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Technical Memorandum No. 33-309

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ABSTRACT

This report documents the design, fabrication, and testing of the *Applications Technology Satellite* apogee motor chamber. On firing, the apogee motor provides the necessary impulse to place the satellite in near synchronous orbit. Details of the materials selection, design, fabrication, and testing of the motor chambers are discussed herein. The choice for the chamber material was Ti-6Al-4V alloy. An optimum design was achieved by a team effort among materials, structures fabrication, propulsion, and design personnel. Certain tradeoffs that were required are discussed in detail. The chamber consists of three components: two half shells and a mounting ring. Fabrication was accomplished by forging to shape, machining to the desired thickness, and welding of the components. Verification of chamber design was determined from hydroburst tests, vibration tests, and acceleration tests.

I. INTRODUCTION

A. Program History

In January of 1963, a program was initiated by Jet Propulsion Laboratory to provide a solid-propellant apogee motor for the *Advanced SYNCOM* satellite. This satellite, being produced by Hughes Aircraft Company under the management of the National Aeronautics and Space Administration's Goddard Space Flight Center, was designed to operate at synchronous altitude and to serve a communications function for voice, teletype, and television.

The *Advanced SYNCOM* program was expanded in January of 1964 to include experimental instrumentation for meteorology, communications, radiation, navigation, gravity gradient stabilization, and various engineering experiments. This redirected program was designated the *Applications Technology Satellite* (*ATS*).

The Jet Propulsion Laboratory was assigned responsibility for the design and fabrication of this solid-propellant apogee motor, which on firing, provides the necessary impulse to achieve synchronous orbit of the *ATS* satellite. In all, twenty-three 6Al-4V titanium alloy chambers have been fabricated for use in developmental tests and as qualification units, as well as for flight units. This report describes the various phases of the design, fabrication, and testing of the motor chamber.

B. Technical Aspects of Expanded Program

Many of the technical requirements for this task date back to the original *SYNCOM* satellite and its associated apogee motor chamber. Some of the decisions made on the *ATS* chamber were predicated on approaches taken during the programs for the *SYNCOM* and *Advanced*

SYNCOM chambers. A brief history of these programs shows their interrelationships.

The original *SYNCOM*, designed to serve a communications function only, had a 12-in.-diam type 410 chromium steel chamber. Chamber material selection was based simply on a performance vs cost relationship, while construction was accomplished by welding formed sheet metal.

With the initiation of the *Advanced SYNCOM*, essentially the same requirements existed, except that the chamber was scaled up to a diameter of 28 in. The *Advanced SYNCOM*, again, was to serve a communications function that would handle voice communication, teletype, and television signals. As it was with *SYNCOM*, materials selection for the chamber was based on a performance vs cost relationship. Since the requirements were essentially identical, it was decided the same material and similar fabrication procedures would be used.

After fabrication had commenced, the purpose of the satellite was changed to include other experimental missions, in addition to communications. This expanded program, designated the *Applications Technology Satellite*, was designed to carry instrumentation for experimentation in the areas of meteorology, communications, radiation, navigation, gravity-gradient stabilization, and others. The added experiments imposed new requirements on the chamber—specifically, that it be nonmagnetic and, since there would be added payload while the size was to remain the same (28-in. diam), that it be of higher efficiency. Consequently, another selection phase was necessary to determine the material to be used in fabricating the chamber; that chosen was Ti-6Al-4V in the solution-treated and aged condition.

A detailed discussion of alloy selection for all three chambers appears in the following section of this report. The design, fabrication, and testing of the titanium alloy chambers are described in subsequent sections.

II. MATERIAL SELECTION

Material selection for the chamber structure was an important phase in the apogee motor development. Criteria and methods of material selection will be discussed chronologically for the three motor chambers, illustrating original requirements and subsequent changes in requirements.

A. *SYNCOM* Motor Material Selection

Specific important criteria used to screen materials for use on the original 12-in.-diam *SYNCOM* chamber were the following:

1. High specific-yield strength (F_{ty}/density)
2. Strength-retaining capability to 200°F
3. Reliability and reproducibility of performance at the selected working stress
4. Nominal material and fabrication costs
5. Achievement of high strength without great distortion
6. Ease in fabrication
7. High weld-joint efficiency
8. Short fabrication time

Candidate materials, with their respective characteristics, are included in Table 1. All exhibit the basic requirements listed above. As is evidenced by the data in Table 1, heat-treated Ti-6Al-4V appears to be the most outstanding of the materials considered for this application. It possesses a specific yield strength of 920,000 in., far superior to all other alloys listed. It is a readily fabricated material and provides adequate toughness and ductility at the strength level selected. The one great disadvantage of this alloy is its higher cost. For the *SYNCOM* program, cost was a prime consideration; and since such high performance characteristics were not required, Ti-6Al-4V was not selected. Instead, a less costly material was chosen—specifically, type 410 chromium steel; although its specific yield strength is considerably lower than that of most of the other alloys screened, it was adequate for the program.

Table 1. Materials comparison for *SYNCOM* chamber

Property	Material									
	4340	17-4PH	AM 350	410	17-7PH	PH 15-7Mo	Ti-6Al-4V	Ti-6Al-4V	B120VCA	2014
	Condition									
	Heat treat to 200	H 900	SCT	Heat treated	RH 950	TH 1050	Annealed	STA	Annealed	-T6
F_{tu}, kpsi[a]	200	190	185	180	210	190	135	160	130	70
F_{ty}, kpsi	176	170	150	150	190	170	125	150	125	60
e, %	13.5	10	9	10	3	4	12	10	10	8
F_{ty}/ρ, 10^3 in.	620	600	530	540	690	610	770	920	710	600
Weld efficiency, %	95	95	90	95	94	80	100	85	100	50
Relative cost[b]	3	3	1	1	1	1	2	3	2	2
Method of construction	c	c	d	d	d	d	d	c	d	c
Reliability[b]	3	2	2	3	1	1	3	3	1	2

[a]Strength levels shown are considered maximum for adequate toughness and ductility.

[b]A value of 3 is maximum.

[c]Forged, machined, and welded.

[d]Formed from sheet and welded.

On the basis of cost vs performance, the 410 chromium steel exhibits the best combination of those criteria considered, as can be seen very readily by examining specific yield strength, relative cost, and reliability entries in Table 1. Data for each of the other alloys in the table compared with that for 410 chromium steel are summarized below. It should be noted that this summary characterizes each material at the time of the *SYNCOM* materials selection in 1961. Except for 2014, the lower reliability factors resulted from lack of prior experience in applying the material to such structures.

4340	Higher construction cost, specifically because of unavailability of thin sheets of this material
17-4PH	Higher cost, and lower reliability
AM 350	Lower specific yield strength and lower reliability
17-7PH	Lower reliability
PH 15-7Mo	Lower reliability
Ti-6Al-4V	Higher cost
B120VCA	Higher cost and lower reliability
2014	Higher cost and lower reliability because of a lack of margin in case of insulation failure where temperatures would exceed the useful limit of this material

Consequently, 410 chromium steel was selected, and it proved to be successful.

B. Advanced *SYNCOM* Motor Material Selection

With the design of the 28-in.-diam chamber for the *Advanced SYNCOM*, these alloys were again reviewed. Essentially, the same conclusions were drawn, resulting in the selection of 410. Here again, high reliability and low cost were of greatest importance, and the chromium steel met design demands.

C. ATS Motor Material Selection

Redirection of the *Advanced SYNCOM* program to provide an *Applications Technology Satellite* with additional instrumentation imposed greater demands on the material to be used for the chamber. Specific onboard experiments required that the material be nonmagnetic, in addition to meeting the previously cited criteria; this requirement precluded the selection of 410. Further, the increased payload weight required a higher efficiency material than the 410 chromium steel used on the earlier chambers.

Of the materials listed in Table 1, only the titanium alloys and 2014 aluminum alloy meet the nonmagnetic requirement. These alloys and other nonmagnetic alloys, some of which had become prominent between the time of the *SYNCOM* materials selection and the *ATS* selection, were reviewed and compared. The basic information used for this comparison—specifically, mechanical properties and density—appear in Table 2. Cost, although important, was not as great a consideration in this selection as it was for *SYNCOM*, since the nonmagnetic plus higher efficiency requirements reflect higher costs.

The selection of material can be focused on the titanium alloys because (1) they are the most efficient, (2) the aluminum alloys were ruled out because they do not provide as great a margin in case of insulation failure, and (3) the Inconel 718, at that time, had not been utilized to any great extent for pressure vessel or chamber applications and, thus, reliability was in question. The superiority of Ti-6Al-4V solution-treated and aged (STA) over the annealed Ti-6Al-4V and B120VCA was demonstrated previously in Table 1. The Ti-5Al-2.5Sn is much less efficient, exhibiting the lowest specific yield strength of the titanium alloys listed in Table 2. Consequently, Ti-6Al-4V (STA) was the ultimate choice of those alloys considered for the *ATS* motor chamber.

At the time of the redirection of the *Advanced SYNCOM* to the *Applications Technology Satellite*, fabrication of the 410 chromium steel chambers was already started. Thirty such chambers were produced for the program and were used in the developmental testing required. Such areas as hydrotest, static firings, static acceleration, vibration, firing under simulated high altitude, and storage were covered in developmental testing of the 410 chromium steel chambers. These were supplemented by tests on the Ti-6Al-4V chambers. Actual qualification and flight units were fabricated from Ti-6Al-4V.

Table 2. Alloy comparison for the *ATS* chamber[a]

Property	Material							
	B120VCA	Ti-5Al-2.5Sn	Ti-6Al-4V	Ti-6Al-4V	2014	2219	6061	Inconel 718
	Condition							
	Annealed	Annealed	Annealed	STA	-T6	-T81	-T6	Heat treated
F_{tu}, kpsi	130	115	135	160	70	60	42	185
F_{ty}, kpsi	125	110	125	150	60	42	35	150
F_{ty}/ρ, 10^3 in.	710	684	770	920	600	412	357	510

[a]Used in conjunction with Table 1.

III. DESIGN

Optimum design and development of the titanium chamber was accomplished by a team that combined the talents of engineering specialists in materials, structures, fabrication, and propulsion as well as the design specialist. The very successful component was the result. This section reports highlights of the chamber design including configuration, special design features, and structural considerations. Primary emphasis is given the titanium alloy chambers, although most of the structural considerations also apply to the steel chambers.

A. Configuration

During the preliminary design phase of the propulsion system, the general configuration of the motor chamber was developed. Many factors were considered in arriving at the chamber's final form. To reach, as nearly as possible, an optimum propulsion system, compromises between the shape of the propellant grain, the nozzle, and the chamber were necessary.

The chamber evolved as a short cylinder with ellipsoidal end closures, as shown in Fig. 1. Bosses in each end accommodate the igniter and the nozzle assemblies, and a cylindrical skirt provides a means for mounting the motor to the spacecraft. This shape was primarily selected to accommodate a cylindrically shaped propellant grain with an internal cylindrical bore. The grain was designed to allow changing the propellant charge by simply machining the bore to a larger diameter. A 2:1 ratio was selected for the curvature of the ellipsoidal closure to provide for a propellant grain with nearly flat ends, which is optimum, while not substantially reducing the efficiency of the chamber. The overall chamber dimensions are 28.78 in. long by 28.13 in. diam. This size was dictated by the amount of propellant required, 760 lb.

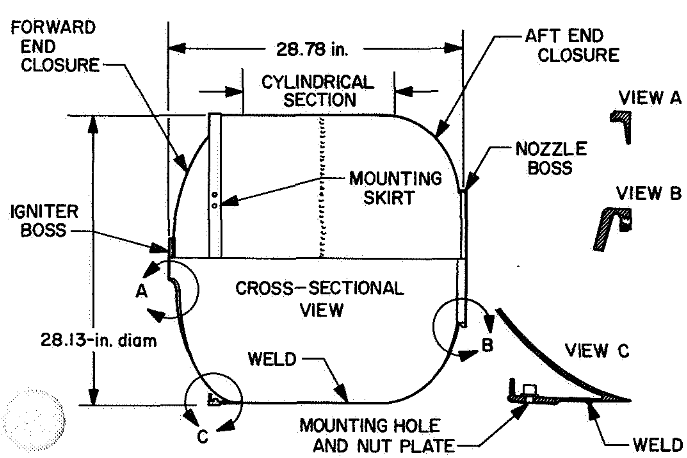


Fig. 1. Chamber configuration, side view

The configuration of the nozzle boss was chosen primarily to allow submerging the nozzle approximately 8½ in. into the chamber, thus accommodating a fully expanded nozzle without unduly increasing the length of the motor. If the nozzle were not submerged, the moment of inertia of the spacecraft in the pitch direction would be so increased as to cause a greater demand on its attitude control system. Enlarging the nozzle boss to accept a submerged nozzle increases the weight of the chamber; however, the overall result is a saving in total spacecraft weight.

From Fig. 1, it can be noted that the nozzle is attached by bolts to a flange turned outward from the centerline of the chamber. This was done to allow through holes for accepting the nozzle bolts. Holes passing entirely through the boss were used for two reasons: first, blind holes can trap propellant during processing which, if not properly removed, can explode when a bolt is tightened into the hole; and second, it is very difficult to tap blind holes in titanium and achieve a precision thread. Alternate means, such as through holes on a flange turned inward, would require the hole to be sealed—a difficult problem in a rocket motor. Thirty-six 10-32 bolts hold the nozzle to the chamber. The large number of relatively small sized bolts are used to keep the nozzle boss flange narrow and thin and, thereby, minimize weight.

Location of the igniter boss in the head end of the chamber is required because the propellant grain can best be ignited from that end. It can be noted from Fig. 1 that the size of this boss is fairly large, thus allowing assembly of the igniter unit into the motor through this opening. The boss was externally threaded in this application because it provided the simplest and lightest-weight design.

The concept of a skirt for mounting the motor to the spacecraft was evolved in cooperation with the spacecraft contractor, Hughes Aircraft Company. From a chamber-efficiency standpoint, this is the best way to mount the motor, since the major structural loads are, thereby, transmitted directly to the spacecraft. The skirt is precision machined to mate into a precision collar on the spacecraft and is held in place by sixteen ¼-in.-diam bolts arranged in 8 pairs equally spaced around the circumference (the spacing being dictated by the structural design of the spacecraft). To aid in achieving precision roundness in the skirt, a thin flange was added to stiffen it in the radial direction. This proved very successful as the maximum out-of-roundness was held to less than 0.001-in. total indicator reading (TIR). Floating nut plates were riveted to the skirt at each hole location to make assembly to the spacecraft as simple as possible.

B. Design Features

Basically, the chamber is designed to be machined from a pair of bell-shaped closed-die forgings, each comprising half of the chamber shell. A third forging is used for the mounting skirt. This method of construction was selected to minimize the amount of welding required for assembly.

By using closed die forgings, it was possible to machine both the igniter and nozzle bosses integral to the forging. In addition, it was possible to machine a small lip onto the forward closure on which the mounting skirt could be welded, thereby isolating this weld from a highly stressed area of the chamber. Thus, only two welds were required to assemble the chamber—one in the center of the cylindrical section and the other attaching the mounting skirt. Conversely, chambers made from sheet metal, as were the 410 chromium steel chambers, required six welds, five of which were located in highly stressed areas.

Associated with welds in titanium are problems of distortion, cracks, porosity, inclusions, and generally poor properties. In addition, welds in Ti-6Al-4V alloy suffer from low-fracture toughness, meaning they have little resistance to the propagation of cracks or crack-like defects. Needless to say, minimum welding promotes higher reliability.

In addition to fewer welds, another advantage gained in using forgings is the ability to tailor the thickness of the shell to the stress at any given point. Weight is saved by making the shell thicker in highly stressed areas and

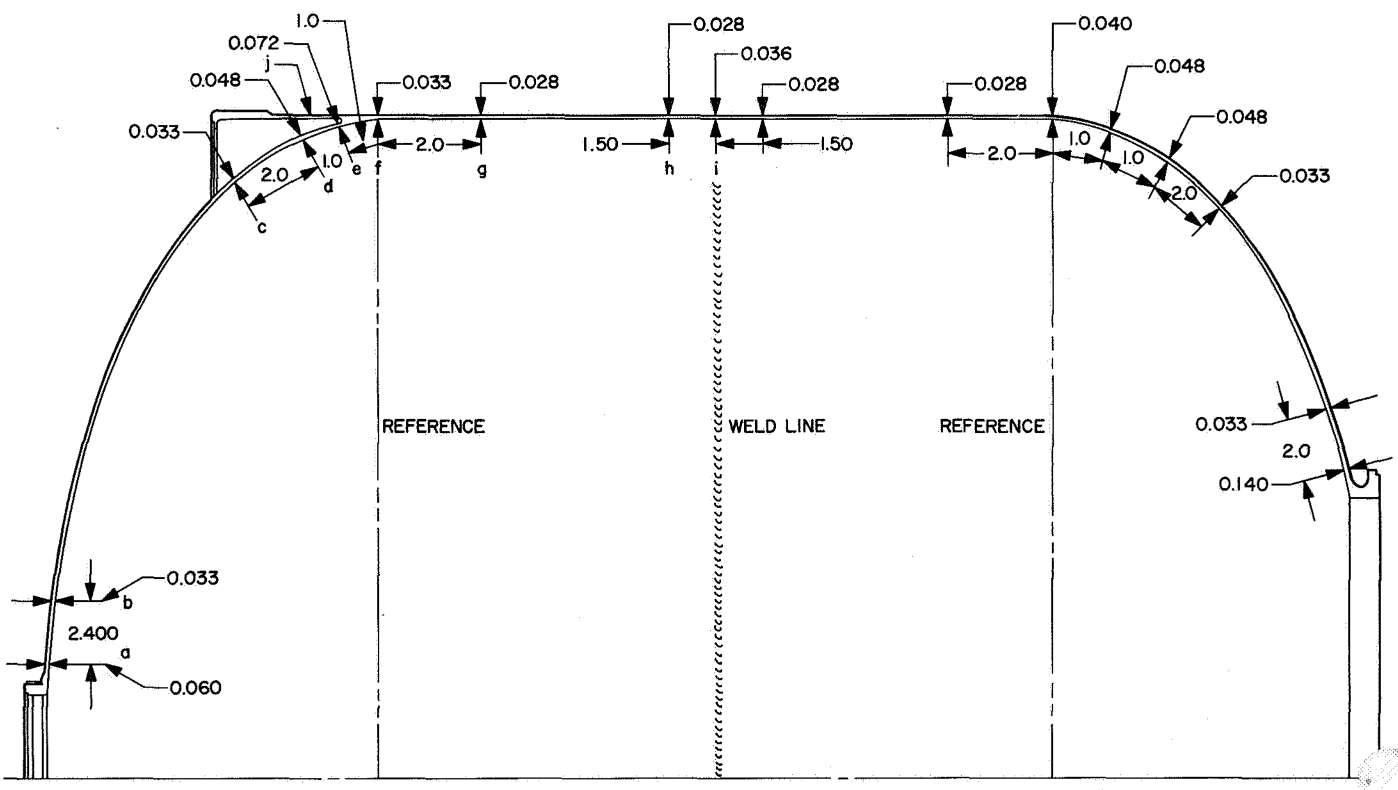


Fig. 2. Cross-sectional view of chamber showing variation in thickness required to optimumly match thickness to membrane stresses in typical areas

thinner where stress is less, instead of using sheet metal construction, in which thickness is nominally constant throughout. To gain the greatest advantage in weight saving, the chamber thickness is varied as shown in Fig. 2. Further discussion of the thickness variation appears under the heading, Structural Considerations.

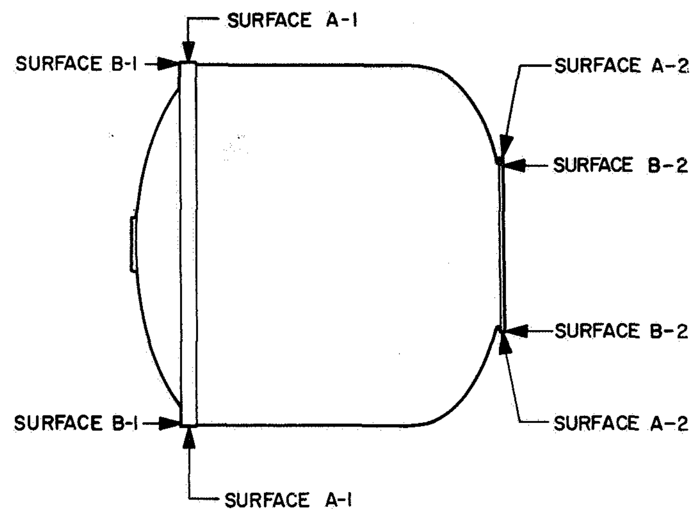
Varying the thickness of a shell machined from a forging is no special production problem because the contour machining methods used for shaping the part easily accommodate thickness control. The equipment needed to accomplish the required machining is standard and readily available. Any lathe or vertical boring mill, equipped with precision tracer control that will accommodate a forging of this size, can machine the shell. Special holding fixtures are required to position the forging on the machine, but are of conventional design.

The configuration of the joint used to attach the mounting skirt (as shown in Fig. 1) locates the weld 0.43 in. away from the point of tangency with the forward-end closure. The tangency point is a highly stressed area; thus, to locate a weld at this point, with its associated poor properties and distortion, would be dangerous. Therefore, the weld was moved far enough to isolate the heat-affected zone (of the weld) and its associated poor properties from the highly stressed shell membrane.

To minimize weight and to meet the propulsion system alignment requirements, very tight dimensional tolerances were necessary. The weight of the shell is significantly affected by the machining tolerances placed on the thickness. The selected tolerance of ± 0.0025 in. is about $\pm 8\%$ of the average shell thickness. Assuming the chamber is machined to the middle of the tolerance, this corresponds to an additional weight of 2 lb caused by the tolerance. Tighter tolerances have been attempted to further reduce weight but are beyond the state of the art using existing machine tools.

Close tolerance was also required on alignment between the nozzle boss and the mounting skirt to assure proper positioning of the motor thrust axis with the spacecraft. Figure 3 shows the alignment dimensions. The actual production units were machined on the critical surfaces as a final operation to ensure meeting these dimensions.

A third area where unusual dimensional control was required is in the roundness of the cylindrical section of the shell. Because the motor is required to be dynamically balanced about its axis, it was necessary to hold the cylindrical section round to within 0.060 in. Since the propellant is cast to the shape of the chamber, any out-of-roundness causes an associated shift of propellant, which results in considerable out-of-balance. The only means of correcting for out-of-balance is to add weights to counteract the unsymmetrical condition. Since this increases the total weight of the motor, it must be minimized.



ALIGNMENT REQUIREMENTS

1. SURFACE A-1 ROUND TO WITHIN 0.005 in.
2. SURFACE B-2 PERPENDICULAR TO SURFACE A-1 WITHIN 0.003 in.
3. SURFACE B-2 PARALLEL TO SURFACE B-1 WITHIN 0.003 in.
4. SURFACE A-2 CONCENTRIC TO SURFACE A-1 WITHIN 0.003 in.

Fig. 3. Critical dimensions required for proper thrust alignment

C. *Structural Considerations*

Prior to the structural design and analysis of the chamber, a set of structural design criteria was established. Most criteria were established by the motor characteristics and spacecraft requirements; however, tradeoffs between other criteria were required to obtain an optimum motor. The motor ellipsoidal ends were allowed to reach 200°F because the insulation required to reduce the temperature would weigh more than the additional titanium alloy required to provide structural integrity at 200°F. The design criteria for the chamber are stated below:

Operating pressure	270 psig

Proof pressure at operating temperature	285 psig
Minimum 0.2% offset yield pressure at temperature	300 psig
Minimum buckling pressure	340 psig
Maximum temperature (at maximum pressure) of ellipsoidal domes	200°F
Maximum temperature (at maximum pressure) of cylinder	110°F
Minimum yield strength (0.2% offset)	
at ambient temperature	150 kpsi
at 110°F	144 kpsi
at 200°F	129 kpsi
Minimum weld strength	140 kpsi
Modulus of elasticity at 200°F	14.6×10^6 psi

The dynamic and static environments of the motor are covered in the section of this report on testing. To prevent dynamic coupling with the spacecraft, it was required that the motor have a resonant frequency greater than 50 cps in the lateral direction and 130 cps in the axial direction. The critical design criteria for the chamber shell is the internal pressure, while for the skirt it is the resonant-frequency requirement. All handling loads were insignificant.

The structural considerations in the design of the forward half of the chamber are similar to the aft half of the chamber. The membrane load in the chamber is obtained from the chamber geometry and internal pressure; consequently, the chamber thickness required for membrane load is easily obtained. Additional chamber thickness is required for bending loads caused by variation in shell thickness, compatibility requirements at ellipsoid–cylinder interface, high compressive hoop loads that may cause buckling, and reduced material properties in the heat-affected zone near the welds. To minimize bending stresses, the wall thickness is tapered over the approximate length $2\sqrt{R\,t_{ar}}$ where

R = radius of curvature of the chamber

t_{ar} = average thickness in tapered region

The bending load caused by the igniter boss in the forward ellipsoid increased the chamber thickness to 0.060 in. at the boss (position **a** of Fig. 2) which tapers to 0.033 in. (position **b** of Fig. 2). The thickness of 0.033 in. is required for the membrane load, plus the small bending load caused by the linear taper. The thickness is increased to 0.048 in. (position **d** of Fig. 2) to prevent buckling caused by large compressive hoop loads. To obtain the required thickness to prevent buckling the following described method was used.

The governing equation predicting buckling stress is assumed to be of a form equivalent to buckling of a cylinder under axial load or of a sphere under external pressure. The equation is:

$$\sigma_b = -\frac{kEt}{R\,[3\,(1-\mu^2)]^{1/2}}$$

where

σ_b = buckling stress

E = modulus of elasticity at operating temperature

t = thickness

μ = Poisson's ratio

k = experimental factor

The maximum compressive hoop stress exists in the ellipsoid at a position 1.50 in. from the ellipsoid–cylinder junction, where the pressure–stress relation can be approximated by:

$$p = -\frac{\sigma t}{0.7r}$$

where

r = major radius of ellipsoid = 14.0 in.

p = internal pressure

By equating the stress values of the two equations and defining $R' = R/k$,

$$p = \frac{Et^2}{0.7R'r\,[3\,(1-\mu^2)]^{1/2}}$$

Hydrotest of geometrically identical stainless steel chambers resulted in a minimum buckling pressure of 329 psig. Other pertinent data of this test are:

$E = 30 \times 10^6$ psi

$\mu = 0.3$

$t = 0.033$ in.

From the data obtained from the stainless steel chambers, it was determined that $R' = 6.1$ in. for this 2:1 ellipsoidal geometry. If $R' = 6.1$ in., the E of titanium at 200°F (14.6×10^6 psi), and the buckling pressure criteria of 340 psig are used, the required thickness determined for the chamber is 0.048 in. The buckling stress at room temperature for $t = 0.048$ in. is -74 kpsi.

The chamber thickness at the supporting ring intersection was approximately the same thickness as the supporting ring to maintain approximately the same stiffness in all segments. The supporting ring is tangential to the chamber to minimize bending caused by the vibration and static loads, while the chamber thickness is gradually tapered to minimize bending stresses caused by loads through the ring and internal pressure in the chamber. The thickness of 0.033 in. is required (position f of Fig. 2) because of bending loads created by displacement compatibility between the ellipsoid and the cylinder. The chamber is tapered to 0.028 in. in the cylindrical section (position g of Fig. 2), the minimum thickness required for the membrane loads. The higher bending stresses created by the taper are accounted for by the Von Mises yield criteria for a 2:1 stress field which indicates an increase in yield strength of about 14%. The thickness is increased from 0.028 to 0.036 in. (position i of Fig. 2) to account for the decrease in material properties in the heat-affected zone and the additional bending load caused by the variation in shell thickness.

The weld joint was made in the supporting ring because the governing design criteria for the ring is stiffness, or the minimum resonant frequency. Thus, lower material properties are acceptable. The ring had to be long enough for flexibility to minimize bending loads caused by possible radial loads at the bolt circle, sufficiently short to minimize weight and to prevent buckling due to axial compressive loads and to increase the first resonant frequency. The skirt was thickened at the bolt circle to obtain more bearing area for the transfer of loads through the bolts.

Other areas requiring structural consideration are the igniter boss threads and the bolts in the nozzle boss. Little difficulty existed in obtaining adequate strength in the igniter boss, but structural tradeoffs were necessary in the nozzle boss. The axial loads in the bolts are fixed, but the bending loads in the bolts can be decreased by increasing the distance from the centerline of the bolt to the outer diameter of the boss. Larger bolts can be used to provide additional strength. Both increasing the distance from the bolt to the outer edge of the boss and increasing bolt size directly increase the weight of the motor assembly. Thirty-six high-strength 10-32 bolts were placed closely together around the boss.

IV. FABRICATION

Fabrication of the *ATS* chamber was accomplished under a fixed-price contract with Pressure Systems, Incorporated, of Los Angeles. Twenty-three chambers were produced in accordance with the requirements set forth in JPL Specification GOM-50369-DTL (see Appendix A) and according to JPL Drawings J 3901790, J 3901791, J 3901792, and J 3901793 (Appendix B). The contract schedule called for delivery of one chamber every 15 days after receipt of the first one in May 1965, thus resulting in a completion date in April 1966. It is noteworthy to mention the high degree of success achieved in the fabrication of these chambers as illustrated by the following facts regarding the program:

1. Delivery of the last unit occurred in December 1965, four months ahead of schedule.
2. Only three chambers were accepted with noted minor discrepancies to the above mentioned specifications and drawings; these were assigned to specific developmental tests.
3. The remaining 20 chambers were acceptable for flight use.
4. The last 18 of the 20 nondiscrepant chambers were produced in succession.

A flow chart of the steps used in fabricating the chambers appears in Fig. 4. For simplicity, specific details regarding fabrication and inspection of the chambers have been excluded from the figure, but are covered in the text.

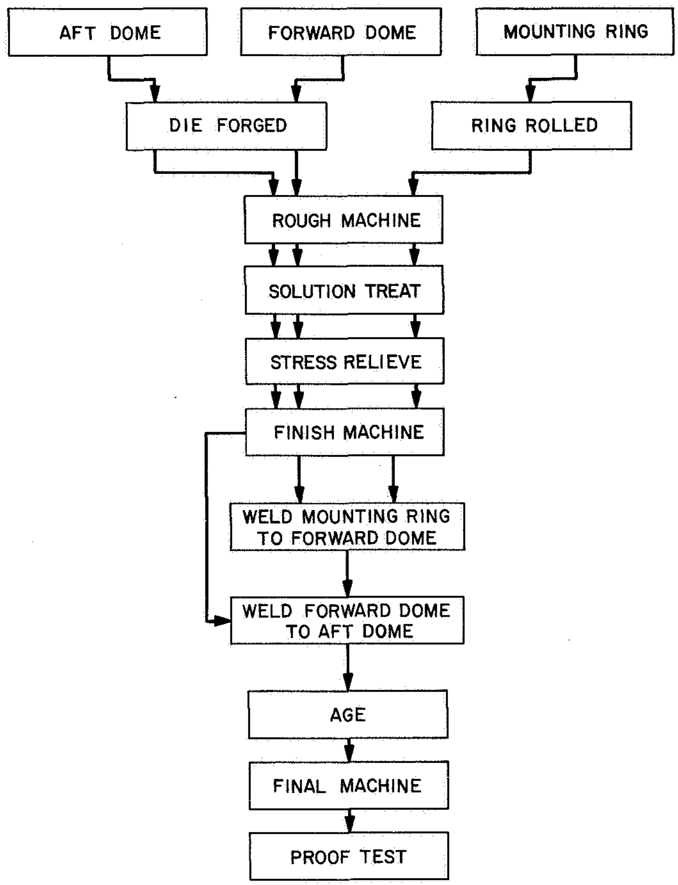


Fig. 4. General fabrication procedure for *ATS* chamber

Table 3. Requirements for the Ti-6Al-4V used for the *ATS* apogee motor chamber

Chemical composition	
Aluminum	5.50 - 6.50%
Vanadium	3.50 - 4.50%
Iron	0.20% max
Carbon	0.10% max
Nitrogen	0.05% max
Oxygen	0.15% max
Hydrogen	0.0125% max
Other elements, Total	0.040% max
Mechanical properties (After forging and heat treatment)	
Ultimate strength, kpsi	160 - 175
Yield strength (0.2% offset), kpsi	150 min
Elongation (gage length = 4 diam), %	10 min
Reduction in area, %	30 min

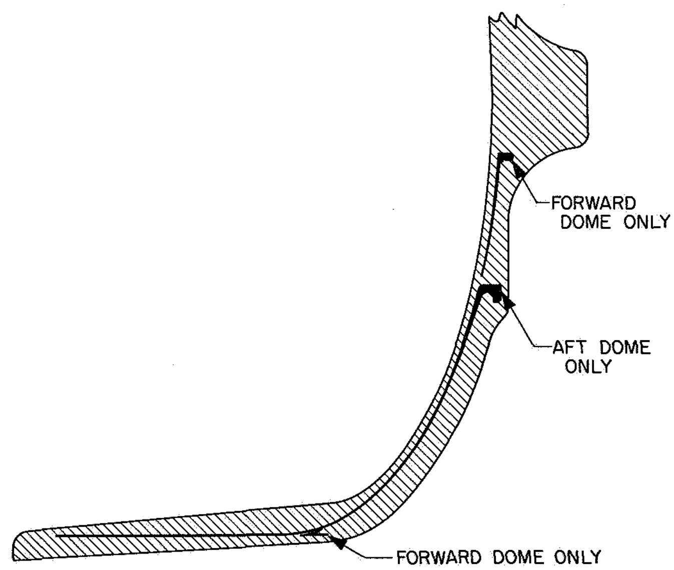


Fig. 5. Forging configuration showing location of aft and forward domes on machining

A. *Materials*

The starting material for forgings was required to meet the chemical composition shown in Table 3 and was required to have an upper beta transus in excess of 1810°F. Table 3 also shows the properties required of the material after forging and heat treatment. In addition, the material was required to pass ultrasonic and penetrant inspection per MIL-STD-271. Shown in Table 4 are the properties and composition of heats used in fabricating the chambers.

B. *Dome Forgings*

The dome forgings were produced by Arcturus Manufacturing Company to the configuration shown in Fig. 5, using the closed-die technique. The starting material for each dome has a mult weighing approximately 350 lb which had been saw-cut from a 14-in.-diam octagonal bar. Each mult was serialized with respect to heat, ingot, and location in the ingot, allowing traceability of a specific dome back to original stock. The material was forged after heating to 1725 ±25°F, requiring eight to nine draws to produce a dome. Figures 6, 7, and 8 show steps in the forging process. Subsequent to forging, the domes were cleaned to remove scale and surface defects.

Table 4. Properties and composition of Ti-6Al-4V used in fabrication of motor chambers

Chemical composition	Heat No.					
	Used for dome					For rings
	8904	8903	8819	9568	9746	8202
Aluminum	6.3	6.4	6.4	6.4	6.2	6.2
Vanadium	4.1	4.2	4.3	4.2	4.1	4.1
Iron	0.10	0.11	0.10	0.15	0.12	0.12
Carbon	0.023	0.022	0.023	0.023	0.022	0.023
Nitrogen	0.014	0.014	0.013	0.013	0.014	0.017
Oxygen	0.15	0.13	0.14	0.14	0.14	0.15
Hydrogen	0.005 - 0.006	0.007 - 0.009	0.005	0.006 - 0.007	0.007 - 0.008	0.010 - 0.011
Mechanical properties (after heat treatment)						
F_{tu}, Top, radius[a]	178.9	176.6	172.8	174.2	170.8	—
tangent	179.3	172.6	177.0	174.8	175.1	174.8
Bottom, radius	175.4	171.0	—	173.3	169.3	—
tangent	171.2	174.1	—	177.7	171.2	169.4
F_{ty}, Top, radius	164.4	162.5	158.4	157.3	157.4	—
tangent	166.0	157.6	165.7	157.3	160.6	160.2
Bottom, radius	162.5	159.7	—	156.8	154.4	—
tangent	158.4	162.2	—	162.0	156.3	163.4
e, Top, radius	13.0	10.0	14.0	13.0	12.5	—
tangent	10.0	13.0	10.0	12.0	11.0	16
Bottom, radius	11.5	11.5	—	14.0	14.0	—
tangent	10.0	10.0	—	10.0	11.0	14.5
RA Top, radius	30.5	25.9	26.5	28.1	32.5	—
tangent	25.1	37.7	29.3	28.1	33.8	50.7
Bottom, radius	27.5	50.3	—	35.7	38.7	—
tangent	42.5	27.8	—	27.2	34.2	38.2
Upper beta transus						
Temp Top	1815-1825	1810-1820	—	1810-1820	1820-1830	1835-1845
Bottom	1810-1820	1810-1825	—	1810-1820	1810-1815	—

[a] Locations apply only to domes.

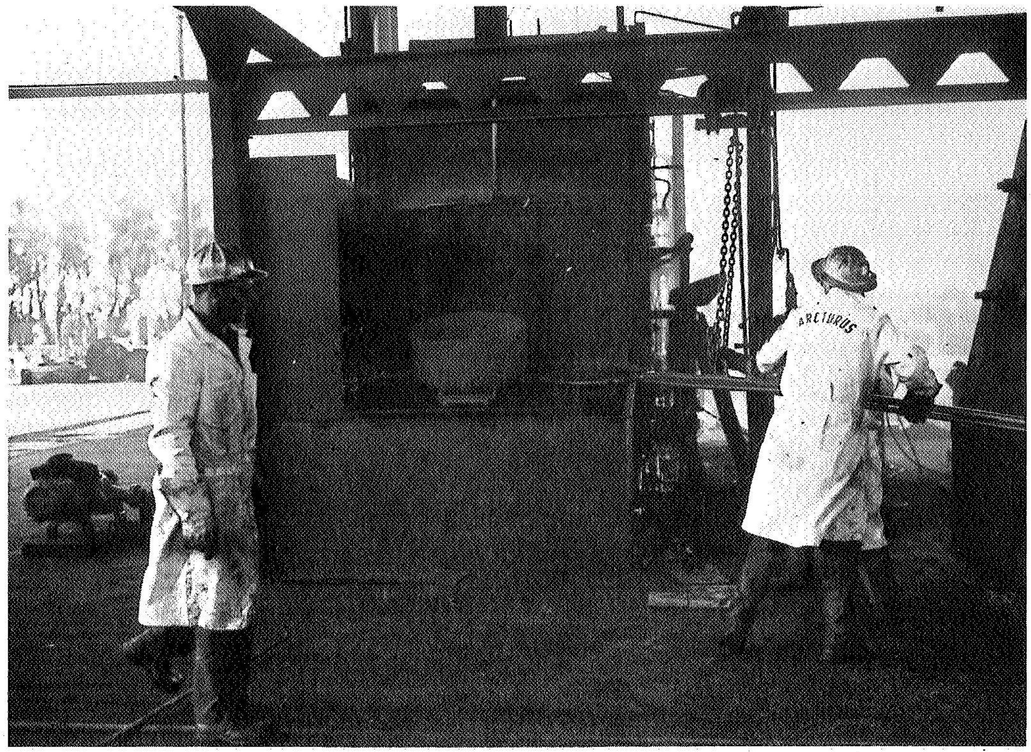


Fig. 6. Dome, after heating, for additional working

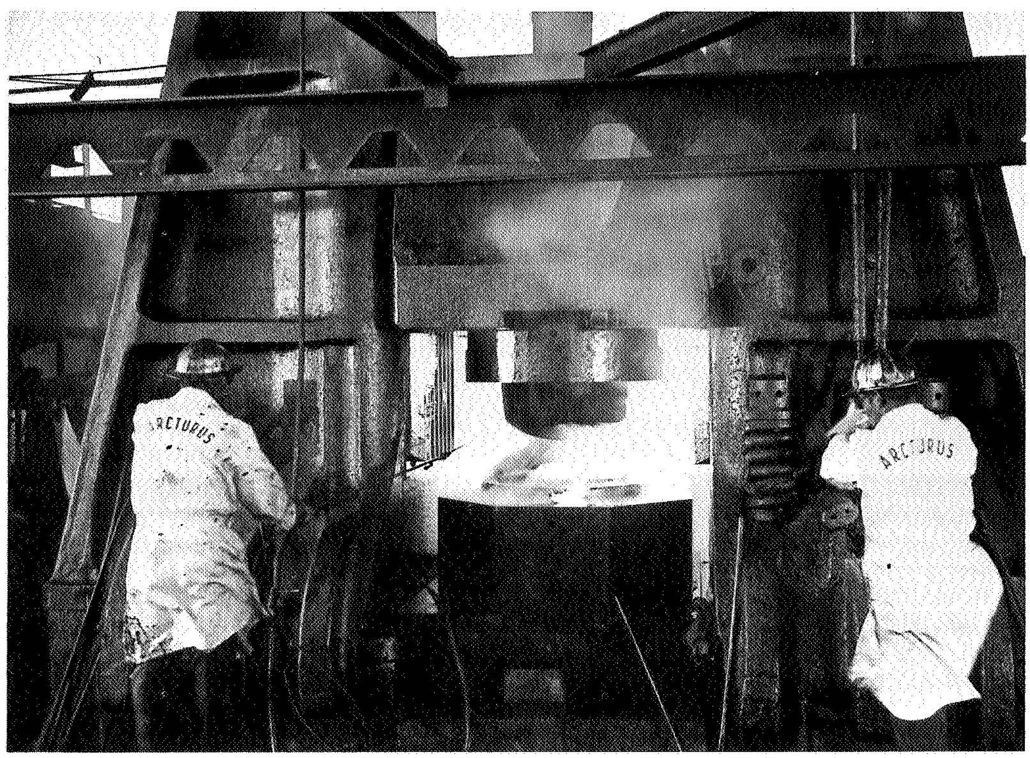


Fig. 7. Forging operation in progress

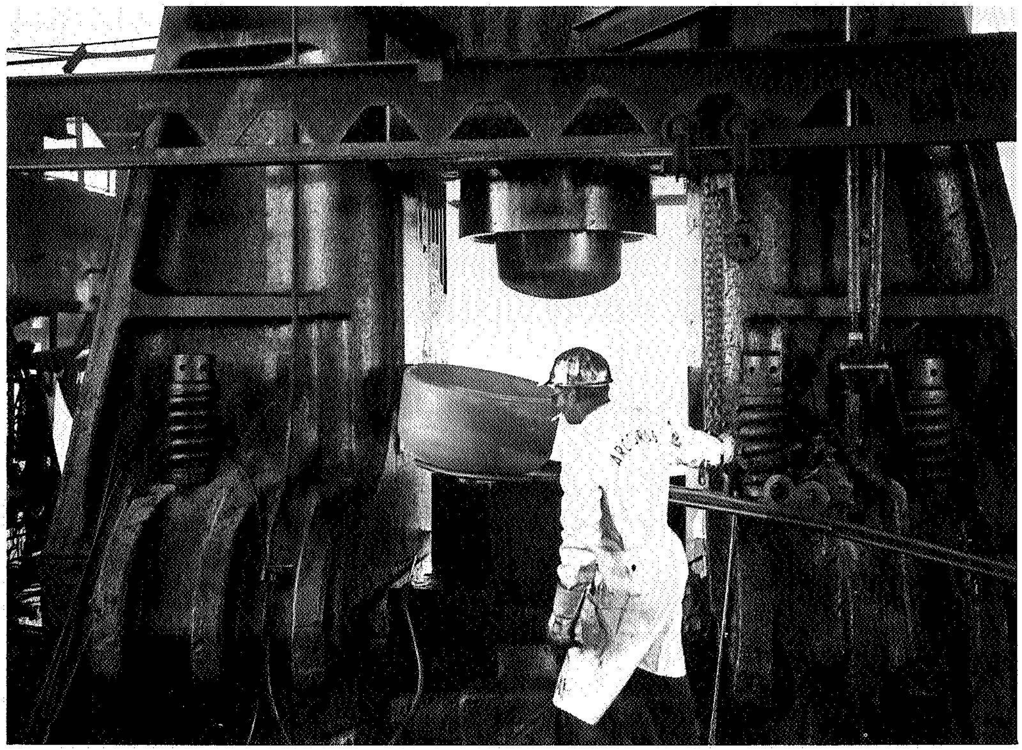


Fig. 8. Finished forging on removing from die

Qualification of forgings was required before and during further processing. Specifically there were three types of qualifications: (1) forging flow, (2) heat qualification, and (3) individual forging qualification.

The first forging produced was sectioned on a plane through the axis of revolution and etched to show the forging flow lines. It was required that all flow lines be parallel to the outside surface of the forging. Qualification with respect to heat and for individual forgings was accomplished during processing of the domes.

Heat qualification, which was required on each new ingot used in forging the domes, consisted of metallographic examination and tensile testing of samples taken from the center and two end forgings of each bar. The microstructure was required to be equiaxed, fine-grained alpha-beta with a maximum of 30% primary alpha (maximum grain size = 6). The tensile specimens were sectioned from the forgings after solution treatment and stress relieving. Domes selected for heat qualification were sectioned according to Figs. 9 and 10. The center forging was destroyed by sectioning; however, the selective manner in which specimens were taken from the end forgings permitted them to be used as aft domes. The specimens were required to meet the properties specified in Table 3 after aging. The results of all heat qualification tests are shown in Table 5. Included are qualification data for the heat used in fabricating the ring forging.

Individual qualification consisted of dimensional and ultrasonic inspection, microstructural examination and evaluation of tensile properties during the processing of the domes. The microstructural requirements for each dome were as described above for the domes used in heat qualification. One tensile specimen was taken from the prolongation at the open end of the forging and accompanied the forging through the stress-relieving and aging cycles, after which it was tested and required to meet the properties in Table 3. In addition, aft dome forgings had a tensile specimen taken from the area of the nozzle boss for qualification. The results of individual-forging qualification appear in Table 6.

After microstructural analysis, the domes were rough machined, leaving 0.150 in. per side (ID and OD). Machining sources used during the fabrication were Juhl Manufacturing and Manlove Manufacturing. Rough machining was followed by dimensional inspection and ultrasonic inspection per MIL-STD-271 and JPL Specification GOM-50369-DTL. The diameter of the dome was then measured and recorded prior to solution treatment.

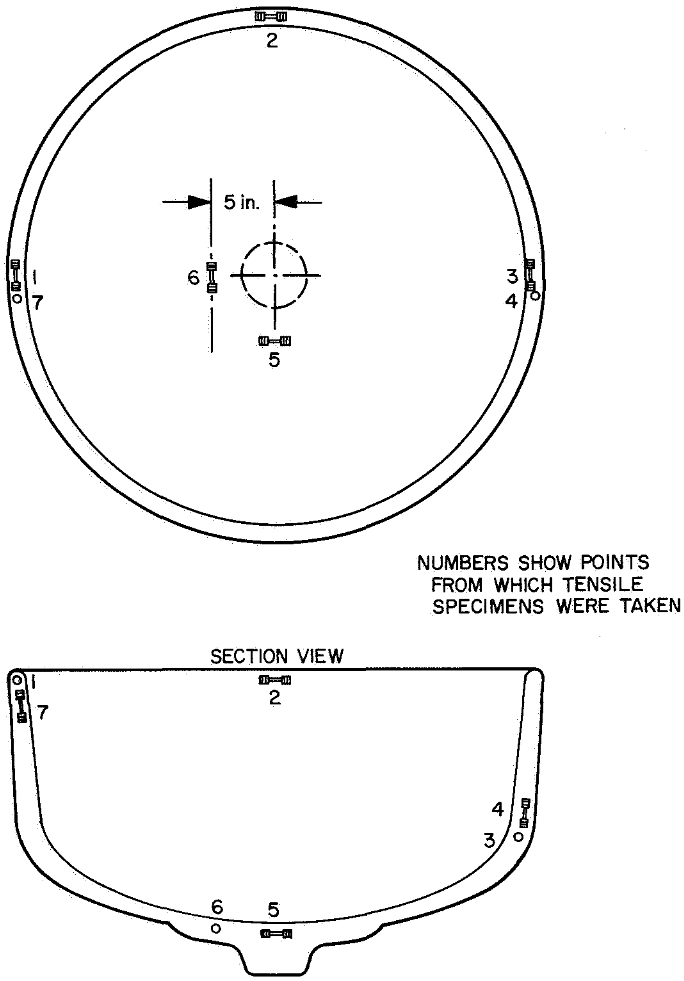


Fig. 9. Center qualification forging

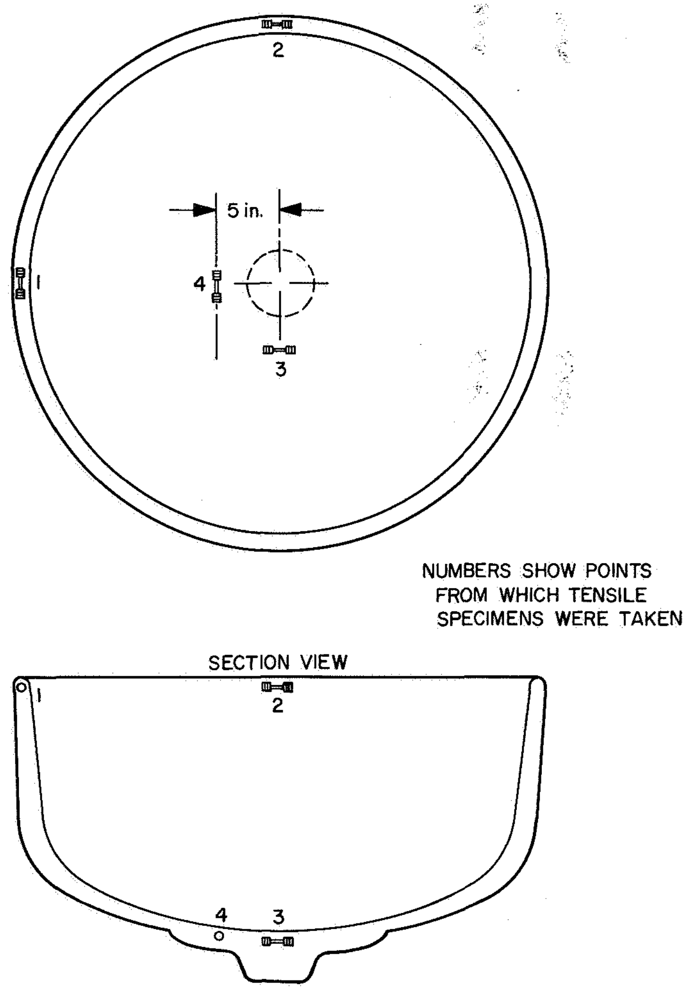


Fig. 10. End qualification forging

Table 5. Results of heat qualification tests

Heat No.	Forging Location[a]	F_{ty}, kpsi	F_{tu}, kpsi	e, %	RA, %	Heat No.	Forging Location[a]	F_{ty}, kpsi	F_{tu}, kpsi	e, %	RA, %
8904[b]	Center	156.7	167.0	14	46.5	8819[c]	Center	156.4	166.0	13	38.5
	(8)	152.3	163.2	15	47.1		(33)	158.4	167.9	14	48.1
		154.3	166.2	14	45.9			165.4	174.8	13	47.1
		159.0	167.2	14	44.7			165.1	173.7	13	40.5
		152.7	164.0	13	38.8			160.8	171.3	12	33.3
		150.3	161.4	14	40.0			158.3	167.8	12	41.2
		161.4	168.6	14	41.2			163.5	173.7	14	46.7
	End	155.9	164.5	13	37.1		End	159.8	170.0	11	37.0
	(1)	153.5	163.2	14	40.6		(31)	160.6	169.8	10	33.8
		152.7	163.4	12	32.4			154.3	166.7	11	35.1
		152.7	164.4	12	38.8			156.3	167.4	12	41.2
	End	156.3	163.9	13	43.7		End	161.4	170.4	12	48.9
	(15)	159.1	166.7	13	37.1		(35)	161.9	169.5	11	33.8
		158.3	167.1	13	37.7			162.2	172.6	10	33.8
		155.1	164.2	11	36.4			163.5	173.5	12	32.5
8903[c]	Center	152.4	164.1	13	46.6	9568[c]	Center	168.3	177.4	13	41.9
	(23)	158.5	170.7	12	34.8		(43)	167.1	176.4	12	38.9
		161.3	172.7	12	37.5			163.5	178.0	11	35.9
		164.1	173.1	11	35.1			166.1	174.8	11	39.0
		157.8	170.7	12	31.9			166.7	176.0	11	30.7
		157.8	170.9	11	33.9			164.7	174.8	11	30.7
		163.9	174.9	10	36.1			163.5	177.4	11	35.9
	End	161.0	172.4	13	45.3		End	165.9	173.9	13.5	46.7
	(16)	161.3	171.5	10	37.9		(36)	167.1	174.7	13.5	45.5
		167.6	168.7	12	36.0			156.3	166.5	12	41.3
		156.3	167.3	11	35.9			157.5	166.4	12	35.6
	End	161.0	170.4	12	43.5		End	163.0	172.8	13	48.3
	(30)	159.0	168.1	12	38.7		(44)	165.8	174.5	12	39.4
		156.0	166.1	13	34.5			158.6	170.8	10	30.8
		157.6	169.9	12	43.2			159.8	171.0	10	30.5

[a] Numbers in parentheses refer to ID numbers of forging mults for dome forgings.

[b] Heat treatment for 8904:
Forgings (8) & (1) solution treat @ 1675°F, age 2 hr @ 1050°F
Forging (15) solution treat @ 1725°F, age 4 hr[e] @ 1050°F

[c] Heat treatment for 8903, 8819, 9568 and 9746:
Solution treat @ 1675°F, age 4 hr @ 1050°F

[d] Heat treatment for 8902:
Solution treat @ 1725°F, (a) Age 2 hr @ 1050°F
(b) Age 3 hr @ 1050°F
(c) Age 4 hr @ 1050°F

[e] The 4-hr aging treatment consisted of 2-hr stress relief, plus 2-hr aging cycle.

Table 5. (Cont'd)

Heat No.	Forging Location[a]	F_{ty}, kpsi	F_{tu}, kpsi	e, %	RA, %
9746[c]	Center	164.0	171.9	11	37.2
	(53)	158.7	166.9	14	51.7
		156.4	171.1	14	50.3
		156.1	168.8	13	43.5
		156.3	167.3	11	31.9
		157.6	167.1	12	37.8
		165.8	173.8	11	38.9
	End	167.9	176.4	12	42.5
	(45)	164.2	172.4	10.5	30.4
		160.3	168.9	10	36.5
		161.1	169.7	12	36.5
	End	159.9	168.3	12	40.1
	(54)	163.6	173.5	10	30.1
		157.6	169.1	11	33.9
		157.2	168.1	10	30.1

Heat No.	Forging Location[a]	F_{ty}, kpsi	F_{tu}, kpsi	e, %	RA, %
8202[d]	Ring	156.0	164.8	14	49.3
	(a)	156.3	168.7	15	50.7
		156.3	166.1	16	53.7
		158.2	167.8	17	49.5
	(b)	157.5	166.4	16	53.3
		157.5	167.8	15	49.5
		155.1	163.6	15	49.9
		155.9	165.8	16	45.9
	(c)	155.5	165.3	14	49.1
		154.3	165.9	15	45.5
		153.5	164.3	15	51.3
		153.9	165.5	14	48.5

[a] Numbers in parentheses refer to ID numbers of forging mults for dome forgings.

[b] Heat treatment for 8904:
Forgings (8) & (1) solution treat @ 1675°F, age 2 hr @ 1050°F
Forging (15) solution treat @ 1725°F, age 4 hr[e] @ 1050°F

[c] Heat treatment for 8903, 8819, 9568 and 9746:
Solution treat @ 1675°F, age 4 hr @ 1050°F

[d] Heat treatment for 8902:
Solution treat @ 1725°F, (a) Age 2 hr @ 1050°F
(b) Age 3 hr @ 1050°F
(c) Age 4 hr @ 1050°F

[e] The 4-hr aging treatment consisted of 2-hr stress relief, plus 2-hr aging cycle.

Table 6. Results of individual forging qualification tests

Chamber No.	Heat No.	Forging ID[a]	F_{ty}, kpsi	F_{tu}, kpsi	e, %	RA, %
1	8904	13	156.3	169.3	12	37.1
		1	158.3	169.3	15	40.1
2		12	151.9	163.1	14	40.1
		14	156.3	166.7	14	39.5
		14B	155.1	166.1	12	38.3
3		4	161.0	170.4	12	42.9
		3	160.7	171.3	12	38.9
		3B	161.0	172.6	11	39.4

Chamber No.	Heat No.	Forging ID[a]	F_{ty}, kpsi	F_{tu}, kpsi	e, %	RA, %
4	8904	6	163.5	173.5	10	36.5
		5	159.7	169.9	12	43.4
		5B	158.7	170.1	10	33.3
5		9	156.0	164.8	14	52.7
		7	162.8	172.5	15	46.9
		7B	158.7	168.9	12	34.5
6	8903	10	157.5	165.8	14	53.3
		11	156.2	164.5	15	47.5
		11B	160.9	170.6	12	31.0

[a] B indicates a specimen taken from nozzle boss.
Others are taken from prolongation at girth.

Table 6. (Cont'd)

Chamber No.	Heat No.	Forging ID[a]	F_{ty}, kpsi	F_{tu}, kpsi	e, %	RA, %
7	8903	17	163.6	172.5	11	41.4
		16	162.4	170.7	12	36.0
		16B	158.7	168.7	12	36.5
8		29	160.7	171.1	11	38.9
		30	158.7	168.7	13	50.1
		30B	155.1	164.5	14	42.5
9		19	157.1	168.7	11	38.9
		18	158.0	166.7	11	43.8
		18B	159.1	168.7	11	34.5
10		20	158.9	169.7	13	40.3
		21	159.5	170.3	13	31.9
		21B	158.6	167.6	12	44.7
11		22	160.0	170.7	15	50.9
		24	160.3	171.7	13	37.1
		24B	158.5	169.5	11	39.1
12		26	160.0	169.7	10	31.3
		25	166.9	174.5	13	42.0
		25B	158.7	167.7	13	41.9
13		28	157.1	165.7	11	33.3
		27	159.9	168.3	13	42.5
		27B	156.7	167.4	12	34.4
14	8819	32	158.7	166.5	12	43.7
		31	161.7	170.3	10	30.1
		31B	160.6	168.4	11	41.2
15		34	163.6	172.3	13	45.5
		35	162.7	173.1	12	43.7
		35B	160.1	169.5	12	40.9
16	9568	42	164.8	173.3	12	39.6
		44	161.1	170.3	12	35.1
		44B	158.4	168.1	12	33.9
17		37	162.4	173.7	12	42.6
		36	166.5	174.8	13	41.0
		36B	157.6	169.1	13	39.6
18		39	164.8	173.5	13	39.0
		38	168.3	174.7	13	47.9
		38B	163.6	173.7	12	35.4
19		41	163.3	173.1	12	30.8
		40	162.4	171.9	11	42.0
		40B	164.0	174.7	10	31.3
20	9746	49	161.2	170.1	11	37.2
		45	163.2	172.9	12	37.2
		45B	163.5	173.9	11	38.3
21		50	158.9	167.8	13	48.7
		54	162.5	172.3	13	36.7
		54B	158.5	170.3	12	32.8
22		51	163.5	170.7	12	43.1
		47	164.1	173.9	12	40.7
		47B	160.0	170.1	12	42.0
23	9746	55	167.1	174.3	13	39.5
	&	15	160.0	168.5	13	44.4
	8904	15B	161.1	171.1	11	33.9

[a]B indicates a specimen taken from nozzle boss.
Others are taken from prolongation at girth.

The solution-treatment range permitted was 1600 to 1750°F for 1 hr, followed by water quenching. Actual solution treat temperatures appear in Table 7. The specific temperatures were determined to meet the required tensile properties. Figures 11 and 12 depict a typical forging entering the heat-treat furnace and a forging on the quench rack, respectively. After solution treatment, the diameter at marked areas was again measured to

Table 7. Heat-treatment cycles used for each unit

Chamber No.	Solution treatment	Stress relieve	Age
0001 and 0002	1 hr at 1675°F, water quenched	None	2 hr at 1050°F, air cooled
0003 through 0023	1 hr at 1725°F, water quenched	2 hr at 1050°F, air cooled	2 hr at 1050°F, air cooled

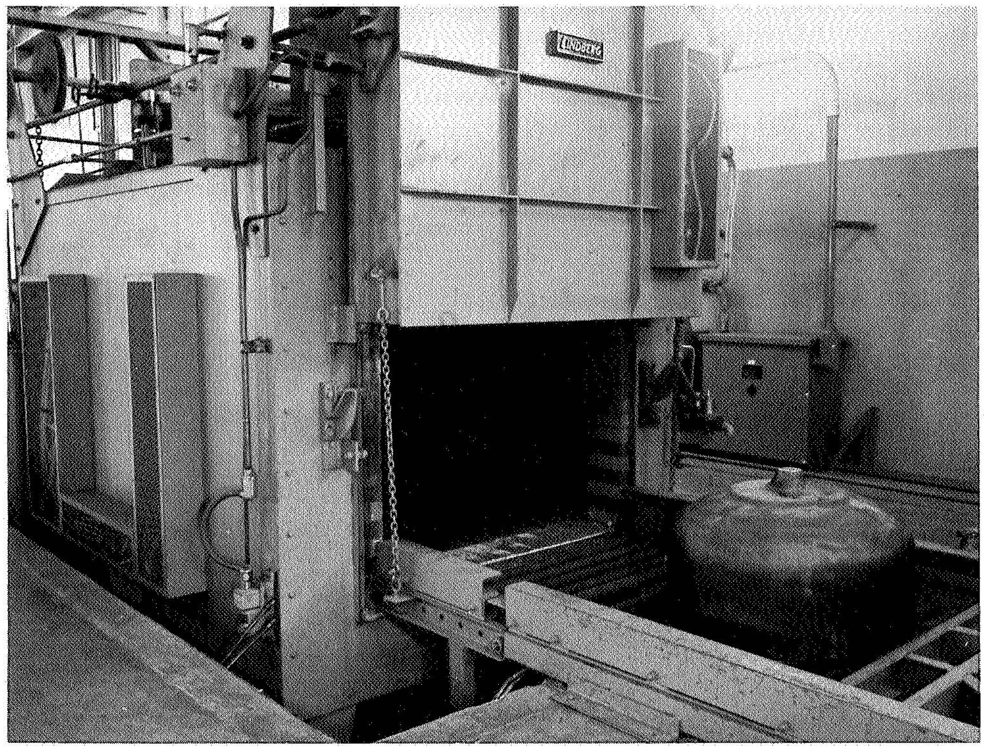


Fig. 11. Forging ready to be inserted into the heat treat furnace

Fig. 12. Forging on quench rack

determine the amount of distortion developed. Following inspection, stress-relieving was carried out, the range permitted being 950–1150°F for 2 hr followed by air cooling. See Table 7 for actual stress-relieving cycle. It was at this point in processing that tensile specimens were sectioned for qualification.

As stated previously, the ingot end qualification forgings were designated aft domes. Where possible, forward and aft domes for a given chamber were taken from the same ingot. In those cases where this could not be done, the forgings from different heats were matched as closely as possible on the basis of chemistry and mechanical properties.

Subsequent to stress relieving, the domes were finish machined to the configuration shown in Figs. 13 and 14. This was done by first removing about 0.050 in. on the OD, followed by finish machining the contour of the ID, then finishing the OD by locating from the ID. The finished domes were then dimensionally inspected to meet

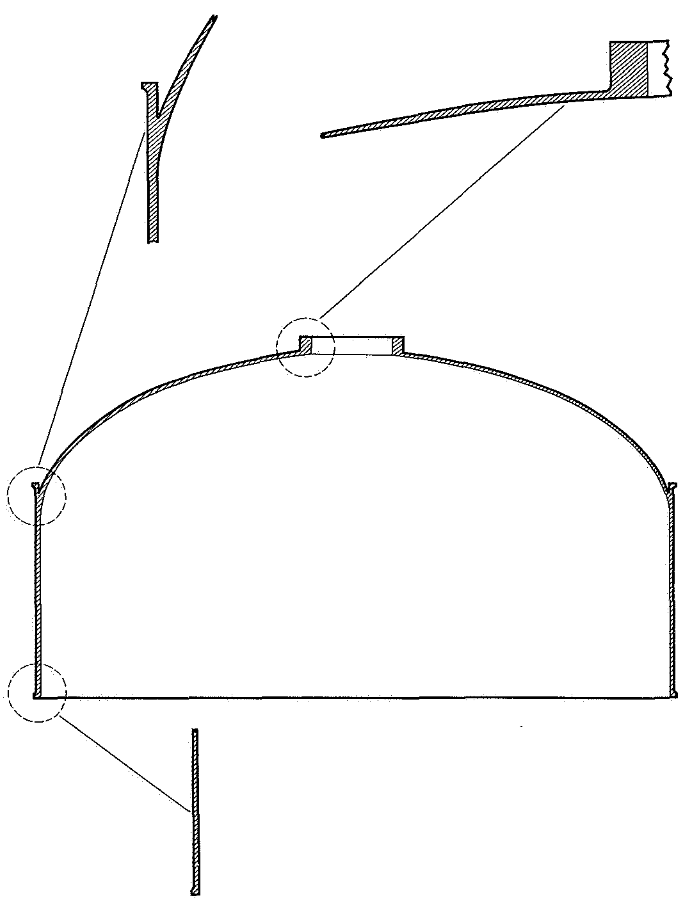


Fig. 13. Configuration of forward dome prior to welding

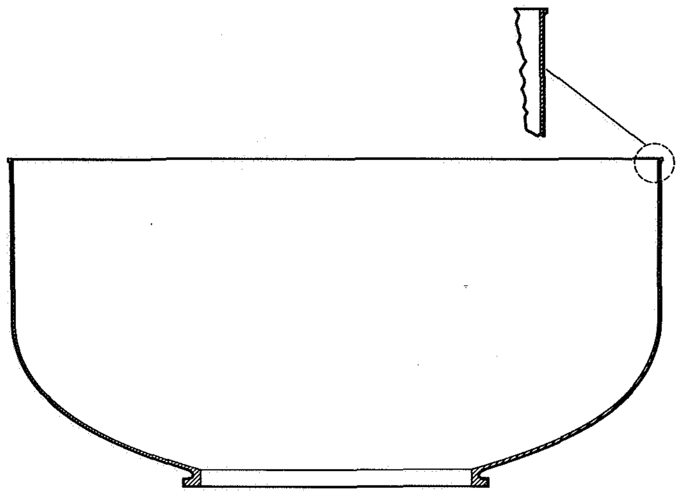


Fig. 14. Configuration of aft dome prior to welding

JPL Drawings J 3901791 and J 3901792 for forward and aft domes, respectively.

Following dimensional inspection, the domes were inspected by fluorescent penetrant per MIL-STD-271 and cleaned to remove all hydrocarbons or other foreign matter prior to welding. The cleaned weld edges were protected by aluminum foil until ready for assembly, at which time the domes were handled with lint-free white gloves.

C. *Ring Forgings*

The ring forgings for the mounting ring were produced by Carlton Forge with the ring-rolling technique. From an 8½-in.-diam octagonal bar, 13-in.-long mults were saw-cut, each weighing about 112 lb. The mults were ring-rolled at a temperature of 1725 ±25°F, requiring 18 to 19 forging cycles to produce the ring. Each forging thus produced was cut in half, resulting in two rings per forging produced. Microstructural qualification was carried out just prior to splitting, the requirements being the same as for the dome forgings. Subsequent fabrication and inspection steps, which were generally the same as for the dome forgings, were as follows:

1. Rough machined
2. Ultrasonic inspection per MIL-STD-271
3. Solution treated at 1600 to 1750°F for 1 hr
4. Stress relieved at 950 to 1150°F for 2 hr
5. Forging qualification by tensile test

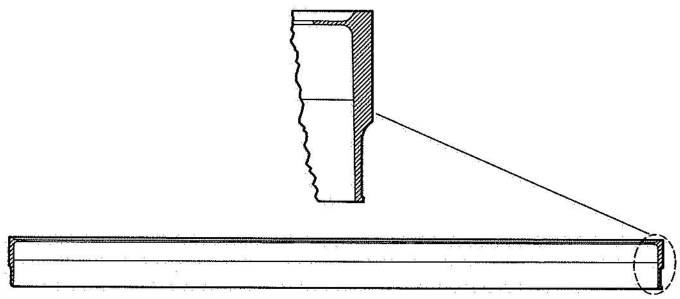


Fig. 15. Configuration of mounting ring prior to welding

6. Finish machined per drawing J 3901793 (see Fig. 15)
7. Dimensional inspection to drawing J 3901793
8. Fluorescent penetrant per MIL-STD-271
9. Cleaned and protected weld edges

Ring forgings were also qualified according to heat. One longitudinal specimen and one transverse specimen were machined from two diametrically opposed locations on a randomly selected ring. After aging, the specimens were tested and required to meet the properties listed in Table 3.

D. Welding

Two circumferential welds were used in constructing the chamber, one to join the mounting ring to the forward dome and the other to join the two domes. All welding was done by the semiautomatic tungsten inert gas (TIG) process and was accomplished in a rigid chamber capable of maintaining a 99.9% pure inert atmosphere. The chamber used for all welding appears in Figs. 16 and 17. No filler wire was used, since the joints were machined to provide their own filler. Repair welding was not permitted.

Prior to welding any chambers, weld qualification was required. With Ti-6Al-4V sheet stock formed to the 28-in. diam, preliminary tests were conducted to determine a weld schedule for qualification. These settings were then used on the simulated production welds to meet qualification requirements. Both the ring-mounting weld and the chamber-girth weld were simulated, two

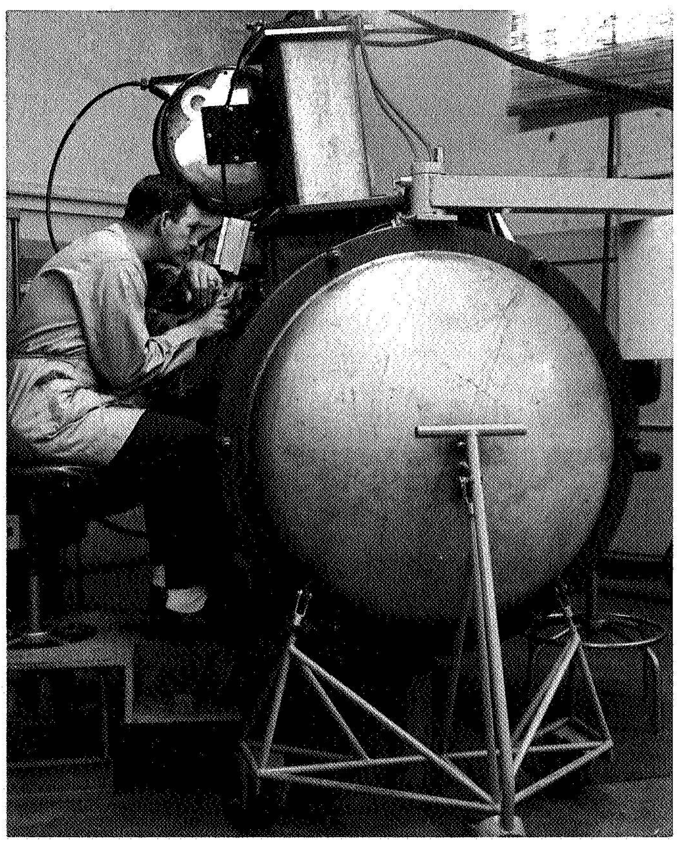


Fig. 16. Weld chamber, observer side

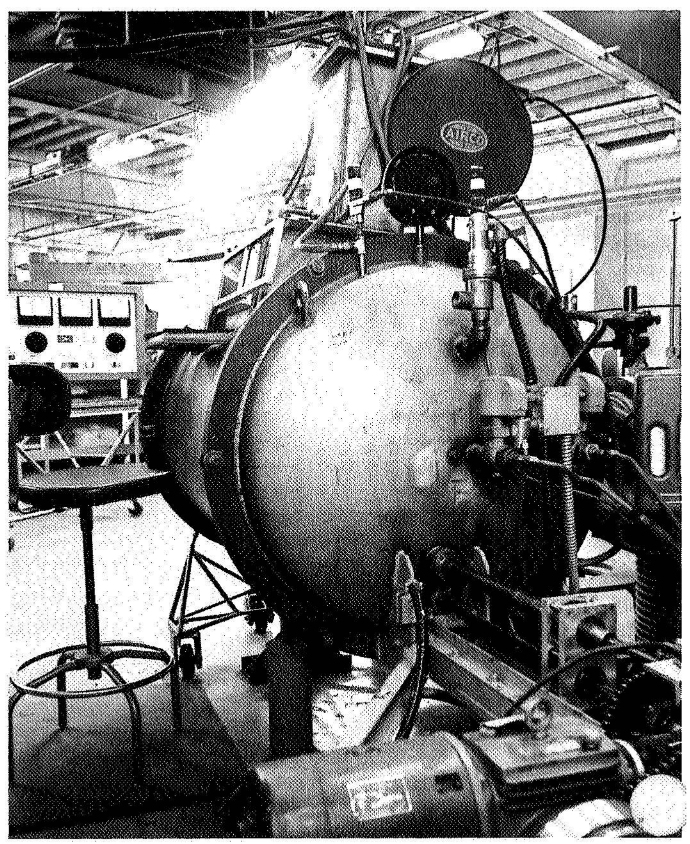


Fig. 17. Weld chamber, operator side

qualification welds being produced for each. The qualification welds were then subjected to radiographic inspection, aging, and penetrant inspection. Following inspection, one tensile specimen was sectioned for each weld made and was subjected to test to see that it met a required minimum weld strength of 140,000 psi. In addition, a microhardness traverse was conducted on samples prepared from each qualification weld. Impressions were made at 0.005-in. intervals across the weld. Hardness of the weld was to be no greater than 30 diamond-hardness numbers above that of the parent metal.

On compliance with weld qualification requirements, production welding was permitted. The first weld performed was that of joining the mounting ring to the forward dome. With precise tooling, the mounting ring was matched to the forward dome in the weld fixture. This was enclosed in the welding chamber, which was then pumped out and back-filled with argon. In the fixture, the dome and ring were rotated, the speed of which was closely controlled. All predetermined settings were made, and the arc was struck and the joint made. The tooling used was disassembled and removed through the nozzle opening. Subsequent to joining, the weld was radiographically and penetrant inspected per MIL-STD-271 and JPL Specification GOM-50369-DTL. The process was then repeated for the chamber-girth weld.

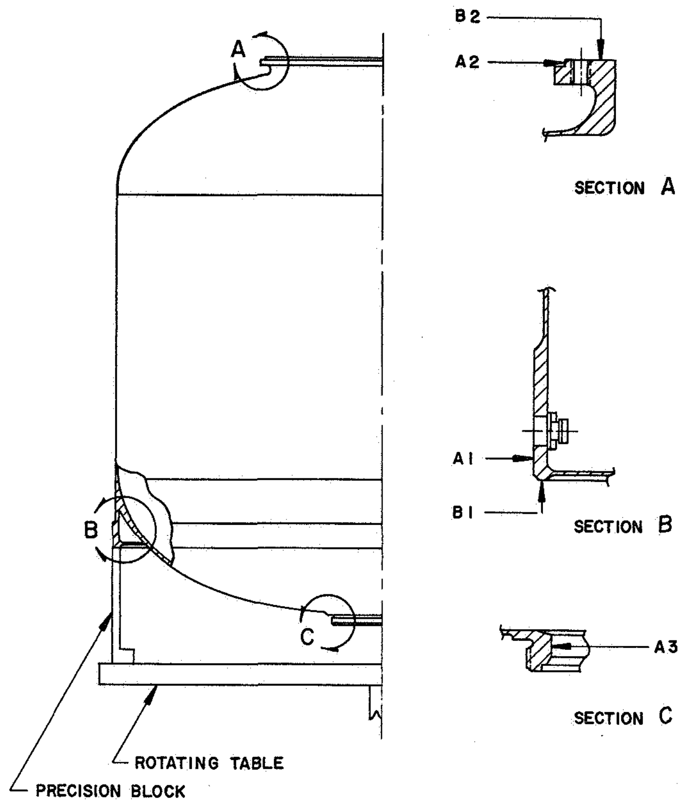


Fig. 18. Chamber alignment inspection positions

E. Finishing and Final Inspection

After welding and its associated inspection steps had been completed, the chamber assembly was ready for the final steps of the fabrication procedure. The chamber was prepared for aging by spraying a protective coating of Turco Pretreat XH-184W on the inside and outside surfaces. The aging range permitted was 950 to 1150°F for 2 hr, followed by air cooling. The actual temperatures used for aging appear in Table 7. Individual tensile specimens for forging qualification accompanied the chamber through the aging cycle and were subsequently tested.

The chamber assembly was then electrochemically etched to remove 0.0002 to 0.0003 in. of material. Surfaces which would provide the critical alignments discussed earlier were then machined. This provided for proper mating of the motor to the spacecraft, as well proper mating of the nozzle to the chamber. (The cal alignment positions on the chamber are shown in Fig. 18.) The holes for fasteners in both bosses were then drilled and tapped, where necessary. In addition,

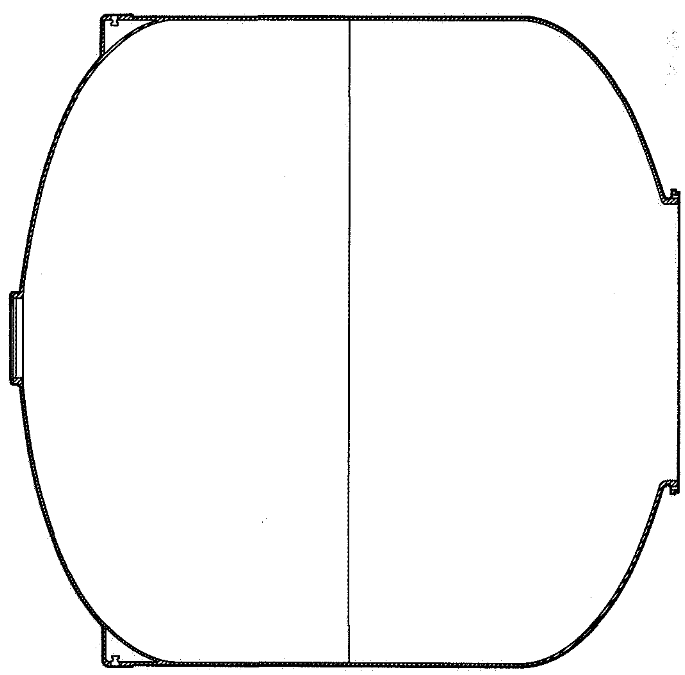


Fig. 19. Chamber after welding and finish machining

32 holes were drilled on the mounting ring to accept the rivets (MS20427-F3-5) and anchor nuts (MF1001-4), which were installed. The complete assembly was then fluorescent-penetrant inspected to MIL-STD-271. The chambers were then glass-bead blasted to prepare the surface for bonding of the rubber insulation.

The units were proof tested at room temperature to 302 psig, held for 5 min, and depressurized. Final dimensional inspection was then carried out. Data from alignment inspection of critical surfaces are shown in Table 8, illustrating the precise alignment achieved. The final configuration of the chamber appears in Fig. 19.

Table 8. Chamber alignment summary

Chamber S/N	Chamber weight, lb	Surface and inspection description[a]						
		A-1 Out of round, in.	A-2 Out of round, in.	A-2 Offset from A-1, in.	A-3 Out of round, in.	A-3 Offset from A-1, in.	B-1 Flatness, in.	B-2 Flatness, in.
1	25.23	0.0004	0.0020	0.0017	0.0010	0.0015	0.0007	0.0060
2	25.00	0.0002	0.0011	0.0018	0.0015	0.0020	no data	0.0035
3	25.34	0.0005	0.0007	0.0005	0.0012	0.0009	0.0006	0.0016
4	24.70	0.0008	0.0012	0.0003	0.0005	0.0008	0.0005	0.0010
5	24.55	0.0003	0.0014	0.0002	0.0032	0.0008	0.0004	0.0016
6	24.35	0.0003	0.0020	0.0005	0.0003	0.0013	0.0004	0.0020
7	23.84	0.0004	0.0012	0.0004	0.0022	0.0010	0.0005	0.0022
8	24.40	0.0003	0.0018	0.0002	0.0015	0.0025	0.0004	0.0016
9	24.13	0.0004	0.0015	0.0004	0.0020	0.0028	0.0004	0.0025
10	24.40	0.0004	0.0018	0.0002	0.0010	0.0015	0.0004	0.0026
11	24.74	0.0002	0.0002	0.0008	0.0015	0.0005	0.0006	0.0015
12	24.56	0.0004	0.0007	0.0005	0.0010	0.0012	0.0007	0.0013
13	24.47	0.0003	0.0010	0.0008	0.0005	0.0020	0.0007	0.0021
14	24.13	0.0004	0.0008	0.0010	0.0018	0.0018	0.0008	0.0028
15	23.92	0.0005	0.0010	0.0004	0.0016	0.0012	0.0008	0.0018
16	23.71	0.0006	0.0012	0.0011	0.0010	0.0016	0.0008	0.0024
17	23.83	0.0007	0.0006	0.0007	0.0014	0.0010	0.0005	0.0024
18	24.09	0.0006	0.0013	0.0007	0.0012	0.0018	0.0006	0.0020
19	23.74	0.0005	0.0018	0.0006	0.0025	0.0020	0.0005	0.0016
20	24.10	0.0005	0.0015	0.0011	0.0022	0.0011	0.0007	0.0023
21	24.63	0.0003	0.0020	0.0007	0.0007	0.0014	0.0008	0.0022
22	24.34	0.0002	0.0010	0.0015	0.0007	0.0019	0.0005	0.0029
23	24.20	0.0004	0.0008	0.0010	0.0014	0.0007	0.0005	0.0029

[a]For definition of inspection surfaces, see Fig. 18.

V. TESTING

A series of tests was conducted to verify the design and structural adequacy of the *ATS* chambers. Included were hydroburst tests, with subsequent metallurgical evaluation, vibration tests, and static acceleration tests. The results of these tests are discussed below.

A. Hydroburst Tests

Three *ATS* chambers were subjected to hydroburst tests to verify adequacy of the design, material, and processing. The first chamber, B-1T, was burst immediately after fabrication to provide early verification of the chamber's capability to hold internal pressure. The second chamber, B-5T, was burst after being instrumented with 18 strain gages for engineering data, and the third chamber, B-6TF, was burst after being fired.

The mounting ring of each chamber was rigidly attached to a handling ring that geometrically simulated the spacecraft interface. Both nozzle and igniter ends were capped prior to internal pressurization with water. At approximately every 20 psig, both the increment of additional water pumped into the chamber and the internal pressure were recorded. Since all tests were conducted at room temperature, the proof pressure requirements were raised to 302 psig from the design

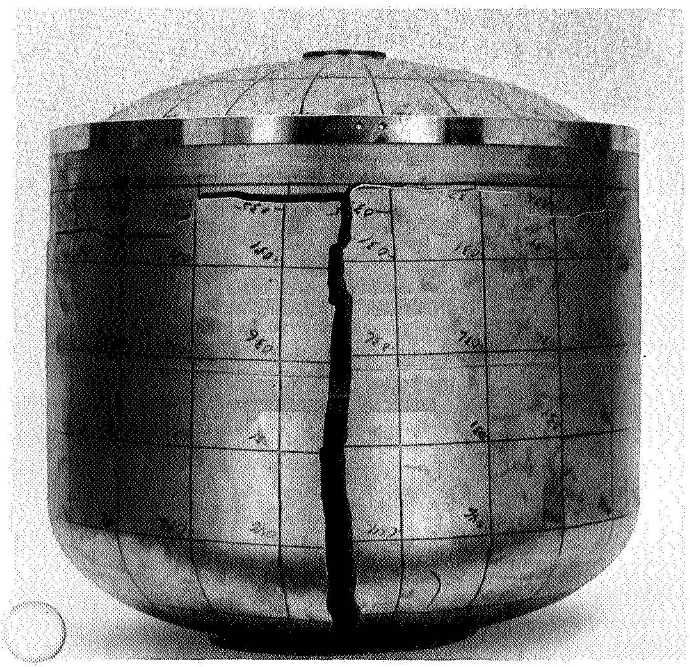


Fig. 20. Chamber B-1T after hydroburst

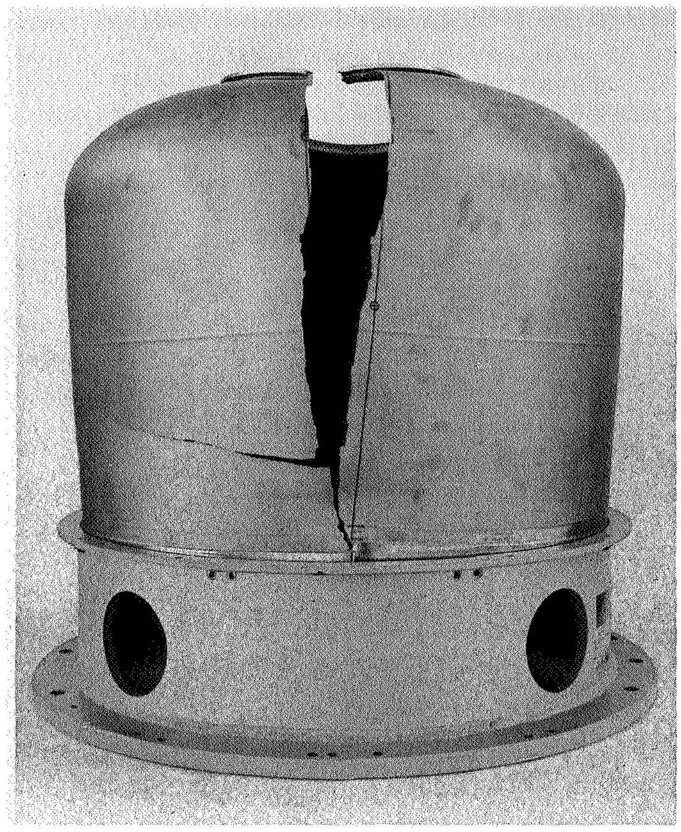


Fig. 21. Chamber B-5T after hydroburst

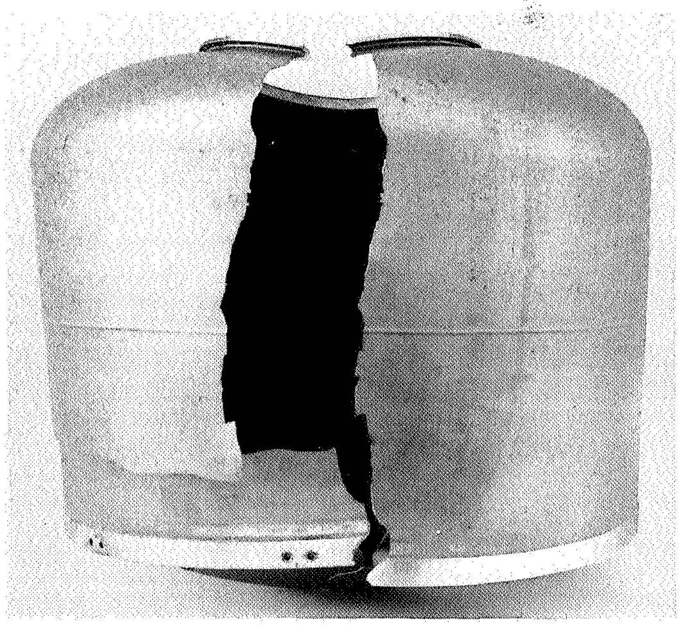


Fig. 22. Chamber B-6TF after hydroburst

pressure of 285 psig at operating temperature. This adjusts for the decrease in material properties associated with the higher design temperature. Figures 20, 21, and 22 show the chambers after hydroburst. Pressure-volume curves were plotted for each chamber (Figs. 23, 24, and 25), and all test values which were normalized to minimum thickness and minimum material properties are listed in Table 9. The actual chamber thicknesses were obtained from inspection reports, and material property data were obtained from the certification reports accompanying each case on delivery from the vendor. Test results and explanation of the normalization of the test pressures are discussed below.

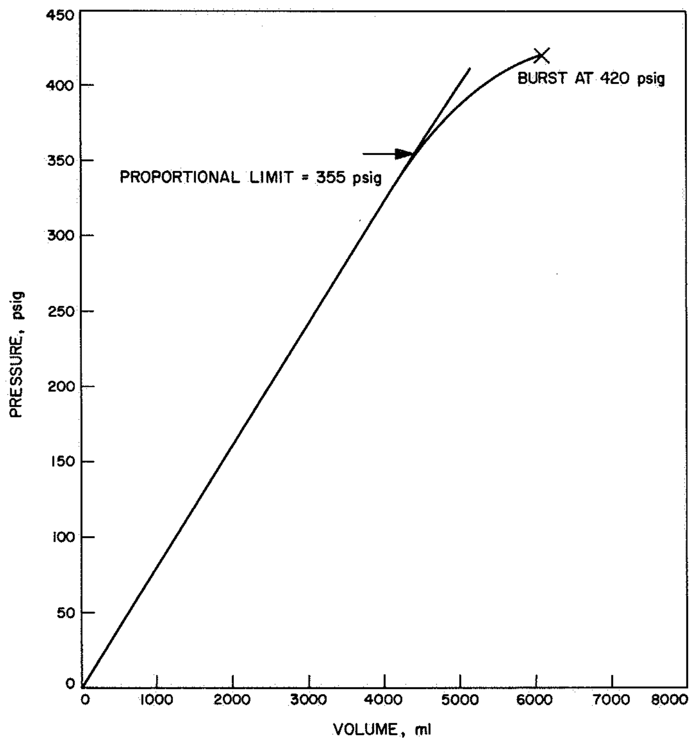


Fig. 23. Pressure-volume curve, chamber B-1T

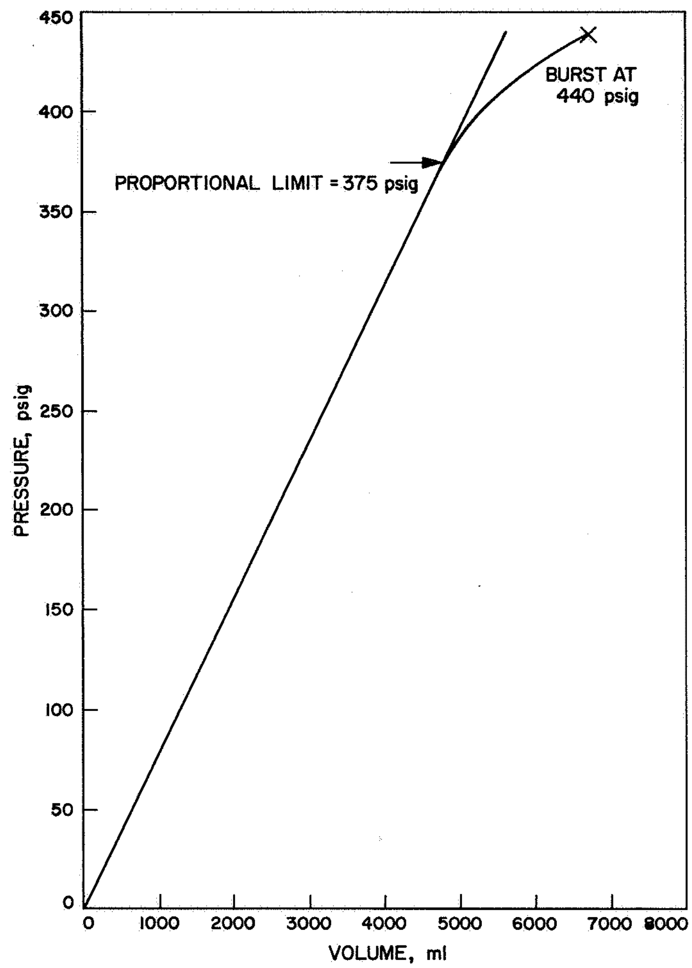


Fig. 24. Pressure-volume curve, chamber B-5T

Table 9. Results of hydroburst tests showing actual values obtained and normalized[a] values

Case No.	Bulk yield pressure, proportional limit, psig		Gross yield pressure corresponding to 0.2 % uniaxial strain, psig		Burst pressure, psig	
	Test value	Normalized	Test value	Normalized	Test value	Normalized
B-1T	355	327	418	380	420	382
B-5T	375	311	430	355	440	363
B-6TF[b]	370	—	—	—	428	—

[a] $P_{norm} = P_{test} \left[\frac{\sigma_y \text{ (theoretical min.)}}{\sigma_y \text{ (test coupon)}} \right] \left[\frac{t \text{ (theoretical min.)}}{t \text{ (actual thickness)}} \right]$

[b] B-6TF was a fired chamber and the pressures were not normalized.

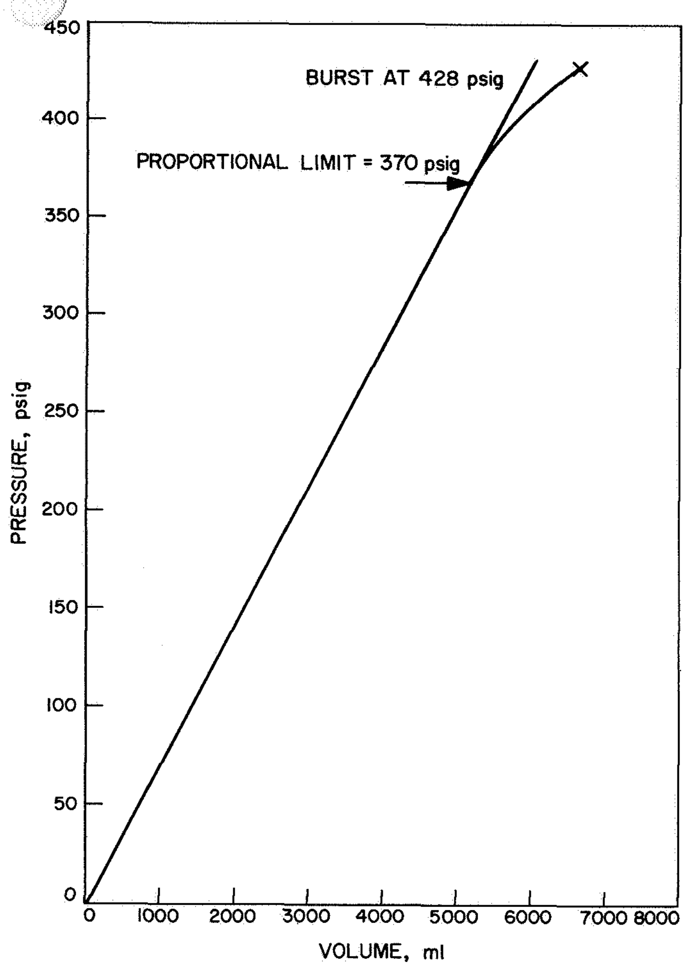


Fig. 25. Pressure-volume curve, chamber B-6TF

The second hydroburst test, of chamber B-5T, is of interest because it was instrumented to obtain stress data at discrete locations. As shown in Fig. 26, three sets of two strain gages along the principal axis were bonded on the chamber-thickness-transition points on both the aft and forward ends; two sets were bonded on the knuckle area of the 2:1 aft ellipsoid to measure the compressive stresses that could cause buckling; and one set was bonded on the thickness-transition points of the cylindrical portion near the girth weld. Plots of strain vs pressure were linear at just above proof pressure (305.2 psig) and, thereby, show no yielding, except those in Fig. 27, which will be discussed later. The strain values corresponding to 305.2 psig at the various locations are listed in Table 10. To obtain an estimate of the stresses near the strain-gage location[1], values of $E = 16 \times 10^6$ psi and $\nu = 0.3$ were used; the results are shown in Table 11.

[1]Only an estimate is possible because the gage is ⅛-in. long and both gages are not recording data at one point.

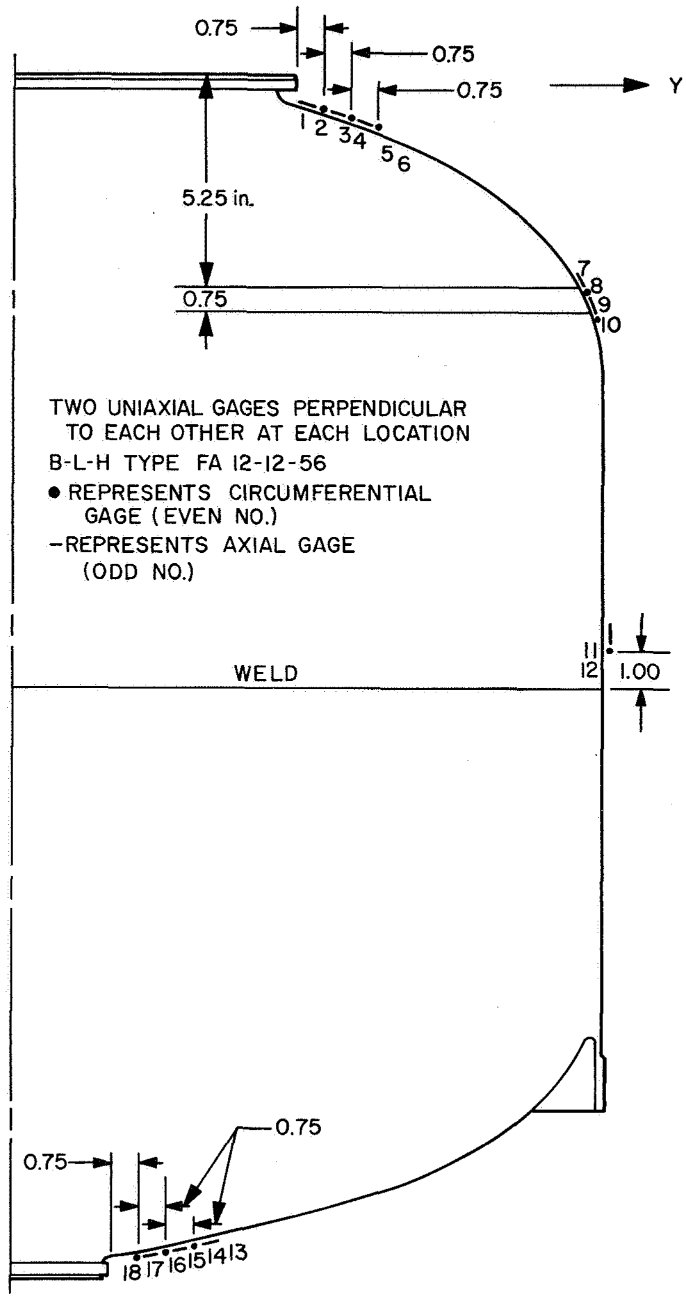


Fig. 26. Strain-gage locations on chamber B-5T

The values in Table 10 indicate that the largest stresses are in the cylindrical section and that failure is initiated in that region. Because stresses were highest in the cylindrical section, actual-thickness to design-thickness ratios of that section of the chamber were used for normalizations of pressure and to estimate the 0.2% offset yield pressure. The chambers did not buckle in the aft ellipsoidal end; however, the strain gages in that area provided data to help confirm the method for predicting

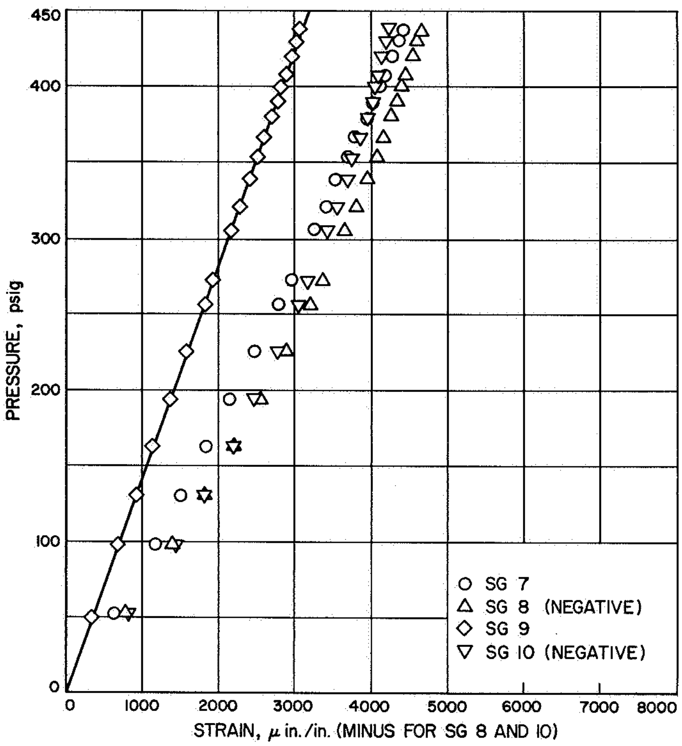


Fig. 27. Pressure-strain curves from chamber B-5T

Table 10. Strain values of hydrotest at 305.2 psig, chamber B-5T

Position	Strain, μ in./in.	Measured case thickness, in.
1	1530	0.095
2	4480	0.082
3	2650	0.050
4	2950	0.042
5	3420	0.0375
6	1090	0.038
7	3250	0.053
8	−3650	0.0525
9	2160	0.053
10	−3440	0.0515
11	1780	0.032
12	6320	0.0335
13	5040	0.0365
14	4080	0.0385
15	3650	0.0445
16	4150	0.047
17	−2150	0.0535
18	4980	0.0565

Table 11. Approximate stress values of hydrotest at 305.2 psig, chamber B-5T

Position	Axial stress, kpsi	Circumferential stress, kpsi
1, 2	50.7	87.0
3, 4	62.0	66.0
5, 6	66.0	37.3
7, 8	38.0	−47.0
9, 10	20.0	−49.0
11, 12	65.0	121.0
13, 14	110.0	98.5
15, 16	86.0	92.5
17, 18	−11.4	76.0

the buckling pressure or stress. The compressive hoop stress in the knuckle region of the aft ellipsoid was approximately 58 kpsi (63 kpsi when normalized to 0.048-in. wall thickness) at 438 psig internal pressure, which is less than the predicted buckling stress of 74 kpsi. As predicted, the chamber did not buckle. The non-linear behavior of the pressure–strain curve of gages 7 to 10 (Fig. 27) shows that an assumption of linear pressure–strain relation will result in a conservative design of the ellipsoid for compressive hoop stresses.

An estimation of the pressures corresponding to a 0.2% uniaxial yield stress is of interest because the chamber design criteria are referred to this pressure, not to the bulk yield pressure obtained from the pressure–volume curves. The pressure corresponding to a 0.2% uniaxial yield stress can be estimated if the yielding of the ellipsoidal ends at room temperature is considered insignificant compared to the cylindrical section. By use of the effective strain relationship and assumption of incompressibility in the plastic range, the following equation is obtained:

$$\varepsilon^p_{eff} = \frac{2}{\sqrt{3}}\left(\varepsilon^{p^2}_1 + \varepsilon^{p^2}_2 + \varepsilon^p_1 \varepsilon^p_2\right)^{1/2}$$

where ε^p_{eff} is effective strain in plastic range and ε^p_i is plastic strain in i^{th} direction. The stress–strain relation in the plastic range (Hencky's Theory of Small Plastic Deformation) is:

$$\varepsilon^p_1 = \frac{1}{E_p}\left(\sigma_1 - \frac{\sigma_2 + \sigma_3}{2}\right),$$

$$\varepsilon^p_2 = \frac{1}{E_p}\left(\sigma_2 - \frac{\sigma_3 + \sigma_1}{2}\right) \quad \text{and}$$

$$\varepsilon^p_3 = \frac{1}{E_p}\left(\sigma_3 - \frac{\sigma_1 + \sigma_2}{2}\right)$$

By equating

$$\sigma_1 = \sigma_\theta;\ \sigma_2 = \sigma_\varphi;\ \sigma_3 = 0;\ \varepsilon_1^p = \varepsilon_\theta^p,\ \varepsilon_2^p = \varepsilon_\varphi^p$$

where $\sigma_\theta = 2\sqrt{\sigma_\varphi}$, the following equation is obtained from the above relationships:

$$\varepsilon_\theta^p = \frac{\sqrt{3}}{2}\varepsilon_{eff}^p$$

Thus a circumferential strain ε_θ^p corresponding to a uniaxial 0.2% yield strain is

$$\varepsilon_\theta^p = \frac{\sqrt{3}}{2}(0.002) = 0.00173 \text{ in./in.}$$

The change in internal volume corresponding to 0.2% uniaxial yield strain is approximated by:

$$\Delta V = 2V\varepsilon_\theta^p = 2V\,(0.00173)$$

where

ΔV = change in internal volume

V = internal volume of chamber = 240,000 ml

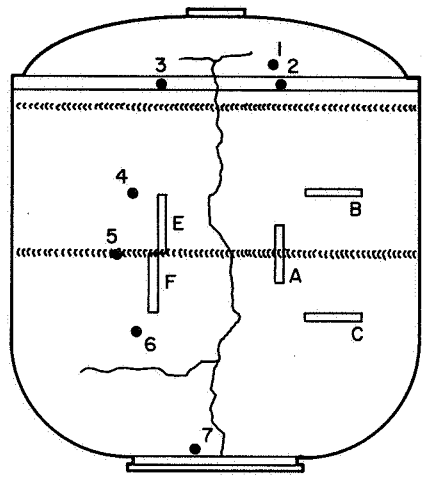
The ΔV corresponding to 0.2% gross uniaxial yield strain is

$$\Delta V = 2(240{,}000 \text{ ml})\,(0.00173) = 830 \text{ ml}$$

The pressures at ΔV = 830 ml obtained from the pressure–volume curves are the estimates of the 0.2% yield pressure.

From the three hydroburst chambers, tensile and metallographic samples were sectioned for evaluation. The tensile specimens were selected from areas to represent welds and parent metal—the latter being represented by two sets of specimens, one circumferential and the other axial. All tensile samples were taken from the cylindrical section of the chambers. Metallographic samples were taken from both welds, the mounting ring, and each half shell. The specimens from the half shells represented both cylinder and dome areas. The general locations from which the test specimens were sectioned appear in Fig. 28.

For comparison, the results of the post-burst tensile tests, minimum design strength, and tensile tests performed during fabrication are shown in Table 12. Generally, the data from production and post-burst tests agree for ultimate strength; however, as expected, they vary somewhat for yield strength. Information obtained



A - WELD TENSILE SPECIMENS
B - CIRCUMFERENTIAL TENSILE SPECIMENS, FORWARD HALF-SHELL
C - CIRCUMFERENTIAL TENSILE SPECIMENS, AFT HALF-SHELL
E - LONGITUDINAL TENSILE SPECIMENS, FORWARD HALF-SHELL
F - LONGITUDINAL TENSILE SPECIMENS, AFT HALF-SHELL
1 - METALLURGICAL EXAMINATION, DOME SECTION OF FORWARD HALF-SHELL
2,3 - METALLURGICAL EXAMINATION, MOUNTING RING
4 - METALLURGICAL EXAMINATION, CYLINDRICAL SECTION OF FORWARD HALF-SHELL
5 - METALLURGICAL EXAMINATION, WELD
6 - METALLURGICAL EXAMINATION, CYLINDRICAL SECTION OF AFT HALF-SHELL
7 - METALLURGICAL EXAMINATION, DOME SECTION OF AFT HALF-SHELL

Fig. 28. General locations of tensile and metallographic samples sectioned from hydroburst chambers

from the post-burst tests is not fully conclusive for a number of reasons. Most obvious is the possibility that the material was damaged during hydroburst. In addition, the specimens taken from the chambers were curved, thus did not exemplify standard tensile specimens. Also, the material has been subjected to stresses exceeding its proportional limit and, therefore, does not represent the material before hydroburst.

Typical metallurgical structures corresponding to the code numbers of Fig. 28 are illustrated in Figs. 29 through 42. These photomicrographs represent the structure found in all three of the chambers examined. The etchant used was $HF\text{-}HNO_3\text{-}H_2O$. In addition, microhardness tests were conducted on samples from each chamber. The values obtained appear in Table 13. Values obtained from the girth weld-hardness traverse reveal a maximum variation of 32 across the weld in chamber B-1T. Chambers B-5T and B-6T exhibited a maximum

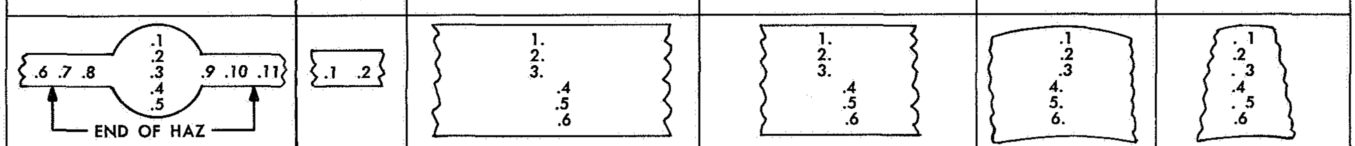
Table 12. Results of post-burst tensile tests as compared with production tests and design requirements

Property	Gen. area	Chamber B-1T Post-burst[a]	Chamber B-1T Production	Chamber B-5T Post-burst[a]	Chamber B-5T Production	Chamber B-6TF Post-burst[a]	Chamber B-6TF Production	Design requirements
F_{tu}	Fwd dome	B 167		B 171		B 163		160 min. 175 max.
		162	169	170	165	170	165	
		E 164		E 165		E —		
		165		169		—		
	Aft dome	C 161		C 177		C 171		
		165	169	173	169	171	165	
		F 168		F 175	172	F 168	171	
		168		175		170		
F_{ty}	Fwd dome	B 152		B 161		B 154		150 min.
		149	158	164	156	162	158	
		E 142		E 151		E —		
		142		155		—		
	Aft dome	C 145		C 170		C 164		
		154	156	165	159	165	156	
		F 152		F 161	163	F 154	161	
		151		161		156		
Weld strength		A 159	—	A 160	—	A 154	—	140 min.
		160		155		153		

[a]Code letters preceding strength values correspond to those of Fig. 27.

Table 13. Microhardness data obtained from hydroburst chambers

Test specimen position and location key



Hardness for chamber No., Knoop hardness using 500 g load

Location No.	Girth-weld traverse B-1T	Girth-weld traverse B-5T	Girth-weld traverse B-6TF	Mounting ring B-1T	Forward cylindrical section B-1T	Forward cylindrical section B-5T	Forward cylindrical section B-6TF	Aft cylindrical section B-1T	Aft cylindrical section B-5T	Aft cylindrical section B-6TF	Forward dome B-1T	Forward dome B-5T	Aft dome B-1T	Aft dome B-5T
1	384.6	384.6	396.4	390.4	390.4	377.3	384.6	368.2	377.3	396.4	379.0	376.3	390.4	384.6
2	379.0	384.6	384.6	384.6	379.0	384.6	396.4	384.6	377.3	384.6	384.6	376.3	373.6	390.4
3	379.0	368.2	390.4	—	390.4	384.6	396.4	384.6	384.6	390.4	396.4	379.0	379.0	390.4
4	384.6	384.6	384.6	—	390.4	390.4	384.6	379.0	390.4	384.6	384.6	379.0	402.4	390.4
5	396.4	373.6	390.4	—	384.6	390.4	390.4	384.6	390.4	384.6	402.4	379.0	402.4	390.4
6	368.2	373.6	390.4	—	396.4	377.3	—	379.0	384.6	—	396.4	379.0	384.6	390.4
7	379.0	358.0	390.4	—	—	—	—	—	—	—	—	—	—	—
8	379.0	384.6	390.4	—	—	—	—	—	—	—	—	—	—	—
9	373.6	377.3	390.4	—	—	—	—	—	—	—	—	—	—	—
10	363.6	368.2	384.6	—	—	—	—	—	—	—	—	—	—	—
11	373.6	384.6	384.6	—	—	—	—	—	—	—	—	—	—	—

Fig. 29. Microstructure of forward dome, location 1 (100×)

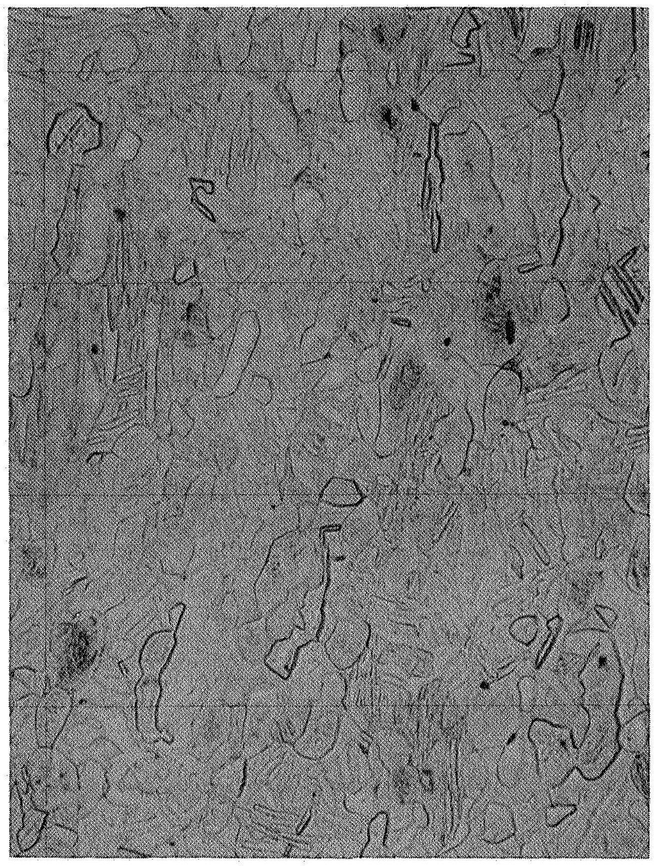


Fig. 30. Microstructure of forward dome, location 1 (500×)

variation in hardness of 28 and 6 hardness numbers, respectively. Consequently, the welds appear to have met the contamination limits called out in the specification. The remainder of the hardness tests indicate little variation in parent material hardness, even between different chambers.

From the above data, it appears the chambers were produced within the requirements of JPL Specification GMO-50369-DTL and were fabricated by accepted techniques.

Table 14. Sinusoidal vibration test environments

Frequency range, cps	Parallel to thrust axis, g rms	Perpendicular to thrust axis, g rms
15 to 250	2.1	2.1
250 to 400	3.5	3.5
400 to 2000	5.0	5.0

Sweep rate = two octave/min from 15 to 2000 cps.

B. Vibration Test

Two *ATS* motors, one inert motor, D2T, and one live motor, D9T, each weighing about 839 lb, were vibrated to 1.5 × the levels expected during the launch phase of the mission. The motor was attached to a rigid fixture at the skirt attachment plane and was vibrated in three orthogonal axes. The qualification vibration levels are listed in Tables 14 and 15.

Table 15. Random vibration test environments

Direction	Wideband acceleration, g rms	Frequency range, cps	PSD, g^2/cps
Perpendicular to thrust axis	11.2	20 to 80	0.04
		80 to 1280	Increasing from 0.04 to 0.07 at 0.61 db/octave
		1280 to 2000	0.07
Parallel to thrust axis	9.9	20 to 1000	0.1

Duration = 6 min in each axis.

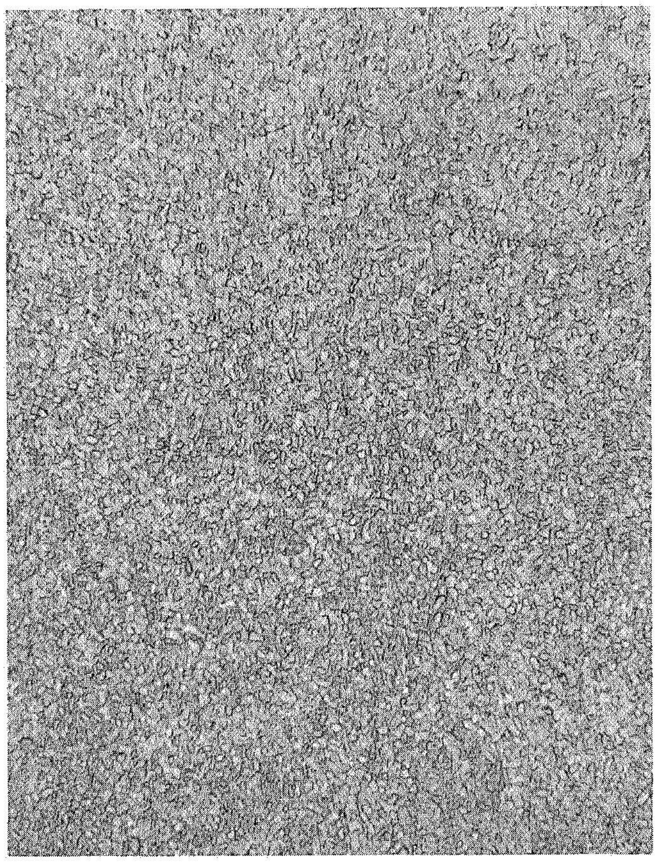


Fig. 31. Microstructure of mounting ring, location 2 (100×)

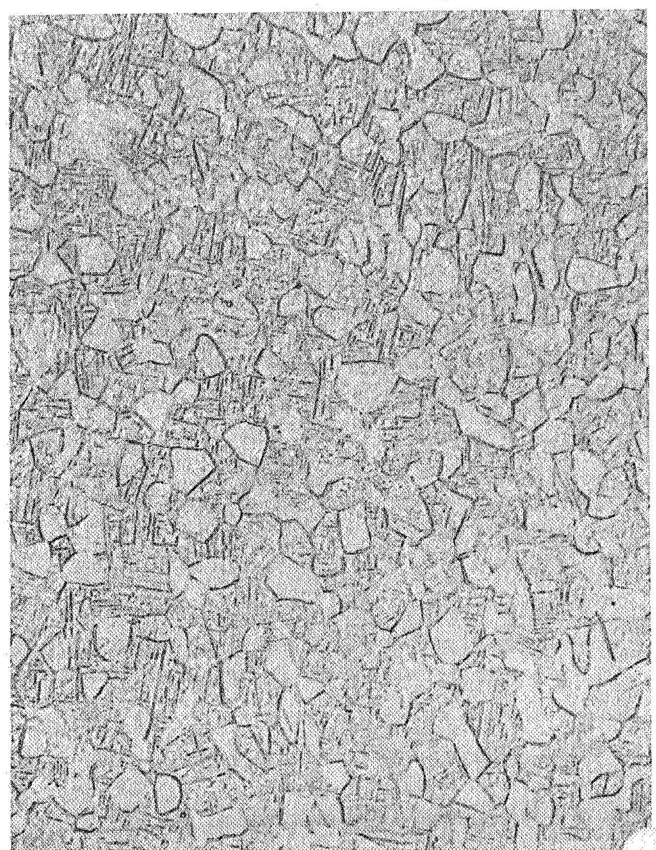


Fig. 32. Microstructure of mounting ring, location 2 (500×)

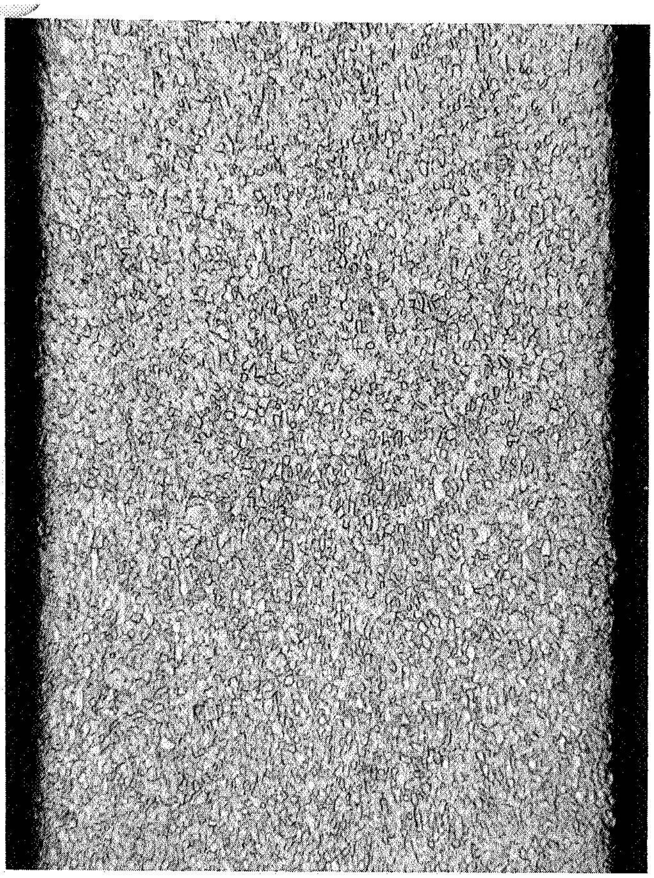


Fig. 33. Microstructure of cylindrical skirt of forward dome, location 4 (100×)

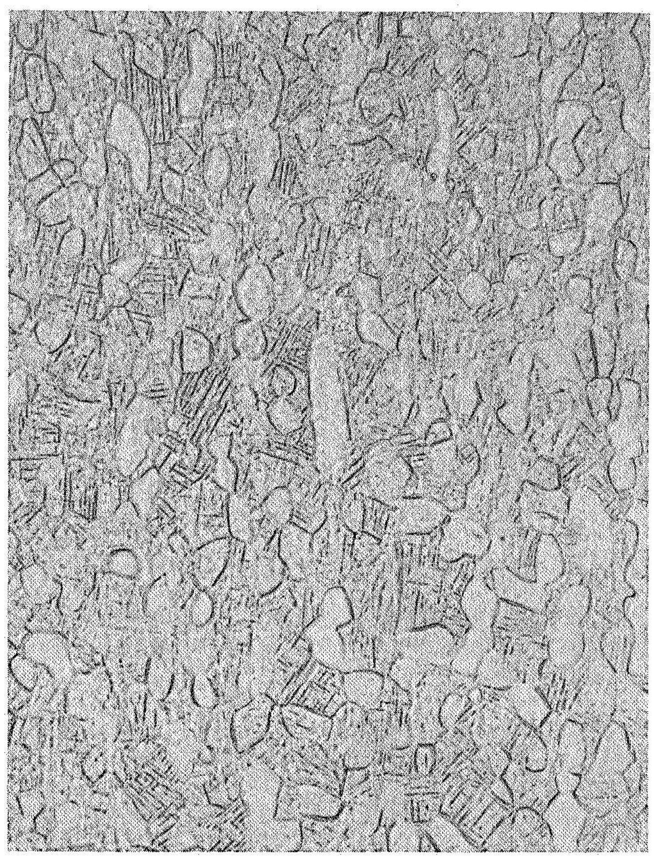


Fig. 34. Microstructure of cylindrical skirt of forward dome, location 4 (500×)

Fig. 35. Macrostructure of welds, location 5 (9×)

Fig. 36. Microstructure of weld center, location 5 (50×)

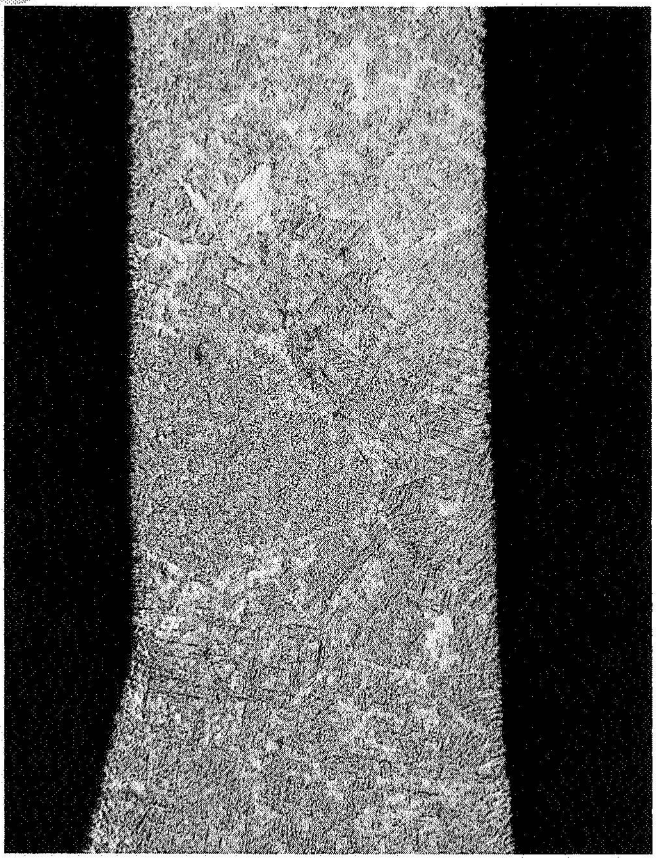


Fig. 37. Microstructure of weld root, location 5 (50×)

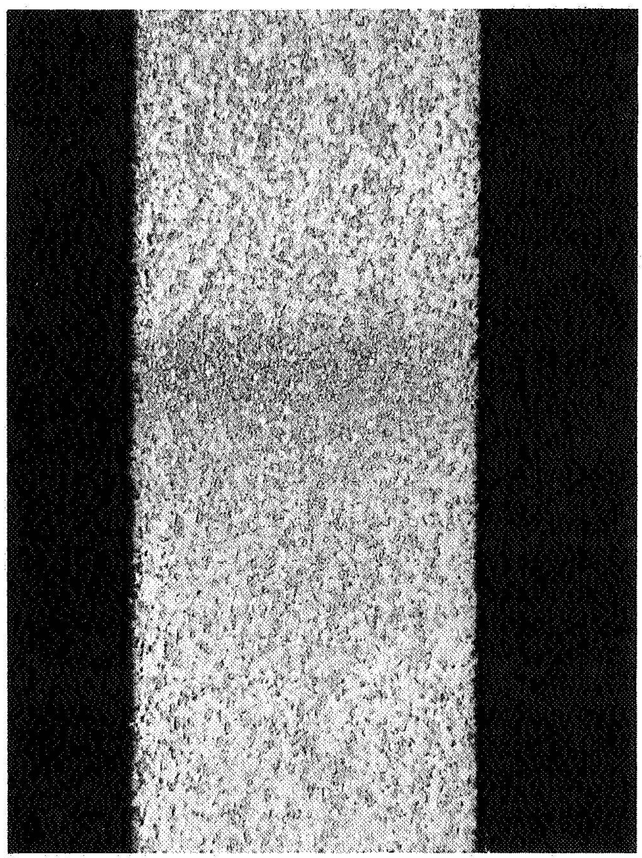


Fig. 38. Microstructure showing limit of HAZ, location 5 (50×)

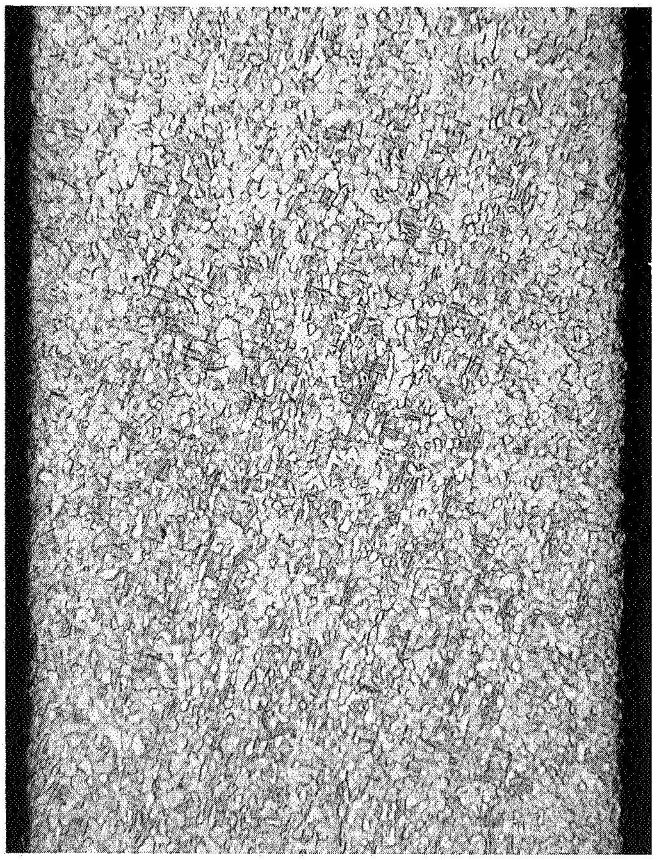


Fig. 39. Microstructure of cylindrical skirt of aft dome, location 6 (100×)

Fig. 40. Microstructure of cylindrical skirt of aft dome, location 6 (500×)

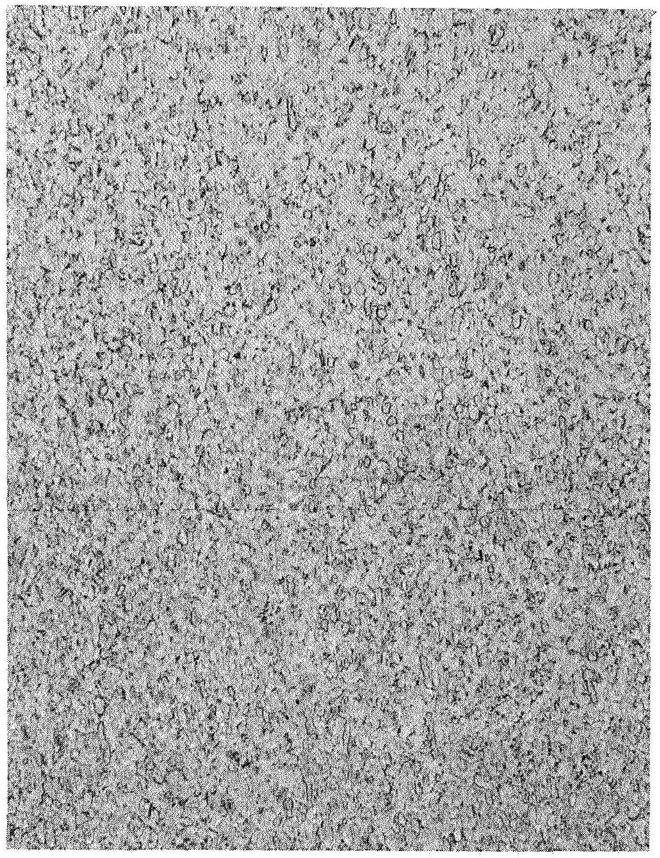


Fig. 41. Microstructure of aft dome, location 7 (100×)

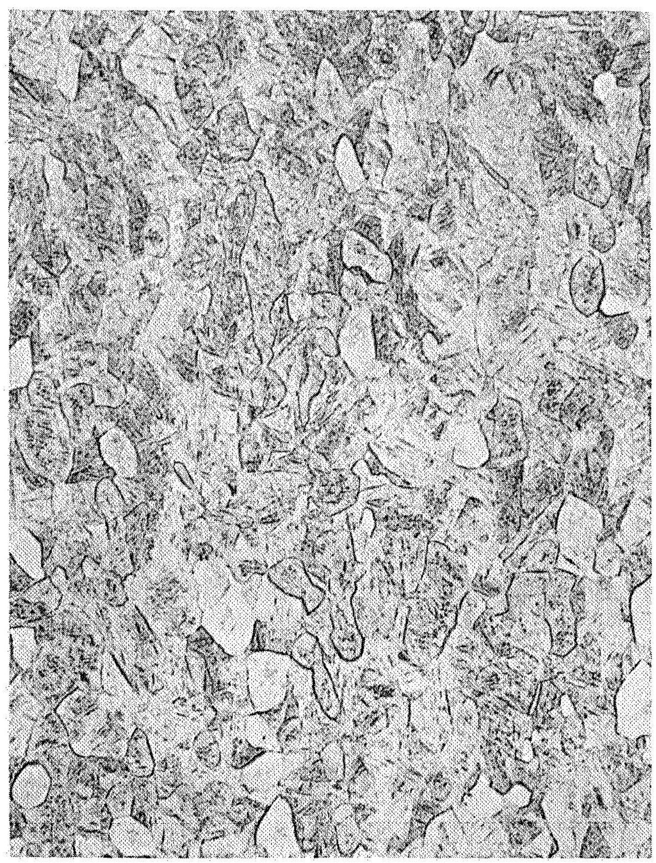


Fig. 42. Microstructure of aft dome, location 7 (500×)

In addition to the qualification levels, 1 g rms sine sweeps from 15 to 2000 cps at 2 octave/min were run prior to each test in each axis to verify the adequacy of the motor and test system.

During each test, 16 accelerometers were mounted on the vibration fixture and motor, as shown in Fig. 43 and detailed by location in Table 16. All data were recorded on magnetic tape and a selective sample observed on the oscillograph.

The resonant frequencies and amplifications of all the inert motors and of the first live motor are listed in Table 17. The resonant frequency was determined by investigating the two input control accelerometers, the response at station C, and the armature current. The response of the accelerometer at station C was chosen to exhibit the behavior of the overall motor. The input was controlled by a root-mean-square average acceleration of the two control accelerometers at station M. As usual, the filtered input acceleration was not equal to the specification values as noted in Table 17.

The data show the symmetry of both the inert and live motor about the x and y axes; however, differences in the dynamic characteristics of the live vs the inert motor

Table 16. Vibration test instrumentation

Accelerometer location	X axis	Y axis	Z axis
XMX	x	x[a]	x
−XM−X	x	x[a]	x
XM−Z	x	—	x[a]
−XM−Z	x	—	x[a]
YMY	x[a]	x	x
−YM−Y	x[a]	x	x
YM−Z	—	x	—
−YM−Z	—	x	—
YAX	x	—	x
YAY	—	x	—
YAZ	x	x	x
XBY	—	x	—
YBX	x	—	x
XB−Z	x	x	x
XCX	x	—	x
XC−Z	x	—	x
YCY	—	x	—
YC−Z	—	x	—
XDX	x	—	x
XD−Z	x	—	x
YDY	—	x	—
YD−Z	—	x	—

[a] Control accelerometers.

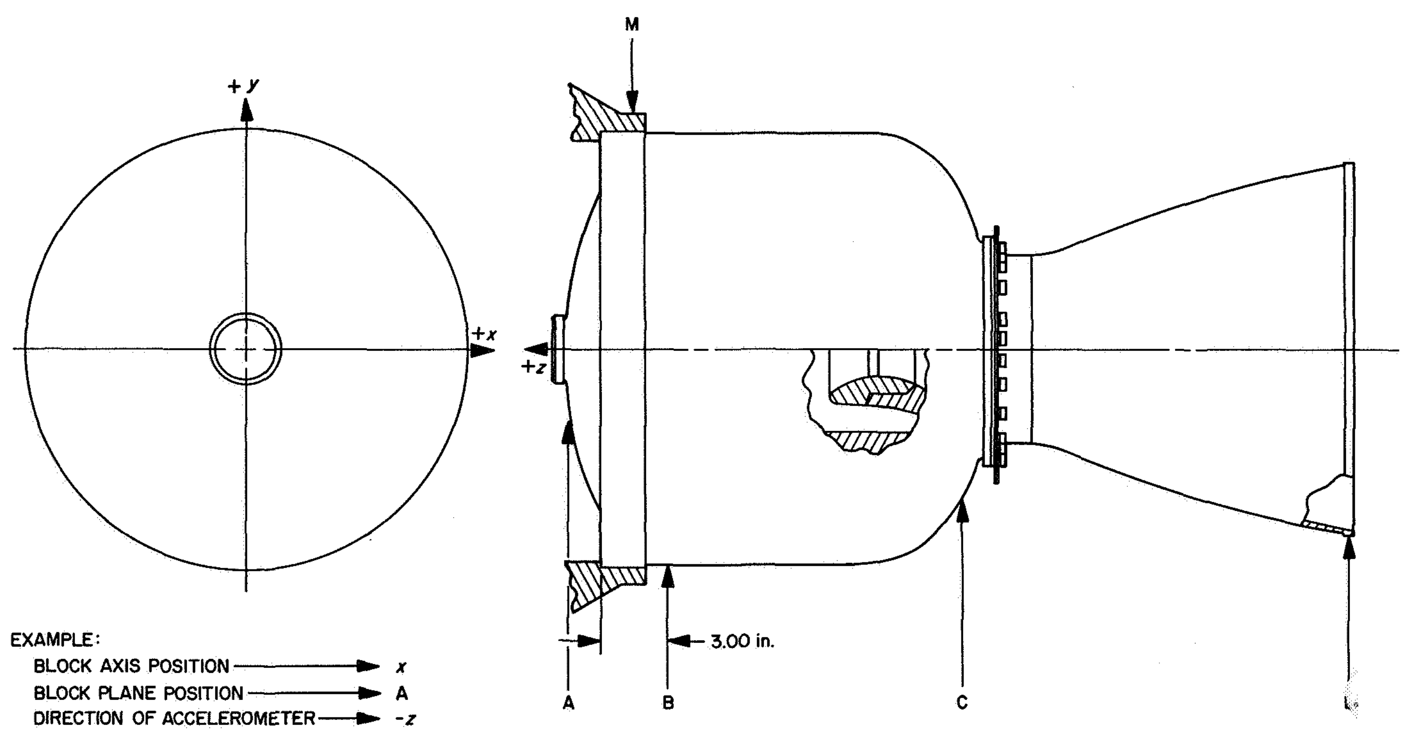


Fig. 43. Accelerometer location and plane identification for vibration test

Table 17. Vibration test results

Motor	Axis	Resonant frequencies, cps	Response at location C, g	Average input acceleration, g	Transmissibility, Q
D2T	x	63	11.2	2.8	4.0
(Inert)	x	112	9.6	2.5	3.8
	x	250	14.0	3.0	4.7
	y	64	10.0	2.6	3.9
	y	114	6.8	2.5	2.7
	y	250	12.0	3.0	4.0
	z	165	15.0	2.0	7.5
D9T	x	75	13.5	1.55	8.7
(Live)	x	110	7.0	2.3	3.1
	x	230	10.0	3.0	3.3
	y	75	13.0	1.5	8.7
	y	115	9.0	2.45	3.7
	y	240	9.5	3.0	3.2
	z	163	15.3	2.0	7.7

exist in the first resonant frequency; the transmissibility is about twice as high. The dynamic characteristics of the other modes and axis are similar for the live and inert motors.

Strain gages were not recorded during the test because small strains were anticipated as a result of the low transmissibility that, in turn, was caused by high damping. The test data substantiate the assumption. Another critical requirement was to limit the lowest resonant frequency of the motor to preclude dynamic coupling with the spacecraft. The resonant frequency of both motors exceeded the design minimum values of 50 cps in the lateral direction and 130 cps in the axial direction.

The use of sixteen ¼-28 bolt–anchor nut combinations to mount the motor to the spacecraft was found to be adequate for its most severe loading—that is, for the vibration loads. The bolts were torqued to 125 ±5 in.-lb; there was no evidence of loosening.

C. *Static Acceleration Test*

Several *ATS* motor chambers loaded with live propellant were subjected to the static acceleration loads that simulated those expected during launch and apogee motor-burn phases of the mission. The loads imposed on the motor skirt attachment plane are listed in Table 18.

A 20-ft-radius centrifuge was used to accelerate the motor to the required levels. The motor was bolted to a rigid fixture at the skirt attachment plane. Engineering data were not obtained during the test because of the low stress levels expected in the chamber. No motor failures were observed during post-test inspection.

Table 18. Static acceleration test environments

Test position	Level, g	Duration, min
Perpendicular to thrust axis	2.3	10
Parallel to thrust axis with skirt in tension	12.0	10
Parallel to thrust axis with skirt in compression	12.0	10

APPENDIX A

Detail Specification, Titanium Rocket Motor Case

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

JPL SPEC GOM-50369-DTL-B

DATE: 14 July 1965

DETAIL SPECIFICATION
JPL-SR-28-3 FLIGHT EQUIPMENT
Ti 6Al 4V TITANIUM ROCKET MOTOR CASE

PREPARED BY: R. E. Melton

APPROVED: H. G. Homan

APPROVED: D. P. Kohorst
Engineer

APPROVED:

Revised and Rewritten

PAGE 1 OF 18 PAGES

REV	AMEND	DATE	AUTHORITY
N/C		10-19-1964	
A		1-21-1965	
B		7-14-1965	

REV	AMEND	DATE	AUTHORITY

JPL 2368 APR 65

1. SCOPE

1.1 This specification covers the detail requirements for materials, fabrication and pressure-testing of the JPL-SR-28-3, Ti 6Al 4V Titanium Rocket Motor Case.

2. APPLICABLE DOCUMENTS

2.1 The following documents, of the issue in effect on the date of purchase form a part of this specification to the extent specified herein:

SPECIFICATIONS

Jet Propulsion Laboratory

ZPO-20002-PRS	Process Specification, Identification Requirements, Parts and Assemblies
20064	General Specification for Packing Flight Equipment for Shipment within the Continental United States

STANDARDS

Federal

FED-STD-151	Metals, Test Methods

Military

MIL-STD-271	Nondestructive Testing Requirement for Metals

DRAWINGS

Jet Propulsion Laboratory

J 390 1790	Chamber Weldment
J 390 1791	Forward Dome
J 390 1792	Aft Dome
J 390 1793	Mounting Ring
J 390 1794	Dome Forging

PUBLICATIONS

American Society for Testing and Materials
ASTM Standards

3. REQUIREMENTS

3.1 Conflicting requirements. Any conflicting requirements arising between this specification and any other document listed herein shall be referred in writing to the Jet Propulsion Laboratory (JPL) for interpretation and clarification.

3.2 Requests for deviation. Any deviation from the requirements of this specification or from the drawings, specifications, publications, materials and processes specified herein shall be considered a change or deviation and shall not be allowed except by written authorization from JPL.

3.3 Parts, materials and processes. Parts, materials and processes employed shall conform to the applicable documents specified herein. Where a definite material, part, or process is not specified, the selection for each application shall be suitable for the use intended, and in accordance with the requirements of JPL.

3.3.1 Quality and condition of parts and materials. All parts and materials shall be sound, of uniform quality and condition, and shall be free from seams, cracks, and other defects which might harmfully affect the strength, endurance, or wear of the equipment. Any part or material hammered, filed, or treated in any other manner to conceal defects herein, shall be subject to immediate rejection. Welding to repair defects in any part or materials shall not be performed unless specifically authorized by JPL.

3.3.2 Contractor processes. To enable JPL to broaden the scope of this specification by taking advantage of the contractor's experience, the contractor shall be required to submit to JPL one copy of his processing specification covering materials, cleaning, forging, welding, machining, heat treating and inspection methods to be approved by JPL and thereafter to become a part of this specification.

3.4 Materials. Ti 6Al 4V titanium alloy shall be used for all components except nut plates and rivets. A lot of material for any component shall be defined as the amount of material needed to produce all components of that type for any procurement.

3.4.1 Chemical composition. The chemical composition of the material shall conform to the following:

Chemical Element	Percent by Weight Min	Max
Aluminum	5.50	6.50
Vanadium	3.50	4.50
Iron		0.20
Carbon		0.10
Nitrogen		0.05
Oxygen		0.15
Hydrogen		0.0125
Other elements, total		0.040

3.4.2 Mechanical properties. All material shall conform to the following properties after forging and heat treatment:

a.	Yield strength (0.2% offset)	150,000 psi min
b.	Ultimate strength	160,000 psi min 175,000 psi max
c.	Elongation (4D)	10% min
d.	Reduction in Area	30% min

3.4.3 Transformation temperature. The upper beta transus temperature for material shall be not less than 1810°F.

3.4.4 Additional requirements. Dome forgings shall be manufactured from the minimum possible number of material heats to complete the order. The chemical composition of all heats used shall be carefully selected to minimize the total variation in composition of the entire lot of material. The forward and aft dome forging of each chamber shall be from the same heat of material to the maximum possible extent. Forgings which cannot be mated to another from the same heat shall be matched as closely as possible on the basis of chemical composition and mechanical properties. The material as it is processed from ingot to bar shall be identified so that bars used for dome forgings can be placed end to end as the material was once located in the ingot.

3.4.5 Ultrasonic quality. All material shall be ultrasonically inspected as specified in MIL-STD-271. Any folds, laps, voids, inclusions, cracks, segregation, coarse-grained structure or other defects, which can be positively identified, shall be cause for rejection.

3.4.6 Penetrant inspection. All material shall be penetrant inspected as described in MIL-STD-271 for Type III or IV. Any detectable flaws shall be cause for rejection.

3.5 Forgings. Dome forgings shall be made by the closed die method only. Mounting ring forgings shall be made by the ring rolling method only.

3.5.1 Material traceability. Material for each dome forging shall be serialized progressively from one end of a heat to the other so that the relative position of each forging in the ingot can be traced. The serial number shall be made up of a heat, bar and mult designation with increasing numbers from the top to the bottom of the ingot. The numbers shall then be transferred to the forging when produced.

3.5.2 Forging operations. The material for forging shall be heated to 1725 ±25°F for a sufficient length of time to heat it throughout. Material shall not be allowed to remain at forging temperature longer than 4 hours. The forging operations shall be at such a rate that the energy imparted to form the part does not raise the temperature appreciably causing the microstructure of the finished part to deviate from the requirements of 3.5.4.1.

3.5.2.1 Furnace equipment. Furnaces for heating material to forging temperature shall be surveyed and certified to have an even temperature distribution throughout the heating zone of within ±25°F of the temperature controller set point temperature. All heating operations during forging shall be in a furnace with a clean hearth and an air atmosphere in the heating zone. Combustion products from gas fired furnaces shall not be allowed to enter the heating zone of the furnace or contact hot material at any time. Furnaces used during forging shall be equipped with recording temperature measuring equipment. The records, or duplicates, from this equipment taken during forging shall be identified and forwarded to JPL as a quality control record.

3.5.3 Qualification - dome forgings. Each forging shall be qualified for further processing by dimensional inspection, ultrasonic inspection and microstructural examination. In addition, the forgings from a given heat of material shall be qualified by destructively testing one forging taken from the center of the heat and non-destructively testing two forgings taken from the ends of the heat. The ends and center of each heat shall be located when the bars of that heat are placed end to end as originally located in the ingot. The end forgings tested shall be assigned as aft dome units for further processing.

3.5.3.1 Heat qualification. The two end and a center (total of 3 forgings) qualification forgings shall be tested for tensile properties and examined for microstructure. The forgings shall be sampled for microstructure, machined to a wall thickness not to exceed 0.5 inch. The thickness tolerance shall be ±0.030 inch. The part shall be heat treated as described in 3.6.2.1 and then aged by the same treatment as production forgings. Seven tensile specimens shall then be prepared from the center forging as shown in Figure 1. Four specimens from each end forging shall be prepared as shown in Figure 2. These specimens shall be prepared and tested as described by FED-STD-151. The size of each specimen shall be identical and of maximum size as permitted by the forging cross section. The results of this test shall conform to the requirements of 3.4.2 Any deviations from these requirements shall be cause for rejection of the entire heat of forgings.

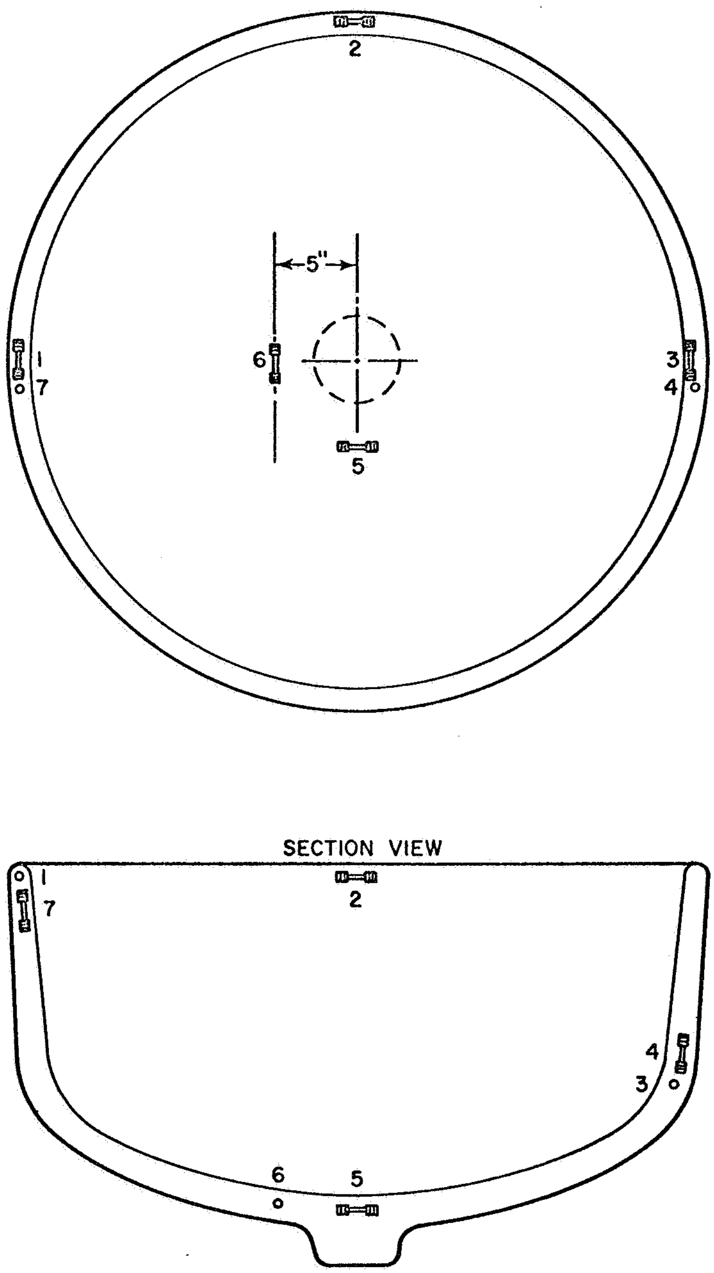


Figure 1. Qualification Forging, Middle

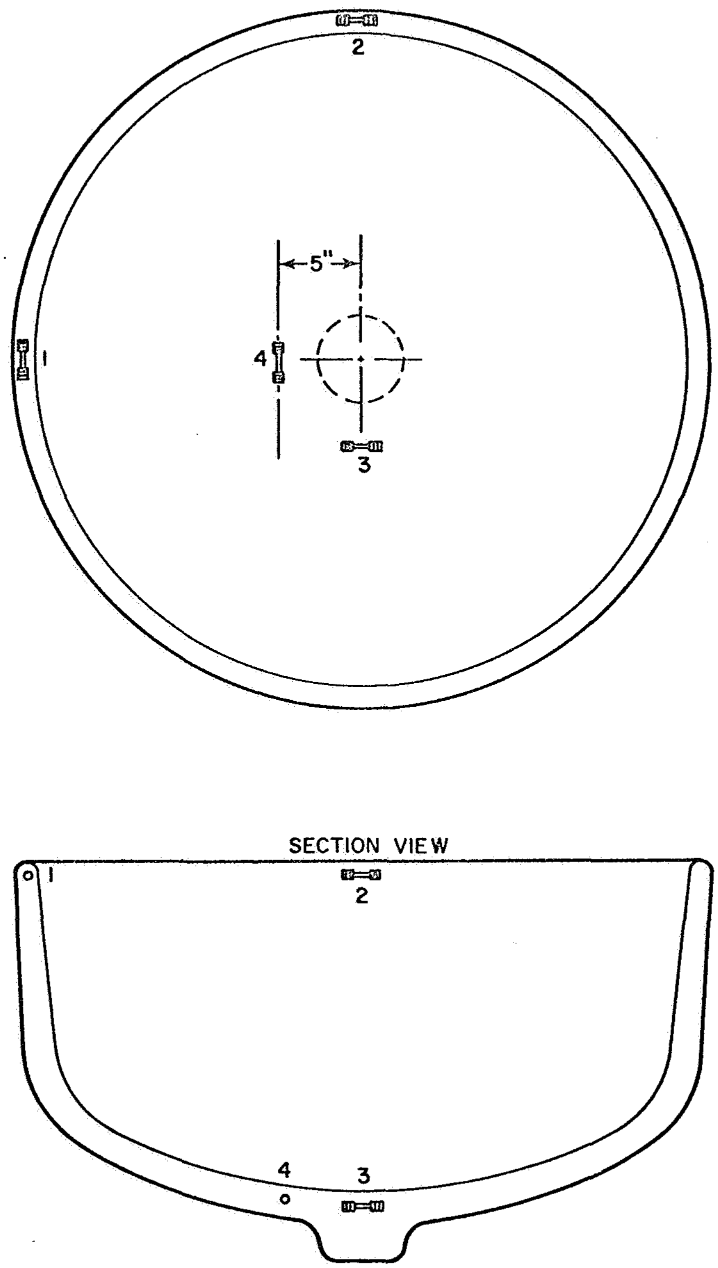


Figure 2. Qualification Forging, End

3.5.3.1.1 First forging. The first forging produced shall be sectioned on a plane through the axis of revolution and macro-etched for forging flow. Examination shall reveal all flow lines parallel to the outside surface of the forging. Any evidence of non-parallel flow shall be cause for rejection of the entire lot of forgings. The first end forging produced shall be sampled in the boss and near the open end for hydrogen analysis. The results of this test shall conform to the requirements of 3.4.1. This forging shall be the center qualification forging of the first heat forged.

3.5.3.1.2 Microstructural analysis. Microstructural analysis of each qualification forging shall meet the requirements of 3.5.3.2 or the tensile results of that forging shall be rejected and a new adjacent forging shall be qualified in its place.

3.5.3.2 Individual qualification. Each dome forging shall be sampled in the "as forged" condition from the open end of the forging for metallographic examination. Examination of the prepared sample shall show an equiaxed fine grain alpha beta microstructure with a minimum of 30 percent primary alpha phase in the alpha-beta matrix. The maximum grain size of the primary alpha phase shall be no larger than 6 as measured by ASTM Method No. E19-46. Deviations from the forging requirements shall be cause for rejection of the forging.

3.5.3.2.1 Ultrasonic inspection. Each forging shall be prepared for ultrasonic inspection by contour machining the inside the outside surfaces, except for the boss area and end prolongation, to the same wall thickness used for heat qualification (3.5.3.1). The maximum thickness tolerance shall be ±0.030 inch. The surface finish shall be 125 rms or better. Ultrasonic inspection shall be accomplished by the 45 degree shear wave technique as described by MIL-STD-271 for ring forgings. The test unit shall be calibrated to a surface notch 0.010 inch deep, 0.020 inch wide and 1.0 inch long. Any defects which exceed one-half the calibration signal height shall be cause for rejection.

3.5.3.2.2 Tensile test. From the prolongation at the open end of each forging, one tensile test specimen shall be prepared after solution heat treatment of the forging has been accomplished as stated in 3.6.2. The specimen shall be the same size as those used for forging lot qualification (3.5.3.1). The specimen shall be aged to the STA condition using the aging treatment determined to meet the mechanical properties specified in 3.4.2. Tensile testing shall be done as described by FED-STD-151. Forgings with tensile properties which deviate from 3.4.2 shall be subject to rejection.

3.5.4 Qualification - mounting ring forging. Ring forgings shall be qualified as a lot (heat) by preparing four tensile test specimens, one longitudinal and one long transverse from two diametrically opposing locations from a ring forging which has been selected at random. The forging shall be solution heat-treated and aged as stated in 3.6.2. The aging treatment shall be the same as used for production units. Specimens shall be prepared and tested as specified in FED-STD-151. The results of these tests shall meet the requirements stated in 3.4.2 or the entire lot of forging shall be subject to rejection.

3.5.4.1 Microstructural inspection. Individual ring forgings shall be qualified by microstructural examination and ultrasonic inspection. Each forging shall be sampled for microstructural examination in the "as forged" condition. The microstructure shall be equiaxed with a minimum of 30 percent primary alpha phase in an alpha-beta matrix. The maximum grain size permitted shall be 6 as measured by ASTM Method No. E19-46.

3.5.4.2 Ultrasonic inspection. Each forging shall be ultrasonically inspected for defects by 45 degree shear wave techniques as specified in MIL-STD-271. Forgings shall be prepared for inspection by machining all surfaces smooth and parallel. Only enough material to clean up the surfaces shall be removed. The surface finish shall not exceed 125 rms. Defects which exceed one-half the signal height produced by a calibration notch 0.020 inch wide, 0.010 inch deep and 1.0 inch long shall be cause for rejection.

3.6 Fabrication. The fabrication of the motor case shall be in accordance with the documents specified in Section 2 herein.

3.6.1 Motor case processing. Processing methods and sequences not covered by this specification shall be established by the contractor. Detailed planning sheets shall be submitted to the JPL cognizant engineer for approval prior to start of manufacture. In addition, the contractor shall be subject to spot-checking by JPL, to assure that good engineering, manufacturing, and quality control practices are being used.

3.6.2 Heat treatment. All forgings (ring and dome) shall be solution heat treated as stated in 3.6.2.1 after being machined to the thickness specified for ultrasonic inspection (3.5.3.1 and 3.5.4.2). After solution treating and before machining to JPL Drawings J 390 1790, J 390 1791, J 390 1792, J 390 1793 and J 390 1794, the parts shall be straightened and stress relieved as stated in 3.6.2.2. Aging shall be accomplished after the parts are welded into the assembly and before final machining. After solution treatment, one (in addition to 3.5.3.2.2) tensile specimen shall be prepared from each dome forging and processed through stress relieving and aging treatments with the part from which it was obtained. These shall be tested as described by FED-STD-151. The results shall conform to the properties stated in 3.4.2. Any deviations shall be cause for rejection of the unit. All parts shall be solvent degreased prior to any heating operation. Chlorinated solvents shall not be used for cleaning parts prior to heat treatment.

3.6.2.1 Solution treatment. All parts shall be solution treated at a temperature between 1600 and 1750°F. The exact temperature shall be determined to meet the tensile requirements of 3.4.2. Parts shall be held for one hour at temperature and quenched in water. The quench delay time for transfer between furnace and quench tank shall be less than 6 seconds. The temperature of the quench water shall not exceed 100°F at the end of the quenching operation. Domes shall be quenched open end down with a 2 inch minimum diameter vent hole through the boss.

3.6.2.1.1 Furnace equipment. Furnaces used for solution heat treatment shall be certified to have a maximum temperature variation in the heating zone of ±10°F from the set point temperature of the furnace controller. Furnaces heated by combustion shall be so designed that combustion products will not enter the heating zone of the furnace or at no time come in contact with hot titanium parts. The furnace shall be equipped with temperature recording equipment which provides a permanent record of the heating cycle. The temperature record (or a copy) of each cycle shall be identified and supplied as a quality control record.

3.6.2.2 Aging and stress relieving. The aging treatment shall be determined by test in conjunction with the solution treating temperature to obtain the properties as described in 3.4.2. The aging temperature shall be between 950 and 1150°F. Any stress relief treatment after solution treating shall be considered as part of the aging treatment. Stress relief shall be at the aging temperature determined to meet the property requirements of 3.4.2 and for one-half the time determined. The aging and stress relieving temperature shall be controlled to ±10°F. Stress relief and aging shall be accomplished in an air atmosphere furnace certified to have a maximum temperature variation in the heating zone of ±10°F from the set point temperature of the furnace controller. Temperature recording equipment shall be used to provide a permanent record of the temperature cycle which shall be supplied as a quality control record.

3.6.3 Machining. Planning and inspection procedures shall be developed for machining of domes and mounting rings to assure that a minimum of 0.10 inch of material is removed from all surfaces after solution heat treatment. Machine finish of all parts shall be 64 rms or better.

3.6.4 Welding. All welding shall be done by the automatic or semi-automatic TIG process or by the electron beam method. All welding shall be done in a rigid chamber capable of maintaining a 99.9 percent pure inert atmosphere with a dew point of less than -60°F or a vacuum of 10^{-4} mm

Hg for electron beam welding. For all TIG welding, reactor grade helium or liquid argon shall be used. The welding technique shall be in conformance with the best practice used for titanium to avoid interstitial contamination. Prior to welding all weld tooling shall be approved by the JPL cognizant engineer.

3.6.4.1 Prewelding requirements. Prior to any welding, the following steps shall be taken to assure conformity of the motor case welds to the requirements of this specification:

a. The optimum ranges of all welding machine variables shall be determined for each weld set up and recorded. The settings will be used on all production units to maintain the required high standards of weld reproducibility.

b. Employing the optimum setting determined in a. above, two simulated production welds for each type of joint shall be made for testing as described in 4.3.3. The welds shall be made on rings of forged material which have been machined to simulate the weld joint.

3.6.4.2 Repair welding. Repair welds are not permitted.

3.6.4.3 Weld discontinuities. The mismatch of all mating parts shall be no greater than 10 percent of the thickness after welding. Material on either side of the weld shall blend smoothly with the weld bead, without any visible contour change or marks from weld tooling.

3.6.4.4 Weld dressing. The chamber girth weld shall have a reinforcement on both sides, greater than 0.003 inch but less than 0.015 inch. The mounting ring weld shall have a reinforcement on both sides, greater than 0.006 inch but less than 0.030 inch. All weld beads shall be straight, smooth, and of constant width.

3.6.4.5 Cleaning prior to welding. All parts and filler wire, if used, shall be cleaned by a suitable means to remove all traces of hydrocarbons and other foreign materials. The clean weld edges shall be protected with aluminum foil until assembly. During assembly, parts will be handled only with clean white lint free gloves.

3.6.5 Electro-chemical etching. After aging, each unit shall be electroetched by the Ti Brite process to remove 0.0002 to 0.0003 inch of material from the inside and outside surfaces. Inside etching shall be done using an inside anode shaped to obtained even metal removal. No additional surface conditioning as cleaning (i.e., glass bead blasting) except for solvent degreasing is required on the outside of the unit.

3.6.6 Internal surface conditioning. The entire interior surface of each unit shall be glass bead blasted to prepare the surface for subsequent bonding-on of rubber insulation. Bead size and impingement velocity shall be such as to provide a matte surface texture with a surface finish not exceeding 64 rms.

3.7 Identification. The identification of motor cases shall be in accordance with JPL Specification ZPO-20002-PRS. Serial and part numbers shall be electroetched on all piece parts and final assemblies. Piece part numbers can be removed during assembly.

3.8 Records. It shall be the responsibility of the contractor to prepare and maintain all records necessary to assure compliance with this specification and the applicable drawings. A copy of all records shall be presented to JPL. These records shall include, but shall not be limited to, the following:

a. Material certifications.
b. Furnace cycle records.
c. Forging certifications.
d. Weld sample qualification reports.

e. Fluorescent penetrant inspection reports.

f. Radiographic inspection reports.

g. Engineering drawing compliance affidavit, including any approved deviations.

h. All data obtained under the quality assurance provisions herein.

3.9 Workmanship. Each unit shall be examined to determine conformance with this specification, as well as the requirements of the applicable documents listed in Section 2 herein, and to verify that the materials, construction finish, marking, and identification, are suitable for the purpose intended and completed in a thorough and workmanlike manner.

4. QUALITY ASSURANCE PROVISIONS

4.1 Inspection. The inspection by the contractor shall include such visual and mechanical examination and testing of materials, subassemblies, and parts during the process of manufacture as may be required to assure that the complete unit will meet all the requirements of this specification. All parts, subassemblies, or assemblies which deviate from the requirements of the applicable drawings or applicable specifications shall be submitted to JPL for acceptance or rejection.

4.2 Inspection provisions. Final inspection of each subassembly and each completed unit will be done in the presence of the JPL source inspector. Spot checks will also be made during processing by the JPL source inspector, to verify that proper quality assurance measures are being taken.

4.2.1 Dimensional inspection records. Dimensions measured during final inspection shall be recorded on the appropriate JPL inspection forms.

4.3 Test methods and procedures.

4.3.1 Fluorescent penetrant inspection. All surfaces of machined parts shall be fluorescent penetrant inspected per MIL-STD-271, Type III or Type IV, prior to welding into any assembly. In addition, all welds and an area within two inches of each side of the weld shall be inspected. Final penetrant inspection of the assembled unit shall be made after heat treating and final machining. Any cracks, folds, laps, or seams detected shall be cause for rejection.

4.3.2 Radiographic inspection. All welds shall be 100 percent inspected by radiographic methods in accordance with MIL-STD-271. Acceptance criteria of welds shall be as follows.

4.3.2.1 Chamber girth weld. Chamber girth weld shall conform to the following:

a. All weld defects other than spherical porosity and spherical inclusions shall be cause for rejection. Inclusions shall be judged by the same standards as porosity.
b. Porosity in excess of 0.010 inch in diameter shall be cause for rejection.
c. Clusters of porosity, 2 or more pores spaced closer than 4 times the maximum adjacent pore diameter, shall be rejectable.
d. More than 10 pores in 1.0 inch of weld length shall be rejectable.

4.3.2.2 Mounting ring weld. Mounting ring weld shall conform to the following:

a. All weld defects other than spherical porosity and spherical inclusions shall be cause for rejection. Inclusions shall be judged by the same standards as porosity.

b. Porosity in excess of 0.030 inch in diameter shall be cause for rejection.

c. Clusters of porosity, 2 or more pores spaced closer than 2 times the maximum adjacent pore diameter in the cluster, shall be cause for rejection.

d. More than 10 pores in 1.0 inch of weld length shall be rejectable.

4.3.3 Weld qualification. Two (solution treated) weld specimens for each joint type shall be made as specified in 3.6.4.1. These specimens shall be prepared at the beginning of the production run. The specimens shall be aged per 3.6.2.2, radiographed, and penetrant inspected. One tensile specimen shall be prepared from each sample having a 2 inch long by 0.5 inch wide gage length. These samples shall be tested. The ultimate strength shall not be less than 140,000 psi. Failure of coupons to meet this requirement will require investigation to determine the cause and rerunning of the weld qualification.

4.3.3.1 Micro-hardness measurement. A sample shall be prepared from each weld specimen for micro-hardness measurements. A hardness traverse with impressions at 0.005 inch interval across the weld shall be made. The hardness shall be not more than 30 diamond hardness numbers above the parent metal hardness.

4.3.4 Proof testing. Hydrostatic pressure testing shall consist of raising the unit to the proof pressure while simultaneously measuring the volume increase of the unit. Pressure shall be measured by a suitable recording transducer system with an overall system accuracy of 1.0 percent. Volumetric measurements can be made manually by measuring vessel displacement or liquid pumped in. Accuracy of volumetric measurements shall be within 1.0 percent. Sufficient data shall be taken during the test to plot a graph, of pressure versus volume increase, with at least 10 data points. The proof pressure cycle shall raise the internal pressure of each motor case to 302 ±2 psi and hold at pressure for 5 minutes. Each unit shall be subjected to only one proof test cycle. A record of the pressure test cycle and the graph, of pressure versus volume, shall be supplied to JPL as part of the quality control records.

5. PREPARATION FOR DELIVERY

5.1 Serializing. Each motor case shall be assigned a serial number after being welded into a complete assembly. This number shall be affixed to all records pertaining to the motor case.

5.2 Packaging. Each motor case shall be sealed in a plastic bag, and packaged in a suitable container which is strong enough to preclude damage in shipment, in accordance with JPL Specification 20064.

6. NOTES

6.1 Intended use. This motor case is intended for use as part of the apogee rocket motor for the Advanced Technology Satellite.

APPENDIX B

Design Drawings, Titanium Rocket Motor Case

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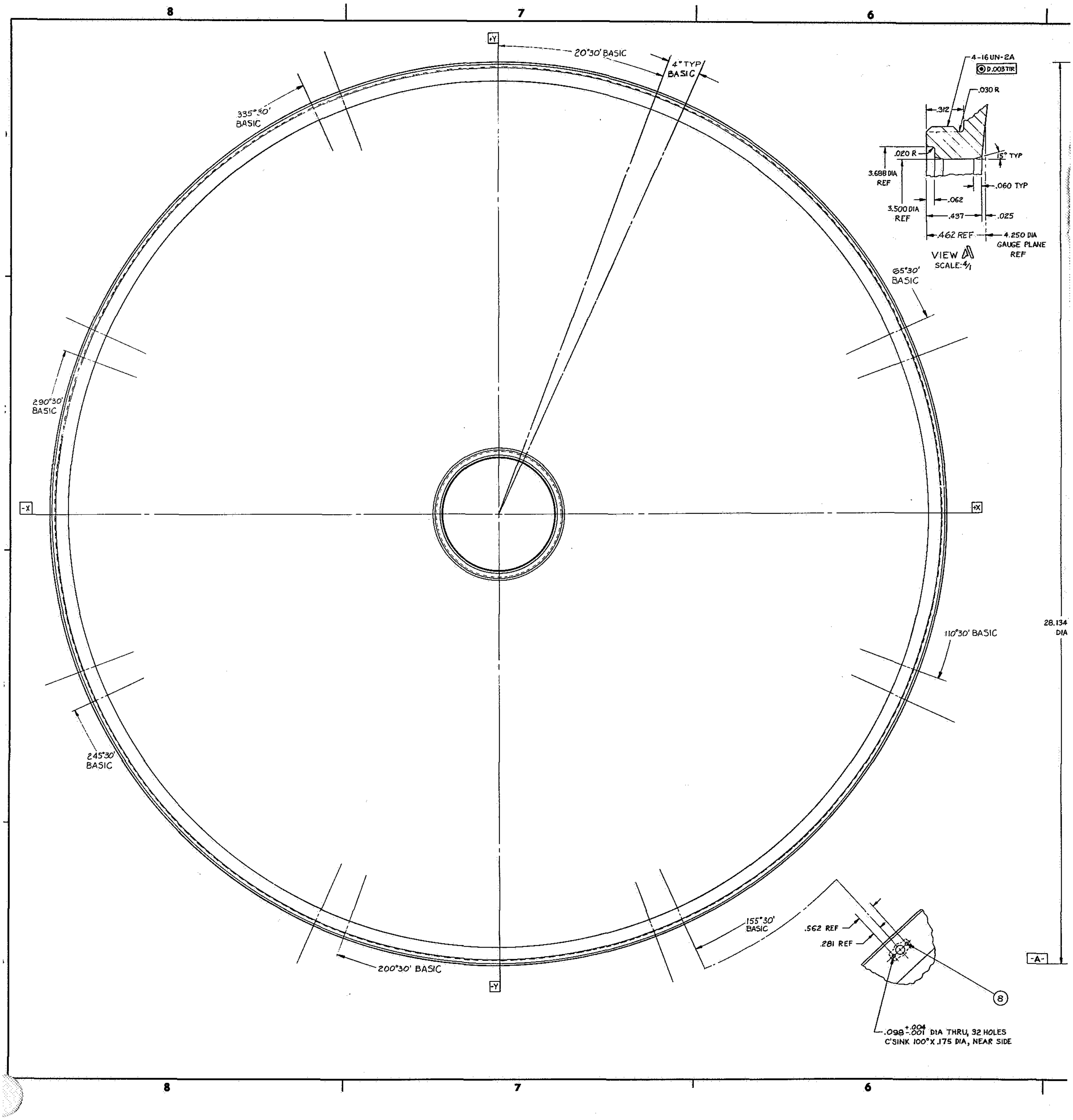

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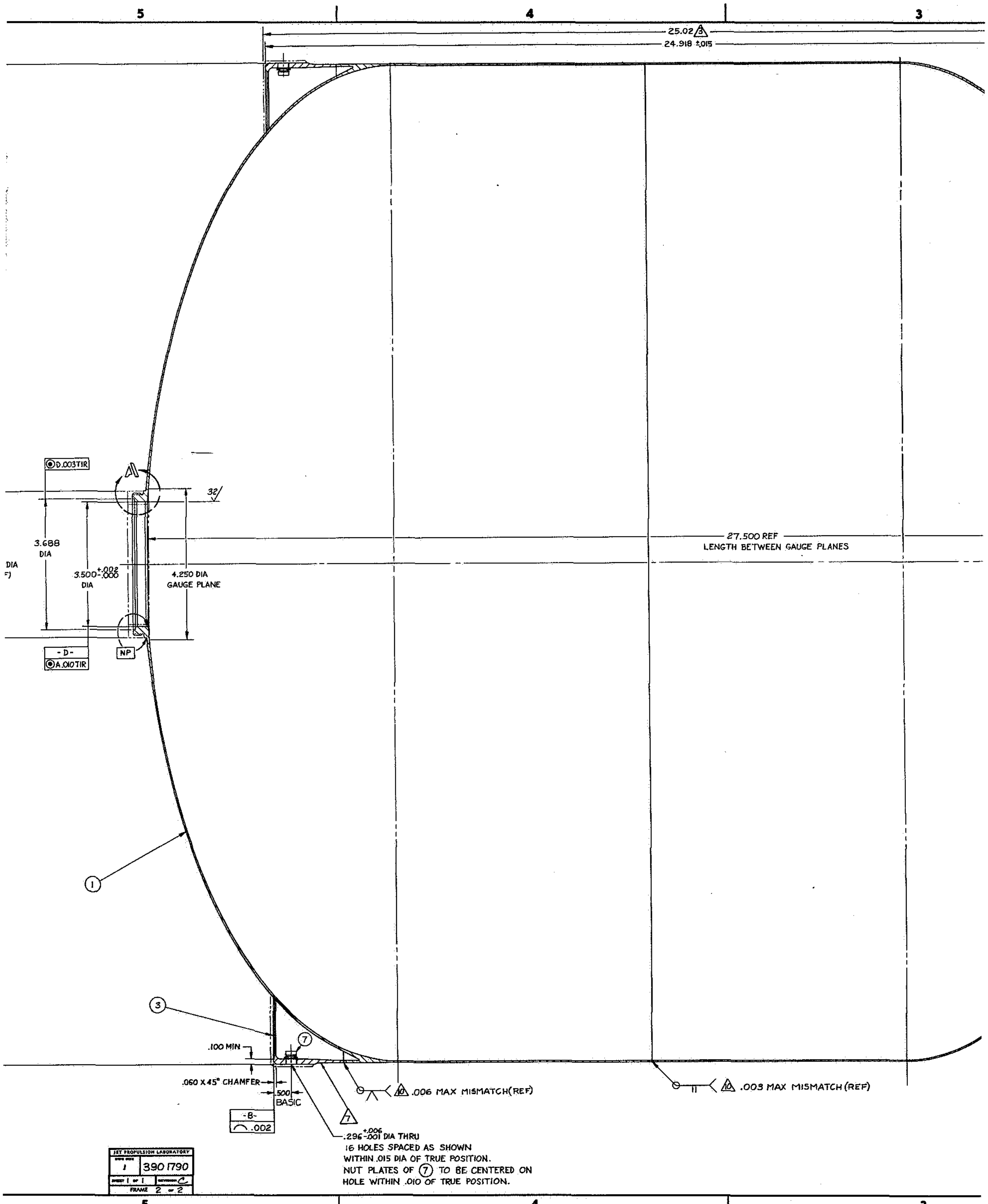

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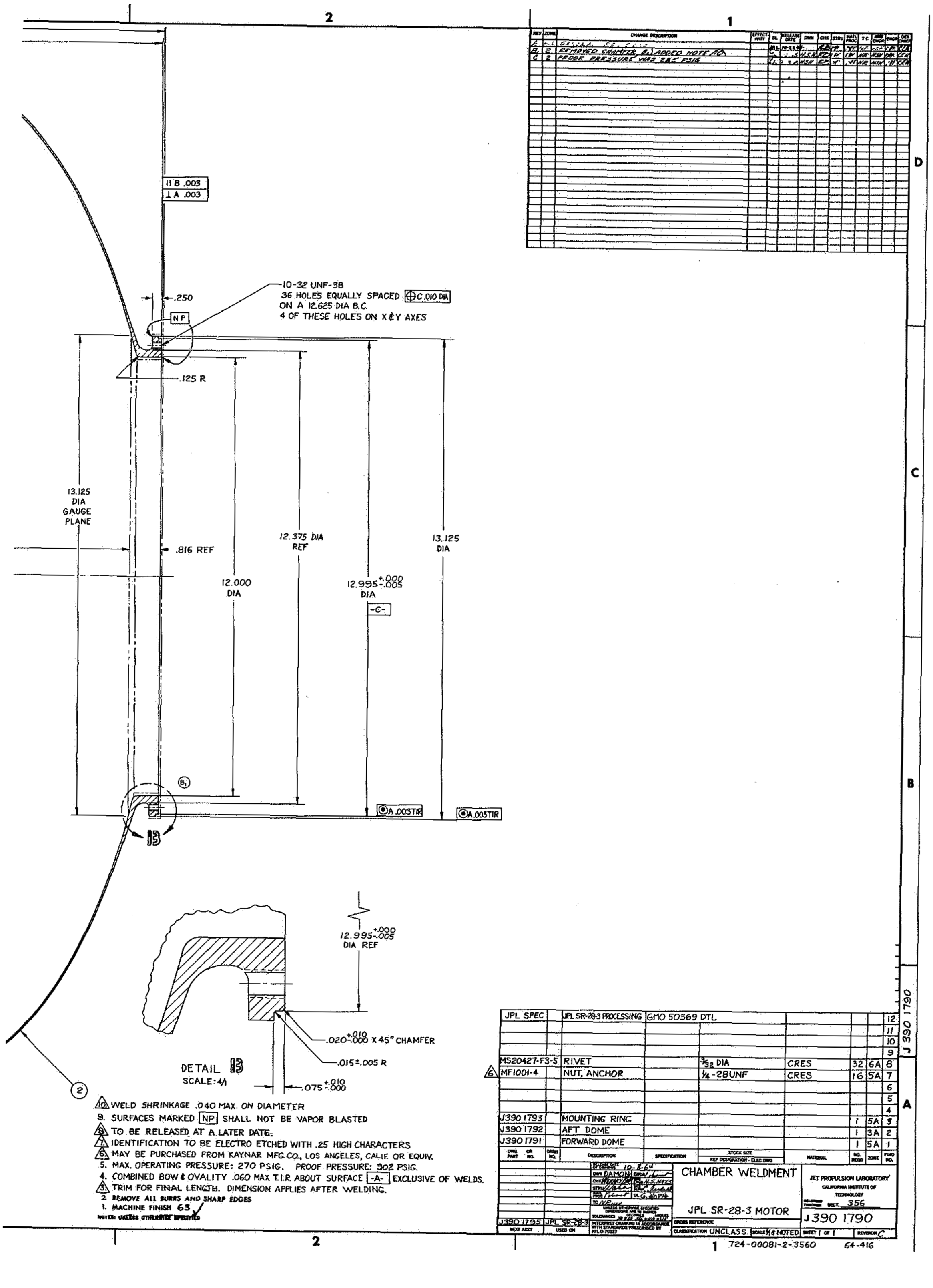
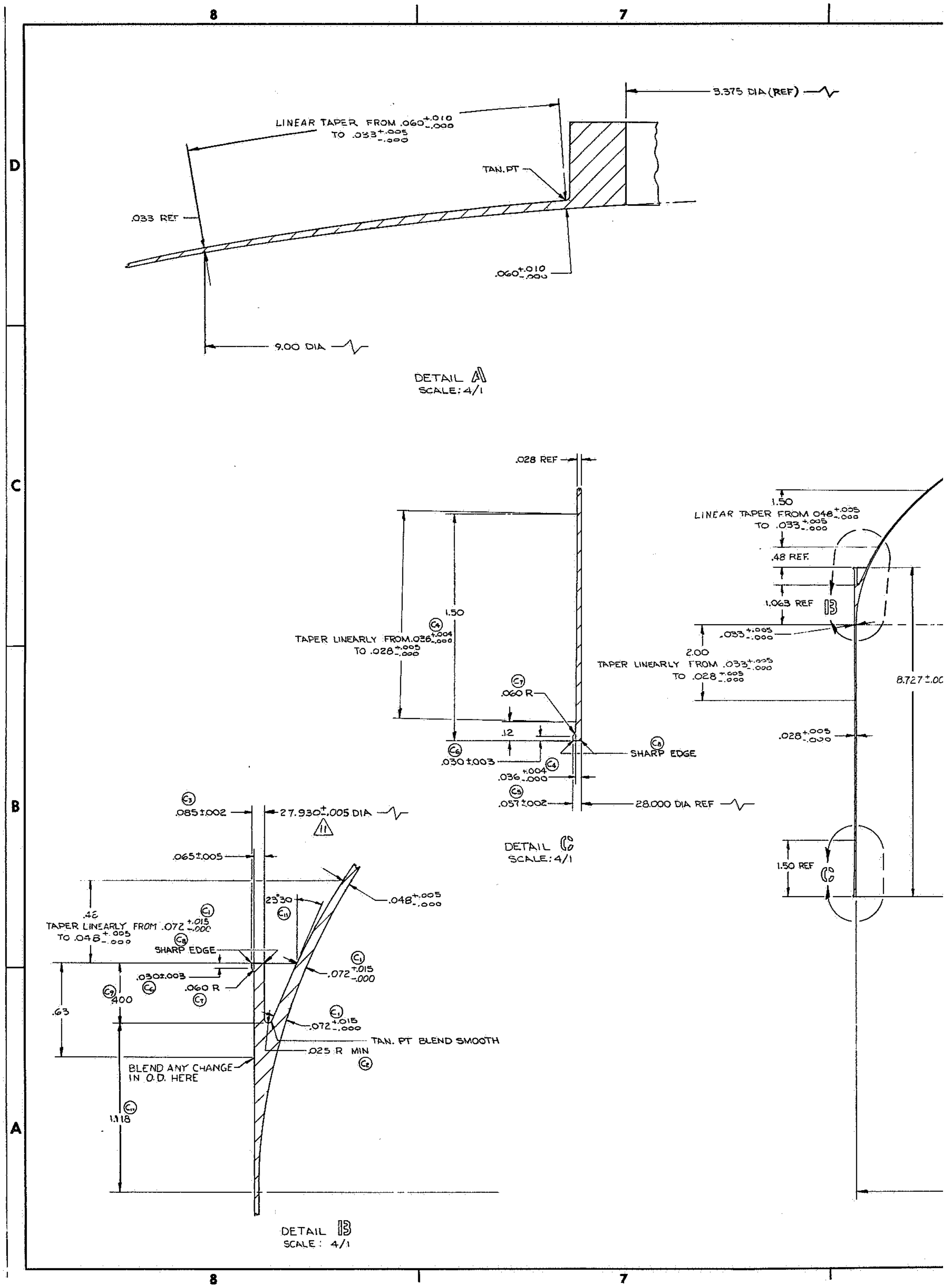
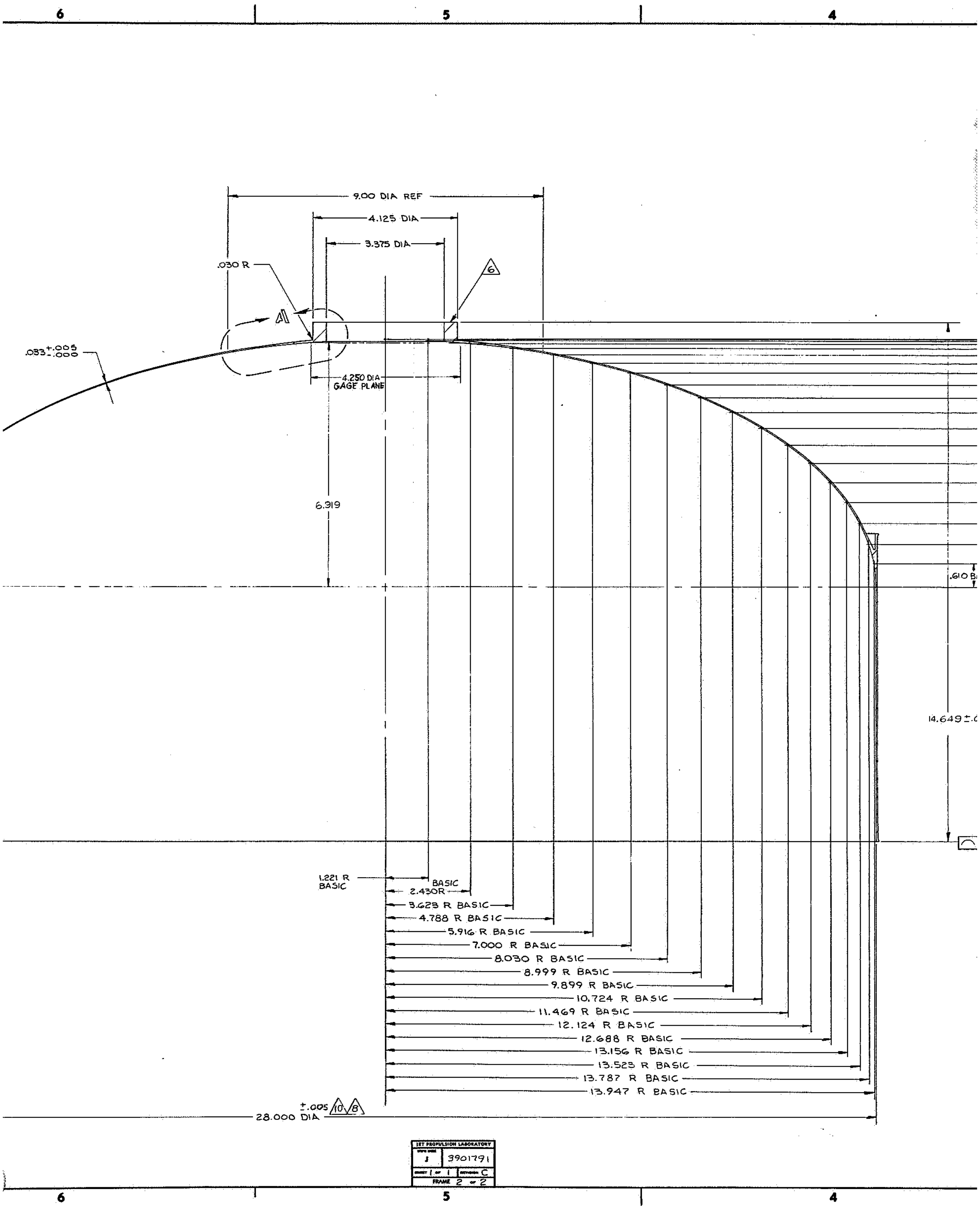


B 2 REMOVED CHAMFER, ADDED NOTE 10
C 2 PROOF PRESSURE WAS 285 PSIG
∥ B .003
⊥ A .003
10-32 UNF-3B
36 HOLES EQUALLY SPACED ⊕ C .010 DIA
ON A 12.625 DIA B.C.
4 OF THESE HOLES ON X & Y AXES
.250
NP
.125 R
13.125 DIA GAUGE PLANE
.816 REF
12.000 DIA
12.375 DIA REF
12.995 +.000 -.005 DIA
-C-
13.125 DIA
A .003 TIR
A .003 TIR
DETAIL B
SCALE: 4/1
12.995 +.000 -.005 DIA REF
.020 +.010 -.000 X 45° CHAMFER
.015±.005 R
.075 +.010 -.000
10 WELD SHRINKAGE .040 MAX. ON DIAMETER
9. SURFACES MARKED NP SHALL NOT BE VAPOR BLASTED
8 TO BE RELEASED AT A LATER DATE.
7 IDENTIFICATION TO BE ELECTRO ETCHED WITH .25 HIGH CHARACTERS
6 MAY BE PURCHASED FROM KAYNAR MFG. CO., LOS ANGELES, CALIF. OR EQUIV.
5. MAX. OPERATING PRESSURE: 270 PSIG. PROOF PRESSURE: 302 PSIG.
4. COMBINED BOW & OVALITY .060 MAX T.I.R. ABOUT SURFACE -A- EXCLUSIVE OF WELDS.
3 TRIM FOR FINAL LENGTH. DIMENSION APPLIES AFTER WELDING.
2 REMOVE ALL BURRS AND SHARP EDGES
1. MACHINE FINISH 63
NOTES: UNLESS OTHERWISE SPECIFIED
JPL SPEC | JPL SR-28-3 PROCESSING | GMO 50369 DTL
MS20427-F3-5 | RIVET | 3/32 DIA | CRES | 32 | 6A | 8
MF1001-4 | NUT, ANCHOR | 1/4-28UNF | CRES | 16 | 5A | 7
J390 1793 | MOUNTING RING | 1 | 5A | 3
J390 1792 | AFT DOME | 1 | 3A | 2
J390 1791 | FORWARD DOME | 1 | 5A | 1
DWG OR PART NO. | DASH NO. | DESCRIPTION | SPECIFICATION | STOCK SIZE / REF DESIGNATION - ELEC DWG | MATERIAL | NO. REQD | ZONE | FIND NO.
10-8-64
DWN DAMON
CHAMBER WELDMENT
JPL SR-28-3 MOTOR
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
SECT. 356
J390 1795 | JPL SR-28-3
NEXT ASSY | USED ON
CLASSIFICATION UNCLASS. SCALE 1/4 NOTED
J390 1790
SHEET 1 OF 1
REVISION C
724-00081-2-3560
64-416



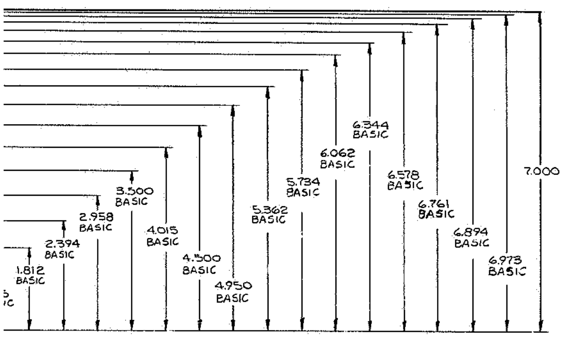
LINEAR TAPER FROM .060 +.010 -.000 TO .033 +.005 -.000
3.375 DIA (REF)
TAN. PT
.033 REF
.060 +.010 -.000
9.00 DIA
DETAIL A
SCALE: 4/1
.028 REF
1.50
TAPER LINEARLY FROM .036 +.004 -.000 TO .028 +.005 -.000
.060 R
.12
SHARP EDGE
.030 ±.003
.036 +.004 -.000
.057 ±.002
28.000 DIA REF
DETAIL C
SCALE: 4/1
LINEAR TAPER FROM .048 +.005 -.000 TO .033 +.005 -.000
.48 REF
1.063 REF
.033 +.005 -.000
2.00
TAPER LINEARLY FROM .033 +.005 -.000 TO .028 +.005 -.000
.028 +.005 -.000
1.50 REF
.085 ±.002
27.930 ±.005 DIA
.065 ±.005
.42
TAPER LINEARLY FROM .072 +.015 -.000 TO .048 +.005 -.000
SHARP EDGE
23°30'
.048 +.005 -.000
.072 +.015 -.000
.030 ±.003
.060 R
.400
.63
.072 +.015 -.000
TAN. PT BLEND SMOOTH
.025 R MIN
BLEND ANY CHANGE IN O.D. HERE
1.118
DETAIL B
SCALE: 4/1

FOLDOUT FRAME



FOLDOUT FRAME 2

FOLDOUT FRAME



⚠11 MATCH DIAMETER OF MATING PART BEFORE WELDING TO ALLOW .006 MAX MISMATCH AFTER WELDING

⚠10 MATCH DIAMETER OF MATING PART BEFORE WELDING TO ALLOW .003 MAX MISMATCH AFTER WELDING.

9. CONTOUR OF ELLIPSE TO BE WITHIN ±.010 OF TRUE SHAPE.

⚠8 CALCULATED FROM PI-TAPED O.D. LESS THICKNESS.

⚠7 SPEC (4) TO BE RELEASED AT A LATER DATE.

⚠6 IDENTIFICATION PER (4).

5. ALL OFFSET DIMENSIONS ARE COORDINATES OF A 14.000 X 23.000 ELLIPSE AT INCREMENTS OF 5° TO INSIDE SURFACE.

4. INSIDE CONTOUR SAME AS J3901792

3. MACHINED FILLET RADIUS: —
2. REMOVE ALL BURRS AND SHARP EDGES
1. MACHINE FINISH 63

NOTES: UNLESS OTHERWISE SPECIFIED

DWG OR PART NO.	DASH NO.	DESCRIPTION	SPECIFICATION	STOCK SIZE / REF DESIGNATION - ELEC DWG	MATERIAL	NO. REQD	ZONE	FIND NO.
JPL SPEC		JPL SR-28-3 PROCESS						4
								3
								2
		DOME		MAKE FROM J390-774				1

NEXT ASSY	USED ON
J390-790	JPL SR-28-3

RELEASE DATE OF DRAWING 10-7-64

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES. INTERPRET DRAWING IN ACCORDANCE WITH STANDARDS PRESCRIBED BY MIL-D-70327

DOME, FORWARD (JPL SR-28-3 MOTOR)

JET PROPULSION LABORATORY CALIFORNIA INSTITUTE OF TECHNOLOGY

RELEASED THROUGH SECT. 356

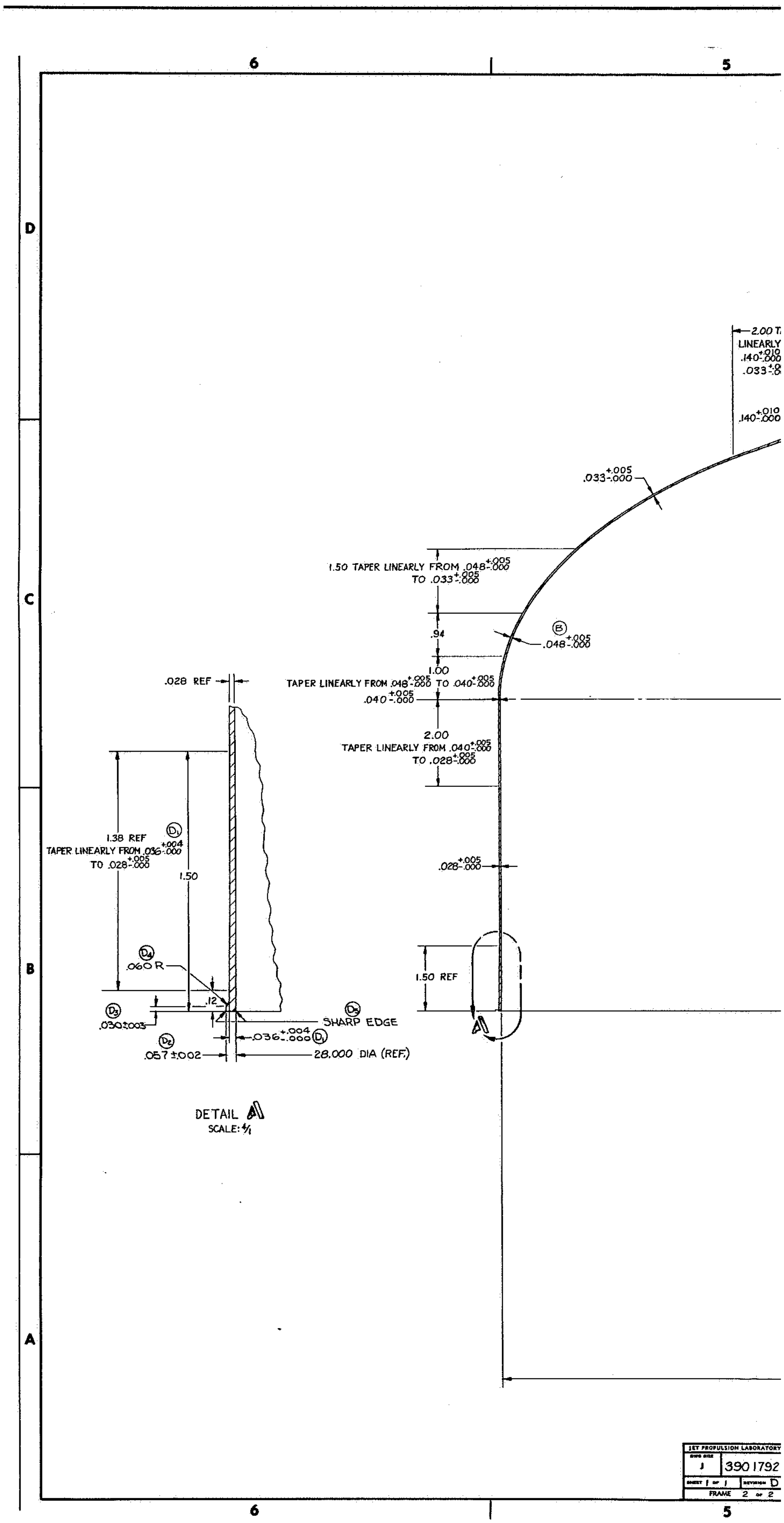
J 3901791

CLASSIFICATION UNCLASS | SCALE ½ & NOTED | SHEET 1 OF 1 | REVISION C

724-00001-2-3560 64-416

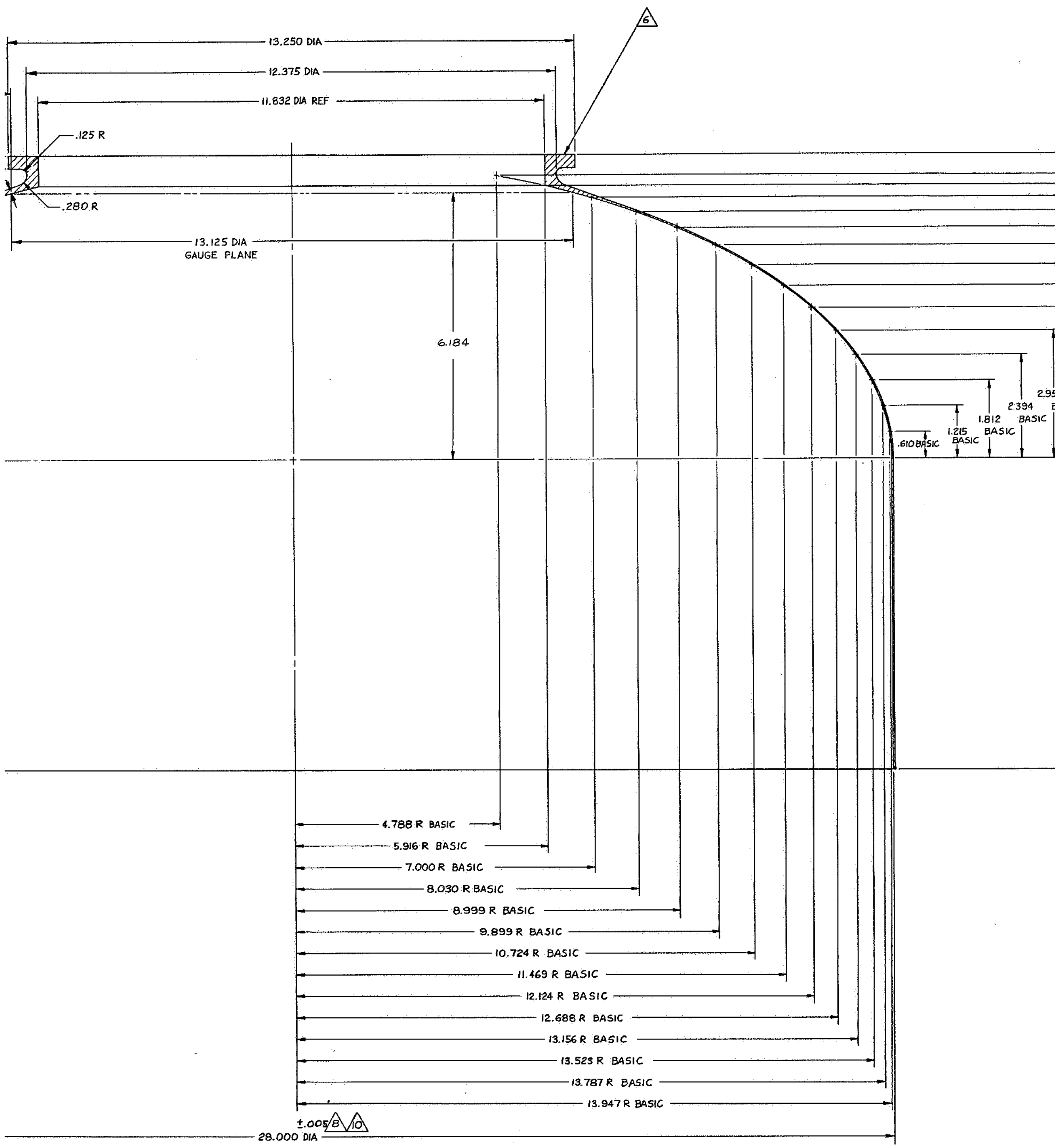
FOLDOUT FRAME 3

FOLDOUT FRAME

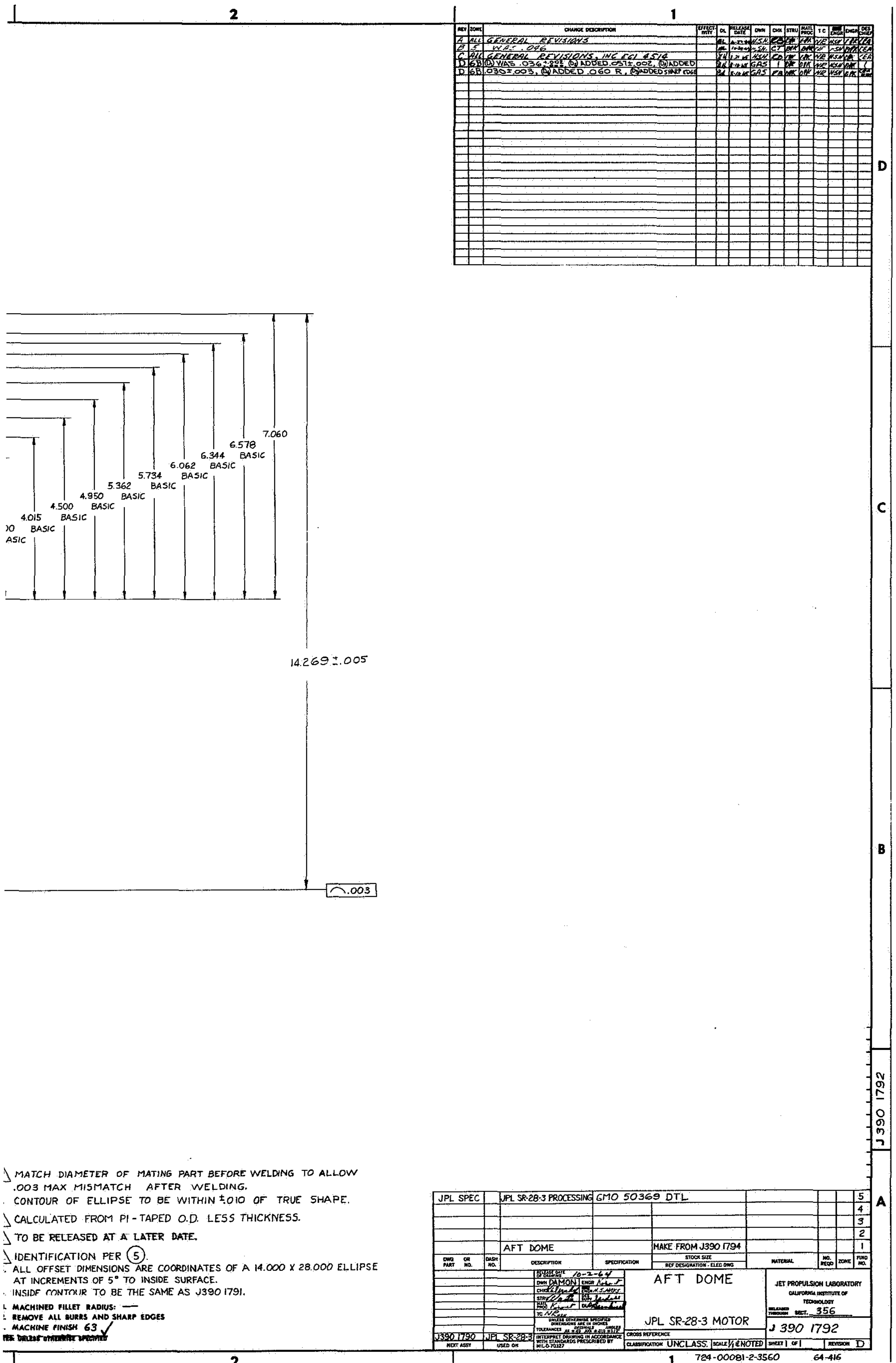


FOLDOUT FRAME

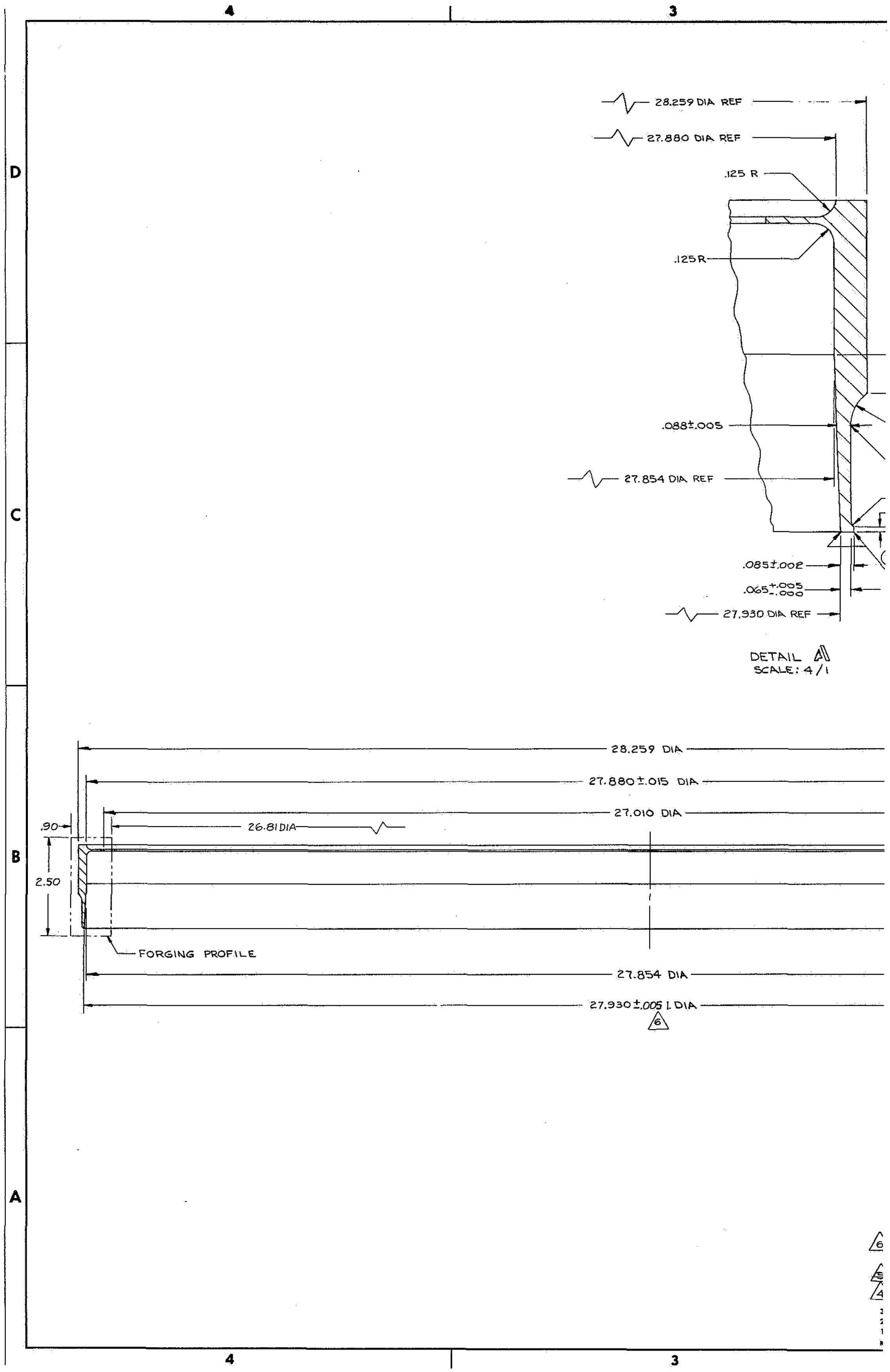
4 3


13.250 DIA
12.375 DIA
11.832 DIA REF
6
.125 R
.280 R
13.125 DIA
GAUGE PLANE
6.184
2.95
2.394
BASIC
1.812
BASIC
1.215
BASIC
.610 BASIC
4.788 R BASIC
5.916 R BASIC
7.000 R BASIC
8.030 R BASIC
8.999 R BASIC
9.899 R BASIC
10.724 R BASIC
11.469 R BASIC
12.124 R BASIC
12.688 R BASIC
13.156 R BASIC
13.523 R BASIC
13.787 R BASIC
13.947 R BASIC
±.005 8 10
28.000 DIA

4 3


GENERAL REVISIONS
GENERAL REVISIONS, INC ECI 4514
7.060
6.578 BASIC
6.344 BASIC
6.062 BASIC
5.734 BASIC
5.362 BASIC
4.950 BASIC
4.500 BASIC
4.015 BASIC
14.269 ±.005
.003
MATCH DIAMETER OF MATING PART BEFORE WELDING TO ALLOW .003 MAX MISMATCH AFTER WELDING.
CONTOUR OF ELLIPSE TO BE WITHIN ±.010 OF TRUE SHAPE.
CALCULATED FROM PI-TAPED O.D. LESS THICKNESS.
TO BE RELEASED AT A LATER DATE.
IDENTIFICATION PER (5).
ALL OFFSET DIMENSIONS ARE COORDINATES OF A 14.000 X 28.000 ELLIPSE AT INCREMENTS OF 5° TO INSIDE SURFACE.
INSIDE CONTOUR TO BE THE SAME AS J390 1791.
MACHINED FILLET RADIUS: —
REMOVE ALL BURRS AND SHARP EDGES
MACHINE FINISH 63
JPL SPEC
JPL SR-28-3 PROCESSING
GMO 50369 DTL
AFT DOME
MAKE FROM J390 1794
AFT DOME
JPL SR-28-3 MOTOR
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
J 390 1792
J390 1790
JPL SR-28-3
CLASSIFICATION UNCLASS.
SCALE 1/1 & NOTED
SHEET 1 OF 1
REVISION D
724-00081-2-3560
64-416

FOLDOUT FRAME

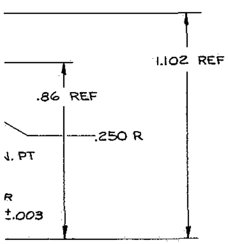


FOLDOUT FRAME

2 1

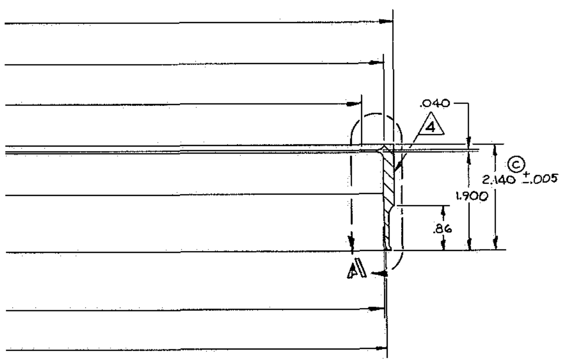
REV	ZONE	CHANGE DESCRIPTION	EFFECTIVITY	DL	RELEASE DATE	DWN	CHK	STRU	MATL PROC	T C	[illegible] ENGR	ENGR	DES CHIEF
A	ALL	GENERAL REVISIONS		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B		ADDED NOTE [illegible] & TOLERANCE WAS ±.001		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
C	2B	WAS 2.060		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
D	3C	REMOVED: 45° & .025±.005; ADDED: .08R±.002,		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
D		.030±.002, .060R, & SHARP EDGE.		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

D



C

RP EDGES



B

J 3901793

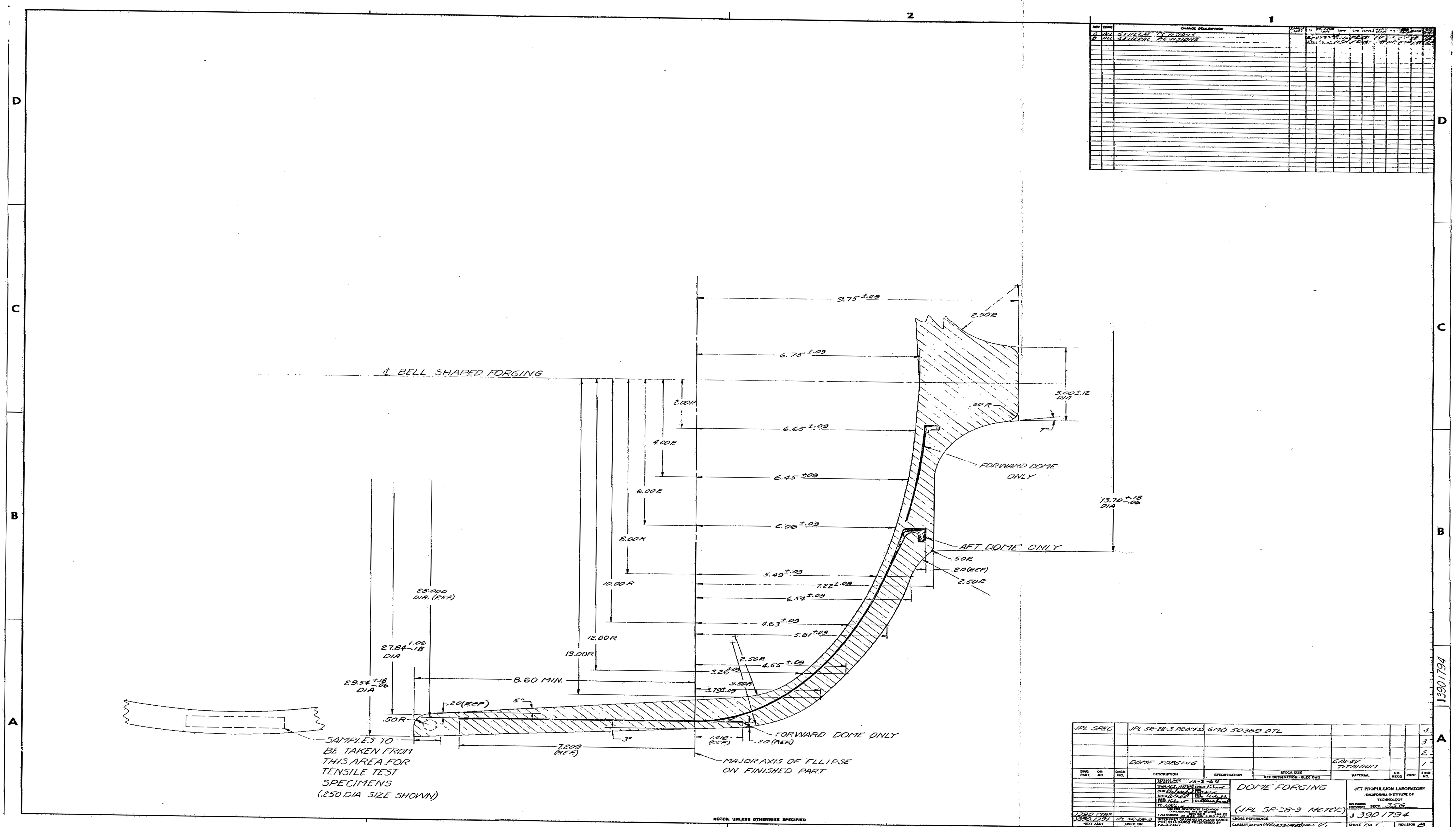
CH DIAMETER OF MATING PART BEFORE WELDING TO
OW .006 MAX MISMATCH AFTER WELDING.
~~(4) TO BE RELEASED AT A LATER DATE.~~
ITIFICATION PER (4).
INED FILLET RADIUS: —
VE ALL BURRS AND SHARP EDGES
INE FINISH 63
ESS OTHERWISE SPECIFIED

DWG OR PART NO.	DASH NO.	DESCRIPTION	SPECIFICATION	STOCK SIZE / REF DESIGNATION - ELEC DWG	MATERIAL	NO. REQD	ZONE	FIND NO.
JPL SPEC		JPL SR-28-3 PROCESS	GMO 50369 DTL					4
								3
								2
		RING		FORGING STOCK AS REQUIRED	TI-6AL-4V TITANIUM ALLOY			1

A

NEXT ASSY	USED ON			
J3901790	JPL SR-28-3	RELEASE DATE OF DRAWING 10-2-64; DWN SWEENEY; ENGR [illegible]; CHK [illegible]; ENGR H.J. HAYS; STRU [illegible]; DES SUPV [illegible]; MATL PROC [illegible]; DL [illegible]; TC NR MJH	RING, MOUNTING (JPL SR-28-3 MOTOR)	JET PROPULSION LABORATORY CALIFORNIA INSTITUTE OF TECHNOLOGY; RELEASED THROUGH SECT. 356
		UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES; TOLERANCES DECIMALS .XX ±.02 .XXX ±.010 ANGLES ±1/2°	CROSS REFERENCE	J 3901793
		INTERPRET DRAWING IN ACCORDANCE WITH STANDARDS PRESCRIBED BY MIL-D-70327	CLASSIFICATION UNCLASS; SCALE ½ & NOTED	SHEET 1 OF 1; REVISION D

2 724-00081-2-3650 1 64-416


℄ BELL SHAPED FORGING
9.75 ±.09
2.50R
6.75 ±.09
2.00R
6.65 ±.09
3.00 ±.12 DIA
.50R
7°
4.00R
6.45 ±.09
FORWARD DOME ONLY
6.00R
13.70 +.18 -.06 DIA
6.06 ±.09
AFT DOME ONLY
8.00R
.50R
.20(REF)
2.50R
5.49 ±.09
7.22 ±.09
10.00R
6.54 ±.09
4.63 ±.09
5.81 ±.09
12.00R
28.000 DIA. (REF)
27.84 +.06 -.18 DIA
13.00R
2.50R
4.55 ±.09
3.26 ±.09
3.50R
3.791.09
29.54 +.18 -.06 DIA
8.60 MIN.
.20(REF)
5°
.50R
3°
7.209 (REF)
1.418 (REF)
.20(REF)
FORWARD DOME ONLY
MAJOR AXIS OF ELLIPSE ON FINISHED PART
SAMPLES TO BE TAKEN FROM THIS AREA FOR TENSILE TEST SPECIMENS (.250 DIA SIZE SHOWN)
NOTES: UNLESS OTHERWISE SPECIFIED
JPL SPEC
JPL SR-28-3 PROCESS GMO 50369 DTL
DOME FORGING
6AL-4V TITANIUM
DOME FORGING
(JPL SR-28-3 METRIC)
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
J 390 1794
J3901794

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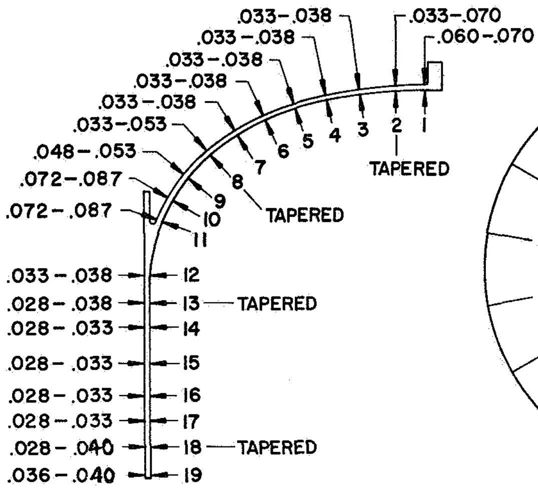
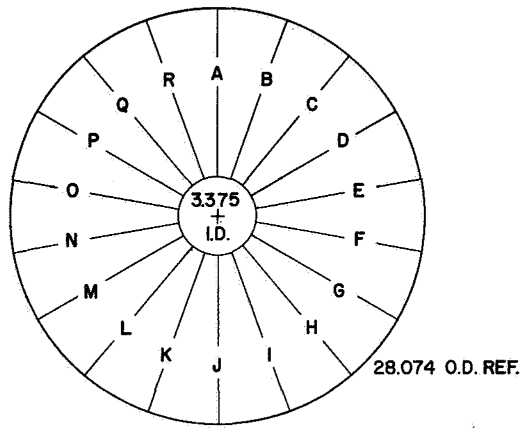
APPENDIX C

Forward- and Aft-Dome Inspection Forms

SATS JPL SR-28-3
FORWARD DOME INSPECTION FORM

PRINT NO. J 390 1791	CHANGE LETTER	SUPPLIER: PRESSURE SYSTEMS INC.
P.O. NO.	SERIAL NO.— BAR —	COGNIZANT ENGINEER: D. KOHORST





	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	
-1																			-1
-2																			-2
-3																			-3
-4																			-4
-5																			-5
-6																			-6
-7																			-7
-8																			-8
-9																			-9
-10																			-10
-11																			-11
-12																			-12
-13																			-13
-14																			-14
-15																			-15
-16																			-16
-17																			-17
-18																			-18
-19																			-19

REMARKS:

INSPECTOR:

DATE:

JPL 2359 APR 65

JET PROPULSION LABORATORY

SATS JPL SR - 28-3
INSPECTION REPORT

QUALITY ASSURANCE INSTRUCTION
No.________

*Page*________*of*________*Pages*

Print Number	*Change Letter*	*Description*
J390 1791		Dome, Forward
PO Number	*Serial Number–* Bar–	*Supplier* Pressure Systems, Inc.

SEQ	REQUIREMENT	ACTUAL	Acc √	Rej X	SEQ	REQUIREMENT	ACTUAL	Acc √	Rej X
1.	28.000±.005 I.Dia.				15.	.085±002 thickness			
2.	⌒ .003 Flatness					DETAIL "B"			
3.	14.649±.005 Dim.				16.	27.930±.005 I.Dia.			
4.	4.125±.010 O.Dia.				17.	.065±.005 thickness			
5.	3.375±.010 I.Dia.				18.	Sharp Edge (2 Pl)			
6.	.030±.010 Rad.				19.	23°-30'±1/2°			
7.	4.250 Dia Gage Plane				20.	$.048^{+005}_{-000}$ thickness			
8.	6.919±.010 Dim. Gage Plane				21.	.48±.030 Dim.			
	DETAIL "A"				22.	(STATION #9-#10) Linear Taper From $.072^{+.015}_{-.000}$ to $.048^{+.005}_{-.000}$ thickness			
9.	$.060^{+010}_{-000}$ thickness								
10.	9.00±030 Dia.				23.	$.072^{+015}_{-000}$ thickness			
11.	(STATION #2) Linear Taper From $.060^{+.010}_{-.000}$ to $.033^{+.005}_{-.000}$ thickness				24.	$.072^{+.015}_{-.000}$ thickness			
					25.	.025 Rad. Min.			
12.	$.033^{+005}_{-000}$ thickness				26.	Tangent Point Blend Smooth			
13.	1.50±.030 Dim.				27.	.400±.010 Dim.			
14.	(STATION #8) Linear Taper From $.048^{+.005}_{-.000}$ to $.033^{+005}_{-000}$ thickness				28.	.63±.030 Dim. (Blend any change in O.Dia.)			
					29.	1.118±010 Dim.			
					30.	.030±.003 Dim.			

Remarks: △10 Dia. Measurement Before Welding

Inspector ________ *Date* ________

JET PROPULSION LABORATORY

SATS JPL SR - 28-3
INSPECTION REPORT

QUALITY ASSURANCE INSTRUCTION
No.______
Page______of______Pages

Print Number	Change Letter	Description
J390 1791		Dome, Forward
PO Number	**Serial Number–**	**Supplier**
	Bar–	Pressure Systems, Inc.

SEQ	REQUIREMENT	ACTUAL	Acc ✓	Rej X
31.	$.060\pm.010$ Rad.			
32.	$.033^{+005}_{-000}$ thickness			
33.	$2.00\pm.030$ Dim.			
34.	(STATION #13) Linear Taper From $.033^{+005}_{-000}$ to $.028^{+005}_{-000}$ thickness			
35.	$.028^{+005}_{-000}$ thickness			
36.	$8.727\pm.005$ Dim.			
37.	DETAIL "C" (STATION #18) Linear Taper From $.036^{+.004}_{-.000}$ to $.028^{+005}_{-000}$ thickness			
38.	$1.50\pm.030$ Dim.			
39.	$.12\pm.030$ Dim.			
40.	$.036^{+004}_{-000}$ thickness			
41.	$.030\pm003$ Dim.			
42.	$.057\pm.003$ thickness			
43.	$.060\pm.010$ Rad.			
44.	Sharp Edge (2 Pl)			
45.	Note #1- 63			
46.	Note #2- Burrs			

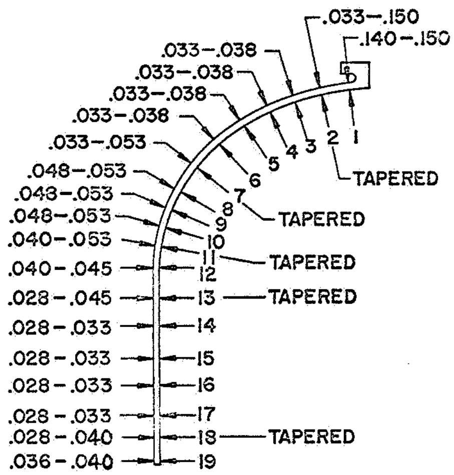
SEQ	REQUIREMENT	ACTUAL	Acc ✓	Rej X
47.	Note #4- Inside Contour Same as 390 1792			
48.	Note #5- 14.00 x 28.00 ellipse inside surface			
49.	△6 Identification			
50.	△8 Pi-Tape O.Dia. less thickness			
51.	Note #9- Contour of ellipse within .010 of true shape			
52.	△10- .003 Mismatch			
53.	△11- .006 Mismatch			
54.	Spec. GOM-50369-DTL-B			

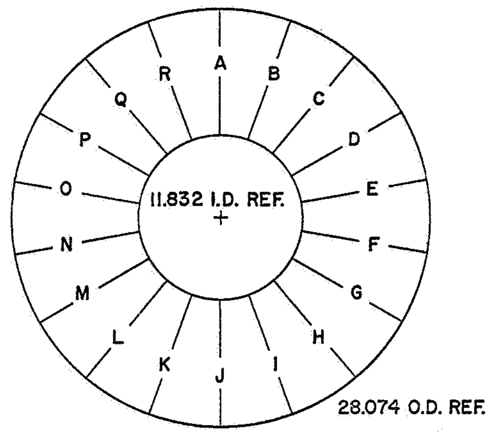
Remarks:

Inspector   Date

SATS JPL SR-28-3
AFT DOME INSPECTION FORM

PRINT NO. J 390 1792	CHANGE LETTER	SUPPLIER: PRESSURE SYSTEMS INC.
P.O. NO.	SERIAL NO.— BAR —	COGNIZANT ENGINEER: D. KOHORST





	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	
–1																			–1
–2																			–2
–3																			–3
–4																			–4
–5																			–5
–6																			–6
–7																			–7
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–10																			–10
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–14																			–14
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–16																			–16
–17																			–17
–18																			–18
–19																			–19

REMARKS:	INSPECTOR:
	DATE:

JPL 2360 APR 65

JET PROPULSION LABORATORY

SATS JPL SR - 28-3
INSPECTION REPORT

QUALITY ASSURANCE INSTRUCTION
No.________
Page______of______Pages

Print Number	Change Letter	Description
J390 1792		Aft Dome
PO Number	**Serial Number–**	**Supplier**
	Bar-	Pressure Systems, Inc.

SEQ	REQUIREMENT	ACTUAL	Acc ✓	Rej X
1.	$28.000 \pm .005$ I.Dia.			
2.	⌒ .003 Flatness			
3.	$14.269 \pm .005$ Dim.			
4.	$13.250 \pm .010$ O.Dia.			
5.	$12.375 \pm .010$ Dia.			
6.	11.832 (Ref.) Dia.			
7.	$13.125 \pm .010$ Dia. Gage Plane			
8.	$6.184 \pm .010$ Dim. Gage Plane			
9.	$.125 \pm .010$ Rad.			
10.	$.280 \pm .010$ Rad.			
11.	$.312 \pm .010$ Dim.			
12.	$.140^{+.010}_{-.000}$ thickness			
13.	$2.00 \pm .030$ Taper Dim.			
14.	(STATION #2) Linear Taper From $.140^{+.010}_{-.000}$ to $.033^{+.005}_{-.000}$ thickness			
15.	$.033^{+.005}_{-.000}$ thickness			
16.	$1.50 \pm .030$ Dim.			

SEQ	REQUIREMENT	ACTUAL	Acc ✓	Rej X
17.	(STATION #7) Linear Taper From $.048^{+.005}_{-.000}$ to $.033^{+.005}_{-.000}$ thickness			
18.	$.94 \pm .030$ Dim.			
19.	$.048^{+.005}_{-.000}$ thickness			
20.	1.00 ± 030 Dim.			
21.	(STATION #11) Linear Taper From $.048^{+.005}_{-.000}$ to $.040^{+.005}_{-.000}$ thickness			
22.	$.040^{+.005}_{-.000}$ thickness			
23.	$2.00 \pm .030$ Dim.			
24.	(STATION #13) Linear Taper From $.040^{+.005}_{-.000}$ to $.028^{+.005}_{-.000}$ thickness			
25.	$.028^{+.005}_{-.000}$ thickness			
	DETAIL "A"			
26.	1.38 (Ref.)Dim.			
27.	(STATION #18) Linear Taper From $.036^{+.004}_{-.000}$ to $.028^{+.005}_{-.000}$ thickness			

Remarks: △10 Dia. Measurement (
Before Welding (

Inspector ________ Date ________

JET PROPULSION LABORATORY

SATS JPL SR - 28-3
INSPECTION REPORT

QUALITY ASSURANCE INSTRUCTION
No.________
Page______of______Pages

Print Number	Change Letter	Description
J390 1792		Aft Dome
PO Number	Serial Number Bar-	Supplier Pressure Systems, Inc.

SEQ	REQUIREMENT	ACTUAL	Acc ✓	Rej x	SEQ	REQUIREMENT	ACTUAL	Acc ✓	Rej x
28.	1.50±030 Dim.								
29.	.12±.030 Dim.								
30.	.036 +.004 -.000 thickness								
31.	Sharp Edge (2 Pl)								
32.	.060±.010 Rad.								
33.	.030±.003 Dim.								
34.	.057±.002 thickness								
35.	Note #1- 63								
36.	Note #2- Burrs								
37.	Note #4- Inside Contour Same As J390 1791								
38.	Note #5- 14.00 x 28.00 ellipse inside surface								
39.	△6 Identification								
40.	△8 Pi-Tape O.Dia. Less Thickness								
41.	Note #9- Contour of ellipse within .010 of true shape								
42.	△10 .003 Mismatch								
43.	Spec. GOM-50369-DTL-B								

Remarks:

Inspector ______ Date ______

APPENDIX D

Chamber Inspection Forms

JPL JET PROPULSION LABORATORY

SATS JPL SR - 28-3
INSPECTION REPORT

QUALITY ASSURANCE INSTRUCTION
No.______

*Page*______*of*______*Pages*

Print Number	*Change Letter*	*Description*
J390 1790		Titanium Chamber Weldment
PO Number	*Serial Number*	*Supplier* Pressure Systems, Inc.

SEQ	REQUIREMENT	ACTUAL	Acc ✓	Rej x	SEQ	REQUIREMENT	ACTUAL	Acc ✓	Rej x
1.	[A] $28.134^{+.000}_{-.005}$ O. Dia.				15.	Four 10-32 UNF-3B Threaded Holes on "X" and "Y" Axes			
2.	.100 Min Thickness				16.	.125±.010 Rad.			
3.	.060 x 45° Chmf.				17.	12.000±.010 I.Dia.			
4.	[B ⌒ .002] Flatness				18.	[C] $12.995^{+.000}_{-.005}$ O.Dia.			
5.	.500 Basic Dim.				19.	[⊙ A .003 TIR] Concentricity			
6.	$.296^{+.006}_{-.001}$ Dia.Thru (16 holes)				20.	13.125±.010 O.Dia.			
7.	Within .015 Dia. of True Position				21.	[⊙ A .003 TIR] Concentricity			
8.	Nut Plates to be Centered on Hole Within .010 Dia. of True Position				22.	DETAIL "B" $.020^{+.010}_{-.000}$ x 45° Chmf.			
9.	[∥ B .003 TIR] Parallelism				23.	.015±.005 Rad.			
10.	[⊥ A .003 TIR] Perpendicularity				24.	$.075^{+.010}_{-.000}$ Dim.			
11.	.250±.010 Dim.				25.	.816(Ref.) Dim. Gage Plane			
12.	10-32 UNF-3B Thd. (36 holes)				26.	13.125 Dia. Gage Plane			
13.	[⊕ C .010 Dia.] True Position				27.	24.918±.015 Dim.			
14.	12.625 Dia. B.C.								

Remarks:

Inspector *Date*

JPL JET PROPULSION LABORATORY

SATS JPL SR - 28-3
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QUALITY ASSURANCE INSTRUCTION
No.________

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Print Number	Change Letter	Description
J390 1790		Titanium Chamber Weldment
PO Number	Serial Number	Supplier
		Pressure Systems, Inc.

SEQ	REQUIREMENT	ACTUAL	Acc √	Rej X	SEQ	REQUIREMENT	ACTUAL	Acc √	Rej X
28.	27.500 (Ref.) length between gage planes (Ref. allowing .021 for shrinkage)				41.	.020±.010 Rad.			
					42.	.312±.010 Dim.			
					43.	.030±.010 Relief Rad.			
29.	3.688±.010 I.Dia. (Counterbore)				44.	4-16UN-2A Thd.			
30.	[⊙ D .003 TIR] Concentricity				45.	[⊙ D .003 TIR] Concentricity			
31.	[D] $3.500^{+.002}_{-.000}$ I.Dia.				46.	20°-30' Basic; 4°-0' Basic (Typ.); 65°-30' Basic; 110°-30' Basic; 155°-30' Basic; 200°-30' Basic; 245°-30' Basic; 290°-30' Basic; 335°-30' Basic.			
32.	[⊙ A .010 TIR] Concentricity								
33.	32√ Finish								
34.	4.250 Dia. Gage Plane								
					47.	281 (Ref.) Dim.			
					48.	.562 (Ref.) Dim.			
35.	VIEW "A" .462 (Ref.) Dim. Gage Plane				49.	$.098^{+.004}_{-.001}$ Dia. thru (32 holes)			
36.	.437±.010 Dim.				50.	C'sink 100° x .175 Dia. Near Side			
37.	.025±.010 Dim.								
38.	.060±.010 Dim. (Typ.)				51.	Note #1- 63√			
39.	15°± ½° (Typ.)				52.	Note #2- Burrs			
40.	.062±.010 Dim.								

Remarks:

Inspector Date

JET PROPULSION LABORATORY

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INSPECTION REPORT

QUALITY ASSURANCE INSTRUCTION
No.________
Page________of________Pages

Print Number	Change Letter	Description
J390 1790		Titanium Chamber Weldment
PO Number	Serial Number	Supplier Pressure Systems, Inc.

SEQ	REQUIREMENT	ACTUAL	Acc √	Rej x	SEQ	REQUIREMENT	ACTUAL	Acc √	Rej x
53.	Note #4- Combined bow and ovality .060 max. TIR about surface A exclusive of welds (.50 to each side of center girth weld) and (4.00 to each side of center girth weld)				58.	28.000 (Ref.) I. Dia. Pi-Tape after machining (.50 to each side of center girth weld) and (4.00 to each side of center girth weld)			
54.	Note #5- Max. operating pressure: 270 P.S.I.G. proof pressure: 302 P.S.I.G.				59.	28.778 (Ref.) overall length (.816 + 27.500 + .462)			
55.	⚠7 Identification to be electro etched				60.	MS 20427-F3-5 Rivet MF 1001-4 Nut, Anchor			
56.	Note #9- Surfaces marked NP shall not be vapor blasted				61.	JPL Spec.- SR-28-3 Processing GMO 50369 DTL-B			
57.	⚠10 Weld shrinkage .040 Max. on Diameter and .003 Max. mismatch (Ref.)								

Remarks:

Inspector Date

CONCENTRICITY INSPECTION DATA FORM

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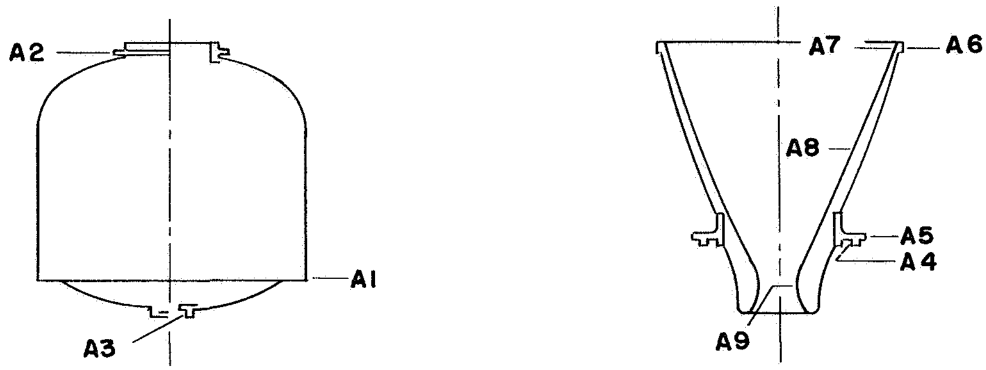
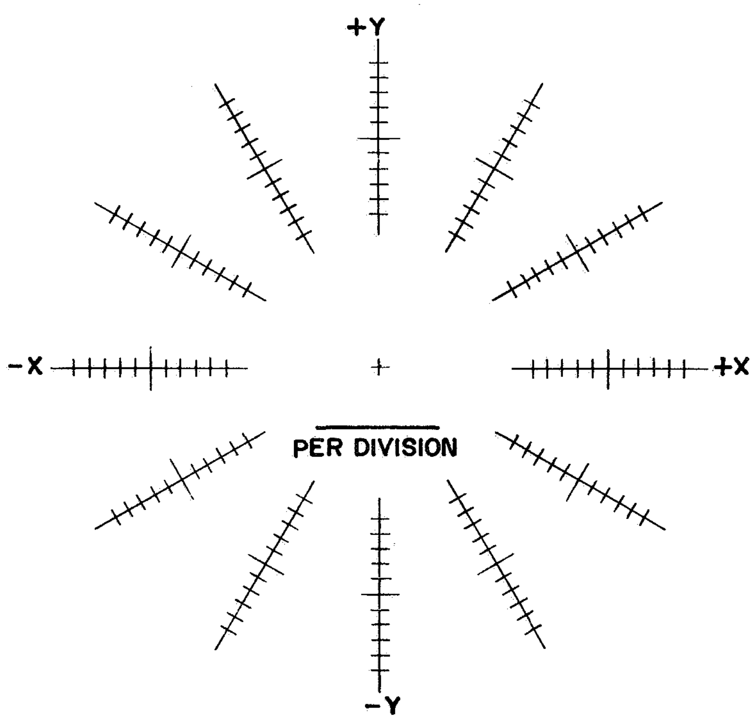
(REF SOP 218) (REF SOP 219) (REF SOP 220)





CONCENTRICITY INSPECTION POSITION: A-1

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REMARKS: ____________

JPL 1949 JUN 64

INSPECT BY: ____________ DATE ____________

CONCENTRICITY INSPECTION DATA FORM

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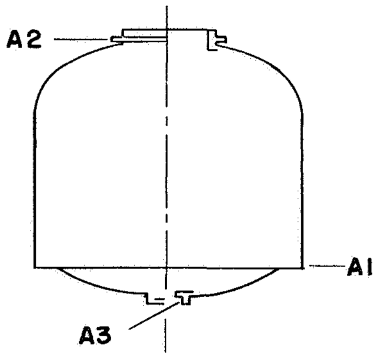

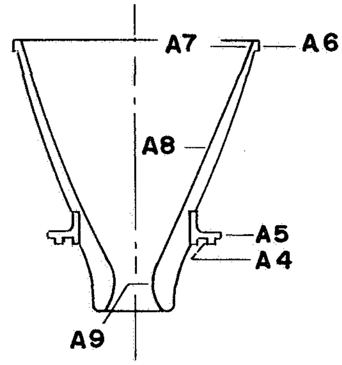

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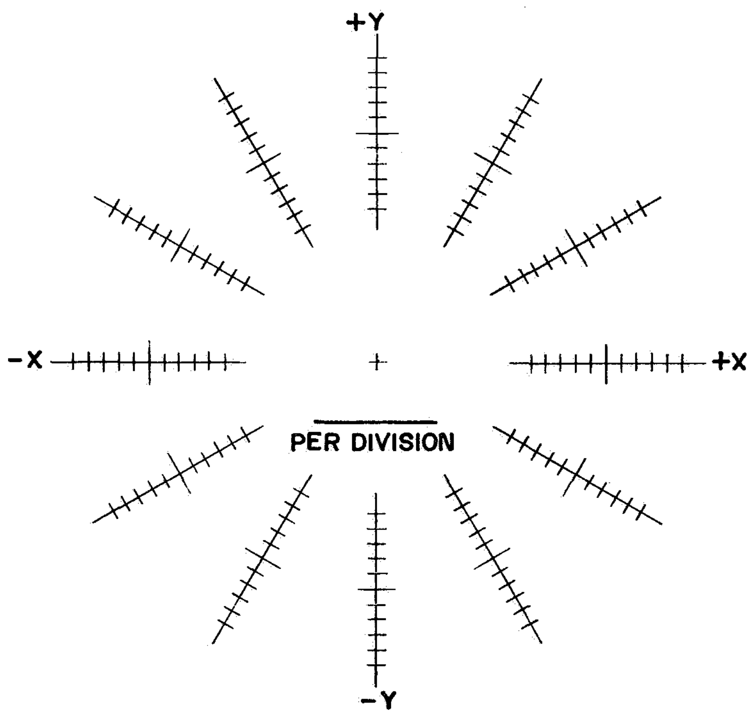

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REMARKS: ____________________

JPL 1949 JUN 64

INSPECT BY: ____________ DATE ____________

PARALLELISM INSPECTION DATA FORM

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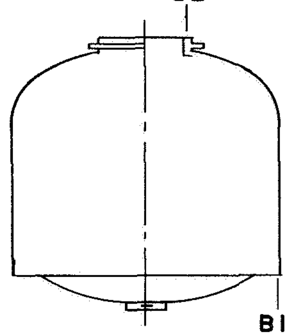

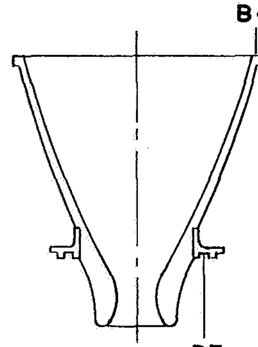

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PARALLELISM INSPECTION POSITION: B-1

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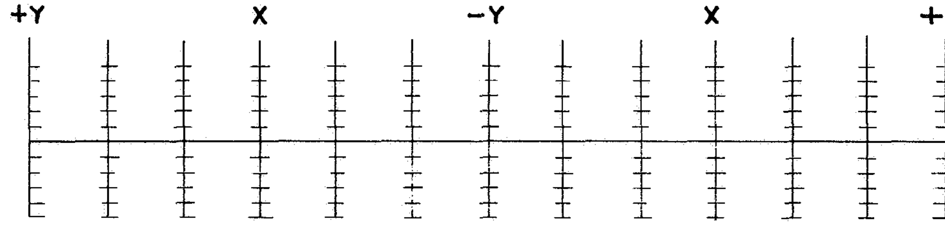

REMARKS: ______________________________

JPL 1950 JUN 64

INSPECTED BY ____________________ DATE __________

PARALLELISM INSPECTION DATA FORM

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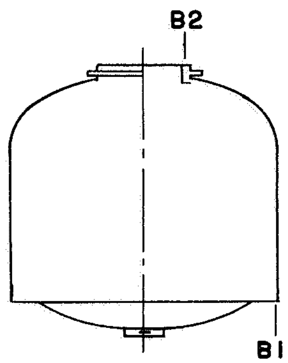

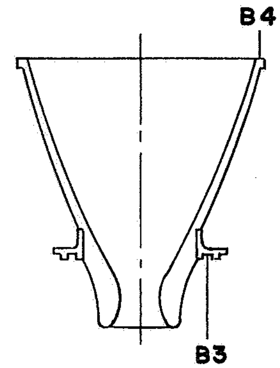

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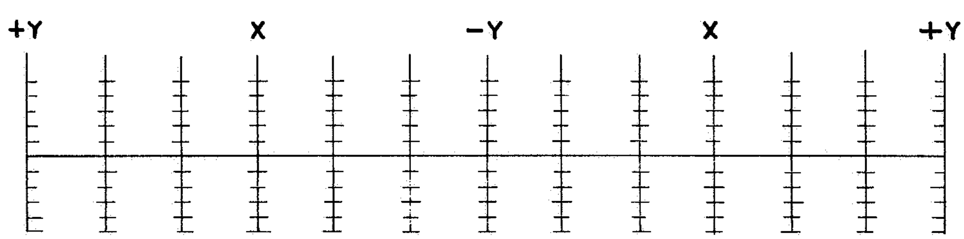

REMARKS: ______________________________

JPL 1950 JUN 64

INSPECTED BY ________________ DATE __________