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Structural Analysis and Testing of the Space Shuttle Orbiter Window System

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This report discusses the structural analysis and testing that was required to certify the Space Shuttle orbiter window design. The three-pane window system was analyzed and tested for aerodynamic pressure and thermal load on the external surface and for cabin pressure on the internal surface. The analysis and testing were completed for 100 mission cycles. The orbiter window design has met all its design requirements and criteria and has been certified.

Introduction

THE Space Shuttle orbiter window design must withstand the combination of differential pressure, substructural deflection and thermal load for 100 missions. Structural analyses were made using a finite-element model, with the fracture mechanics method used for flaw growth analysis and the finite difference method used for thermal stresses. Since the effect of these loads on the structural integrity of the window design for the orbiter operational service life could not be completely determined by analysis, a design verification test program was included to complete the certification of the orbiter window design.

Design

The Space Shuttle orbiter window design calls for a three-pane uncovered window (Figs. 1 and 2). The outer thermal pane is made of annealed glass (fused silica, CGW 7940), which has a low coefficient of linear thermal expansion to minimize thermal stresses from the high temperatures of entry heating. For the same reason, this material is used for the redundant middle panes. The inner pressure panes are thermally protected by the outer panes, operate at lower temperatures, and are therefore fabricated of high-strength tempered glass (aluminosilicate, CGW 1723). Windowpane materials are summarized in Table 1.

The function of the outer thermal pane is to carry all aerodynamic pressure loads and thermal loads for 100 missions. Both nominal and peak pressure loads for the outer thermal pane are presented in Table 2. Thermal loads are summarized in Table 3. The inner pressure pane must resist the internal crew module pressure of 14.7 psi for 99 missions and 16.0 psi (valve failure) for 1 mission. The function of the redundant pane is to carry the cabin pressure in the event of pressure pane failure. In addition to this load, the redundant panes are to be subjected to stresses caused by substructure edge deflection for 100 missions.

The general requirement for the orbiter window system is that it must withstand the specified conditions for 100 missions without rupture or collapse. Because annealed glass exhibits static fatigue, the design criteria calls for each glass pane to be evaluated for initial and final strength and to have a minimum factor of safety as follows. For annealed glass, the initial factor of safety must be 2.0; the final factor of safety, 1.0. For tempered glass, the initial factor of safety must be 2.0; the final factor of safety, 2.0. The factor of safety required for each window is summarized in Table 4.

Glass Strength

The strength of the glass for initial strength calculations is the strength obtained in proof tests—fused silica (8600 psi) and aluminosilicate (see Table 5). These tests are performed in dry nitrogen with each pane pressure loaded so that it will bear the proof test stress levels at its maximum stress location.

The final strength calculations are based on the ultimate strength of the glass, or its ability to withstand critical stress levels for a given load duration time, which is dependent upon the load duration time and the flaw size of the glass. Maximum load durations and ultimate strength are summarized in Table 6. In a moist environment, the ultimate strength diminishes with time and stress, so that the capability for the final mission normally is less than that for the first mission (there is a threshold stress below which this effect does not occur—1720 psi). To account for the strength reduction, the

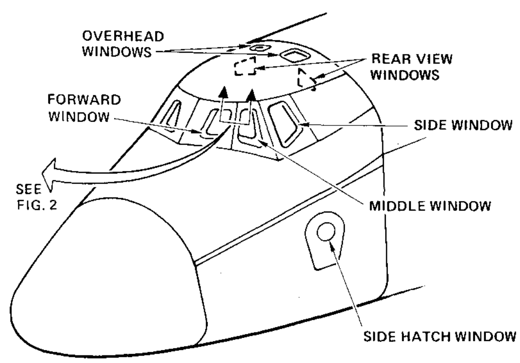

Fig. 1 Shuttle orbiter window system.

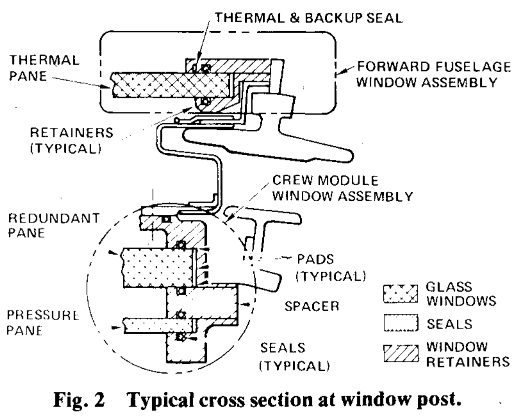

Fig. 2 Typical cross section at window post.

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Table 1 Summary—window material

Window	Pane	Material
Forward	Thermal	Fused silica
	Redundant	Fused silica
	Pressure	Aluminosilicate
Middle	Thermal	Fused silica
	Redundant	Fused silica
	Pressure	Aluminosilicate
Side	Thermal	Fused silica
	Redundant	Fused silica
	Pressure	Aluminosilicate
Overhead	Thermal	Fused silica
	Redundant	Aluminosilicate
	Pressure	Aluminosilicate
Rear view	Redundant	Aluminosilicate
	Pressure	Aluminosilicate
Side hatch	Thermal	Fused silica
	Redundant	Fused silica
	Pressure	Aluminosilicate

Table 2 Thermal pane pressure loads (psi)[1]

	Ascent	Forward	Middle	Side	Overhead	Side hatch
Nom.	Burst	0.0	−0.9	0.0	−1.3	−2.6
	Crush	2.3	0.8	2.7	0.7	0.0
Max.	Burst	0.0	−1.5	−0.3	−1.3	−3.2
	Crush	3.0	1.2	3.2	0.9	0.0
	Descent	**Forward**	**Middle**	**Side**	**Overhead**	**Side hatch**
Nom.	Burst	0.0	−0.4	−0.4	−0.3	−0.8
	Crush	0.7	0.4	0.6	0.4	0.2
Max.	Burst	−1.0	−2.0	−3.2	−2.9	−2.6
	Crush	2.9	1.9	2.0	1.4	1.0

Table 3 Window temperatures[2]

Windows	Pane	Temperature, °F
Forward	Thermal	1084
	Redundant	374
	Pressure	183
Middle	Thermal	824
	Redundant	295
	Pressure	179
Side	Thermal	721
	Redundant	258
	Pressure	157
Overhead	Thermal	376
	Redundant	245
	Pressure	130
Side hatch	Thermal	770
	Redundant	410
	Pressure	290

Table 4 Design factor of safety

Window	Pane	Factor of safety: Initial	Factor of safety: Final
Forward	Thermal	2.0	1.0
	Redundant	2.0	1.0
	Pressure	2.0	2.0
Middle	Thermal	2.0	1.0
	Redundant	2.0	1.0
	Pressure	2.0	2.0
Side	Thermal	2.0	1.0
	Redundant	2.0	1.0
	Pressure	2.0	2.0
Overhead	Thermal	2.0	1.0
	Redundant	2.0	2.0
	Pressure	2.0	2.0
Rear view	Redundant	2.0	2.0
	Pressure	2.0	2.0
Side hatch	Thermal	2.0	1.0
	Redundant	2.0	1.0
	Pressure	2.0	2.0

Table 5 Aluminosilicate (tempered glass) proof pressure stress

Window	Proof test stress (psi) for factor of safety = 2.0
Forward	17,100
Middle	15,200
Side	15,600
Overhead	21,500
Rear view	20,200
Side hatch	19,750

Table 6 Load duration and ultimate strength, F_{tu}

Window	Pane	Duration of maximum stress, s	Ultimate strength, psi
Forward	Thermal	10	5,010
	Redundant	500	4,400
	Pressure	605,000	15,700
Middle	Thermal	10	5,010
	Redundant	500	4,250
	Pressure	605,000	15,700
Side	Thermal	10	5,010
	Redundant	500	4,010
	Pressure	605,000	15,700
Overhead	Thermal	10	5,010
	Redundant	500	4,460
	Pressure	605,000	15,700
Rear view	Redundant	605,000	15,700
	Pressure	605,000	15,700
Side hatch	Thermal	10	5,010
	Redundant	500	4,460
	Pressure	605,000	15,700

methodology (glass static fatigue curve) used by S.M. Wiederhorn was applied to determine the ultimate strength for the final mission.[3-5] The glass static fatigue curves are presented in Figs. 3 and 4. Also, further analyses were required on the aluminosilicate glass because tong marks were left on it. (During the heat treating and quenching of the tempered glass, the tongs used to support it make surface indentations which reduce its strength wherever they exist.) Testing and analysis have demonstrated that the glass at the tong marks possesses more than adequate strength to meet the initial and final strength requirements.

Analysis

For the orbiter mission, the total stress on the windowpanes is from a combination of four sources—direct pressure load on the pane, substructural bending, substructural post out-of-

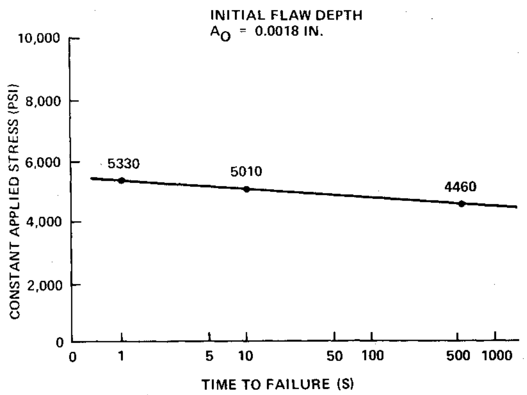


Fig. 3 Static fatigue curve CGW 7940 fused silica glass.

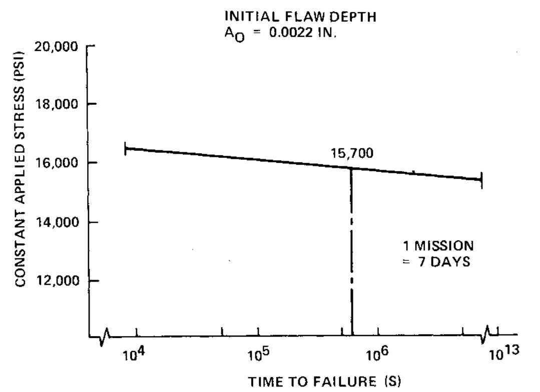


Fig. 4 Static fatigue curve CGW 1723 aluminosilicate glass.

plane deflection, and thermal stress. The stresses from mechanical loads are directly proportional to the pressure load and are computed using a finite-element model of the window and its support structure (correlated with actual vehicle testing). Thermal stresses were calculated using a finite difference thermostructural model.

The forward fuselage windshield (Fig. 2) was modeled using NASTRAN.[6] The three-dimensional model included all three windows (forward, middle, and side) as shown in Fig. 5. The window glass is simply supported at the edges. The total number of node points and elements used was 735 and 906, respectively. The elements included bars, rods, quadrilateral plates, and triangular plates. The model was loaded with differential pressure, initial out-of-plane structural deflection at the corners (as obtained from the orbiter structural model and verified by testing), and adjacent panel loads where appropriate. The overhead window was modeled as a two-dimensional model. The side hatch window was analyzed using classical methods because of its circular geometry.

Each of the crew module windows (Fig. 2) was individually modeled as a two-dimensional model using NASTRAN. The elements used were similar to those used in the three-dimensional model. A typical two-dimensional model that used 124 node points and 135 elements is shown in Fig. 6. The crew cabin windows are loaded in a manner similar to that in which the forward fuselage windows are loaded.

A typical thermal stress model is shown in Fig. 7. Temperature distribution for a particular window assembly is typically represented by section A-A (Fig. 7) and is assumed to be the same for all sections of the window assembly. The analytical method calls for the following:

1) Restrain unit length dl of section from end translation and rotations.

2) Calculate end forces and moments for both glass and frame caused by temperature gradients (ΔT).

3) Remove restraint and satisfy equilibrium by applying forces and moments in the opposite direction.

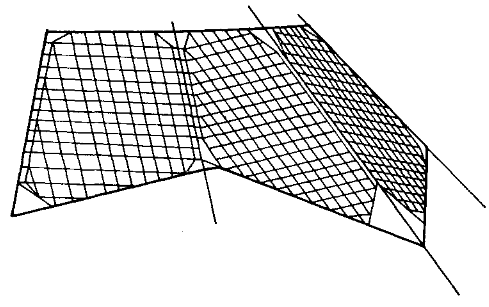


Fig. 5 Forward fuselage windshield, three-dimensional NASTRAN model.

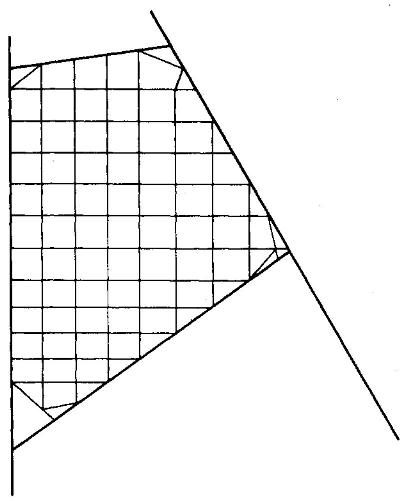


Fig. 6 Crew module window, two-dimensional NASTRAN model.

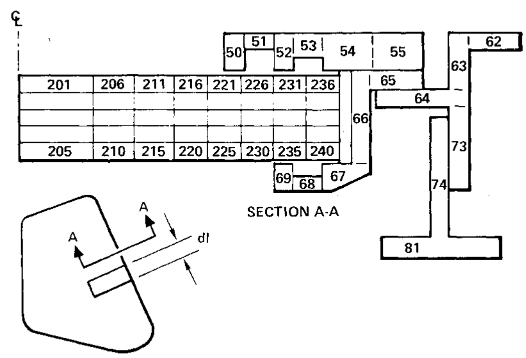


Fig. 7 Thermostructural model.

4)

$$\sigma_G = \frac{P}{A} + \frac{(M_G + M_I)y}{I_G} - \alpha E \Delta T \tag{1}$$

where M_G = moment in glass; I_G = moment of inertia of glass; M_I = interaction moment between glass and frame (moment which brings both to a common position); σ_G = glass stress; A = glass area; P = axial force; α = glass coefficient of thermal linear expansion; E = glass modulus; and ΔT = temperature difference.

Fracture mechanics analysis in glass is treated by considering flaw and tensile stresses. An initial flaw size of 0.0018 is assumed for all glass panes strictly from a manufacturing limitation due to the glass grinding process. Initial flaw depth was computed by[3-5]

$$K_{Ic} = 1.95\ \sigma A_0^{1/2} / C_f \tag{2}$$

where K_{Ic} = critical stress intensity factor at which failure occurs instantly, $(\text{N/m})^{3/2}$ = 766,000; σ = proof test stress = 8600

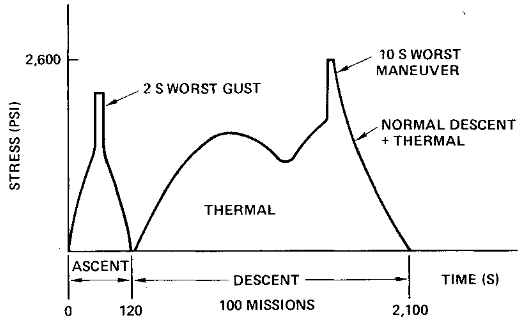


Fig. 8 Thermal pane stress cycles.

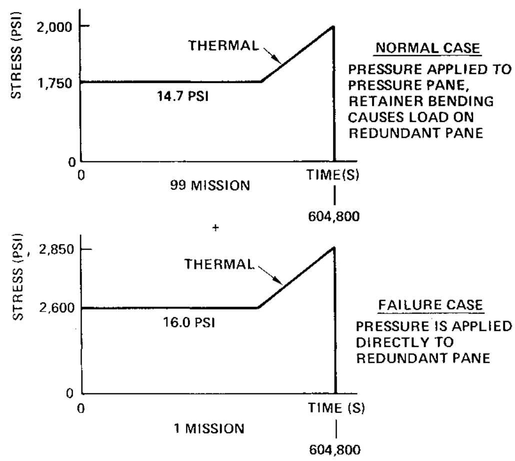


Fig. 9 Redundant pane stress cycles.

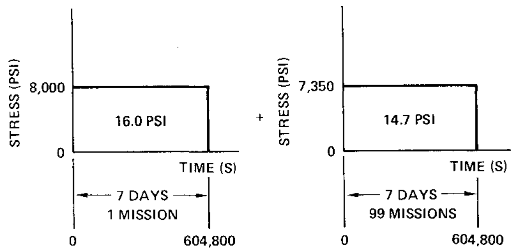


Fig. 10 Pressure pane stress cycles.

psi; C_f = units conversion factor = 0.00091; and A_0 = initial flaw depth, in. Then,

$$A_0 = \left(\frac{(0.00091)(766{,}000)}{(1.95)(8600)}\right)^2 = 0.0018$$

Flaw growth after a time t was computed by,

$$A = A_0 + \int_0^t v\,\mathrm{d}t \tag{3}$$

where

$$v = (\log)^{-1}(b + mK_I) = \text{crack velocity, m/s}$$

$$K_I = 1.95\sigma(t)A^{1/2}/C_f = \text{stress intensity factor, N/m}^{3/2}$$

$$b, m = \text{constants} \tag{4}$$

A computer program was employed to integrate Eq. (3) and obtain flaw growth during 100 missions. The final flaw size, A_f, computed was used to determine the allowable stress, F_{tu} in the glass pane. It is noted here that the aforementioned fracture mechanics method was used for annealed glass. The inner pressure pane made of tempered glass did not require fracture mechanics analysis because the limit stress levels were below the temper stress of 12,600 psi (compression). Hence, no flaw propagation occurred with time.

Margins of safety are computed for both initial strength and final strength criteria based on allowable stresses and factor of safety criteria. The margins are as follows:

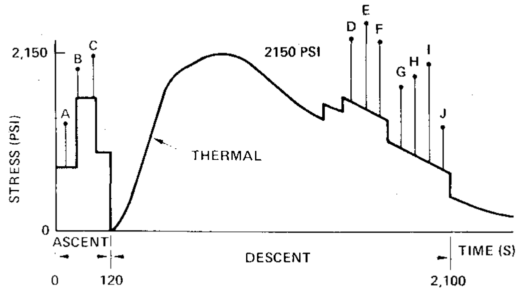
$$\text{Initial MS} = \frac{F_{pt}}{(\text{FS})(\sigma)} - 1 \tag{5}$$

where MS = margin of safety; FS = factor of safety; F_{pt} = proof test stress; and σ = working stress.

$$\text{Final MS} = \frac{F_{tu}}{(\text{FS})(\sigma)} - 1 \tag{6}$$

where F_{tu} = ultimate strength per glass fatigue curve.

Typical stress cycles for use in fracture life analysis for each window type are shown in Figs. 8-10.



MAXIMUM PEAK STRESSES (PSI)

	A	B	C	D	E	F	G	H	I	J
DURATION CYCLE	13 SEC	3 SEC	2 SEC	30 SEC	10 SEC	10 SEC	20 SEC	10 SEC	10 SEC	20 SEC
1	1,002	1,737	2,004	2,463	2,624	2,460	1,804	1,903	2,006	1,175
7	948	1,717	1,957	2,330	2,470	2,320	1,722	1,802	1,893	1,141
24	842	1,677	1,864	2,063	2,163	2,029	1,544	1,602	1,666	1,075
36	735	1,636	1,770	1,795	1,856	2,093	1,375	1,402	1,439	1,003
24	628	1,596	1,677	1,528	1,548	1,478	1,201	1,201	1,211	941
8	521	1,556	1,583	1,261	1,241	1,198	1,023	1,001	984	874

Fig. 11 Stress-history curve forward thermal window.

Table 7 Stress breakdown—forward thermal window—point E, psi

	Region			
	Center		Edge	
Source	Outboard	Inboard	Outboard	Inboard
Thermal	242	235	640	620
Pressure	409	1211	183	541
Substructure bending	292	865	475	1403
Post out-of-plane deflection	29	86	20	60
Total	972	2397	1318	2624

Results

A stress-history curve is given in Fig. 11 for a forward outer thermal window. Note that the peaks are the result of wind gusts of brief duration. The stress contributions are presented in Table 7. As shown, the pressure load is the prime contributor.

Additional analysis was made with respect to natural environments (rain, hail, fungus, humidity, ozone, lightning, salt spray, sand and dust, solar radiation, wind, snow, and meteoroids) and induced environments (vibration, shock, and acoustics). Most of these environments are not critical because of testing, material selection, protective coatings, very low probability of occurrence, and lower loads than design

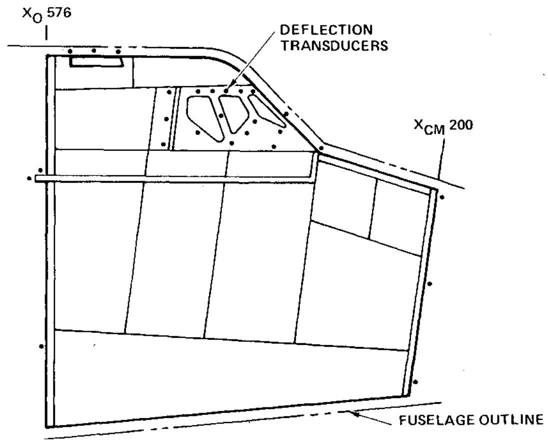


Fig. 12 Crew module proof pressure test.

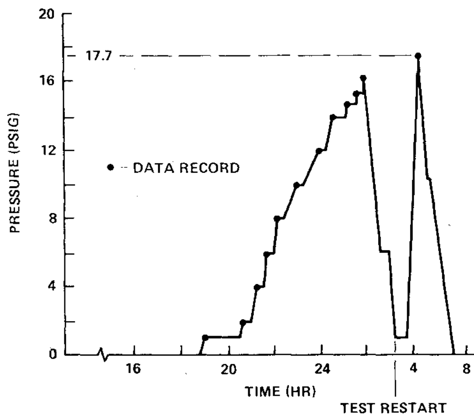


Fig. 13 Proof pressure test profile.

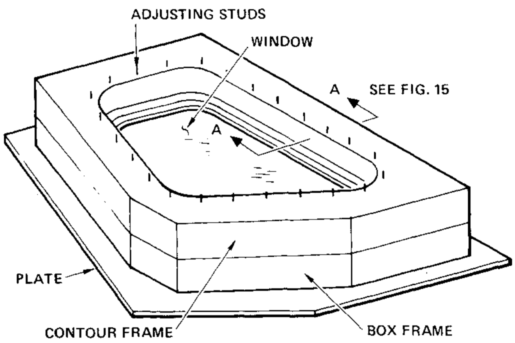


Fig. 14 Test fixture.

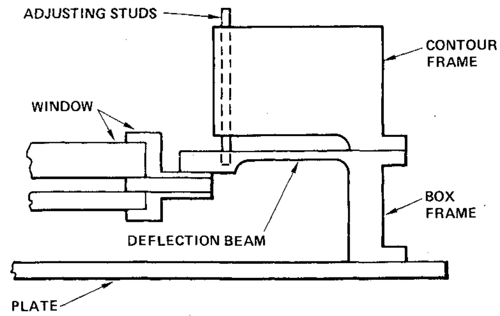


Fig. 15 Section *A-A* test fixture.

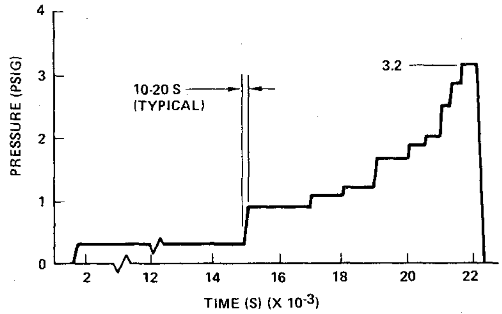


Fig. 16 Fuselage window, descent pressure profile.

loads. Only the meteoroid has a significant impact, and this will be handled by post-flight inspection and replacement of windows as required.

Test Overview

The test program consisted of subjecting the orbiter's windows to combinations of pressure, thermal stress, structural deflection, and time loading. Each combination was dependent upon the loads each window would be subjected to during every mission profile.

Two kinds of windows were used during the test program. The first kind, identified as test specimen *A*, used aluminum plates in lieu of the window's glass panes. The use of a substitute for the glass substantially reduced the handling of the glass, especially during strain gaging, and therefore reduced the probability of damaging a glass pane. Aluminum was chosen because it has the same stiffness (Young's modulus) as glass, so the stress data obtained were directly transferable to glass.

The second kind of window, identified as test specimen *B*, used glass panes as illustrated in the analysis above. These windows were used for life and thermal tests.

System Test Phase

During the development phase of the Shuttle orbiter, the first full-scale crew module structure was pressurized to 17.7 psig to verify proof pressures, structural analysis, and deflections. As "piggy backs" to this test, the crew module windows (of the test specimen *A* sort) were installed and instrumented with strain gages. Also, the window frames were instrumented with linear deflection transducers as shown in Fig. 12.

The transducers measured the physical movement of the windows, thereby gaging the amount of deflection (or twisting) each window assembly experienced. From this data, residual stresses were determined and deflection values for further testing calculated.

Figure 13 illustrates the pressure profile run discussed above.

Additional test data were obtained from the full-scale forward fuselage structural test article. Deflection and strain gage data were correlated with the NASTRAN model.

Individual Window Test Phase

Three crew module windows and two fuselage windows were selected for detailed qualification testing. The selection was based on the unique loads imposed upon the windows during a mission, such as highest temperature deflection, pressure, and stress, as well as combinations of the above.

All testing was accomplished within test fixtures that would duplicate the orbiter mounting and structural deflections. The fixture is illustrated in Figs. 14 and 15.

The windows were mounted to a box frame through use of a thin deflection beam. It was possible to bend this beam (and thus the window) using adjustment studs threaded in a rigid, unmovable contour frame. In this manner, the windows were deflected (or twisted) to duplicate conditions expected during a mission. The deflection values ranged from 0 to 0.250 in.

The window, in combination with the fixture's plate and box frame formed an air-tight cavity for applying pressure and/or a vacuum to the window panes. GN_2 was the medium used for applying pressure. A typical pressure cycle is shown in Fig. 16.

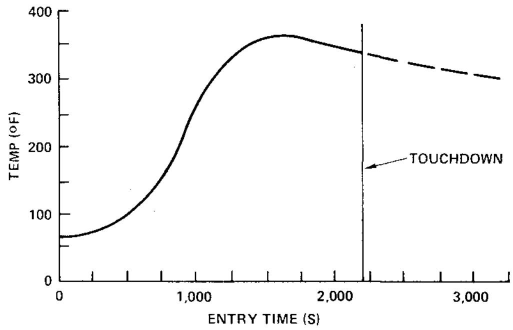


Fig. 17 Thermal profile, descent crew module window.

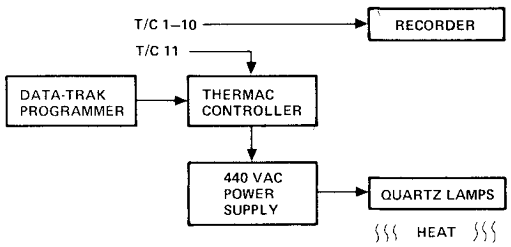


Fig. 18 Thermal control diagram.

Thermal loads were applied to the windows by a quartz heat lamp array placed approximately 8 in. above the glass. Quartz lamps provide radiant heat, which can pass through the glass panes to heat only the test fixture. To prevent this condition, a carbon lampblack coating was applied to the outboard surface of the glass. The coating absorbed the radiant heat, and the heating below it was conductive, thus simulating real-life conditions. Figure 17 is a typical test thermal profile which represents the thermal loads expected during an orbiter descent.

Thermocouples (T/C) were installed at various positions on the window to record surface temperatures. One T/C, No. 11, was used to control the quartz lamp heating. As shown in the thermal control diagram of Fig. 18, a copy of the profile of Fig. 17 was placed on the revolving drum of a data track programmer.

The programmer transmitted a reference signal to a thermac controller that compared the reference signal to the T/C No. 11 signal. The controller determined if T/C No. 11 was lower than the reference signal and, if it was so, commanded the 440 voltage ac power supply to proportionately increase voltage to the quartz lamp.

Typical Test Sequence

Stress

Test specimen *A* first had aluminum plates coated with a hard, brittle lacquer paint that is crack sensitive to tension-bending stresses. After installation in the test fixture, the test specimen (crew module window) was placed under structural deflection and pressurized to 32 psig. The pattern of cracks that developed on the stress coating identified those locations of high stress which would require strain gages for the next test and verified the preliminary math analysis.

Rosette strain gages were then installed on the aluminum plates at the chosen locations. The test specimen was pressurized to 16 psig in 4-psig increments, with data being recorded at each increment by the laboratory's computer analysis system. A complete data printout of each gage's stress, strain (maximum and minimum), and angle of maximum stress was obtained and compared to data obtained in the crew modle proof test.

Initial Verification Test

This was the last test performed on the aluminum panes and was used to determine maximum stress levels for the windows. After the fixture's structural deflections were changed, a pressure spike of 32 psig was applied to the window. Strain gage data was taken and analyzed.

It should be noted that during testing of the crew module's windows, the tests had to be repeated for both the pressure and redundant panes (see Fig. 2).

Thermal Calibration

In the thermal calibration test, test specimen *B* was installed within the test fixture. As this was the first instance in which the glass was placed under heat loads, no deflections were imposed upon it. A secondary test purpose was to check out the heating/control system of Fig. 18. The test consisted of applying one cycle of heating, as illustrated in Fig. 17. The data obtained was then plotted and compared with Fig. 17.

Operational Verification

This test was performed to verify the window integrity for 100 cycles of reentry. The window was made to experience structural deflections, heated as in the thermal calibration test, and pressurized to 14.7 psig during heating. This process was repeated for 100 cycles. The test criteria were that the window was to show no visual evidence of damage, discoloration, crazing, and/or other optical degradation of the windowpane coating.

Life Test

Test specimen *B* was next put under new structural deflection values, pressurized to 14.7 psig and placed in storage for 700 days. This represents 100 missions at 7 days/mission. The 14.7 psig is the pressurization of the orbiter's crew module in flight.

Final Verification

At the conclusion of the life cycle test (700-day test at 14.7 psi—entry/orbit phase), the tempered glass will be tested for the final strength verification.

Status

Certification tests have been completed successfully by two forward fuselage window assemblies (forward and side). Three crew module window assemblies (forward, side, and overhead) have successfully completed all certification tests except the life-cycle test, which is currently in process. The remaining windows were not tested because of their similarity (material, design, and geometry) to the tested window and because their load conditions were either less severe than or equal to the tested-window conditions.

Acknowledgment

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