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SPACE SHUTTLE ORBITER WINDSHIELD SYSTEM DESIGN AND TEST FINAL REPORT

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FOREWORD

This report is submitted to NASA Langley Research Center by North American Rockwell through its Space Division in fulfillment of the requirements of Contract NAS1-10957 as amended.

ABSTRACT

This report summarizes the development and testing of primary structural elements that are necessary to design a windshield system for the Space Shuttle orbiter. The elements include the outer (heat shield) panes, the inner pressure panes, the seals for both panes, and components of both window frames.

One test article representing a pressure pane, including frames and seals, was tested under two sets of conditions. One set represented 100 mission cycles with temperature and pressure typical of those exerted on the innermost pane of the three-pane window system, and the second set represented 100 mission cycles with temperature and pressure typical of those exerted on a middle pane.

A second test article representing an outer (heat shield) pane was tested to conditions of 120 entry cycles, which equates to 100 entry cycles plus sufficient fatigue on the pane to account for 100 boost cycles. All elements of the design survived the test conditions in good condition except a small bumper strip. This strip was mounted on the frame of the heat shield window to prevent abrasion of the glass in the event of contact due to thermal distortion. The program demonstrated the feasibility of an exposed window system for the Shuttle orbiter vehicle.

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1. INTRODUCTION

1.1 OBJECTIVE

The Space Shuttle vehicle is being designed to ferry men, supplies, and equipment between orbiting space laboratories and the earth. The crew must have visibility to perform maneuvers ranging from operations in space to earth landings upon return from space. The object of the Space Shuttle orbiter window system design and test program (Contract NAS1-10957) was to define, develop, and test structural elements necessary to the design of a window system for the Shuttle orbiter.

This report documents and summarizes results of the contractual work. Included is a summary of the tasks, the development of window-system concepts, prototype design analysis, test plan, and testing results.

In the concept selection phase, window design elements were reviewed to select candidates for testing and for further Space Shuttle orbiter design effort. The goal was to develop elements for a window system that would provide the required visibility with maximum simplicity and reliability. The approach was to trade off the concepts through analysis and to demonstrate the viability of the final design concept through testing.

1.2 SUMMARY TASK STATEMENT

The program objective was pursued in two major phases, the principal tasks of which are summarized in the following paragraphs.

1.2.1 Window Concept Phase

The design conditions to be used in the window system analysis for all Shuttle mission phases were determined by using NASA-approved trajectory data. Candidate window system were proposed that, after NASA selection, were analyzed in sufficient depth to provide relative assessment data for design. The selected design concepts were analyzed and evaluated for reliability, weight, and cost. The analyses included (1) size, shape, and number of windows and the relationship to the pilot's visibility; (2) all seals associated with the window system; (3) temperature, thermal gradients, expansion, stress and distortion, and pressure; (4) erosion and/or penetration resulting from mission phase environment; (5) compatibility of materials and environment conditions; and (6) fabrication and assembly techniques and estimates of service life. The preferred concept was reviewed by NASA and chosen for the testing phase.

1.2.2 Testing Phase

A prototype design of the preferred concept was developed in sufficient detail to describe the window system. Included were detail drawings; descriptions of the system functional elements; and identifications of known and potential problems with proposed solutions. A test program was defined to demonstrate the window system's ability to perform to the design conditions established in the concept phase. The test plan defined the test article and presented the rationale for its selection. With NASA concurrence, the test article was fabricated and tested. Test results are summarized in this final report, and documented in the laboratory reports of References 1 and 2.

1.3 PROGRAM TECHNICAL APPROACH

The technical approach for the definition, development, and test of an advanced window system for the Shuttle orbiter was directed to the structural aspects of the window system with emphasis on glass-seal-frame interfaces. This interface area offers at once the more severe temperature problems and the greater latitude for state-of-the-art advancement with the least danger of becoming configuration dependent. Where vehicle configuration was necessary to the definition of concepts, the fully reusable Phase B Shuttle orbiter configuration known as 161C was used (Figure 1). Windows unprotected by external covers have been assumed. Uncovered windows apparently can be realized for the baseline configuration. Even where uncovered windows cannot be realized, the study results can be useful as a hot-temperature limit for configurations with externally covered windows.

The calculated window design temperature and pressure for the critical entry and boost phases of the baseline Shuttle orbiter mission are shown in Section 2.2.2 (Figures 9 and 10). Analysis was based on the worst case local condition for the forward windshield. The worst case burst and crush pressure was determined by assuming that the cavity immediately behind the outer pane was vented alternately to the highest pressure and to the lowest pressure in the local area. The tests were used to demonstrate the integrity of the designed pane and seal elements under exposure to the Shuttle environment.

The overall schedule used during the development program is shown in Figure 2.

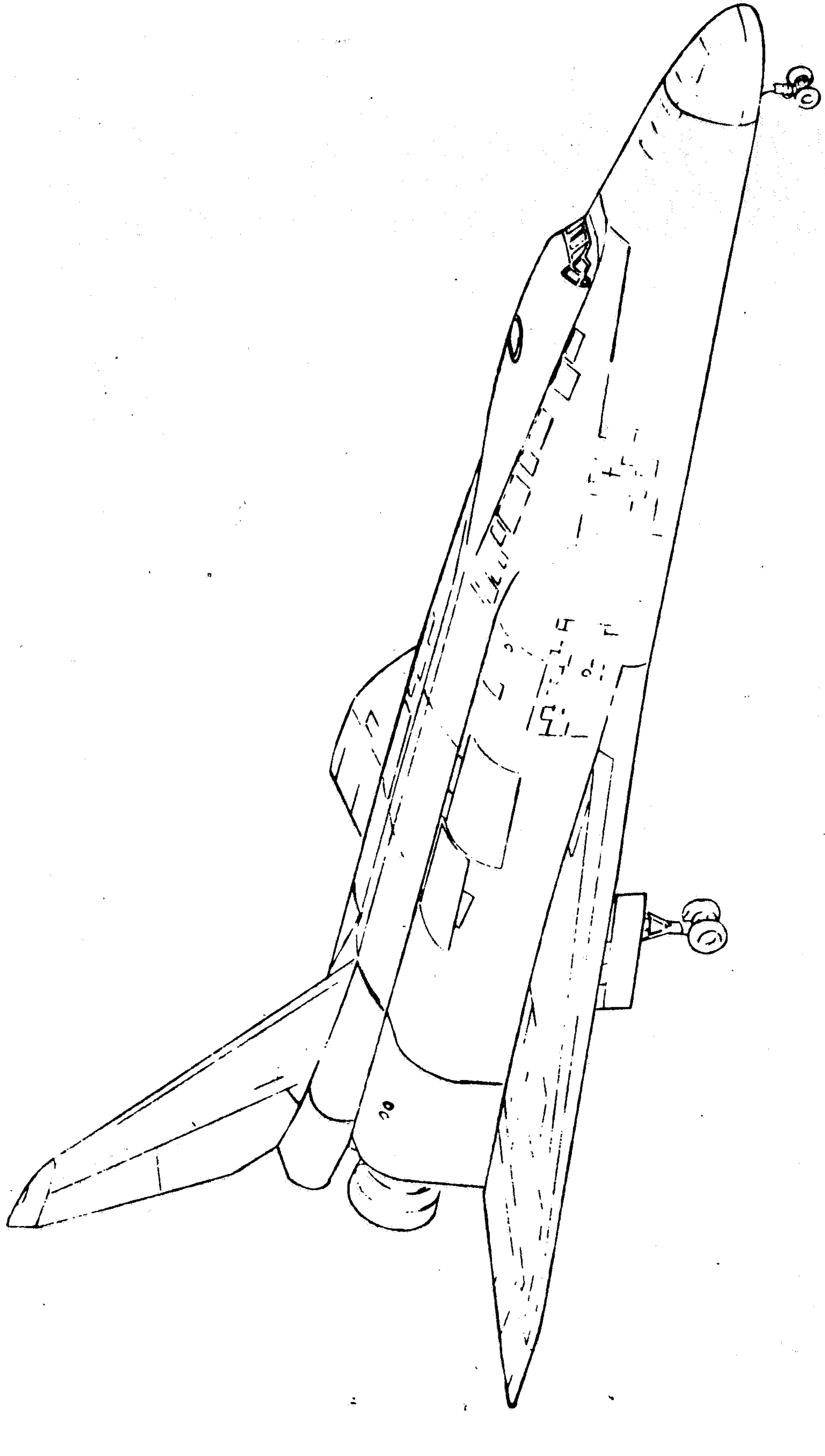


Figure 1. Baseline Overall Shuttle Orbiter Configuration

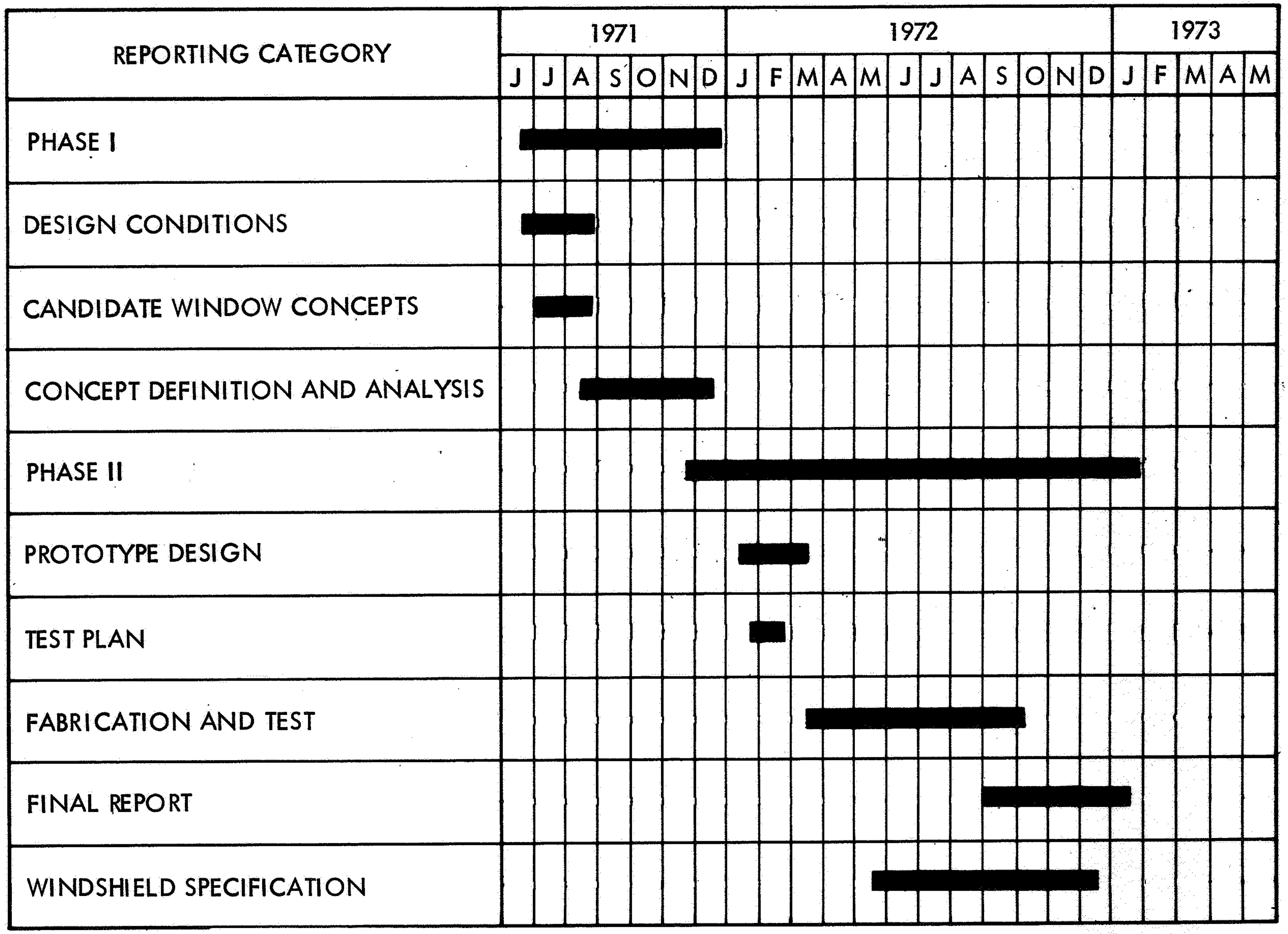


Figure 2. Overall Program Schedule

2. DESIGN SELECTION (CONCEPT PHASE)

The objective of the design phase was to choose a concept for a window system that would meet the requirements of a fully reusable orbiter vehicle with a design life of 100 missions. Concepts of uncovered and covered windows were considered. All phases of operation were surveyed for critical environmental conditions affecting structural integrity. Thermal, structural, and design analyses were performed for boost and entry conditions. Environmental hazards such as bird impact, hail damage, rain erosion, and meteoroid penetration were assessed for effects on the windows. Prime consideration was given to reliability, with emphasis on structural aspects. A major effort was concentrated on the search for an outer window seal capable of satisfying the requirements of high-temperature-material compatibility and multiple cycles.

2.1 SELECTED CONCEPT

The three-pane window concept was selected as the preferred window configuration. In this concept, the outer pane acts as a heat shield. The inner pane is the primary pressure containing pane. The middle pane serves as a redundant member for both the outer heat shield pane and the inner pressure pane. This concept is illustrated in Figure 3.

The glass baseline profile configuration was determined by applying MIL-STD-850A (Reference 3) to the Shuttle vehicle 161C configuration in the forward windshield area. These pane sizes are significantly larger than those employed in the Apollo and other manned space vehicles. The pane size for the outer window is shown in Figure 4. The pane size for the inner and middle window is shown in Figure 5.

The outer window pane is manufactured from fused silica glass. The design temperature for the outer window on the Shuttle orbiter baseline configuration is 1270^{o}F at the nominal thickness of 1 inch or 1600^{o}F at radiation equilibrium. Consideration of current design temperature, reliability, and capacity to accept increased temperature eliminated all but fused silica (Corning Glass Works 7940). Fused silica is generally considered to have a design allowable temperature of 1800^{o}F maximum.

The inner window pane is manufactured from heat-tempered aluminosilicate glass. For the cabin pressure panes of the Shuttle orbiter windshield, four panel materials were initially considered. These were heat-tempered aluminosilicate, heat-tempered borosilicate, heat-tempered

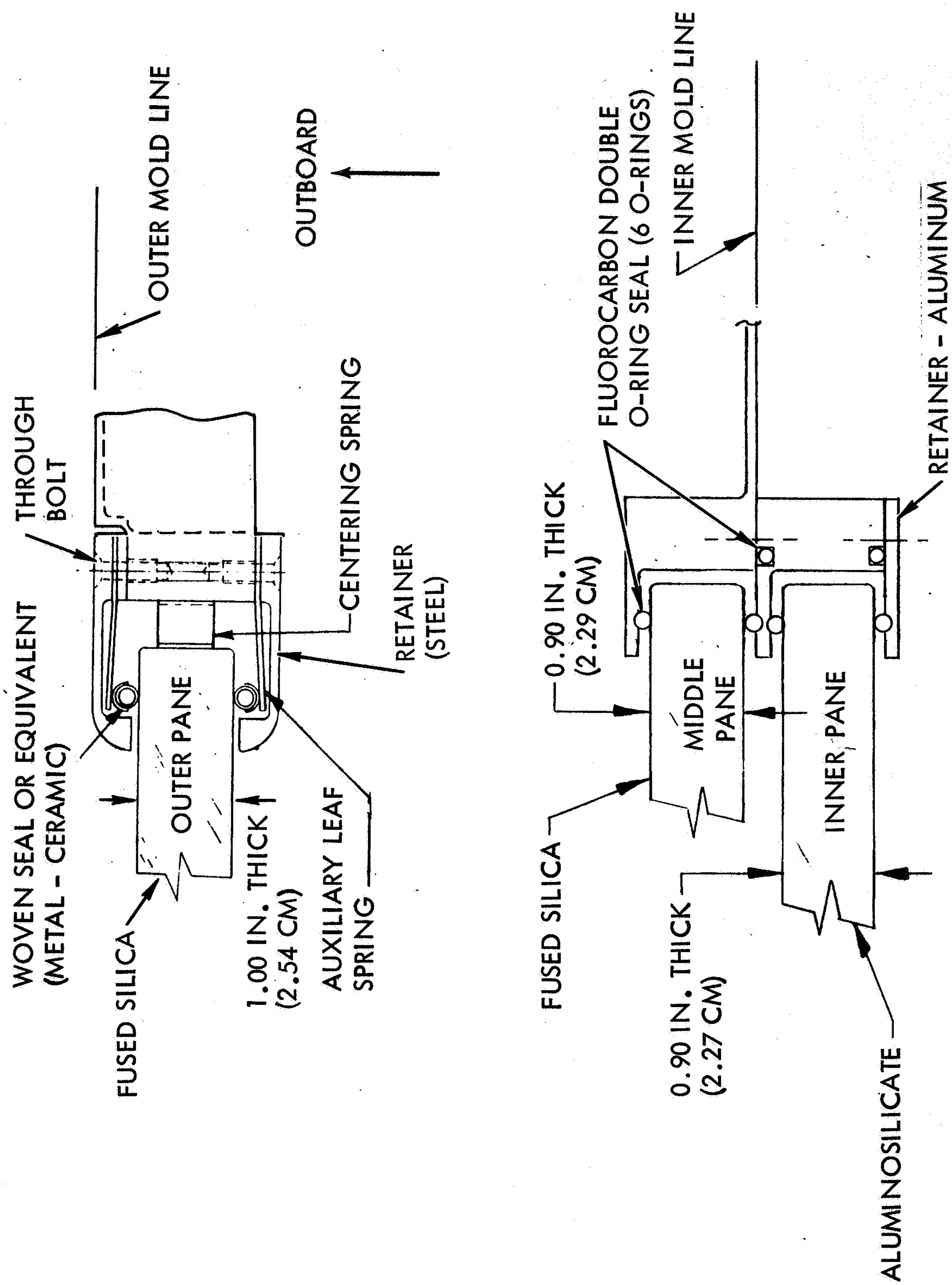


Figure 3. NR Selected Window Design Concept

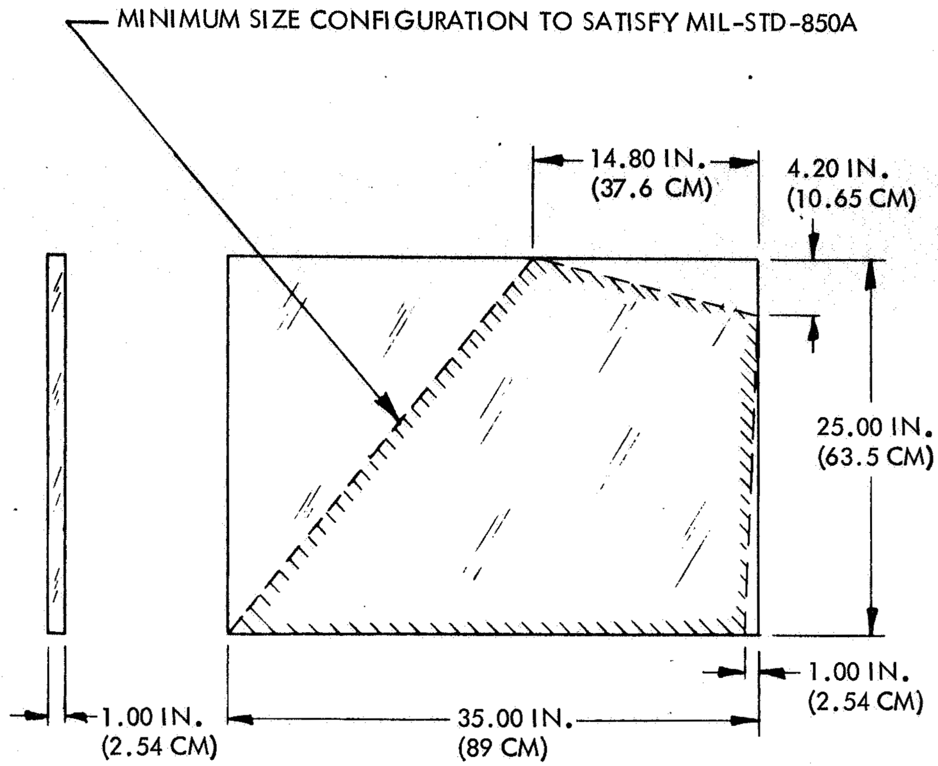


Figure 4. Minimum Outer Window Size and Prototype Outer Window Configuration

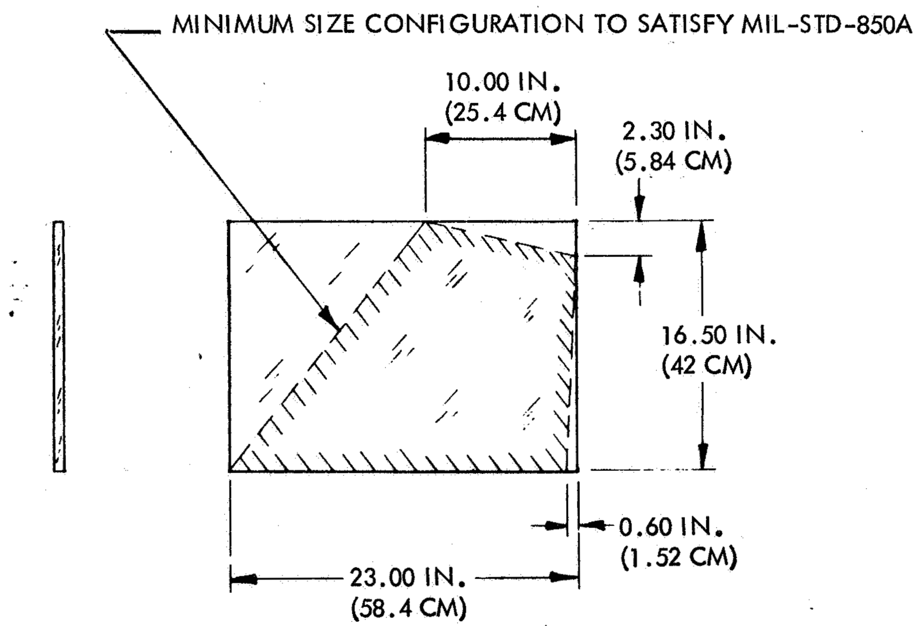


Figure 5. Minimum Inner Window Size and Prototype Inner and Middle Window Configuration

soda lime, and chemically tempered glass. Borosilicate was eliminated because of poor optical qualities. Aluminosilicate was considered to be superior to soda lime in any range of temperature usage. Aluminosilicate, having a coefficient of thermal expansion equal to one-half that of soda lime, will develop one-half the stresses in response to the applied temperature differentials. The resulting increased reliability of aluminosilicate over soda lime more than compensates for the increased cost when consequences of window failure are considered on the Space Shuttle orbiter. The heat-tempering process protects the pane both against extreme sensitivity to handling and service flaws and against static fatigue.

Although the maximum temperature usage of chemically tempered glass varies according to source of information, Kerper and Scuderi (Reference 4) report the maximum long-term usage without loss of strength to be about 300°F. Aluminosilicate, then, has a considerable advantage over chemically tempered glass in its capacity to accept high temperatures. Further consultations with Corning Glass Works produced an opinion that, because of the greater depth of the layer in heat-tempered glass (approximately 1/6 of glass thickness versus 0.015 to 0.030 inch), aluminosilicate would be significantly less sensitive to scratches and flaws induced by handling than would chemically tempered glass. Since the Shuttle orbiter design is aimed at 100 missions, this ruggedness factor narrowed the choice to heat-tempered aluminosilicate glass for the windshield pressure panes.

Under the study configuration and design conditions used, the middle- and inner-window panes of the orbiter windshield could, from the glass strength standpoint, be 0.5 inch thick were they both of tempered aluminosilicate glass. If 0.5-inch panes were subjected to entry heating, however, the middle pane would heat to 690°F, which is above that allowable for the elastomerics considered for hermetic sealing. Further, the inner surface of the inner pane would heat to 480°F, whereas the limit is 300°F, because of the proximity of the pilot to the windshield. Alleviation of these over-tolerance conditions would add complexity and could add weight and reduce reliability.

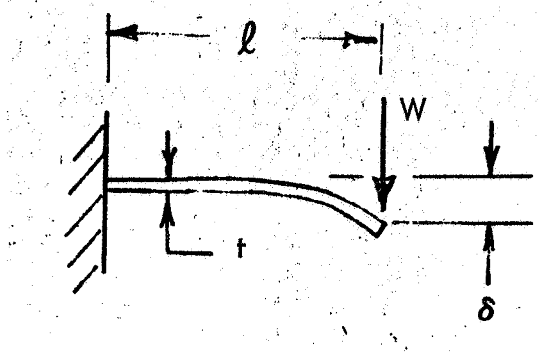
On the other hand, if both middle and inner windows are made 0.90 inch thick, the middle window reaches only 570°F, and the inner surface of the inner window reaches only 240°F at overshoot touchdown, both of which are below that needed for operation of active systems during entry. For the foregoing reason, reduction of middle and inner windows to minimum weight could be a suboptimization. The weight to be balanced against the weight and complexity of an active system is that of 0.4 inch of inner pane thickness (since the middle pane must be fused silica and thus 0.9 inch thick for reasons of redundancy). For the glass density of 0.10 pound per cubic inch, the weight becomes 120 pounds. This has not been judged excessive in exchange for a passive window system which provides a heat sink capability.

The outer window seals are wire mesh cores jacketed with woven ceramic cloth. This seal is not hermetic but is intended to block the penetration of plasma flow. The woven cloth cover does not bond to, leave deposits on, or scratch the glass pane as did many of the candidate seal surfaces. An auxiliary leaf spring is used to assist the seal spring-back recovery. Centering springs maintain relative position of the floated pane within its frame. The seal configuration is shown in Figure 3.

Because of minimal springback in candidate seals when tested at high temperature, an auxiliary spring in the form of a cantilever leaf is placed in series with the seal. The spring could take many forms, including that of a Belleville washer, but a cantilever leaf is simple in concept and manufacture and offers a reasonable number of variables for manipulation. With a required deflection (or springback), an allowable stress σ (taken as the stress to produce 0.5 percent creep in 100 hours), and a modulus of elasticity (E), one may vary the length of the cantilever (ℓ), the thickness of the leaf (t), or the number of leaves to produce the desired deflection without exceeding the allowable stress. The relationships are shown in Figure 6.

It appears that $1400^{\circ}F$ is the upper temperature limit at which significant elastic springback can be achieved with currently known production materials. Figure 6 indicates the reason. Springback over a range of temperatures was investigated with advantageous material at each temperature. As can be seen in columns 5 and 6 of Figure 6, when ℓ and δ are held at acceptable levels of one inch and 0.05 inch, respectively, material thicknesses drop drastically above $1400^{\circ}F$, and the load levels (W) drop to an unacceptable level. (A load of about 4 or 5 pounds per inch is required to deflect the seals and maintain glass-seal-frame contact.) Essentially the same information is shown in columns 7 and 8 where t and δ are held to acceptable minimums and the cantilever length is allowed to vary. The $1400^{\circ}F$ upper temperature limit appears to be sufficiently high to allow design at Shuttle orbiter windshield temperatures.

The inner and middle window seals are fluorocarbon O-rings. This seal concept provides better slippage capability than does a potted seal design and the seal can be pre-cured prior to installation to prevent outgassing at specified temperatures. The fluorocarbon material, Viton, allows elastic recovery after thermal exposure from $-10^{\circ}F$ to $+400^{\circ}F$. The seal is hermetic with a maximum allowable leakage rate of 0.1 scim per foot seal length. The seal configuration is shown in Figure 3.



$$\delta = \frac{4\ W\ell^3}{Et^3}$$

$$\sigma = \frac{6\ W\ell}{t^2}$$

$$t = \frac{2}{3}\left(\frac{\ell^2}{\delta}\right)\left(\frac{\sigma}{E}\right)$$

Material	Temp °F (°C)	E x 10^{-6} psi (newton/meter^2)	σ x 10^{-3} at 0.5% Creep lb/in. (newtons/cm)	ℓ = 1 in. (2.54 cm) δ = 0.05 in. (0.13 cm)		t = 0.03 in. (0.076 cm) δ = 0.05 in. (0.13 cm)	
				t in. (cm)	W lb (newtons)	ℓ in. (cm)	W lb (newtons)
Ti 6Al-4V	750 (399)	13 (89,600.0)	60 (105)	0.061 (0.154)	37 (8.3)	0.7 (1.8)	12.8 (32.5)
Inc 718	1200 (649)	24 (165,000.0)	78 (136)	0.043 (0.109)	24 (5.4)	0.83 (2.1)	14.2 (36.1)
René 41	1400 (760)	22 (152,000.0)	45 (78.5)	0.027 (0.068)	5.5 (1.2)	1.05 (2.7)	6.4 (16.3)
René 41	1500 (816)	20 (138,000.0)	17 (29.7)	0.111 (0.281)	0.34 (0.07)	1.62 (4.1)	1.59 (4.04)
Hastelloy X	1600 (871)	17 (117,000.0)	4.5 (7.8)	0.003 (0.007)			
Haynes 188	1700 (927)	18 (124,000.0)	5.0 (8.7)	0.004 (0.010)			
TDNiCr	2000 (1093)	6 (41,400.0)	3.0 (5.2)	0.007 (0.018)			

Figure 6. Cantilever Leaf Spring

Outgassing would not seem to be a major problem. Nine silicone elastomeric materials are available that meet or better the 1-percent maximum weight-loss requirement and 0.1-percent volatile condensable material (VCM) requirements of SP-R-022, "Specification-Vacuum Stability Requirements of Polymeric Material for Space Application" (Reference 5). Indicated Viton outgassing is also less than specification requirements, with a weight loss of 0.33 percent and a VCM listed as zero (Reference 6). The possibility of outgassing, however, is one of the prime reasons for choosing an O-ring design over a potted design. Many compounds require curing and post-curing under vacuum conditions at elevated temperatures to drive off volatiles. O-rings can be cured, post-cured, and then installed. Potted assemblies lack this flexibility and thus are more susceptible to outgassing.

The mass of the inner window panes is used as a heat sink to prevent excessive temperatures on the middle pane seals and at the inner surfaces of the inner window. Specific analyses to support this conclusion are as previously discussed in this section.

All window panes are allowed relative thermal growth or shrinkage with respect to the frame; and centering is provided. The seal design is essentially a pin joint and will allow pane edge rotation. Out-of-plane bowing of the pane edges is constrained to some extent by the frame-seal-auxiliary leaf-spring combination. Such constraint can be beneficial provided that excessive local pressure is not imposed or the frame itself is not bowed excessively by thermal differentials. This beneficial effect is shown by the reduction of edge stresses from 3280 psi to 2580 psi when the edge conditions are changed from free plate to pinned (Reference 7, page 97).

The 1.5 factor of safety was used. A larger factor of safety would have added little except weight. Its imposition on the pressure requirement, for example, would cause an increase in thickness of the outer window pane. This, in turn, would cause an increased temperature differential and, since the thermal stresses are to a degree independent of thickness, would cause an actual increase in thermal stresses.

All the recommendations for the prototype testing were made and approved by NASA as follows:

Item	Recommendation
Approach	Exposed windows
Factor of safety	1.5
Structural failure	Glass fracture
Outer pane size	32 by 25 inches
Inner pane size	23 by 16-1/2 inches
Pane configuration	3-pane dual redundancy
Material	Fused silica (outer and middle window) Aluminosilicate (inner window)
Seal (outer pane)	Ceramic cloth covered wire mesh core Spring-loaded
Seal (pressure panes)	Viton O-ring
Active systems	None
Passive system	Venting of cavity inboard of outer pane

2.2 DESIGN CONDITIONS

2.2.1 Inner Pane Thermal and Pressure Requirements

The windshield design temperature levels are shown in Figure 7 for entry and Figure 8 for ascent. The design limit pressures for the window panes are shown in Table 1. p_1-p_2 represents the differential pressure on the innermost pane. p_2-p_3 represents the differential pressure on the middle pane. The 17.2 psi pressure acting outboard on the inner pane assumes regulator value malfunction such that relief-valve pressure occurs in the cabin (p) and assumes p_2 has slowly vented to space. The -17.2 psi pressure inboard assumes an equalization of p_2 with a cabin pressure (p) that is at relief-valve pressure. This equalization is assumed to occur through slow leakage and is followed by a loss of cabin pressure.

The 17.2 psi outboard on the middle pane is obtained by equalization of p_2 with cabin relief-valve pressure while in space. The -14.7 psi inboard on the middle pane is obtained by assuming a descent to sea level after p_2 has slowly vented to space.

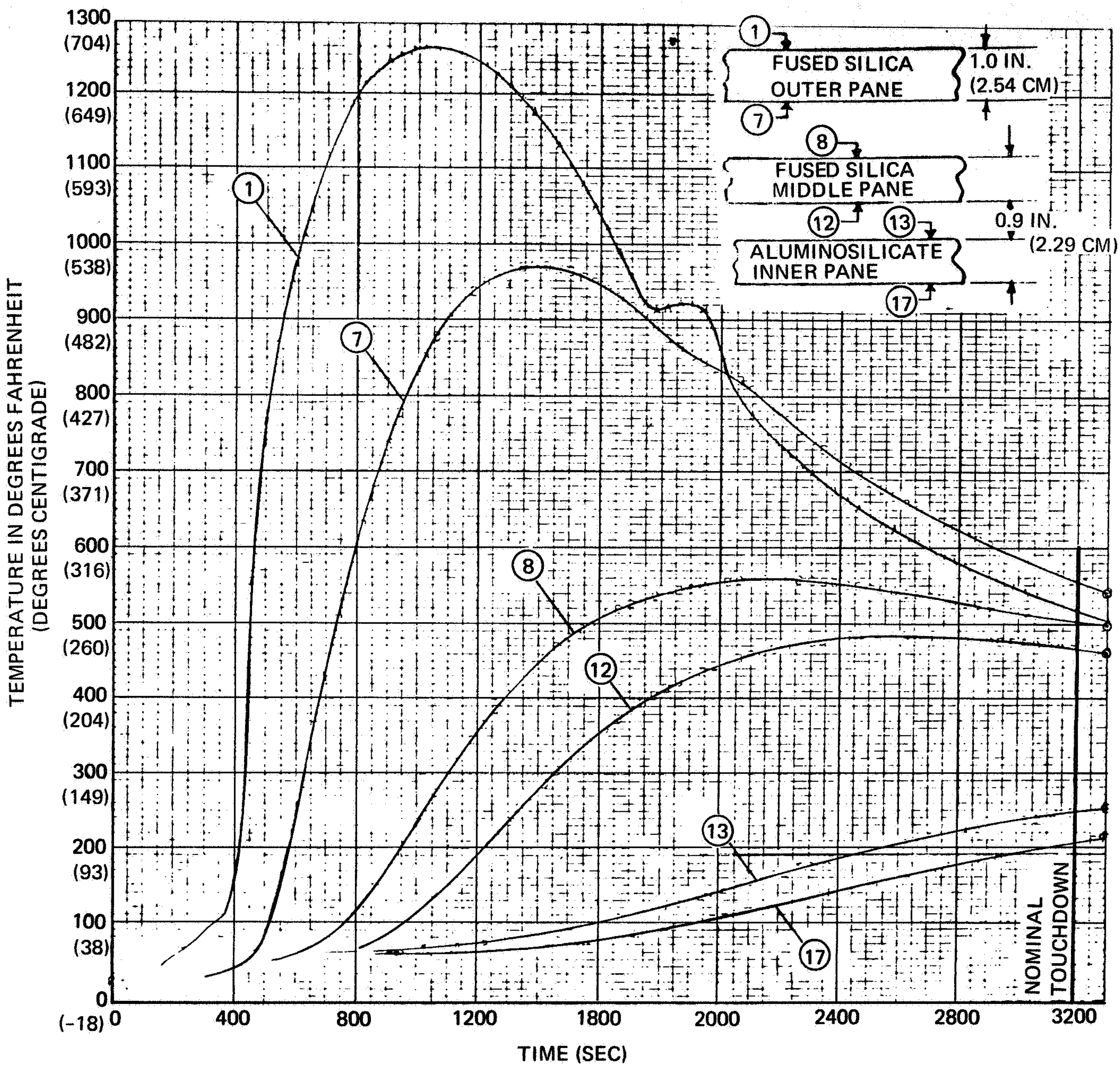


Figure 7. Design Entry Temperatures, Window Surfaces

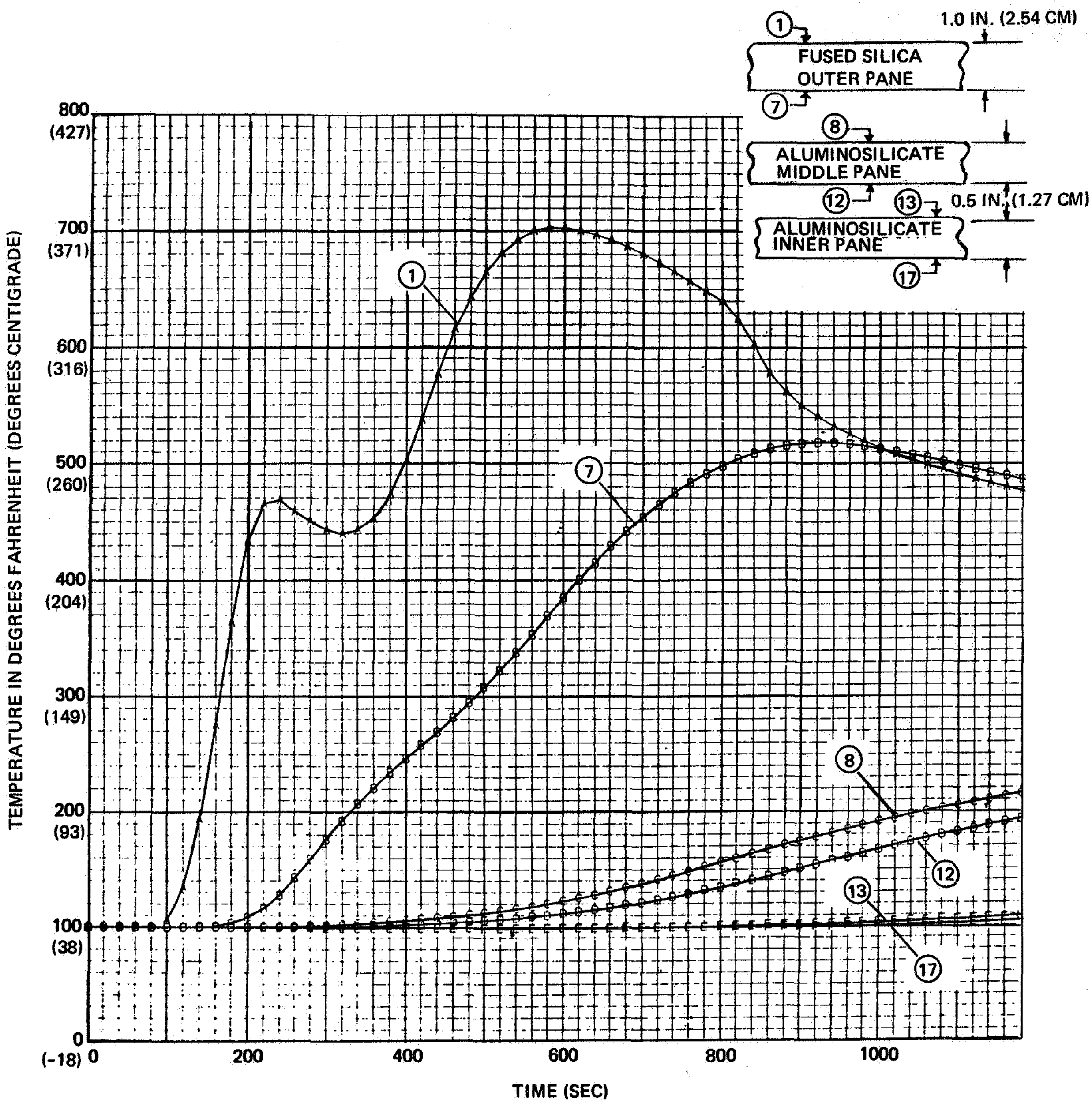


Figure 8. Design Ascent Temperatures, Window Surfaces

Table 1. Maximum Limit Window Pressure

Condition	Pressure, psi (Newtons/meter^2)						
	p_1	p_2	p_3	p_4	$p_1 - p_2$	$p_2 - p_3$	$p_3 - p_4$
Descent	17.2[B] (118 x 10^3)	0[D] (0)	14.7 (101 x 10^3)	14.7 (101 x 10^3)	17.2 (118 x 10^3)	-14.7 (-101 x 10^3)	0 (0)
Cabin pressure loss	0 (0)	17.2[E] (118 x 10^3)	0 (0)	0 (0)	-17.2 (-118 x 10^3)	17.2 (118 x 10^3)	0 (0)
Boost-dynamic crush	- -	- -	0 (0)	8 (55 x 10^3)	- -	- -	-8 (-55 x 10^3)
Boost-dynamic burst	- -	- -	8 (55 x 10^3)	0 (0)			8 (55 x 10^3)

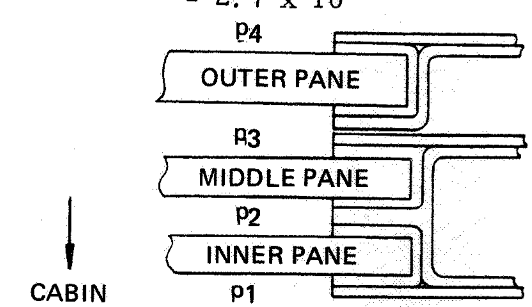
A - Reg valve pressure = 14.7 ± .5 psia (For reference only) (101.3 x 10^3 ± 3.4 x 10^3 N/M^{2a})

B - Positive relief valve pressure = $17 \begin{matrix} +0.2 \\ -0.4 \end{matrix}$ = 17.2 psia max (117.2 x 10^3 $\begin{matrix} +1.4 \times 10^3 \\ -2.7 \times 10^3 \end{matrix}$ = 118.6 x 10^3 N/M^{2a} Max)

C - Negative relief valve pressure = -2.0 psig (For reference only) -14 x 10^3 N/M^{2}G

D - Assume slow venting to space

E - Assume previous slow venting to cabin relief valve pressure



2.2.2 Outer Window Thermal and Pressure Requirements

The factors that created the necessity for an advanced window system for the Space Shuttle orbiter were high heat rate and high heat-load boost and entry and long service life. The purpose of this project, which was to design and develop elements for such a window system and to demonstrate viability by test, was best served by concentration on those factors. A reliable system to withstand the high thermal and pressure environments for a 100-mission life was the goal, and the high thermal and pressure environments occur during the boost and entry. Therefore, design temperatures came from the data of Figures 7 and 8.

Significant data for ascent are shown in Figure 9. Temperatures were calculated for a location on the forward window of the crew compartment, which receives the maximum aerodynamic heating. For this plot the outer window pane was assumed to be 1.0-inch-thick fused silica. Not shown are results of computations that indicate that temperatures on other crew compartment windows would peak at below 400°F. The temperature histories shown in Figure 9 have been revised upward (from a maximum temperature of 560°F) based on AEDC heating-rate test data. A close evaluation of these data indicated that ascent heating rates on the canopy should be raised, but the increase was far too small to make ascent temperatures higher than entry temperatures. It must be noted that temperatures shown in Figure 9 are for positions on the window unaffected by the frame. Pressure and pressure difference information for ascent design is plotted on Figure 9. Several conditions for venting the cavity between the outer and inner windows were assumed, along with trajectory information and pressure coefficient test data. Maximum crush-pressure differences resulted when there was consideration of a point on the forward window having maximum local pressures along with a separate vent located in an area of negative coefficients. If venting of the window cavity was carried out via a system that would be required to limit the pressure difference across the orbiter load-carrying structure to 2.0 psi, average, and if the window under consideration was in a negative coefficient area, a burst pressure difference would result as shown in Figure 9. Since the decay of a 2.0-psi differential across the vent was undetermined, the design pressure difference across the outer windows at the time of peak surface temperatures would range from 2.0-psi burst to a negligibly small value of crush.

Pressure and temperature window data for Shuttle atmospheric entry are plotted in Figure 10. As before, the outer window was assumed to be 1.0-inch-thick fused silica. The maximum temperature of 1270°F was well below the strain-point temperature for this glass. Results from computer

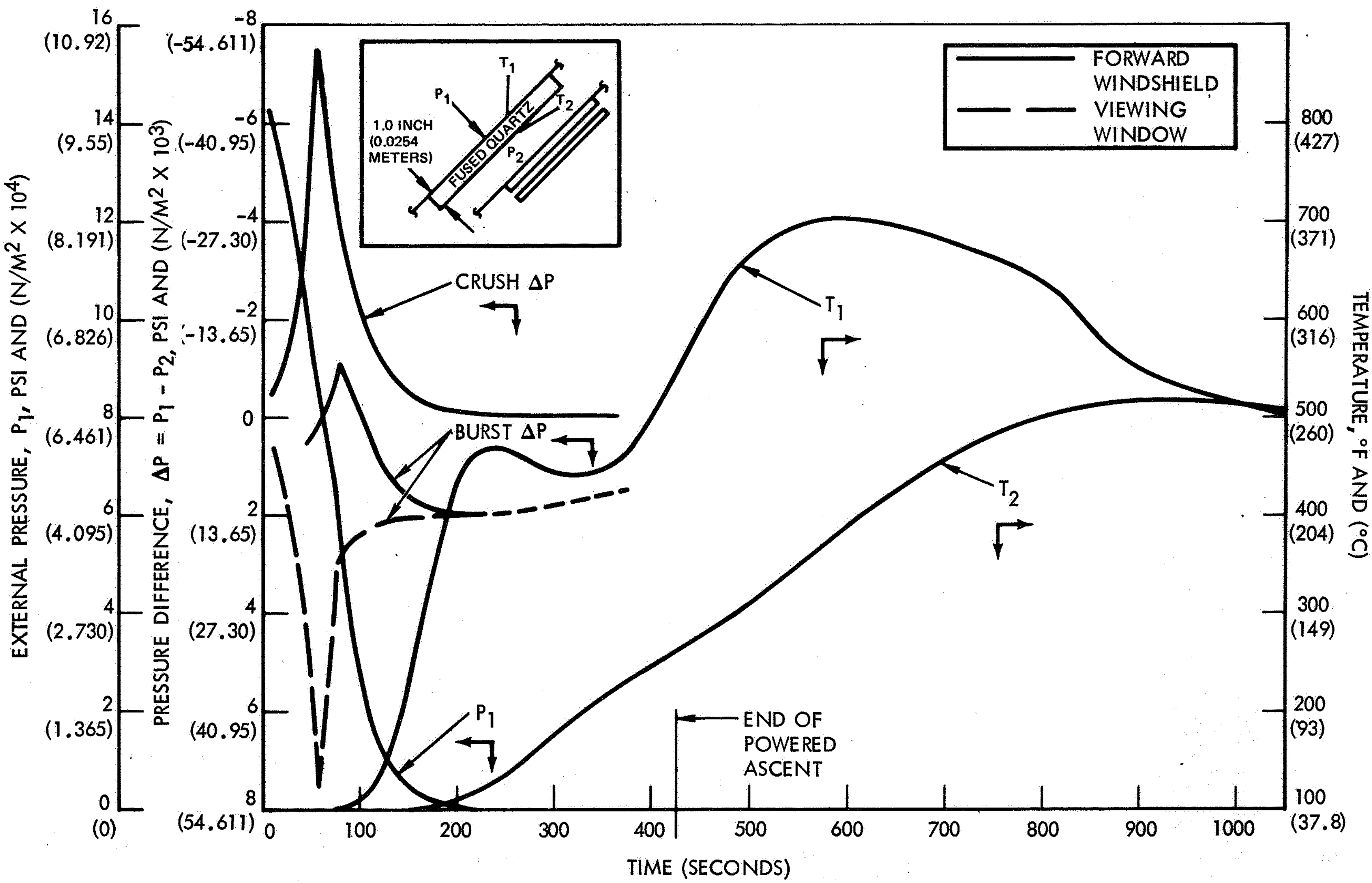


Figure 9. Ascent Pressure and Temperature

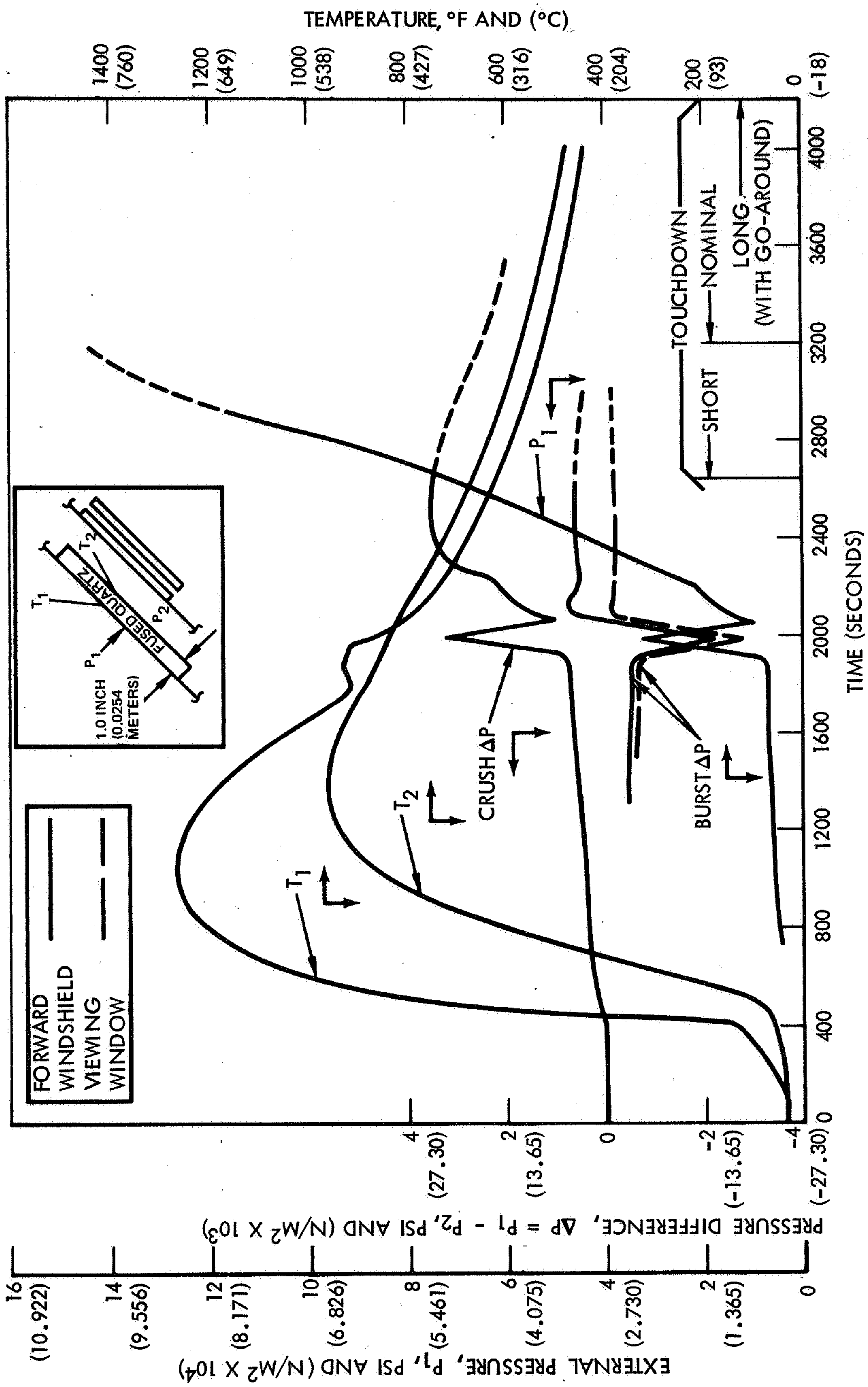


Figure 10. Entry Pressure and Temperature

calculations not illustrated here showed maximum entry temperatures as low as 830°F at other canopy window locations. Assumptions regarding vent positions and specific window locations have been reversed from those explained above in order to produce the pressure difference curves shown. It can be seen that the pressure difference spikes, occurring during vehicle pitchover from 23 degrees to a 10-degree angle of attack, came when the glass temperatures were still high and when temperature gradients through the thickness were turning negative (i.e., $T_1 < T_2$). The magnitude of the pressure difference spikes was somewhat less during entry compared to ascent. Recommended design limit pressures and pressure differentials are shown in Table 1. These figures supplement Figures 9 and 10 in that they add to the external environment the effects of cabin pressure, of configuration, and of possible design failure and limit tolerance values.

During boost, the pressure and temperature pulses were considered to occur separately. The pressure pulse has peaked and essentially disappears before the temperature starts to rise (Figure 9). Maximum outer-pane pressure occurred during boost and reached its design value of 8 psig 60 seconds after liftoff. Temperatures during boost (700°F maximum and 350°F differential) were not critical stresses for any of the conditions investigated. The stress at the center of the long edge reached a peak value calculated to be between 2580 psi and 3280 psi, depending on the extent to which the seal and frame design restrained out-of-plane bowing at the glass edge (Reference 7, page 97). The point of peak temperature, peak in-plane differential temperature, and peak stress, which occurred at 930 seconds in the entry, was the outer-window design and test condition.

2.2.3 Environmental Debris Assessment

Hail Damage

The probability of the Space Shuttle orbiter encountering hail in flight is extremely small, on the order of one in 50 million. Even if hail were encountered that had sufficient hardness and cohesion to penetrate glass, the average penetration would be on the order of 0.09 cm or 1/28th of the glass thickness. Only in the extreme would it reach 0.8 cm. These findings indicate that no special precautions are necessary regarding Space Shuttle orbiter encounters with hail. The detailed analysis for hail damage is present in Reference 8.

Bird Impact

The airworthiness standards for transport-category aircraft state that, if it can be shown by analysis or test that the probability of occurrence of a critical windshield fragmentation condition is of a low order, the aircraft need not have a means of minimizing this danger to the pilot from flying windshield fragments due to bird impact. An analysis was made to show that the probability of bird impact for the Shuttle orbiter was 0.00058 (Reference 8). It is concluded, therefore, that the Shuttle window need not be designed for bird impact.

Rain Erosion

A survey of aircraft currently flying in the speed range of the Shuttle orbiter at altitudes where rain might be encountered indicated that rain erosion was not a concern (Reference 8). It was concluded that the Space Shuttle orbiter was not subject to window damage from rain erosion.

Meteoroids

With fracture-velocity data, the ASKA windshield-pane stress analysis, and the meteoroid environments of NASA-SP-013 (Reference 9), the probability of no windshield failure from meteoroid damage was calculated and found to be 0.9991 if a post-mission windshield inspection and replacement procedure is assumed. The detailed calculations are reported in SD 71-358, Space Shuttle Orbiter Window System Design and Test Program Phase 1 Study Report (Reference 7).

2.3 CANDIDATE WINDOW CONCEPTS AND ANALYSIS

2.3.1 Panes

Redundancies have been standard practice in the design of spacecraft windows. The four-pane configuration furnishes the utmost in reliability but results in the highest weight penalty. The three-pane configuration with the middle pane redundant to both the outer pane and the inner pane (dual redundancy) is a logical approach. However, since the center pane is annealed fused silica at an approximate allowable strength of 4000 psi instead of tempered aluminosilicate at 16,900 psi, this system is heavier than the three-pane system with standard redundancy. The three-pane standard redundancy does not provide a backup for the high-temperature pane. For this reason, the three-pane system with dual redundancy was preferred.

Consideration of the fact that window-pane redundancy exists for reasons of reliability, and that reliability is an inverse function of flaw size, may lead to the two-pane configuration shown in the lower right-hand corner of Figure 11, i.e., a single inner pane of the same weight may be more reliable than two (redundant) panes. If one designs and sizes two redundant panes for given pressure and criteria, and then puts the weight of the two

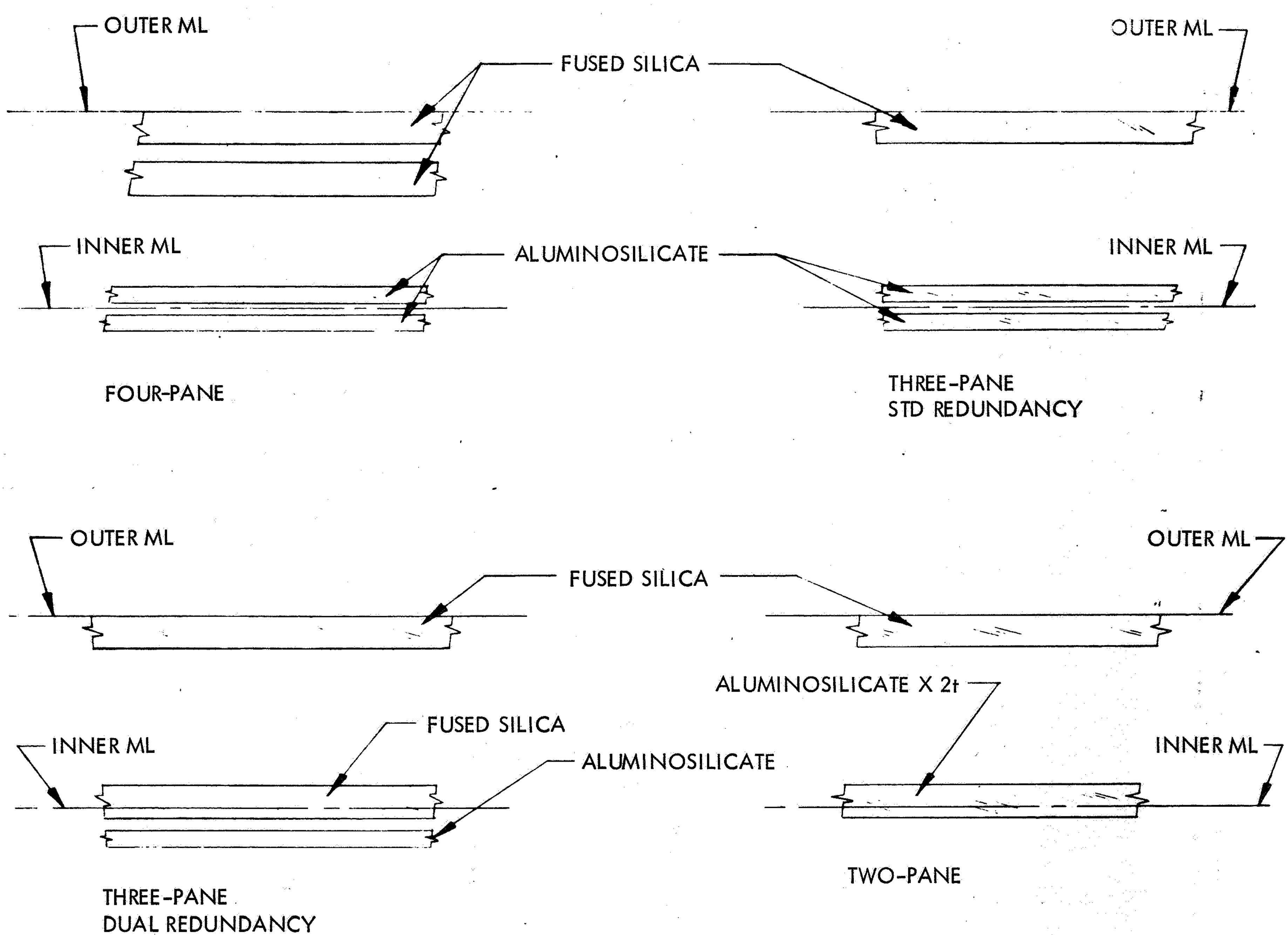


Figure 11. Redundancy Configurations for Spacecraft Windows

panes into a single pane, the single pane will be twice as thick. The critical stress intensity factor will be

$$K_{Ic} = 1.95\sigma_c \sqrt{a/Q} \qquad \text{(Reference 10)}$$

where

σ_c = stress level in the surface (not considering a flaw)

Q = factor varying with flaw shape and taken as 1.0

a = flaw depth,

but

$$\sigma = \frac{m}{z} \quad \alpha \quad \frac{m}{t^2}$$

where

m = bending moment

z = section modulus

t = thickness of glass

for window of width b, $z = bt^2/6$

or

$$\sigma = \frac{6m}{bt^2} = \frac{K_{Ic}}{1.95\sqrt{a/Q}}$$

therefore

$$t^2 = \frac{6m}{b}\left(\frac{1.95\sqrt{a/Q}}{K_{Ic}}\right)$$

or

$$a/Q = t^4\left[\frac{b}{6m}\ \frac{K_{Ic}}{1.95}\right]^2$$

Thus, the allowable flaw depth varies as the fourth power of the glass thickness under the same pressure. This means that the pane twice as thick as the first is allowed a flaw $(2)^4 = 16$ times as deep before failure will occur. The question then arises as to whether a flaw of a given depth with a probability P (h) is more likely to occur simultaneously in two panes (with a probability of $[P(H)]^2$) than another flaw 16 times as deep with a probability of P (16h) is to occur in a single pane. More succinctly, the question is whether the relationship expressed below holds:

$$\left[P(h)\right]^2 > P(16h)$$

If it does, the single pane is more reliable than the redundant system and should be used.

A survey of Apollo window Material Review dispositions involving scratched windows was undertaken in an attempt to obtain sample information on the nature of glass scratches. A sample of such information should involve flaws of significant depth. A total flaw depth of 0.001 inch (equal to a visible flaw depth of 0.00033 inch) is considered significant. Unfortunately, of 473 scratches surveyed, only two were significant (Table 2). Thus, lacking firm logic for departing from the customary three-pane redundancy, the two-pane redundancy was abandoned. This left the three-pane dual redundancy as the sole surviving candidate, and that concept was adopted.

Table 2. Apollo Window Scratch Depth Distribution

Scratch Depth (in. x 10^5)	Outer Window V-321	Inner Window V-311	Misc Windows
0 - 4.99	129	208	90
5 - 9.99	18	3	0
10 - 14.99	15	0	0
15 - 19.99	7	0	0
20 - 24.99	0	0	0
25 - 29.99	0	1	0
30 - 34.99	1	0	0
35 & above	0	1	0
	170	213	90

Total scratches = 170+213+90 = 473
Total significant scratches ($\geq 33 \times 10^{-5}$)" = 2
1 inch = 25.4 millimeters

Preliminary parametric studies were made of the pane thickness on the basis that the window pane must be thick enough to withstand stress levels induced by the various thermal, pressure, and impact environments. Baseline configurations are chosen, and induced stress levels are calculated. Minimum thicknesses are then determined by reference to Figures 12 and 13. These figures are based on a maximum allowable stress of 4000 psi and a pressure of 12 psi for the outer window and a maximum allowable surface stress of 16,900 psi and a pressure of 25.8 psi for the inner and middle window. Thicknesses are shown in Figure 14 for candidate window concepts.

2.3.2 Seals

Outer Seals

During Phase I, a test program evaluated the qualities of selected seal concepts (Reference 11). Candidate seal materials were heated under pressure in contact with fused silica glass at 2000°F and at 1600°F to determine compatibility with the glass material. Relative sealing qualities of O-ring seals, braided jacketed seals, and metal-foil-jacketed seals were also evaluated. Problems were encountered. Candidate seal materials bonded to the glass spalled the glass significantly under some coupons. Metal from the candidate materials was deposited on the glass when they were moved along the glass surface to simulate window-frame expansion.

It was hypothesized that excessive local pressures were the largest contributing factor to the bonding, metal-depositing, and damaged glass surface problems. Even though average pressures had been kept low, irregularities in the unyielding metal and glass surfaces could create pressures ranging in the thousands of psi. It was believed that woven metal or woven-ceramic-jacketed seals could solve the problems. Each thread of a woven metal or ceramic jacket is made up of hundreds of finely drawn metal or ceramic fibers. Each thread of the jacket is more pliable than the equivalent component of a braided seal. It was believed, therefore, that the jacket itself would exhibit more flexibility than the glass-contacting surface of previously tested seals and that this flexibility would eliminate the pressure-generating high spots. Testing of primarily woven-jacketed seals was initiated to test the hypothesis. Results indicated that the aforementioned problems were solved with both the woven-metal-jacketed and woven-ceramic-jacketed seals.

Inner Seal

Silicone and fluorocarbon elastomeric seals were candidates to seal the middle and inner windows. Temperature on the middle window will reach 570°F at the center of the pane. Several silicones seemed to be available which would seal at that temperature. Dow-Corning's RTV 3120

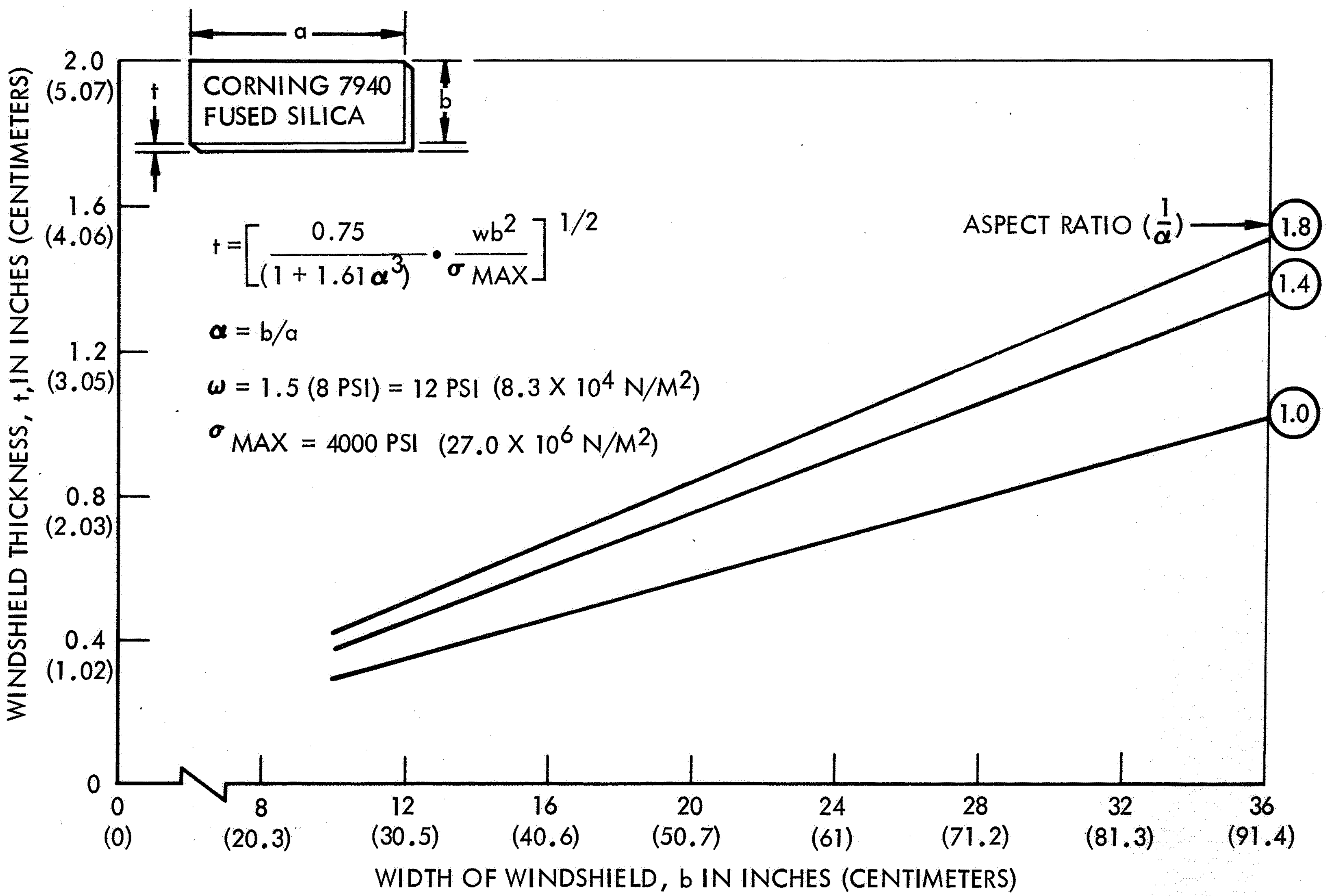


Figure 12. Thickness Versus Width as Function of α for Outer Windshield Panes

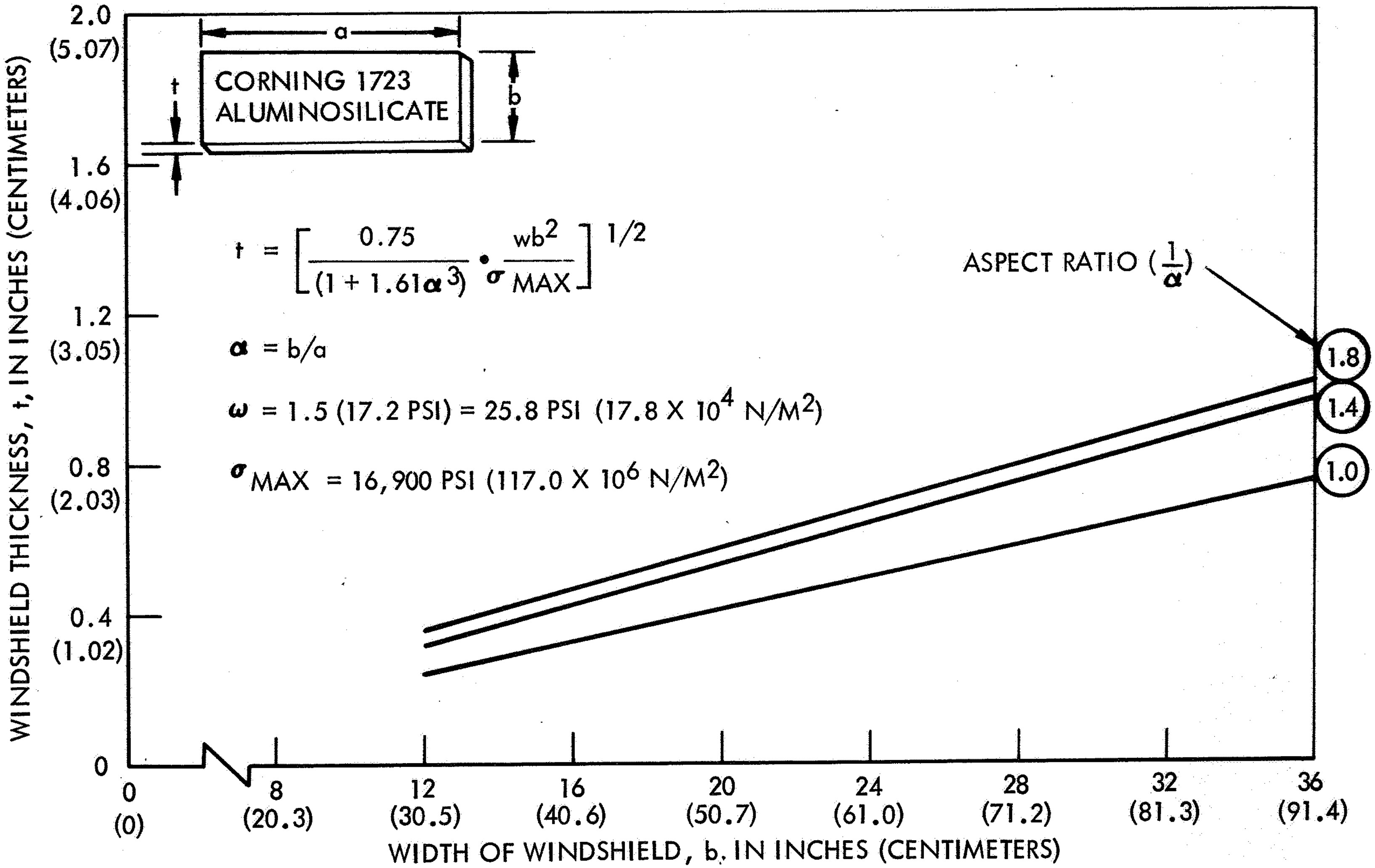


Figure 13. Thickness Versus Width as Function of α for Inner and Middle (Pressure) Windshield Panes

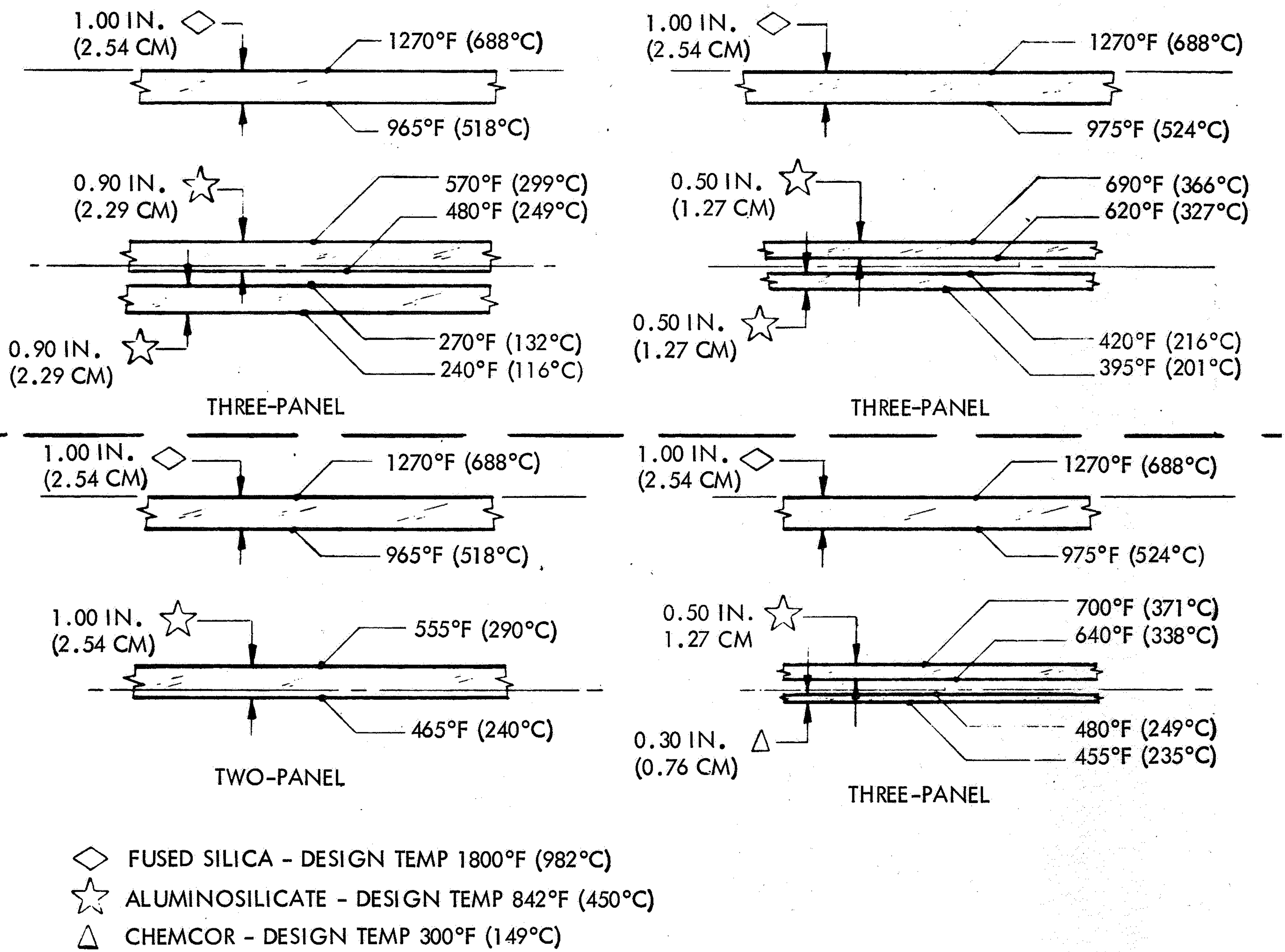
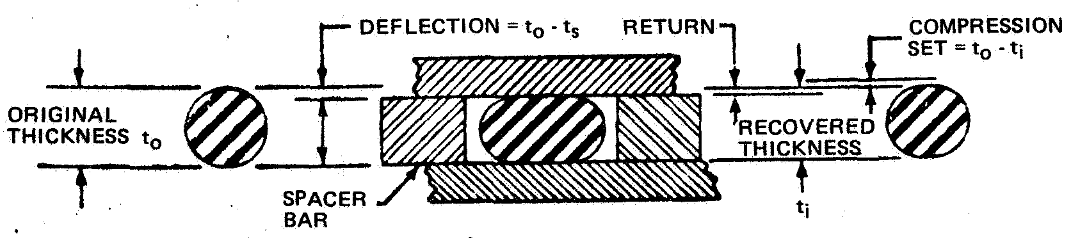


Figure 14. Thermal Analysis Results

is advertised for long-time usage at 300°C, and GE publishes information on several methyl-phenyl and dimethyl compounds that would indicate sealing capabilities at 600°F. In comparative tests, however, Viton showed a marked superiority over a top silicone (Parker S455) in the high-temperature regions expected on the Shuttle vehicle. It also has a capacity to accept low temperature down to about -10° to -20°F. The low temperature predicted on Shuttle is +30°F.

The basic calculations on the 0.275-inch-diameter Viton seal are presented in Figure 15. The allowable seal compression is 30 percent of the undeflected diameter. The seal will have a recovery of about 80 percent or compression set of about 20 percent of the compressed value at 400°F. The recovery (or return) required is 0.057 inch. This is made up of 0.052 inch of maximum tolerance return plus 0.005 inch of squeeze at minimum compression (Figure 15). With the foregoing factors given, the relationships of Figure 15 hold. Thus the 0.275-inch-diameter Viton meets the required 0.057-inch deflection with a margin of 0.066-0.057 = 0.009 inch. The 0.139-inch-diameter seal is squeezed tight between two plates bolted in contact. No recovery is required. Thus, the dimensions are not so critical as those just presented.



t_o = UNDEFLECTED SEAL DIAMETER = 0.275 IN. (0.698 CM)

D = DEFLECTION = $t_o - t_s$ = 0.3 X 0.275 = 0.0825 IN. (0.2095 CM)

R = RETURN = $t_i - t_s$ = 0.80 X 0.0825 = 0.066 IN. (0.1676 CM)

Figure 15. Inner Seal Deflection

2.3.3 Thermal and Pressure Control Systems

While the study emphasis was on passive systems for reasons of simplicity and reliability, several active backup systems were available to solve existing problems, and use of some of these systems is possible in the final Shuttle orbiter design. A window shade barrier would be effective during maximum heating but should be deactivated as quickly as possible thereafter. Provisions for cooling air, while adding to weight and complexity, may be required to preserve cabin pressure redundancy and minimize hermetic seal leakage.

The outer window seal combines problems of large size with extreme heat, significant pressures, and long-term repeated usage. A simple purging of the window area before flight with a dry gas would be sufficient to prevent fogging and a relatively complex cavity pressurization system would not be necessary.

Venting of the heat shield system may be a vehicle design consideration and could be tapped to vent the cavity inboard of the outboard window. Evacuation and sealing of the area between window panes have been utilized in the past, but no significant benefits result and detrimental conditions may occur; hence, this approach was not recommended.

2.3.4 Coatings

No firm requirements for glass coatings have been identified on the Shuttle orbiter. Temperature control coatings are possible but generally are not compatible with the rough usage except in the Shuttle mission. Reflectivity problems can be increased seriously by coatings, particularly in multi-pane windows. Care must also be taken that coatings are compatible with the environment. For example, infrared and ultraviolet coatings (blue-red) will seriously degrade the capability of fused silica to withstand high temperatures. The proper place for the consideration of coatings would be in the vehicle design stages. A maximum effort should be expended in meeting the optical transmission requirements without use of coatings. If coatings become necessary, the glass windows with coated panes should be optically homogenous and free of optical distortion. Each window should provide a minimum light transmittance of 70 percent to assure adequate vision for the Shuttle crew. Heat transfer by radiation into the crew compartment during entry must be minimized; thus electromagnetic radiation transmission in the infrared and ultraviolet portions of the spectrum must be limited.

Based on present Apollo and Skylab requirements, limits for radiation transmission in these portions of the electromagnetic spectrum may be specified. Ultraviolet light transmission should be less than a density of 3 or transmittance of 0.1 percent in the range of 180 to 290 millimicrons at an incidence angle of 45 degrees. Infrared transmission should be less than a density of 1 or transmittance of 10 percent for infrared radiation beyond 800 millimicrons at an incidence angle of 45 degrees. It is reasonable to establish design goals to improve upon these limits. With reduced transmittance, the windows would operate cooler and be less subject to degradation, especially in the hermetic seal area. Ultraviolet transmission of less than a density of 4 or transmittance of 0.01 percent in the range of 180 to 290 millimicrons should be a design goal. Infrared transmission of less than a density of 2 or transmittance of 1 percent for infrared radiation beyond 800 millimicrons should be a design goal. Of course, the infrared and ultraviolet transmission must be reduced without reducing the pilot's visibility.

3. PHASE II TESTING

3.1 TEST ARTICLE

3.1.1 Inner Windshield

The inner window test specimen shown in Figure 16 is defined in detail by Drawing VT70-3119 (Langley Drawing 154780). An aluminosilicate pane 0.90 by 16.5 by 23.0 inches is mounted in 0.275-inch-diameter fluorocarbon (Viton) O-rings. The O-rings are contained in upper and lower retainers of 2024-T351 and 6061-0 aluminum, respectively. The lower retainer is welded to the test fixture. The upper retainer is bolted to the lower on one-inch centers with NAS501-3 bolts. A third Viton seal (0.139 inch diameter) is compressed between the two retainers. It provides pressure redundancy along any potential leak path. Silicone rubber spacers (Silastic 82, Dow Corning, Midland, Michigan) provide lateral pane location and cushioning.

The test article forms a cover for the pressurizing box. It was heated from the outside so that pressure (simulating cabin pressure) was applied on the side opposite the heating pulses. The article was tested twice. The first test represented the inner window conditions, and the second represented the middle window conditions. During each test the window was held under 14.7-psig limit pressure while being thermally cycled on a heating profile representative of the appropriate window.

Glass

The inner window pane is aluminosilicate (CGW 1723) cast, finished, and thermally tempered by Corning Glass Works, Corning, New York, per NR Drawing VT70-3101 (Langley Drawing 154762). Aluminosilicate was chosen for its ability to accept heat tempering and still provide adequate optical properties and a relatively low stress response to thermal differential.

The glass was acceptance-tested by pressurizing it to 26 psig. Thermal shock testing was deleted to minimize uncontrolled propagation of surface flaws. The glass was heat-tempered to a 20,000-psi modulus of rupture, which corresponds to about 8700-psi surface compression. The glass need be only about 0.45 inch thick to withstand 26 psi at its long time strength.

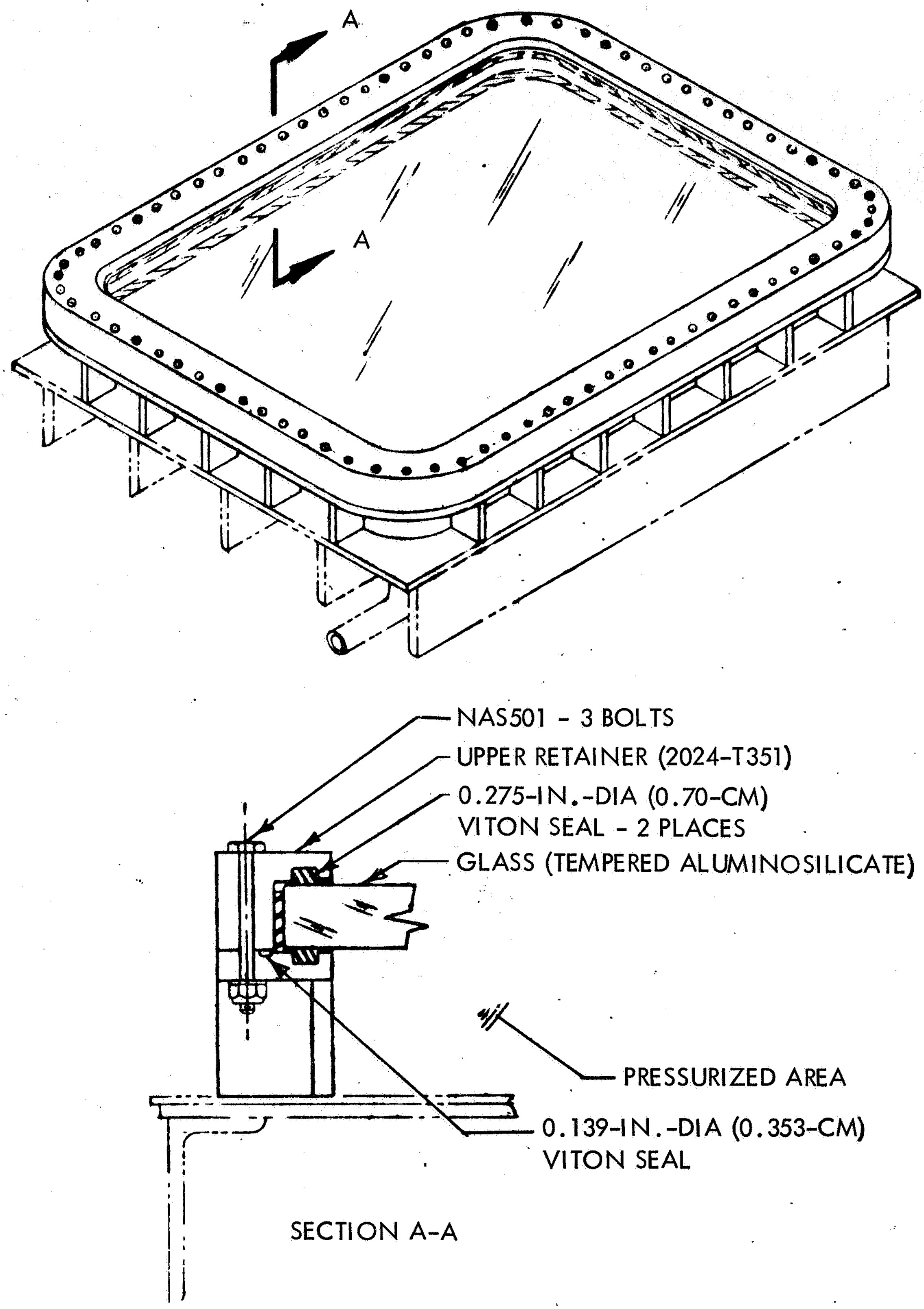


Figure 16. Inner Window Test Specimen Configuration

Since the glass, for heat-sink reasons, is 0.90 inch thick, the pressure is expected to load the glass to only approximately 2280 psi, which does not overcome the surface compression and would not be expected to cause loss of strength with time (Reference 7).

Thermal stresses in the glass are sensitive to differential temperature in the frame. The maximum glass stresses with the glass unconstrained by the frame are calculated to be about 3800 psi. Without measures to relieve the stresses, frame interactions would add about 4900-psi stress to the glass, for a total stress of 8700 psi (Reference 7, page 97). Relief was provided by drilling oversize holes at the frame-retainer interface. This allowed relative slippage between the frame and retainer and prevented warpage, which would otherwise occur.

Seals

The aluminosilicate inner pane was mounted between two 0.275-inch-diameter Viton O-ring seals manufactured by Parker Seal Company, Culver City, California. A third Viton seal 0.139 inches in diameter, also manufactured by Parker, produces redundancy along any leak path. A cross section of the inner seal is illustrated in Figure 16.

3.1.2 Outer Windshield

The outer window test specimen in Figure 17 is defined in detail by Drawing VT70-3120 (Langley Drawing 154781). A CGW 7940 fused silica pane 25 by 35 by 1 inch is mounted in a support frame of low carbon steel that represents the metallic window framework of the vehicle. The frame is grooved radially to minimize forces from thermal warping. The window retainers and auxiliary spring assembly are bolted to the support frame with NAS 501-3 bolts 1 and 1/2 inches on center.

The seals are riveted to the auxiliary spring on 3/4-inch centers with 3/32-inch steel rivets countersunk into 1/2-inch-diameter washers 0.040 inch thick. The auxiliary spring, with a preload adjusted by shims, compensates for lack of springback in the seal to keep the seal in contact with the glass at and after exposure to temperatures. Lateral centering springs position the window and present free play. The insulating cover of a 30-gauge chromel-alumel wire is bonded to the metal retainer. It cushions the contact between the glass and retainer during the test.

Glass

The outer window pane is fused silica (CGW 7940) case and fabricated by Corning Glass Works, Corning, New York, per NR Drawing VT70-3100

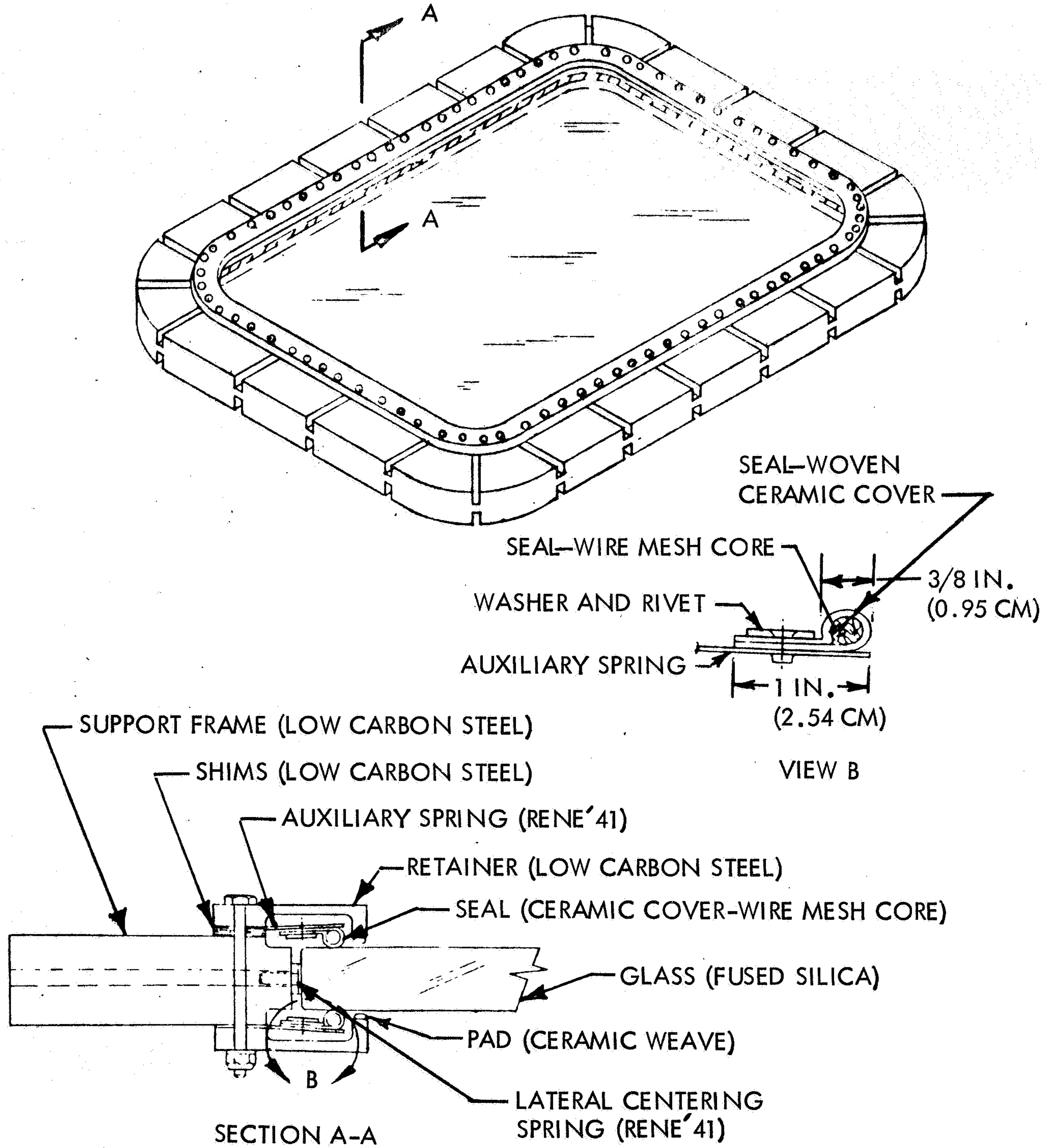


Figure 17. Outer Window Test Specimen Configuration

(Langley Drawing 154761). Fused silica was selected for its ability to withstand the 1270°F expected maximum temperatures and concomitant temperature gradients. The glass is annealed. Acceptance testing by the vendor establishes that the pane has a minimum strength equal to or greater than that required by vehicle use. The acceptance testing is in accordance with the most recent theories and data on fracture propagation in glass. Three modulus-of-rupture specimens were fabricated, ground, and polished identically and in the same process with the fused silica pane. These specimens were then tested in bending to failure in liquid nitrogen. Acceptance of the pane was contingent upon the modulus of rupture for each specimen exceeding 7020 psi.

Results of bending tests in liquid nitrogen on these three samples are presented in Table 3. All the tensile bending test specimens gave moduli of rupture in excess of 7020 psi. The 7020-psi value was a current estimate of liquid-nitrogen strength required to produce a working strength in water of 3300 psi for 100 hours. The 3300-psi value represents the highest level of stress in the outer window pane during the critical entry phase of the mission (Reference 7).

Table 3. Bending Test Results on Outer Window
Fused Silica Glass Specimens

Specimen No.	Thickness		Width		Load		Flexural Strength	
	cm	in.	cm	in.	Newtons	lb	N/M^2	psi
2	0.63	0.248	2.48	0.976	416	94.6	94.8×10^6	13,750
3	0.645	0.254	2.51	0.988	296	67.4	66.5×10^6	9,650
4	0.643	0.253	2.50	0.986	321	73.0	73.4×10^6	10,650

The glass pane edges were etched with hydrofluoric acid. This avoided the chance of lowering the mechanical strength of the edges and reduced the chance of edge damage. Either hydrofluoric acid etching or fire polishing would have provided the proper edge finish. On a micro-scale, these operations reduce the size of the invisible surface flaws and minimize the chance of a failure originating from the edges (edge cracking).

Seal

The outer window seal is a tadpole type manufactured by Gaskets, Inc., Rio, Wisconsin, as Type 2, G/I-I-8D-20. Its size is 3/8 by 1 inch. The seal cross section is illustrated in Figure 17, View B. The seal has a woven ceramic-cloth cover and an Inconel mesh cable core. It is offered for use at 2000°F. Space Division tested the seal for compatibility with fused silica at 1200°F and found that, of the seals tested, it had the least effect on the glass and was most suitable for high-temperature use without further development (Reference 11, page 7). The woven cloth cover did not bond to, leave deposits on, or scratch the glass pane as did some of the metals tested for compatibility. Neither did the Inconel core rigidize to the extent exhibited by ceramic cores.

Because of the seal's minimal springback when tested at high temperatures, a René 41 auxiliary spring in the form of a cantilever leaf was placed in series with the seal. The spring was installed to augment seal springback by 0.050 inch. The seal and auxiliary spring assembly are detailed on Drawings VT70-3104 through VT70-3106 and VT70-3109 (Langley Drawings 154765 through 154767 and 154770).

During entry, the seals are intended to reduce the inflow of hot plasma to a level that causes an insignificant increase in the temperature environment of critical inboard components. To date no exact definition of allowable leakage has been possible. The problem is not considered extremely critical because during the time of high differential pressure, aerodynamic temperature is low and during the time of high aerodynamic temperature, differential pressure is low. Thus, allowable leakage is expected to be higher than that permitted by the seal adopted.

3.2 TEST PLAN

3.2.1 Inner (Pressure) Pane Test Fixture

The inner window test fixture is illustrated in Figure 18. It consists of a reinforced, water-cooled, pressure box with an integral window frame and glass forming the closeout and an externally supported flat radiant heating array assembled from tubular quartz infrared heat lamps. Each heat lamp is 25 inches long and has a rated output of 2500 watts.

The window was pressurized by the introduction of gaseous nitrogen into the test box and regulating it to the desired level of 14.7 psig. Seal leakage was determined by observing the pressure decay of the locked-off pressure box together with accurate knowledge of the system volume.

Power to the quartz lamp heating array was regulated by automatic servo-controlled devices to achieve the desired temperature conditions on the window front surface. A black coating deposited from a carbon powder and water mixture was applied to the window front surface to absorb the heat energy. A temperature sensor in contact with the window front surface

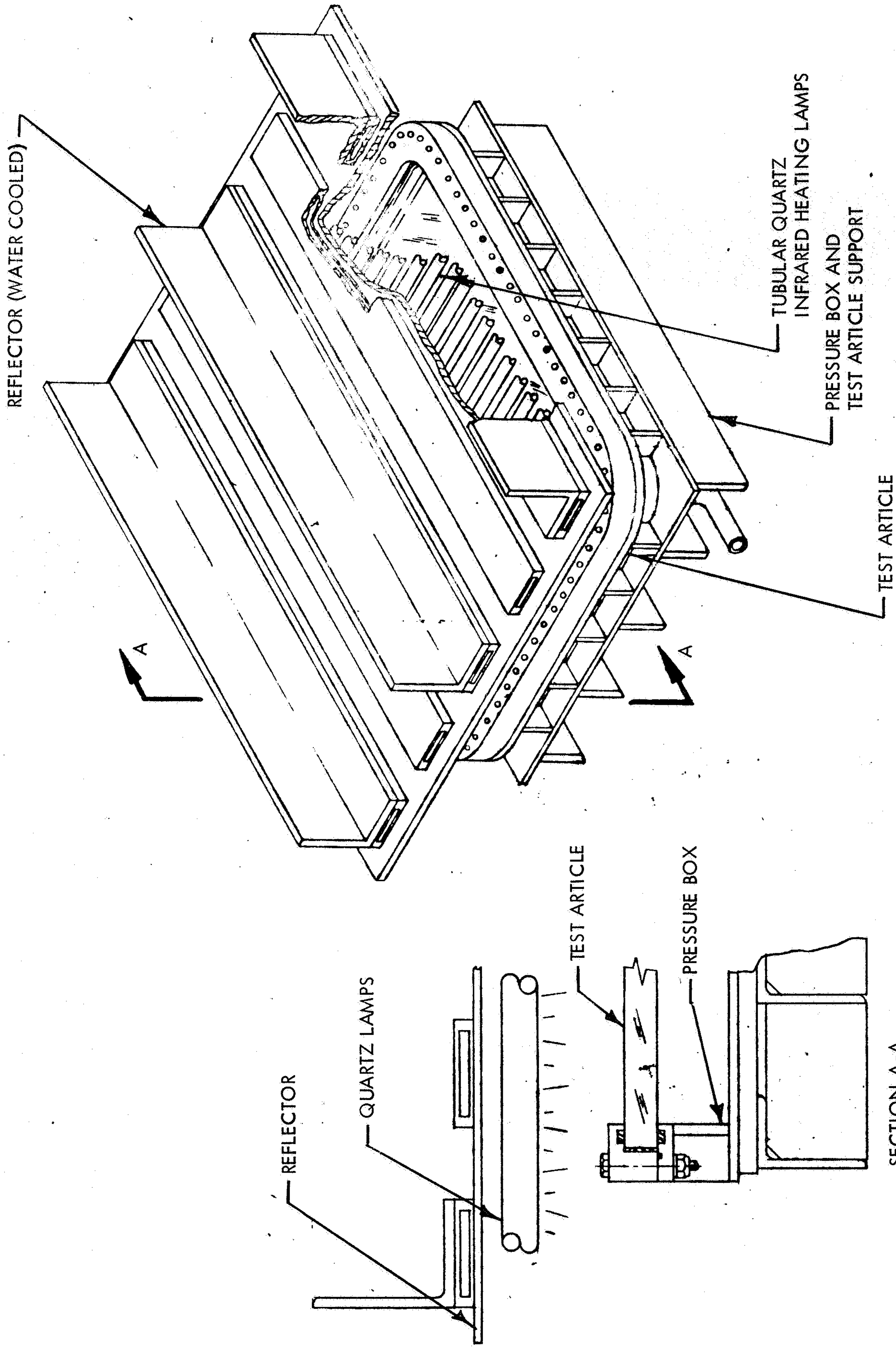


Figure 18. Inner Window Test Fixture

provided the feedback signal for automatic temperature control. The differential temperature across the window was monitored during the first cycle to verify that it did not exceed the predicted allowable limit. The thermocouple locations are shown in Figure 19.

3.2.2 Outer (High-Temperature) Pane Test Fixture

The outer window test fixture is illustrated in Figure 20. It consists of a frame that supports the test article and a flat radiant heating array assembled from tubular quartz infrared heating lamps. The support frame also contains a set of heat lamps located beneath the bolt ring. The radiant heating array is assembled from 42-inch-long heat lamps having a rated output of 3800 watts each.

Power to the quartz lamp heating array is regulated by automatic servo-controlled devices to achieve the desired temperature conditions on the window front surface. A coating consisting of equal parts of water, iron oxide, and potassium silicate is applied to the window front surface to absorb the heat energy. Redundant temperature sensors in contact with the window front surface provide the feedback signal for automatic temperature control.

The differential temperature across the window was monitored during the first thermal cycle to verify that it did not exceed the predicted allowable limit. Locations of the thermocouples on the outer window test specimen are indicated in Figure 21. The locations of the deflection gauges on the outer window test specimen are indicated in Figure 22.

3.3 TEST CRITERIA

3.3.1 Inner Window

The objective of the test program was to demonstrate the ability of the prototype inner and middle window system to withstand the critical design environments established during the earlier phases of this contract effort. The test program is successfully completed, if the following conditions are observed at the conclusion of 100 cycles.

1. Inner and middle window seal leakage of less than 0.1 standard cubic inch per minute (scim) per linear foot of seal length.

2. No evidence of window contamination from the seal that would reduce visibility.

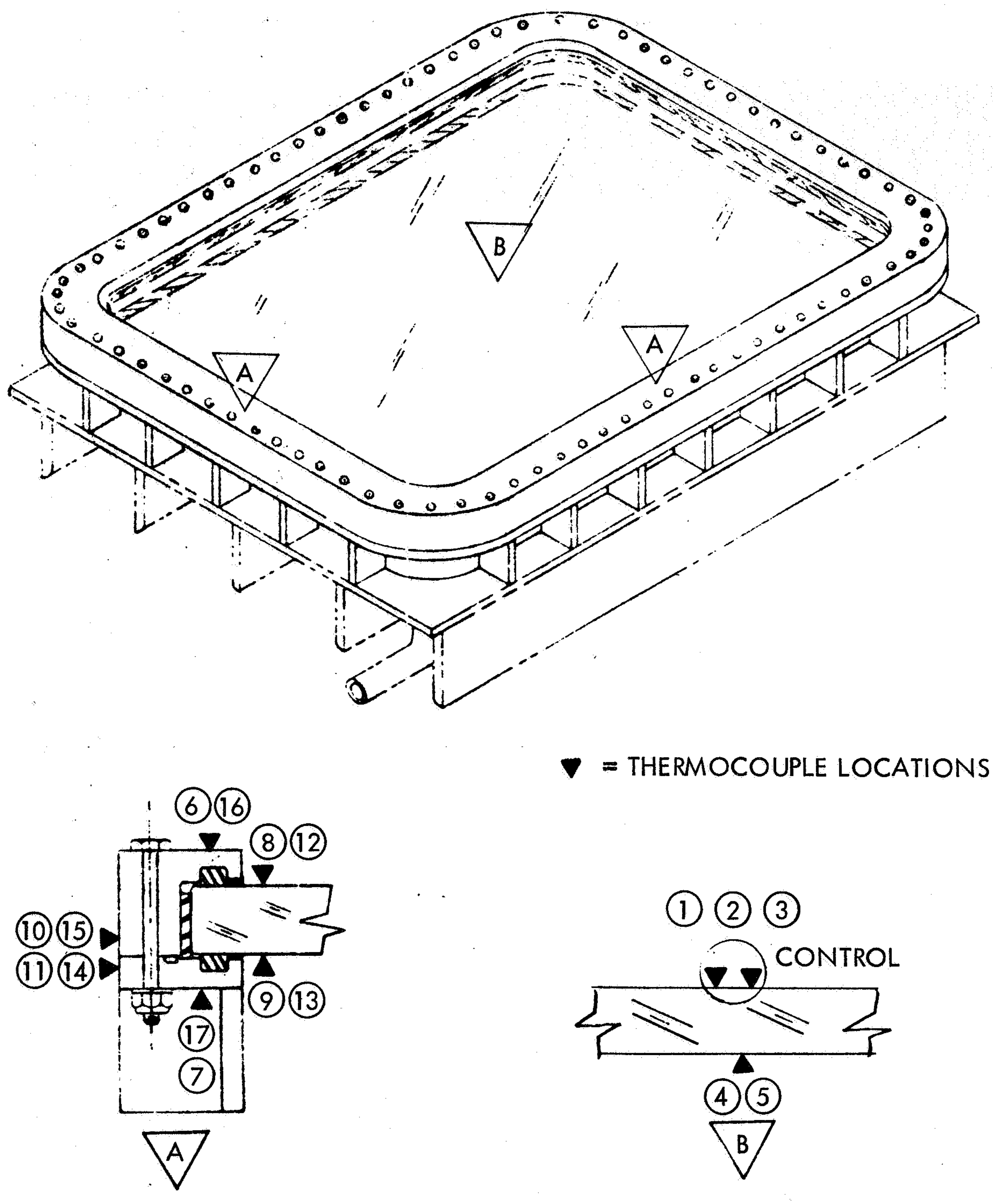


Figure 19. Inner Window Temperature Measurements

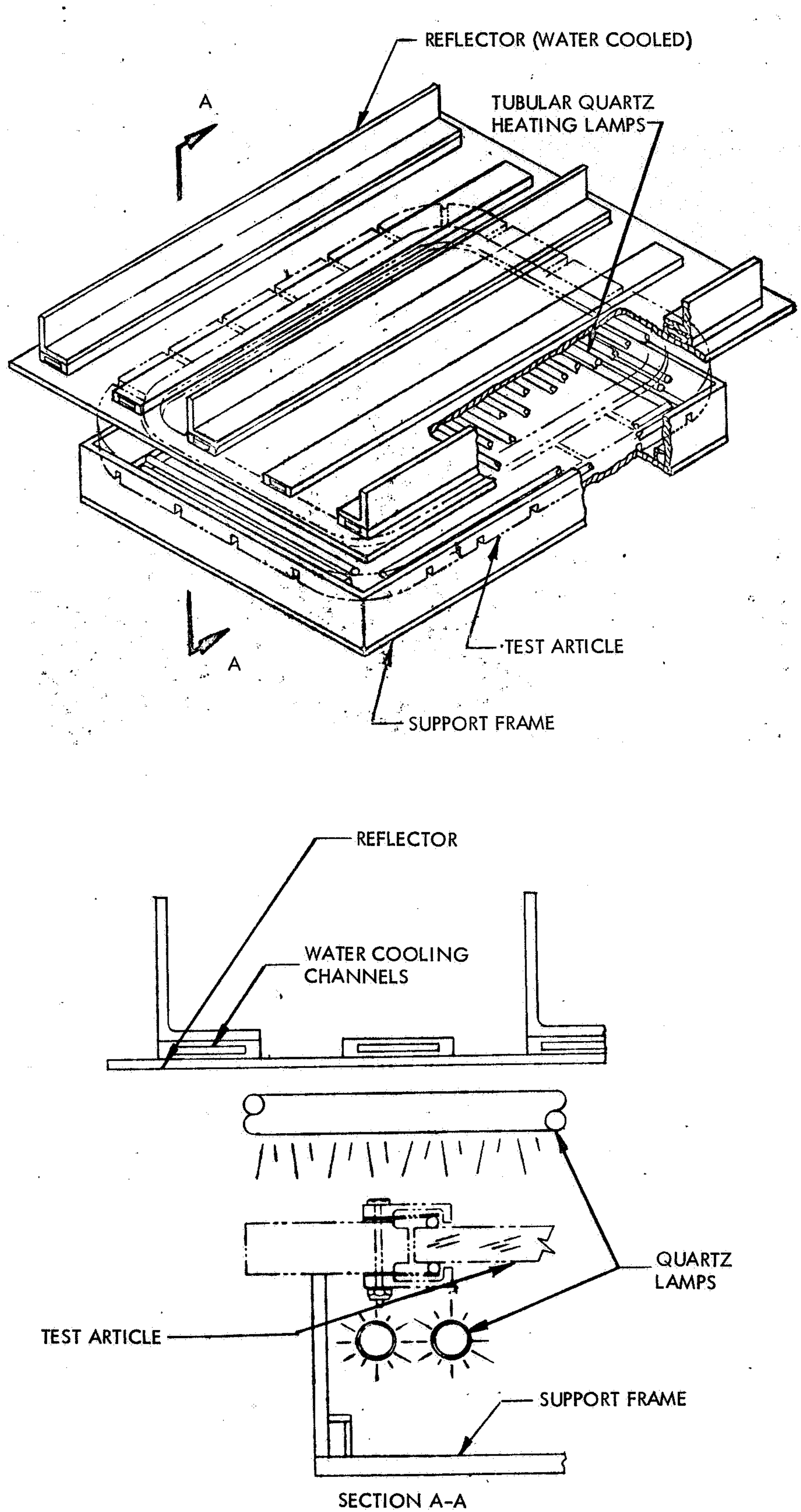


Figure 20. Outer Window Test Fixture

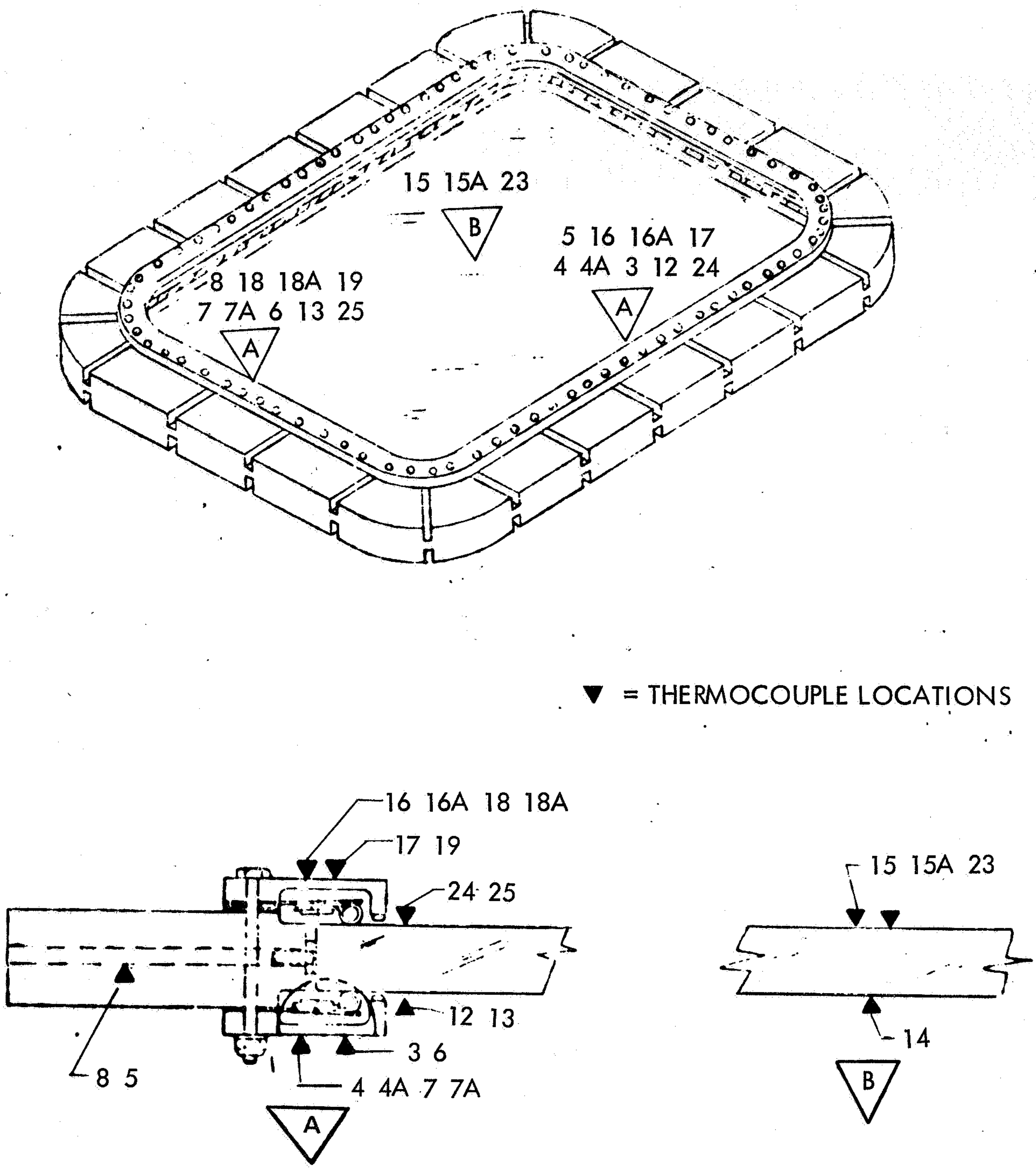


Figure 21. Outer Window Temperature Measurement Locations

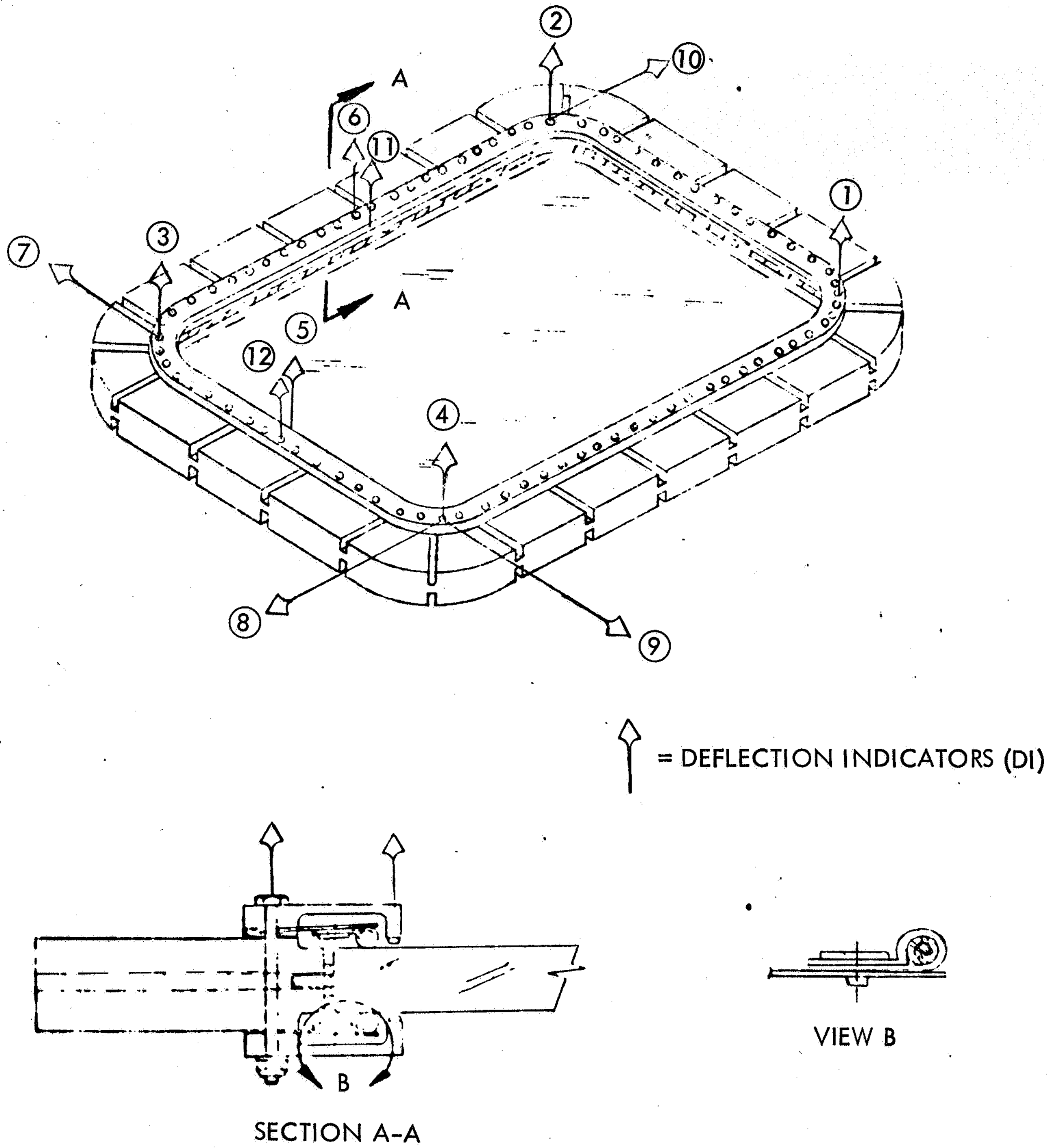


Figure 22. Outer Window Deflection Measurement Locations

3. Primary test components intact.

4. Primary test components intact at end of off-limit tests.

3.3.2 Outer Window

No gross physical or structural degradation was anticipated as a result of thermal cycling of the outer window test article. The test program was considered successfully completed, if the following conditions persist at the conclusion of 120 test cycles:

1. Seal wear less than that which would cause the outer jacket to tear open.

2. Flat compression springs at 80 percent of their original spring compression.

3. Combined seal and spring recovery such that the seal maintains contact with the glass throughout its periphery.

4. Window contact surface free of abrasion or deposits that would cause window failure.

5. Primary test components intact.

3.4 TESTING

3.4.1 Inner Window

After individual test article components were received, they were checked for conformance to their respective control drawings. In a similar manner, mating parts were joined to check for proper clearances. Here use was made of the plexiglass window replica.

Inspection of the primary window test article disclosed the presence of tong marks and scratches. Although they were found to be within 1/16 inch of the sealing surface, the marks and scratches were judged to be acceptable for this test. The tong scratch depth was examined with an Ace optical micrometer and found to be less than 0.001 inch deep. The serial numbers, as marked in the glass, fall directly over the sealing surface. After the test article was wiped with solvent, etching was found, but it was so small it was thought it would not affect the sealing qualities. A fingerprint was found on one surface near an edge. It could not be removed and was assumed to have been placed before the tempering cycle.

Thermocouples were installed on the aluminum frame and on compression springs inside the pressure vessel prior to installation of the window panel. With a rubber seal installed, the window panel was put into position, the technician using cotton gloves to prevent contamination by finger oil. Next the silicon rubber spacers VT70-3114 were placed in position. All of them dropped into position except the two on one short side. The window was a bit tight in the long direction. A phenolic wedge was made and gently driven between the glass and the aluminum frame. This displaced the window about 0.020 inch, allowing the remaining spacers to be positioned. This tight installation permitted the window frame to be turned upside down without the glass falling out. This proved to be an aid in installation of the remaining assembly. After the remaining seals were placed, the window and frames were bolted together. The bolts were torqued to 28 inch-pounds. Then the remaining thermocouples were taped in place, and the entire window surface was painted with a mixture of lamp black. Figure 23 illustrates the inner windshield test specimen as installed in the test fixture.

The inner-window test was performed in three phases. In the first, the pane of the inner window was subjected to 100 thermal entry cycles with a pressure differential of 14.7 psia maintained across it. In the second phase, a middle window pane was subjected to 100 thermal entry cycles with a pressure differential of 14.7 psia maintained across it. In the third phase, the complete window system was subjected to an ultimate pressure test of 26 psia at maximum temperature of 570°F for one cycle.

In the initial run, the inner windshield window was tested to 270°F at 14.7 psig for 100 cycles. The thermal pressure profiles over one cycle are shown in Figure 24. During the run, the pressure gauge for the inner windshield fixture indicated an excessive pressure decay. This decay was attributed to the pressure escaping through the thermocouple wire, which recorded the inside surface of the aluminosilicate window. Since the resulting loss of differential-temperature indication was not considered critical at these relatively low temperatures (270°F), the thermocouple wire was cut at the bulkhead fitting, and the fitting was capped. This brought the leakage rate within the allowable of 0.1 scim per linear foot of sealing edge. During the remaining 82 cycles, the leakage rate remained well within the allowable rate. New seals were then installed.

The second 100-cycle test simulated the thermal and pressure environment of the middle windshield window. The window was aluminosilicate (same pane used in inner-window test) instead of the fused silica as recommended in the design phase. In this test of the inner and middle window, the accumulation of experience in the manufacture, handling, and analysis of the thick, heat-tempered, aluminosilicate pane of larger size was judged to

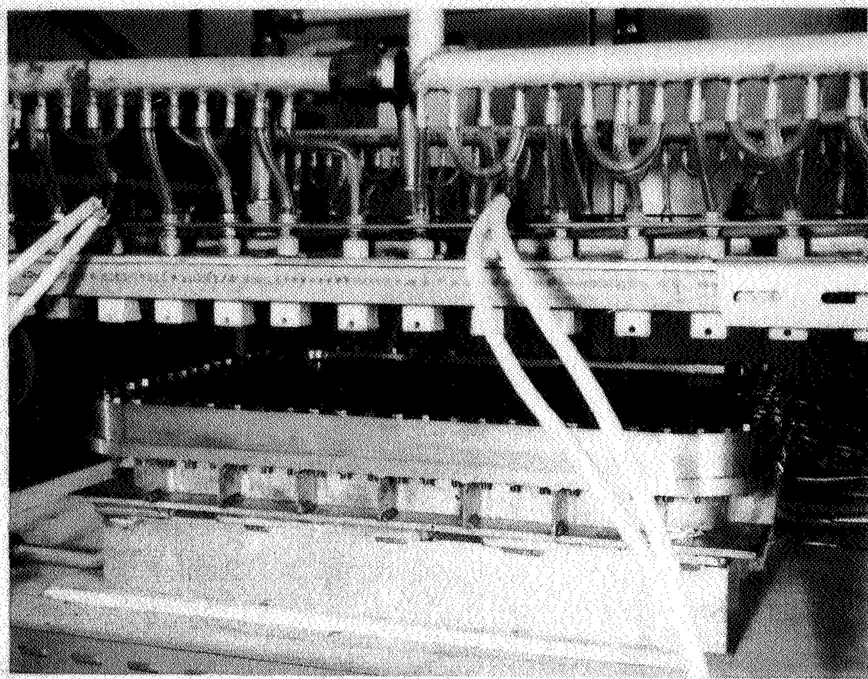


Figure 23. Inner Windshield Window Test Specimen

be more valuable than the testing of another fused silica window (outer window). With the pressure across the middle window at 14.7 psig and the temperature at 570 °F, the middle window specimen sustained 100 cycles of simulated entry. The final ultimate pressure test subjected the window to 26 psig differential. This is one and one-half times the assumed pressure relief valve setting of 17.2 psig. The thermal exposure during this test was 570 °F. At the conclusion of the ultimate pressure test of 26 psig at 570 °F, the leakage rate was 0.013 scim per foot of seal. The inner/middle window design verification test is described in detail in Reference 1.

3.4.2 Outer Window

After individual test article components were received, they were checked for conformance to their respective control drawings. In a similar manner, mating parts were joined and checked for proper clearances.

With use of the plexiglas window replica, a window installation technique was developed. To compress the window centering springs, 0.030-inch-thick stainless steel "shoehorns" were fabricated. Each was long enough to contact all of the springs on one side. With the shoehorns in place, the window was pushed down into place accompanied by an inward prying action

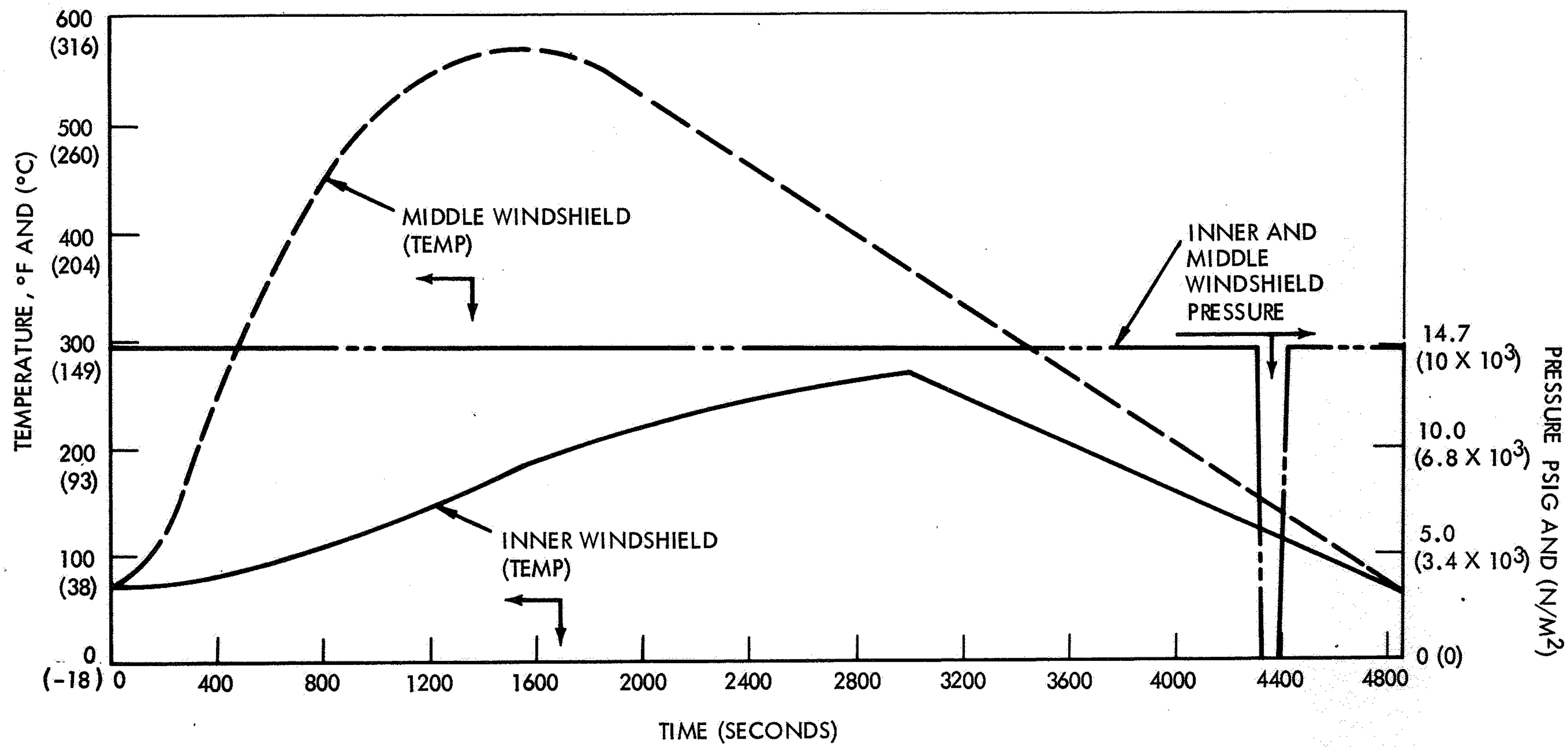


Figure 24. Normal Inner/Middle Windshield Window Verification Test—Thermal and Pressure Profiles

to compress the centering springs. Once the window was pushed down into position, the shoehorns were pulled out. To facilitate shoehorn removal, Molycoat dry film lubricant was sprayed onto the shoehorn surface that was in contact with the centering spring. Holes were provided in the top edges of the shoehorn to bolt on a pry bar. Smoothest removal was by prying up on only one end of the shoehorn while the glass was held down to prevent it from being dragged up with the shoehorn tool.

The test article was assembled to the appropriate configuration for the preliminary thermal testing. Figure 25 is a photograph of the outer windshield window test fixture.

Chromel alumel thermocouples were welded to the metallic components by capacitive discharge techniques. Spring-loaded thermocouple probes were used for measurements on the glass. Inconel 602 wire loops were welded to the upper retainer to provide attachment points for the deflection indicators. Four strands of quartz thread were used to couple the deflection indicators to the welded wire loops. After the test article was assembled and the instrumentation was installed, all test specimens were checked for satisfactory operation.

Preliminary tests were performed with the dummy windows to verify the thermal cycle. Difficulties in achieving the peak temperature were resolved by adjusting the thermal control gain and by replacing the two-heat-lamp arrays used on the short sides with three-lamp arrays for additional heating.

The fused silica test article window was next installed with the 0.030-inch shoehorns as earlier described. Four technicians were used during this procedure. Those touching the glass wore rubber gloves to avoid possible contamination from finger oil. The lower seal and retainer were in place before the window was installed, then the upper shims, seal, and retainers were positioned. The window frame bolts were torqued to 30 inch-pounds. A carbon paste opaque coating was originally applied to the outer window surface but was found to be unsatisfactory after the first heat cycle, thus another coating system was selected. It consisted of equal parts of water, iron oxide, and potassium silicate.

The temperature and deflection data from the first test cycle on the glass were consistent with those from the preliminary test cycles on a marinet window replica tested earlier, so that testing of the fused silica window was continued.

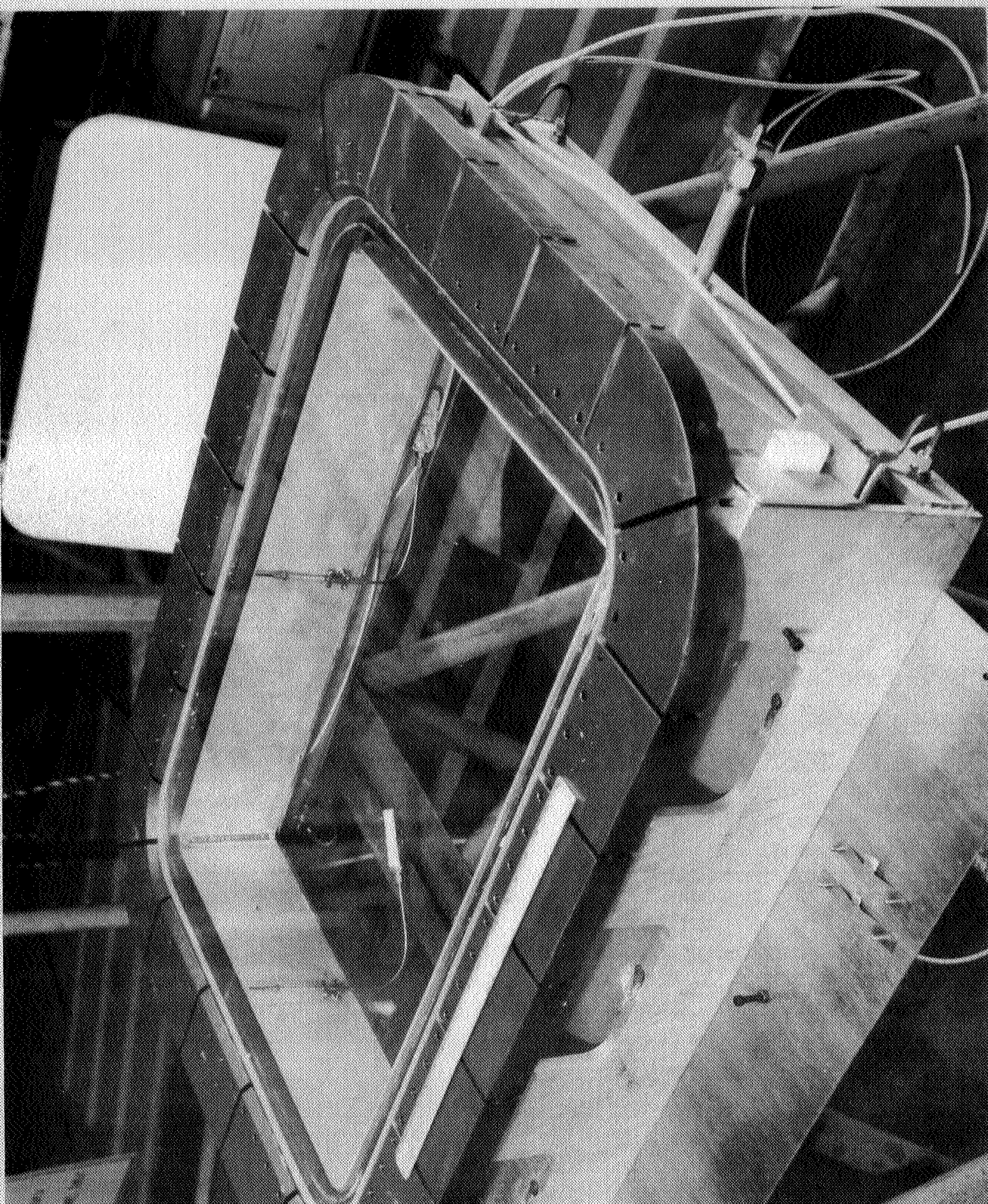


Figure 25. Outer Windshield Window Test Fixture

Figure 26 presents the temperatures and deflections as recorded on magnetic tape for the first cycle of the outer window test. These data are representative of a normal cycle and tend to verify the test analysis. Specimen testing and condition were noted as follows during the 100 simulated cycles:

Cycle 7. The long-side control recorder jammed at 500°F. The test was terminated until the recorder was repaired.

Cycle 20. Inspection after cycle 20 showed the Refrasil bumper to be pulling away from the upper retainer in one corner. It had debonded during assembly but remained in position at that time.

Cycle 40. The Refrasil bumper retracted to approximately 1-1/4 inches at its maximum from where it was bonded at the corner.

Cycle 42. At the start of the morning shift it was found that the recorder controlling the long-side underside heat lamps had its ink pen jammed in the strip chart paper. The evidence indicates, however, that the controller maintained peak surface temperature. This condition apparently limited the upscale travel of the recorder, which would have the effect of reducing the maximum call for heat on the underside lamps.

Cycle 54. After cycle 54, the test article was removed from the test setup. The upper retainer was removed and inspection results were noted (Figure 27).

The lower seal and retainer were not removed during this inspection. Since the Refrasil bumpers were no longer functional, they were completely removed from both the upper and lower retainers for the remaining test cycles. New bolts were used to reassemble the test article for continuation of the test cycling.

The bumper strip detached from the retainer at one corner (Figure 28). The strip (Thermo Electric HG/HG) was bonded to the retainer with Sauereisen cement. This adhesive apparently embrittled the bumper strip material, thereby increasing its shrinkage. The resulting debonding is considered secondary. The bumper strip is designed as a cushion between the metal retainer and the fused silica outer windowshield surface. It is apparent that the bumper strip is not necessary to the test configuration because no visible scratches appeared on the surface of the windshield

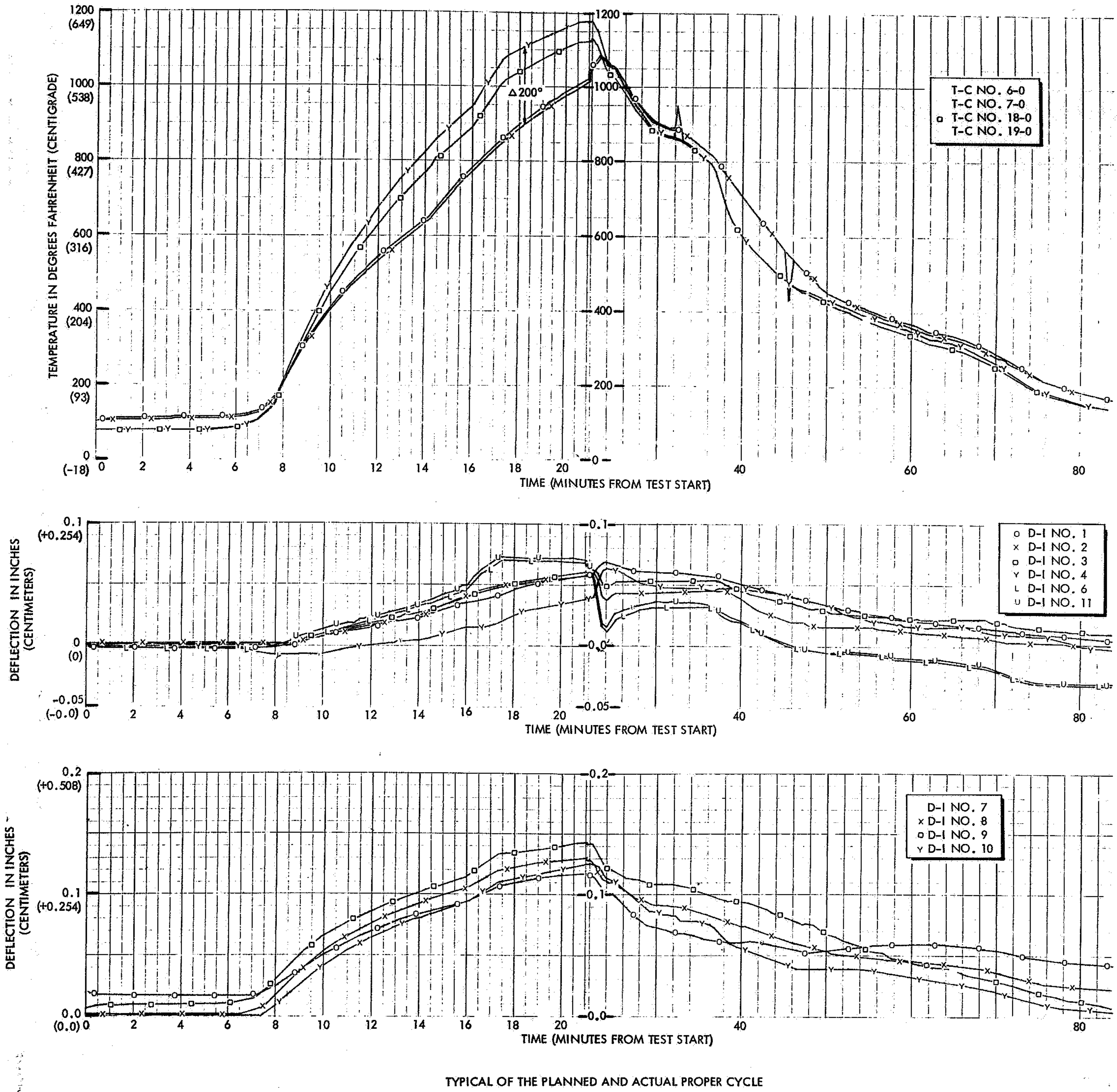


Figure 26. Temperature and Deflection of Outer Window Test Specimen During First Cycle (Sheet 1 of 3)

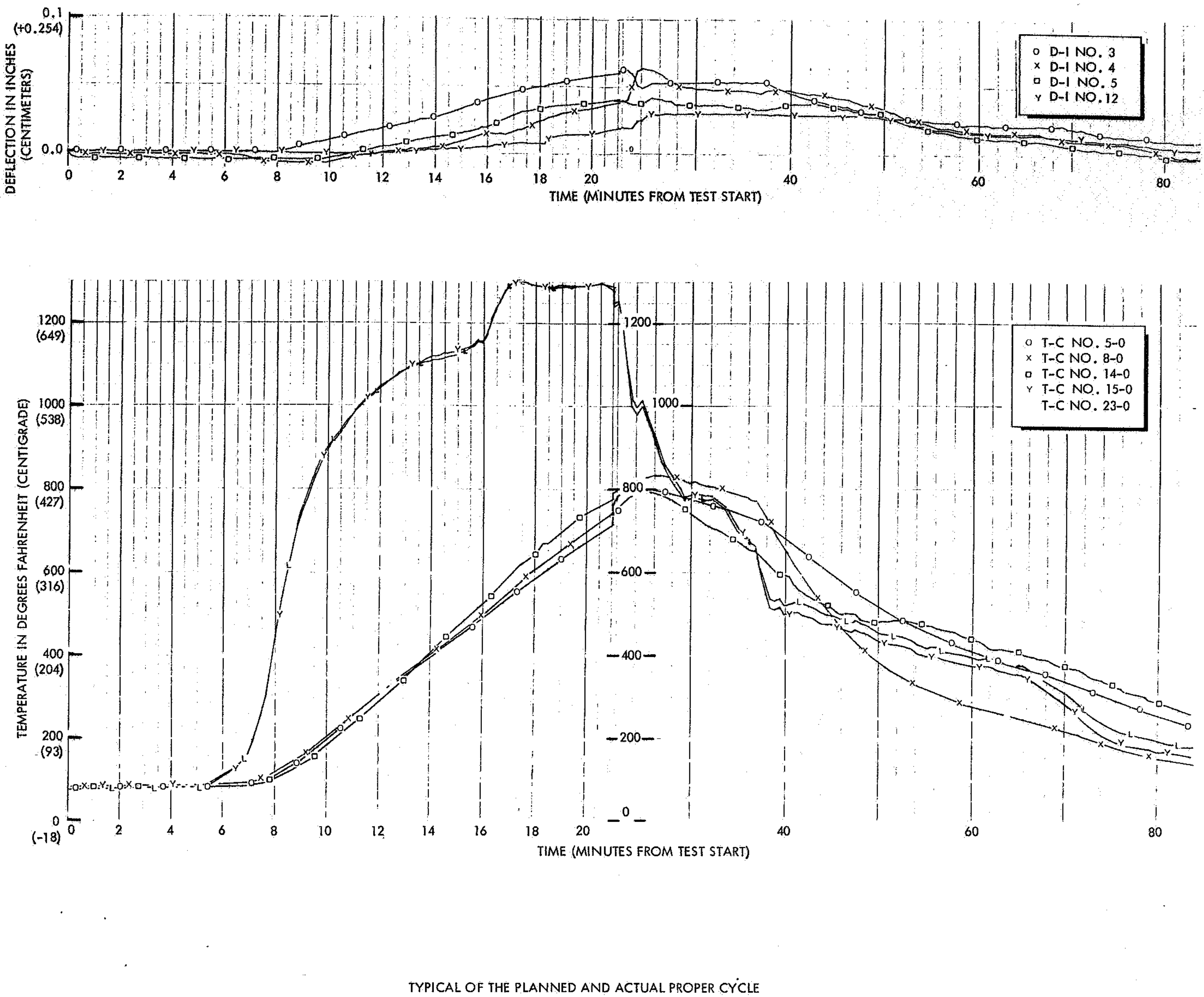
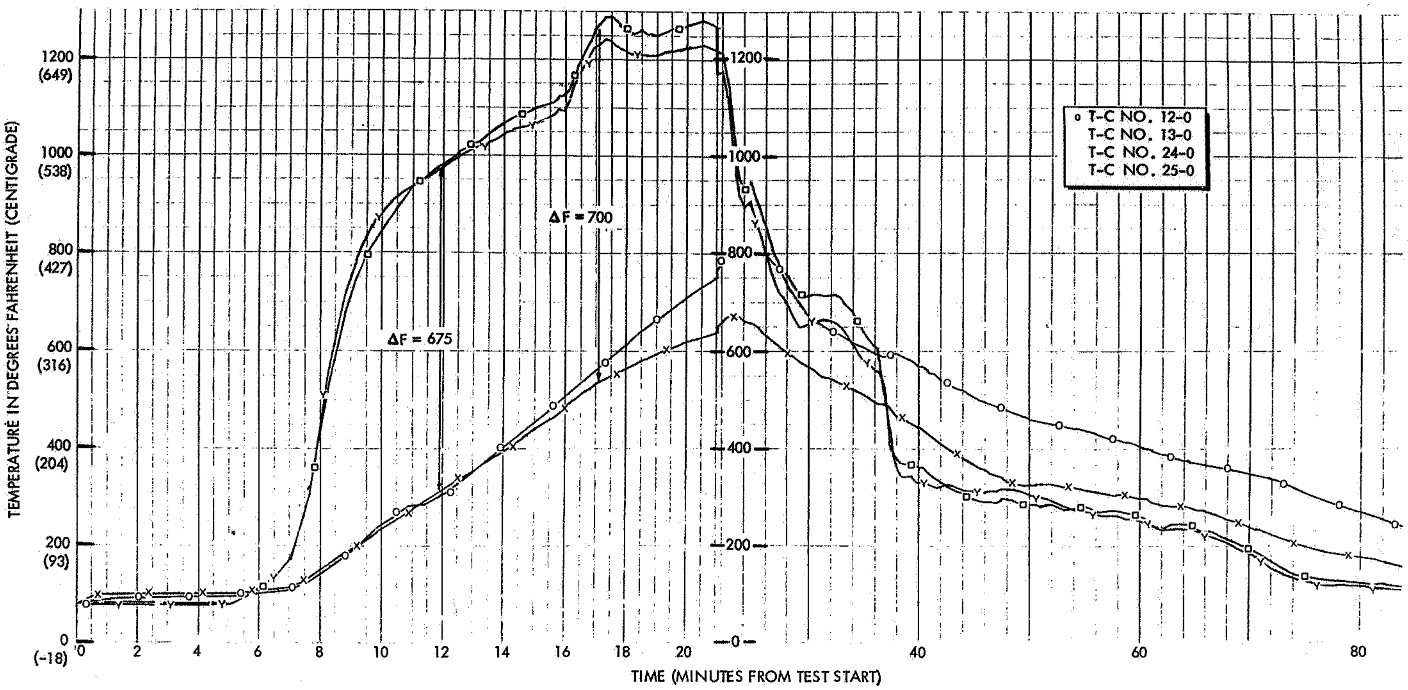
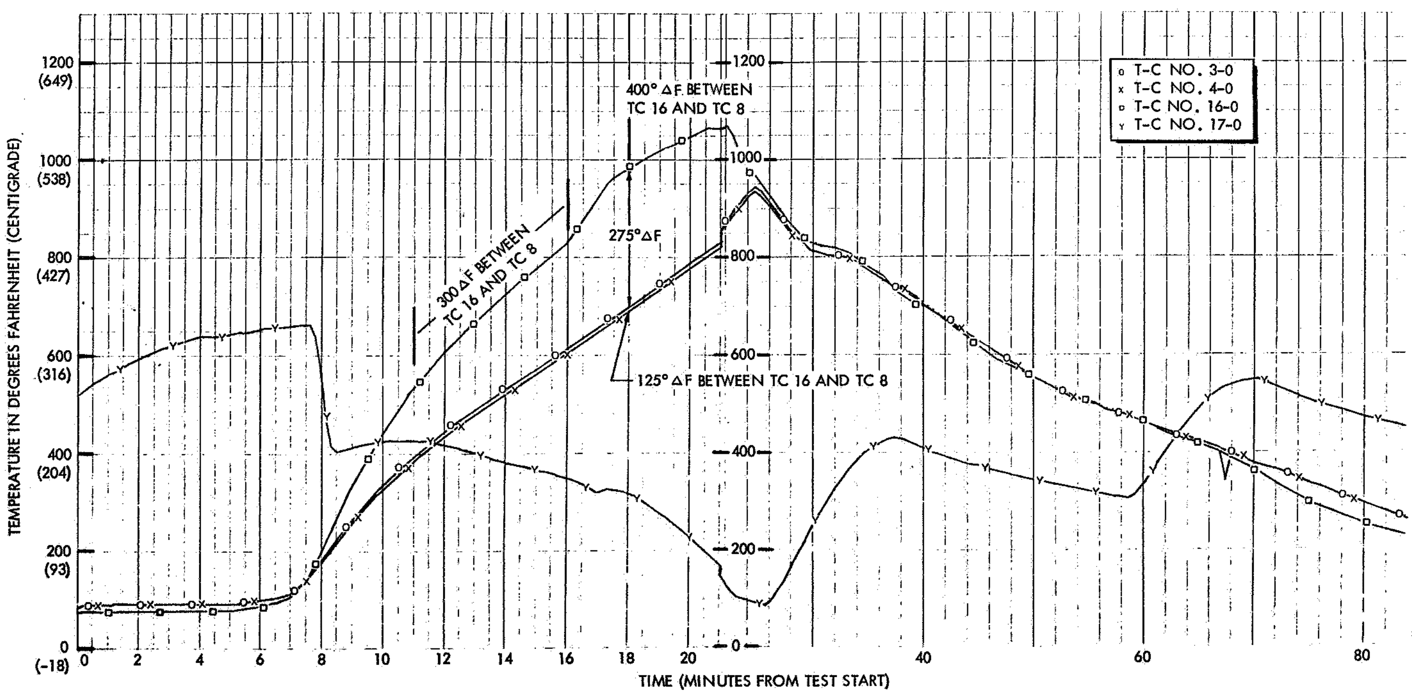


Figure 26. Temperature and Deflection of Outer Window Test Specimen During First Cycle (Sheet 2 of 3)





TYPICAL OF THE PLANNED AND ACTUAL PROPER CYCLE

Figure 26. Temperature and Deflection of Outer Window Test Specimen During First Cycle (Sheet 3 of 3)

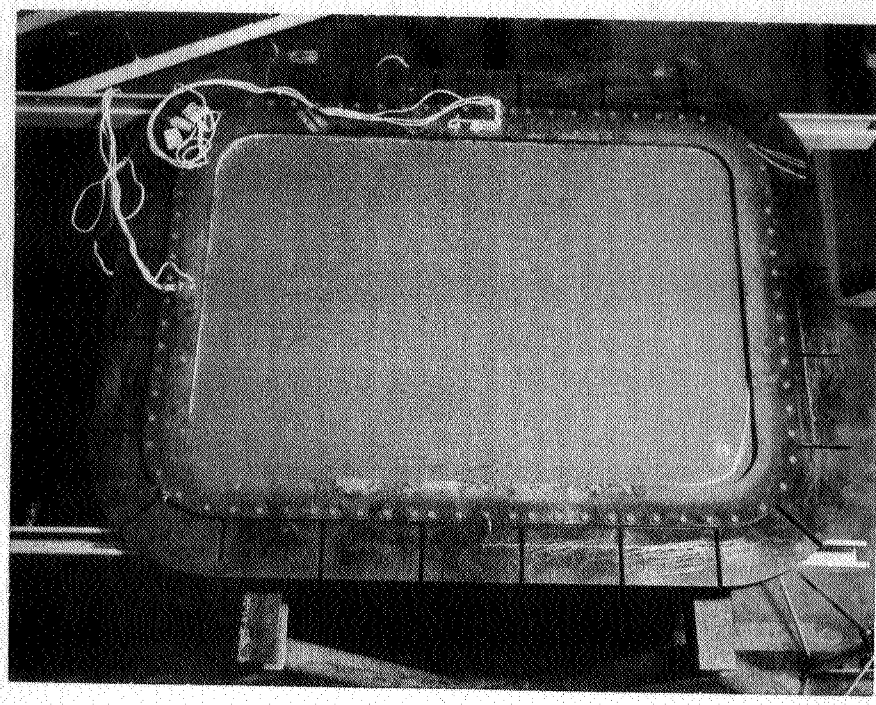


Figure 27. Outer Windshield Test Specimen After 54th Cycle

Figure 28. Closeup of Debonded Bumper Strip on Outer Windshield Test Specimen

specimens during the remaining tests. But the future windshield frame design should consider such a cushion between the retainer and glass surface because the windshield frame may be of lighter construction.

After the 54th cycle was completed, the following observations were made:

1. The Refrasil bumper on the top side was unbonded over 20 percent of its length. The bumper on the bottom was unbonded over 80 percent of its length. The bumper strip is of a secondary nature, not being part of the plasma seal.

2. After the through-bolts holding the test fixture assembly together were removed, it was found that some were bent at the corner of the test fixture so that it was difficult to remove them from the frame. All bolts were finally removed.

3. No degradation of the iron oxide opaque window coating was apparent.

4. The flat René 41 springs were intact, and the seal surface appeared to have a flat surface where it contacted the glass. The seal had approximately a 15-percent reduction is diameter.

5. Only slight traces of seal abrasion could be detected on the surface of the glass. The glass was intact and functional.

6. A white hazy substance appeared on the underside of the glass next to the fasteners that joined the lower seal to the flat spring. This slight discoloration was outside the vision envelope of the window.

Specimen conditions and/or anomalies are noted as follows for cycles 55 to 120:

Cycle 55. Thermocouple 18, which controls the lower heat lamps on the short side, was shorted for 20 minutes. This would have the effect of reducing the heat to the underside of the frame. It did not affect peak temperature exposure.

Cycle 72. Testing was discontinued after this cycle to replace the lower heat lamps that were noted to be defective. It was not known exactly when failure occurred. After replacement of the heat lamps, the test was continued.

Cycle 75. Thermocouple 18 was shorted. Testing was stopped, and the thermocouple was repaired. After repair, the test was continued.

Cycle 120. Corner bolts were found to be bent upon disassembly.

During the outer window test, a test equipment malfunction occurred that increased the temperature differential on the frame and retainers. On the 71st cycle it was noted that the lamps on the underside of the long side of the test frame (low-temperature side) had burned out. This malfunction increased the temperature differential between the outer and inner retainers to 650°F for approximately 11 cycles. The normal test differential was 280°F. A trace of the temperature profile during this malfunction is shown in Figure 29. The burned-out lamps were replaced immediately on the 72nd cycle. The peak temperature exposure was maintained, and the test thermal exposure was more severe than planned.

On the 74th cycle, the retainers along the short side of the windshield test specimen sustained a severe differential temperature of 813°F. The high differential temperature was a result of improper low-side heat control because of a shorted thermocouple. The resulting temperature profiles are shown in Figure 30. The large differential is evident as the difference between monitoring thermocouples 19 and 6. The faulty controller thermocouple was immediately repaired, and the test was continued. The monitoring thermocouple then returned to nominal values, as evident on the left in Figure 30. Neither of these two extreme differential thermal exposures harmed the glass windshield pane. On the 42nd cycle the controller pen was found jammed for the recorder of the control thermocouple for the underside of the long side of the windshield. This caused a higher than normal differential thermal exposure between the same outer and inner retainers, as described. This condition had occurred overnight and prevailed for 11 cycles. About a 570°F differential temperature occurred compared to the normal differential temperature of 280°F. However, this thermal exposure was much less severe than that encountered on cycles 72 and 74, as described. For the reasons discussed (more severe thermal gradient exposure than planned and maintenance of peak temperature) these test equipment malfunctions are not considered critical and did not affect the primary objectives of the test. Details of the outer window design verification test are contained in Reference 2.

Figure 31, 32, and 33 gives the temperature and deflection profile of cycle 76. This cycle is enclosed for comparison of the deflection and temperature behavior of the retainer without the bumper strip. Figure 26 illustrates results of the deflection of the retainer with the bumper strip in place.

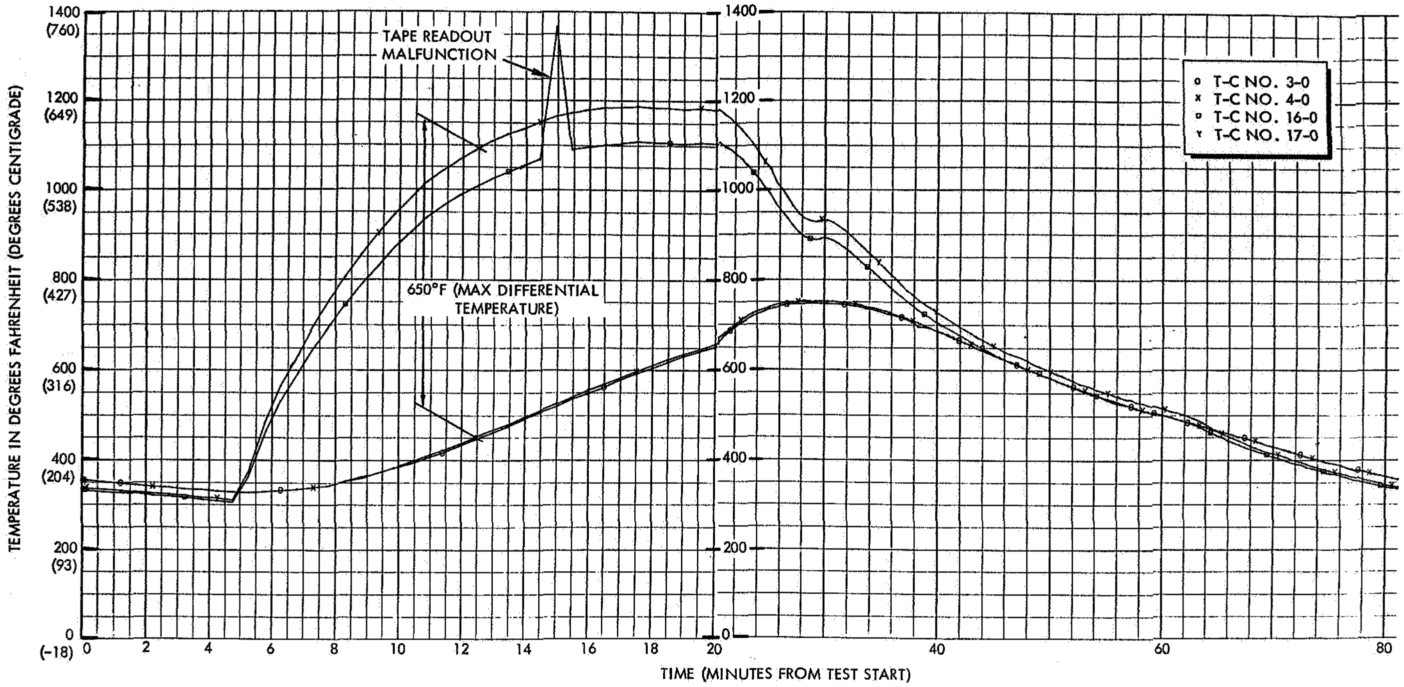


Figure 29. Excessive Thermal Exposure Evident in Outer Windshield Window Test on Cycle 70

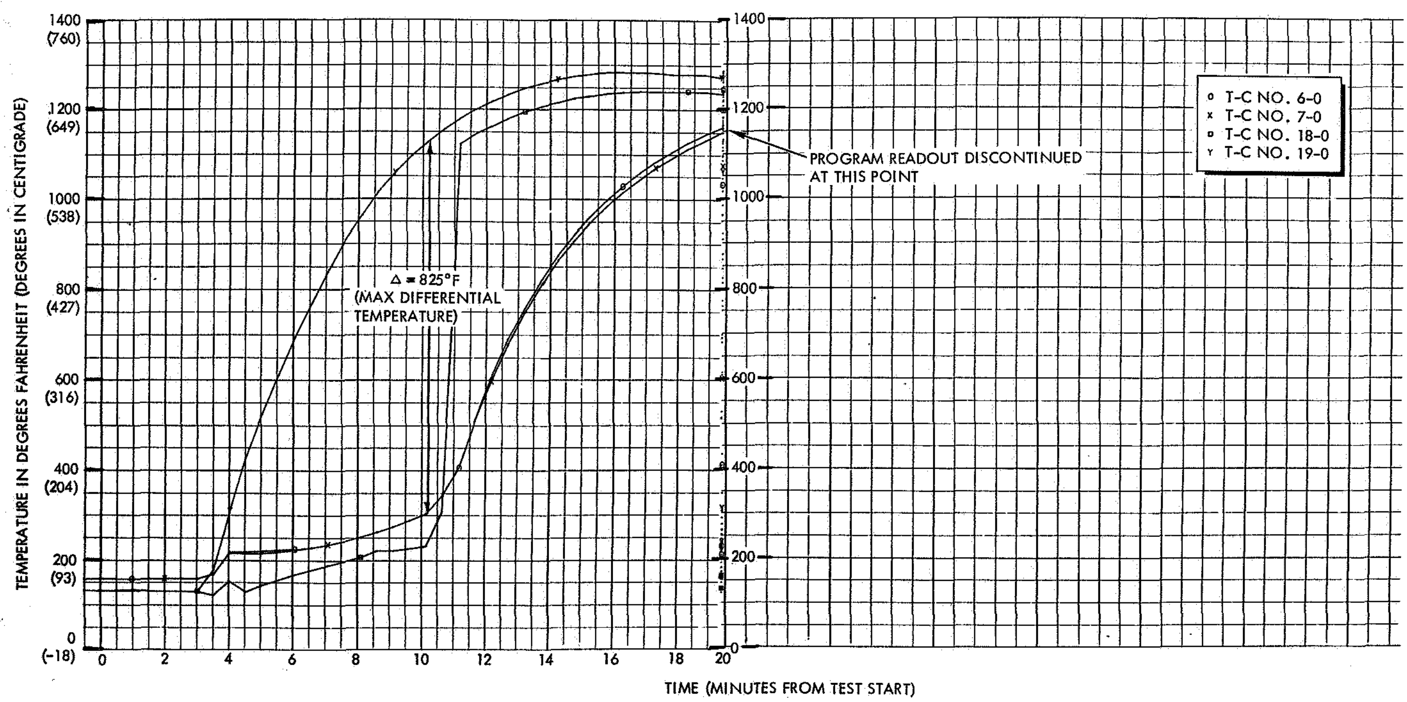


Figure 30. Excessive Thermal Exposure Evident in Outer Windshield Window Test on Cycle 74

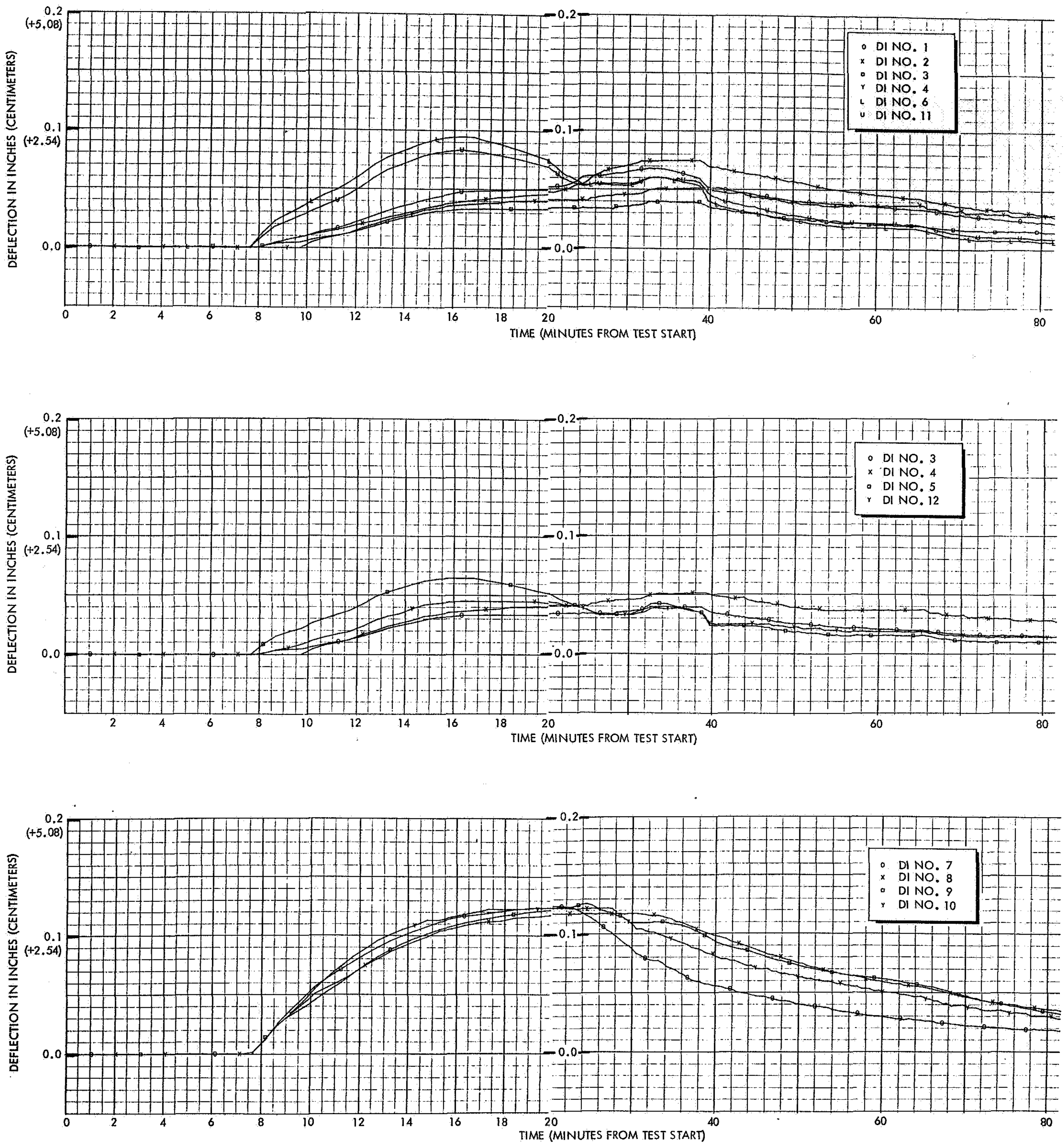
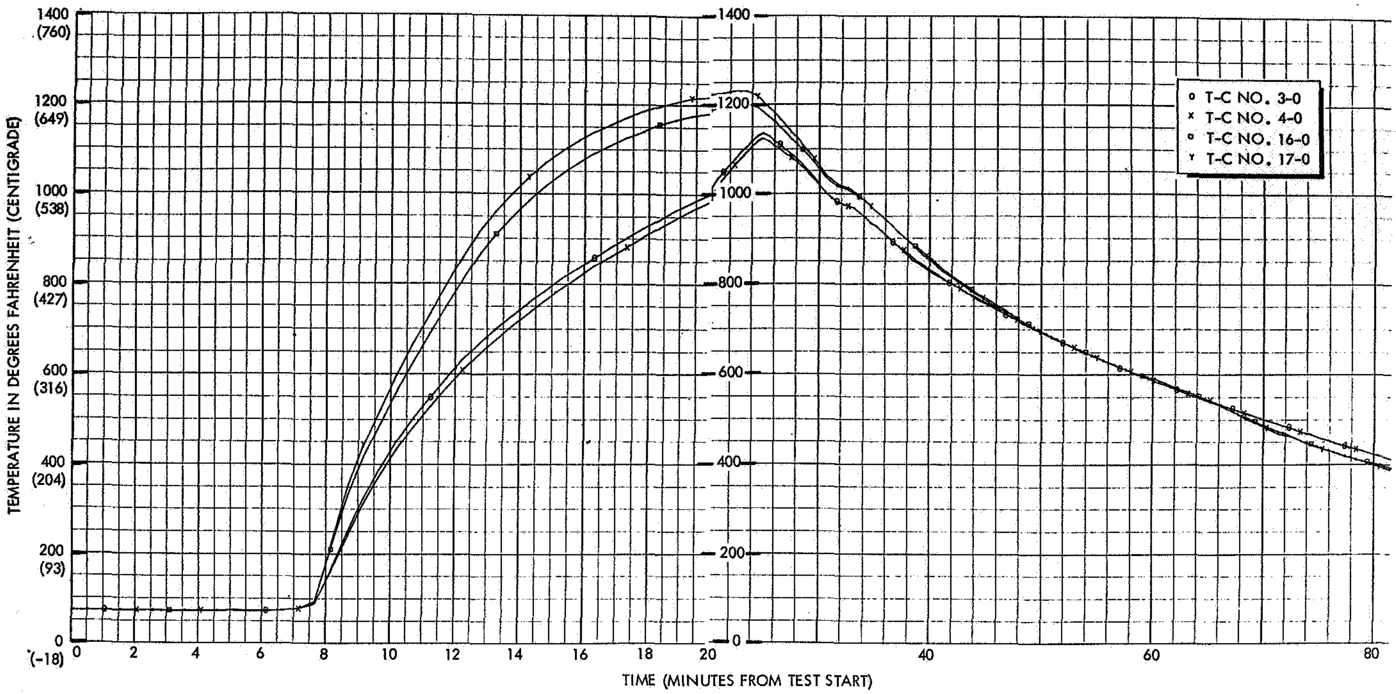


Figure 31. Temperature and Deflection of Outer Window Test Specimen During 76th Cycle



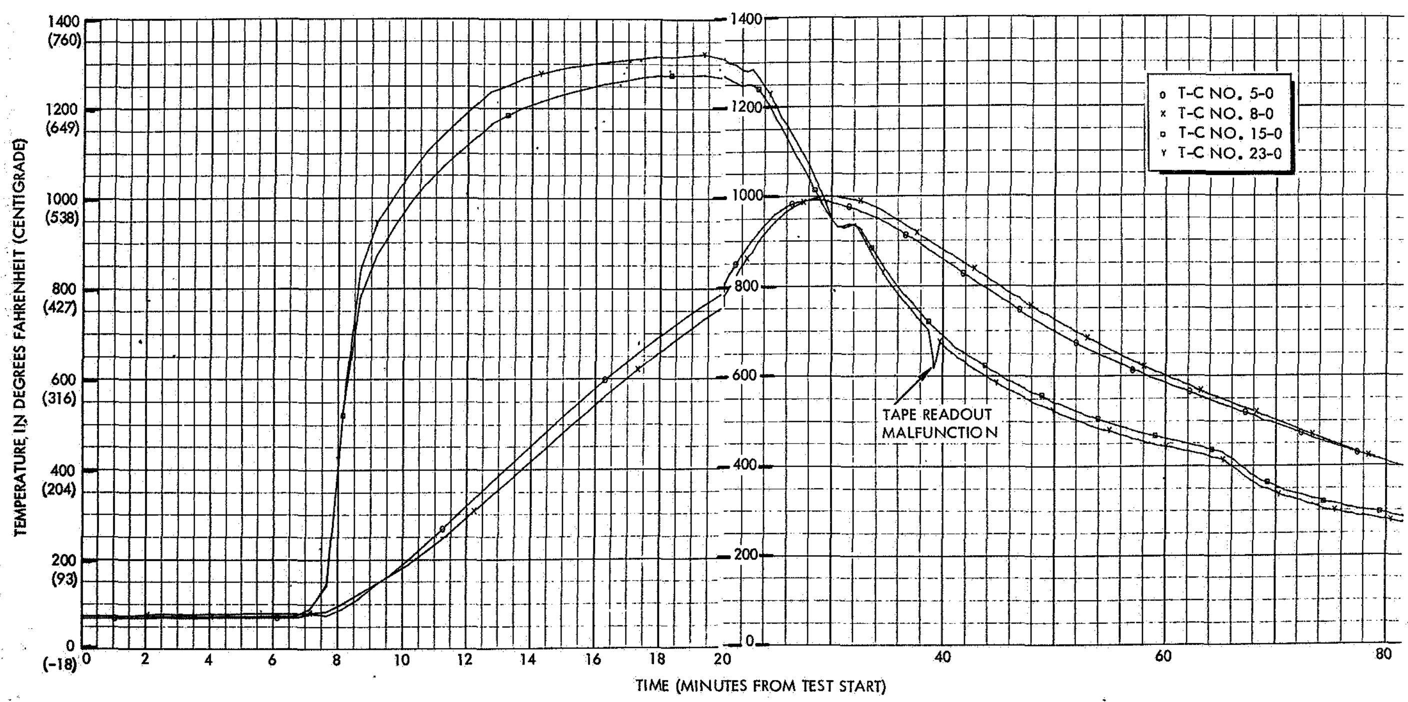
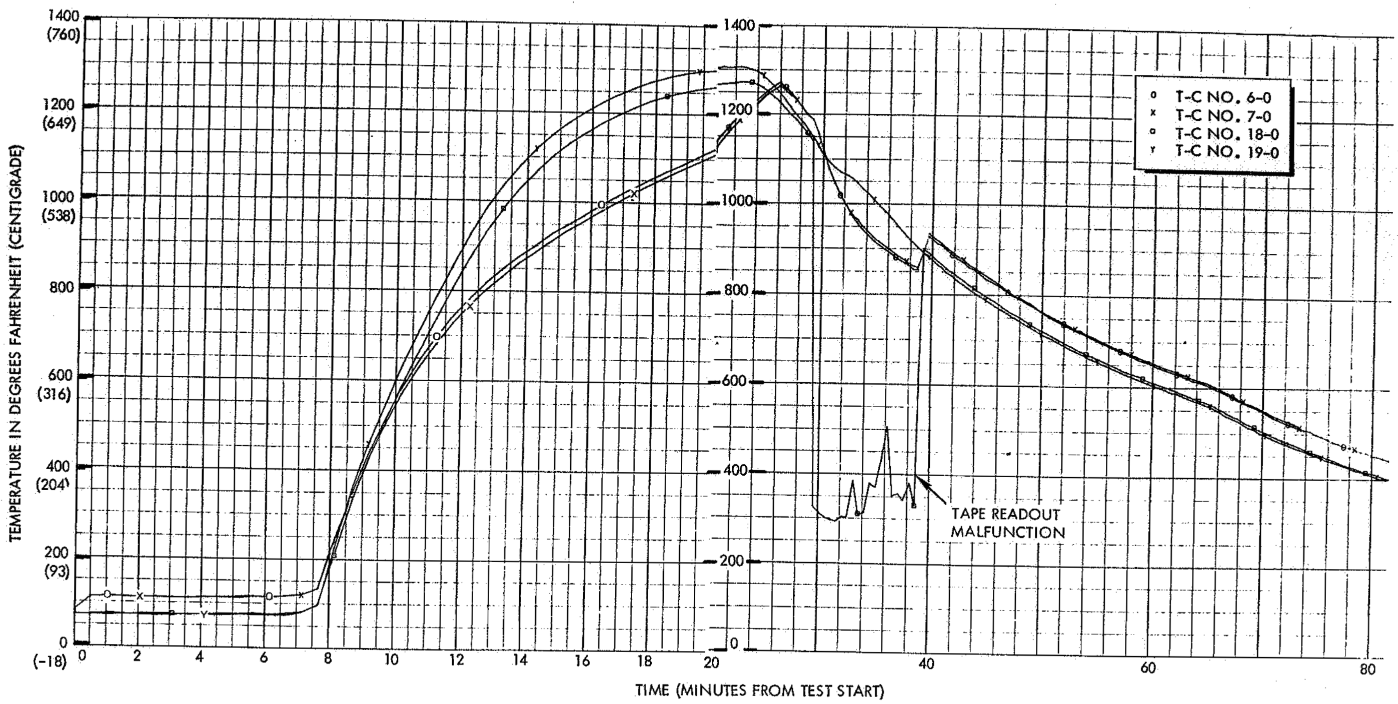


Figure 32. Temperature and Deflection of Outer Window Test Specimen During 76th Cycle (T-C No. 3-0, 4-0, 16-0, 17-0, 5-0, 8-0, 15-0, and 23-0)



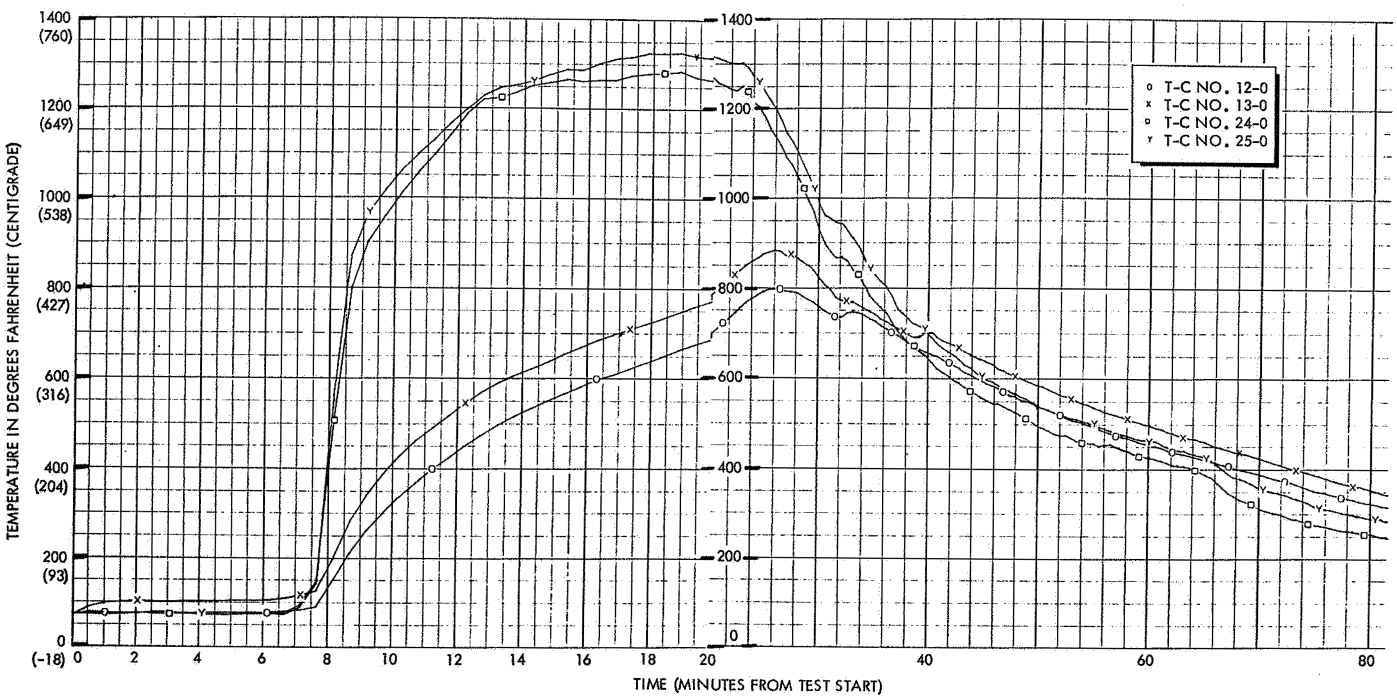


Figure 33. Temperature and Deflection of Outer Window Test Specimen During 76th Cycle(T-C No. 6-0, 7-0, 18-0, 19-0, 12-0, 13-0, 24-0, and 25-0)

Comparing the deflections between the first and 76th cycles reveals no significant differences with and without the bumper strip.

3.5 TEST RESULTS

3.5.1 Inner Windshield Window Pane

The inner windshield window successfully withstood 100 simulated entries that duplicated the thermal and pressure environment. Specific conditions evaluated were (1) inner window seal leakage, (2) effects of thermal expansion on structural integrity, (3) material compatibility as evidenced by the absence of structural degradation (galling and spalling), and (4) general structural integrity. During the 100 simulated entries, no evidence was found of structural damage. The seal leakage rate was well within the allowable of 0.1 scim per linear foot of sealing surface. The thermal expansion was as expected, and no evidence was found of degradation of structural integrity. Material compatibility was verified as evidenced by the absence of structural degradation. In general, the 100 simulated entry cycles verified the inner windshield window design.

3.5.2 Middle Windshield Window Pane

The window was subjected to 100 entry cycles that duplicated the middle window thermal environment. The aluminosilicate window survived the 100 entry cycles with temperatures up to 570°F and the pressure at 14.7 psig. Aluminosilicate glass was used because it was desirable to accumulate experience in the manufacture, handling, and analysis of the thick, heat-tempered, aluminosilicate pane of large size. Specific conditions evaluated were (1) window seal leakage, (2) effects of thermal expansion on structural integrity, (3) material compatibility as evidenced by the absence of structural degradation (galling and spalling), and (4) general structural integrity. During the 100 simulated entries, no evidence was found of structural damage. The seal leakage rate was well within the allowable of 0.1 scim per linear foot of sealing surface. The thermal expansion was as expected, and no evidence was found of degradation of structural integrity. Material compatibility was verified as evidenced by the absence of structural degradation. In general, the 100 simulated entry cycles verified the middle windshield window design.

After the middle window test, the window was subjected to an ultimate pressure test of one cycle at 26 psig and 570°F. Seal leakage was less than 0.1 scim per foot of seal length.

3.5.3 Outer Windshield Window Pane

The objective of the outer windshield window test was to verify the windshield design with respect to 120 simulated entry cycles. Specific items evaluated were (1) outer window compressive spring effectiveness, (2) effect of thermal expansion on structural integrity, (3) material compatibility as evidenced by the absence of structural degradation, and (4) general structural integrity.

The fused silica outer windshield window withstood exposure to 120 entry cycles with temperatures up to 1270°F. The simulated entries demonstrated that the prototype windshield system can withstand the critical entry environment defined in the design phase of this contract. After the outer windshield window test was completed, the windshield seal, auxiliary spring, pane, and retainer were all in good condition.

3.5.4 Seal

Initially, the leakage of the inner windshield seal was 0.033 scim per foot compared to the allowable leakage of 0.1 scim. After the 100th entry cycle, the leakage rate was 0.017 scim per linear foot of seal surface, which is well below the maximum of 0.1. The initial leakage rate was 0.027 scim per foot prior to the middle window test. After the 100th entry cycle for the middle window, the leakage rate was 0.036 scim per foot. At the conclusion of the ultimate pressure test, the leakage rate was 0.013 scim per foot, again well within the allowable rate. All seal leakage rates were well within the allowable rate.

The test criteria were met for all three parts of the inner window test. All leakage rates were well below the maximum acceptable 0.1 scim per linear foot of sealing surface. There was no evidence of surface contamination on the windshield pane from the fluorocarbon seal. All primary windshield test components were structurally sound and intact.

4. PROGRAM SUMMARY

A preliminary design and test program has been performed with the objective of developing and verifying the structural integrity of elements of the orbiter windshield that are relatively independent of specific vehicle configuration. The program has resulted in a three-pane windshield design. Tests simulating thermal and pressure entry environments have been performed. A successful pressure window prototype has resulted with a leakage rate of less than 0.1 scim per foot of seal length. The outer window successfully withstood thermal cycling to temperatures of 1270°F.

4.1 DESIGN SUMMARY

The windshield design resulting from efforts of this program was a three-pane concept with a middle pane serving as a redundant member to both the outer high temperature pane and the inner pressure pane. The panes are large (16 by 23 inches and larger). Fused silica glass is used for the outer and middle panes. Thermally tempered aluminosilicate is used for the inner pane. The outer plasma blockage seal is a wire mesh core jacketed with woven ceramic cloth. An auxiliary leaf spring is used to assist outer seal spring-back recovery. Centering springs maintain relative position of the floated outer pane within its frame. The inner hermetic seal consists of two Viton O-rings and maintains a seal leakage rate below the maximum of 0.1 scim per foot of seal length. The mass of the inner windows is used for thermal control. The glass panes are designed with a factor of safety of 1.5 and with special considerations of fracture mechanics and surface finish. The windshield design is based on an exposed window and allows for external temperatures of exposure to 1270°F.

4.2 TESTING SUMMARY

The inner and middle prototype windshields were subjected to combined thermal and pressure tests consisting of thermal fatigue on a full-scale inner and middle window test article. The test article consisted of a Corning 1723 aluminosilicate window pane (0.9 by 16.5 by 23.0 inches), window retainers, and fluorocarbon seals. The program was conducted in three parts. The first part consisted of 100 temperature and pressure cycles to 270°F and 14.7 psig. The second part consisted of 100 temperature and pressure cycles to 570°F and 14.7 psig. The third part was one cycle to 570°F and 26.0 psig. A second set of seals was installed after the first 100 cycles. Specific satisfactorily demonstrated test objectives were a combined seal leakage of less than 0.1 scim per linear foot of seal length and the absence of window contamination from the seal that would reduce visibility. No specimen failures resulted.

The outer prototype windshield test consisted of a thermal fatigue test program on a full-scale orbiter outer window test article. The test article consisted of a pane of fused silica 1.0 by 25.0 by 35.0 inches and mounting components. It was thermally cycled to 1270°F for 120 simulated entry cycles. Specific satisfactorily demonstrated test objectives were: (1) the feasibility of a metallic leaf spring as an auxiliary device to aid high temperature seal recovery; (2) the feasibility of seal designs allowing slippage for differential thermal growth between the window frame and the window pane; (3) material compatibility between seals, frame, and panes at high temperatures; and (4) structural integrity of the prototype article under 100 mission cycles. No specimen failures resulted.

4.3 CONCLUSIONS

1. Exposed outer windows without window shades are a feasible concept for the fully reusable Shuttle orbiter vehicle.

2. Currently available materials and manufacturing methods are sufficient to accomplish the design objectives for the Shuttle windshield system.

3. Temperature exposure limits are about 1400°F for the current outer seal design; about 1300°F for the outer window pane, and about 400°F for the elastomeric hermetic seal, all based on present state-of-the-art materials.

4. The exposed windows require the inspection of each pane for meteoroid damage between Shuttle missions due to the meteoroid environment encountered.

5. For the mission model used in this report, special precautions are not required to prevent window damage from bird impact, rain erosion, and encounters with hail.

4.4 RECOMMENDATIONS

1. Detailed design of the Shuttle orbiter window system should proceed within the design framework specified by MC 332-006, "Windshield - Glass Panes, Space Shuttle Orbiter," and associated documents (this report and those of the Related Documents section).

2. Programs to generate information on the effect of run-out and feed-rate variations in the grinding process are necessary and important for the adoption in production of the liquid nitrogen type of acceptance proof testing used in this program.

3. Acceptance proof testing should be performed on all orbiter window panes.

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RELATED DOCUMENTS

SD 71-134-1	Technical Proposal for a Window System Design and Test Program for Space Shuttle Orbiter (16 April 1971)
SD 71-172	Space Shuttle Orbiter Window System Design and Test Program Design Conditions and Candidate Window Concepts Report (August 1971)
SD 71-358	Space Shuttle Orbiter Window System Design and Test Program, Phase I Study Report (December 1971)
SD 72-SH-0040	Space Shuttle Orbiter Window System Design and Test Program Test Article Final Design Report (May 1972)
SD 72-SH-0122	Rationale for Windshield Glass System Specification Requirements for Shuttle Orbiter (October 1972)