NASA TECHNICAL STANDARD	NASA-STD-5018
National Aeronautics and Space Administration Washington, DC 20546-0001	Approved: 08-12-2011

STRENGTH DESIGN AND VERIFICATION CRITERIA FOR GLASS, CERAMICS, AND WINDOWS IN HUMAN SPACE FLIGHT APPLICATIONS

MEASUREMENT SYSTEM IDENTIFICATION:
METRIC/SI (ENGLISH)

DOCUMENT HISTORY LOG

Status	Document Revision	Approval Date	Description
Baseline		08-12-2011	Initial Release

FOREWORD

This Standard is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods that have been endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item.

This Standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers.

This Standard establishes uniform design and development requirements across NASA Centers for the design of glass and ceramic components that require high structural reliability and integrity within a human-rated space vehicle, space suit, or habitat. Requirements contained herein also provide design hazard controls for the unique hazards presented by brittle materials, including non-structural components, in an enclosed area inhabited by humans. Documenting these requirements in a NASA Standard allows each NASA program to rely upon an established set of practices that have a proven heritage and that have evolved from lessons learned across the spectrum of previous programs and designs.

This Standard was prepared by Johnson Space Center. It has evolved from a series of program requirements documents implemented by Apollo, the Space Shuttle, and the International Space Station. This document also benefits greatly from certification and verification experiences encountered during the development of each of these programs.

Requests for information, corrections, or additions to this Standard should be submitted via "Feedback" in the NASA Standards and Technical Assistance Tool at http://standards.nasa.gov.

Original Signed By: ***08-12-2011***

Michael G. Ryschkewitsch
NASA Chief Engineer

Approval Date

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STRENGTH DESIGN AND VERIFICATION CRITERIA FOR GLASS, CERAMICS, AND WINDOWS IN HUMAN SPACE FLIGHT APPLICATIONS

1. SCOPE

1.1 Purpose

The purpose of this Standard is to specify the minimum structural design requirements for the design, development, and verification of windows, glass, and ceramic structure included in National Aeronautics and Space Administration (NASA) vehicles/elements, habitats, space suits, all orbital support equipment (OSE), and flight support equipment (FSE). Although this Standard primarily addresses structural design requirements for glass and ceramics, it also includes design and verification requirements for non-structural glass and ceramic components. Optical performance and radiation specifications are not provided in this document.

1.2 Applicability

This Standard is applicable to all human-rated flight vehicle and element hardware, including orbital replacement units, space suits, OSE, and FSE. The requirements in this Standard also apply to all human-inhabitable structures built beyond Earth's surface.

This Standard does not apply to windowpanes made from non-brittle materials, including plastics. Windowpanes designed with non-brittle materials are to comply with standard engineering design requirements for primary structure.

Adherence to this document in and of itself does not exempt flight windows, glass, or ceramics from any safety, fault-tolerance, or hazard control requirements. Any such reduction in requirements shall be established and approved by the appropriate NASA Technical Authority of the program invoking this document.

This Standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers, and may be cited in contract, program, and other Agency documents as a technical requirement to ensure the structural integrity and reliability of human-rated spacecraft. This Standard may also apply to the Jet Propulsion Laboratory or to contractors, grant recipients, or parties to agreements only to the extent specified or referenced in their contracts, grants, or agreements.

Requirements are numbered and indicated by the word "shall." Explanatory or guidance text is indicated in italics beginning in section 4.

1.3 Tailoring

Tailoring of this Standard for application to a specific program or project shall be formally documented as part of program or project requirements and approved by the Technical Authority.

WARNING: Significant inherent risks exist with the use of brittle materials, such as glass and ceramics, in spacecraft, either as structural components or as non-structural components. The requirements specified in this Standard have been established by decades of lessons learned in window designs during Apollo, Shuttle, and International Space Station programs. These requirements guide window and glass/ceramic designs that ensure the safety of flight. Tailoring of these requirements is not recommended and should only be accomplished with close consultation with the appropriate knowledgeable NASA Technical Authority.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section contain provisions that constitute requirements of this Standard as cited in the text.

2.1.1 The latest issuances of cited documents shall be used unless specific versions are designated.

2.1.2 Non-use of specific versions as designated shall be approved by the responsible Technical Authority.

The applicable documents are accessible via the NASA Standards and Technical Assistance Resource Tool at http://standards.nasa.gov or may be obtained directly from the Standards Developing Organizations or other document distributors.

2.2 Government Documents

NASA

NASA-STD-6016	Standard Materials and Processes Requirements for Spacecraft

2.3 Non-Government Documents

ASTM, International (ASTM) (formerly American Society for Testing Materials)

ASTM C1368	Standard Test Method for Determination of Slow Crack Growth Parameters of Advanced Ceramics by Constant Stress-Rate Flexural Testing at Ambient Temperature
ASTM C1421	Standard Test Methods for Determination of Fracture Toughness of Advanced Ceramics at Ambient Temperature
ASTM C1576	Standard Test Method for Determination of Slow Crack Growth Parameters of Advanced Ceramics by Constant Stress Flexural Testing (Stress Rupture) at Ambient Temperature

2.4 Order of Precedence

This Standard establishes requirements for the minimum structural design requirements for the design, development, and verification of windows, glass, and ceramic structure included in the vehicle/element, habitats, space suits, all OSE, and FSE and does not supersede nor waive established Agency requirements found in other documentation.

2.4.1 Conflicts between this Standard and other requirements documents shall be resolved by the responsible Technical Authority.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

®	registered trademark
°	degree(s)
° C	degree(s) Celsius
° F	degree(s) Fahrenheit
>	greater than
≥	greater than or equal to
<	less than
≤	less than or equal to
±	plus or minus
µm	micron
ADP	acceptance data package
ASTM	ASTM, International (formerly American Society for Testing Materials)
cm	centimeter(s)
DID	data item description
EVA	extravehicular activity
FSE	flight support equipment
GCVP	glass and ceramics verification plan
GCVR	glass and ceramics verification report
in	inch(es)
IR	infrared
IVA	intravehicular activity
K_I	stress intensity
K_{IC}	critical stress intensity
lb	pound(s)
mm	millimeter(s)
MM/OD	micro meteoroid/orbital debris
MOR	modulus of rupture
MS	margin of safety
N	Newton
NASA	National Aeronautics and Space Administration
OSE	orbital support equipment
sec	second(s)
STD	Standard
UV	ultraviolet

3.2 Definitions

Definitions cited here are applicable to the context of this document.

Acceptance Test: A specified level of testing in which all functional aspects of the hardware are thoroughly and systematically verified to ensure that the product performs according to the specification. Tests are conducted in accordance with an approved verification plan and approved test procedures. The test is required before acceptance, certification, and delivery of production hardware. It demonstrates that the hardware complies with specification requirements and is free of defects. Specific pass/fail criteria, tolerances, and test conditions are documented in implementing test requirements documents. The acceptance test verifies the workmanship of the flight hardware. Acceptance tests are performed on every deliverable unit.

Brittle Material: Materials, such as glass and ceramics, that are characterized by the fact that rupture occurs without any noticeable earlier change in the rate of elongation, i.e., there is no plastic deformation before fracture. The material will not yield under load before breaking. There is no difference between the ultimate strength of the material and its breaking strength.

Catastrophic Hazard: A hazard that can result in a disabling or fatal personnel injury or loss of flight hardware, ground facilities, or mission-critical equipment.

Ceramics: Materials that are joined by ionic or covalent bonds and are complex compounds, consisting of both metallic and non-metallic elements. These are hard, brittle, high-melting-point materials with good chemical and thermal stability and high compressive strengths. The most important of the non-crystalline ceramic materials are glasses.

Certification: This process consists of qualification testing, any major ground testing, acceptance testing, and any other testing and the analyses required to determine that the design hardware from the component through the subsystem level meets the specified requirements.

Critical Hazard: A hazard that can result in a non-disabling personnel injury; damage to flight hardware, ground facilities, or mission-critical equipment; or loss of mission.

Critical Stress Intensity (K_{IC}): A material property that delineates the combination of stress and flaw size that will precipitate failure. This property is also referred to as fracture toughness.

Design Life: The interval that begins with entry of a vehicle/element or part into operation or the design environment and ends with completion of its intended design mission.

Dynamic Amplification Factor: The factor applied to a load to account for the dynamic nature of the load when applied on a structure. Dynamic amplification factors infrequently exceed 2.0.

Flaw: An imperfection or discontinuity in the glass or ceramic. Flaws include scratches, pits, craters, bubbles, inclusions, chips, bruises, and cracks of any sort. Flaws may be acceptable or rejectable.

Dynamic Factor of Safety: The factor of safety applied to the dynamic load during the application of the dynamic load. This factor of safety is reduced (from 3.0 (see section 4.4.1.a of this Standard)) since the dynamic load is well understood either by test or by enveloping theory.

Flight Article: The hardware, firmware, and software unit that is used operationally in a flight environment. This unit is designed and manufactured under strict quality control, with complete records of unit manufacturing, testing, and shipping and handling.

Glass: A large class of materials with highly variable mechanical and optical properties. Glass solidifies from the molten state without crystallization and is typically made by fusing silicates with boric oxide, aluminum oxide, or phosphorus pentoxide. Glass is generally hard, brittle, and transparent or translucent. Glass is an amorphous (non-crystalline) material that is isotropic and elastic.

Glass Ceramics: Materials that are formed as a glass and then made to partly crystallize by heat treatment. Mechanically, they are very strong materials and can sustain repeated thermal shocks. They have very low heat conduction coefficients and can be made nearly transparent.

Glass Pane or Pane or Windowpane: The glass structural component or element of a window.

Initial Design Flaw Depth: The total flaw depth that is used to establish the allowable design stress that does not induce manufacturing flaws to grow to failure during the design life of the glass structure, assuming 100 percent moisture.

Limit Load: The maximum anticipated load, or combination of loads, on the hardware during its design service life, including ground handling, transport to and from orbit (including abort conditions), and on-orbit operations.

Margin of Safety (MS): A computation that demonstrates the structural reserve existing when comparing a material's ability to sustain load to the predicted maximum service load with a factor of safety applied. Typically, the MS computation is written as

$$MS = (\text{Allowable stress}/(\text{predicted service stress x factor of safety}))-1.$$

For glasses and ceramics, the allowable stress is generally equal to the stress generated in the glass during an acceptance proof test.

Modulus of Rupture (MOR): The failure stress in bending, as determined by bend test specimens or MOR bars.

Non-Structural Glass: Any glass component that is not a part of a structural load path or a part of a pressure vessel. The only loads non-structural glass carries are inertial. Failure of this type of hardware does not violate redundancy requirements for crew safety but could cause the loss of an important function and could present a significant hazard. An example of non-structural glass is a camera lens that is not subjected to pressure loading.

Qualification Article: A hardware, firmware, and software unit that is identical to the flight unit or production unit in form, fit, and function, as well as in manufacturing processes, parts, and quality control. This unit is used for verification and certification credit for all environmental requirements and performance requirements as needed.

Qualification Test: A test program of statistically valid length under combined loads, cyclic loads, and time-varying environmental conditions that simulate conditions expected in service use. Qualification tests expose flight-like hardware to the actual environments in which it is expected to operate. The qualification test proves that the hardware, as designed, can function and perform in the applied environments over the design life. Pass/fail criteria are developed to define the minimum performance requirements that the flight-like unit under test has to meet for certification by NASA. Qualification test levels are applied with the appropriate specified test factors.

Static Fatigue: In glass and ceramics, flaws grow as a function of stress, flaw size, environment, and time. The strength degradation with time resulting from the flaw growth is referred to as static fatigue.

Structural Glass: Any glass component that provides the required structural integrity or redundancy for crew safety. Structural glass sustains loads or pressure necessary for a mission to succeed. Failure of a structural glass component results in a significant hazard and is potentially catastrophic.

Subsurface Flaws: The portion of a flaw that extends into the thickness of the glass, such as the tail of a damage that propagates down into the substrate. All subsurface flaws have their genesis at the surface of the glass or from the bottom of a surface damage.

Tempering: A process that leaves the surface of the glass in compression. The thickness of the surface compressive layer is different for the various tempering techniques. Two common types of tempering include heat tempering and chemical tempering.

Total Flaw Depth: The sum of the depth of the visible flaw, depression, or crater and the depth of the tail that cannot always be seen. Typically, the total flaw depth is estimated to be three times the depth of the visible flaw depth.

Ultimate Allowable Load: For glass and ceramics, the ultimate allowable load in the margin calculation is the proof test load. The proof factor is used for the proof pressure test that subjects the structure to a stress level sufficiently high to show that flaws above a chosen size do not exist or else the pane would not have survived the proof test.

Window: A sub-assembly of a greater vehicle element that provides through viewing. The term refers to an assembly that contains all glass components (multiple panes, for instance) and their associated frames and assembly hardware. The window hardware includes the fastening system to the vehicle but not beyond it.

4. REQUIREMENTS

This Standard primarily addresses structural and non-structural design and verification requirements for glass and windows in human-rated space vehicles, space suits, and habitats. The same requirements apply to ceramics, which have similar characteristics. The sole use of the word "glass" does not preclude requirement applicability to ceramics.

4.1 Introduction

Glass is a brittle material that obeys Hooke's law until failure. Glass failures result from tensile stresses and usually originate from a pre-existing flaw on or near the surface. Flaws that propagate below the surface can emanate from manufacturing defects; good design and manufacturing practice minimize all types of flaws on or near the surface.

The strength of a particular glass composition and configuration can vary widely because of randomly occurring flaws. Often, manufacturing flaws in glass cannot be detected by visual inspection because the visible portion of the flaw is removed in the finishing process.

Flaws in glass can be initiated easily by contact with objects; therefore, glass requires special protection subsequent to manufacturing.

Flaws in glass grow as a function of stress, flaw depth, environment, and time; this phenomenon is called static fatigue, flaw growth, or stress corrosion cracking. Structural degradation occurs with time for glass in tension, and failure can result if adequate precautions are not exercised.

Because of the inherent structural characteristics of glass, special precautions and assumptions are required in the design, analysis, and verification of glass structural elements.

4.2 Planning and Reporting

The vehicle/element responsible organization is accountable for certification of the window system, including the overall design, planning, demonstration, and management of glass and windows for the vehicle/element.

The vehicle/element prime contractor has the responsibility for demonstrating that each requirement has been met to the satisfaction of the appropriate NASA Technical Authority.

The vehicle/element prime contractor has the responsibility to prepare a glass and ceramics verification plan (GCVP).

a. The GCVP shall describe the test/analysis data and methods to be used, as well as test success criteria for each component or assembly-level test.

b. The data requirements for the GCVP shall be in accordance with the data item description (DID) in Appendix A of this Standard.

c. NASA Technical Authority approval of the GCVP shall be obtained before implementation of the plan.

Modifications to the plan in progress may be made with prior NASA Technical Authority approval as the design develops.

The contractor has the responsibility to prepare a glass and ceramics verification report (GCVR) describing methodologies, processes, procedures, analyses, and test results used to verify the adequacy of glass and ceramic designs and show compliance with each explicit requirement contained in this document.

d. Documentation of mathematical model correlations shall be included in the GCVR.

e. The GCVR DID, found in Appendix A of this Standard, shall apply to these requirements.

4.3 Environments and Loads

4.3.1 Applied Environments

Where applicable, spacecraft windows shall be capable of meeting the requirements specified herein during all phases of the vehicle/element mission, including the launch, entry, and landing phases and, if applicable, ferry flights or atmospheric transfers, after exposure to any single or combination of the following environments:

a. Pressure (total pressure, positive and negative differential pressures, aerodynamic, plume impingement).

b. Vacuum.

c. Thermal.

(1) Liftoff aerodynamic heating.
(2) On-orbit temperature extremes.
(3) On-orbit plume heating and thermal shock.
(4) Entry aerodynamic heating.
(5) Terrestrial.

d. Low-frequency and transient and dynamic loads.

e. Loads associated with pane failures.

f. Shock.

(1) Pyrotechnic.
(2) Landing impact.
(3) Handling.

g. Vibration.

(1) Random.
(2) Vibroacoustic.

h. Humidity.

i. Foreign Object Debris impacts.

j. Micro meteoroid/orbital debris (MM/OD) flux.

k. Fungus.

l. Ozone and atomic oxygen.

m. Rain.

n. Lightning.

o. Salt spray.

p. Solar radiation.

q. Geomagnetic trapped (Van Allen) radiation, both protons and electrons.

r. Acoustic noise.

s. Sand and dust.

t. Hail, snow, and ice.

u. Wind.

v. Acceleration.

w. Any other program-specific/mission-specific environments and conditions, including loadings and chemicals, to which the vehicle/element can be exposed.

4.3.2. Window Inter-pane Purging and Venting

Pressures shall not exceed the limit design pressure for the windows during purging and venting.

The window configuration may use passive venting to minimize potential surface contamination by material offgassing or moisture condensation.

4.3.3 Inadvertent Contact

a. The glass assembly shall be capable of withstanding inadvertent contact of up to 685 N (154 lb) (limit), applied as a uniform pressure load over a 10.2-cm by 10.2-cm (4.0-in by 4.0-in) area.

b. If this area is unavailable to inadvertent contact, the load shall be distributed over the area exposed to the inadvertent contact in a manner consistent with inadvertent contact but not applied over a dimension greater than 10.2 cm (4.0 in) maximum.

4.3.4 Impact Hazards to Glass and Ceramic Structures and Components

The flight or mission environment presents hazards, such as released shards or cracking resulting from impacts on glass or ceramics, to crew safety and the structural integrity of the vehicle/element.

a. All structural glass and non-structural glass or ceramic components exposed to tool impact, e.g., the component design permits contact with the brittle material surface, shall not create a hazardous condition when impacted.

b. All sources of potential impacts shall be considered, including but not limited to MM/OD impacts, intravehicular activity (IVA) and extravehicular activity (EVA) inadvertent contacts, IVA and EVA tool impact hazards, and launch debris impacts.

c. If these requirements cannot be positively demonstrated, then appropriate hazard controls shall be implemented.

4.3.5 Impact Damage Tolerance Requirement for Structural Glass

a. All vehicle/element windows shall be designed to maintain the structural and functional integrity of the window during all appropriate design environments after an impact event.

b. The damaged structural glass or ceramic structure shall maintain a margin of safety of 0.0 or greater for the duration of the mission being assessed.

c. The damaged structural glass or ceramic component shall have sufficient remaining life to allow repair or replacement of the damaged part without loss of mission.

4.3.6 Glass-to-Metal Contact

a. The window seal shall prohibit glass-to-metal contact before, during, and after exposure to the flight random vibration and vibroacoustic environments.

b. The window design shall prohibit glass-to-metal contact before, during, and after exposure to two times the maximum combined limit load.

4.3.7 Glass Slipping and Rattling

The window design shall prevent slipping and rattling of the glass during exposure to the flight and ground transportation, as well as handling, random vibration, and vibroacoustic environments.

4.3.8 Glass Pane-to-Seal (or Cushion) Interface

a. The window seal shall meet its performance requirements within the temperature extremes of the seal-to-windowpane interface for the duration of the design life of the window, precluding degradation from the environment or aging.

b. The window design shall prohibit the phase change (glassy transition) of the seal (or cushion) material in contact with the glass at the lower temperature extremes of the seal/glass pane interface.

In this context, the seal is any material in contact with the glass in the assembly.

The material does not necessarily have to function as a seal for this requirement to be applicable.

4.3.9 Combined Loads

The glass component design shall be assessed for all combined loads that can occur.

The combined loads may be applied in a time-consistent manner.

4.3.10 Inner and Outer Surfaces

Both the inner and outer surfaces of each windowpane shall be designed to carry the maximum combined loads for the design life required.

4.4 Design Factors

4.4.1 Minimum Factor of Safety for Annealed Glass

Glass and other brittle materials typically have large scatter in material properties. Additionally, brittle materials are prone to sudden failure without prior warning. These features require a higher safety factor than standard, well-characterized materials.

a. Annealed glass shall be designed to a minimum ultimate factor of safety of 3.0 applied to the maximum combined limit load (section 4.3.9 of this Standard) at the beginning of life.

b. Annealed glass shall be designed to a minimum ultimate factor of safety of 1.4 applied to the maximum combined limit load (section 4.3.9 of this Standard) at the end of life.

4.4.2 Minimum Factor of Safety for Tempered Glass

Tempered glass shall be designed to a minimum ultimate factor of safety of 3.0 applied to the maximum combined limit load (section 4.3.9 of this Standard).

4.4.3 Dynamic Amplification Factor

The potential for dynamic amplification of the load in the event of a pressure pane failure exists.

a. A dynamic amplification factor of at least 2.0 shall be applied to the combined load (section 4.3.9 of this Standard) for the assessment of a pressure pane failure event.

b. If specifically measured during a dynamic redundancy test, the dynamic amplification factor for analysis shall be the measured value in lieu of section 4.4.3.a of this Standard.

4.4.4 Dynamic Factor of Safety

a. The factor of safety applied to the load during the dynamic event precipitated by the failure of a pressure pane shall be 2.0.

b. This factor shall be applied only to the dynamic event and in addition to the dynamic amplification factor defined in section 4.4.3 of this Standard.

c. After quasi-static conditions are reached, the factor of safety specified in section 4.4.1 or section 4.4.2 of this Standard, as appropriate, shall apply.

4.5 Window Life

4.5.1 Uncertainty Factor on Stress for Flaw Growth Analysis

The data in table 1, Flaw Growth Analysis Uncertainty Factor versus Design Life, shall be used for selecting an uncertainty factor to be used on the stress for the flaw growth analysis.

Table 1—Flaw Growth Analysis Uncertainty Factor versus Design Life

Design Life	Uncertainty Factor*
Design Life ≤ 1 week	1.4
1 week < Design Life ≤ 1 month	1.3
1 month < Design Life ≤ 1 year	1.2
Design Life > 1 year	1.1

**The required uncertainty factor is larger for shorter design life because the flaw growth velocity is sensitive to small variations in the stress intensity.*

4.5.2 Life Factor

A life factor of 4 shall be applied to the design life to account for scatter.

4.5.3 Assembly Life

The installation of the window into the vehicle/element shall not cause:

a. Damage to the glass over the service life of the vehicle.

b. Deterioration of the sealing capabilities over the service life of the vehicle.

4.5.4 Induced Residual Stresses

The glass design shall preclude any potential source of strength degradation caused by induced residual tensile stresses or local stress concentrators.

Features that concern designers include certain bonds on glass, localized structural deformation, localized thermal gradients, inside curves or cuts, and sharp corners.

4.6 Window Coating Requirements

4.6.1 Strength Degradation Caused by Coatings

Thermal cycling and thermal shock testing of glass coatings in previous designs have initiated coating cracks that have propagated into the glass, causing strength degradation.

The strength effects of coatings selected for glass components shall be determined.

4.6.2 Coated Windowpane Structural Integrity

Windowpane coatings shall be located on surfaces to minimize structural degradation of the panes.

4.6.3 Windowpane Coatings for Infrared and Ultraviolet Photography or Sensing

In the event that a vehicle/element window is to be used for infrared (IR) and ultraviolet (UV) photography or sensing, the location of the window coatings shall provide for IR and UV viewing through windowpanes without degrading the structural integrity.

4.7 Structural Analysis Requirements

The primary critical loading condition in windowpanes is typically the bending stress resulting from applied pressures. All polished glass or ceramic windows contain invisible micro cracks critical to the strength and life of the finished product. Fracture mechanics and static fatigue analyses, which are valid for most spacecraft windows, are based on the assumption that the critical flaws are much smaller than the thickness of the glass.

4.7.1 Structural Analysis Requirements for Windowpanes, Glass, and Ceramic Structure

a. Fracture mechanics technology and the related flaw growth methodology as detailed herein shall be used to assure adequate life of any glass structure.

b. All static fatigue assessments on the structural glass life shall consider all load events to which the component has been and will be exposed.

c. The glass/ceramic component predicted life shall be greater than the design life with the appropriate life factor applied (section 4.5.2 of this Standard).

4.7.2 Analysis Methods for Annealed Glass

a. One of the methods in sections 4.7.3 or 4.7.4 of this Standard shall be used to verify the life requirement.

b. Other analytical techniques may be used, but NASA Technical Authority approval shall be obtained before implementation.

4.7.3 Use of NASGRO®

The analysis method provided in the NASGRO® computer program is an acceptable method for analysis of vehicle/element glass structure with the following constraints and assumptions:

a. The exponential equation model of flaw growth shall be selected.

b. The length-to-depth ratio of the initial flaw shall be assumed to be ≥20.

The appropriate material critical strength intensity (K_{IC}) in the NASGRO® database may be used, or test-derived K_{IC} in accordance with section 4.7.5 of this Standard may be entered manually into the program.

4.7.4 Flaw Growth Analysis for Annealed Glass

a. The following flaw growth velocity equation shall be used for vehicle/element glass structural life prediction:

$$v = v_0 e^{\beta K_I} \quad \text{(Eq. 1)}$$

where:

v = Flaw growth velocity
v_0 = Material parameter
β = Material parameter
K_I = Stress intensity.

b. v_0 and β in equation 1 shall be determined by test in accordance with ASTM C1368, Standard Test Method for Determination of Slow Crack Growth Parameters of Advanced Ceramics by Constant Stress-Rate Flexural Testing at Ambient Temperature, or ASTM C1576, Standard Test Method for Determination of Slow Crack Growth Parameters of Advanced Ceramics by Constant Stress Flexural Testing (Stress Rupture) at Ambient Temperature, for each material used, in the environment established for windowpane design.

c. The data generated in section 4.7.4.b of this Standard shall be fit to equation 1.

d. The test reports shall be delivered to the NASA Technical Authority as part of the verification package.

e. The following equation for stress intensity shall be applicable for glass structure where the critical flaw depth is small with respect to the thickness of the glass:

$$K_I = 1.1 \cdot \sigma \cdot \left(\frac{\pi a}{Q} \right)^{1/2} \quad \text{(Eq. 2)}$$

where:

K_I = Stress intensity
σ = Stress
a = Flaw depth
Q = Shape factor, Q = 1 for long flaws with respect to depth (length/depth ≥20).

The time to failure of a glass structural element (static fatigue life) is found by:

$$t = \left(\frac{2Q}{1.21 \cdot \pi \sigma^2} \right) \cdot \int_{K_{I_i}}^{K_{IC}} \left(\frac{K_I}{v} \right) dK_I \qquad \text{(Eq. 3)}$$

where:

K_I = Stress intensity
K_{IC} = Critical stress intensity
σ = Stress
Q = Shape factor, Q = 1 for long flaws with respect to depth (length/depth ≥20)
v = Flaw growth velocity.

f. Equation 3 shall be used to establish the static life of a glass or ceramic component.

g. Material parameters for each material used shall be determined by test in the environment established for windowpane design.

h. The equation for K_I (equation 2) shall be appropriate for the configuration that is analyzed.

4.7.5 Material Data Scatter and Average Flaw Growth Properties

a. Each windowpane shall be designed using average flaw growth properties (K_I versus velocity) and four times the required design life to account for scatter in the flaw growth data.

b. The K_{IC} used to determine failure shall be based on the average inert K_{IC} minus three standard deviations of the K_{IC} as determined by analysis of the material test data developed in accordance with ASTM C1421, Standard Test Methods for Determination of Fracture Toughness of Advanced Ceramics at Ambient Temperature, or as provided in NASGRO®.

c. NASA Technical Authority approval shall be obtained for the number of test samples required to establish K_{IC}.

The flaw growth properties contained in NASGRO® may be used, if available.

4.7.6 Total Flaw Depth versus Visible Flaw Depth

Empirical data from glass polishing and handling experience show that an invisible crack tail extends past the visible flaw into the glass to an approximate distance of twice the visible crack depth, making the total effective crack depth three times the visible flaw depth.

a. The total flaw depth shall be assumed to be three times the measured visible flaw depth.

b. All life analyses shall be based on the total flaw depth.

4.7.7 Initial Design Flaw Depth

a. Vehicle/element windowpanes shall be designed by first choosing the limiting flaw depth, i.e., maximum initial design flaw depth.

b. The initial design flaw depth shall be used for the initial fracture and life analysis of all glass or ceramic structural components.

c. The initial design flaw depth shall be limited on the lower bound to 0.0457-mm (0.0018-in) total flaw depth to provide reasonable damage discovery since the windowpanes receive damage during use.

4.7.8 Flaw Shape

Long flaws with respect to the depth (length/depth ≥20) and flaw shape factor Q = 1 shall be assumed for the glass structure life predictions.

4.7.9 Flaw Growth Environment: 100 Percent Moisture

Flaw growth properties assuming 100 percent moisture shall be used for all windowpane life predictions.

4.7.10 Glass or Ceramic Structural Component Stress Distribution

a. The stress distribution in any glass or ceramic structural component shall be determined.

b. The applied stress distribution in the component shall be determined in a manner that considers the actual boundary conditions of the actual pressurized vehicle and includes all significant (>10 percent of total predicted stress) sources of stress in the component.

c. The applied stress distribution shall determine the point of maximum stress on the surface of the component for the maximum combined load case.

4.7.11 Stress Distribution Correlation

The stress distribution across the window surfaces shall be obtained during vehicle testing and correlated to an analytical model with the same load cases applied.

4.7.12 Spring Stiffness

a. Spring stiffness (load versus deflection) shall be determined for all springs and seals and combinations included in the window design.

b. The measured stiffness for the springs and seals shall be used for all analyses and models of the window assembly.

4.7.13 Stress Analysis Requirements and Reports

The stress analysis of the glass or ceramic structural component shall be in accordance with the current best practices for structural design, analysis, and reporting standards and methodologies.

4.7.14 Analysis Methods for Tempered Glass

a. The methodology for flaw growth analysis in tempered glass shall be the same as for annealed glass (section 4.7.2 of this Standard) for any tensile stress on the surface of the pane when loaded, such as during proof testing.

If the total stress at the initial design flaw depth is compressive after combining the temper stresses and the proof tensile stresses, then a flaw growth analysis is not required.

b. Where tempered glass is used in the window design, the pre-compression of each surface of each windowpane shall be measured and recorded.

4.7.15 Temper Layer Preservation

The sum of the measured temper surface stress and two times the applied limit surface tensile stress shall be equal to or less than zero (compressive).

4.8 Safety and Structural Integrity Assurance Requirements

4.8.1 Redundancy

4.8.1.1 Pressure Redundancy

a. All vehicle/element windows that are or can be a part of the crew-inhabiting pressure shell shall have redundant pressure panes.

b. The redundant and pressure panes shall be designed to maintain the vehicle/element internal pressure in the event that either pane fails.

c. The dynamic effects of the primary pane failure on the redundant pane shall be included in the design and analysis of the redundant pane.

d. Subsequent to the pressure pane failure event, the redundant pane shall have sufficient remaining life to prevent a catastrophic or critical failure for the time required to reinstate pressure redundancy.

4.8.1.2 Redundancy Restoration

In the event of a pressure pane failure or loss of the pressure redundancy function, an immediately available alternate means of restoring pressure redundancy shall be provided.

4.8.1.3 Thermal Redundancy

The windows shall maintain pressure integrity in the event of the failure of the primary thermal pane during re-entry.

4.8.2 Material Selection

Material selected for use in the assembly shall meet the requirements of the latest version of NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft.

4.8.3 Failure Propagation

Component or element failures within the window assembly shall not propagate sequentially to other elements of the window system.

4.8.4 Protective Covers

a. Where surface scratching, pitting, or staining cannot be prevented by other means, removable window protective surfaces shall be provided.

b. A non-structural outer pane shall be provided to protect the pressure panes from damage caused by MM/OD impacts.

A mechanical shutter may be provided over the window to meet certain requirements specified by NASA for the vehicle/element.

4.8.5 Containment

Glass and other brittle materials pose several health hazards (ingestion, inhalation) should they fail in a microgravity environment. Additionally, the debris from such a failure poses hazards to mechanical equipment.

Materials that can shatter shall not be used in inhabited compartments unless positive protection is provided to prevent fragments greater than 50 μm (0.0020 in) maximum dimension from entering the cabin environment.

4.8.6 Tempered Glass

Where tempered glass is used in the window design, it shall withstand the types of damages (including impact) that can be incurred in the design environment to preclude hazards from shattering failure (section 4.8.5 of this Standard).

4.9 Manufacturing Requirements

4.9.1 Manufacturing Grinding Schedule

A manufacturing grinding schedule shall be implemented to limit the maximum initial flaw depth to less than or equal to the initial design flaw depth.

Reference NASA-HDBK-6007, Handbook for Recommended Material Removal Processes for Advanced Ceramic Test Specimens and Components.

4.9.2 Proof Test Loading

Past failures have been attributed to failure to proof the pane in a manner consistent with the flight loading condition.

Proof testing shall be performed in a manner consistent with and similar to the significant loading condition expected during the windowpane design life.

4.9.3 Proof Test Stress Distribution

The stress distribution across the pane or glass structure during proof testing shall be equal to or greater than the stress distribution on the pane when installed on the vehicle and subjected to the same applied pressure differential.

4.9.4 Proof Factor for Annealed and Tempered Glass

a. The proof factor shall generate a minimum of three times the stress associated with the maximum combined limit load.

b. The magnitude of the proof factor to screen manufacturing flaws shall be determined by a fracture mechanics analysis based on the structural analysis requirements for windowpanes and glass structure as specified in section 4.7 of this Standard.

c. The proof factor shall be the results of these analyses or 3.0, whichever is higher.

4.9.5 Proof Pressure Verification

If pressure is used to control the proof stress generated in the glass, then:

a. Proof pressures shall be measured during proof test using pressure gages installed in the chambers on both sides of the glass or test plate or by differential gages.

b. The maximum delta pressure achieved on each side shall be documented in the proof test quality records.

4.9.6 Window Drying before Proof Loading

a. Care shall be exercised to remove humidity from the test chamber and encapsulated water from the surface of the glass.

b. To extract moisture from the windowpane surfaces before proof testing, which limits potential flaw growth during the test, the test fixture purge vent dew point shall not be greater than -31 °C (-24 °F) immediately before testing.

4.9.7 Proof Stress Duration

Inherent flaws in glass grow when exposed to tensile loading in the presence of moisture and certain other chemicals.

a. To minimize the reduction in strength related to the growth of flaws, the applied proof stress shall be held for no longer than a 1-sec duration.

b. The duration of the proof pressure shall be documented in the proof test quality records.

4.9.8 Proof Test Unloading Rate

Studies show that flaws inherent in the glass propagate in the presence of load and continue to propagate during the release of the load.

a. To minimize flaw growth during pressure release, means shall be taken to maximize the unloading rate.

b. NASA Technical Authority approval of the test procedure shall be obtained before implementation.

4.9.9 Modulus of Rupture (MOR)

a. Since windowpane edges are extremely difficult to proof test adequately, special finishing techniques like acid etch shall be used.

b. The process shall be certified by MOR tests to demonstrate that the edges are as strong as or stronger than the window surfaces.

4.10 Window Maintenance Design Requirements

4.10.1 Window Servicing

Equipment and supplies that will not degrade the windowpane structural or functional integrity shall be provided for window cleaning on orbit and on the ground.

4.10.2 Window Raghavement

The vehicle/element windows or individual windowpane assemblies shall be designed to be replaced within the normal vehicle/element servicing timeframe during flights/missions or on the ground.

4.10.3 Window Protection during Vehicle Processing

a. Windows shall be protected from damage by covers, except during window processing or inspections.

b. Window protection shall be installed at all other feasible times.

4.10.4 Maintainability/Inspection Requirements

4.10.4.1 Inspection Specification

a. An inspection specification shall be developed.

b. The inspection procedure shall document damage sizes (length, width, depth, and type), damage locations on the window, and date of discovery.

c. The inspection process shall detect visible flaws that are at least 0.015 mm (0.0006 in) deep, giving a total flaw depth of 0.046 mm (0.0018 in), as defined in section 4.7.7 of this Standard, unless other verified and approved methods are used to identify flaws that have potential to affect pane structural integrity.

d. NASA Technical Authority approval shall be obtained before implementation of the inspection specification.

4.10.4.2 Inspection Frequency

As a minimum, surfaces shall be inspected for surface flaws before integration into retainers or frames, before and following integration into the vehicle, before customer delivery, and immediately before each flight.

4.10.4.3 Inspection Method Reliability

The inspection method shall be capable of detecting flaws that are equal to and larger than the initial design flaw depth.

4.10.4.4 In Situ Inspections

If specific conditions, e.g., edge lighting, are required for reliable inspections, a means of providing the appropriate conditions in situ (while the window is installed in the vehicle) shall be designed.

4.10.5 Flaws Subsequent to Proof Test

4.10.5.1 Flaw Detection Following Proof Test

All surface flaws that may have occurred subsequent to the proof test and that exceed the initial design flaw depth shall be identified, mapped, and assessed using the fracture mechanics methodology outlined in this document and sections 4.7 and 4.4.1.a or 4.4.2 of this Standard, as applicable.

A minimum requirement for flaw detection inspection interval is provided in section 4.10.4.2 of this Standard.

4.10.5.2 Visible Flaw Depth Measurement

The depth of all visible flaws exceeding the initial design flaw size shall be measured and recorded on a map of each windowpane surface during every inspection following the proof test.

4.11 Non-Structural Glass

Non-structural glass shall sustain the stresses caused by thermal gradients, induced displacements from boundary conditions, crew impact loads (inadvertent and intentional), and loading necessary to support its own weight under the various dynamic and quasi-static load environments of a mission.

4.11.1 Requirements Applicable to Non-Structural Glass

The following requirements, as defined in this Standard, shall be applicable to non-structural glass components:

4.3.3	Inadvertent Contact
4.3.4	Impact Hazards to Glass and Ceramic Structures and Components
4.3.9	Combined Loads
4.4.1	Minimum Factor of Safety for Annealed Glass
4.4.2	Minimum Factor of Safety for Tempered Glass
4.5.4	Induced/Residual Stresses
4.6.1	Strength Degradation Caused by Coatings
4.8.2	Material Selection
4.8.5	Containment
4.8.6	Tempered Glass
4.12	Requirements for Windowpanes, Glass, and Ceramic Structure for which a Proof Test is not Feasible

Other requirements may be applicable as determined by the NASA Technical Authority based on the specific application, design, or hazards presented by the glass or ceramic component.

4.11.2 Hazard Control of Non-Structural Glass

Non-structural glass or ceramic component designs shall prevent the release of shattered materials into human habitats when exposed to expected design loads, events (including impacts), or stresses.

4.11.3 NASA Approval of Design and Verification Methods

NASA Technical Authority approval shall be obtained for all design methods and verifications for non-structural glass and ceramics before implementation.

4.12 Requirements for Windowpanes, Glass, and Ceramic Structure for which a Proof Test is not Feasible

NASA Technical Authority approval shall be obtained before implementation (manufacture) of design for any glass, ceramic, or window verification methodology that does not include a proof test for all structural glass or ceramic components.

5. VERIFICATIONS

5.1 Introduction

5.2 Planning and Reporting

a. Verification shall be by inspection and approval of the GCVP.

The vehicle/element prime contractor has the responsibility for demonstrating that each design requirement in section 4 of this Standard has been met by verification in accordance with section 5 of this Standard and for submitting evidence via test reports and analyses.

b. Verification of the GCVP shall be by inspection of the report and demonstration that it is in compliance with Appendix A of this Standard.

Analysis or qualification test data from previously verified designs can be used, if appropriate.

NASA reserves the right to witness any verification testing (qualification or acceptance).

c. Verification of the GCVP shall be by NASA Technical Authority approval letter.

d. Verification of the GCVR shall be by analysis and inspection of the GCVR.

e. While the GCVR may be submitted in discrete sections as verifications are completed, the sum of all sections shall include verification of all requirements.

5.3 Environments and Loads

5.3.1 Applied Environments

Requirement 4.3.1 shall be verified by qualification test and analysis.

The responsible organization is accountable to the NASA Technical Authority for the delivery of a copy of the glass acceptance data package (ADP) for each hardware item; an analysis report demonstrating positive margins of safety on strength and life for all environments for each unique window, component, and configuration; and engineering test reports documenting successful completion of the qualification test program.

5.3.2 Window Inter-pane Purging and Venting

Pressures during purging and venting shall be verified by qualification test and analysis.

5.3.3 Inadvertent Contact

Requirement 4.3.3 shall be verified by acceptance test and/or analysis.

5.3.4 Impact Hazards to Glass and Ceramic Structures and Components

a. Requirement 4.3.4.a shall be verified by qualification test and/or analysis.

b. If the component design permits contact with the brittle material's surface, a special analysis shall be performed to assess this event.

See "Strength Degradation of Glass Impacted with Sharp Particles," S. M. Wiederhorn and B. R. Lawn, Journal of the American Ceramic Society, 1979.

Testing that replicates the impact event may also be performed to demonstrate a non–hazardous failure mode, i.e., a mode that does not generate glass pieces greater than 50 µm (0.0020 in).

c. Requirement 4.3.4.b shall be verified by inspection of the analysis reports.

d. Requirement 4.3.4.c shall be verified by hazard analysis and inspection of appropriate documentation of controls.

5.3.5 Impact Damage Tolerance Verification for Structural Glass

a. The structural integrity of the damaged structural glass or ceramic shall be verified by a combination of qualification test and analysis.

b. Requirement 4.3.5.b shall be verified by analysis.

c. Requirement 4.3.5.c shall be verified by analysis and/or test.

5.3.6 Glass-to-Metal Contact

a. It shall be demonstrated by qualification test that glass-to-metal contact does not occur during the worst-case vibration environments.

b. It shall be demonstrated by qualification test that glass-to-metal contact does not occur at two times maximum combined limit load.

c. Pressure shell deflections shall be included in the qualification test described in section 5.3.6.b of this Standard.

This may be accomplished by an ultimate pressure test of the pressure shell with glass windows installed.

5.3.7 Glass Slipping and Rattling

It shall be demonstrated by qualification test and/or analysis that pane slipping or rattling does not occur during the worst-case vibration environments.

5.3.8 Glass Pane-to-Seal (or Cushion) Interface

The function of the glass pane-to-seal (or cushion) interface and material properties shall be verified by qualification test of flight-like configurations over the predicted temperature extremes of the glass pane/seal interface.

Glass interfaces that will experience predicted temperature extremes between 0 to 38 °C (32 to 100 °F) only may be exempt from this test requirement.

5.3.9 Combined Loads

Requirement 4.3.9 shall be verified by qualification test and analysis.

5.3.10 Inner and Outer Surfaces

a. Both the inner and outer surfaces of each windowpane or glass structure shall be subject to an acceptance proof test in accordance with section 4.9 of this Standard to screen flaws greater than the maximum initial design flaw.

b. Verification shall be by inspection of the ADP documenting the proof test.

5.4 Design Factors

5.4.1 Minimum Factor of Safety for Annealed Glass

Requirement 4.4.1 shall be verified by a combination of acceptance test and analysis.

5.4.2 Minimum Factor of Safety for Tempered Glass

Requirement 4.4.2 shall be verified by a combination of acceptance test and analysis.

5.4.3 Dynamic Amplification Factor

a. Requirements 4.4.3.a and 4.4.3.b shall be verified by analysis.

b. If a test is performed to measure a specific dynamic amplification factor, an engineering test report shall be delivered to the NASA Technical Authority.

c. The amplification factor shall be verified by inspection of the engineering report and the analysis.

5.4.4 Dynamic Factor of Safety

Requirements 4.4.4.a, 4.4.4.b, and 4.4.4.c shall be verified by analysis that shows all margins of safety are 0.0 or above, considering the maximum combined loads.

5.5 Window Life

5.5.1 Uncertainty Factor on Stress for Flaw Growth Analysis

Requirement 4.5.1 shall be verified by analysis.

5.5.2 Life Factor

Requirement 4.5.2 shall be met by analysis and verified by inspection of the analysis.

5.5.3 Assembly Life

The final flight configuration assembly shall undergo a life test that includes the life factor specified in section 4.5.2 of this Standard to show that the assembly does not cause damage to the glass or deterioration of the sealing capabilities over the projected life of the hardware.

This test may be conducted as a fleet leader.

5.5.4 Induced Residual Stresses

Verification to demonstrate that the window assembly design prevents potential sources of strength degradation caused by induced residual stresses or local stress concentrators shall be by test on an acceptance basis.

5.6 Window Coating Requirements

5.6.1 Strength Degradation Caused by Coatings

a. The strength effects of chosen coatings on glass shall be verified by a statistical testing of samples, which has been approved by the NASA Technical Authority and which includes conditions simulating the expected design environmental conditions, i.e., pressure loads, thermal loads, shock, cycling.

b. If degradation is indicated, each coated pane shall be appropriately subjected to an acceptance proof test to ensure the degradation does not cause a critical loss of strength or function over the design life of the component.

5.6.2 Coated Windowpane Structural Integrity

Verification of windowpane coatings location shall be accomplished by qualification test, analysis, and inspection of the installation drawings.

5.6.3 Windowpane Coatings for Infrared and Ultraviolet Photography or Sensing

The specific window coating configuration for IR and UV photography and sensing shall be verified by qualification test, analysis, and inspection of the installation drawings.

5.7 Structural Analysis Requirements

5.7.1 Structural Analysis Requirements for Windowpanes, Glass, and Ceramic Structure

a. The glass analysis using fracture mechanics technology shall be verified by inspection of the analysis.

b. Verification of the load events considered shall be documented by analysis.

c. The vehicle/element structural life verification for the glass pane area shall be based on analysis of the flaws screened by the proof test and an understanding of the flaw growth process.

5.7.2 Analysis Methods for Annealed Glass

a. Verification of life analysis method shall be by inspection of the analysis.

b. A NASA Technical Authority approval letter shall be the verification of the alternate analysis technique employed.

5.7.3 Use of NASGRO®

Requirements 4.7.3.a and 4.7.3.b shall be verified by analysis.

5.7.4 Flaw Growth Analysis for Annealed Glass

a. Verification of proper velocity equation shall be by inspection of analysis.

b. Verification of equation 1 parameters shall be by test.

c. Verification of data fit (section 4.7.4.c of this Standard) shall be by analysis.

d. Verification of section 4.7.4.d of this Standard shall be by inspection of the test reports.

e. Verification of section 4.7.4.e of this Standard shall be by inspection of analysis.

f. Verification that equation 3 has been applied to compute static fatigue life shall be by analysis.

g. A statistically significant sample test process, approved by the NASA Technical Authority, shall establish material flaw growth parameters.

h. The equation for K_I (equation 2) shall be verified by inspection of the analysis.

5.7.5 Material Data Scatter and Average Flaw Growth Properties

a. Requirement 4.7.5.a shall be verified by the life analysis and by inspection of the analysis to demonstrate the proper selection of material properties.

b. Requirement 4.7.5.b shall be verified by inspection of the material test data and analysis.

c. Verification of requirement 4.7.5.c shall be by NASA Technical Authority approval letter.

5. 7.6 Total Flaw Depth versus Visible Flaw Depth

Requirements 4.7.6.a and 4.7.6.b shall be verified by analysis and inspection of the analysis.

5.7.7 Initial Design Flaw Depth

a. Requirement 4.7.7.a shall be verified by analysis, by inspection of the windowpane drawings, and by proof test to screen flaws that are greater than the initial design flaw depth.

b. Requirement 4.7.7.b shall be verified by analysis.

c. The initial flaw depth screened by the proof test shall be based on the average inert K_{IC} plus one standard deviation.

d. The magnitude of the proof factor shall be based on a fracture mechanics analysis to assure the required design life.

e. Requirement 4.7.7.c shall be verified by inspection, test, and analysis.

5.7.8 Flaw Shape

Requirement 4.7.8 shall be met by analysis and verified by inspection of the assessment.

5.7.9 Flaw Growth Environment: 100 Percent Moisture

Requirement 4.7.9 shall be verified by analysis.

5.7.10 Glass or Ceramic Structural Component Stress Distribution

a. Qualification testing shall provide sufficient strain data to demonstrate a good understanding of the stress distribution across the glass or ceramic component.

b. The applied stress distribution in the windowpane or glass structure shall be verified by detailed qualification test that includes the actual boundary conditions of the actual pressurized module and all significant sources of stress.

c. Qualification testing shall locate the point of maximum stress on the surface of the window for the maximum combined load case.

5.7.11 Stress Distribution Correlation

a. Requirement 4.7.11 shall be verified by a combination of qualification test and analysis.

b. Correlation shall be defined as model prediction results that are within ±10 percent of the test results for specific tested load conditions and hardware configurations.

c. If correlation cannot be achieved, NASA Technical Authority approval of the verification model shall be obtained.

5.7.12 Spring Stiffness

a. Spring stiffness shall be verified by qualification test.

b. Requirement 4.7.12.b shall be verified by inspection of the analysis and models.

5.7.13 Stress Analysis Requirements and Reports

Requirement 4.7.13 shall be verified by inspection of the analysis report.

5.7.14 Analysis Methods for Tempered Glass

a. Verification of requirement 4.7.14.a shall be by analysis

b. Verification of requirement 4.7.14.b shall be by examination of the ADP.

5.7.15 Temper Layer Preservation

Requirement 4.7.15 shall be verified by measurement of the temper compression layer and analysis.

5.8 Safety and Structural Integrity Assurance Requirements

5.8.1 Redundancy

5.8.1.1 Pressure Redundancy

The requirements listed in section 4.8.1.1 of this Standard shall be verified by a combination of qualification tests, analyses, and inspections.

5.8.1.2 Redundancy Restoration

Requirement 4.8.1.2 shall be verified by qualification test.

5.8.1.3 Thermal Redundancy

Requirement 4.8.1.3 shall be verified by a combination of qualification test, analysis, and inspection.

5.8.2 Material Selection

Requirement 4.8.2 shall be verified by inspection of the window engineering drawings and specifications.

5.8.3 Failure Propagation

Requirement 4.8.3 shall be verified by a combination of qualification test, analysis, and inspection of the engineering drawings.

5.8.4 Protective Covers

The requirements listed in section 4.8.4 of this Standard shall be verified by test, analysis, and inspection of design.

5.8.5 Containment

Requirement 4.8.5 shall be verified by a combination of qualification test, analysis, and inspection of the engineering drawings.

5.8.6 Tempered Glass

a. Where tempered glass is used in the window design, it shall be demonstrated by qualification test that the glass can withstand the types of damages that can be incurred in the design environment without a failure.

b. Tempered glass that is contained shall demonstrate positive containment by test.

5.9 Manufacturing Requirements

5.9.1 Manufacturing Grinding Schedule

Requirement 4.9.1 shall be verified by inspection of the manufacturing grinding schedule provided as part of the ADP and by a proof test to screen flaws that are greater than the initial design flaw depth.

5.9.2 Proof Test Loading

Verification that the pane proof loading is consistent with the expected significant loading condition shall be by inspection of the proof test plan and the predicted loading analysis for the window in the vehicle.

5.9.3 Proof Test Stress Distribution

Requirement 4.9.3 shall be verified by test and analysis.

The intent of this requirement is to ensure that the minimum required proof factor is achieved over the entire area of the glass. The appropriate NASA program and Technical Authorities may opt to allow the intent of the stress distribution requirement to be met in lieu of the literal interpretation.

5.9.4 Proof Factor for Annealed and Tempered Glass

Requirements listed in section 4.9.4 of this Standard shall be verified by test and analysis.

5.9.5 Proof Pressure Verification

a. Requirement 4.9.5.a shall be verified by inspection of proof pressure test procedures.

b. Maximum delta pressure achieved shall be verified by inspection of the ADP.

5.9.6 Window Drying before Proof Loading

a. Verification for the removal of humidity from the test chamber and encapsulated water from the surface of the glass shall be by test and the results recorded in the test quality records and provided in the ADP.

b. Requirement 4.9.6.b shall be verified by inspection of proof test procedures and quality records.

5.9.7 Proof Stress Duration

a. Requirement 4.9.7.a shall be verified by test and inspection of acceptance test procedures.

b. Quality records shall be verified by inspection.

5.9.8 Proof Test Unloading Rate

a. Requirement 4.9.8.a shall be verified by inspection of the acceptance test procedures and the ADP to ensure that:

(1) The time to apply, hold, and drop the proof test pressure/load has been limited to the minimum practical time to accomplish the proof test.

(2) Special care has been taken to assure that the unloading rate is the maximum that is practical.

b. A NASA Technical Authority approval letter shall verify prior approval for requirement 4.9.8.b.

5.9.9 Modulus of Rupture (MOR)

a. The MOR shall be verified by test in an inert environment.

b. A minimum of three MOR bars shall pass to demonstrate edge viability.

c. MOR bars shall be processed with the parent pane and have the same processes applied to the edges and surfaces.

5.10 Window Maintenance Design Requirements

5.10.1 Window Servicing

Requirement 4.10.1 shall be verified by tests, analyses, and inspections of the equipment and supplies.

5.10.2 Window Raghavement

Requirement 4.10.2 shall be verified by timed demonstration (test) on flight-like hardware and in the proper vehicular configuration.

5.10.3 Window Protection during Vehicle Processing

Requirement 4.10.3 shall be verified by inspection of processing procedures and Quality Control records.

5.10.4 Maintainability/Inspection Requirements

5.10.4.1 Inspection Specification

Verification of the inspection process shall be by inspection of the inspection specification and NASA Technical Authority approval letter.

5.10.4.2 Inspection Frequency

Verification shall be by the inspection of the processing procedures, window inspection specification, build documentation, and Quality Control records.

5.10.4.3 Inspection Method Reliability

The probability of detection for the inspection method(s) shall be determined through testing and analysis techniques.

5.10.4.4 In Situ Inspections

Requirement 4.10.4.4 shall be verified by inspection of the design and test of the in situ inspection process.

5.10.5 Flaws Subsequent to Proof Test

5.10.5.1 Flaw Detection Following Proof Test

a. Verification of requirement 4.10.5.1 shall be through inspection of ADP maps of the window surfaces and analysis of any flaws detected after the acceptance proof test.

b. An initial map of all surface defects shall be provided as part of the ADP of the windowpane, glass, or ceramic structure.

c. The maps shall be maintained and updated to support future evaluations of the windowpanes.

d. Each window inspection event and findings shall be recorded and dated on each map.

e. Analytical assessment of discovered flaws shall be verified by inspection of the analysis that demonstrates positive margins of safety for all design conditions and design life.

5.10.5.2 Visible Flaw Depth Measurement

Requirement 4.10.5.2 shall be verified by inspection of the window ADP.

5.11 Non-Structural Glass

Requirement 4.11 shall be verified by analysis and testing.

5.11.1 Requirements Applicable to Non-Structural Glass

Verifications for the requirements listed in section 4.11.1 of this Standard shall be applied in accordance with the applicable verification paragraph for those requirements.

5.11.2 Hazard Control of Non-Structural Glass

Verification of requirement 4.11.2 shall be by inspection of drawings, analysis, and/or qualification test of the flight design.

5.11.3 NASA Approval of Design and Verification Methods

Verification shall be by NASA Technical Authority approval letter accepting the proposed methodologies.

5.12 Requirements for Windowpanes, Glass, and Ceramic Structure for which a Proof Test is not Feasible

Requirement 4.12 shall be verified by NASA Technical Authority approval letter accepting the design and verification plan.

APPENDIX A

DATA ITEM DESCRIPTIONS

A.1 Purpose and/or Scope

The purpose of this appendix is to present requirements for Data Item Descriptions.

A.2 Data Item Description (DID) 1: Glass and Ceramics Verification Plan (GCVP)

Purpose:
The GCVP describes the tests and analyses to be performed by the contractor and the verification criteria that the tests and analyses results are to meet in order to satisfy the glass and ceramics requirements. The GCVP provides the means for the NASA Technical Authority to evaluate and judge the acceptability of the contractor-proposed glass and ceramic verification program.

Use/Relationships:
This DID contains the format and content preparation instructions for that data generated under the work described by section 4 of NASA-STD-5018, Strength Design and Verification Criteria for Glass, Ceramics, and Windows in Human Space Flight Applications.

The data item is applicable to the vehicle/element glass and windows that require verification in accordance with contractual requirements. When subsystems or components are procured individually, the applicable sections of the GCVP should be used.

The GCVP should contain as much detail as is practicable commensurate with the state of program development at the time the GCVP is prepared. Each requirement in this document shall be specifically addressed by the GCVP. The GCVP should be continually updated as necessary to maintain an accurate description of the required tasks necessary to meet the requirements of section 4 of NASA-STD-5018.

Preparation Instructions:
<u>Content</u>: The GCVP shall include the test and analyses data and methods to be used, as well as the pass/fail definitions for each subsystem/component to verify glass and ceramics designs for those designated as Catastrophic or Critical.

The plan shall contain the following elements as a minimum:

a. Applicable documents.
b. Objectives and requirements fulfillment.
c. Description of test articles.
d. Pass/fail criteria.
e. Test hardware definition.

f. Pertinent test/analysis details.
g. Set-up details.
h. Test schedule.

Format: The GCVP format shall be contractor selected. Unless effective presentation would be degraded, the initially used format arrangement shall be used for all subsequent submissions.

A.3 DID 2: Glass and Ceramics Verification Report (GCVR)

Purpose:
The GCVR presents the results of analyses, tests, and other data needed to verify the adequacy of glass and ceramics designs for all systems, subsystems, and/or components whose failure is designated as Catastrophic or Critical. The GCVR provides the means for the NASA Technical Authority to evaluate and judge the acceptability of the contractor's glass and ceramics designs and hardware.

Use/Relationships:
This DID contains the format and content preparation instructions for that data generated under the work described by section 4 and verified in section 5 of NASA-STD-5018.

The data item is applicable to the vehicle, subsystem, or component for which a GCVP has been prepared as a result of a contractual requirement.

Preparation Instructions:
General: The GCVR shall include analyses, test, and/or data used to verify glass and ceramics designs for all systems, subsystems, and/or components whose failure is designated as Catastrophic or Critical. The GCVR shall specifically address each requirement contained in this document, and address appropriate sections in the GCVP in both format and content.

Content: The report shall contain the following elements as a minimum:

a. Description and photographs of test setup.
b. Date, personnel performing test, and location of test.
c. Test environments used.
d. Test measurement records.
e. Test results.
f. Statement of qualification.
g. Requirements fulfillment.

Format: The GCVR format shall be contractor selected and reflect the GCVP format. Unless effective presentation would be degraded, the initially used format arrangement shall be used for all subsequent submissions.

APPENDIX B

REFERENCE DOCUMENTS

B.1 Purpose and/or Scope

The purpose of this appendix is to provide guidance through information in the reference documents listed below.

B.2. Government Documents

NASA-HDBK-6007	Handbook for Recommended Material Removal Processes for Advanced Ceramic Test Specimens and Components
NASGRO®	Fatigue Crack Growth Computer Program

B.3 Non-Government Documents

Wiederhorn, S.M.; Lawn, B.R. (1979). "Strength Degradation of Glass Impacted with Sharp Particles," Journal of the American Ceramic Society.