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DESIGN AND DEVELOPMENT OF A WINDOW ASSEMBLY FOR A G.A.S. PAYLOAD

Bev Christie and Bob Tough
Bristol Aerospace Limited
Winnipeg, Manitoba

BW741890

ABSTRACT

A requirement exists for a sealed window assembly for G.A.S. payloads. Bristol Aerospace Limited has designed and developed a synthetic fused silica window assembly for the National Research Council of Canada's G.A.S. payload 'PHOTONS' G-494. The details of the design and development of this window assembly are given in this paper.

1. INTRODUCTION

For some G.A.S. payloads utilizing the Motorized Door Assembly (MDA) option, a requirement exists for a sealed window assembly. In addition to satisfying the scientific design requirements, the window assembly must also meet the NASA safety related requirements for payload flight-qualification.

Bristol Aerospace Limited has designed and developed a synthetic fused silica window assembly for the National Research Council of Canada's G.A.S. payload 'PHOTONS' G-494 (refer to Figure 1 for general payload layout). This paper will describe the requirements and details of the actual design and development phases of this window assembly. It should be noted that at the date of publication of this paper, the 'PHOTONS' payload has not been flown.

2. REQUIREMENTS

2.1 Scientific Requirements

The experiment, to be conducted by Dr. F. Harris of the Herzberg Institute of Astrophysics, NRC, is named PHOTOMETRIC OXYGEN NIGHT GLOW STUDY (PHOTONS), and it will measure terrestrial night glow emissions from atomic and molecular oxygen atmospheric band. The experiment will also make observations of the shuttle RAM glow, quantify the spectrum, and evaluate its significance to measurements made from the shuttle bay.

There were four primary scientific requirements which established the design of the window assembly, these were:

1) Optical Requirements - The windows must allow transmission of O and O_2 emissions from the U.V. to the near I.R. (wavelengths ranging from 2860 to 8653 Angstroms). Windows must be provided for:

Two 3-barrel photometers
One single-barrel photometer
One bright light sensing diode

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2) Field-of-View Requirements - Uni-directional measurements to be taken by photometers (8° maximum conical field-of-view).

3) Thermal Constraints - The payload thermal limits are -20°C to +40°C while the temperature limits of the photometer filters, which are immediately behind the windows, are -30°C to +30°C.

4) Leak Rate - Photometers are sealed to prevent leakage and subsequent high voltage breakdown. However, for redundancy, it is required that the payload be sealed and, based on typical shuttle flight duration times of 3 to 4 days, not leak at a rate greater than 1 psi every 24 hours based on a nominal one atmosphere pressure inside the G.A.S. container.

2.2 NASA Requirements

NASA requirements consist largely of safety considerations. It also includes physical size and weight constraints, in accordance with the G.A.S. concept. The safety considerations include structural criteria, and material selection criteria.

Detail structural design requirements, which are presented in subsequent sections, are obtained from the G.A.S. payloads safety manual (Reference 1). Included are design loads and factors of safety which are to be used in structural analyses.

The NASA materials selection criteria is contained in Reference 2. Materials used on G.A.S payloads should have low susceptibility to corrosion and pitting, high resistance to stress-corrosion cracking and resistance to brittle crack propagation. The use of dissimilar metals in contact should be avoided, wherever possible.

The physical size and weight constraints of G.A.S payloads utilizing the MDA option are as follows:

Maximum diameter: 19.75 inches
Maximum length: 28.25 inches
Maximum weight: 165 lbs

3. DESIGN

3.1 General Configuration

The design of the top plate assembly involved trade-offs between weight, manufacturability, and cost. The layout of the window assembly is shown in Figure 2. It consists of an aluminum plate having four high purity fused silica windows - two large windows (6.25 inch diameter) for the 3-barrel photometers, and two small windows (3.0 inch diameter) for the single-barrel photometer and the bright light sensing photo diode. All four windows are sealed with neoprene rubber gaskets and held in place by retainers which are bolted to the top plate. The outer edge of the plate is clamped between two rings which are part of the G.A.S container assembly. The plate is sealed at the outer edge by O-rings. To reduce the heat transfer through the plate, it is highly polished on the outer surface and is alodined on all surfaces on the payload side. A weight breakdown of the window assembly is given in Table 1.

TABLE 1. Weight Breakdown of Top Plate Assembly

COMPONENT	WEIGHT (LBS)
Top Plate Machining	21.0
Window Retainers - Large 2 @ 0.383 lbs each	0.77
- Small 1 @ 0.173 lbs	0.17
- Diode 1 @ 0.433 lbs	0.43
Gaskets (Neoprene), and diode window retainer O-ring	0.60
Windows - Large 1 @ 1.278 lbs and 1 @ 1.277 lbs	2.56
- Small 1 @ 0.292 lbs and 1 @ 0.287 lbs	0.58
TOTAL	26.11 lbs

3.2 Materials Selection

The following is a list of the window assembly components, the materials selected, and the rationale.

1) Windows -The following window specification was derived to meet the requirements for spectral transmission and optical flatness:

   Material - Dynasil UV-1000 synthetic fused silica
   Flatness - Both faces flat to λ/4 @ 546 mm
   Parallel - Faces parallel to 5 arc minutes
   Surface Finish - Scratch and dig 40-20

   The windows were supplied by Interoptics Ltd. of Ottawa.

2) Structure - In order to meet weight constraints, aluminum alloy 6061-T6 was chosen for the structure based on its high strength to weight ratio and for its high resistance to stress-corrosion and brittle fracture.

3) Seals - Neoprene AMS3207 rubber was chosen as a gasket material because of its low static seal leak rate, low outgassing, and its ability to retain required physical and mechanical properties of temperatures as low as -40°C.

4) Hardware - Stainless steel hardware was chosen for mechanical fasteners because of its high resistance to corrosion and stress-corrosion cracking.

3.3 Structural Design Criteria

Pressure Loads

A G.A.S. canister pressure of 1.5X atmospheric (22 psi) was established as a conservative pressure for the fracture analysis of the windows. This constituted the maximum pressure loading applied to the windows during flight, including a factor of safety. In order to account for uncertainties in the structural analysis of the top lid assembly, NASA specified a design case of 4X atmospheric pressure (60 psi). This ultimate factor of safety was used in stressing the windows and the aluminum plate.

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Flight Loads

The inertial flight loads were obtained from the G.A.S. Payload Safety Manual (Reference 1) and are summarized in Table 2.

TABLE 2. Design Flight Loads (Acceleration in g's)

Direction	Limit Load	Yield Load	Ultimate Load
X	± 6.0	± 9.0	±12.0
Y	± 6.0	± 9.0	±12.0
Z	±10.0	±15.0	±20.0

The axis orientation is shown in Figure 1. The loads are combined using the X, Y and Z loads in the worst possible combination. The Yield Loads give a factor of safety of 1.5 on the Limit Loads and the Ultimate Loads give a factor of safety of 2.0. These loads are for design analysis which is not verified by testing.

Temperature Limits

The temperature design limits for the payload during the mission are -20°C to +40°C.

3.4 Structural Analysis of Lid Assembly

Preliminary calculations indicated that the stresses and deflections in the lid assembly were of small magnitude, and a finite element analysis of the lid was not warranted. The stress levels were estimated with sufficient accuracy using conservative, classical analysis techniques.

In the top plate assembly, discontinuity stresses occur at locations of abrupt change in geometry, such as adjacent to the window mounts and the holes in the plate. In order to estimate the maximum stresses in the plate, a discontinuity stress analysis was performed on these areas. The analysis consisted of separating the structure into a number of elements of simple geometry, such as flat plates, rings and cylinders, which approximated the lid and structural discontinuities. A system of redundant forces and moments was calculated at each element edge. These are required to maintain structural continuity when the structural loads are applied. The redundant forces and moments are found by solving a system of simultaneous equations which express the compatibility of deformations at adjacent element edges. Stresses due to the system of redundant forces and moments are then calculated for each element and superimposed on the "free-body" pressure stresses in each element.

In performing the analysis, conservative, simplifying approximations are made for the actual top plate geometry. The modelled geometry is less stiff than the actual geometry, therefore, stresses predicted by this method are conservatively high.

The structural analysis performed addressed pressure loads, thermal loads, and flight loads. Vibration stresses were verified by testing, the details of which are covered in subsequent sections. Stresses in the lid and synthetic fused silica windows were calculated for the design pressure of 60 psi, and were found to give positive margins of safety based on the material yield strength of 6061-T6 aluminum, and ultimate strength values for UV 1000 synthetic fused silica. Pressure stresses in the windows were also calculated for the maximum service pressure of 22 psi. These stress levels were used in conducting the fracture analysis of the windows. The stresses due to differential thermal expansion between the windows and aluminum were considered negligible since the windows are isolated from the top plate by neoprene rubber gaskets at the edges. Stresses due to thermal gradient across the window thickness were found to be negligible. Flight loads were found to produce substantially lower stresses in the lid and windows than the pressure loads and were therefore considered negligible.

3.5 Fracture Analysis of Glass Windows

Analysis Method

Brittle materials, such as glass, which are subjected to static loading exhibit a decrease in strength with time known as static fatigue. Brittle fracture is preceded by subcritical crack growth which results in delayed failure. The principles of fracture mechanics can be used to predict the structural lifetimes and to develop acceptance tests for glass subjected to load. (Reference 3).

The time-to-failure of glass under external load is determined as the time necessary for surface flaws to grow from an initial, sub-critical length to a final critical size at which spontaneous failure occurs. The time-to-failure can be calculated from the crack velocity, $V = \frac{dL}{dt}$, and the stress intensity factor, K_I, which is a measure of the stress field at the crack tip. The stress intensity factor is defined by the Griffith criterion as,

$$K_I = \sigma Y \sqrt{L} \qquad (1)$$

where

Y = crack geometry factor
L = crack length
σ = surface stress in the vicinity of the crack tip

For a constant stress, the failure time, t, is found by substituting equation 1 into the expression for crack velocity.

$$t = \frac{2}{\sigma^2 Y^2} \int_{K_i}^{K_{IC}} \left(\frac{K_I}{V}\right) dK_I \qquad (2)$$

where

K_i = initial stress intensity at the most critical initial flaw

The fracture calculations indicated essentially infinite lives for the single-barrel photometer window and the diode window and a lifetime of 167 years for the three-barrel photometer window, at a continuous service pressure of 22 psi.

3.6 Thermal Design

A thermal model has been developed to simulate the modes of heat transfer of the G.A.S. payload assembly (conduction and radiation). The results of the thermal analysis have determined that low transmission of energy through the top plate assembly is required in order to achieve the design temperature limits. A highly polished surface was chosen for the top of the aluminum plate for its very low emittance and absorptance of thermal energy. The surfaces on the payload side of the top plate assembly could not be easily polished, and were therefore alodined. This surface finish has a low emittance and absorptance. The fused silica windows have a high transmittance in the infra-red spectrum, but are required for the experiment.

4. TEST PROGRAM

4.1 Scope of Work

The test program included leak, vibration, thermal cycle, qualification proof pressure, and flight acceptance proof pressure tests. The leak test was performed to ensure that the pressure of the G.A.S. container would not drop below the critical level. The vibration test was required to verify structural integrity and pressure seal function under anticipated vibration loads. The thermal cycle test was also performed to verify pressure seal serviceability over the temperature design range. The qualification proof pressure test was performed to verify structural integrity of both the plate and the windows. The flight acceptance proof pressure test was essentially a repeat of the qualification proof pressure test; its purpose was to ensure that the actual flight windows were structurally acceptable. This test was conducted immediately prior to shipment of these components.

4.2 Leak Test

The acceptable leak rate was established as a drop of less than 5 psia from the nominal container pressure of 15 psia over the 5 day flight duration. The test fixture shown in Figure 4 was connected to a pressure transducer which monitored the internal test fixture pressure. The test fixture was pressurized to the maximum anticipated pressure (1.1 atmos or 16.5 psig, this pressure accounts for pressurization due to thermal effects) at 20°C ambient temperature. All connections were checked for leaks with OXYTEC, and the pressure was monitored for 24 hours, during which a drop of less than 1 psig was measured; this met the leak rate requirement noted in para 2.1.

4.3 Vibration Test

For the vibration test, the test fixture (Figure 4) was mounted to a vibration mounting plate which was in turn mounted to a shaker. The test fixture was again pressurized to 16.5 psig at 20°C ambient temperature and all connections checked for leaks. The top plate assembly was subjected to the following vibration levels (Black Brant V Sounding Rocket Subsystem Qualification Levels):

K_{IC} = critical stress intensity factor at which failure occurs

The crack velocity, V, is established as a function of the stress intensity factor, K_I, by fracture testing. For fused silica, a least squares fit of experimental data gives a function of the form

$$V = e^{\left(\frac{K_I - a}{b}\right)}, \quad \text{where a and b are constants}$$

In performing the analysis, experimental values for K_{IC}, a and b were obtained from published data for fused silica (Reference 4).

Proof-Pressure Testing

Typically, the initial surface flaws which exist in glass after grinding and polishing operations are too small to be measured by conventional non-destructive testing techniques. The most effective approach to determine K_i is by proof testing. Proof testing imposes a load on the component which is higher than the maximum expected service load. This establishes an upper limit for the maximum size of flaw that can be present after the proof test has been completed. Survival of the proof test guarantees that the stress intensity at the most serious flaw is less than the critical stress intensity factor because fracture is almost instantaneous when $K_i = K_c$. Thus by the Griffith criterion,

$$K_{IC} \geq \sigma_p Y \sqrt{L_i} \qquad (3)$$

where

σ_p = proof stress

L_i = initial flaw size

For the service stress, σ, the initial flaw size results in a stress intensity of:

$$K_i = \sigma Y \sqrt{L_i}$$

From equation 3, $L_i = \left(\frac{K_{IC}}{\sigma_p Y}\right)$

Therefore,

$$K_i = \left(\frac{\sigma}{\sigma_p}\right) K_{IC}$$

Lifetime Estimates for Glass Windows

Using fracture properties for fused silica from Reference 4, the times-to-failure were calculated from equation 2. The glass windows were assumed to be subjected to a continuous service pressure of 22 psi. The proof test pressure used was 60 psi, which is in agreement with recommended values from literature (Reference 4).

Sinusoidal Vibration

Longitudinal
7.5 g peak, 2000 to 27 Hz,
0.2 in peak to peak, 27 to 15 Hz

Lateral
7.5 g peak, 2000 to 38 Hz,
0.1 in peak to peak, 38 to 15 Hz

NOTE: Each vibration test is a single logarithmic sweep with a total duration of 115 seconds (3.7 octaves/min) starting at the high frequency end and having no dwell time at any frequency other than the starting point.

The test was repeated in each of the three principal axes. After vibration, the assembly was maintained at 20°C ambient temperature for 24 hours. The acceptance criteria was that the test fixture internal pressure did not drop more than 1 psi. In fact, no measurable drop in pressure was observed.

4.4 Thermal Cycle Test

The thermal cycle test set-up had the test fixture assembly (Figure 4) inside an environmental control chamber (Conviron). The test fixture assembly was pressurized to 16.5 psig at 20°C ambient temperature and subjected to the temperature profile shown in Figure 3. During testing, the top plate temperature and test fixture internal pressure were monitored. The test acceptance criteria was that a pressure drop of less than 1 psi occur over the test duration. Again, no measureable pressure drop was observed.

4.5 Qualification Proof Pressure Test

The test fixture (Figure 4) was connected to a mechanical pressure gauge, and in steps of 5 psi, was pressurized to 60 psig. Strain gauges, which were attached to various places of concern on the top plate, recorded strains at each step. At maximum pressure, strain and pressure readings were taken every minute for 10 minutes, at which time the pressure was reduced in steps of 10 psi to zero, recording strain at each step. The acceptance criteria was based on achieving the following factors of safety:

Yield Reserve factor = 1.25
Ultimate Reserve factor = 1.5

The results of the qualification proof pressure test indicated a maximum stress of 8630 psi occuring adjacent to the diode window on the central axis towards the centre. This gives a yield reserve factor of 4.1 and an ultimate reserve factor of 4.9, both well above the acceptance criteria and the theoretical results (theoretical yield reserve factor = 1.99).

4.6 Flight Acceptance Proof Pressure Test

The set-up for the flight acceptance proof pressure test was similar to that of the qualification test but did not include the strain gauges. The internal test fixture pressure was increased to 60 psig at a rate of 10 psi/minute. The pressure was maintained at 60 psig for 1 minute and then decreased at a rate of 10 psi/minute until 0 psig was reached. The acceptance criteria was based quite simply on the windows carrying the maximum pressure load without failure. This test was successful.

5. CONCLUSIONS

Based on the design and development phase described above, the following conclusions may be stated.

1) Structural integrity has been demonstrated in accordance with NASA safety requirements.

2) Nominal pressure seal requirements have been satisfied for normal operating conditions.

3) The scientific optical requirements have been met.

4) The top plate assembly has been designed to satisfy the payload temperature design limits.

In summary, all tests and analyses have demonstrated that the top plate assembly is flight-ready.

REFERENCES

1 - Get Away Special Payloads Safety Manual, Appendix A

2 - JSC11123 - Space Transportation System Payload Safety Guidelines Handbook.

3 - Wiederhorn, S.M.; "Prevention of Failure in Glass by Proof-Testing"; Journal of the American Ceramic Society, Vol. 56, No. 4, April 1973.

4 - Evans, A.G.; Roberts, D.E.; Wiederhorn, S.M.; "A Fracture Mechanics Study of the Skylab Windows"; Fracture Mechanics of Ceramics, Vol. 2.

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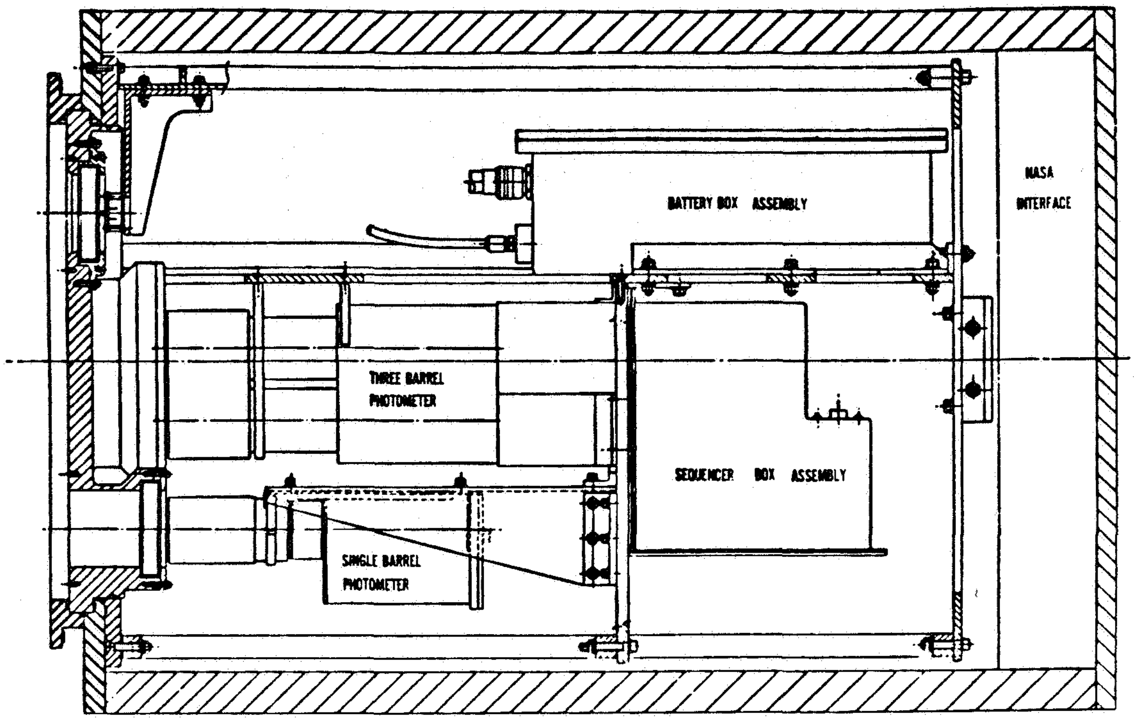

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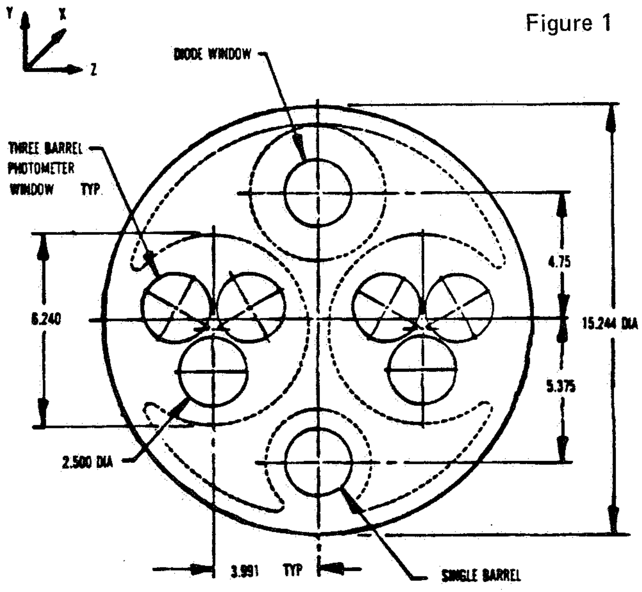

Figure 2

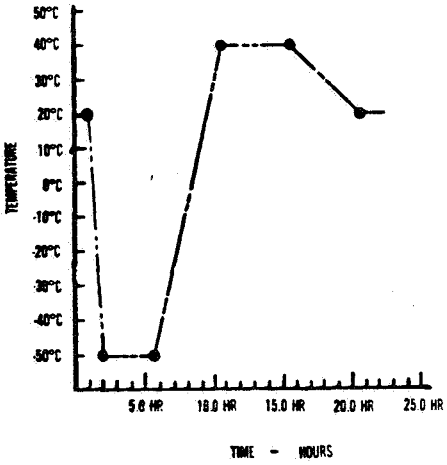

Figure 3

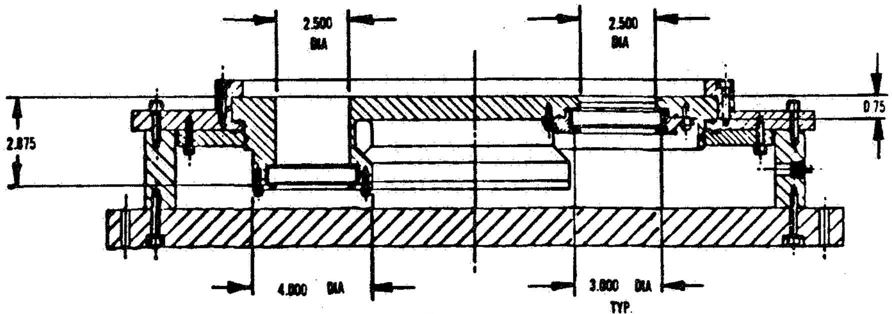

Figure 4