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BASELINE

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OPTICAL PROPERTY REQUIREMENTS FOR GLASSES, CERAMICS AND PLASTICS IN SPACECRAFT WINDOW SYSTEMS

REVISION AND HISTORY PAGE

Status	Revision No.	Change No.	Description	Release Date
Baseline	-		Initial release	12/14/11

NOTE: Updates to this document, as released by numbered changes (Change XXX), are identified by a black bar on the right margin.

FORWARD

This is a preliminary draft of a standard published by the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) that is intended to provide uniform window optical design requirements in support of the development of human-rated spaceflight hardware. The material covered in this standard is based on data from extensive testing by the Advanced Sensing and Optical Measurement Branch at NASA Langley Research Center, and compiled into requirements format by the NASA JSC Structural Engineering Division. At the time of this initial document release, a broader technical community has not reviewed this standard.

The technical content of this standard is primarily based on the Constellation Program Orion Crew Exploration Vehicle Window Optical Properties Requirements, CxP 72407, Baseline. Unlike other optical requirements documents available for human rated spacecraft, this document includes requirements that ensure functionality for windows that contain glass/ceramic and/or plastic window substrate materials. These requirements were derived by measuring the optical properties of fused silica and aluminosilicate glass window assemblies and ensuring that the performance of any window assembly that includes a plastic pane or panes will meet the performance level of the all-glass assemblies. The resulting requirements are based upon the performance and parameter metrology testing of a variety of materials, including glass, transparent ceramics, acrylics, and polycarbonates. In general, these requirements are minimum specifications for each optical parameter in order to achieve the function specified for each functional category, A through D.

Because acrylic materials perform at a higher level than polycarbonates in the optics regime, and CxP/Orion is planning to use acrylic in the Orion spacecraft, these requirements are based heavily on metrology from that material. As a result, two of the current Category D requirements for plastics are cited in such a way that will result in the screening out of polycarbonates. It is acknowledged that many polycarbonates can perform the functions of Category D, such as piloting and imagery with lens with apertures up to 25mm, without performance issues. Therefore, this forward warns users that certain requirements, such as birefringence and wavefront, for Category D plastics need to be revised to allow those polycarbonates that perform adequately in Category D to be accepted, while at the same time, screen out those materials that do not perform up to par. At the time of document release, the requirements in question have been identified by a “TBD” beside the proposed requirement criteria (which is based upon acrylic performance). Vehicles that are designed with acrylic materials for windowpanes are encouraged to use the values presented in this document for all requirements, in order to ensure adequate optical performance.

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1.0 INTRODUCTION

1.1 PURPOSE

This document defines the optical performance requirements for the various spacecraft windows depending on the intended functionality of the window.

The following definitions differentiate between requirements and other statements:

Shall is the only verb used for the binding requirements.

Will is used for stating facts or declaration of purpose.

Should or **May** are used for stating non-mandatory goals.

Strength and structural design requirements for brittle materials are given in JSC-62550, Strength, Design, and Verification Criteria for Glass, Ceramics, and Windows in Human Space Flight Applications. Strength and structural design requirements for non-brittle materials should be determined through the applicable program documentation.

Note that the requirements of this document pertain to windows at delivery and do not apply over the life of the window unless specified otherwise.

1.2 SCOPE

Architectural elements for crewed spacecraft include several different types of spacecraft, modules, landers, transfer vehicles and habitats. Each of these elements will contain windows that the crew will use for various tasks. It is important that the optical and mechanical properties of the windows be not only well understood but also clearly specified through the use of detailed performance requirements.

1.3 WINDOW MATERIAL DEFINITIONS

Unless otherwise specified, in the functional performance requirements to follow, the term glass will refer to fused silica, borosilicate, aluminosilicate, ceramics and similar brittle window materials. The term plastic will refer to plastic, acrylic, polymer, and similar non-brittle window materials.

1.4 CHANGE AUTHORITY/RESPONSIBILITY

NASA JSC Structural Engineering Division has change authority over this document.

The appropriate NASA Office of Primary Responsibility (OPR) identified for this document is the Research and Technology Directorate, Advanced Sensing and Optical Measurement Branch at the NASA Langley Research Center.

2.0 DOCUMENTS

2.1 APPLICABLE DOCUMENTS

The following documents include specifications, models, standards, guidelines, handbooks, and other special publications. The documents listed in this paragraph are applicable to the extent specified herein.

ASTM-D1003	Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics
ASTM-F733	Standard Practice for Optical Distortion and Deviation of Transparent Parts Using the Double-Exposure Method

2.2 REFERENCE DOCUMENTS

The following documents contain supplemental information to guide the user in the application of this document.

ASTM-D1925	Test Method for Yellowness Index of Plastics
JSC-62550	Strength Design and Verification Criteria for Glass, Ceramics, and Windows in Human Space Flight Applications
MC-332-0006	Specification for Window Panes, Space Shuttle Orbiter
SSP 50005	International Space Station Flight Crew Integration Standard

2.3 ORDER OF PRECEDENCE

In the event of a conflict between the text of this specification and an applicable document cited herein, the text of this specification takes precedence unless it conflicts with requirements on structural integrity or safety, then those requirements take precedence over this document. All specifications, standards, exhibits, drawings or other documents invoked as "applicable" in this specification are as cited. All other documents to which an applicable document refers are for reference, guidance, and information only unless otherwise specified herein.

3.0 OPTICAL REQUIREMENTS

The number, size, shape, location, and orientation of windows should support one or more of the following tasks without visual or image degradation:

a. Normal and contingency piloting tasks

b. External observation and inspection

c. Photography

d. Motion imagery

e. Crew psychological support and welfare

3.1 PLANNING AND REPORTING

a. The vehicle/element prime contractor shall be responsible for demonstrating that each optical requirement has been met to the satisfaction of the appropriate NASA authority.

b. The vehicle/element prime contractor shall deliver an optical requirements verification plan (ORVP), subject to customer approval, delineating the procedures and processes to be used in meeting the requirements of this document.

    1. The ORVP shall include the test/analysis data and methods to be employed as well as test success criteria for each optical test to be performed.

    2. The data requirements for the ORVP shall be in accordance with the data item description in Appendix B, Data Item Descriptions.

    3. NASA approval of the ORVP shall be obtained prior to implementation of the plan. Modifications to the plan in progress may be made with prior NASA approval.

c. The contractor shall prepare and deliver an optical requirements verification report (ORVR) describing methodologies, processes, procedures, analyses, and test results used to show compliance with each explicit requirement contained in this document.

    1. The data requirements for the ORVR shall be in accordance with the data item description in Appendix B.

    2. NASA reserves the right to perform independent optical testing of window samples to verify the accuracy of the contractor data provided in the ORVR.

3.2 WINDOW CATEGORIES

Optical performance requirements will be selected based on a functional category of the window in which the pane material is to be used. These categories are specified as follows:

Category A: Custom Optical Window Ports: Window ports based on customer-unique requirements and developed on a case-by-case basis.

Note: For windows that will be utilized for observations in the ultraviolet and mid- and long-wave infrared wavelengths, additional transmittance specifications will be required to allow passage of these wavelengths. For specialized lasers, window users must provide customized optical requirements such that the window is compatible with their particular device. It is recommended that customers with unique window optical requirements start with those specified for category B or D windows and tailor them according to their functional needs.

Category B: Long Focal Length Photography and Piloting Window Ports: Windows with a minimum clear viewing area equal to that of a circle 40 cm in diameter to support piloting tasks and psychological support. These windows also support higher definition motion imagery and higher resolution photography than Categories C and D, including cameras utilizing lenses with apertures up to 150 mm diameter (generally lenses with focal lengths of 400 mm and greater), and all tasks listed in Categories C and D.

Category C: General Photography and Piloting Window Ports : Window ports with a minimum clear viewing area equal to that of a circle 30 cm in diameter to support motion imaging, general photography, including cameras utilizing lenses with apertures less than 50 mm in diameter (generally lenses with focal lengths of less than 180 mm), and all tasks included in Category D.

Category D: Point & Shoot Photography and Piloting Window Ports: Window ports with a minimum clear viewing area equal to that of a circle 20 cm in diameter to support piloting and robotic tasks, psychological support, limited photography and motion imaging, including cameras utilizing lenses with apertures up to 25 mm in diameter (generally lenses with focal lengths of less than 100 mm), short term crew viewing (to view into a closed module through a hatch door or to view the Earth during exercise with protective covers in place), and long term crew viewing.

Each window category supports a particular set of optical instruments and observation tasks. Table 3-1, Window Port Categories Versus Instrument/Tasks Supported, presents the instruments and tasks that each category supports.

TABLE 3-1 WINDOW PORT CATEGORIES VERSUS INSTRUMENT/TASKS SUPPORTED

Window Port Category vs. Instrument/Task Supported	Supported Instrument or Task	Custom Window (A)	Long Focal Length Photography and Piloting Window (B)	General Photography and Piloting Window (C)	Point and Shoot Photography and Piloting Window (D)
Lenses on Visible & Near IR Instruments, Telescopes, Cameras & Photographic Equipment	Up to a 200mm diameter aperture (400 mm lens @f/2.8), Spectrometers, & Telescopes	√	√(2)		
	Up to a 150 mm diameter aperture (400 mm lens@f/2.8)		√		
	Up to a 50 mm diameter aperture (180 mm lens@ f/2.8)		√	√	
	Up to a 25 mm diameter aperture (100 mm lens@ f/4)		√	√	√
Visual Quality	Piloting & robotic operations		√	√	√
	Long Term Crew viewing(1)		√	√	√
	Short Term Crew Viewing and Psychological Support(1)		√	√	√
Other Instruments	Higher Definition Motion Imagers	√	√(2)		
	Laser and Infrared Ranging Devices	√	√(2)		

Note 1: Long-term crew viewing is defined as greater than 30 minutes in duration. Short-term crew viewing is defined as 30 minutes or less in duration.

Note 2: Category B requirements may suffice for this use. Users should review category B requirements to ensure they meet the requirements for their instrument functionality. Windows intended to support such devices may need tailored requirements.

3.3 WINDOW CLEAR VIEWING APERTURES

In order to support the activities planned for window use, the minimum clear viewing aperture for windows should conform to the specifications in Table 3-2, Clear Viewing Apertures for Windows.

TABLE 3-2 CLEAR VIEWING APERTURES FOR WINDOWS

Window Category	Minimum Clear Viewing Aperture
A	Not applicable
B	40 cm
C	30 cm
D	20 cm

3.4 MULTIPURPOSE WINDOWS

Windows used for multiple purposes shall meet the requirements for the highest category of use.

3.5 WINDOW OPTICAL REQUIREMENTS

Unless otherwise specified, the following requirements apply to all window categories. It is not intended that the requirements in this section be verified under flight loads, pressure loads, and temperature gradients.

3.5.1 Finished Window Performance

Requirements stated in this section shall be met after all optical coatings have been applied and, if applicable, after all tempering and laminating steps have been completed.

3.5.2 Striae

Windowpanes shall contain no visible striae, streaks or cords.

3.5.3 Allowable Defects

3.5.3.1 Open Inclusions in Glass and Category B Plastic

For all glass and category B plastic windowpanes, the maximum number of open inclusions per surface shall not exceed three. Individual open inclusions shall not exceed 0.51 millimeters (0.020 inch) in diameter. Open inclusions separated by less than 2.0 inches are not permitted. Open inclusions equal to or less than 0.08 millimeters (0.00315 inch) in diameter will be disregarded.

3.5.3.2 Allowable Optical Defects in Category D Plastic

For category D plastic windowpanes, the window shall contain no optical defects, such as embedded particles, bubbles, scratches, or imperfections that reduce visibility through the sheet by causing an angular deviation of more than 5 minutes within a distance of no more than 50 cm. The plastic/polymer pane shall contain no surface irregularities that cause angular deviations that are greater than the limits specified in Table 3-3, Angular Deviation Limits for Non-Glass Windows. Requirements for category C plastic panes are reserved.

TABLE 3-3 ANGULAR DEVIATION LIMITS FOR NON-GLASS WINDOWS

Window Thickness	Maximum Angular Deviation
0.15 – 0.56 cm (0.060 – 0.220 inch)	7 minutes at any location within the central 80% of the clear viewing aperture
>0.56 – 0.64 cm (>0.220 - 0.250 inch)	7 minutes at any location within the central 60% of the clear viewing aperture and 9 minutes at any location in the area between 60% and 80% of the clear viewing aperture
>0.64 – 0.95 cm (>0.250 - 0.375 inch)	7 minutes at any location within the central 60% of the clear viewing aperture and 12 minutes at any location in the area between 60% and 80% of the clear viewing aperture
>0.95 – 1.3 cm (>0.375 - 0.500 inch)	7 minutes at any location within the central 60% of the clear viewing aperture and 14 minutes at any location in the area between 60% and 80% of the clear viewing aperture
>1.3 cm – 2.5 cm (>0.5 – 1.0 inch)	12 minutes at any location within the central 60% of the clear viewing aperture and 20 minutes at any location in the area between 60% and 80% of the clear viewing aperture

3.5.4 Haze

3.5.4.1 All Glass and Category B Plastic Panes

For all glass and category B plastic windowpanes, the transmission haze after all coatings have been applied shall be less than 0.5 percent.

3.5.4.2 Category D Plastic Panes

For category D plastic windowpanes, the transmission haze after all coatings have been applied shall be less than 3 percent. Requirements for category C plastic panes are reserved.

3.5.5 Parallelism

3.5.5.1 Window Panes Mounted in Common Structure

Each surface of a multi-element window shall be within 0.2 degrees minimum and 1.5 degrees maximum of being parallel to all other element surfaces when windowpanes are mounted in a common structure.

3.5.5.2 Window Panes Mounted in Separate Structures

The parallelism specification does not apply to windowpanes mounted in separate structures; however, efforts should be made to keep the panes within the specifications of parallelism cited in paragraph 3.5.5.1.

3.5.6 Wedge

3.5.6.1 All Glass Panes

For glass, the wedge of any individual windowpane shall be less than or equal to 5 arc minutes in any direction.

3.5.6.2 All Plastic Panes

For plastic, the wedge of any individual windowpane shall meet the specifications in Table 3-4, Wedge Requirements for Plastic Windows.

TABLE 3-4 WEDGE REQUIREMENTS FOR PLASTIC WINDOWS

Category	Wedge
A	Not applicable
B	≤ 11 arc minutes in any direction
C	≤ 13 arc minute in any direction
D	≤ 15 arc minutes in any direction

3.5.7 Birefringence

3.5.7.1 Glass and Category B Plastic Window Panes

The birefringence shall be less than 12 nanometers of retardance per centimeter of window thickness over visible wavelengths of 450 nm to 650 nm.

3.5.7.2 Category D Plastic Window Panes

The birefringence shall be less than 24 nanometers of retardance per centimeter of window thickness over visible wavelengths of 450 nm to 650 nm **[<TBD (see forward)>]**. Requirements for category C plastic panes are reserved.

3.5.8 Reflectance

3.5.8.1 Anti-reflective Coatings

To reduce reflectance, an anti-reflective (AR) coating shall be applied to both surfaces of every pane used in any window. The external-most surfaces of windows on vehicles exposed to terrestrial atmospheric reentry are exempt from this requirement.

3.5.8.2 Specular Reflectance

Specular reflectance of normally incident light (minimum rms wavefront error) between 450 and 800 nanometers from each coated window surface shall not exceed 2% absolute (based on the integration of photon flux over the 450-800 spectral range).

3.5.9 Transmittance

3.5.9.1 Window Assembly Luminous Transmittance

For all window assemblies, the total luminous transmittance shall be as specified in Table 3-5, Window Assembly Luminous Transmittance.

TABLE 3-5 WINDOW ASSEMBLY LUMINOUS TRANSMITTANCE

Material	Pane Thickness	Luminous Transmission (% min)
Glass	All thicknesses	**82%**
Plastic	.152 - .475 cm (0.06 - .187 inch) as received	**82%**
	>.475 - .792 cm (>0.187 – 0.312 inch) as received	**82%**
	>.792 – 1.06 cm (>0.312-0.417 inch) as received	**78%**
	>1.06 – 2.54 cm (>0.417 – 1.00 inch) as received	**68%**

3.5.9.2 All Glass and Category B Plastic Pane Luminous Transmittance

For individual glass windowpanes and category B plastic panes, the luminous transmittance shall be greater than 92% when coated or 90% when uncoated.

3.5.9.3 Category D Plastic Pane Luminous Transmittance

For category D individual plastic windowpanes, the luminous transmittance minimum percentage shall be as specified in Table 3-6, Luminous Transmittance of Plastic Windows. Requirements for category C plastic panes are reserved

TABLE 3-6 LUMINOUS TRANSMITTANCE OF PLASTIC WINDOWS

Thickness	Luminous Transmission (% min)
.152 - .475 cm (0.06 - .187 inch) as received	**85%**
>.475 - .792 cm (>0.187 – 0.312 inch) as received	**82%**
>.792 – 1.06 cm (>0.312-0.417 inch) as received	**80%**
>1.06 – 2.54 cm (>0.417 – 1.00 inch) as received	**70%**

3.5.10 Color Balance

3.5.10.1 Glass

For each glass pane design, the maximum allowable color shift for a D65 Standard Illuminant shall be bounded by a rectangular color space on the 1931 CIE Chromaticity Diagram. The boundaries of the rectangular color space range between 0.312 and 0.321 (inclusive) in the x coordinate, and between 0.329 and 0.340 (inclusive) in the y coordinate. The bounding box representing the allowable color shift, along with the location of the unshifted D65 Standard Illuminant, is illustrated schematically in Figure 3-1, 1931 Chromaticity Diagram.

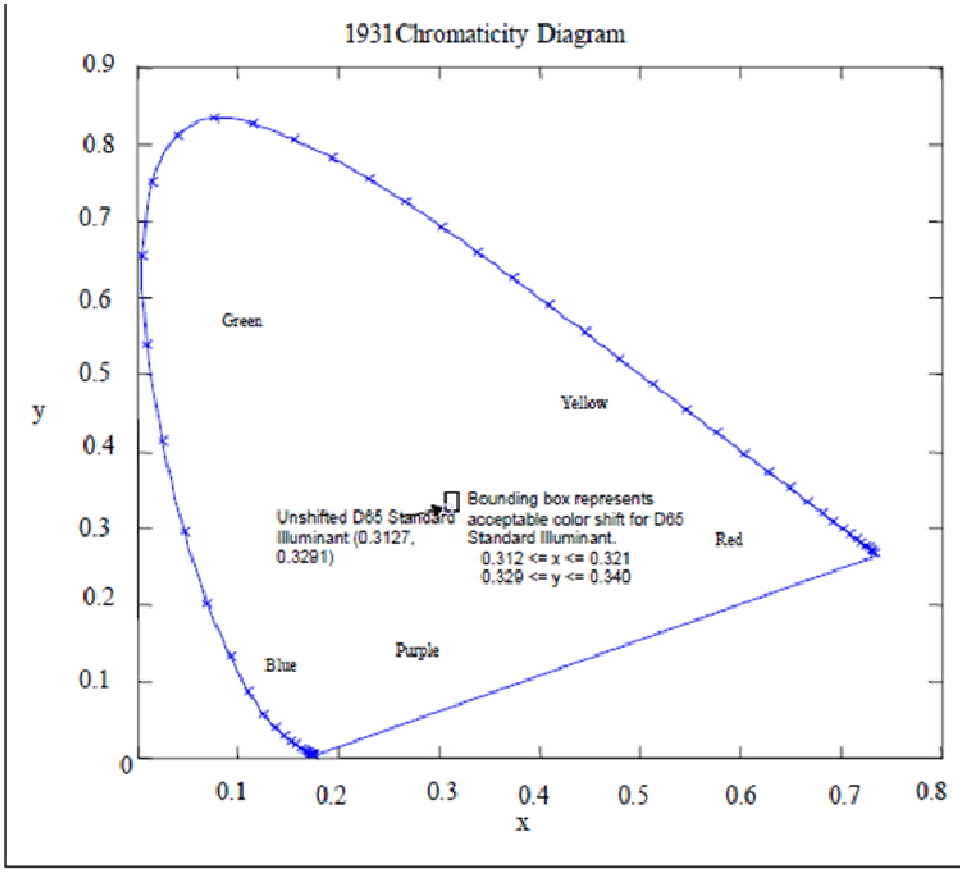

FIGURE 3-1 1931 CHROMATICITY DIAGRAM

3.5.10.2 Plastic

For plastic windowpanes, the yellowness index shall be less than 0.5

3.5.11 Wavefront Quality

3.5.11.1 Normal Incidence Viewing

3.5.11.1.1 Individual Window Panes

For individual window panes and normal incidence viewing, the allowable peak-to-valley (P-V) wavefront error with piston and tilt components removed, P-V wavefront error with piston, tilt and defocus wavefront components removed, and root mean square (RMS) wavefront error with piston, tilt and defocus components removed shall not exceed the values shown in Table 3-7, Maximum Allowable Normal Incidence Viewing Wavefront Errors for Individual Panes, when measured over any sub-aperture of area shown in the table and measured within the central 80 percent of the window physical diameter, excluding flight loads, pressure loads, and temperature gradients.

TABLE 3-7 MAXIMUM ALLOWABLE NORMAL INCIDENCE VIEWING WAVEFRONT ERRORS FOR INDIVIDUAL PANES [<TBD-Cat D (See Forward)>]

Category	Sub-aperture Area Diameter (mm)	P-V Wavefront Error with Piston & Tilt Removed (waves),	P-V Wavefront Error with Piston, Tilt and Defocus Wavefront Components Removed (waves)	RMS Wavefront Error with Piston, Tilt & Defocus Removed (waves)
All Glass Categories	150	**7**	**5.5**	**1**
Plastic B	150	**12**	**10.3**	**1.7**
Plastic C	*Reserved*	*Reserved*	*Reserved*	*Reserved*
Plastic D	25	**3.0 [<TBD>]**	**1.5 [<TBD>]**	**0.5 [<TBD>]**

3.5.11.1.2 Assemblies Containing Glass and/or Category B Plastic Panes

For normal incidence viewing window assemblies consisting of a combination of glass and category B plastic panes, the allowable P-V wavefront error with piston and tilt components removed, P-V wavefront error with piston, tilt and defocus wavefront components removed, and RMS wavefront error with piston, tilt and defocus components removed, shall not exceed the values shown in Table 3-8, Maximum Allowable Normal Incidence Viewing Wavefront Errors for Combinations of Glass and/or Category B Plastic Panes, when measured over any sub-aperture of area shown in the table and measured within the central 80 percent of the window physical diameter, excluding flight loads, pressure loads, and temperature gradients.

TABLE 3-8 MAXIMUM ALLOWABLE NORMAL INCIDENCE VIEWING WAVEFRONT ERRORS FOR COMBINATIONS OF GLASS AND/OR CATEGORY B PLASTIC PANES

Sub-aperture Area Diameter (mm)	P-V Wavefront Error with Piston & Tilt Removed (waves)	P-V Wavefront Error with Piston, Tilt and Defocus Wavefront Components Removed (waves)	RMS Wavefront Error with Piston, Tilt & Defocus Removed (waves)
150	**25**	**16**	**2.3**

3.5.11.1.3 Assemblies Containing Category D Plastic Panes [<TBD (See Forward)>]

For normal incidence viewing, window assemblies containing one or more category D plastic panes, the allowable P-V wavefront error with piston and tilt components removed, P-V wavefront error with piston, tilt and defocus wavefront components removed, and RMS wavefront with piston, tilt and defocus components removed shall not exceed the values shown in Table 3-9, Maximum Allowable Normal Incidence Viewing Wavefront Errors for Assemblies Containing Category D Plastic Panes, when measured over any sub-aperture of area shown in the table and measured within the central 80 percent of the window physical diameter, excluding flight loads, pressure loads, and temperature gradients.

TABLE 3-9 MAXIMUM ALLOWABLE NORMAL INCIDENCE VIEWING WAVEFRONT ERRORS FOR ASSEMBLIES CONTAINING CATEGORY D PLASTIC PANES [<TBD (See Forward)>]

Sub-aperture Area Diameter (mm)	P-V Wavefront Error with Piston & Tilt Removed (waves)	P-V Wavefront Error with Piston, Tilt and Defocus Wavefront Components Removed (waves)	RMS Wavefront Error with Piston, Tilt & Defocus Removed (waves)
25	**4 [<TBD>]**	**3.0 [<TBD>]**	**0.5 [<TBD>]**

3.5.11.2 Off-Axis (Non-Normal Incidence) Viewing

3.5.11.2.1 Individual Window Panes

For off-axis viewing through individual window panes, the allowable P-V wavefront error with piston and tilt components removed, P-V wavefront error with piston, tilt and defocus wavefront components removed, and RMS wavefront error with piston, tilt and defocus components shall not exceed the values shown in Table 3-10, Maximum Allowable Off-Axis Viewing Wavefront Errors for Individual Panes**,** when measured over any sub-aperture of area shown in the table and measured within the central 80 percent of the window physical diameter, excluding flight loads, pressure loads, and temperature gradients.

TABLE 3-10 MAXIMUM ALLOWABLE OFF-AXIS VIEWING WAVEFRONT ERRORS FOR INDIVIDUAL PANES [<TBD-Cat D (See Forward)>]

Category	Sub-aperture Area Diameter (mm)	P-V Wavefront Error with Piston & Tilt Removed (waves)	P-V Wavefront Error with Piston, Tilt and Defocus Wavefront Components Removed (waves)	RMS Wavefront Error with Piston, Tilt & Defocus Removed (waves)
All Glass Categories	150	**9**	**7**	**1.0**
Plastic B	150	**11**	**8**	**1.6**
Plastic C	*Reserved*	*Reserved*	*Reserved*	*Reserved*
Plastic D	25	**6.0 [<TBD>]**	**3.6 [<TBD>]**	**0.55 [<TBD>]**

3.5.11.2.2 Assemblies Containing Glass and/or Category B Plastic Panes

For off-axis viewing through window assemblies consisting of a combination of glass and category B plastic panes, the allowable P-V wavefront error with piston and tilt components removed, P-V wavefront error with piston, tilt and defocus wavefront components removed, and RMS wavefront error with piston, titl and defocus components removed shall not exceed the values shown in Table 3-11, Maximum Allowable Off-Axis Viewing Wavefront Errors for Combinations of Glass and/or Category B Plastic Panes, when measured over any sub-aperture of area shown in the table and measured within the central 80 percent of the window physical diameter, excluding flight loads, pressure loads, and temperature gradients.

TABLE 3-11 MAXIMUM ALLOWABLE OFF-AXIS VIEWING WAVEFRONT ERRORS FOR COMBINATIONS OF GLASS AND/OR CATEGORY B PLASTIC PANES

Sub-aperture Area Diameter (mm)	P-V Wavefront Error with Piston & Tilt Removed (waves)	P-V Wavefront Error with Piston,Tilt and Defocus Wavefront Components Removed (waves)	RMS Wavefront Error with Piston, Tilt & Defocus Removed (waves)
150	**20**	**18**	**3.0**

3.5.11.2.3 Assemblies Containing Category D Plastic Panes [<TBD (See Forward)>]

For off-axis viewing through window assemblies containing one or more category D plastic panes, the allowable P-V wavefront error with piston and tilt components removed, P-V wavefront error with piston, tilt and defocus wavefront components removed, and RMS wavefront error with piston, tilt and defocus components removed shall not exceed the values shown in Table 3-12, Maximum Allowable Off-Axis Viewing Wavefront Errors for Assemblies Containing Category D Plastic Panes, when measured over any sub-aperture of area shown in the table and measured within the central 80 percent of the window physical diameter, excluding flight loads, pressure loads, and temperature gradients.

TABLE 3-12 MAXIMUM ALLOWABLE OFF-AXIS VIEWING WAVEFRONT ERRORS FOR ASSEMBLIES CONTAINING CATEGORY D PLASTIC PANES [<TBD (See Forward)>]

Sub-aperture Area Diameter (mm)	P-V Wavefront Error with Piston & Tilt Removed (waves)	P-V Wavefront Error with Piston,Tilt and Defocus Wavefront Components Removed (waves)	RMS Wavefront Error with Piston, Tilt & Defocus Removed (waves)
25	**6 [<TBD>]**	**3.6 [<TBD>]**	**0.65 [<TBD>]**

3.5.12 Coating Uniformity and Durability

3.5.12.1 Glass

3.5.12.1.1 Tape Press

The coated optical surface shall show no evidence of coating removal when cellophane tape is pressed firmly against the coated surface and quickly removed at an angle normal to the coated surface.

3.5.12.1.2 High Temperature Exposure

After exposure in an atmosphere of 120^{o}F ± 4^{o}F and 95 to 100% relative humidity for a period of no less than 24 hours, the coated optical surface shall have no evidence of flaking, peeling, cracking, blistering, or blemishes such as stains, smears, discolorations, or cloudiness.

3.5.12.1.3 Cheesecloth Abrasion

The coated optical surface shall show no signs of deterioration such as streaks or scratches when abraded with a dry, clean cheesecloth pad a minimum of 50 straight line strokes.

3.5.12.1.4 Low Temperature Exposure

After exposure to temperatures of -20^{o}F and +20^{o}F for 2 hours at each temperature, the coated optical surface shall have no evidence of flaking, peeling, cracking, blistering, or coating removal.

3.5.12.1.5 Chemical Resistance

After sequential immersion in trichloroethylene, acetone, and ethyl alcohol for a minimum of 10 minutes each (air drying between each solution), and wiping with cheesecloth, the coated optical surface shall show no evidence of coating removal or scratches.

3.5.12.1.6 Taber Abrasion

The coating shall be required to pass a Taber abrasion resistance test with no more than 4.2% haze after 100 revolutions of a CS10F wheel under a load of 500 grams, and no more than 27% haze after 500 revolutions.

3.5.12.1.7 Saline Resistance

After immersion in a saline solution for a period of 24 hours, the coated optical surface shall have no evidence of flaking, peeling, cracking, blistering, or blemishes such as stains, smears, discolorations, or cloudiness.

3.5.12.1.8 Distilled Water Resistance

After immersion in distilled water for a period of 24 hours, the coated optical surface shall have no evidence of flaking, peeling, cracking, blistering, or blemishes such as stains, smears, discolorations, or cloudiness.

3.5.12.2 Plastic

3.5.12.2.1 Tape Press

The coated optical surface shall show no evidence of coating removal when cellophane tape is pressed firmly against the coated surface and quickly removed at an angle normal to the coated surface.

3.5.12.2.2 High Temperature Exposure

After exposure in an atmosphere of $120^{o}F \pm 4^{o}F$ and 95 to 100% relative humidity for no less than 24 hours, the coated optical surface shall have no evidence of flaking, peeling, cracking, blistering, or blemishes such as stains, smears, discolorations, or cloudiness.

3.5.12.2.3 Cheesecloth Abrasion

The coated optical surface shall show no signs of deterioration such as streaks or scratches when abraded with a dry, clean cheesecloth pad for a minimum of 50 straight line strokes.

3.5.12.2.4 Low Temperature Exposure

After exposure to temperatures of $-20^{o}F$ and $+20^{o}F$ for 2 hours at each temperature, the coated optical surface shall have no evidence of flaking, peeling, cracking, blistering, or coating removal.

3.5.12.2.5 Taber Abrasion

The coating shall be required to pass a Taber abrasion resistance test with no more than 4.2% haze after 100 revolutions of a CS10F wheel under a load of 500 grams, and no more than 27% haze after 500 revolutions.

3.5.12.2.6 Saline Resistance

After immersion in a saline solution for a period of 24 hours, the coated optical surface shall have no evidence of flaking, peeling, cracking, blistering, or blemishes such as stains, smears, discolorations, or cloudiness.

3.5.12.2.7 Distilled Water Resistance

After immersion in distilled water for a period of 24 hours, the coated optical surface shall have no evidence of flaking, peeling, cracking, blistering, or blemishes such as stains, smears, discolorations, or cloudiness.

4.0 VERIFICATIONS

4.1 PLANNING AND REPORTING

a. The vehicle/element prime contractor shall be responsible for demonstrating that each optical property has been met by verification per Section 4.0.

b. Verification of the ORVP shall be by NASA approval letter.

c. Verification shall be by inspection of the ORVR and demonstration that it is in compliance with Appendix B. The ORVR may be submitted in discrete sections as verifications are completed; however, the sum of all sections shall include verification of all requirements.

4.2 WINDOW CATEGORIES

No shall statement provided in requirement.

4.3 WINDOW CLEAR VIEWING APERTURES

No shall statement provided in requirement.

4.4 MULTIPURPOSE WINDOWS

Multipurpose windows shall be verified by test and analysis.

4.5 WINDOW OPTICAL REQUIREMENTS

No shall statement provided in requirement.

4.5.1 Finished Window Performance

This requirement shall be verified by acceptance test and analysis.

4.5.2 Striae

a. This requirement shall be verified by acceptance test and analysis.

b. Each windowpane shall be inspected for striae using a striaescope.

c. The evaluation of striae content shall be made in the direction perpendicular to the direction of intended use of the windowpane, in the direction of the maximum light path.

4.5.3 Allowable Defects

No shall statement provided in requirement.

4.5.3.1 Open Inclusions in Glass and Category B Plastic

Visual uniformity shall be verified by acceptance test and inspection.

4.5.3.2 Allowable Optical Defects in Category D Plastic

Visual uniformity shall be verified by acceptance test per ASTM-F733, Standard Practice for Optical Distortion and Deviation of Transparent Parts Using the Double-Exposure Method.

4.5.4 Haze

No shall statement provided in requirement.

4.5.4.1 All Glass an Category B Plastic Panes

This requirement shall be verified by acceptance test per ASTM-D1003, Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics, and analysis.

4.5.4.2 Category D Plastic Panes

This requirement shall be verified by acceptance test and analysis per ASTM-D1003.

4.5.5 Parallelism

No shall statement provided in requirement.

4.5.5.1 Window Panes Mounted in Common Structure

This requirement shall be verified by analysis and/or acceptance test.

4.5.5.2 Window Panes Mounted in Separate Structures

No shall statement provided in requirement.

4.5.6 Wedge

No shall statement provided in requirement.

4.5.6.1 All Glass Panes

a. This requirement shall be verified by acceptance test and analysis.

b. The wedge orientation shall be marked on each pane in an inconspicuous area such as on the edge of the pane or within 13 mm (~0.5 in) of the perimeter of the clear viewing area. The individual windowpanes shall be assembled and positioned in the frame for a window assembly such that line of sight deviation is minimized wherever possible.

4.5.6.2 All Plastic Panes

a. This requirement shall be verified by acceptance test and analysis.

b. The wedge orientation shall be marked on each pane in an inconspicuous area such as on the edge of the pane or within 13 mm (~0.5 in) of the perimeter of the clear viewing area. The individual windowpanes shall be assembled and positioned in the frame for a window assembly such that line of sight deviation is minimized wherever possible.

4.5.7 Birefringence

No shall statement provided in requirement.

4.5.7.1 Glass and Category B Plastic Window

a. This requirement shall be verified by acceptance test and analysis of each windowpane.

b. The birefringence, effective optical retardance values, shall be measured over a grid of measurement points extending across the clear viewing aperture of the windowpane, to within 2.54 cm (1.0 inch) of the edge of the aperture. The measurement grid spacing shall not exceed 1.0 cm (0.39 inches) in any direction. The birefringence shall be computed at each measurement location.

4.5.7.2 Category D Plastic Window Panes

a. This requirement shall be verified by acceptance test and analysis of each windowpane.

b. The birefringence, effective optical retarder values, shall be measured over a grid of measurement points extending across the clear viewing aperture of the windowpane, to within 2.54 cm (1.0 inch) of the edge of the aperture. The measurement grid spacing shall not exceed 1.0 cm (0.39 inches) in any direction. The birefringence shall be computed at each measurement location.

4.5.8 Reflectance

No shall statement provided in requirement.

4.5.8.1 Anti-reflective Coatings

This requirement shall be verified by inspection.

4.5.8.2 Specular Reflectance

This requirement shall be verified by qualification test and analysis. Reflectance shall be measured in 5 nm increments over the specified spectral range.

4.5.9 Transmittance

No shall statement provided in requirement.

4.5.9.1 Window Luminous Transmittance

a. This requirement shall be verified by qualification test and analysis.

b. Measurements shall be performed in accordance with ASTM-D1003 or equivalent.

c. Spectral transmittance data from 380 – 800 nanometers using a 5-nanometer wavelength resolution shall be provided to NASA in electronic format.

4.5.9.2 All Glass and Category B Plastic Pane Luminous Transmittance

a. This requirement shall be verified by qualification test and analysis.

b. Measurements shall be performed in accordance with ASTM-D1003 or equivalent.

c. Spectral transmittance data from 380 – 800 nanometers using a 5-nanometer wavelength resolution shall be provided to NASA in electronic format.

4.5.9.3 Category D Plastic Pane Luminous Transmittance

a. This requirement shall be verified by qualification test and analysis.

b. Measurements shall be performed in accordance with ASTM-D1003 or equivalent.

c. Spectral transmittance data from 380 – 800 nanometers using a 5-nanometer wavelength resolution shall be provided to NASA in electronic format.

4.5.10 Color Balance

No shall statement provided in requirement.

4.5.10.1 Glass

This requirement shall be verified by qualification lot test and analysis. Witness samples may be used in lieu of flight articles for this testing.

4.5.10.2 Plastic

a. This requirement shall be verified by qualification lot test and analysis.

b. The contractor may use withdrawn standard ASTM-D1925, Test Method for Yellowness Index of Plastics, as appropriate for the verification.

4.5.11 Wavefront Quality

No shall statement provided in requirement.

4.5.11.1 Normal Incidence Viewing

No shall statement provided in requirement.

4.5.11.1.1 Individual Window Panes

a. These requirements shall be verified by acceptance test on each individual windowpane.

b. An interferometer shall be used to perform the wavefront measurements, operated at a wavelength of 632.8 nm.

c. The individual windowpanes shall be tested over at least six sub-apertures distributed within the test area. The test area is defined as an area ≥ 80% of the physical area of the pane, with one test aperture being located at the center of this area.

d. The P-V wavefront with piston and tilt removed,, P-V wavefront with piston, tilt and defocus removed and RMS wavefront with piston, tilt and defocus removed shall each be decomposed into Zernike Polynomial coefficients and provided to NASA in electronic format.

4.5.11.1.2 Assemblies Containing Glass and/or Category B Plastic Panes

a. These requirements shall be verified by acceptance test on the complete window assembly.

b. An interferometer shall be used to perform the wavefront measurements, operated at a wavelength of 632.8 nm.

c. The window assembly shall be tested over at least six sub-apertures distributed within the test area. The test area is defined as an area ≥ 80% of the physical area of the assembly, with one test aperture being located at the center of this area.

d. The P-V wavefront with piston and tilt removed, P-V wavefront with piston, tilt and defocus removed and RMS wavefront with piston, tilt and defocus removed shall each be decomposed into Zernike Polynomial coefficients and provided to NASA in electronic format.

4.5.11.1.3 Assemblies Containing Category D Plastic Panes

a. These requirements shall be verified by acceptance test on the complete window assembly.

b. An interferometer shall be used to perform the wavefront measurements, operated at a wavelength of 632.8 nm.

c. The window assembly shall be tested over at least six sub-apertures distributed within the test area. The test area is defined as an area ≥ 80% of the physical area of the assembly, with one test aperture being located at the center of this area.

d. The P-V wavefront with piston and tilt removed, P-V wavefront with piston, tilt and defocus removed and RMS wavefront with piston, tilt and defocus removed shall each be decomposed into Zernike Polynomial coefficients and provided to NASA in electronic format.

4.5.11.2 Off-Axis (Non-Normal Incidence) Viewing

No shall statement provided in requirement.

4.5.11.2.1 Individual Window Panes

a. These requirements shall be verified by acceptance test on each individual window pane.

b. An interferometer shall be used to perform the wavefront measurements, operated at a wavelength of 632.8 nm.

c. The individual windowpanes shall be tested at a viewing angle of 30 degrees from normal incidence over at least six sub-apertures distributed within the test area. The test area is defined as an area ≥ 80% of the physical area of the pane, with one test aperture being located at the center of this area.

d. The P-V wavefront piston and tilt removed, P-V wavefront with piston, tilt and defocus removed and RMS wavefront with piston, tilt and defocus removed shall each be decomposed into Zernike Polynomial coefficients and provided to NASA in electronic format.

4.5.11.2.2 Assemblies Containing Glass and/or Category B Plastic Panes

a. These requirements shall be verified by acceptance test on the complete window assembly.

b. An interferometer shall be used to perform the wavefront measurements, operated at a wavelength of 632.8 nm.

c. The window assembly shall be tested at a viewing angle of 30 degrees from normal incidence over at least six sub-apertures distributed within the test area. The test area is defined as an area ≥ 80% of the physical area of the assembly, with one test aperture being located at the center of this area.

d. The P-V wavefront piston and tilt removed, P-V wavefront with piston, tilt and defocus removed and RMS wavefront with piston, tilt and defocus removed shall each be decomposed into Zernike Polynomial coefficients and provided to NASA in electronic format.

4.5.11.2.3 Assemblies Containing Category D Plastic Panes

a. These requirements shall be verified by acceptance test on the complete window assembly.

b. An interferometer shall be used to perform the wavefront measurements, operated at a wavelength of 632.8 nm.

c. The window assembly shall be tested at a viewing angle of 30 degrees from normal incidence over at least six sub-apertures distributed within the test area. The test area is defined as an area ≥ 80% of the physical area of the assembly, with one test aperture being located at the center of this area.

d. The P-V wavefront piston and tilt removed, P-V wavefront with piston, tilt and defocus removed and RMS wavefront with piston, tilt and defocus removed shall each be decomposed into Zernike Polynomial coefficients and provided to NASA in electronic format.

4.5.12 Coating Uniformity and Durability

No shall statement provided in requirement.

4.5.12.1 Glass

No shall statement provided in requirement.

4.5.12.1.1 Tape Press

This requirement shall be verified by qualification test on witness samples.

4.5.12.1.2 High Temperature Exposure

This requirement shall be verified by qualification test on witness samples

4.5.12.1.3 Cheesecloth Abrasion

This requirement shall be verified by qualification test on witness samples

4.5.12.1.4 Low Temperature Exposure

This requirement shall be verified by qualification test on witness samples.

4.5.12.1.5 Chemical Resistance

This requirement shall be verified by qualification test on witness samples.

4.5.12.1.6 Taber Abrasion

This requirement shall be verified by qualification test on witness samples.

4.5.12.1.7 Saline Resistance

This requirement shall be verified by qualification test on witness samples.

4.5.12.1.8 Distilled Water Resistance

This requirement shall be verified by qualification test on witness samples

4.5.12.2 Plastic

No shall statement provided in requirement.

4.5.12.2.1 Tape Press

This requirement shall be verified by qualification test on witness samples

4.5.12.2.2 High Temperature Exposure

This requirement shall be verified by qualification test on witness samples.

4.5.12.2.3 Cheesecloth Abrasion

This requirement shall be verified by qualification test on witness samples.

4.5.12.2.4 Low Temperature Exposure

This requirement shall be verified by qualification test on witness samples.

4.5.12.2.5 Taber Abrasion

This requirement shall be verified by qualification test on witness samples.

4.5.12.2.6 Saline Resistance

This requirement shall be verified by qualification test on witness samples.

4.5.12.2.7 Distilled Water Resistance

This requirement shall be verified by qualification test on witness samples.

APPENDIX A
ACRONYMS AND ABBREVIATIONS AND GLOSSARY OF TERMS

A1.0 ACRONYMS AND ABBREVIATIONS

AR	Anti-Reflective
ASTM	American Society for Testing and Materials
CIE	International Commission on Illumination
HD	High-definition
NASA	National Aeronautics and Space Administration
ORVP	Optical Requirements Verification Plan
ORVR	Optical Requirements Verification Report
P-V	Peak-to-Valley
RMS	Root Mean Square
UV	Ultra Violet

A2.0 GLOSSARY OF TERMS

Term	Description
Birefringence	The difference between indices of refraction in a material that has two indices of refraction. Often birefringence is measured in terms of effective retardance.
Bubbles	Gaseous voids entrapped within a bulk material such as in glass, plastics, laminates, and etc. of generally circular cross section and usually the result of the manufacturing process.
Clear Viewing Aperture	The area of the window not covered by the assembly frame or other structure that would block incident light rays.
Deviation	The change in angle that an emergent ray of light makes with the incident ray as it passes through a glass pane or optical device.
Diffuse Reflection	The fraction or percentage of incident light at a specified wavelength that is reflected in a broad range of directions. The most familiar example of a diffuse reflection is glossy and matte paints or photo prints.
Distortion	A general term referring to the situation in which an image is not a true-to-scale reproduction of an object where the resultant image looks misshapen caused by a changing wedge angle between two glass pane surfaces or by material non-homogeneities or irregularities in the optical surface.
Haze	The fogged appearance of a window or lens that occurs when light rays deviate from the incident beam by forward scattering as they pass through the window, measured as a percentage of the transmitted light that is deviated. Fine surface roughness, contamination, scratches, or internal non-homogeneities and inclusions cause haze.
Inclusions	A generic term used to denote the presence of all localized defects within bulk materials of essentially circular cross section including bubbles, seeds, striae knots, small stones, sand, and crystals. Inclusions scatter light in proportion to their area. Near an image plane, inclusions can be objectionable because of their visibility in images.
Index of refraction	A material property referring to the ratio of the speed of light in a vacuum with the phase velocity in the material. It is wavelength and temperature dependent. The index of refraction of vacuum is 1.0.
Luminous Transmittance	The fraction or percentage of incident light passing through a medium, typically specified over a wavelength range of

Term	Description
	380 to 800 nanometers.
Open Inclusion	Bulk material inclusions that have become exposed at the surface due to polishing or other processing steps.
Optical Path Length	The path that light actually travels within a medium, described as OPL = (n)t where n is the index of refraction of the material or medium and t is the physical length of the path. OPL is wavelength dependent.
Retardance	The optical path difference of two birefringent wavefronts.
Scratches	Any marking or tearing of the native surface material, substrate, surface coating, or surface laminate along the line of the surface appearing as though caused by the movement of a rough or a hard, sharp object which leaves a roughened depression.
Seeds	A term used to denote a gaseous inclusion in glass.
Specular Reflection	The fraction or percentage of incident light at a specified wavelength that is reflected from a surface. Specular reflection is the perfect, mirror-like reflection of light (or sometimes other types of waves) from a surface, in which light from a single incoming direction is reflected into a single outgoing direction.
Striae	Spatially short range variations (0.1 mm to 2 mm) in the index of refraction of a transparent material, usually of glass especially when formed into panes. Striae are different from spatially global index of refraction non-homogeneities that affect the complete material piece. Striae induce wavefront errors.
Transmittance	The fraction or percentage of incident light at a specified wavelength that passes through a medium.
Wavefront	Light travels as an electromagnetic wave. A wavefront is defined as a surface joining all adjacent points on a wave that have the same phase.
Wavefront Error	Wavefront error is the total optical path difference induced into a wavefront with respect to a reference wavefront. It is wavelength dependent.
Wedge	The angle formed by and between the two surfaces of an individual windowpane.

Term	Description
Window	The finished assembly including the frame structure (includes all gaskets, bolts, spacers, and other such parts) and all window panes that would normally be used at a specific location with any protective panes, permanent coatings, polycarbonate films, or laminates applied or in place. This term is used interchangeability with window port.
Window port	Term used interchangeability with window.

APPENDIX B
DATA ITEM DESCRIPTIONS

Data Item Description 1: Optical Requirements Verification Plan (ORVP)

Purpose:

The ORVP describes the inspections, tests and analyses to be performed by the contractor and the verification criteria that the inspection, test, and analyses results must meet to satisfy the optical requirements specified in this document. The ORVP provides the means for NASA evaluation and judgment of the acceptability of the contractor proposed optical parameter verification program.

Use/Relationships:

This data item description contains the format and content preparation instructions for data generated under the requirements described in Section 3.0 and the verifications described in Section 4.0 of this document.

The ORVP should contain as much detail as is practicable commensurate with the state of program development at the time the ORVP is prepared. Each requirement in this document shall be specifically addressed by the ORVP.

Preparation Instructions:

General: The ORVP 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 plastic designs for those designated as Catastrophic or Critical.

Content: The plan shall contain the following as a minimum:

- Applicable documents
- Objectives and requirements fulfillment
- Description of test articles
- Pass/fail criteria
- Test hardware definition
- Pertinent test/analysis details
- Setup details
- Test schedule

Format: The ORVP format shall be contractor selected. The plan shall be submitted electronically to NASA. Unless effective presentation would be degraded, the initially used format arrangement shall be used for all subsequent submissions.

Data Item Description 2: Optical Requirements Verification Report (ORVR)

Purpose:

The ORVR presents the results of inspections, analyses, tests, and other data needed to verify the adequacy of the optical parameters for glass and plastic materials for all system, subsystems, and/or components whose failure is designated Catastrophic or Critical. The ORVR provides the means for NASA evaluation and judgment of the acceptability of the contractor's glass and plastic window designs and hardware.

Use/Relationships:

This data item description contains the format and content preparation instructions for data generated under the requirements described in Section 3.0 and the verifications described in Section 4.0 of this document.

This data item is applicable to the vehicle, subsystem, or component for which an Optical Requirements Verification Plan (ORVP) has been prepared as a result of a contractual requirement.

Preparation Instructions:

General: The ORVR shall include analyses, test, and/or data used to verify the optical parameters for all systems, subsystems, and/or components whose failure is designated Catastrophic or Critical. The ORVR shall specifically address each requirement contained in this document, and address appropriate sections in the ORVP in both format and content.

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

- Description and photographs of test setup
- Date, personnel performing test and contact information, and location of test
- Test environments used
- Test measurement records
- Test results
- Statement of qualification
- Requirements fulfillment
- Test schedule

Format: The ORVR format shall be contractor selected, but shall reflect the format selected for the ORVP. The report and data shall be submitted electronically to NASA. Unless effective presentation would be degraded, the initially used format arrangement shall be used for all subsequent submissions.