

STRUCTURAL VERIFICATION OF GLASS AND CERAMIC COMPONENTS FOR MANNED SPACEFLIGHT

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Overview

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- **Requirements**
- **Safety aspects**
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 - Structural verification**
 - Analysis
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- **Damage tolerance verification**
 - Static fatigue of glass and ceramics
- **Non-destructive inspection**
 - Aided visual inspection
 - Proof pressure test for flaw screening
- **Conclusions**
 - ...Questions & answers session

Introduction

Overview



ESA Columbus module



ESA Jules Verne journey to ISS

Inspiring records! Unforgettable moments...
...and lots of significant data
Glass and ceramics play important role

*"Good design and good planning makes
hardware development successful when glass
(and anything else) is part of the picture"*

Introduction

Overview

ISS payload experiments require the utilization of glass-like materials in the form of window panes, viewports, sample cells, optical components, etc

Design and verification of such **brittle** and **unforgiving** parts for safe operation in a manned spaceflight environment is a challenging assignment!!

Experiments range from *in situ* studies covering human research, physics interactions like convection in fluids or behaviour of liquid interfaces, chemical interactions, processes regulating the relations of life with the environment on Earth, etc



ISS micro-g environment

Potential failure of these parts operated in a habitable area, in particular within a micro-g environment, may cause **critical** and **catastrophic consequences**

Engineers shall implement appropriate design practices and features to mitigate the risks of failure

Introduction

Overview

CUPOLA is an ESA-built observatory module for the ISS and will provide crew members with a direct view of robotic operations and docked spacecraft, as well as an observation point for watching the Earth

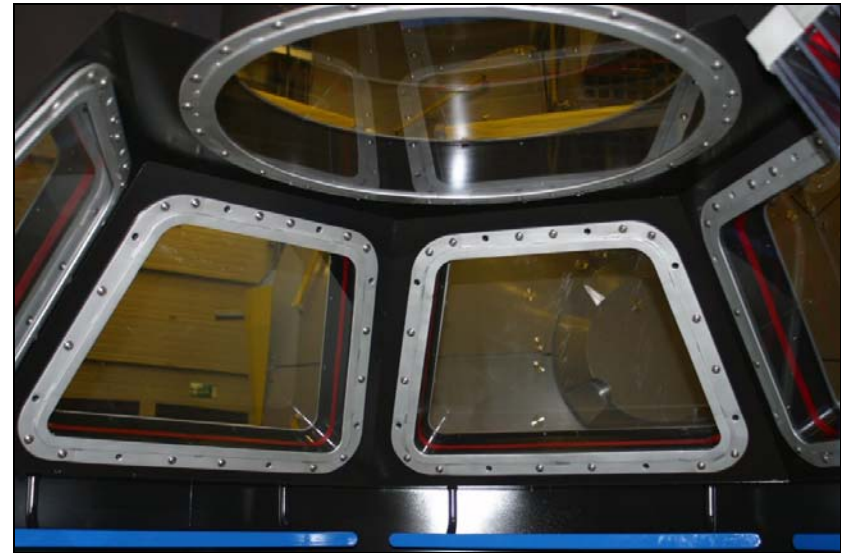
Design encompasses six side windows and a top window, made of:

- Fused silica
- Borosilicate glass

all of which equipped with shutters to protect them from damage by micrometeorites and orbital debris

Launch: STS-130 foreseen Dec. 2009

Final location: Node 3 of ISS



Inside of Cupola windows (Alenia Spazio)

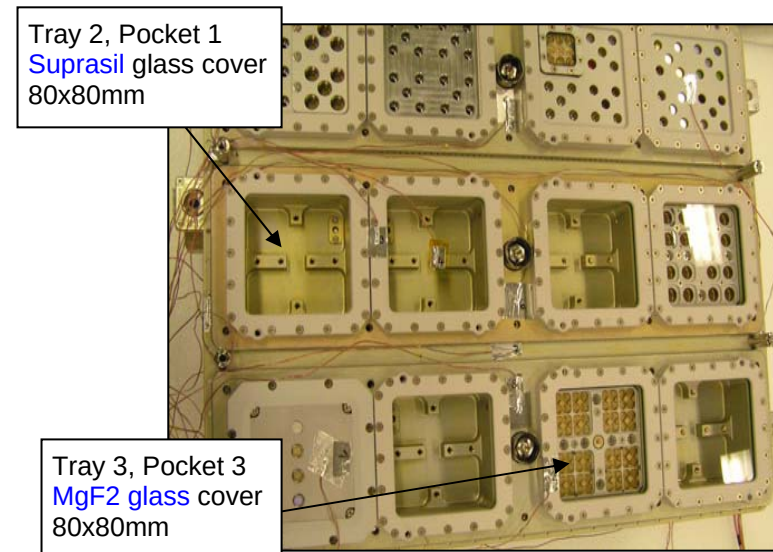
Introduction

Overview

Failures have occurred during different phases of hardware development and its qualification for the mission environments

Summary & lessons learned

- Glass failures due to small mechanical tolerances between the glass window and the metallic frame
- Glass failures due to the use of hard adhesives which do not compensate the different thermal expansion coefficients of the metallic frame and the glass window. Silicone-based adhesives can accommodate deformations from materials with different coefficients of thermal expansion



*Glasses within EXPOSE trays
(Kayser-Threde/ RUAG)*

Requirements

Applicable documents

Requirements and recommended design practices:

1. ECSS-E-ST-32C, *Space Engineering - Structural general requirements*
2. ECSS-E-ST-32-01C, *Space Engineering - Fracture Control*
3. SSP 30560, *Glass, Window, and Ceramic Structural Design and Verification Requirements*, ISS Program
4. NASA-STD-5003, *Fracture Control Requirements for Payloads using the Space Shuttle*
5. NSTS 14046, *Payload Verification Requirements*
6. SSP 52005C, *Payload Flight Equipment Requirements and Guidelines for Safety–Critical Structures*, ISS Program
7. NASA-HDBK-5010, *Fracture Control Implement. Handbook for Payloads, Experiments and similar hardware*
8. JSC-62550, *Strength Design and Verification Criteria for Glass, Ceramics and Windows in Human Space Flight Applications*

Requirements

Summary

ECSS-E-ST-32C, Space Engineering - Structural general requirements

4.5.10.1 Glass and ceramics

a. Design allowables for glass and ceramics shall be derived through a probabilistic approach, covering all size effects.

*NOTE For brittle materials such as glass and ceramics the lack of ductility results in very low failure strains. **The large scatter observed in component testing is primarily caused by the variable severity of flaws distributed within the material (volume flaws) or flaws extrinsic to the material volume (surface flaws).** The different physical nature of the flaws results in dissimilar failure response to identical external loading conditions. Due to the **random distribution of flaws** the failure of a complex structural part can be initiated not only at the point of highest stress.*

Requirements

Summary

ECSS-E-ST-32-01C, Space Engineering - Fracture Control

Requirements for glass components are updated, including improved coherence with SSP 30560A

8.7 Glass components

- a. The verification of all potential fracture critical glass components, except those verified as fail-safe or contained, shall include an analysis of crack growth under conditions of the stresses and the environments encountered during their service life.*
- b. A fracture mechanics analysis for potential sustained crack growth (da/dt) shall be performed in conformance with clauses 7, 8.7c, 8.7j, 8.7k and 8.7l for each safe life glass item, in order to demonstrate that the item **sustains after four (4) times its service life at least one and four tenths (1,4) times the design limit load without fracture.***
- c. The sustained crack growth analysis shall apply **factors to the sustained stresses** of the stress spectrum as specified in Table 8-1, depending on the duration of each load event that induces sustained stress.*
- d. The initial crack depth used for design and analysis of glass items shall:*
 - 1. Not be smaller than three (3) times the detectable flaw depth based on the NDI methods used.*
 - 2. Be subject to approval by the customer.*
- e. The smallest crack aspect ratio used for analytical life predictions shall be $a/c = 0,1$.*
- f. Crack growth properties at **100% moisture** shall be used for life predictions.*

Requirements

Summary

ECSS-E-ST-32-01C, Space Engineering - Fracture Control

8.7 Glass components (cont'd)

g. *Proof testing* or NDI, consistent with the loading expected during service life, shall be conducted to screen for manufacturing flaws in each potential fracture-critical glass item based on the result of the fracture mechanics analysis, with the following conditions:

1. Proof testing is performed for acceptance of pressurized glass components (such as windows and viewports) to screen the flaws larger than the initial crack depth, with minimum proof pressure of two (2) times the MDP.
2. Proof testing is performed in an environment suitable to limit flaw growth during test.
3. Humidity and encapsulated water is removed from the surface of the glass before proof testing.

NOTE Encapsulated water can be accumulated during e.g. storage before proof testing

- h. *If a factor of safety on strength of 5 or greater can be shown, and if approved by the customer, the proof test in conformance with 8.7m.1 may be omitted.*
- i. *It shall be demonstrated that glass inside a habitable area is safe from breakage by safe life verification in conformance with 8.7b, or is contained, or that released particles are smaller than 50 μm .*

Safety aspects

Overview

Metallic containers with glass windows on external walls are a common design solution for various experiments, allowing a closer insight into its evolution and offering the possibility for monitoring the trials

Presence and operation of glass parts in micro-g habitable modules poses several hazards for the crew members and the equipments around.

Hazards may come either from:

- **loss of containment capability** of systems operating toxic substances or otherwise hazardous
- **release of shatterable materials fragments**

ESA PSRP is carefully looking at all glass and ceramic parts within payload systems, for assuring compliance with applicable safety and structural integrity requirements

All potential hazards associated with failure of glass or ceramic parts shall be addressed in the early design stage, since these aspects are often driving the **design philosophy**



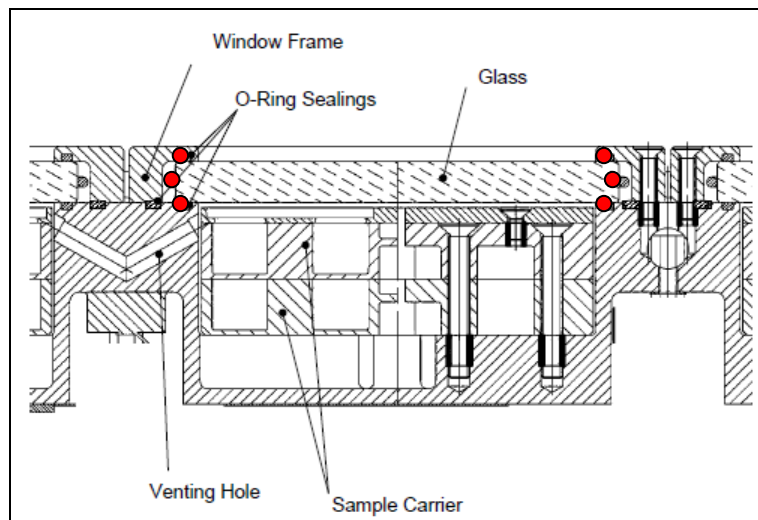
*GEOFLOW EC: on-orbit configuration
- PC protection cover on glass window*

Safety aspects

Overview

Containment of hazardous fluids

ESA PSRP internal policy over the years has been clear in **prohibiting direct containment of catastrophic hazardous fluids with a single layer of glass**. Supplementary containment barriers shall be in place



Sealing concept of glass window

Glass-to-metal contact

Glass-like materials are extremely brittle and distinguished for their peculiar failure pattern, occurring suddenly and with no preceding deformation. Stress concentrations, even if localized, might induce immediate rupture of the part

Internal ESA PSRP policy is clear in **prohibiting designs promoting contact between glass and metallic parts**

Therefore, it shall be avoided by implementing soft-mounting conditions, e.g. *Viton* o-rings or soft glues like silicone.

The effectiveness of the solution shall be positively verified under the worst-case deformation scenario for no glass-to-metal contact

Safety aspects

Overview

‘Safe on-arrival’ concept

Experience has shown the importance of verifying the hardware’s integrity on-arrival, after the hard launch environment

ESA PSRP review process covers the whole mission lifetime, therefore also the ‘on-arrival’ phase

Plastic bags

The utilization of transparent plastic bags is a common practice, allowing astronauts to inspect carefully the condition of the parts once on-orbit, before opening and removal of the items

Protective covers

Transparent protective covers made of commercial polycarbonates, e.g. Lexan[®] or Makrolon[®] are often used:

- allow a final verification of the hardware condition by inspecting for scratches, cracks or any debris
- prevent any broken glass shatters from escaping into crew environment, if rupture had occurred
- provide shielding function against kick-loads, inadvertent contact or impact of tools during crew handling activities

Safety aspects

Containment approach

Generally the preferred design solution from the safety standpoint

- reduces significantly the amount of required verifications and prevents the PO from running into time consuming analyses, testing and inspection activities to demonstrate the damage tolerance capacity of the parts
- transparent protective covers made of commercial polycarbonates
- metallic protective meshes that prevent the release of any glass fragments larger than 50µm are acceptable means for providing containment against release of shatterable materials

- application of adhesive films is sometimes considered; nevertheless experience has shown this to be unfeasible in some cases due to interference with optical performance

Although the preferred solution, containment approach is not always feasible...

Safe from breakage approach

In this case, the part has to be shown 'safe-from-breakage' for the mission lifetime by means of adequate fracture mechanics methodology

Structural verification

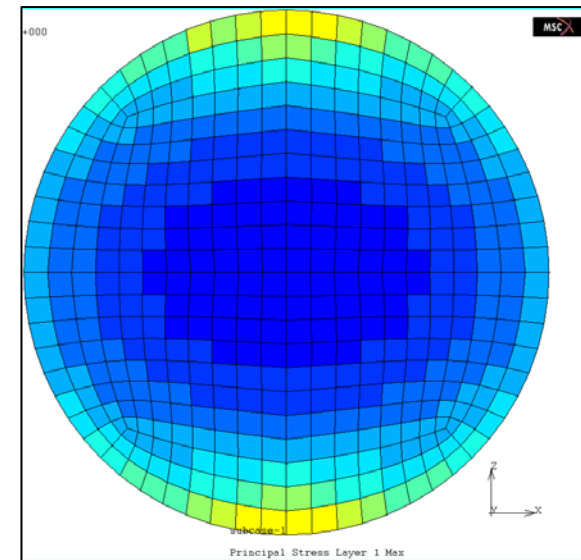
FE Analysis

Any glass part not shown to be contained shall be subjected to detailed stress analysis to determine existing MoS

- an accurate and conservative analysis of the stress distribution is a key element of the verification process
- special precautions and conservative assumptions are required in the design, analysis, and verification of glass parts

Mechanical strength of any glass composition is a function of the existing flaws and imperfections on the part and of the surface condition

High quality of the manufacturing process and **tight control** are therefore essential



GEOFLOW window: stress distribution of flight configuration @ MDP

Due to the **random distribution of flaws** the failure of a complex structural part can be initiated not only at the point of highest stress

Structural verification

FE Analysis

Comprehensive FE analysis

- covering different **quasi static** and **dynamic load environments**: inertial loads, worst-case pressure loads (ISS depress. scenario) and thermal gradients
- considering any loads induced by adjacent mounting deformation
- using materials properties at extreme environmental conditions (water induces stress-corrosion effects in many glass-like materials)
- anticipating the worst-case combination of the responses of different parts
- results evaluated in terms of **Principal Stress** criterion

Safety factors

Verification of glass or ceramic safety critical flight parts within payload systems shall comply with applicable ISS requirements

	Ultimate	Proof
Static test & analysis (non-pressur.)	3.0	1.2
Static test & analysis (pressurized)	3.0	2.0 ¹
Analysis only (non-pressurized)	5.0	--

*Minimum FoS for payload flight structures
(SSP 52005 Rev. C)*

¹ Where applicable, proof factor resulting from fracture mechanics analysis shall be used if larger than 2.0

Structural verification

Qualification Testing

Strong qualification program of the glass assembly shall encompass:

- vibration testing
- thermal life cycling
- proof pressure testing
- impact testing (if applicable)

This qualifies the glass-assembly design for the foreseen transportation and on-orbit loading environments

Acceptance Testing

Flight parts shall be submitted to the worst-case loading environment enveloping all foreseen conditions. Therefore, as a general principle, **all ready-for-flight hardware** shall have been **tested to the max. predicted load level**, as minimum

Damage tolerance

Safe-from-breakage approach

Potential fracture critical glass parts which are not contained shall be verified as safe-life items by means of fracture mechanics concepts

A verification approach based on **analysis**, **testing** and **inspection** shall demonstrate the design robustness for the foreseen loading environments and guarantee the necessary ‘safe-from-breakage’ life time

- In glass-like materials flaws grow as a function of stress, flaw depth, environment, and time; this is normally referred as **static fatigue** degradation

Life analysis

Sustained crack growth life analysis with:

- **scatter factor of 4** applied on the sustained load duration,
- duration-dependent **factor on stress**
- after 4 service lifetimes the part shall still sustain **1.4 x limit load** without fracture

Duration of sustained stress level	Factor on stress
life $\leq$ 1 week	1.4
1 week < life $\leq$ 1 month	1.3
1 month < life $\leq$ 1 year	1.2
life > 1 year	1.1

Factor on stress for sustained crack growth analysis of glass and ceramics, ECSS-E-ST-32-01C

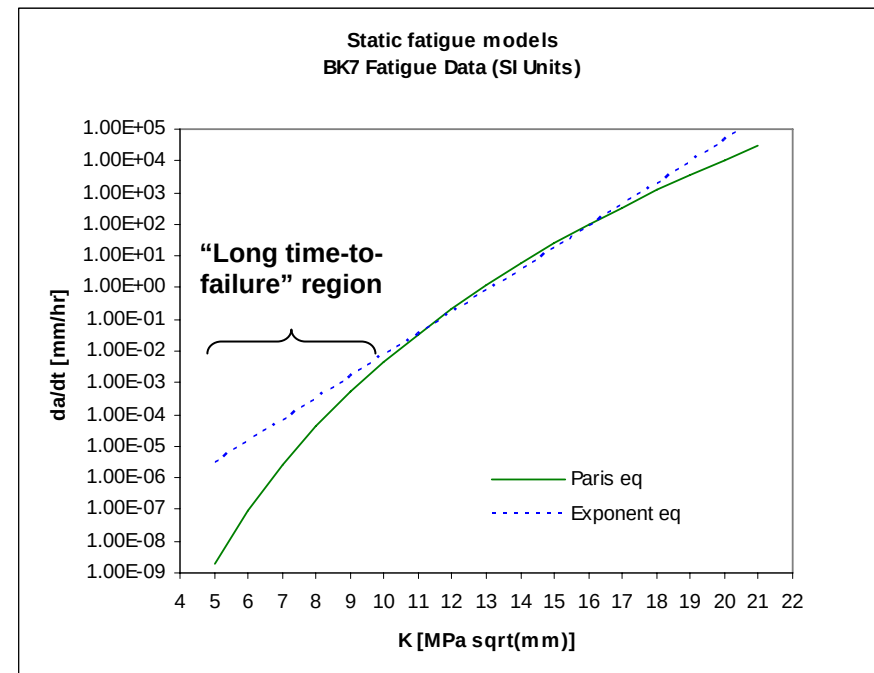
NOTE The factor on stress is larger for shorter design life because of the flaw growth velocity sensitivity to small variations in the stress intensity

Damage tolerance

NASGRO software

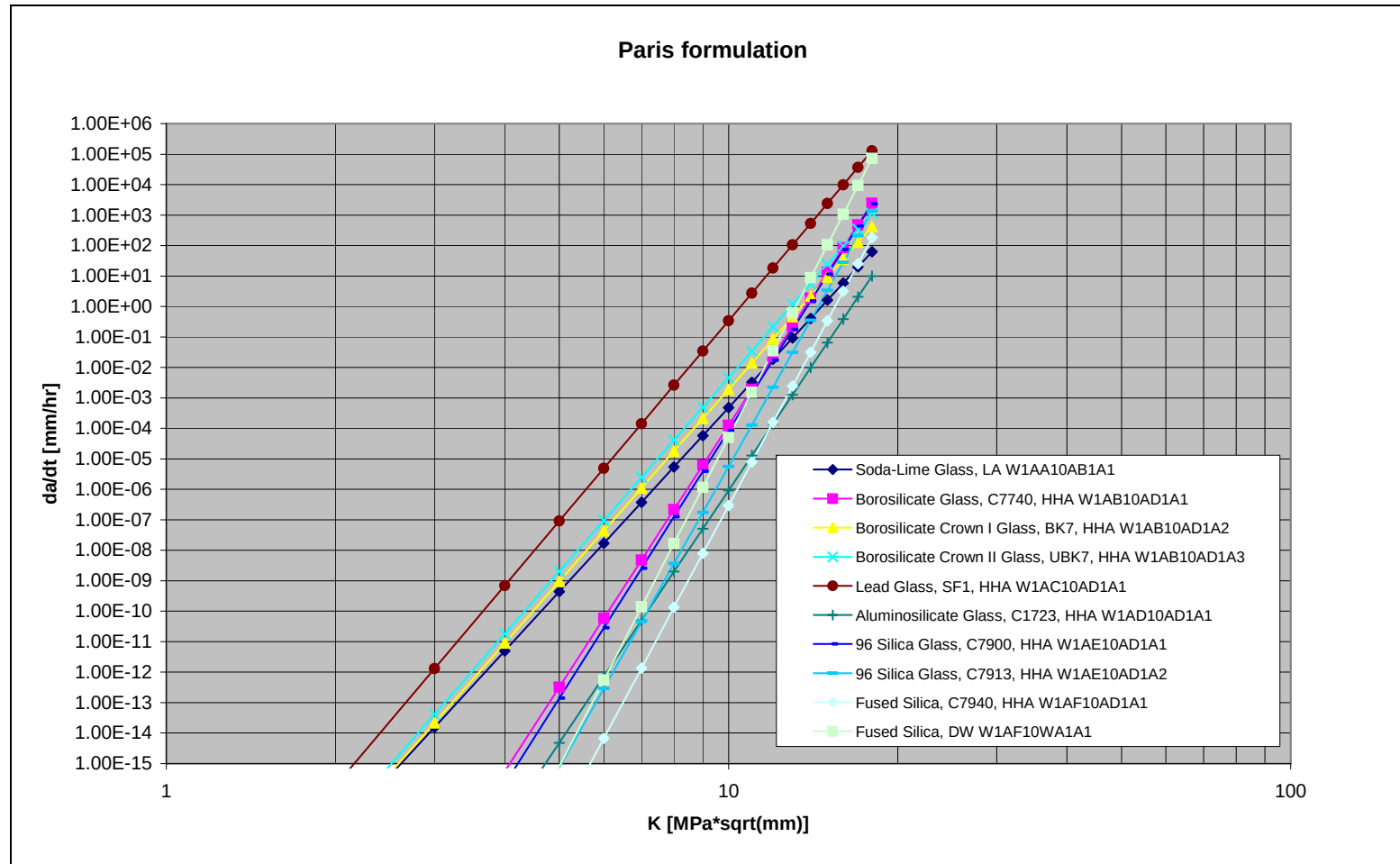
Fatigue crack growth software NASGRO[®] offers a dedicated module for performing life assessments of glass-like parts under sustained loading

- **Exponential** and **Paris models** for crack growth prediction
- materials database including experimental ' $da/dt - \Delta K$ ' data and respective fits for various materials (e.g. soda-lime glass, borosilicate, lead glass, aluminosilicate, silica, fused silica and sapphire) and environmental conditions (high humidity air - HHA, and distilled water - DW)
- curve fitting constants for material and environment combinations



NASGRO curve fits for sustained stress data of Borosilicate Crown II Glass, UBK7, in HHA

On web: <http://www.nasgro.swri.org>

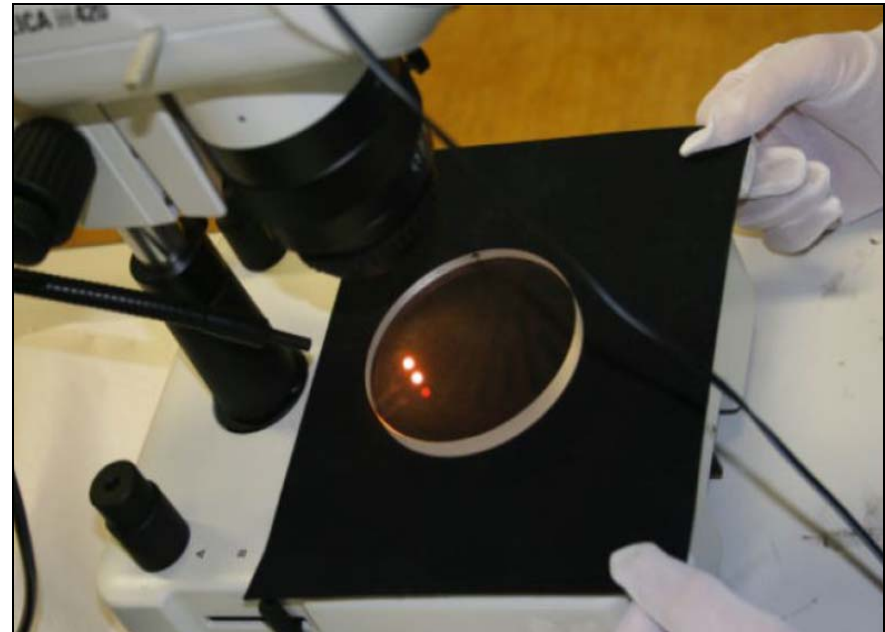


Inspection

Visual inspection

Aims for detecting defects larger than the ICD size, defined as the maximum pre-existing flaw size for which the part would survive exactly four service lifetimes

- Minimum required NDI capabilities defined by the ICD size
- Visual inspection with **minimum of 10 times magnification** shall be applied in all fracture critical glass-like parts
- Flaw detection is assisted by application of high intensity lightning at the right angles on the critical flaw orientations, to see reflections of existing **surface flaws**



Inspection of GEOFLOW glass window under microscope (10x magnification)

Inspection

Proof pressure test for flaw screening

Test shall be designed based on fracture mechanics assessments using conservative assumptions:

- Sustained loading
 - under nominal conditions
 - potential ISS depress. scenario to be considered
- Scatter factor of 4 applied on load durations
- Different critical crack locations considered
- Different crack aspect ratios
 - $a/c = 0.1$ and
 - $a/c = 1.0$
- Fracture mechanics properties acc. to NASGRO database, if applicable
- Sustained crack growth analysis to determine the ICD sizes, based on
 - lower boundary fracture toughness (in wet condition), 0.7 x mean value
- Proof pressure level that leads to failure of cracks larger than ICD, based on:
 - upper boundary fracture toughness (in dry condition), 1.3 x mean value
- Safety factor of 1.4 after four service lifetimes and in the CCS determination for the proof test level

Inspection

Proof pressure test for flaw screening

One or more test jigs for proof test for screening of flaws

- duration of the proof test should be as short as possible
- during the test it is important to keep the time to unload the window short; cracks may still grow during unloading
- however it has to be assured that the required proof load has been reached and that unloading is controlled
- proof pressure (or proof load) determined by crack growth analysis, being **2.0 times MDP as minimum**



GEOFLOW Proof test jig no. 1 – Symmetric

Inspection

Proof pressure test for flaw screening

The proof test shall be performed in both possible orientations to avoid configuration controls for the proper installation in the flight hardware

- Same **boundary conditions** for the proof test as for the window installed in the flight hardware
- Ensure that there is no glass-metal contact during the proof test. The glass-metal contact is more likely during the proof pressure test because the deformations can be significantly larger (pending on the proof factor)
- Jig may have to be stronger to support the proof level, depending on the proof factor, which may affect stress distribution in the glass



GEOFLOW Proof test jig no. 2 - Asymmetric

Conclusion

Over the years ESA has been involved in the design of payload systems containing [safety-critical glass and ceramic components](#) and has built a safe history in the verification of parts made of these fragile and unforgiving materials

- Various applicable safety and structural requirements have been presented and discussed
- Design and verification process for acceptance of glass and ceramic flight parts within manned spaceflight hardware represents a unique challenge
- Diverse hazardous consequences posed by the potential failure of such parts within habitable micro-g environment need to be identified in an early stage
- The criticality of these parts has to be assessed, controlled and whenever possible reduced by appropriate design solutions

ESA PSRP is carefully looking at all glass and ceramic parts within their payload systems, assuring an appropriate design and verification process in compliance with applicable safety and structural integrity requirements