International Space Station

Meteoroid / Orbital Debris Survivability and Vulnerability

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International Space Station

Elements currently in orbit
International Space Station

Data Points

- FGB / first element launch: November 20, 1998
- Node1, PMA1, & PMA2 launch: December 4, 1998
- Assembly complete surface area: ~12,000 square meters
- Service life: 15 years
- Meteoroid / orbital debris shielding
  - Weight of dedicated shield, support structure, or primary structure mods
    - 30k - 40k pounds at assembly complete

Current Stats

<table>
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<th></th>
<th>Today</th>
<th>Percent</th>
<th>At Complete</th>
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<td>Weight (lbs)</td>
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<td>Volume (cf)</td>
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<td>Power (kw)</td>
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<td>Atmosphere (psi)</td>
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<td>Altitude (miles)</td>
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<td>Crew (persons)</td>
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<td>Assembly Flights</td>
<td>3</td>
<td>4.3%</td>
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Image courtesy NASA,
International Space Station Fact Book

Survivability and Vulnerability
International Space Station

Data Points

THE SPACE STATION
International Participation

Meteoroid / Orbital Debris
Survivability and Vulnerability
Boeing Space Station Survivability and Vulnerability

- 1983  Space Station Phase A
- 1984 / 1985  Space Station Phase B
- 1987  Space Station Integrated Wall Damage and Penetration Damage Control Contract  *(Bumper code development)*
- 1987  Space Station Phase C/D *(Inhabited Modules)* Contract
- 1993/1994  International Space Station Prime Contract  *(Integration role)*
- 2000  Space and Air Survivability Workshop 2000
### Today's Boeing

**Company Capabilities**

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6/14/00

Meteoroid / Orbital Debris
Survivability and Vulnerability
• Space station natural and induced environments
• Meteoroid and orbital debris threat definition
• Requirement definition
• Assessment methods
• Shield development
• Component vulnerability
• Other
• Concluding remarks
Space station natural and induced environments

- Meteoroid and orbital debris threat definition
- Requirement definition
- Assessment methods
- Shield development
- Component vulnerability
- Other
- Concluding remarks
Space Environments

- Contamination
- Material Loss
- Etc

Requirements and design to mitigate
Space Environments
Neutral Atmosphere and Atomic Oxygen

Neutral Atmosphere Environment
- Natural Atmosphere
- Vacuum Venting
- Transfer Vehicle Operations
- Reboost / attitude control
- Off-gas / Out-gas
- Leaks
- EVA/Airlock

Interaction
- Erosion
- Ram / Wake
- Deposition

Component
- Structures
- Solar Arrays
- Surface Materials
- Payloads

Effect
- Contamination
  - Reflectance
  - Absorbivity
  - Emissivity
- Material Loss
- Coating Loss
- Thermal Control
- Instrumentation
  - Accuracy
  - Sensitivity

Atomic Oxygen Environment
- LEO Natural Atmosphere
- Direct impingement
- High Velocity Impact with ram surfaces
- Excited species generation causing surface glow

Interaction
- Surface Materials
- Solar Arrays
- Optical Sensors
- Payloads
- Lubricants
- EVA suits

Component
- Material erosion and loss
- Coating loss, degradation, or discoloration
- Power loss from solar arrays
- Changes in exposed surface optical properties
- Spacecraft glow
- Instrumentation
  - Accuracy
  - Sensitivity
  - Field of obstruction and interference
- Increase of local particulate contamination

Survivability and Vulnerability
Space Environments

External Contamination and Ionizing Radiation

**Sources**
- Material outgassing and offgassing
- Ground processing and non-volatile residue
- Particulate/non-volatile residue redistribution
- Line-of-sight deposition
- Ambient scattering
- UV-enhanced deposition
- Interaction with atomic oxygen

**Component**
- Surface Materials
- Solar Arrays
- Radiators
- Optical Sensors
- Payloads

**Interactions**
- External Contamination Environment

**Effects**
- Thermal and optical property changes
- Material loss
- Coating loss or degradation
- Power loss from solar arrays
- Instrumentation
  - Accuracy
  - Sensitivity
  - Field of obstruction and interference
- Electrostatic charging of contaminant

**Sources**
- Cosmic rays
- Solar flare
- Trapped belt
- Electrons/protons (South Atlantic Anomaly/Trapped Belt)
- On-board sources

**Component**
- Electronics
  - Crew
  - Optical materials
  - Solar arrays
  - Polymers

**Interactions**
- Ionizing Radiation Environment

**Effects**
- Inoperable systems
- Reboot/reset
- Component replacement
- EVA duty limits/long term effects
- Degradation
- Discoloration

**Survivability and Vulnerability**

6/14/00
Space Environments
Plasma and Thermal

**Sources**
- Natural Plasma
- UV ionizations
- Solar Arrays
- Charge exchange
- Experiments/Probes/EM sources
- Charge balance
- Discharges: corona, arc
- Currents: conductors, dielectrics
- Fields: \( \mathbf{V} \times \mathbf{B}, \mathbf{E}, \mathbf{B} \)
- Sheaths
- Sputtering
- Ram / wake
- Photoelectron emission
- Secondary electron generation

**Interaction**
- Plasma Environment

**Component**
- Solar Arrays
- Structures
- Electronics
- Cabling
- Antennas
- Payloads

**Effects**
- Power loss
- Pinhole growth
- Changes in optical properties
- EMI
- Torque and drag
- Enhanced contamination
- Instrumentation corruption

**Sources**
- Solar
- Earth albedo
- Earth IR
- Spacecraft self-radiation
- Plasma currents

**Interaction**
- Thermal Environment

**Component**
- Surface materials
- Insulation
- Pressurized elements
- Payloads
- High pressure tanks
- Radiators
- Power distribution
- Heat transport system
- EVA
- Crew

**Effects**
- Over heating or cooling
- Surface property degradation
- Subsystem failure
- Component reliability
- Payload performance
- Crew comfort
- Degradation of optical properties
- Utility placement and routing

Meteoroid / Orbital Debris
Survivability and Vulnerability
Space Environments

Thermal Vacuum and Meteoroids/Orbital Debris

Sources

- Space vacuum and thermal radiation sources
  (See Thermal Environment)

Interaction

- Outgassing
- Evaporation
- Sublimation

Exposed materials
- Multi-layer insulation
- Seals
- Lubricants
- Crew / EVA suits
- Solar arrays
- Optical sensors
- Thermal control

Component

- Material constituent loss
- Moisture loss
- Degradation of properties
- Contamination

Thermal Vacuum Environment

Effects

- Satellite break-up
- Break-up and fragmentation of upper stages
- ASAT operations
- On-orbit collisions of debris
- Interplanetary Dust
- Asteroid belt
- Comet dust

Meteoroids and Orbital Debris Environment

Sources

- Impacts
  - Perforations
  - Craters
  - Ricochet

Component

- Debris shield
- MLI
- Structures
- External components
- Payloads
- Crew
- Solar arrays
- Radiators

Interaction

- Debris shield
- MLI
- Structures
- External components
- Payloads
- Crew
- Solar arrays
- Radiators

Effect

- Structural failure / pressure loss
- Degradation of optical properties of exposed equipment
- Component failure and degradation
- EVA threat
- Surface coating penetration
Any of the assessed environments can degrade mission performance and/or result in mission loss with improper design.

In general, meteoroids / orbital debris and ionizing radiation are the two natural and induced environments that pose survivability and vulnerability concerns.

Worst case threats posed by ionizing radiation can be mitigated by design.

Worst case meteoroid / orbital debris threats cannot be fully mitigated with current design practices.

- Typically and fortunately, the probability of a mission ending impact is relatively low.
Boeing Space Station Survivability and Vulnerability

Presentation Outline

- Space station natural and induced environments
- Meteoroid and orbital debris threat definition
- Requirement definition
- Assessment methods
- Shield development
- Component vulnerability
- Other
- Concluding remarks
Comparative Orbital Debris and Meteoroid with SSP 30425
Orbital Debris Environment Shown

Legend:

A - Pressure vessel penetrations highly unlikely

B - Possible penetrations depending on impacted region and impacting particle. Likelihood generally increases as you move to the right. Often can be mitigated with passive shields.

Subscripts:
f - functional failure onset
p - pressure vessel penetration onset

C - No existing countermeasures

D - Ground tracking for collision avoidance transition region. 85% confidence at 10 cm (600 km alt) to 95% at 30 cm. Ground tracked objects will be avoided based on collision probability.

E - High confidence ground tracking for collision avoidance maneuver.
Threat Definition

- SSP 30425 environment models
  - Meteoroids and orbital debris
  - Models defined on Boeing contract
  - Design of shields

- ORDEM96
  - Orbital debris only
  - 1996 update to NASA orbital debris model
    - ORDEM2K currently under development by NASA
  - Component vulnerability analyses
  - Performance assessments
  - Catastrophic risk assessments
• Space station natural and induced environments
• Meteoroid and orbital debris threat definition

Requirement definition
• Assessment methods
• Shield development
• Component vulnerability
• Other
• Concluding remarks
• Requirement Definition

- Probability of no catastrophic failure (PNCF)
- Probability of no penetration (PNP)
- Probability of no subcomponent penetration (PNSP)

- M/OD critical item
  - An item is defined as M/OD critical when effects resulting from meteoroid or orbital debris impact will endanger the crew or Space Station survivability
• Probability of no penetration (PNP)
  – Penetration of pressure wall of a pressurized element or other high energy device
  – ISS specification is 0.76 for 10 years
    • Design requirements based on SSP 30425 environment models
      – 1991 orbital debris environment definition
    – PNP = \( e^{-n} \)
      • Where \( n = f \times a \times t \) = the expected number of perforations
        – \( f \) = penetrating flux
        – \( a \) = exposed critical area
        – \( t \) = exposure time

• Probability of no catastrophic failure
  – Program requirement is 0.95 for 10 years
  – PNCF = PNP\(^R\) = \( e^{-fatR} \)
    • \( R \) = number of catastrophic events per penetration
Boeing Space Station Survivability and Vulnerability

Requirement Definition

- Probability of No Penetration
  - Limited to the performance of the M/OD protection subsystem
    - Shield performance testing
    - Shield performance equations
    - Probabilities of shield system failure based on shield performance and environment

- Probability of No Catastrophic Failure
  - Assessment of the effects of a penetration of a M/OD critical item
    - Includes effects of crew responsive
    - Generalized characterization of effects of a penetration on ISS systems
    - Currently assessed
      - Unzipping event
      - Thrust induced structural failure
      - Fragment injury loss
      - Critical module depressurization
    - Critical equipment loss
    - Hypoxia related losses
    - Secondary injury loss
    - Non-fatal injuries
  - Assessed but not included in catastrophic risk tally
• Probability of no subcomponent penetration
  – Lesson learned
  – Partially implemented due to "pre-existing hardware" and other constraints

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<th>System-level Criticality</th>
<th>MTBF (hours)</th>
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• Penetration
  - Defined as through hole or detached spall
    • Through hole determined by light tightness or dye penetrant
  - High pressure vessel or high energy device penetration defined as perforation of last wall of shield system, not tank or device wall
    • Examples
      – Plasma contactor xenon tank (3000 psi)
      – Control moment gyros

• Subcomponent Penetration is defined as:
  - Complete perforation
  - Creation of detached spall
  - For close-clearance items that could be affected by case deformation, a deformation equal to one-half the case thickness or any impingement into the dynamic envelope between the case and the protected component
  - For cables, a complete severing of a wire or a reduction in its cross-sectional area by 30% or greater
  - Reduction in wall thickness such that design pressure would no longer be contained
Boeing Space Station Survivability and Vulnerability

Presentation Outline

- Space station natural and induced environments
- Meteoroid and orbital debris threat definition
- Requirement definition
  - Assessment methods
    - Shield development
    - Component vulnerability
    - Other
- Concluding remarks
Boeing Space Station Survivability and Vulnerability

Assessment methods

- Analysis codes
  - Bumper-II software
    - Probability of no penetration
    - Probability of no subcomponent penetration
    - Probability of no impact
  - MSCSurv
    - Probability of no catastrophic failure

- Testing
  - Hypervelocity impact testing
    - Two stage light gas gun to 7 km/sec
      - Aluminum spheres
    - Limited inhibited shaped charge shots at 11 km/sec
      - Hollow aluminum cylindrical projectiles
  - Test data used to formulate shield performance equations
    - Coded into Bumper-II and MSCSurv
Bumper Shield Assessment Methodology

Spacecraft Configuration (I-DEAS)
- Describes spatial relationships of spacecraft components
- Defines spacecraft orientation (velocity and zenith directions)
- Defines M/O/D shield regions

Meteoroid & Debris Environments (GEOMETRY)
- Threat directions
- Velocity distribution
- Shadowing

Critical Particle Diameter Calculation (RESPONSE)
- Protection capability

Computation of Penetrating Flux and PNP (SHIELD)

Graphical Interpretation of Results (EXCEL & I-DEAS)

Space Station Orbital Debris Threat Assessment

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<th>Station/Region</th>
<th>Probability of Impact</th>
<th>Velocity (km/sec)</th>
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<th>OD of Penetration</th>
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MSCSurv 4.1 FLOWCHART

MSCSurv cascades from "immediate" failure modes (such as critical cracking of the module) to "later" hazards (such as crew hypoxia).
Boeing Space Station Survivability and Vulnerability

Assessment Method Process Flow

- Acceptable Risk Definition
- Environmental Model
- Impact Testing
- Penetration Mechanics
- Find Critical Particles
- Calculate Hazard Probability
- Are Results Acceptable?
  - Yes → Stop
  - No → Acceptable Options for Mitigating Risk
    - Trade Studies:
      - On Orbit Detection & Repair
      - Flight Restrictions
      - Hardware Modifications
      - Etc.
- Mission Parameter Definition
- FMEA & Hazard Analysis
- System Analyses
- Spacecraft Configuration Definition
• Space station natural and induced environments
• Meteoroid and orbital debris threat definition
• Requirement definition
• Assessment methods

Shield development
• Component vulnerability
• Other
• Concluding remarks
Boeing Space Station Survivability and Vulnerability

Shield Development

- Ballistic limit equation development
- Designing to a probabilistic requirement
- Shield design considerations
- Shield qualification
Boeing Space Station Survivability and Vulnerability

Shield Development

Ballistic limit equation development

- Hypervelocity impact tests parameters
  - Solid, spherical, aluminum projectiles
  - Impact velocities to 7 km/sec
  - Destructive tests: 2 - 3 times as many targets as required data points
  - Typical test matrix
    - 3, 5, and 7 Km/sec
    - Impact angles: 0°, 30°, & 60°
    - Three shots per ballistic limit point to find failure point

- Built starting with existing database
  - Whipple shield impact data

- Generalized shape of curve based on NASA shield concept testing

- Test types
  - Development
  - Pre-declared development
  - Certification

Approximately 50 test articles per shield configuration for performance equations for ideal case
Boeing Space Station Survivability and Vulnerability

Shield Development

Designing to a probabilistic requirement

• Flexibility to designer
  – Allows shield layout adjustment to accommodate other design requirements
  – Allows probability matching
  – Allows for the introduction of localized weak spots
  – Allowed wide diversity in number of ISS shield types
  – Not good where a specific design solution is desired

• Design / development approach
  – Ballistic limit equations for conceptual design
  – Initial assessment (ideally at SRR) of performance against spec
  – Allow margin for changes associated with maturing design
    • Coverage
    • Certification tests
    • Process specification / manufacturability issues
    • Programmatic changes
Top Shield Design Considerations and Issues

- Weight
- Static discharge
- Ascent venting
  - Blanket
  - Outer shield
- Touch temperature
- Intermediate Nextel/Kevlar blanket per "customer request"
- Contamination
  - Kevlar, Nextel sizing
- Blanket fabrication
- Brackets for intermediate shielding "anywhere" on cylinder
- Assembly sequence and configuration changes due to self shadowing
- Late design modifications or operational changes that removed shielding
LAB PRIMARY DEBRIS SHIELD, INTERMEDIATE DEBRIS SHIELD & MLI BLANKET INSTALLATION

LONGERON CAP
Primary Structure

Tridair Fastener

PRIMARY DEBRIS SHIELD (Al)

Secondary Structure (Al)

Quarter-Turn Fasteners

Primary Debris Shield Bracket (Al)

MLI BEAM WRAP

MLI

INTERMEDIATE DEBRIS SHIELD
Kevlar/Nextel Blanket

1.9 in.

4.1 in.

Intermediate Debris Shield Bracket (Ti)

Intermediate Debris Shield Stave (Stainless)

Intermediate Debris Shield Bracket (Al)

Note: Similar MLI Bracket (Al)

Omitted for Clarity

MLI
• Verified by analysis supported by test data
• Shield certification tests performed on “flight-like” hardware
  – Material certification records
    • Ideally from same mill run
  – Full participation of Quality Assurance
    • Checked test articles compared to test control documentation
    • Checked off on each step of test procedures
• Test facility requirements
  – Tests [parameters] are repeatable
  – Projectile velocity validated by at least two independent methods
  – Integrity of the projectile prior to impact must be verifiable
  – Test must be “clean”
    • No other material such as sabot material, piece of burst valve, piston material, etc. has impacted the test sample
Boeing Space Station Survivability and Vulnerability

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- Space station natural and induced environments
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Component vulnerability
- Other
- Concluding remarks
"Just tell me which (wire, tube, box, etc.) is going to break and we will shield it."

ISS S0 Truss Segment during component installation at Kennedy Space Flight Center
Boeing Space Station Survivability and Vulnerability

Component Vulnerability

What was tested and/or analyzed

- Wiring
  - 1553 data cables (22 gauge)
  - Small power cables (8 gauge)
  - Large power cables (4 gauge)
  - Configuration / implementation
    - Wire harnesses, Remote Manipulator Arm

- Stainless tubing
  - 0.028" thick ammonia lines

- Crew return vehicle thermal protection materials
- EVA suit materials
- Solar alpha rotary joint
- Radiator configurations
- Solar array materials
- Composite tubes
- Slidewire cord

Meteoroid / Orbital Debris
Survivability and Vulnerability
Boeing Space Station Survivability and Vulnerability

Component Vulnerability

What was found

- Most vulnerable components
  - 1553 data cables
  - Stainless tubing
- Failure modes
  - EM shielding on 1553 cables shorted to conductor upon impact
  - Holes in tubing
- Surprises
  - Beta cloth shroud on S0 increased failing particle size (for unprotected 1553) from ~0.35 mm to ~2 mm based on test results
  - Beta cloth wrap on tubing increased failing particle size from ~0.35 mm to ~1 mm
Boeing Space Station Survivability and Vulnerability

Presentation Outline

- Space station natural and induced environments
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- Component vulnerability

Other

- Concluding remarks
• **Ground-tracked objects collision avoidance**
  - ~1% risk of collision without collision avoidance
  - ~1/2% for manned modules without collision avoidance

• **Leak location, leak detection, and repair**
  - Common repair kit under development
  - Methods to detect and isolate hole under development

• **Unstable crack growth mitigation**
  - Drove change in thickness of cylindrical section of pressure wall
    - 0.125" to 0.188" on US, European, and Japanese modules
  - Implemented via contract direction
    - Difficulties in implementing requirement
    - Upon determination that tooling could handle additional thickness, minimal impact
  - Russian design not susceptible to unstable crack growth
    - Softer alloy (AMg6)
    - Closely spaced rib pattern
• Space station natural and induced environments
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• Other

Concluding remarks
Concluding Remarks

**Boeing Space Station**
- Space environments
- Threat environments
- Boeing's development approach
- Established processes
  - Testing
  - Assessment
  - Shield design and fabrication

**Workshop**
- Summarize environmental hazards and directed threats to commercial and military spacecraft performance
- Explore how aircraft survivability analysis and enhancement methodologies may be applied to improve spacecraft survivability from these hazards
- Discuss current spacecraft and aircraft survivability analysis methods, tools, and testing
Orbital Debris Risk Mitigation

Reduce \( N_{\text{impact}} \)
- Environmental Definition
- Debris Reduction, Tracking, & Avoidance

Reduce \( P_{\text{penetration/impact}} \)
which is to say Increase \( P_{\text{NP}} \)
- Penetration
- Ricochet
- Spallation

Augmented Shields and Materials
Analysis Tool: BUMPER

\[
P_{\text{loss}} = 1 - \exp(-N_{\text{impact}} \times P_{\text{penetration}}) \\
= 1 - \exp(-N_{\text{pen}} \times P_{\text{loss}}) \\
PNCF = P_{\text{NP}}^R \quad \text{(Chart 20)}
\]

Reduce \( P_{\text{loss/penetration}} \) \( (R) \)
- Critical Cracking
- Thrust Hazard
- Critical Equipment Loss
- Injury Loss
- Hypoxia
- Critical module Depressurization

Equipment Locations
- Hatches Open/Closed
- Crew Position in Modules
- Sealing/Repair Strategies
- Internal Spall Blanket

Analysis Tool: MSCSurv
(Manned Spacecraft Crew Survivability)

6/14/00
Typical Ballistic Limit Curve

Smallest particle which perforates rear wall

Impact Velocity (km/sec)

0 2 4 6 8 10 12 14 16 70

Projectile intact  Breakup  Melt  Vaporization

Two stage light gas guns

Limited test methods - no production methods

Momentum

Energy

Meteoroid / Orbital Debris
Survivability and Vulnerability

6/14/00
Boeing Space Station Survivability and Vulnerability

Concluding Remarks

What about 7km/s+?
What about shape effects?
What about particle density?

Is a penetration always a failure?

Acceptable Risk Definition

Environmental Model

Impact Testing

Penetration Mechanics

What about the uncertainties and time variability?

Spacecraft Configuration Definition

Find Critical Particles

Calculate Hazard Probability

Are results acceptable?

Acceptable Options for Mitigating Risk

Trade Studies
- On Orbit Detection & Repair
- Flight Restrictions
- Hardware Modifications
- Etc

Programmatic response to mitigation options.
"Is this a make work change?"

Stop

Yes

No

No

Acceptable Options for Mitigating Risk

Trade Studies
- On Orbit Detection & Repair
- Flight Restrictions
- Hardware Modifications
- Etc

Programmatic response to mitigation options.
"Is this a make work change?"
US Laboratory and Airlock Enhanced
Meteoroid / Orbital Debris Shielding

**Space facing**

- **Outer shield**: 0.20 cm (0.080 in) Aluminum 6061-T6
- **Multilayer thermal insulation**
- **Intermediate debris shield blanket**: 6 layers Nextel 312 Style AF-62 (top), 6 layers Kevlar 29 Style 710 (bottom) encased in Betacloth
- **Pressure wall**: 0.48 cm (0.188 in) Aluminum 2219-T87

**Module Interior**

High threat areas on European and Japanese modules are protected with similar shielding with variations in spacing, thicknesses, and material composition, primarily in the composition of the intermediate shield.

Nextel is a registered trademark of the 3M company.

Kevlar is a registered trademark of the DuPont company.
US Laboratory and Airlock
Meteoroid / Orbital Debris “Whipple” Shield

Space facing

---

Outer shield
0.20 cm (0.080 in) Aluminum 6061-T6

10.8 cm (4.232 in)

Multilayer thermal insulation

Pressure wall
0.48 cm (0.188 in) Aluminum 2219-T87

Module Interior

Shields on Node 1, the Pressurized Mating Adapters, endcones of the US Lab, Airlock, European, and Japanese are similar with slight variations in spacing, thicknesses, and material composition.
Cupola Trapezoidal Window

Space facing

Outer meteoroid/debris pane
0.93 cm (0.37 in) Fused Silica

Redundant pressure pane
2.54 cm (1.0 in) Fused Silica

Primary pressure pane
2.54 cm (1.0 in) Fused Silica

Inner scratch pane
1.14 cm (0.45 in) Fused Silica

Module Interior

The round window in the end of the Cupola, the European Cupola windows, and US module windows are similar with slight variations in spacing and thicknesses.