051 +(0.020)	+0.163 +(0.064)	+0.099 +(0.039)			
9	G21R0592	+0.058 +(0.023)	+0.15 +(0.059)	+0.127 +(0.050)			
10	G21R0593	+0.06 +(0.024)	+0.137 +(0.054)	+0.157 +(0.062)			
11	G21R0594	+0.066 +(0.026)	+0.16 +(0.063)	+0.198 +(0.078)			
12	G21R0595	-0.325 -(0.128)	-0.297 -(0.117)	-0.447 -(0.176)	+1.22 +(0.480)	+1.45 +(0.571)	+1.73 +(0.462)
13	G3AR0001	-0.102 -(0.040)	+0.577 +(0.227)	-0.025 -(0.010)	–	–	–
14	G3AR0011	-0.269 -(0.106)	-1.321 -(0.520)	-0.046 -(0.018)	–	–	–

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\+ Outboard Spanwise Displacement
\- Inboard Spanwise Displacement

Table 2-3. – Net spanwise relative displacements of wing and elevon.

Item	SF76 Data Load Group	Inboard Elevon Net Relative Displacements of Node pt 96 & 164, cm (in.)			Outboard Elevon Net Relative Displacements of Node pt 2 & 164, cm (in.)		
		Mech	Therm	Comb	Mech	Therm	Comb
1	G21R0585	+0.112 +(0.044)	-0.178 -(0.070)	0.290C (0.114)	+0.048 +(0.019)	-0.277 -(0.109)	0.325E (0.128)
2	G21R0586	+0.091 +(0.036)		0.269C (0.106)	+0.069 +(0.027)		0.345E (0.136)
3	G21R0587	+0.076 +(0.030)		0.25C (0.100)	+0.097 +(0.038)		0.373E (0.147)
4	G21R0588	+0.094 +(0.037)		0.276C (0.107)	+0.132 +(0.052)		0.409E (0.161)
5	G21R0589	-0.028 -(0.011)		0.648C (0.081)	-0.122 -(0.048)		0.155E (0.061)
6	G09R0590	-0.168 -(0.066)	-0.178 -(0.070)	0.010C (0.004)	-0.155 -(0.061)	-0.277 -(0.109)	0.122E (0.048)
7	R09R1300	-0.168 -(0.066)	+0.231 +(0.091)	0.064C (0.025)	-0.155 -(0.061)	+0.046 +(0.018)	0.201C (0.079)
8	G21R0591	+0.112 +(0.044)		0.343C (0.135)	+0.048 +(0.019)		0.0025E (0.001)
9	G21R0592	+0.091 +(0.036)		0.323C (0.127)	+0.069 +(0.027)		0.023E (0.009)
10	G21R0593	+0.076 +(0.030)		0.307C (0.121)	+0.097 +(0.038)		0.051E (0.020)
11	G21R0594	+0.094 +(0.037)		0.325C (0.128)	+0.132 +(0.052)		0.086E (0.034)
12	G21R0595	-0.028 -(0.011)	+0.231 +(0.091)	0.259C (0.102)	-0.122 -(0.048)	+0.046 +(0.018)	0.168C (0.066)
13	G3AR0001	+0.678 +(0.267)	—	0.678C (0.267)	+0.318 +(0.125)	—	0.318C (0.125)
14	G3AR00II	-1.052 -(0.414)	—	1.052E (0.414)	-0.262 -(0.103)	—	0.262E (0.103)

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+	Outboard Displacement	C	Compression of Wing Elevon End Seal
-	Inboard Displacement	E	Extension of Wing Elevon End Seal

Table 2-4. – Maximum relative displacements.

Condition	Inboard elevon wing, cm (in.)	Outboard elevon wing cm (in.)
Reentry	0.343(0.135) C,0.000E	0.201(0.079) C,0.409(0.161)E
Post heating	0.678(0.267) C,1.052(0.414)E	0.318(0.125) C,0.262(0.103)E

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C Compression of wing/elevon seal

E Extension of wing elevon seal

Maximum relative displacement between the outboard elevon and wing stub are smaller than for the inboard elevon. The largest displacement in the compression direction is 0.32 cm (0.125 in.) and 0.41 cm (0.161 in.) in the extension direction for a total excursion of 0.73 cm (0.286 in.)

Based on the above data, the following end seal displacement criteria were selected:

Flight	Displacement cm (in.)		
Condition	Compression	Extension	Total
Reentry	0.71 (0.280)	0.46 (0.180)	1.17 (0.460)
Postheating	0.92 (0.280)	1.07 (0.420)	1.78 (0.700)

The 0.71 cm (0.280 in.) displacement in the compression direction provides adequate room to prevent seal crushing. In the other direction, the seal will be required to prevent leakage with a 0.46 cm (0.180 in.) extension of the interface. The 1.07 cm (0.420 in.) extension requirement is noted for informational and structural clearances only. These criteria are illustrated in figure 2-2.

2.3 REFERENCE

2-1 Rockwell International, "Shuttle Wing and Elevon Internal Loads Report - Vehicle 102 Vertical Flight," March 1977.

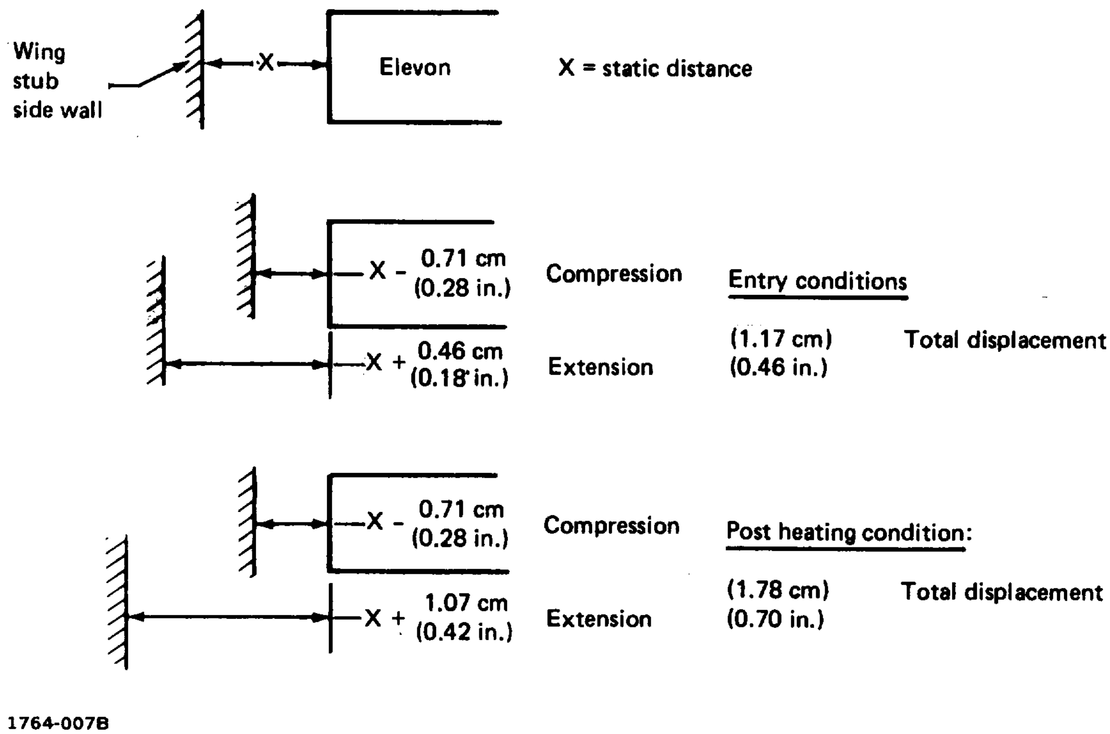

Figure 2-2. — End seal displacement criteria.

Section 3

METAL MEMBRANE SEAL CONCEPT DEVELOPMENT

3.1 METAL MEMBRANE SEAL CONCEPTS

Metal membrane seals were studied under the present program. Although they introduce peculiar structural problems, they offer the unique advantage of higher temperature capability without the use of thermal shields.

Various seal shapes were studied, and the more promising configurations are illustrated in figure 3-1 ("W" shape), figure 3-2 ("S" shape), and figure 3-3 ("C" shape). Note that the lower surface of the wing is shown facing upward for consistency with the orientation of the test apparatus in the wind tunnel.

3.2 METAL MEMBRANE SEAL ANALYSIS

The three seal configurations, made of René 41 material, were analyzed for structural integrity under the complex structural and thermal loading conditions expected. Table 3-1 summarizes the results of the analysis, and the calculations are given in appendix A. As shown, the seal can be subjected to at least seven types of loading. Additionally, some of the loading conditions occur simultaneously. No attempt was made to combine the various conditions, but each condition was analyzed as simply as possible to determine the relative magnitude of the stresses. The "W" and "S" shapes were not checked for all conditions because they were inferior to the "C" shape.

As shown, the most severe stresses occur under seal bending (condition II) and differential elevon/wing expansion (condition V). Under condition II, the stresses are beyond yield limits of the material. Although the seal could possibly survive the 100-mission requirements, fatigue failure will eventually occur. A small working model (see figures 3-4 and 3-5) for applying flexure tests to the metal membranes, was fabricated with heat treated Rene 41 "W" and "S" shaped seals detailed in figure 3-6.

During rotation, yielding occurred at both limits of elevon travel, 40° up and 25° down. Under condition V, extremely high stresses occur due to the shear deformation of the seal. These stresses result from differential expansion between the wing and elevon. The stress is zero at the fixed center hinge and increases to the maximum at the elevon edges, 178 cm (70 in.) each side of the hinge centerline. It is estimated that substantial deformation of the seal would occur beyond the limits of the material. For that reason, and because of the time and man-hour limits in the seal development program, no additional work was performed on metal curtain seals.

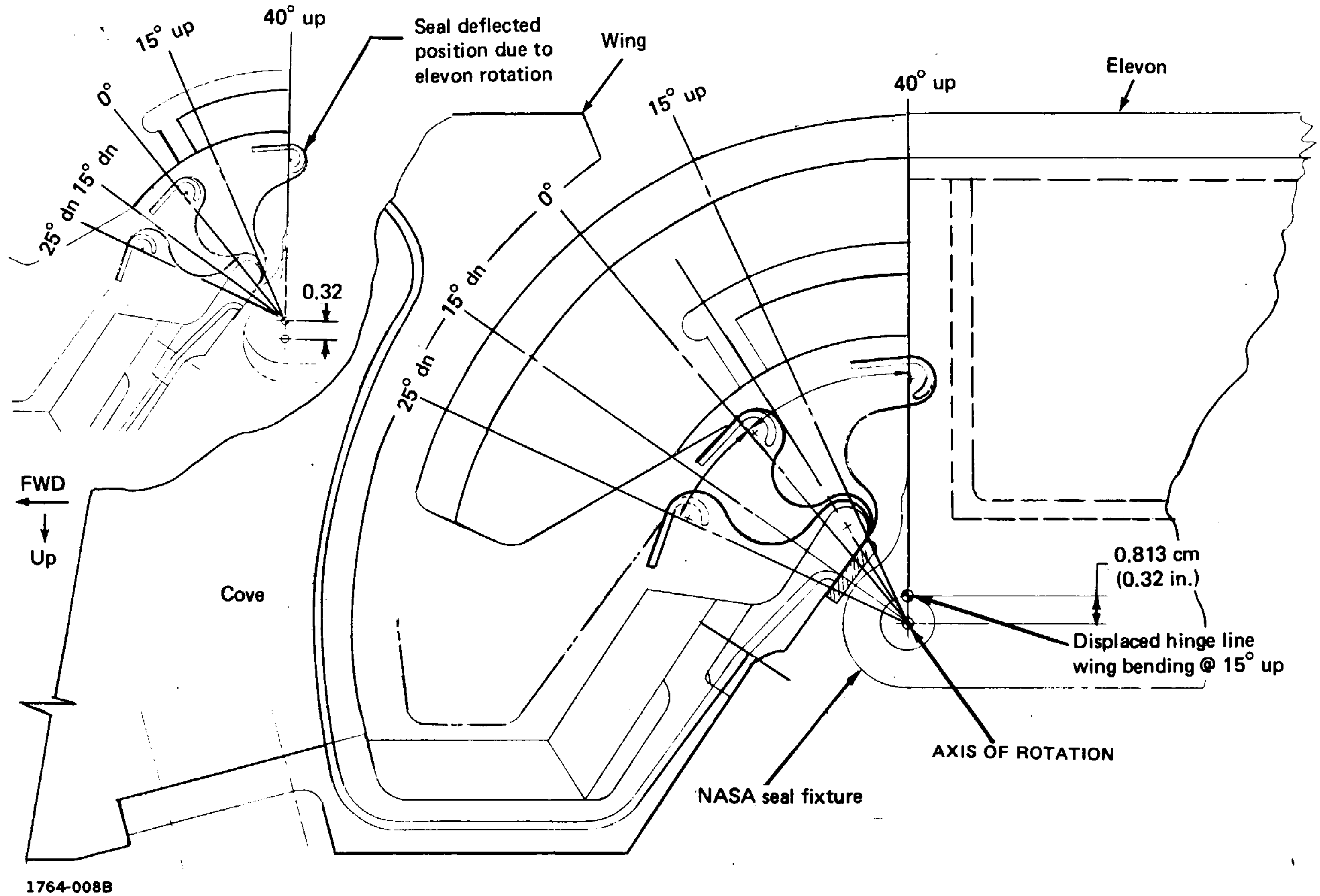

Figure 3-1. – Metal seal - "W" shape membrane.

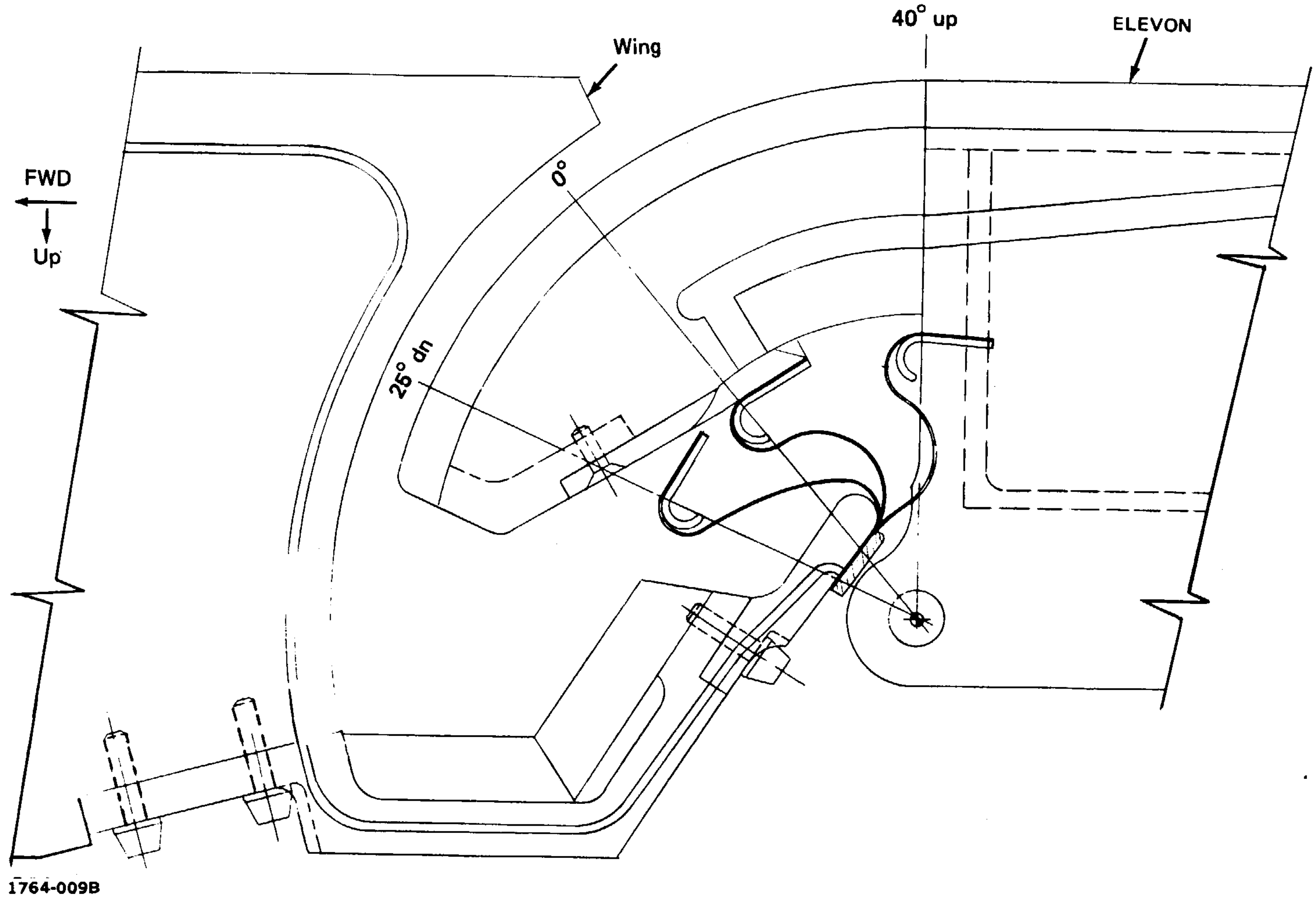

Figure 3-2. – Metal seal - "S" shape membrane.

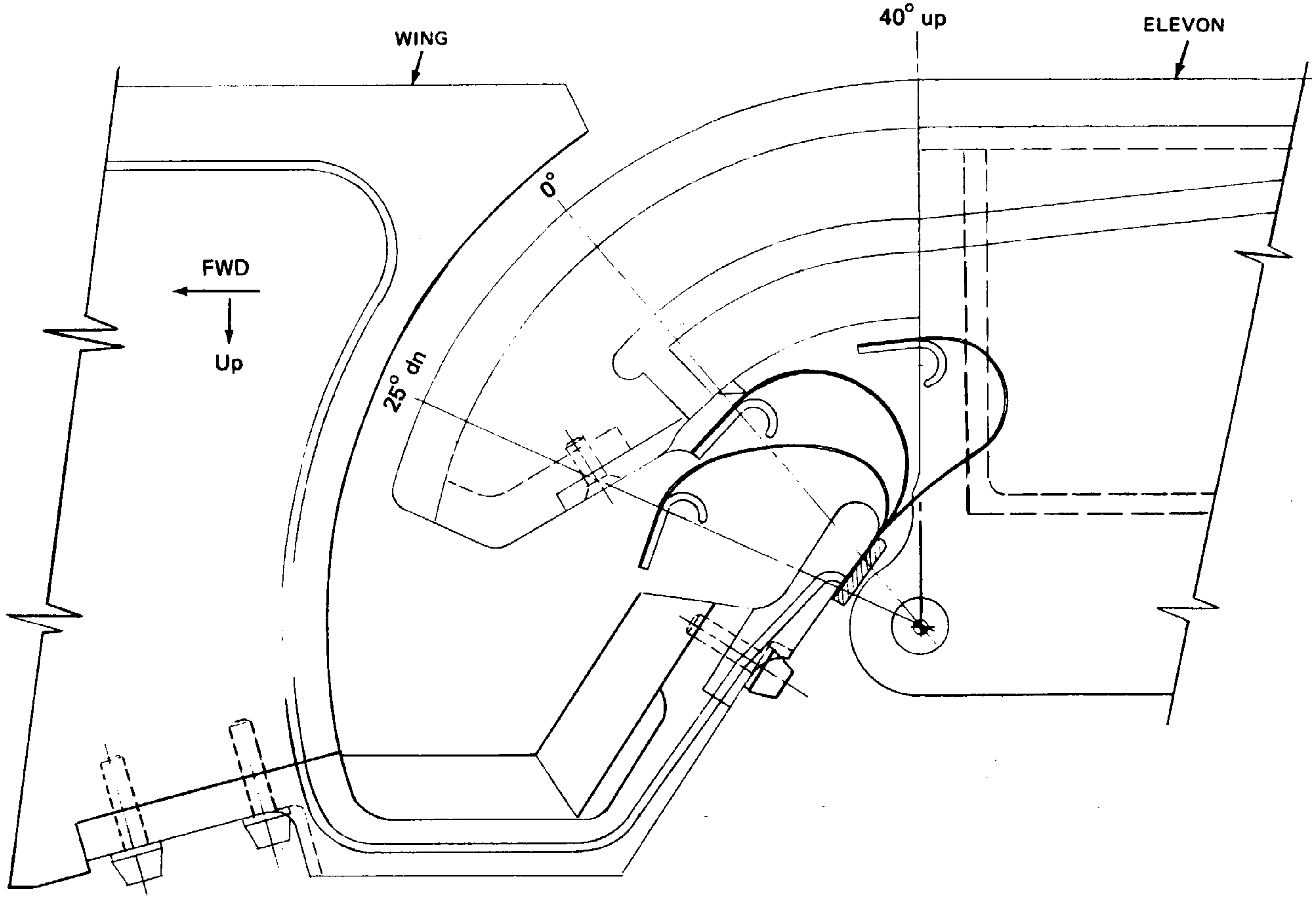

Figure 3-3. – Metal seal - "C" shape membrane.

Table 3-1. – Metal membrane seal analysis summary.

Loading condition	"W" seal	"S" seal	"C" seal
I. Bending stress due to 0.81 cm (0.32 in.) displacement parallel to hinge axis (no rotation)	±906 MPa, (131.5 ksi) ①	±547 MPa, (79.3 ksi) ①	±275 MPa, (39.9 ksi) ①
II. Bending stress due to 25° rotation (no displacement)	–	At fixed end ±3973 MPa, (576 ksi) At middle ±1941 MPa, (281.6 ksi) ①	At fixed end ±1660 MPa, (240.7 ksi) At middle ±960 MPa, (139.2 ksi) ①
III. Spanwise bending stress of wing vs elevon for 0.81 cm (0.32 in.) max displacement between hinges	–	–	±30 MPa, (4.35 ksi) ①
IV. Axial stress due to cold and hot (uniform temp) soak alum wing, Rene 41 seal	–	–	@T = 172 K (-150°F) = 309 MPa (44.9 ksi) ②
			@T = 450 K (+350°F) = 331 MPa (47.9 ksi) ①
V. Shear stresses due to elevon and wing differential expansion of ±0.22 cm (0.086 in.)	At end, 178 cm (70 in.) = 2202 MPa (319.5 ksi) At middle 89 cm (35 in.) = 1101 MPa (159.7 ksi) ③	This condition is combined with condition VI	
VI. Axial stress due to ΔT between wing/elevon/seal (only "C" shape analyzed)	Wing 244 K (-20°F) 217 K (-70°F)	Elevon 297 K (75°F) 289 K (25°F)	T_{max} seal: 450 K (350°F), 811 K (1000°F) Stress: -605 MPa, (-87.8 ksi) ② -1680 MPa, (-243.6 ksi) ③
VII. Pressure differential across seal. ΔP = 0.029 MPa (4.2 psi; ultimate pressure (values listed are ΔP capability in hoop compression with fixed edges)	–	–	@ Room temp = 0.072 MPa (10.5 psi) @ 533 K (500°F) = 0.063 MPa (9.2 psi) ④

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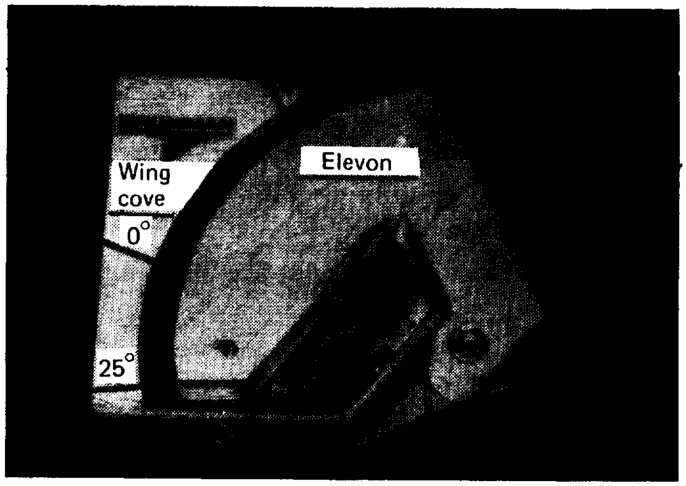
① F_{ty} = 896 MPa (130 ksi)

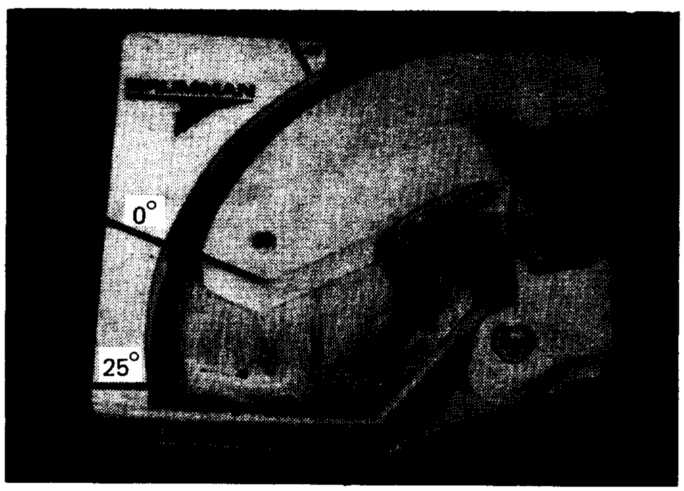
② F_{crit} = -1013 MPa (-147 ksi) Buckling of curved panel under compression

③ F_{crit} = 172 MPa (25 ksi) Stability of curved shell under edge shear

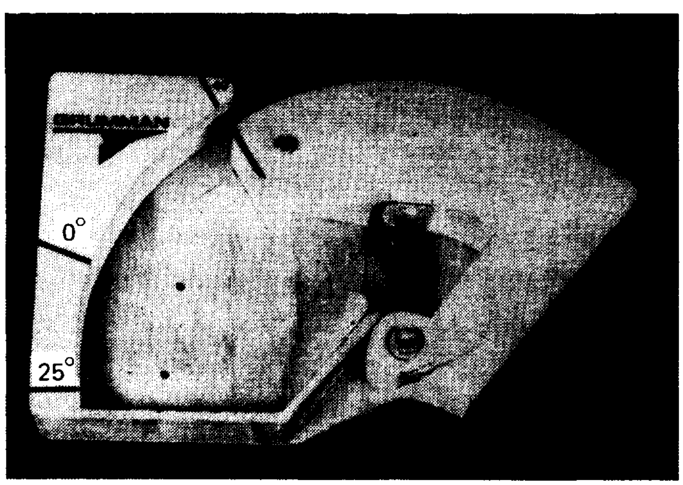
④ Collapse pressure



Elevon 25° down



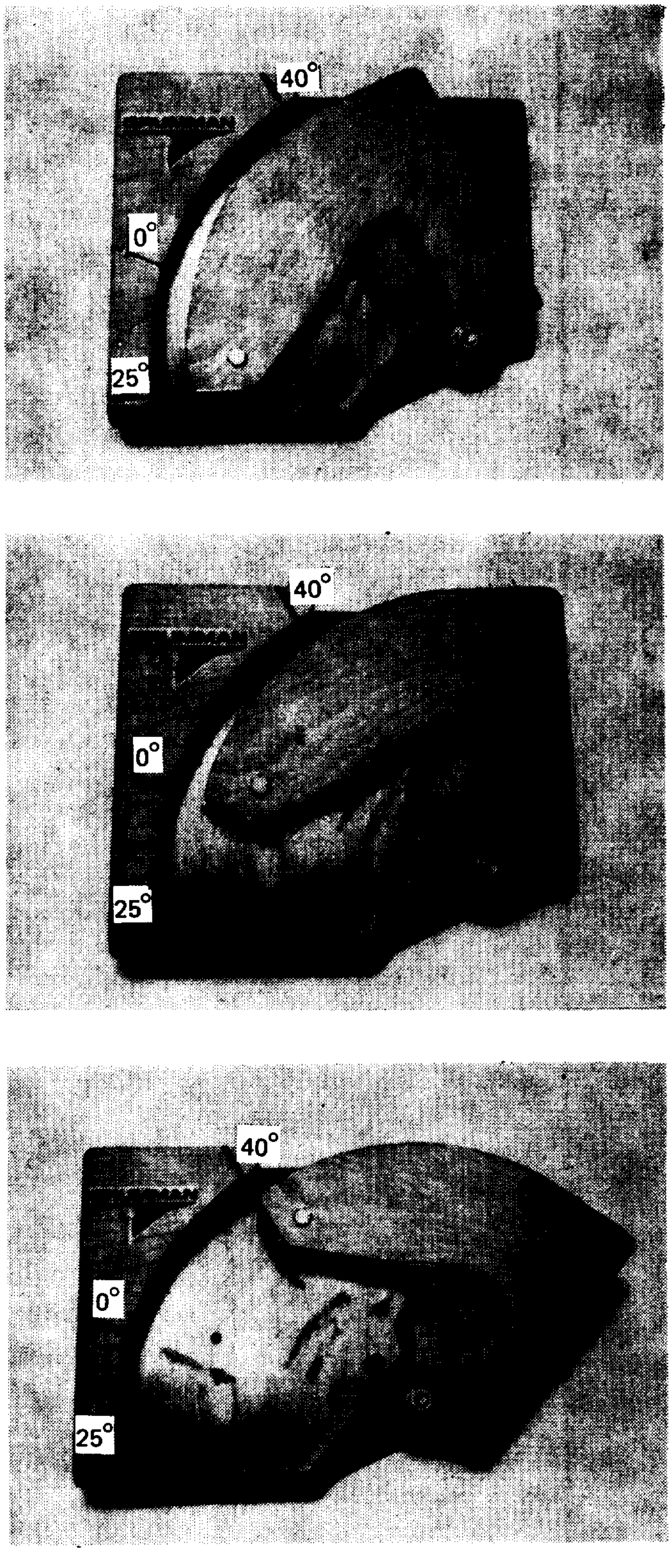
Elevon 0° (neutral)



Elevon 40° up

1764-012B

Figure 3-4. – Model of metal "S" membrane seal.



Elevon 25° down

Elevon 0° (neutral)

Elevon 40° up

1764-013B

Figure 3-5. – Model of metal "W" membrane seal.

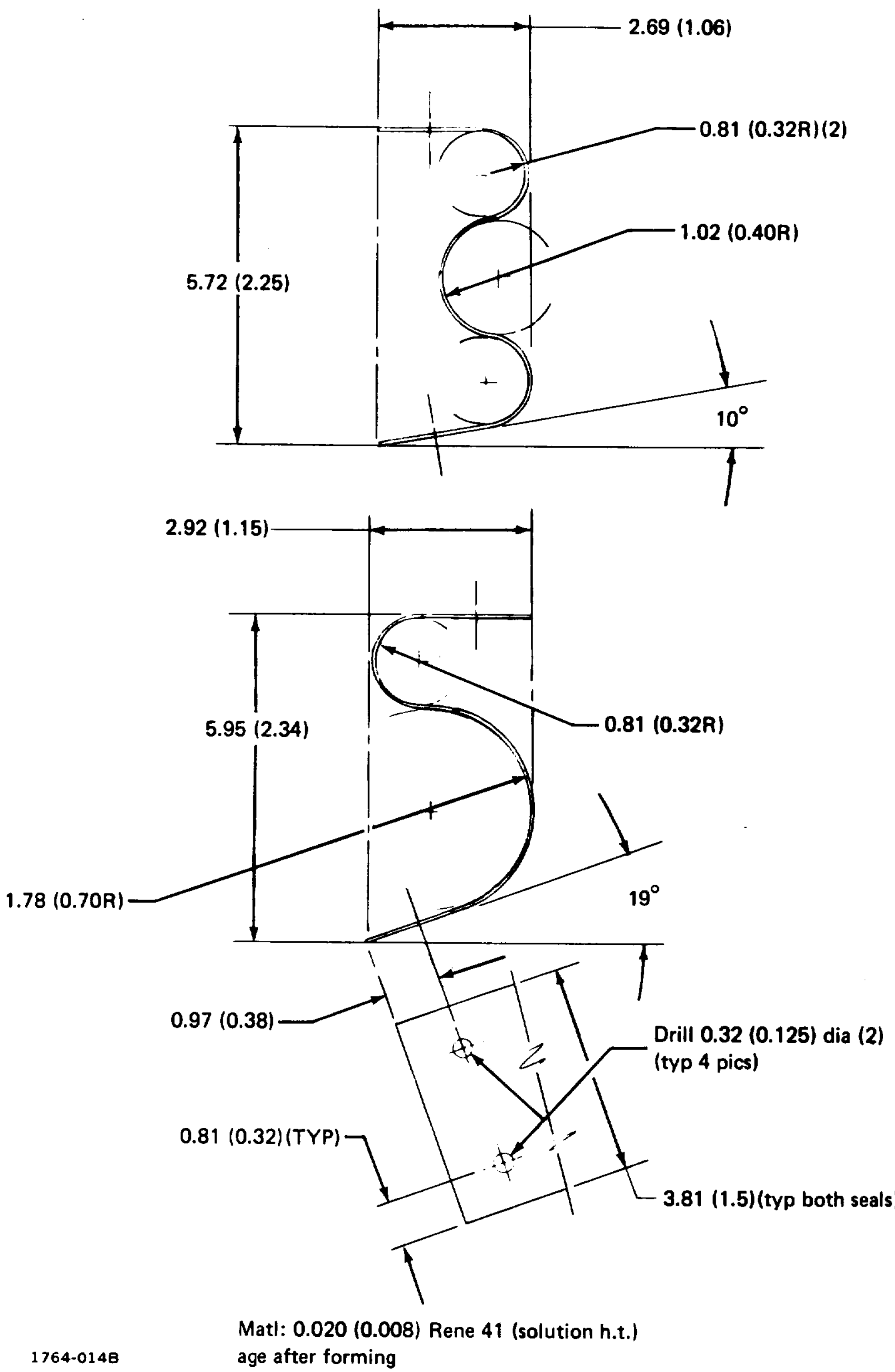


Figure 3-6. – Flexure test model seals.

Section 4

NON-METALLIC MEMBRANE SEAL CONCEPT DEVELOPMENT

4.1 STRETCH MEMBRANE

4.1.1 Design Concept

Non-metallic (rubber) materials, although temperature limited, offer good potential for meeting cove seal requirements. Basically, a non-metallic seal consists of a membrane that is slightly stretched between two support members attached to the elevon and wing. The concept is illustrated in model form in figure 4-1 where the elevon is shown in neutral, maximum down, and maximum up positions. As indicated, membrane stretching occurs during elevon rotation. This feature is accomplished by locating the membrane attachment to the wing off the elevon hinge axis. The primary advantage of this concept is its ability to accept any conceivable structural deformation between the wing and elevon without leakage. The seal material is GE Silicone Rubber SE-577 which is stable up to 589 K (600° F) and has a brittle point below 158 K (-175°F). This material can be stretched over 200% with no permanent set and has a minimum tensile strength of 9.65 MPa (1400 psi).

Figure 4-2 illustrates a stretch concept curtain that can endure higher tempertures than the concept shown in figure 4-1. This capability is accomplished by adding a thermal blanket to the front surface of the membrane. The blanket will employ a suitably coated high-temperature silicone cloth to retain a glass fiber felt insulation, which would be selected for insulative efficiency at around 811 K (1000° F). The blanket is designed in the neutral (0°) position with adequate length (see detail of figure 4-2) so that it does not stretch during elevon deflection. To eliminate any gaps between the blanket and the seal and to keep the outer blanket firm, a separate half-moon shaped filler blanket is employed as illustrated. Figure 4-2 also shows the estimated configuration of the blanket and seal in the 25° down and 40° up positions, which are the limits of expected elevon rotation.

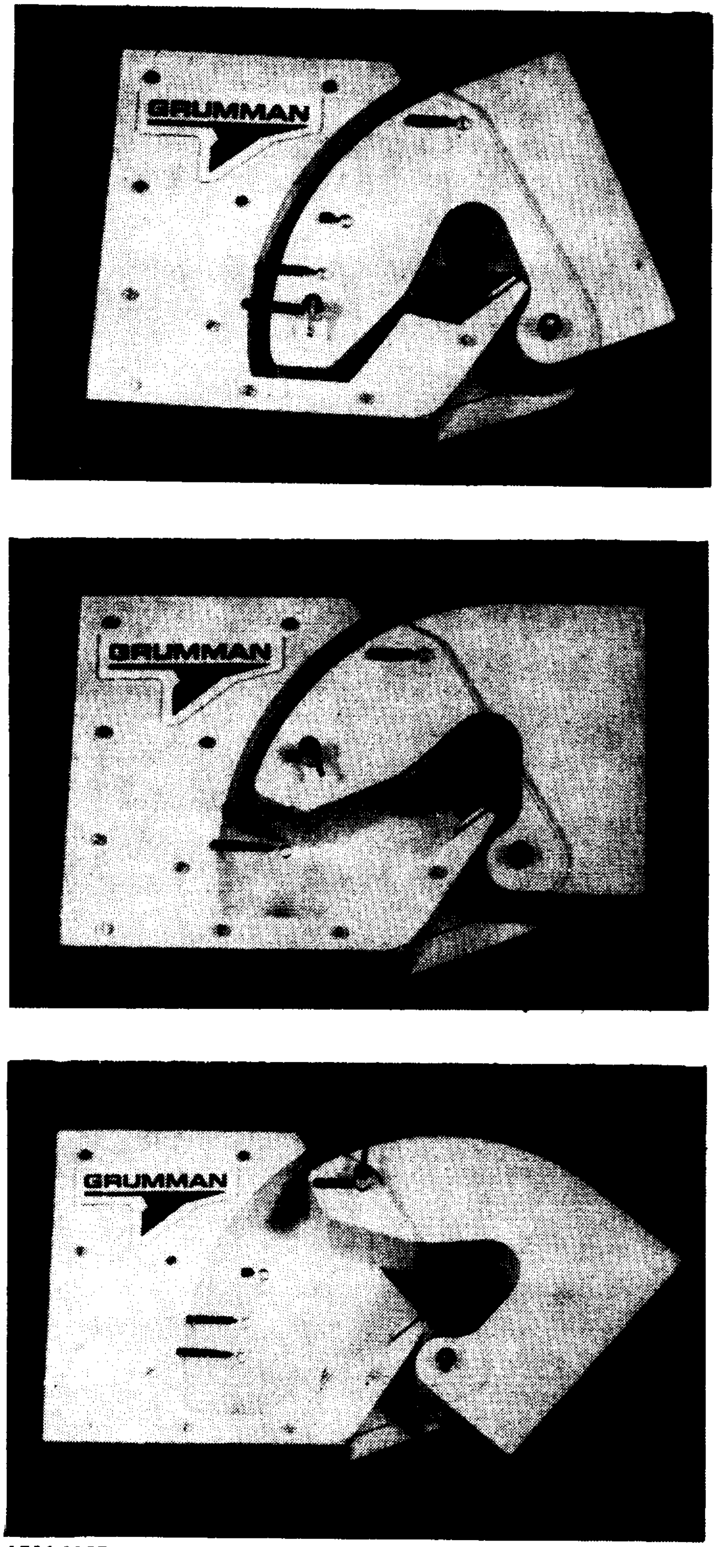
4.1.2 Stretch Membrane Pressure Analysis

The stretch membrane seal was analyzed to determine membrane stresses and deflections under the 29.4 kPa (4.2 psi) ultimate pressure load for the shuttle wing tabulated in paragraph 2.1. A 0.20 cm (0.080 in.) thick membrane of GE Silicone Rubber (SE-577 compound) was assumed. The results of the analysis, whose calculations are given in appendix B, are as follows:

Max tensile stress = 0.405 MPa (58.8 psi); allowable 9.65 MPa (1400 psi)

Max deflection = 1.133 cm (0.445 in.)

Max elongation = 24% (allowable 200%)



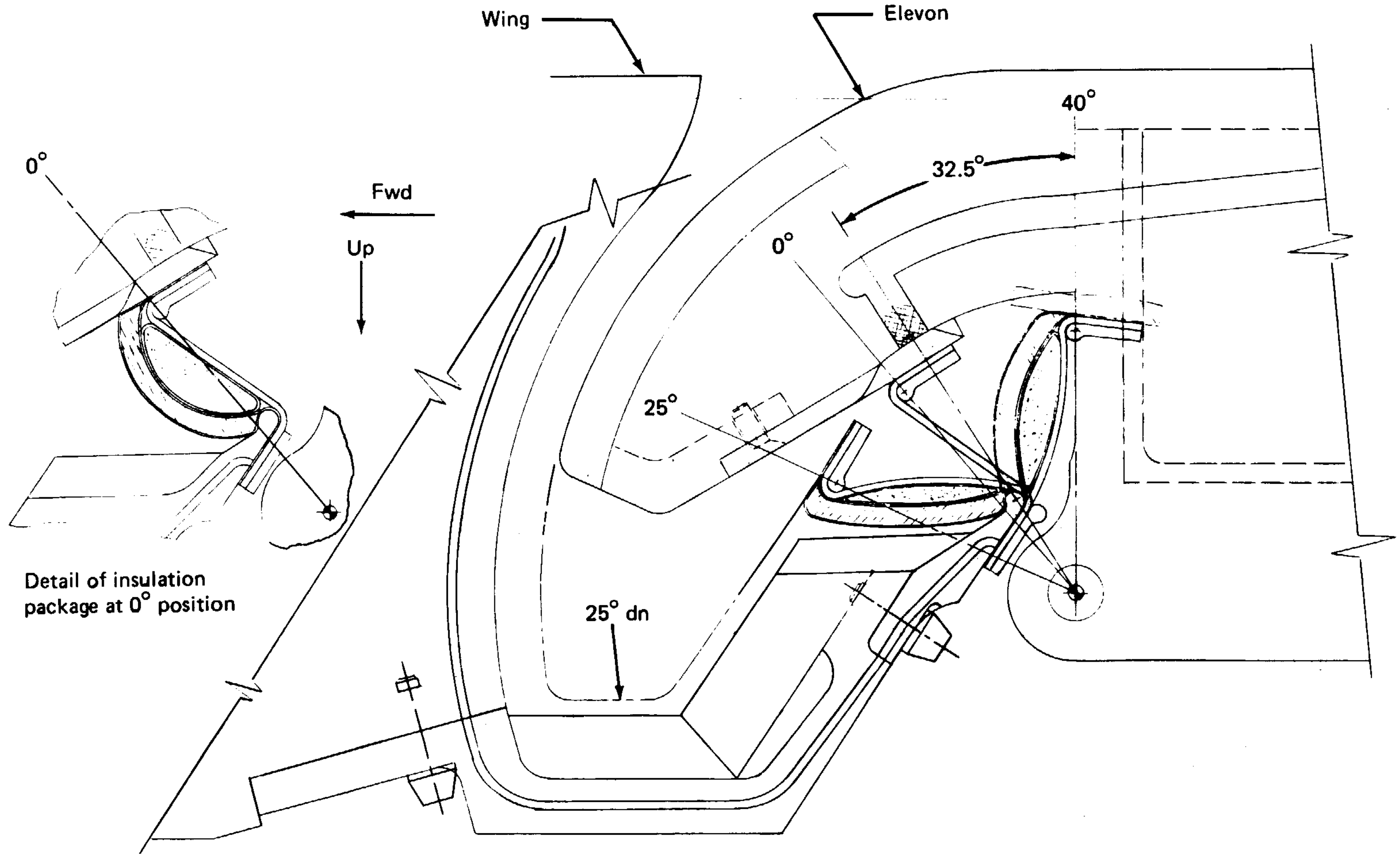
Elevon 25° down

Elevon 0° (neutral)

Elevon 40° up

1764-015B

Figure 4-1. – Model of stretch membrane seal.



1764-016B

Figure 4-2. – Stretch concept silicone rubber membrane seal with heat shield.

As indicated, the stress and elongation are well within the material allowable limits.

4.2 NON-STRETCH MEMBRANE

4.2.1 Design Concept

The non-stretch membrane seal is an alternative for meeting cove seal requirements. This concept, shown in figure 4-3, is configured as a letter "C" with adequate length so that stretching does not occur during elevon rotation and deflection. The concept offers two important advantages: first, the seal can be fabricated with a Nomex cloth reinforcement which will significantly increase the membrane tear strength; second, the thermal blanket can be directly bonded to the membrane and thereby provide a more predictable thermal barrier. To help maintain the required shape, metal battens are molded within the rubber at suitable intervals. To improve edge sealing, the end batten is designed to provide edge stiffness for sealing ends of the membrane.

4.2.2 Non-Stretch Membrane Pressure Analysis

The non-stretch membrane was also analyzed for pressure loads. The calculations are shown in appendix C. The stress, deflection, and elongation were determined for a non-reinforced rubber membrane and are as follows:

Max tensile stress (rubber)	=	0.316 MPa (45.9 psi); allowable 9.65 MPa (1400 psi)
Max deflection	=	0.58 cm (0.23 in.)
Max elongation	=	18% (allowable 200%)

In this case, the stress and elongation in the rubber are also well within allowables.

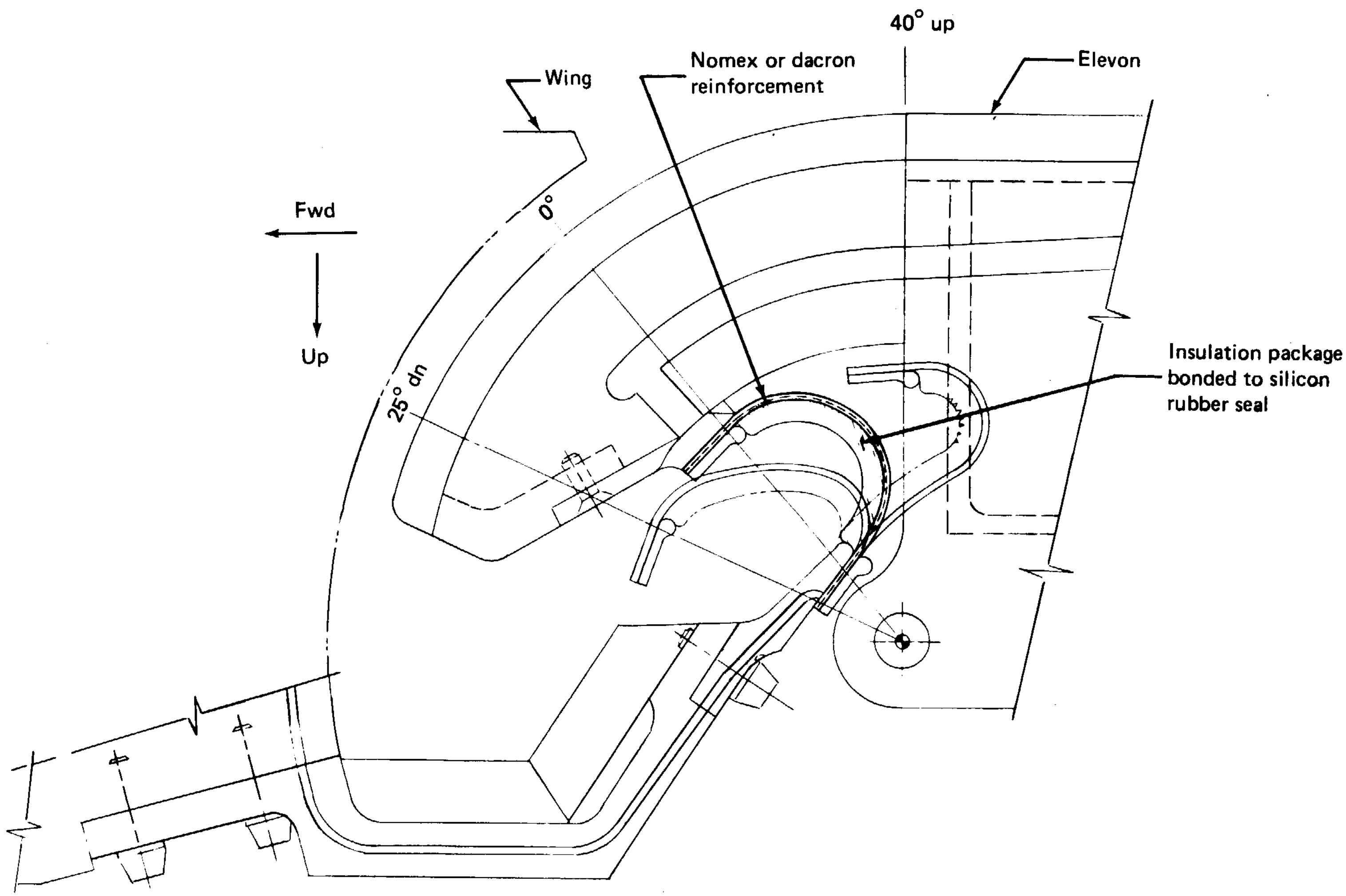
The Nomex cloth reinforcement was also checked for positive pressure. The stresses and elongation, however, are negligible because the cloth was a modulus of elasticity of 1379 MPa (2 x 10^5 psi), which is approximately 800 times stiffer than the rubber membrane. For negative pressure, the metal battens will maintain the shape.

4.3 NON-METALLIC END SEAL CONCEPTS

Membrane end seal configurations made of several materials were evaluated in various mated combinations using the seal development fixture shown in figure 4-4 (a). With this fixture, end seals were cycled against an end plate.

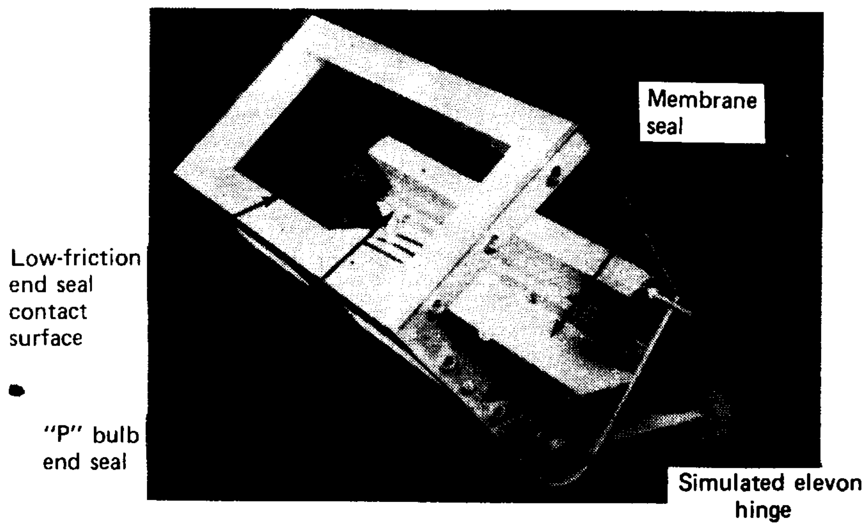
4.3.1 "P" Bulb End Seal

A basic "P" bulb end seal is shown in figure 4-4 (b) and on drawing AD1001-204 (see appendix D). This design employs an integrally molded "P" bulb to achieve edge sealing. Metal battens are used to support and maintain bulb contact against the end

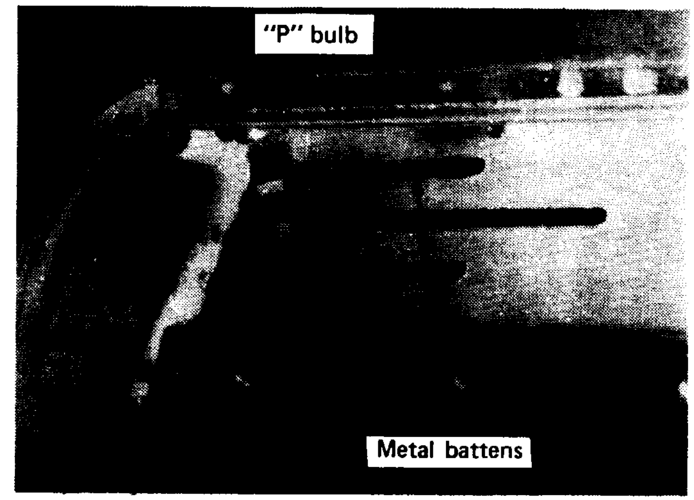


1764-017B

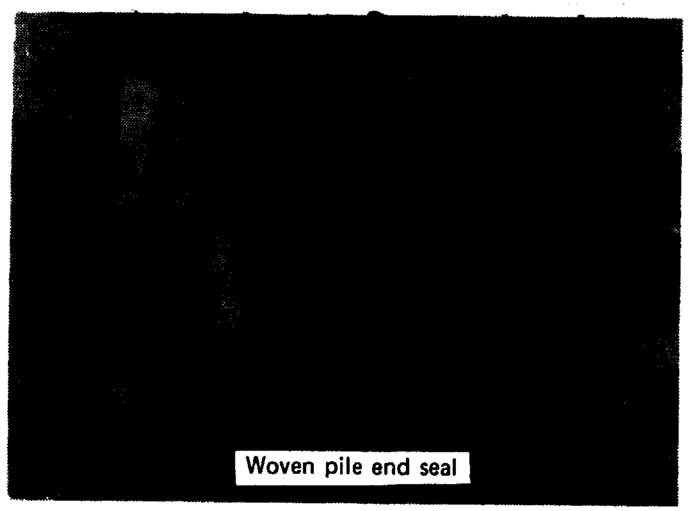
Figure 4-3. – Non-stretch concept reinforced rubber membrane seal.



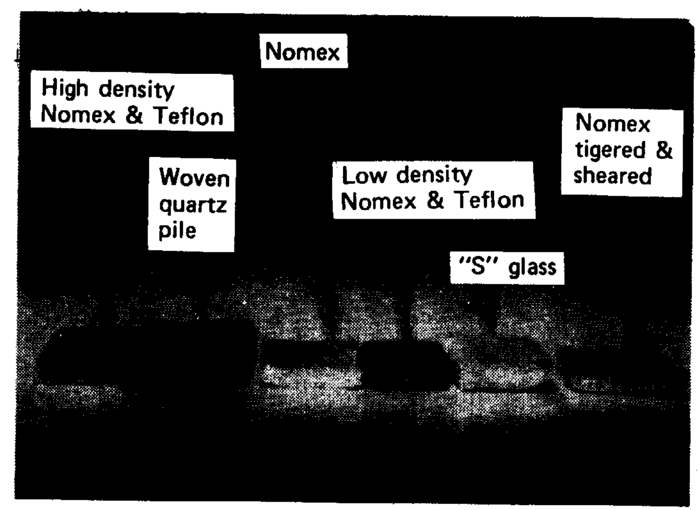
(a) Seal development model fixture



(b) "P" bulb with metal battens



(c) Nomex woven pile end seal



(d) Woven pile materials

1764-018B

Figure 4-4. – Seal development fixture model, end seal concepts, and materials.

plate. The advantage of this design is that no seal wiper pads are required on the edges of the membrane, and it may be used with either the stretch or non-stretch design concepts. The bulb is designed with adequate diameter so that edge sealing is maintained during relative motion between the elevon and end plate. A ceramic dry-film coating (Vitro Lube, NP11220), capable of service at temperatures up to 700 K (800° F), was used on the end plate to reduce friction at the interface. However, during rotation of the seal in the seal development fixture, some amount of bulb rolling was encountered when engagement between the seal and end plate surface was increased. Further testing indicated the need to reduce friction substantially to increase bulb life.

4.3.2 Low Friction Bulb End Seal

A low friction bulb end seal is illustrated on drawing AD1001-206 (see appendix D). This design utilizes an ovalized "P" bulb with a Nomex elastic strip that is bonded to the seal. The maximum compression of the oval "P" bulb is illustrated in figure 4-5. However, for tests to evaluate frictional resistance in the seal development fixture, a "Spandex" rub strip was used in lieu of the Nomex elastic strip. The seal was rotated in the fixture in contact with a Vitro Lube coated end plate, and results indicated a smooth sliding action without apparent bulb rolling. Three test articles were developed employing three variations of "Spandex" rub strips which will be tested in an end seal test fixture at NASA Langley Research Center.

4.3.3 Carpet End Seal

A carpet end seal is shown in figure 4-4 (c) and on drawing AD1001-205 (see appendix D). This design employs a Nomex high density pile carpet wiper pad. The carpet is engaged by the silicon rubber membrane which is edge stiffened with internally

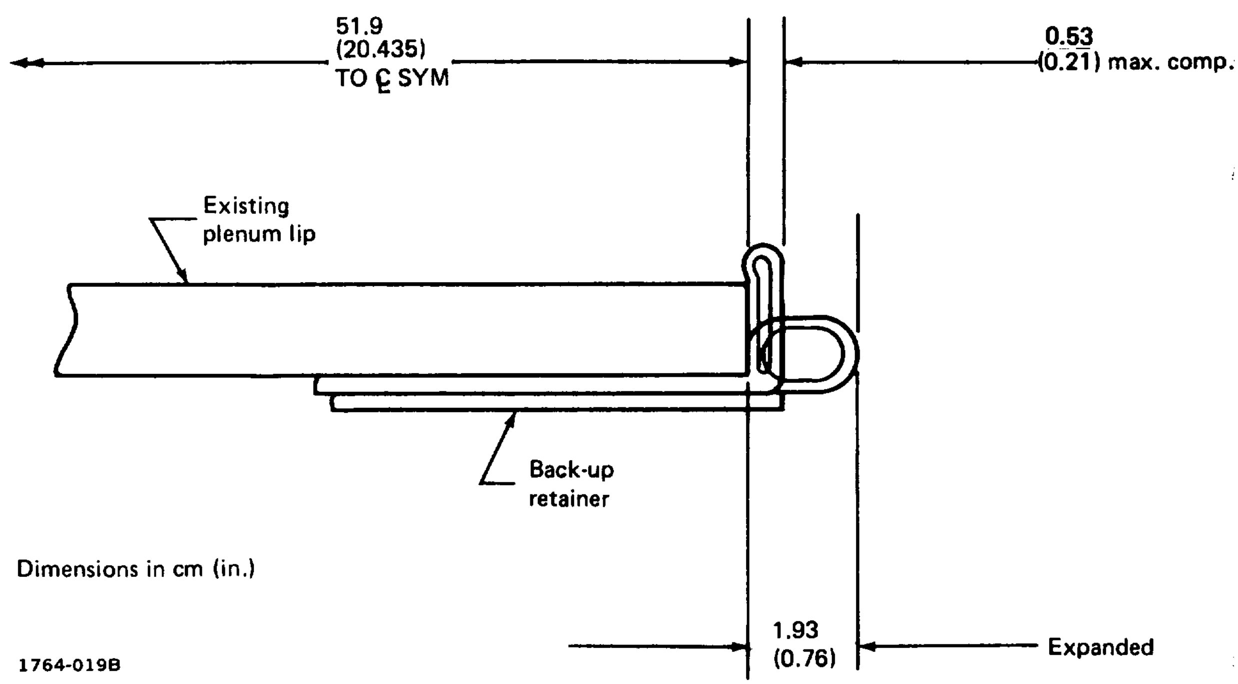


Figure 4-5. – Maximum compression of oval end seal.

molden thin metal battens. Various woven pile materials such as Nomex, Nomex and Teflon, and quartz fiber, shown in figure 4-4 (d), were tested in the seal development fixture for frictional resistance and cycle life.

The fiber pads were cycled to various engagement depths by the membrane, and the following results were indicated:

- Excessive air leakage occurred at all levels of membrane penetration
- Drag encountered at maximum membrane penetration resulted in seal fold-over due to frictional resistance between the silicone rubber and fiber rub pad.
- Increased fiber length to reduce drag resulted in greater air leakage
- Excessive fiber shredding occurred from high friction of the silicone rubber membrane.

Section 5

NASA COVE SEAL TEST APPARATUS MODIFICATION

5.1 DESCRIPTION OF PROGRAM

The existing cove seal test apparatus in the Langley 8-foot, high-temperature structures tunnel (figure 1-1) was originally designed for testing a spring-loaded wiper seal. The decision by NASA to evaluate a membrane seal required modifying various components to accommodate membrane seal installation. These modifications are shown on engineering drawings presented in appendix D.

5.1.1 Seal Installation, Drawing AD1001-200

Final assembly and installation of a Nomex fiber carpet and a "P" bulb end seal are indicated. Included in this drawing are the fence and elevon assembly rework required for the cove seal test apparatus.

5.1.2 Leading Edge Assembly, Drawing AD1001-201

The leading edge of the elevon was redesigned to accept the membrane seal and both the "P" bulb and carpet end seals. This was accomplished by the use of separate end plates mounted to the leading edge.

5.1.3 Seal Holder, Drawing AD1001-202

A seal holder was required to accommodate attachment of one edge of the membrane seal to the wing-cove housing. The seal holder will be attached to the original cove housing as shown in drawing AD1001-200.

5.1.4 Seal Adapters, Drawing AD1001-203

Various adapters were required to permit evaluation of both the "P" bulb and carpet end seals using the same test apparatus. The design criteria were based on a predetermined membrane seal stretch requirement in the elevon neutral position (0°).

5.1.5 Seal Assembly, Drawing AD1001-204

The membrane seals to be used in the cove seal test apparatus are equipped with either a "P" bulb end seal or a flat end which will engage a Nomex carpet rub plate. For both types of end configuration, steel battens are used to support the end seals and to provide stiffness during elevon rotation. Each seal was matched to its respective adapters for mounting in the test fixture.

5.1.6 Rub Plate Assembly, Drawing AD1001-205

Two end seal rub plates were designed to function with both end seal concepts. Each contains provisions for thermocouple installation to monitor temperature on either side of the membrane seal.

5.2 NASA END SEAL TEST FIXTURE

A test fixture was designed by NASA to obtain cyclic life data for a typical "P" bulb end seal configuration. The fixture, illustrated in figure 5-1, has the capability of maintaining a designated pressure on the membrane seal and adjustment for stretch and end seal pressure. The "P" bulb end seal configurations to be tested in this fixture are shown on drawing AD1001-206.

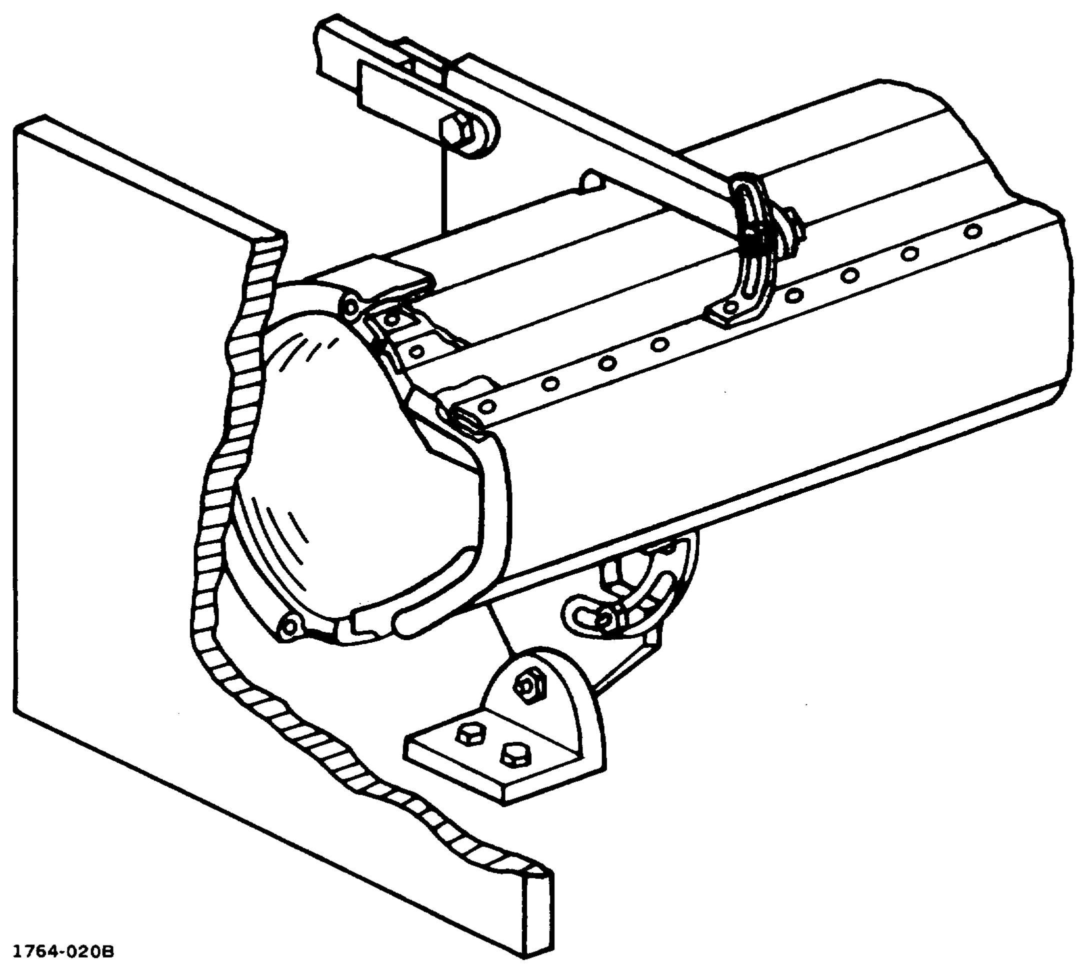


Figure 5-1. — NASA end seal test fixture.

Section 6

ALTERNATE SEAL CONCEPTS

6.1 ALTERNATE CONCEPTS FOR SPACE SHUTTLE ELEVON COVE SEAL

Three additional seal design concepts were developed and relate specifically to adaptation of the non-metallic membrane concept for use as the space shuttle elevon cove seal. The membrane concept could be utilized as either the primary seal or to provide redundancy.

6.1.1 Primary Seal Concept

Figure 6-1 illustrates use of the membrane concept as the primary elevon cove seal for the shuttle. In this application, the honeycomb support structure on the wing would be slightly modified so that the attachment of the membrane to the wing is located on the hinge axis to preclude membrane stretching. A membrane attachment fitting would also be required on the elevon leading edge structure as shown. Also shown is a relatively simple thermal blanket that has been added to protect the membrane for temperatures above 533 K (500° F). "P" bulb and carpet end seals are shown in section A-A.

6.1.2 Redundant Concept

Figure 6-2 illustrates use of the membrane concept as a redundant seal that could be added to the current shuttle primary cove seal. As shown, one end of the membrane seal is directly attached to the existing rub tube but behind the existing elevon wiper seal. The other end is attached to the elevon leading edge structure, which would require minor modification for an attachment fitting. Installed in this manner, the membrane would provide the required redundancy, but since the attachment to the rub tube is off the hinge line, the membrane must stretch.

6.1.3 Wiper/Membrane Redundant Concept

Figure 6-3 illustrates a fully redundant design that uses a wiper seal forward and a membrane seal behind it. This particular design places the rub surface on the elevon, which provides additional room for the wiper seal and permits placement of the bending edge of the membrane close to the hinge axis for minimum stretching. The detail shown at the lower left in figure 6-3 illustrates some optional features which are possible with this design concept. These include use of a thermal barrier system and a gas purge system to block entry of hot boundry-layer gas past the wiper seal.

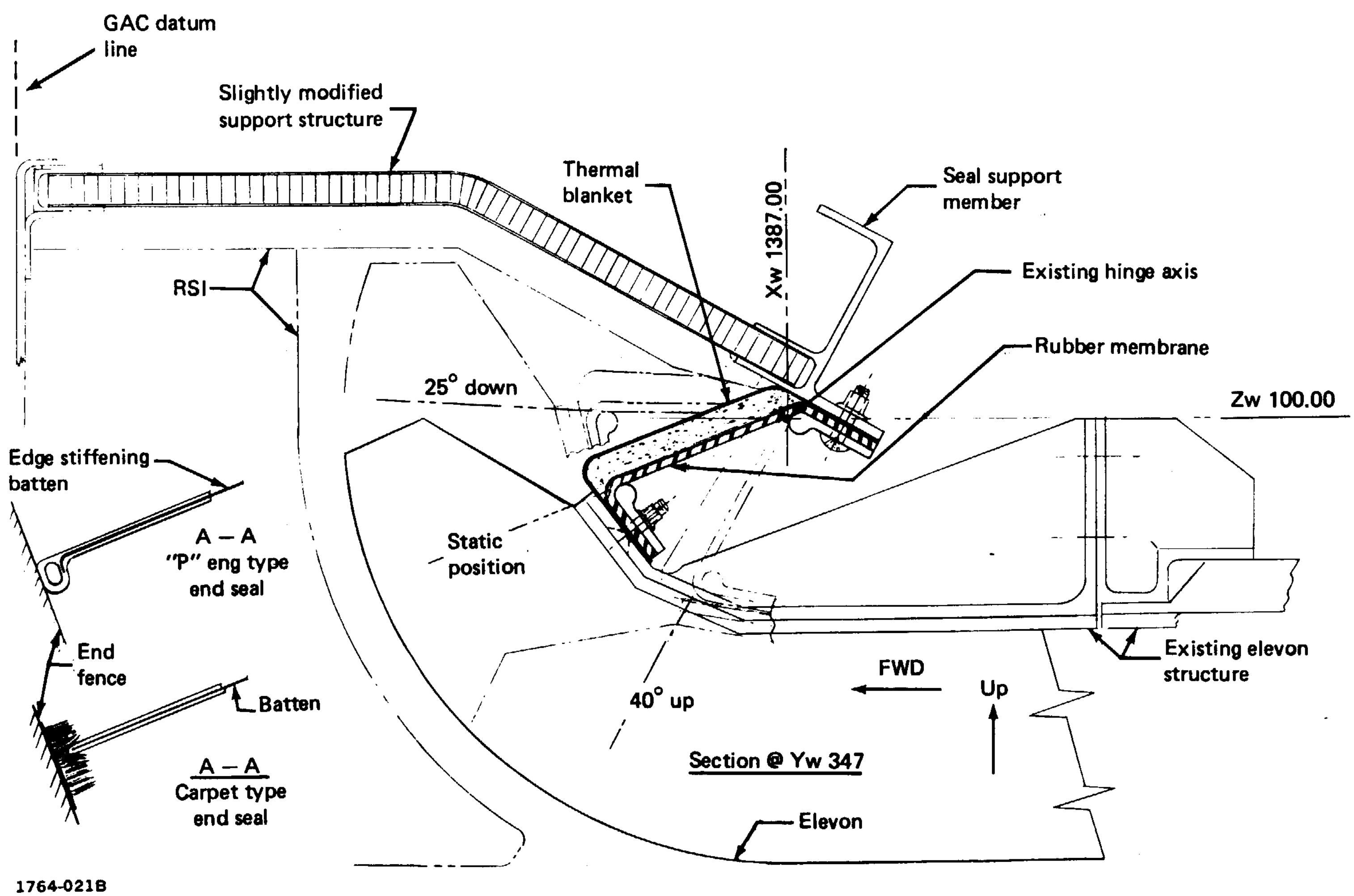


Figure 6-1. – Non-metallic membrane as primary elevon cove seal for shuttle.

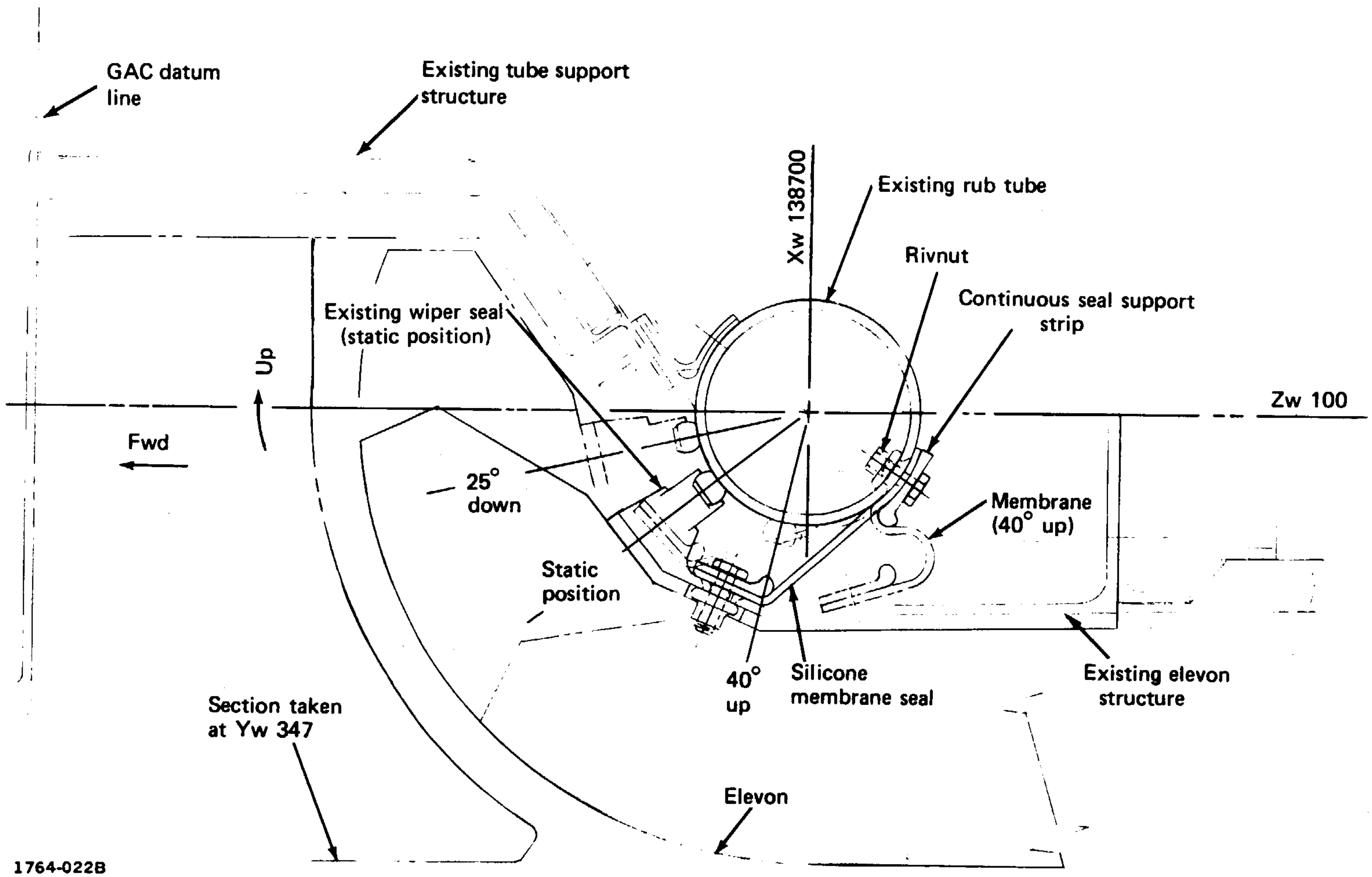


Figure 6-2. — Non-metallic membrane as redundant seal addition to current shuttle primary elevon cove seal.

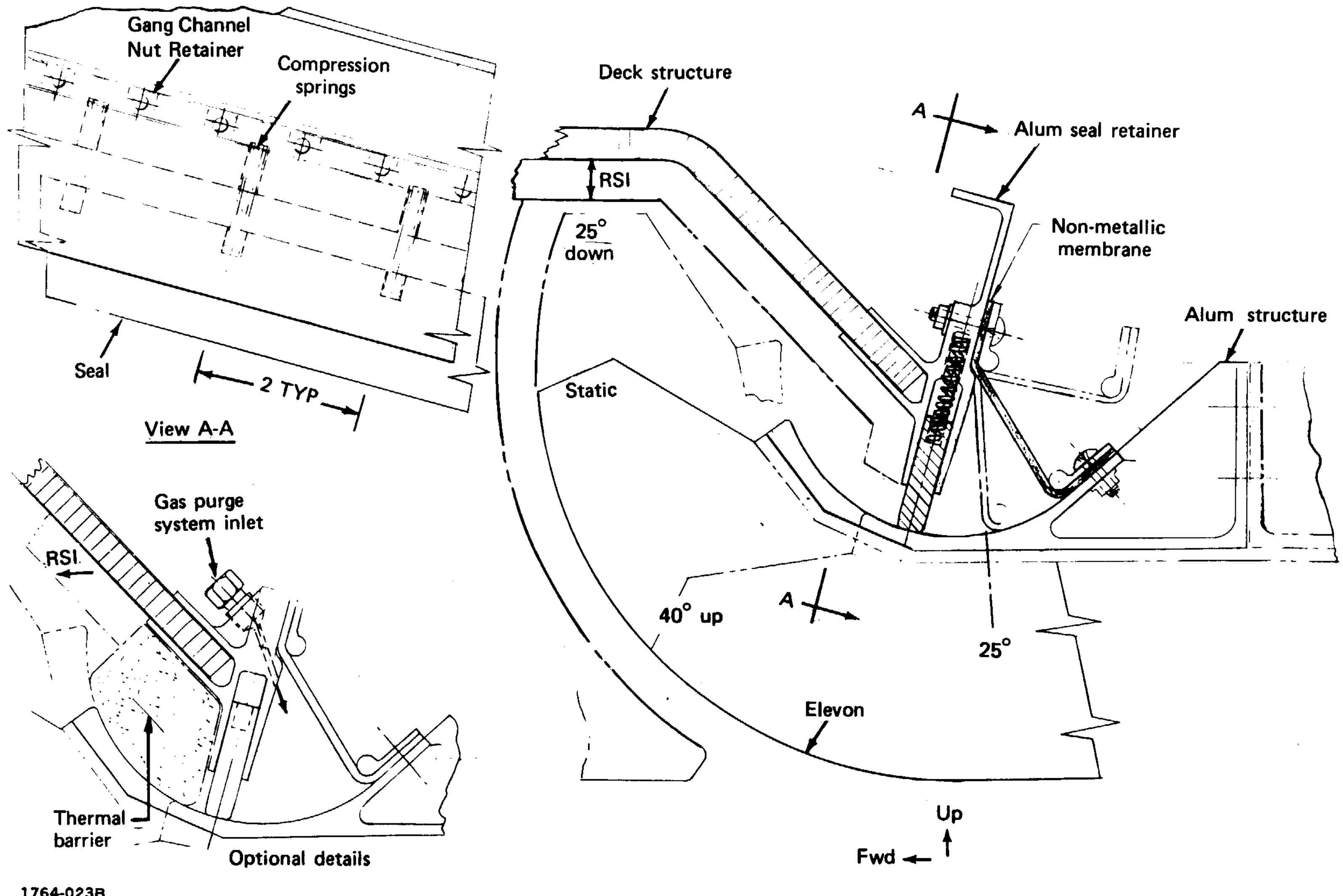


Figure 6-3. – Concept of fully redundant seal for shuttle.

Section 7

CONCLUSIONS

The present design study was conducted to develop a flightweight, effective, reusable seal for use along the elevon cove of shuttle-type, reentry, and hypersonic cruise vehicles. The basic design approach focused on membrane seals, both metallic and non-metallic. The seals will be evaluated in a NASA cove seal test apparatus that is used in the Langley 8-foot high-temperature structures tunnel, which is a large Mach 7 blowdown facility.

There are many varying factors which must be considered from the design aspect for membrane seals. Among these is structural mass which relates to different thermal expansions. Other factors include elevon cove size limitations, effects of spanwise flow on temperature, and rotational axis location relative to the adjoining structure which affects membrane stretch. The stretch non-metallic membrane seal, with or without insulation, would accomplish the primary objective of elevon cove sealing along the span. However, the problem of sealing the ends of the membrane is quite significant since reentry conditions produce large deflections from mechanical and thermal loading in a spanwise direction. These deflections produce large gaps which must be sealed during elevon rotation. The application of dense woven fiber pile at the ends of the membrane was ineffective in sealing these large gaps and allowed a high leakage rate. However, a "P" bulb molded into the ends of the membrane proved very effective in sealing the ends when rotated against a low-friction surface. Membrane seals with a "P" bulb at the ends were delivered to the NASA Langley Research Center and will be evaluated for cyclic life characteristics in an end seal test fixture.

Appendix A

METAL SEAL ANALYSIS

Units Conversion

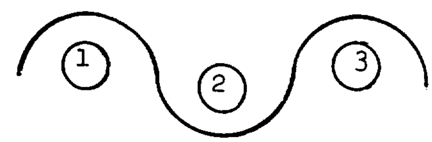
All calculations and dimensions are in U.S. Customary Units. The following conversions can be used to convert to the International System of Units:

Multiply	By	For
inches	2.540	cm
pound-force/inch^2 (psi)	6894.757	Pa
Pounds (mass)	0.4536	kg
pounds (force)	4.4482	N
pound-force-inch	0.11298	N·m
pound-mass/foot^2	4.8825	kg/m^2
degree Fahrenheit	(5/9)(temp °F + 459.67)	K

Appendix A

METAL SEAL ANALYSIS

CONDITION 1



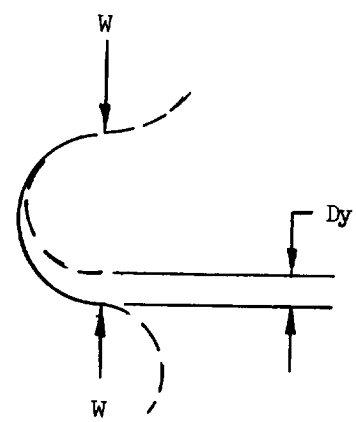
Displacement parallel

to hinge axis = Dy_T

$$S = \frac{\text{Deflection}}{\text{Load}} = \frac{Dy}{W}$$

"W" for complete tube gives same results

as $\frac{W}{2}$ for $\frac{1}{2}$ tube



$\therefore$ for $\frac{1}{2}$ tube with

ends continuous

$$Dy = \frac{0.149(2W)(R^3)}{EI}$$

Total deflection of 1 + 2 + 3 = $Dy_T = Dy_1 + Dy_2 + Dy_3$

$Dy_1 = Dy_3 \therefore Dy_T = 2Dy_1 + Dy_2$

Load W is same for all elements

$$\therefore Dy_1 = \frac{0.149(2W)(R_1^{\,3})}{EI}$$

$$Dy_2 = \frac{0.149(2W)(R_2^{\,3})}{EI}$$

$$W = \frac{Dy_1 EI}{.298R_1^{\,3}} = \frac{Dy_2 EI}{.298R_2^{\,3}}$$

$$Dy_T = \frac{.596WR_1^{\,3}}{EI} + \frac{.298WR_2^{\,3}}{EI} = \frac{.149W(4R_1^{\,3} + 2R_2^{\,3})}{EI}$$

$$Max + M = .3183 \ WR$$

$$W = \frac{Dy_T EI}{.149(4R_1^{\ 3} + 2R_2^{\ 3})}$$

Calculate load per inch of length then:

$$I = \frac{bt^3}{12} = \frac{t^3}{12}$$

$$W = \frac{Dy_T Et^3}{1.788(4R_1^{\ 3} + 2R_2^{\ 3})}$$

$$Max + M = .3183 \ WR_2 = \frac{.3183R_2 Dy_T Et^3}{.1788(4R_1^{\ 3} + 2R_2^{\ 3})}$$

$$M \ Max = \frac{.1755R_2 Dy_T Et^3}{4R_1^{\ 3} + 2R_2^{\ 3}} = \frac{.0878R_2 Dy_T Et^3}{2R_1^{\ 3} + R_2^{\ 3}}$$

$$f \ Max = \frac{M \ Max \ C}{I} = \frac{M \ Max \ 12t}{2t^3} = \frac{6 \ M \ Max}{t^2}$$

$$f \ Max = \frac{.5265R_2 Dy_T Et}{2R_1^{\ 3} + R_2^{\ 3}}$$

Assume .008 Rene' 41 - Solution H.T.

$E = 31.6 \ (10^6)$ psi @ Room Temp

$R_1 = .32$ in.

$R_2 = .40$ in.

$$f\ Max = \frac{.5625(.40)(31.6)(10^6)(.008)Dy_T}{2(.32)^3 + (.40)^3} = 4.11\ (10^5)Dy_T$$

Dy_T, in.	f Max, psi	w, #/in.
0.5	$205.5(10^3)$	17.46
0.6	$246.6(10^3)$	20.96
0.7	$287.7(10^3)$	24.45

$$W = \frac{Dy_T\ 31.6(10^6)(.008)^3}{1.788\ [4(.32)^3 + 2(.40)^3]} = 34.92Dy_T\ \#/in.$$

All radii the same size ("W" Seal)

$$R_1 = R_2 = R_3; \quad R = \frac{1.04}{3} = .347\ in.$$

$$E = 31.6(10^6)\ psi; \ t = .008\ in.$$

$$f\ Max = \frac{.5265\ Dy_T Et}{3R^2}$$

$$f\ Max = \frac{.5625(31.6)(10^6)(.008)(Dy_T)}{3(.347)^2} = 3.68(10^5)Dy_T$$

Dy_T, in.	f Max, psi
0.5	$184.2(10^3)$
0.6	$221.0(10^3)$
0.7	$257.9(10^3)$

One Large Radius ("C" Seal)

$$Dy = \frac{0.149(2WR^3)}{EI}; \quad W = \frac{DyEI}{298R^3}$$

$$M\ Max = .3183\ WR = \frac{1.068Dy_T EI}{R_2}; \quad I = \frac{t^3}{12}$$

$$f\ Max = \frac{M\ Max\ C}{I} = \frac{1.068EDy_T C}{R_2} = \frac{.534EDy_T{}^t}{R_2}$$

$R = 1.04$ in.; $E = 31.6(10^6)$ psi; $t = .008$ in.

$$f\ Max = \frac{.534(31.6)(10^6)(.008)Dy_T}{(1.04)^2} = 1.25(10^5)Dy_T$$

Dy_T, in.	f Max, psi	W, #/in.
0.5	$62.4(10^3)$	2.09
0.6	$74.9(10^3)$	2.50
0.7	$87.4(10^3)$	2.90

$$W = \frac{Dy(31.6)(10^6)(.008)^3}{12(.298)(1.04)3} = 4.18Dy$$

Two Different Radii ("S" Seal)

$R_1 = .32$ in.; $R_2 = .70$ in.

$$Dy_T = \frac{.298WR_1{}^3}{EI} + \frac{.298WR_2{}^3}{EI} = \frac{.298W(R_1{}^3 + R_2{}^3)}{EI}$$

$$\text{Max} + M = .3183WR$$

$$W = \frac{Dy_T EI}{.298(R_1^3 + R_2^3} = \frac{Dy_T Et^3}{3.576(R_1^3 + R_2^3)}$$

$$\text{Max} + M = .3183WR_2 = \frac{.0878R_2 Dy_T Et^3}{R_1^3 + R_2^3}$$

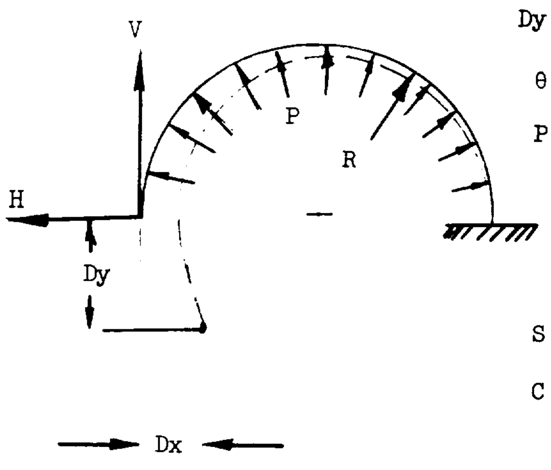
$$f\ \text{Max} = \frac{M\ \text{Max}\ C}{I} = \frac{6\ M\ \text{Max}}{t^2}$$

$$f\ \text{Max} = \frac{.5265R_2 Dy_T Et}{R_1^3 + R_2^3} = 2.479(10^5)Dy_T$$

Dy_T, in.	f Max, psi
0.5	$123.9(10^3)$
0.6	$148.8(10^3)$
0.7	$173.6(10^3)$

CONDITION II

(Rotation only -25°)



$Dx = -.15$ in. $I = \frac{t^3}{12} = \frac{(.008)^3}{12} = 4.26(10^{-8})$ in.^{4}

$Dy = -1.0$ in. $E = 31.6(10^6)$ psi

$\theta = 0$ $EI = 1.348$ in.

$P = 0$ $\theta = \pi$

$\frac{1}{EI} = .7418$

$R = 0.7$ in.

$S = \text{Sin}\ \theta = 0$

$C = \text{Cos}\ \theta = -10$

$$Dy = \frac{1}{EI}\left[\pi R^2 Mo + \frac{3\pi}{2}R^3 V + 2R^3 H\right]$$

$$Dx = \frac{1}{EI}\left[2R^2 Mo + 2R^3 V + \frac{\pi}{2}R^3 H\right]$$

$$\theta = \frac{1}{EI}\left[\pi R Mo + \pi R^2 V + 2R^2 H\right]$$

$$M = Mo + HR\left[\sin(\pi - x)\right] - VR\left[\cos(\pi - x) + 1\right]$$

$$-1.0 = .7418\left[\pi(.7)^2 Mo + \frac{3\pi}{2}(.07)^3 V + 2(0.7)^3 H\right]$$

$$-1.0 = 1.1419Mo + 1.199V + .5089H$$

$$-.15 = .7418\left[2(.7)^2 Mo + 2(.7)^3 V + \frac{\pi}{2}(.7)^3 H\right]$$

$$-.15 = .7270Mo + .5089V + .3997H$$

$$0 = .7418\left[\pi(.7)Mo + \pi(.7)^2 V + 2(.7)^2 H\right]$$

$$0 = 1.6313Mo + 1.1419V + .7270H$$

$$+1.4286 = -1.6313Mo + (-1.7129V) + (-.7270H)$$

$$1.4286 = -.571V$$

$$V = \frac{1.4286}{-.571} = -2.502$$

$$1.1232 = .7270Mo + .3997H$$

$$-1.2732 = -.7270Mo + (-.3240H)$$

$$-.15 = .0757H$$

$$H = \frac{-.15}{.0757} = -1.982$$

$$Mo = \frac{-1.1419(-2.502) - .7270(-1.982)}{1.6313} = 2.635 \text{ in.-lb}$$

$x = \pi$ (fixed end)

$$M = 2.635 - (1.982)(0.7)(0) - (-2.502)(.7)(\text{Cos } 0 + 1) = 6.1378 \text{ in.-lb}$$

$$f = \frac{MC}{I} = \frac{(6.1378)(.004)}{4.26(10^{-8})} = \pm 576319 \text{ psi}$$

$x = \frac{\pi}{2}$ (middle)

$$M = 2.635 - 1.982(.7)(1.0) - (-2.502)(.7)(\text{Cos } \frac{\pi}{2} + 1) = 2.999 \text{ in.-lb}$$

$$f = \frac{MC}{I} = \frac{2.999(.004)}{4.26(10^{-8})} = \pm 281596 \text{ psi}$$

$x = 0$ (moving end)

$$M = 2.635; \quad f = \frac{2.635(.004)}{4.26(10^{-8})} = 247418 \text{ psi}$$

$R = 1.04$ in.

$$-1.0 = 2.5206Mo + 3.9321V + 1.6689H$$

$$-.15 = 1.6047Mo + 1.6689V + 1.3108H$$

$$0 = 2.4236Mo + 2.5206V + 1.6047H$$

$$+.9615 = -2.4236Mo + (-3.7808V) + (-1.6047H)$$

$$.9615 = -1.2602V$$

$$V = \frac{.9615}{-1.2602} = -.7630$$

$$1.9232 = 2.4236Mo + 1.6047H$$

$$\underline{-1.6967 = -2.4236Mo + (-2.4236H)}$$

$$.2265 = -.8189H$$

$$H = \frac{.2265}{-.8189} = -.2766$$

$$Mo = \frac{(-2.5206)(-.7630) - (1.6047)(-.2766)}{2.4236} = .9767 \text{ in.-lb}$$

$x = \pi$ (fixed end)

$M = .9767 + .7630(1.04)(2.0) = 2.5637$ in.-lb

$$f = \frac{2.5637(.004)}{4.26(10^{-8})} = \pm 240726 \text{ psi}$$

$x = \frac{\pi}{2}$ (middle)

$M = .9767 - .2766(1.04)(1.0) + .7630(1.04)(1.0) = 1.4826$

$$f = \frac{1.4826(.004)}{4.26(10^{-8})} = \pm 139211 \text{ psi}$$

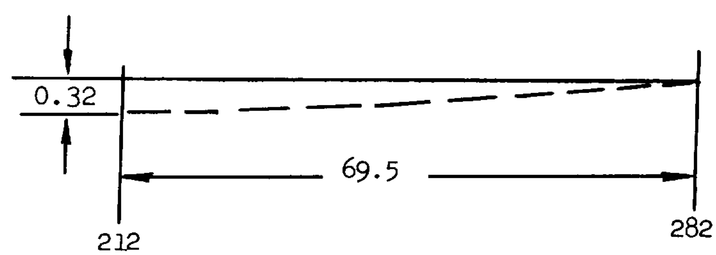
(moving end)

$$f = \frac{.9767(.004)}{4.26(10^{-8})} = \pm 91709 \text{ psi}$$

CONDITION III (Bending of Seal with wing)

CONSTANT MOMENT CURVE (R = Constant)

$$y = \frac{Ml^2}{2EI}$$



$$M = \frac{2yEI}{l^2}$$

$$f = \frac{MC}{I} = \frac{2yEIC}{Il^2} = \frac{2ECy}{l^2}$$

$y = .32$ in.; $l = 69.5$ in.; $E = 31.6(10^6)$ psi; $C = 1.04$ in.

$$f = \frac{2(31.6)(10^6)(1.04)(.32)}{(69.5)^2} = \pm 4354 \text{ psi (constant along length)}$$

CONDITION IV (Compression in Seal Due to Cold Soak @ -150°F)

$\Delta T = -220°F$

$f = 34(10^6)(\alpha AL - \alpha Rene') -220 = -44880$ psi in Seal

where: $\alpha AL = 13 \times 10^{-6}$ & $\alpha Rene' = 7 \times 10^{-6}$

(tension in seal due to max. temperature @ 350°F uniform)

$\Delta T = +280°F$

$f = 28.5(10^6)(13-7)(10^{-6})(280) = +47880$ psi in Seal

CONDITION V (Shear Stresses due to End displacement; Elevon-Wing Differential Expansion)

$\epsilon_s = \frac{.086}{3.267} = .0263 \ ^{in}/_{in}$ max

developed length of "U"

$fs - \epsilon_s G$

$G = \frac{E}{2(1+v)} = \frac{31.6(10^6)}{2(1.3)} = 12.15(10^6)$ psi

(at seal end) $fs = .0263(12.15)(10^6) = 319545$ psi

(at mid point) $fs = 159773$ psi

(effects of differential spanwise thermal expansion between wing and elevon)

Largest distance between hinges:

$Yw = 282 - Y = 212.5 = 69.5$ in.

Wing colder than elevon by 95°F

$\delta = \alpha \Delta TL = 13(10^{-6})(95)(69.5) = +.086$ in.

Wing hotter than elevon by 95°F - $\delta = -.086$ in.

Total movement = .172 in. @ Yw = 282

CONDITION VI (Metallic Seal - Effect of ΔT Between Wing, Elevon & Seal)

Max. Seal Temp. = 500°F @ 5700 Sec. (Mission 3)

Mission 2: T Wing = 20°F

T Elevon = 75°F

T Seal = 350°F (500-150 for mission 2)

Between Yw = 282-Yw = 212.5 = 69.5 in.

δ Wing $= 13(10^{-6})(-90)(69.5) = -.0813$ in.

δ Elevon $= 13(10^{-6})(5)(69.5) = +.0045$ in.

δ Seal $= 7(10^{-6})(280)(69.5) = +.1362$ in.

ϵ Wing = -.00117 $^{in}/_{in}$

ϵ Elevon = +.000065 $^{in}/_{in}$

ϵ Seal = +.00196 $^{in}/_{in}$

Average ϵ of Wing & Elevon = -.000818 $^{in}/_{in}$

Stress in Seal = (-.00196-.000818)31.6(10^6) = -87770 psi

Max. Seal Temp. = 1000°F @ 5300 Sec.

T Wing = -70°F

T Elevon = +25°F

T Seal = 1000°F

ϵ Wing = 13(10^6)(-140) = -.00182 $^{in}/_{in}$

ϵ Elevon = 13(10^6)(-45) = -.000585 $^{in}/_{in}$

ϵ Seal = 7(10^6)(930) = +.00651 $^{in}/_{in}$

Average ϵ of Wing & Elevon = -.00120 $^{in}/_{in}$

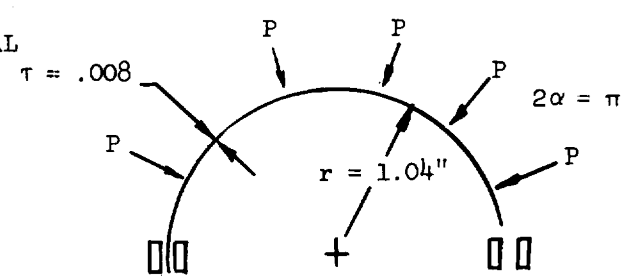
Stress in Seal = (-.00651-.00120)(31.6)(10^6) = -243636 psi

CONDITION VII

PRESSURE DIFFERENTIAL ACROSS SEAL

Case 1 $\quad r = 1.04$ in.

Straigth Edges Clamped



$$P_{crit} = \frac{Et^3(k^2-1)}{12r^3(1-v^2)}$$

where $k = 3.0$
$\alpha = 90°$

$$P_{crit} = \frac{(31.6 \times 10^6)(.008)^3(9-1)}{12(1.04)^3(.91)} = 10.54 \text{ psi @ R.T.}$$

$= 9.24$ psi @ 500°F

Case 2 $\quad r = .70$ in.

Straight Edges Clamped

$$P_{crit} = \frac{(31.6 \times 10^6)(.008)^3(8)}{12(.7)^3(.91)} = 34.57 \text{ psi @ R.T.}$$

$= 30.30$ psi @ 500°F

Appendix B

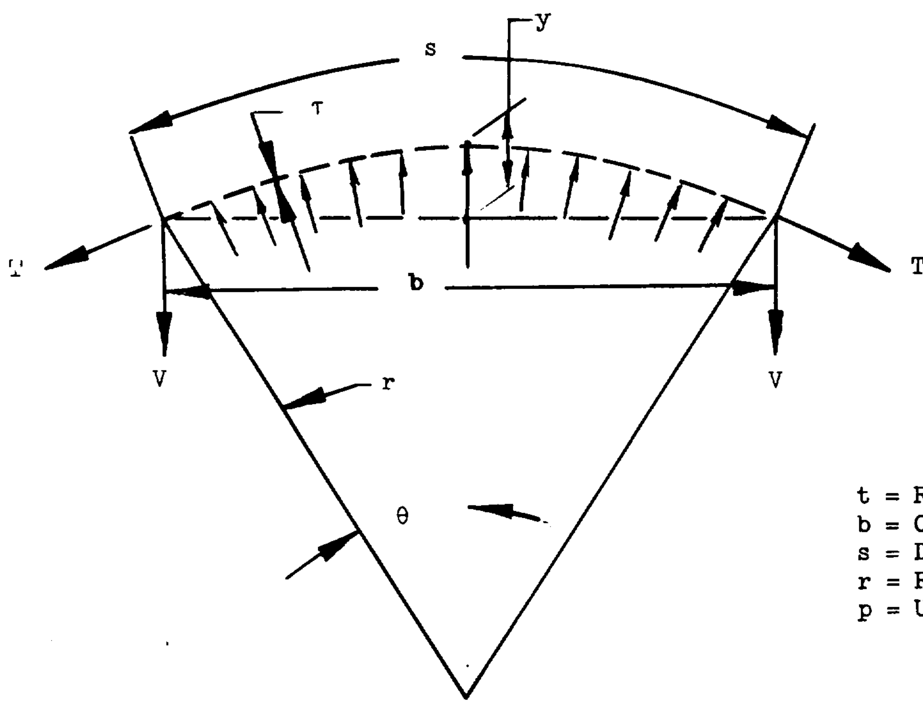
STRETCH CONCEPT PRESSURE ANALYSIS

Units Conversion

All calculations and dimensions are in U.S. Customary Units. The following conversions can be used to convert to the International System of Units:

Multiply	By	For
inches	2.540	cm
pound-force/inch^2 (psi)	6894.757	Pa
Pounds (mass)	0.4536	kg
pounds (force)	4.4482	N
pound-force-inch	0.11298	N·m
pound-mass/foot^2	4.8825	kg/m^2
degree Fahrenheit	(5/9)(temp °F + 459.67)	K

APPENDIX B
STRETCH CONCEPT PRESSURE ANALYSIS



t = Rubber Thickness
b = Orig. Length
s = Deflected Length
r = Radius of Curvature
p = Uniform Pressure Load

$$S = b + bE = b(1 + E)$$

$$T = \frac{V \text{ Sin } \theta}{\text{Sin } \theta} \qquad \text{Sin } \theta = \frac{T}{V}$$

$$V = \frac{Pb}{2} \qquad \text{Sin } \theta = \frac{2T}{Pb}$$

$$f = \frac{T}{t}$$

$$f = \frac{Pb \text{ Sin } \theta}{2t}$$

$$\text{Sin } \theta = \frac{b}{2r}$$

$$f = \frac{Pb^2}{4rt}$$

$$\varepsilon = \frac{Pb^2}{4rtE}$$

$$S = b(1 + \frac{Pb^2}{4rtE})$$

$$S = 2\ \theta r \quad (\theta \text{ is in radians})$$

$$\theta = \text{Sin}^{-1} \frac{2T}{Pb}$$

$$T = \frac{Pb^2}{4r}$$

$$S = 2r \text{ Sin}^{-1} \frac{b}{2r}$$

$$r \text{ Sin}^{-1} \frac{b}{2r} - \frac{b}{2} (1 + \frac{Pb^2}{4rtE}) = 0$$

$$\text{Sin}^{-1} \frac{b}{2r} - \frac{b}{2r} (1 + \frac{Pb^2}{4rtE}) = 0$$

Therefore:

$b = 2.0$ in.

$t = .08$ in.

$E = 250$ psi

$P = 4.2$ psi

$$\text{Sin}^{-1} \frac{1}{r} - \frac{1}{r} - \frac{.21}{r} = 0 = f(r)$$

r, in.	f(r)
1.0	+ .360
1.10	+ .040
1.20	- .023
1.15	+ .001

$$f = \frac{Pb^2}{4rt} = \frac{4.2(2)^2}{4(1.15).08} = 45.6 \text{ psi}$$

$$y = r(1 - \cos\theta) = 1.15(1 - \cos 60.4) = .582 \text{ in.}$$

$$E = \frac{f}{E} = \frac{45.6}{250} = .183 \text{ in./in.} = 18.3\%$$

$$\theta = \text{Sin}^{-1} \frac{b}{2r} \quad \sin^{-1} \frac{2}{2(1.15)} = 60.4^{\circ}$$

Appendix C

NON-STRETCH CONCEPT PRESSURE ANALYSIS (NON-REINFORCED RUBBER MEMBRANE)

Units Conversion

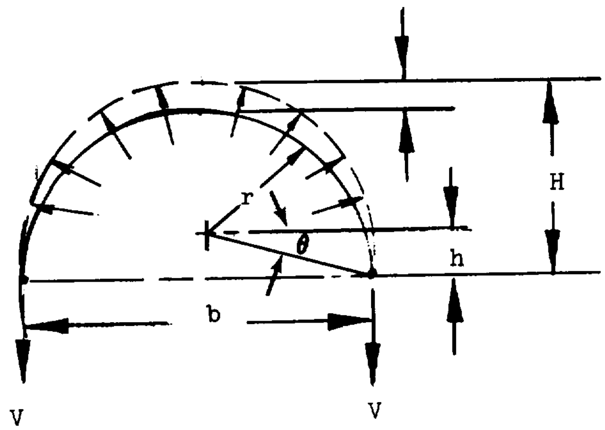
All calculations and dimensions are in U.S. Customary Units. The following conversions can be used to convert to the International System of Units:

Multiply	By	For
inches	2.540	cm
pound-force/inch^2 (psi)	6894.757	Pa
Pounds (mass)	0.4536	kg
pounds (force)	4.4482	N
pound-force-inch	0.11298	N·m
pound-mass/foot^2	4.8825	kg/m^2
degree Fahrenheit	(5/9)(temp °F + 459.67)	K

Appendix C

NON-STRETCH CONCEPT PRESSURE ANALYSIS

(NON-REINFORCED SILICONE RUBBER MEMBRANE)



$$S = \frac{\pi b}{2}(1 + E)$$

$$V = \frac{Pb}{2}$$

$$T = Pr$$

$$T = \frac{V}{\cos\theta}$$

$$f = \frac{Pr}{t}$$

$$\varepsilon = \frac{Pr}{tE}$$

$$S = \frac{\pi b}{2}\left(1 + \frac{Pr}{tE}\right)$$

$$S = \pi r + 2\theta r = r(\pi + 2\theta)$$

$$\cos\theta = \frac{V}{T} = \frac{b}{2r}$$

$$\theta = \cos^{-1}\frac{b}{2r}$$

$$S = r\left(\pi + 2\cos^{-1}\frac{b}{2r}\right)$$

$$\pi r + 2r\cos^{-1}\frac{b}{2r} - \frac{\pi b}{2}\left(1 + \frac{Pr}{tE}\right) = 0$$

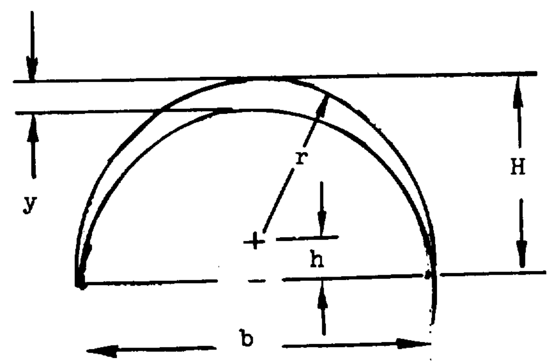
$$\cos^{-1}\frac{b}{2r} - \frac{\pi b}{4r} - \frac{\pi Pb}{4tE} + \frac{\pi}{2} = 0$$

$$y = h + r - \frac{b}{2}$$

$$h = \sqrt{r^2 - \frac{b^2}{4}}$$

$$f = \frac{Pr}{t}$$

$$H = h + r$$



$b = 1.7$ in.

$t = .08$ in.

$P = 4.2$ psi

$E = 250$ psi

$$\cos^{-1}\frac{.85}{r} - \frac{1.335}{r} + 1.290 = 0 = f(r)$$

r, in.	f(r)
1.0	+.5098
.90	+.1415
.86	-.1096
.87	-.0296
.88	+.0348
.875	+.0039
.874	-.0025

$\therefore$ $r = .8745$ in.

$$f = \frac{Pr}{t} = \frac{4.2(.8745)}{.08} = 45.9 \text{ psi}$$

$$\epsilon = \frac{45.9}{250} = .184 = 18.4\%$$

$$y = h + r - \frac{b}{2}$$

$$h = \sqrt{r^2 - \frac{b^2}{4}} = .206$$

$$y = .206 + .8745 - \frac{1.7}{2} = .23 \text{ in.}$$

$$H = h + r = .206 + .8745 = 1.0805 \text{ in.}$$

Appendix D

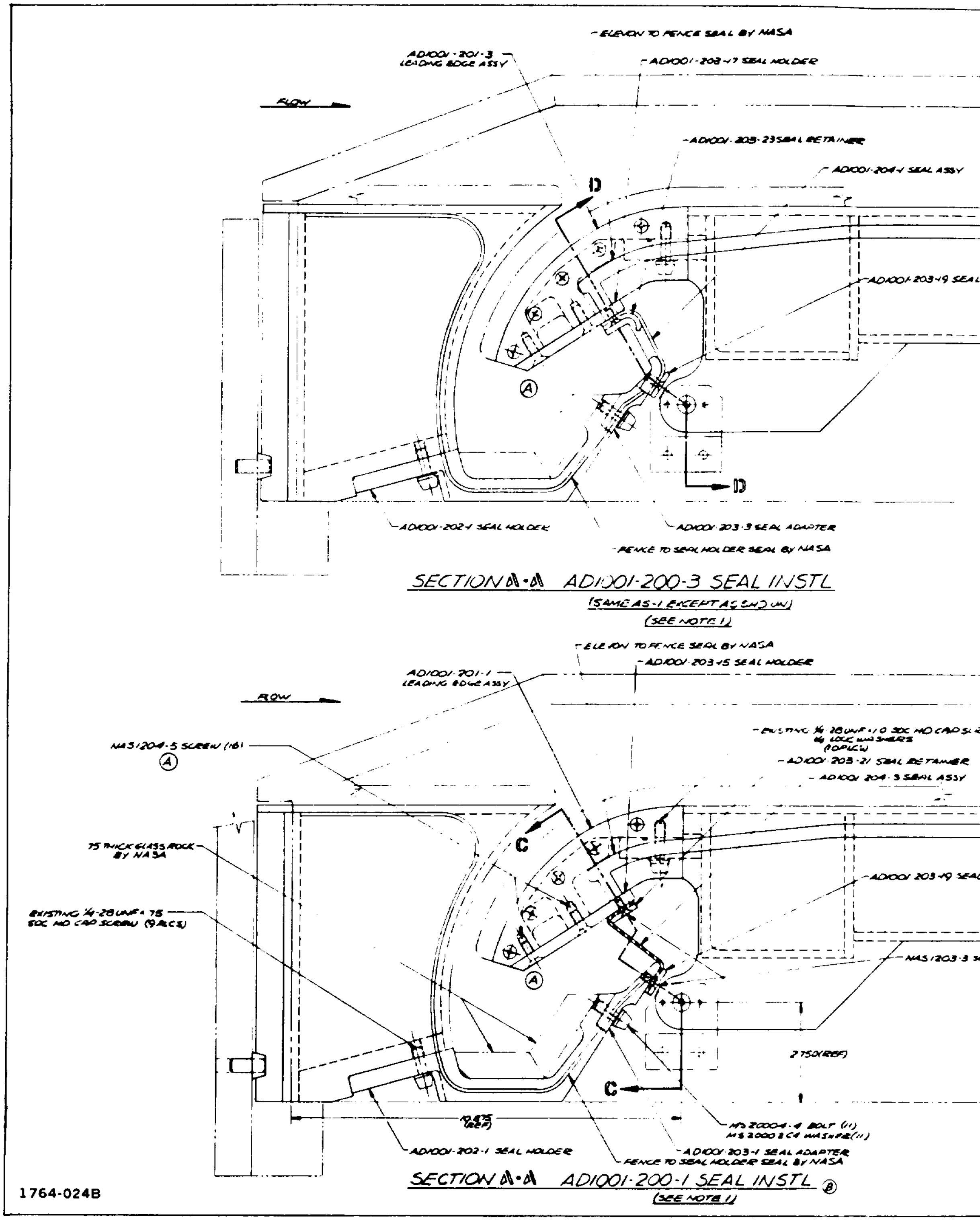
COVE SEAL TEST MODEL DRAWINGS

The parts required to modify the Langley cove seal test apparatus are shown on the following drawings:

AD1001-200	Seal Installation
AD1001-201	Leading Edge - Elevon
AD1001-202	Seal Holder
AD1001-203	Seal Adapter
AD1001-204	Seal Assembly
AD1001-205	Rub Plate Assembly
AD1001-206	Seal Assembly - Spandex Rub Strip

UNIT CONVERSION

All dimensions shown on the drawings are in inches; to convert to centimeters multiply by 2.540.



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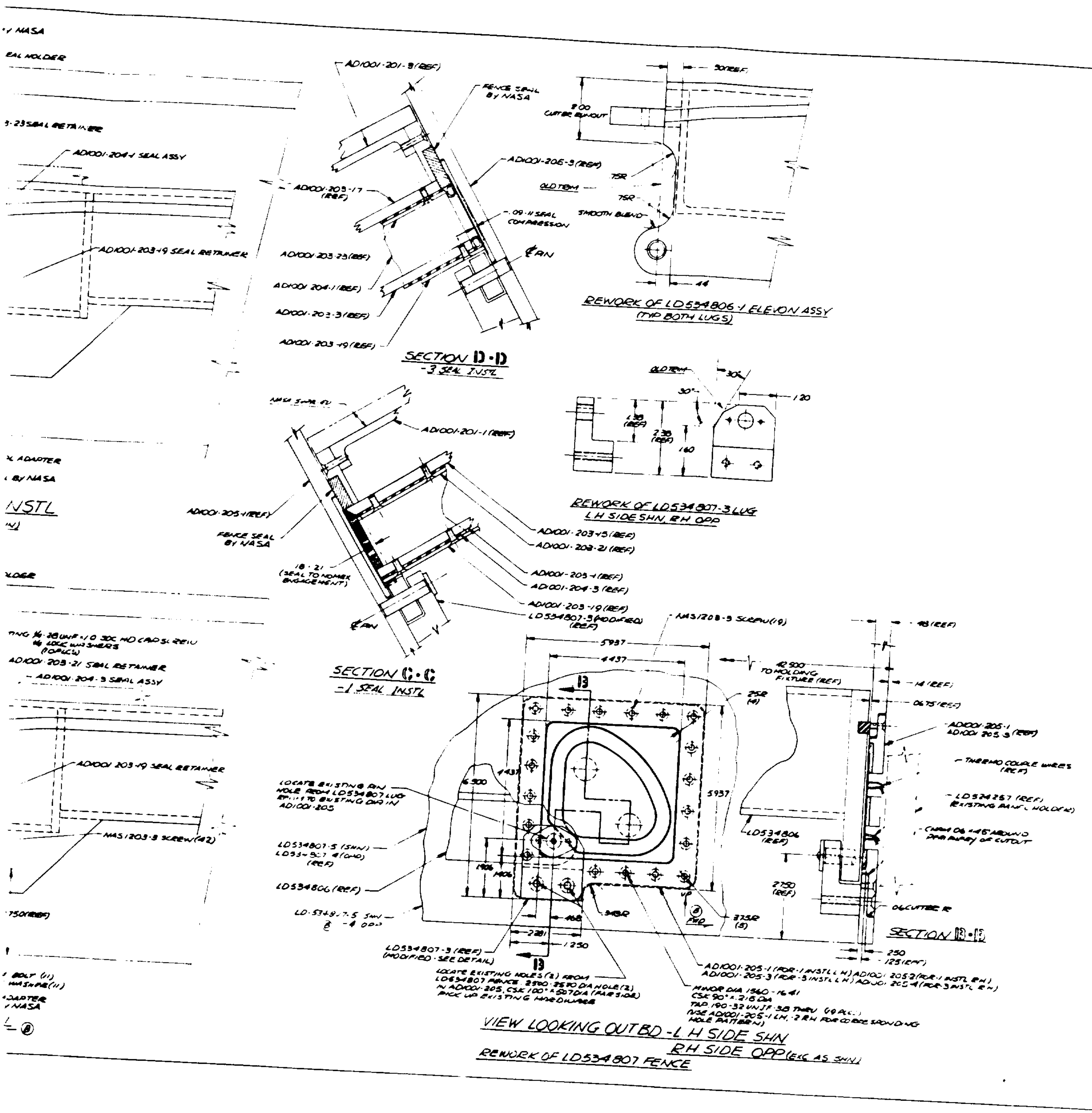

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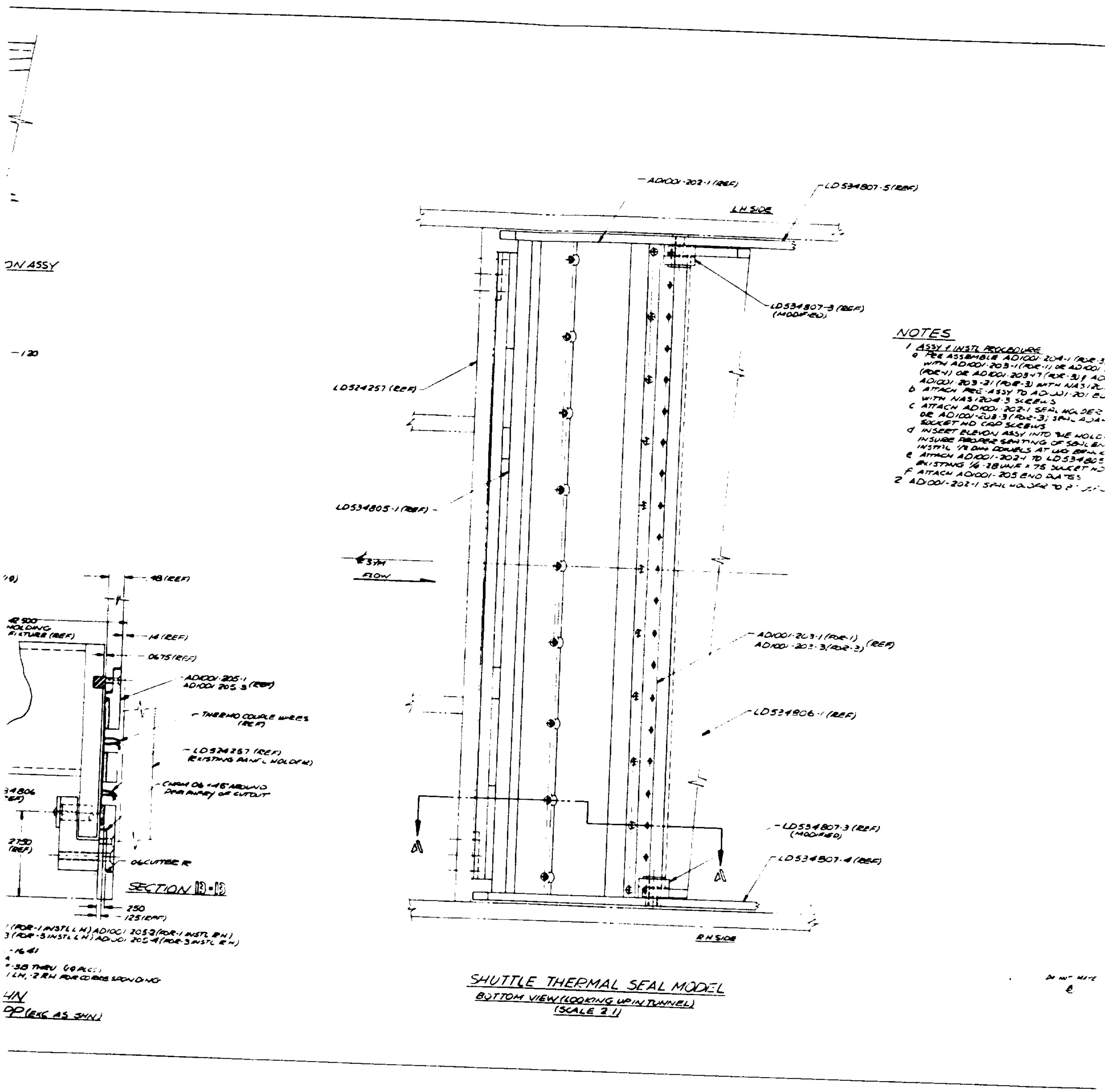

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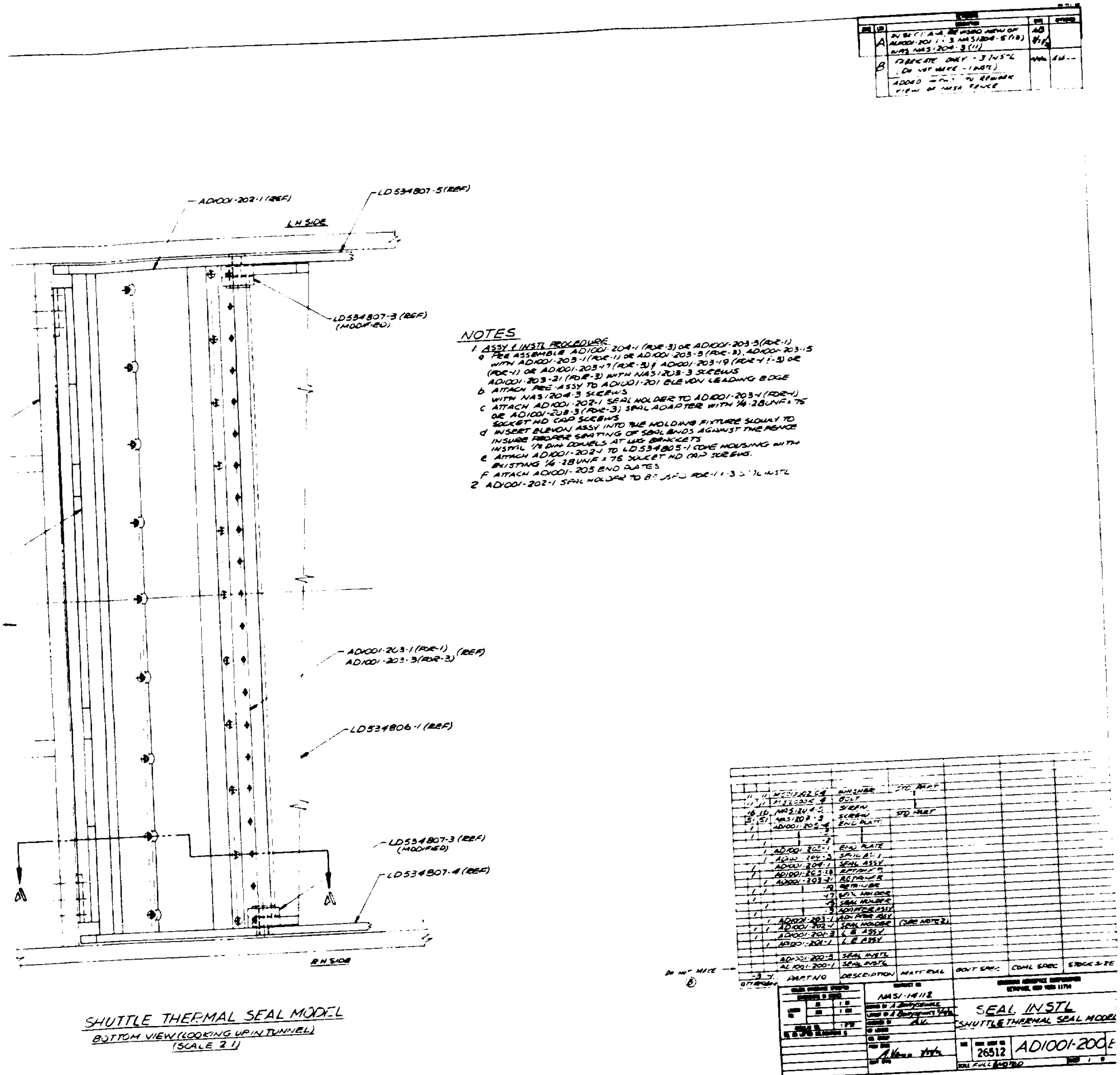

Figure D-1. – AD1001-200 Seal Installation

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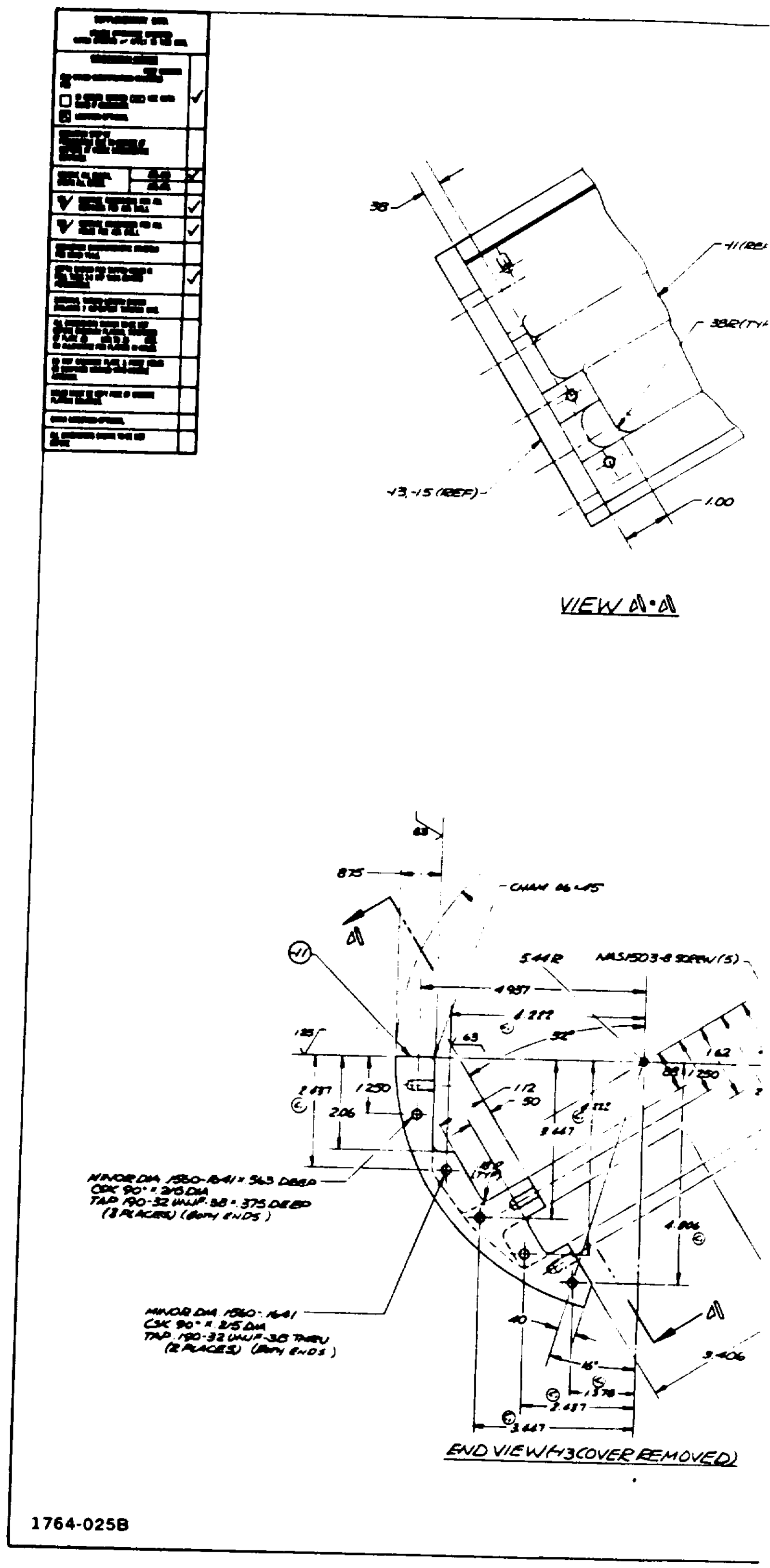

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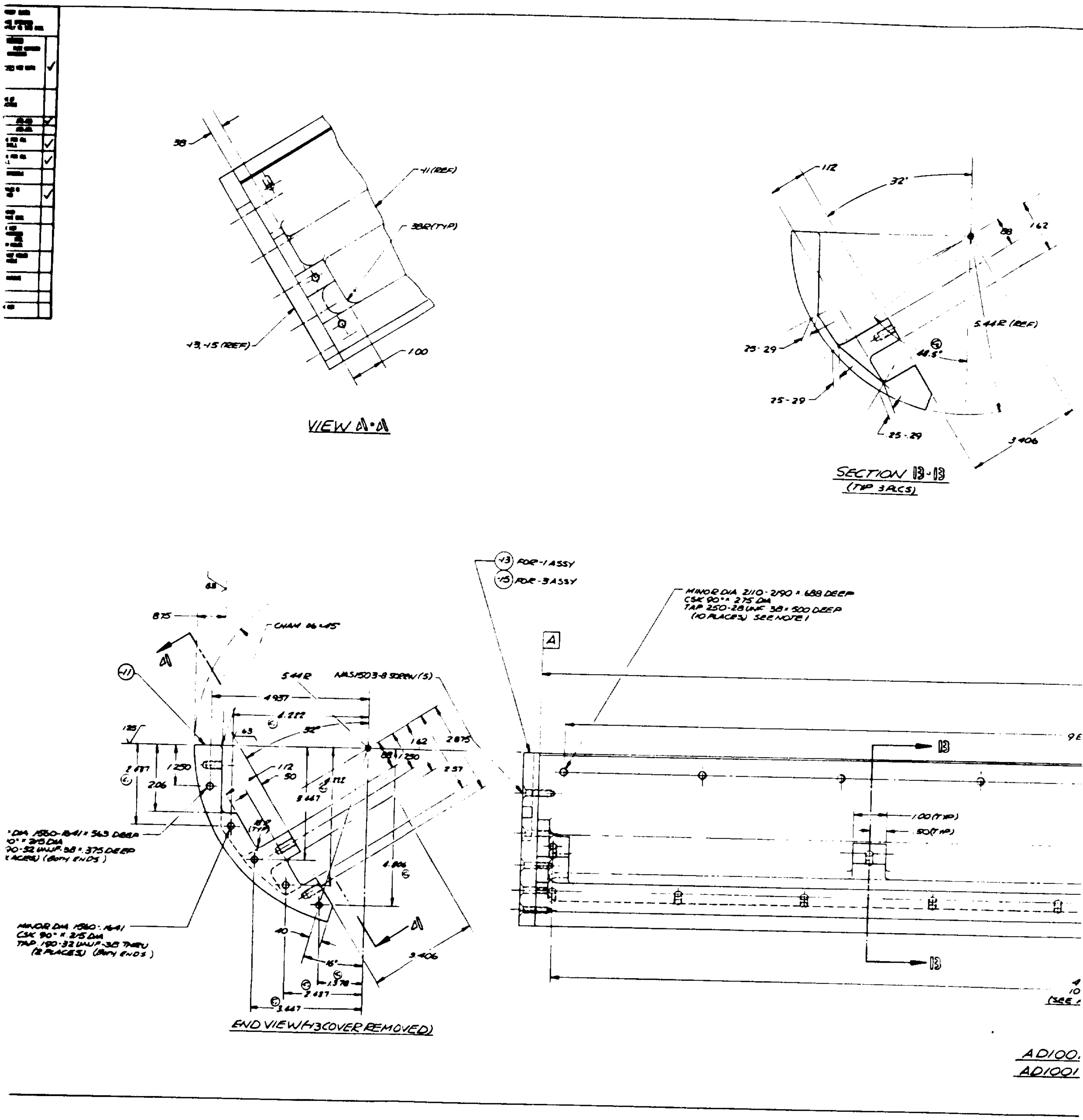

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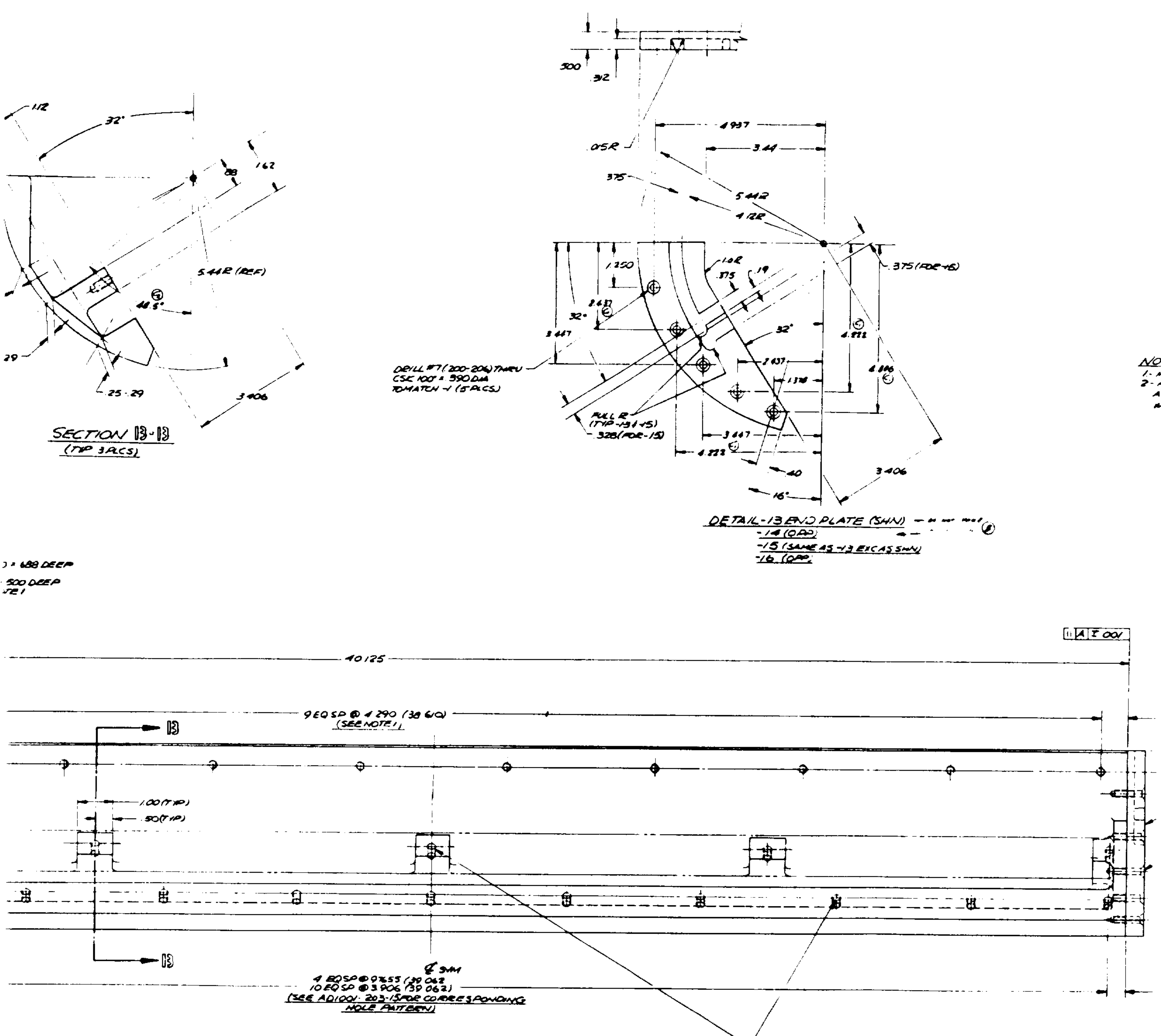

AD1001-201-1 LEADING EDGE ASSY
AD1001-201-3 (SAME AS -1 EXCEPT AS SHOWN)

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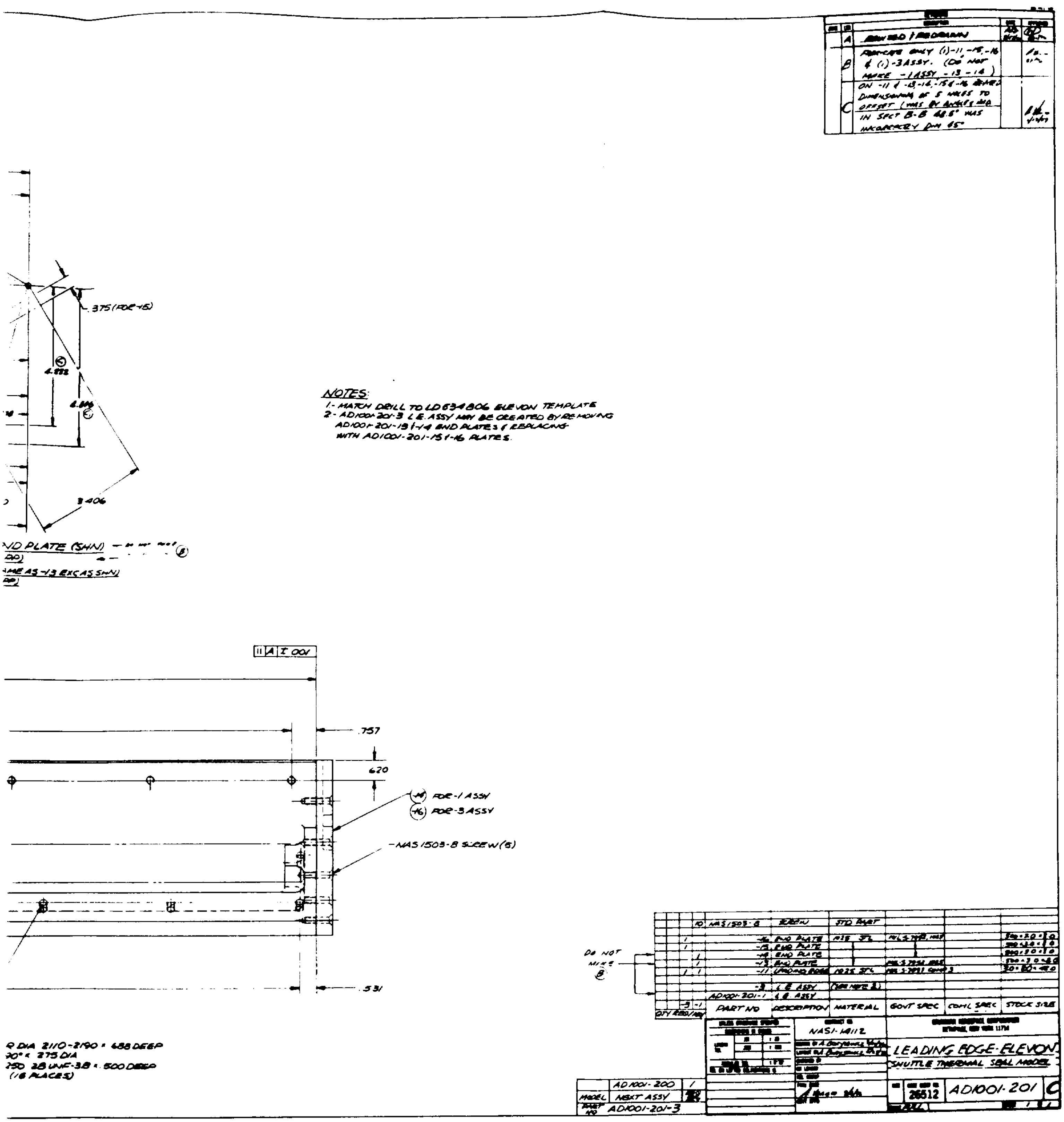

Figure D-2. – AD1001-201 Leading Edge – Elevon

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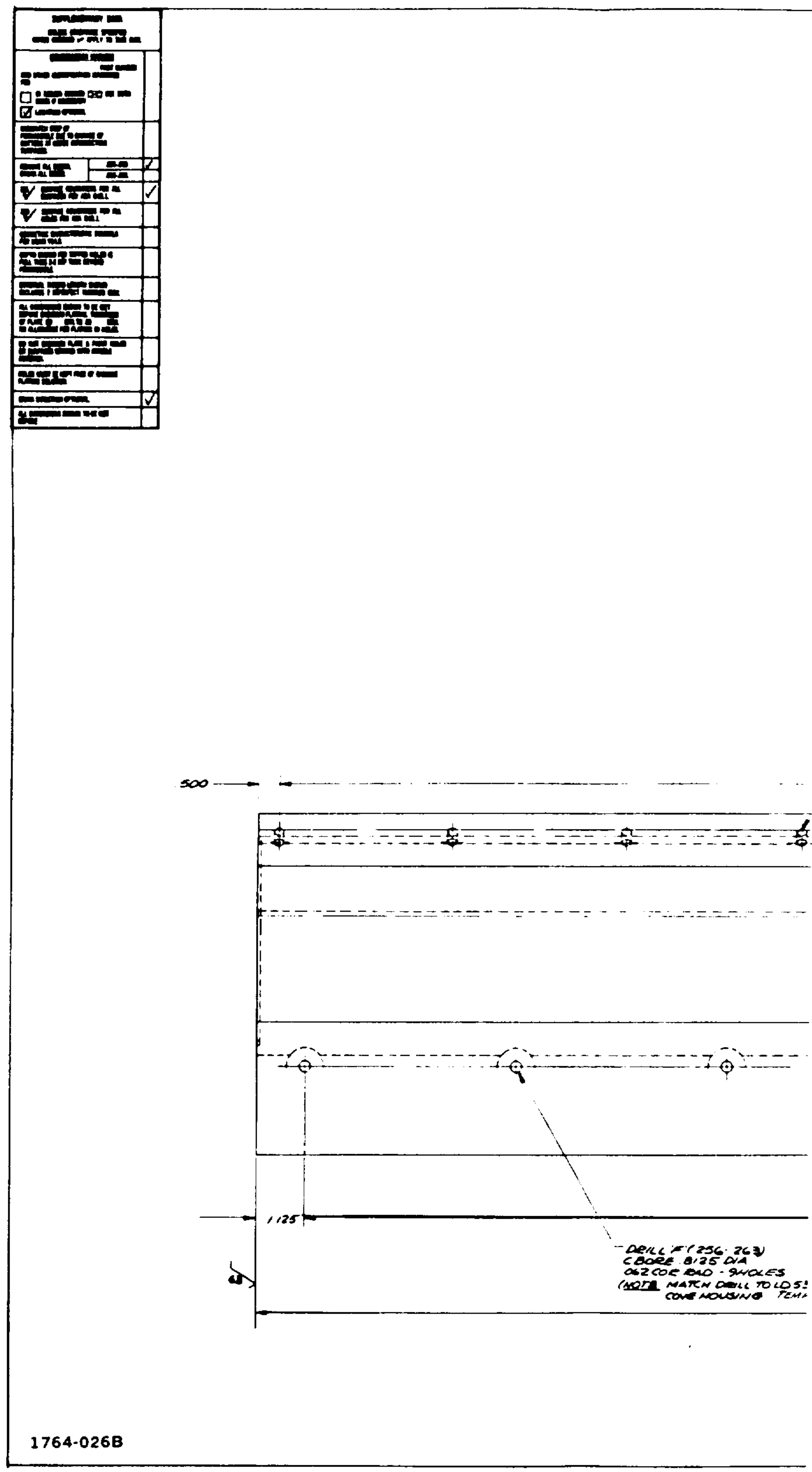

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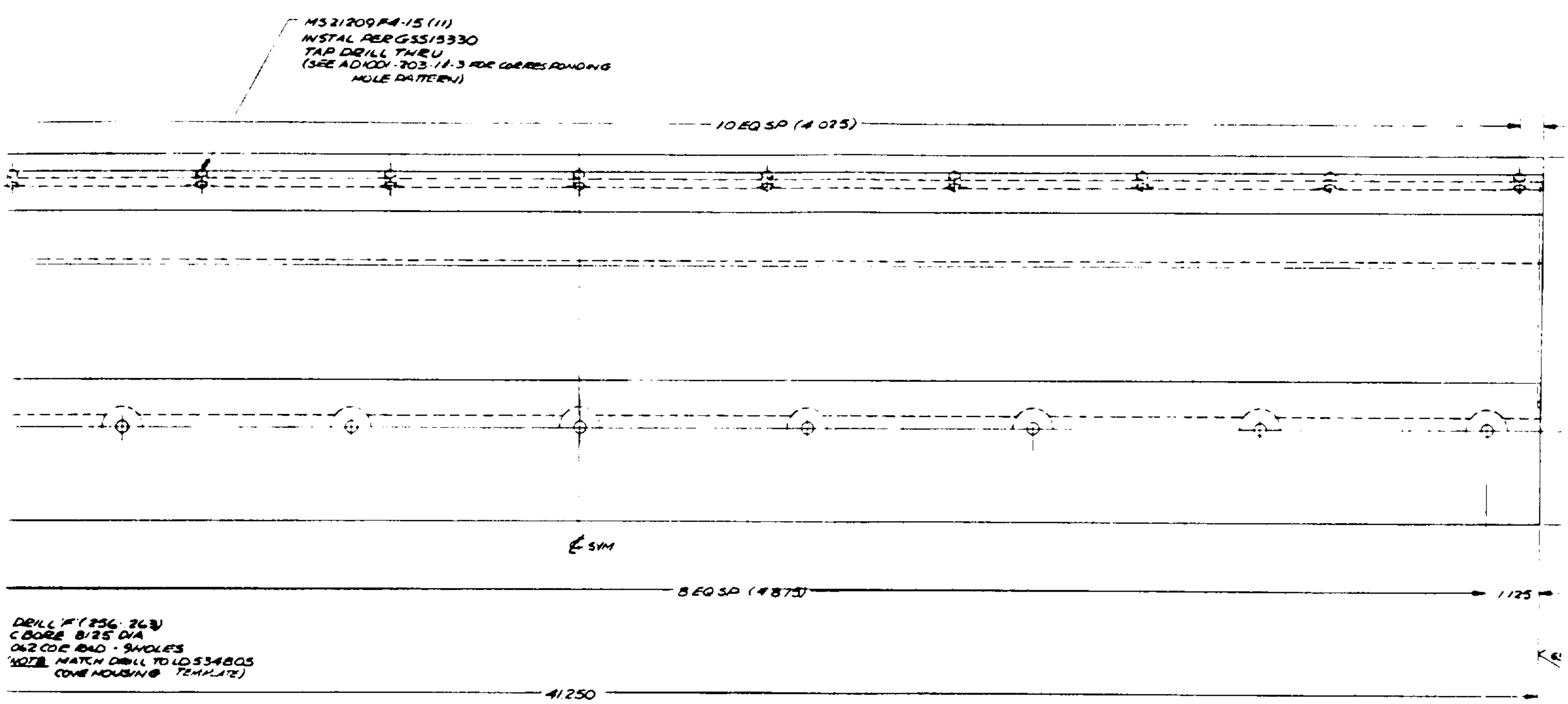

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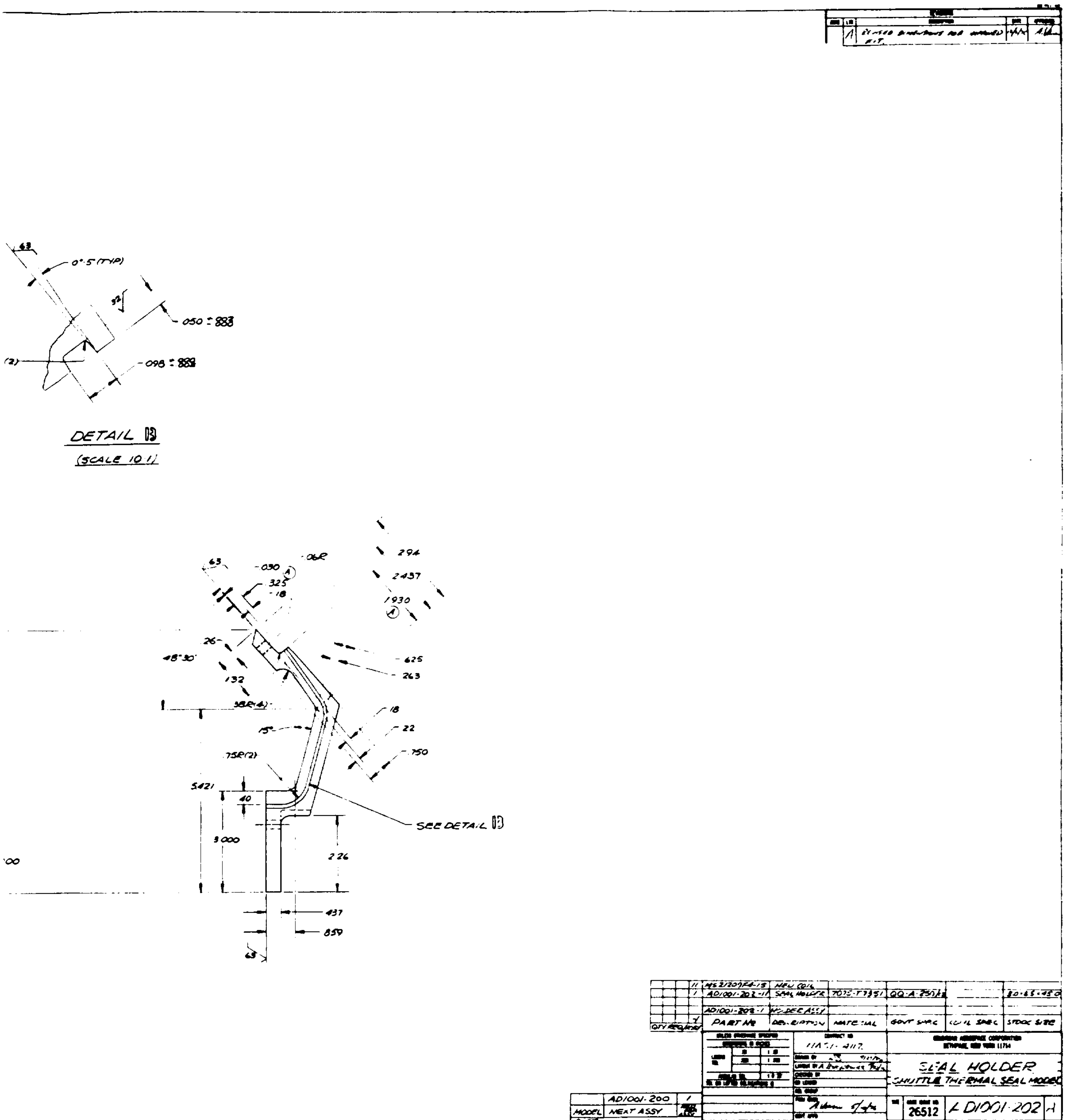

Figure D-3. – AD1001-202 Seal Holder

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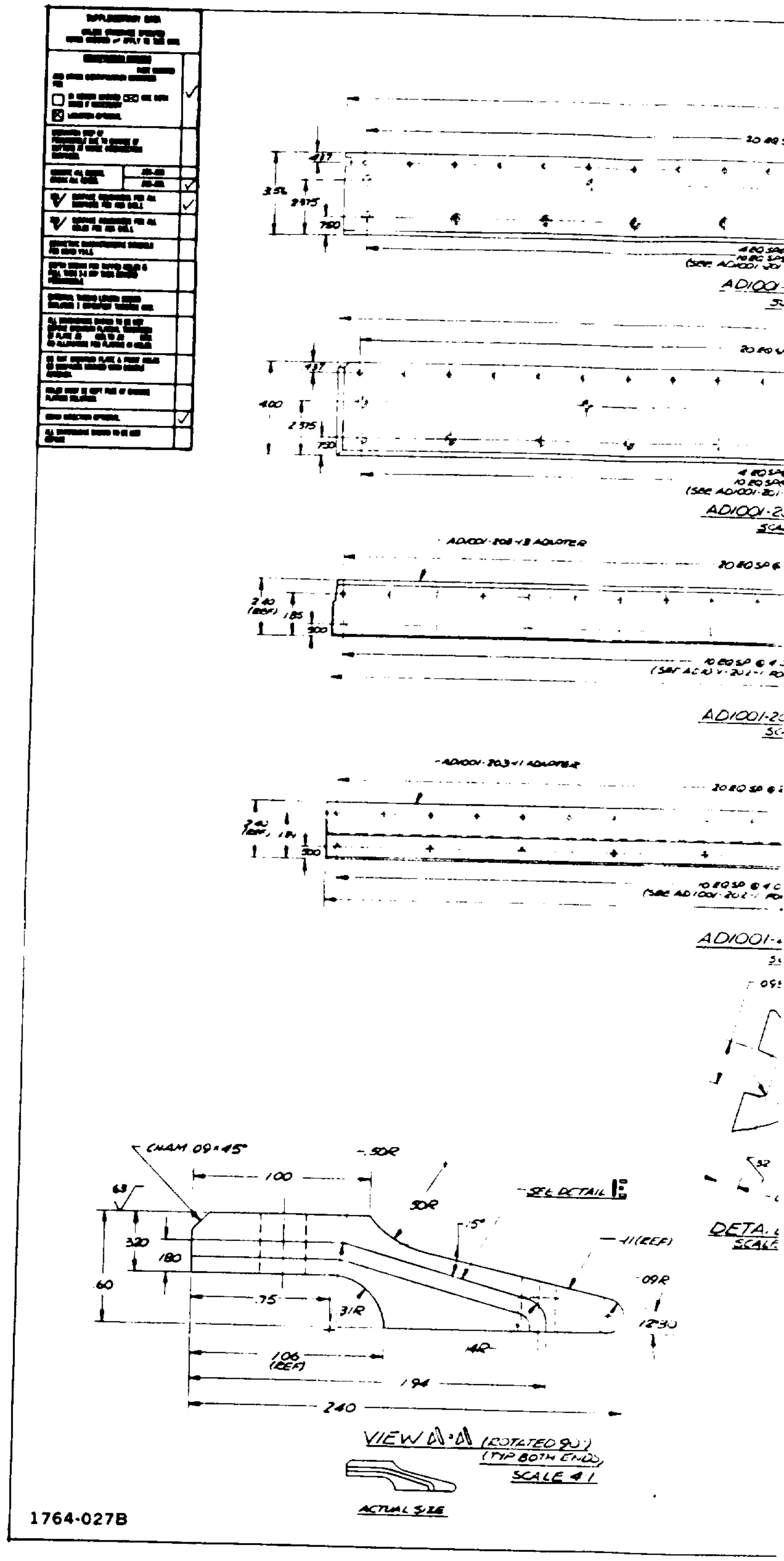

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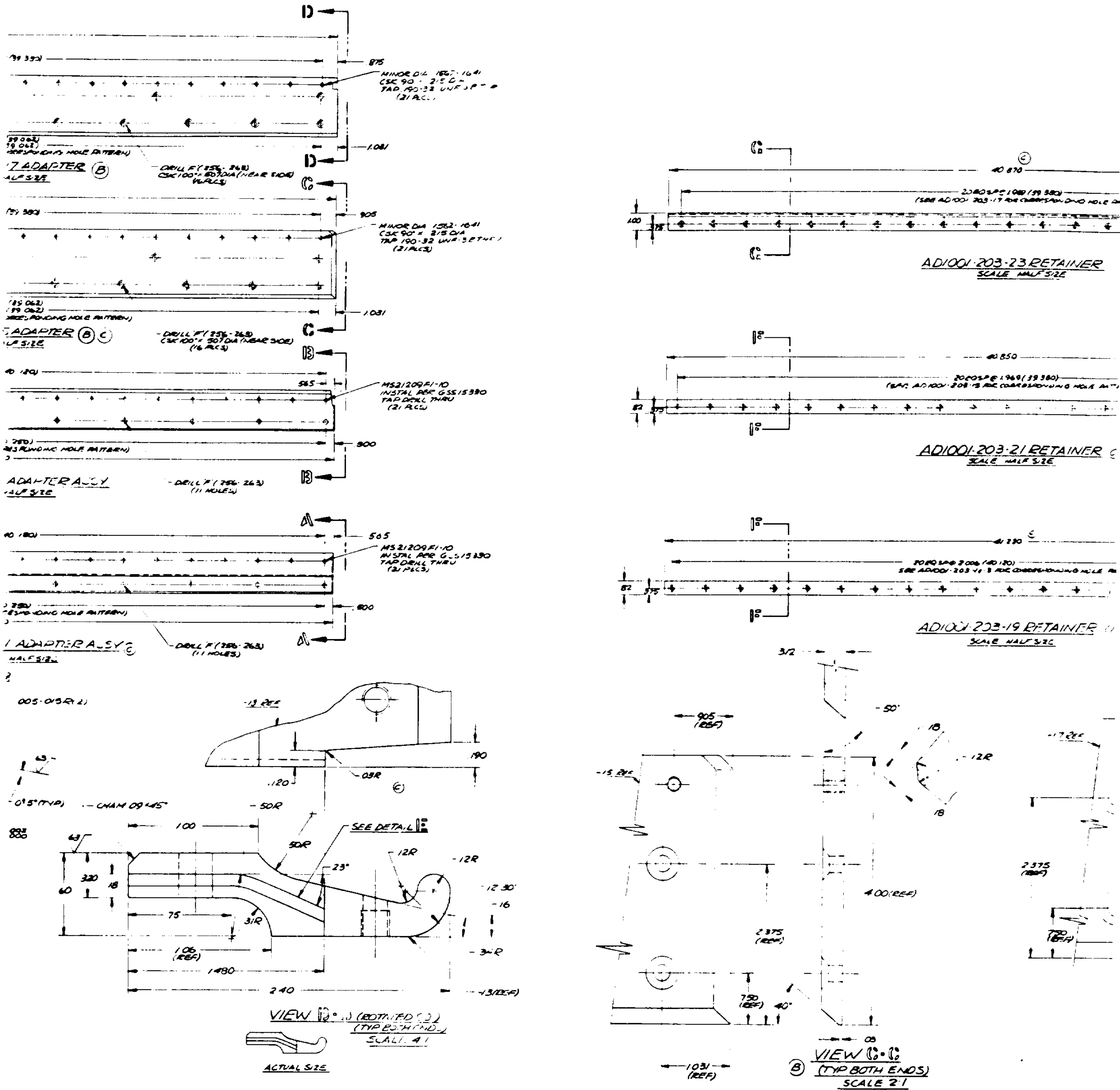

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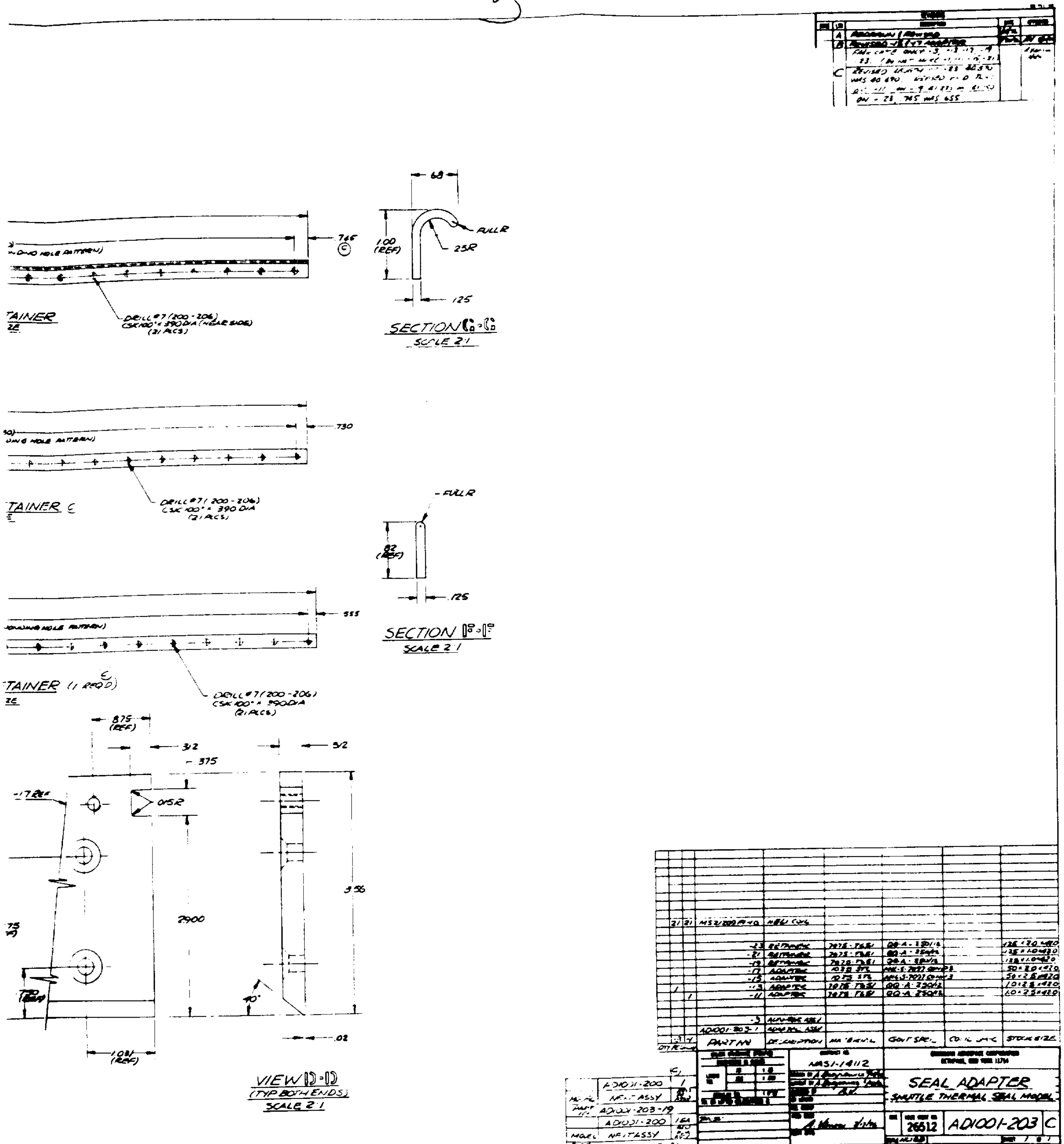

Figure D-4. – AD1001-203 Seal Adapter

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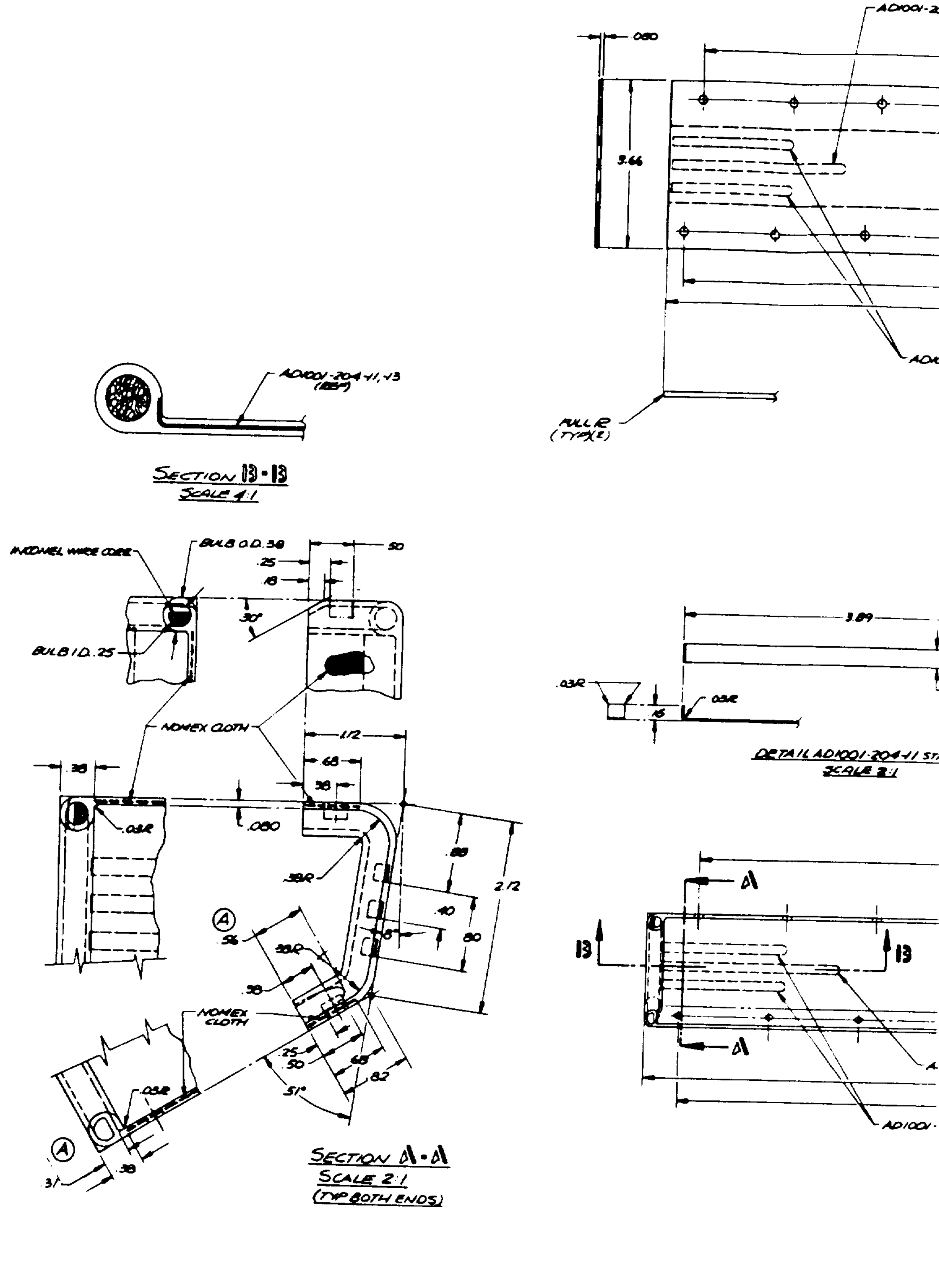

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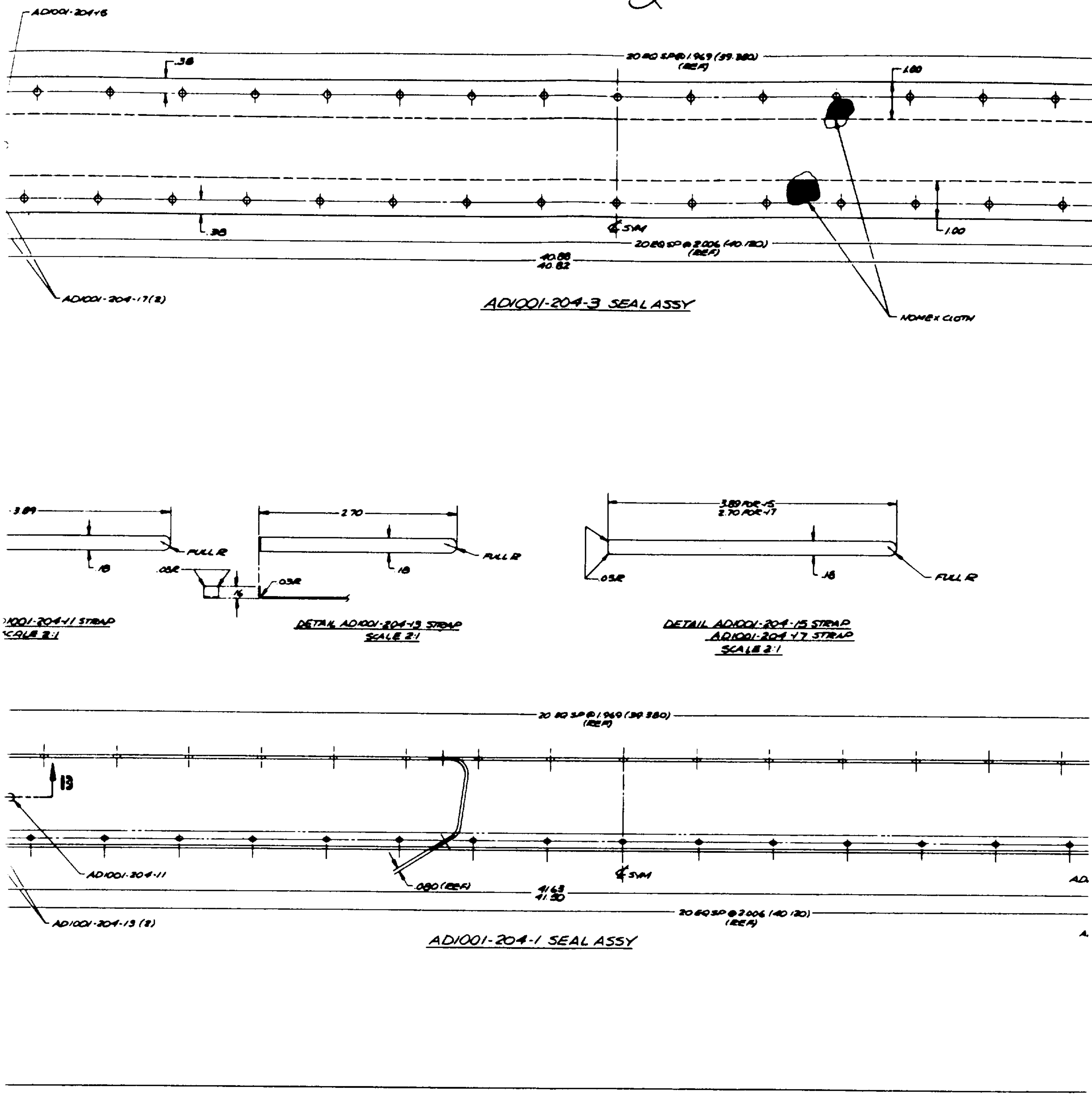

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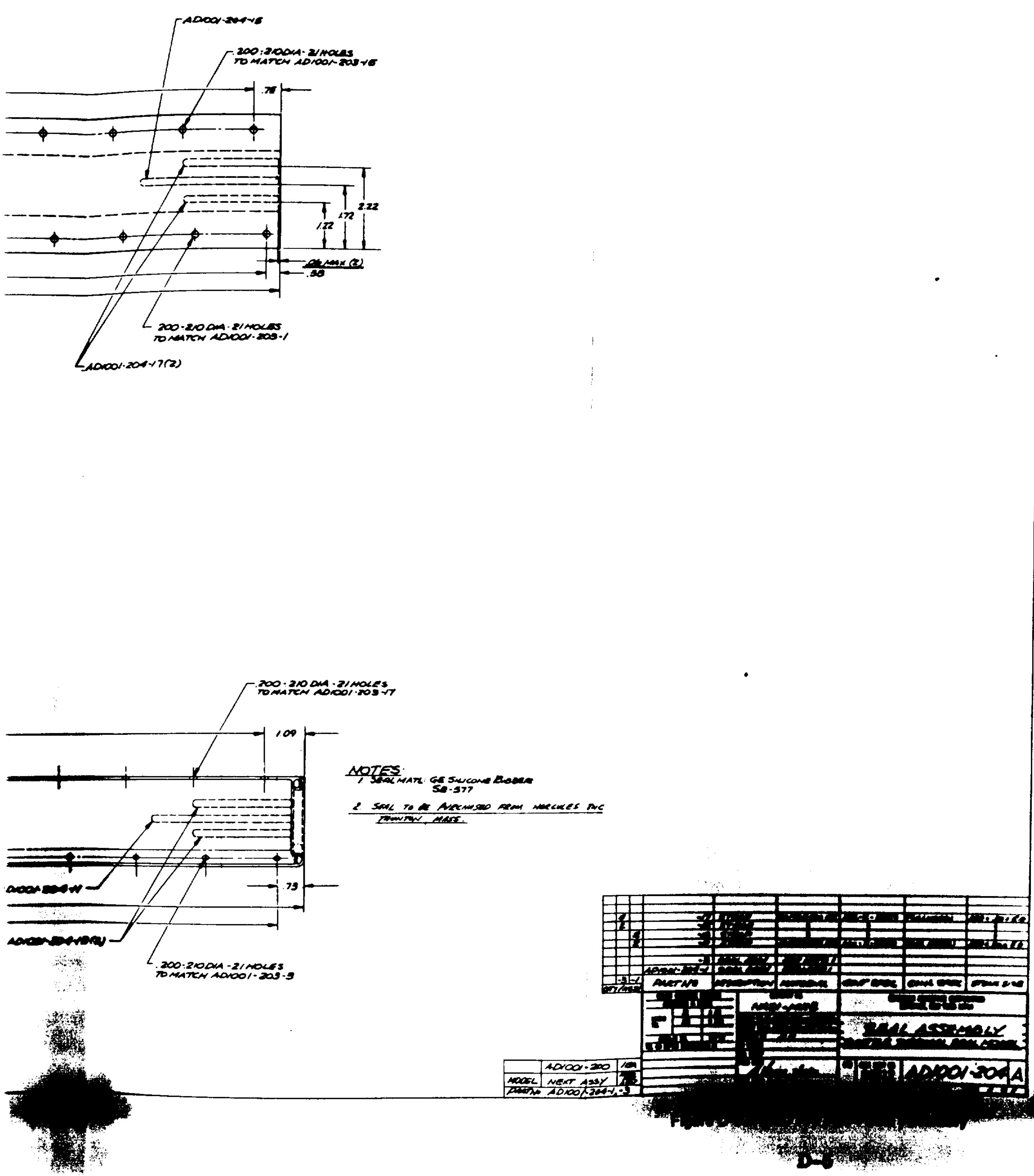

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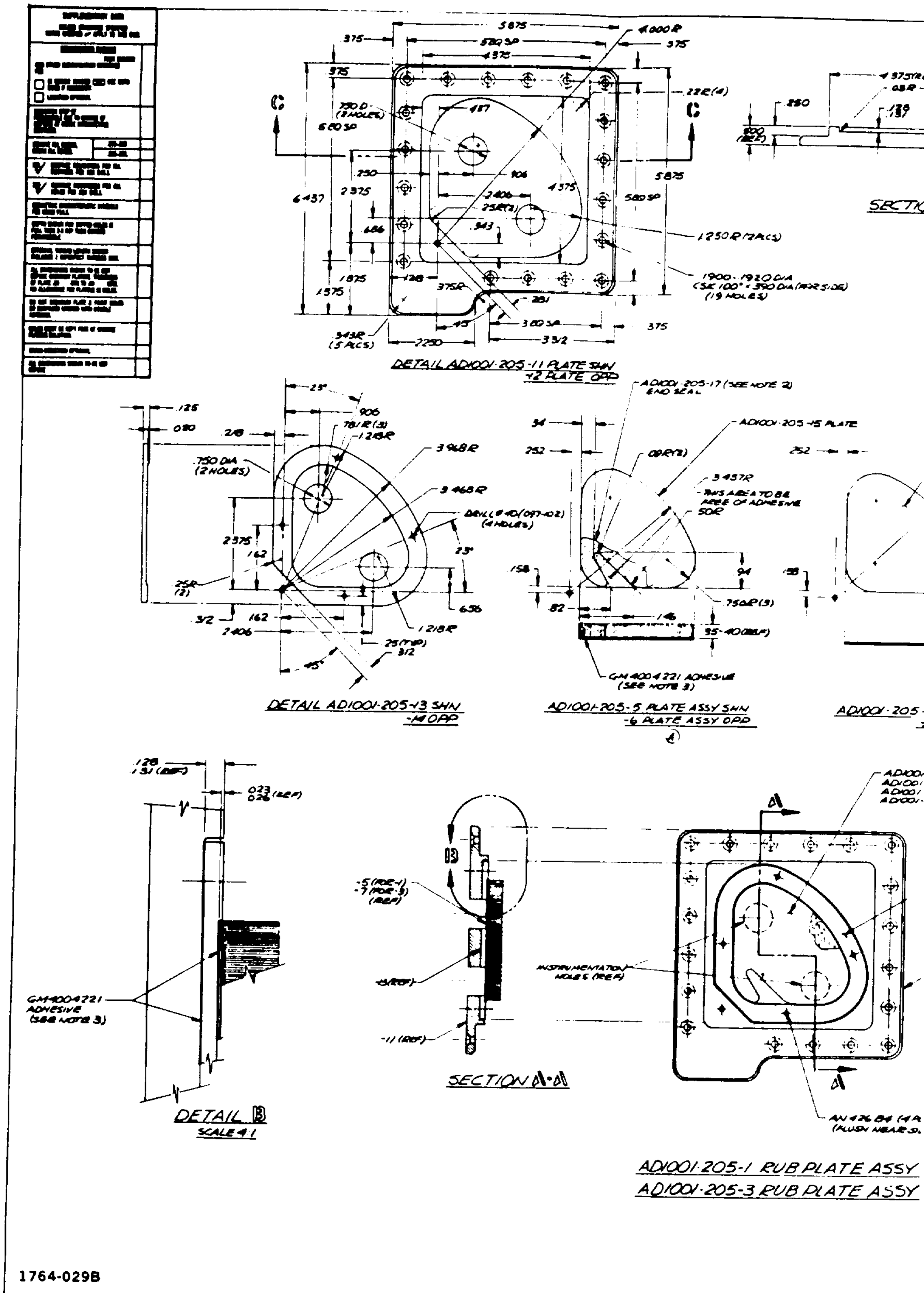

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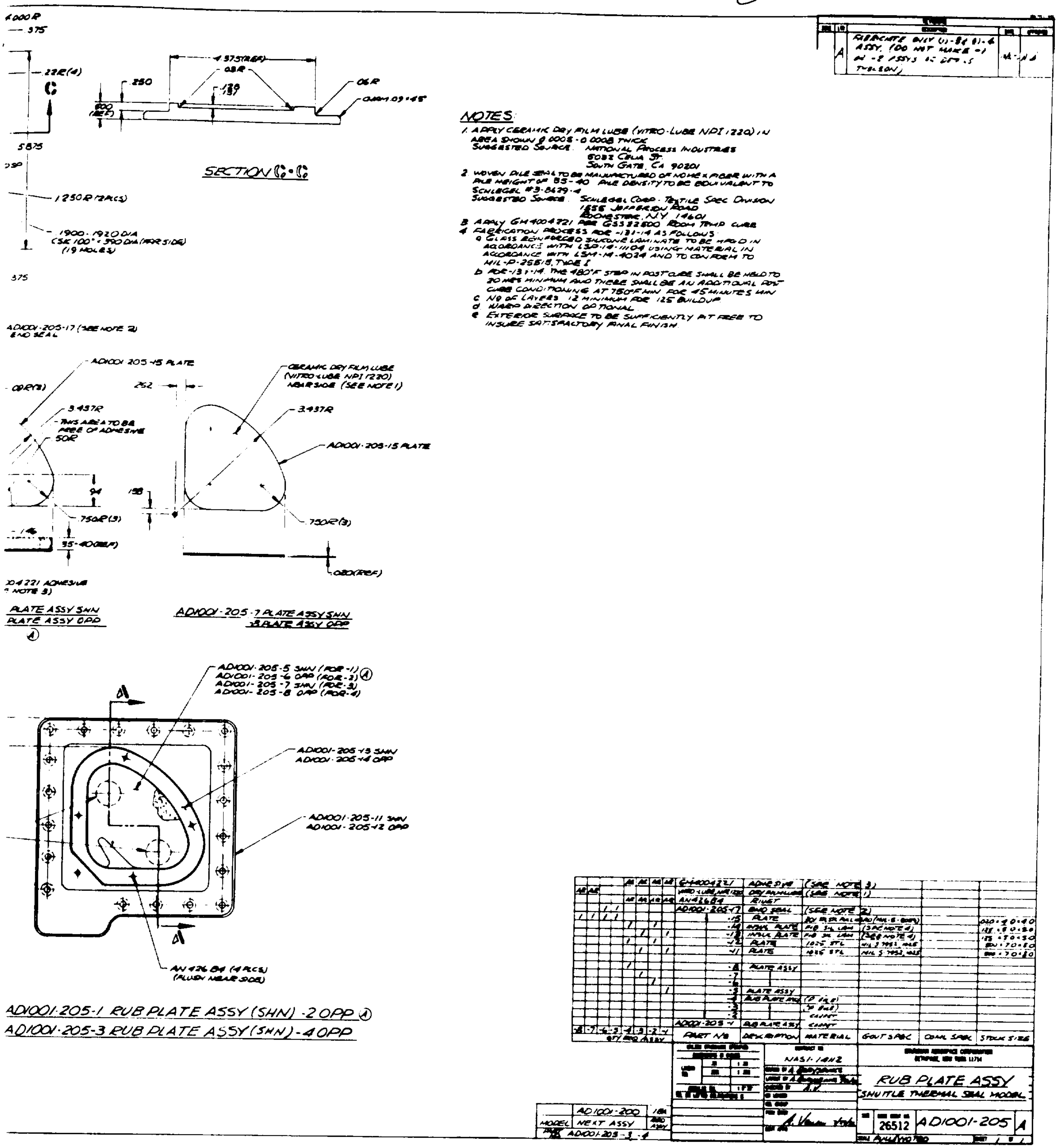

Figure D-6. – AD1001-205 Rub Plate Assembly

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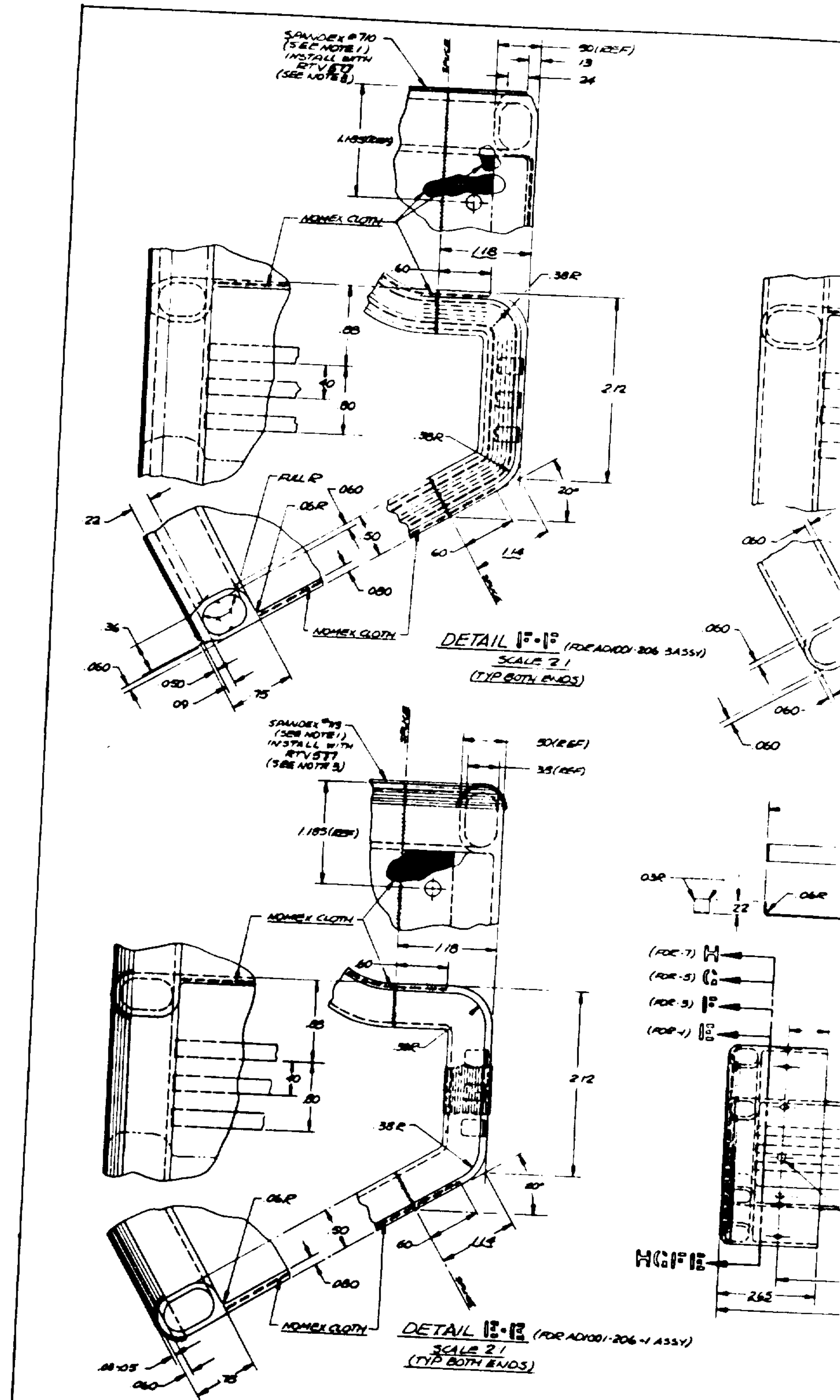

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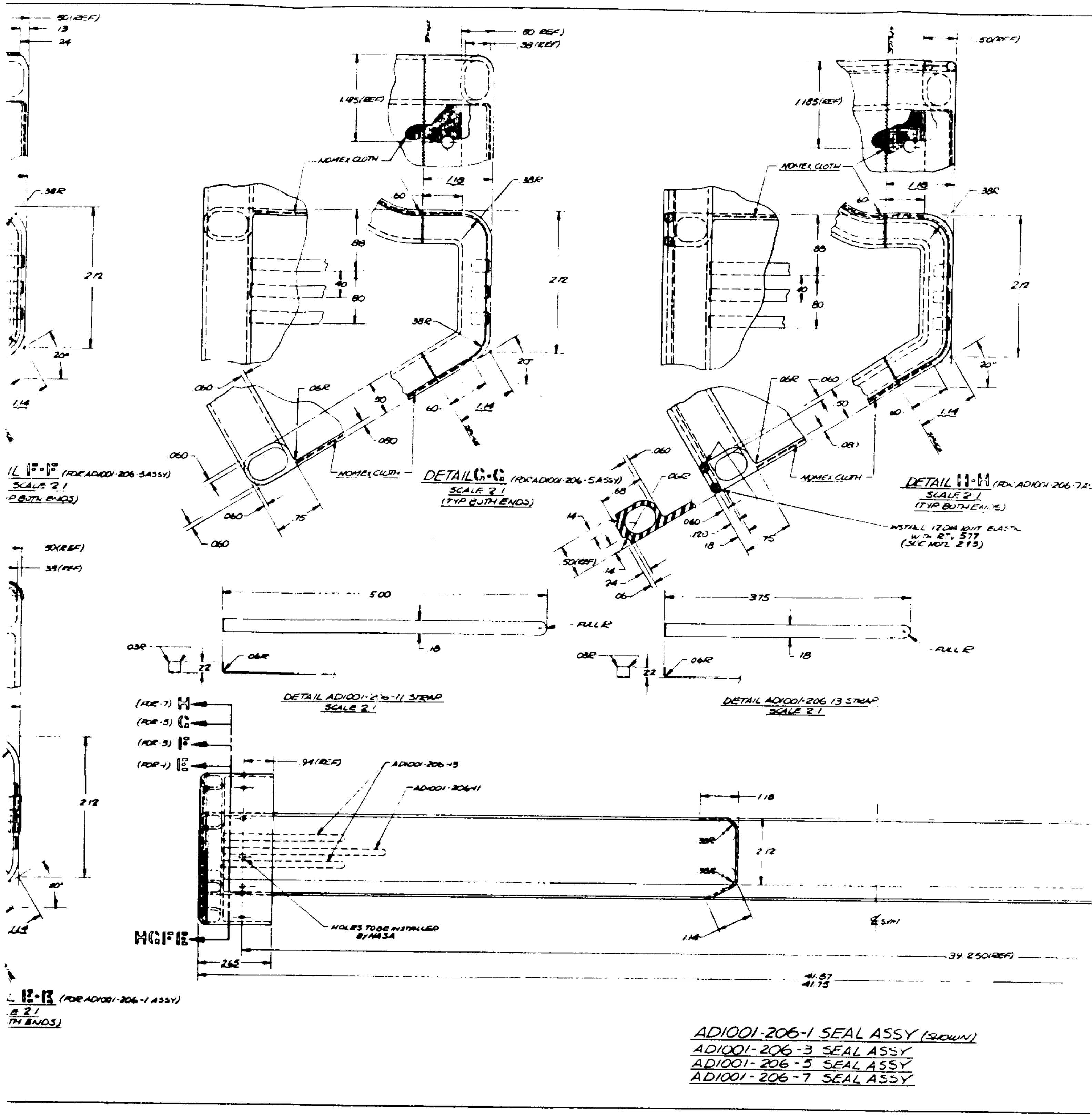

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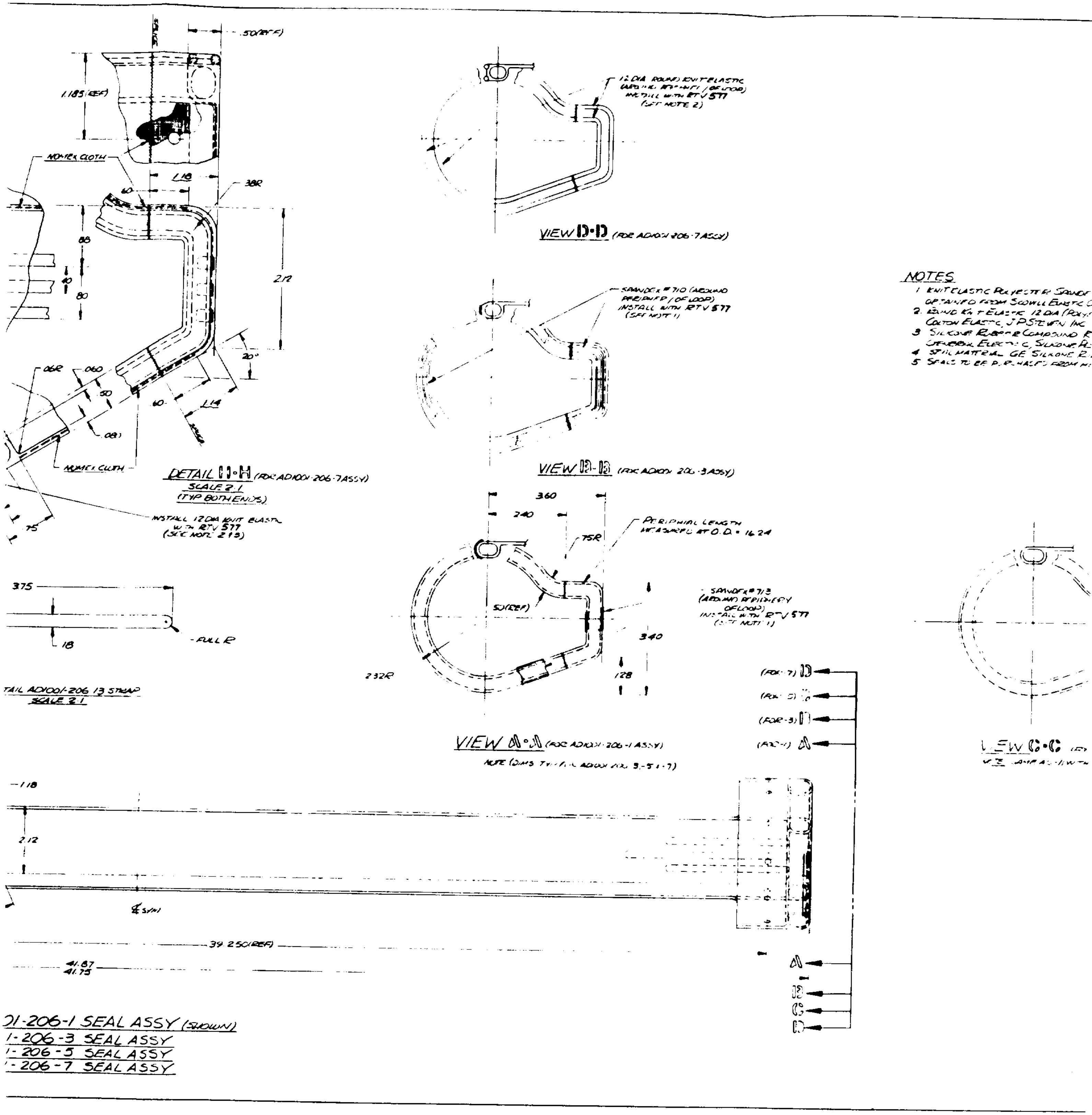

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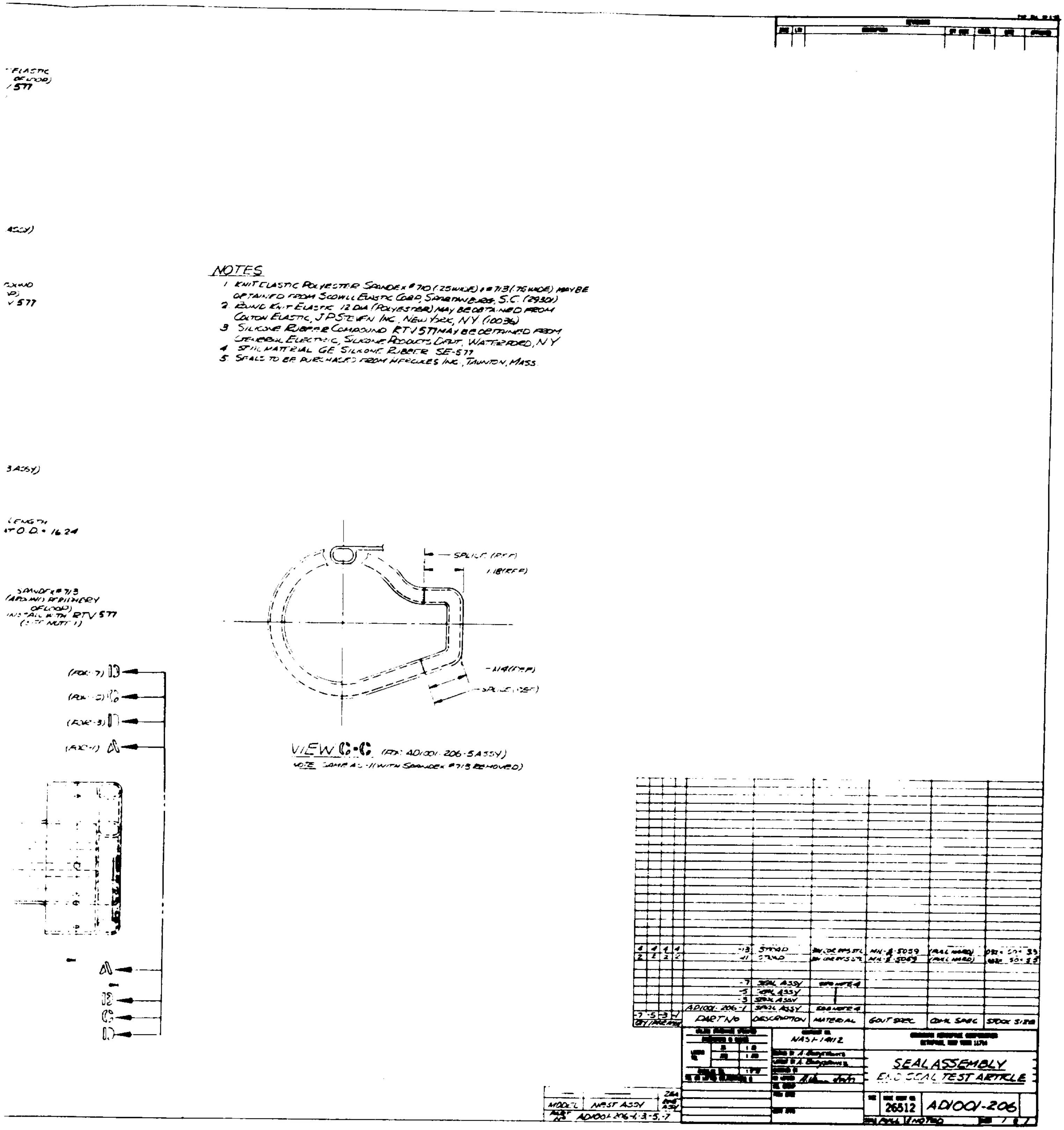

Figure D-7. – Seal Assembly – Spandex Rub Strap

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Contrast Monitor: L. Roane Hunt and William D. Deveikis

16. Abstract

A design study was undertaken to develop and fabricate a flightweight, effective, reuseable seal for use along the elevon cove of shuttle-type reentry and hypersonic cruise vehicles. The development work included in this report deals primarily with membrane seals, both metallic and non-metallic. This type of seal spans the cove gap between the wing and elevon, and does not depend on spring tension to maintain contact along a flexing wing span. Technical requirements and criteria were generally derived from the space shuttle and utilized for seal design.

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