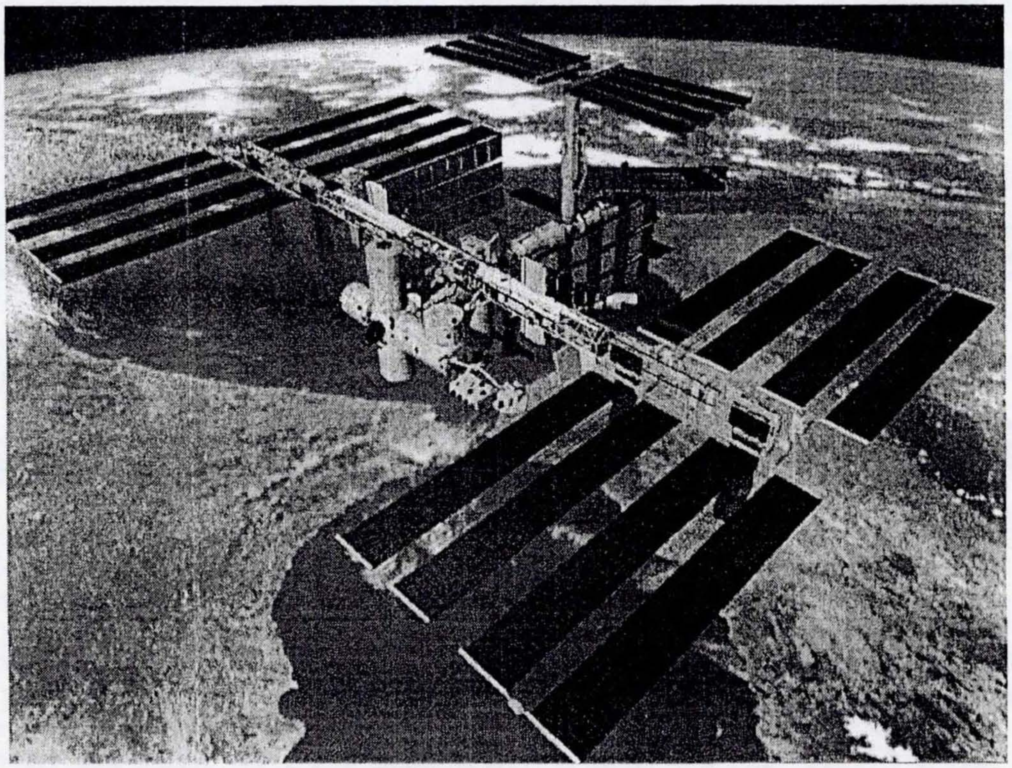

Image courtesy NASA

Space and Air Survivability Workshop 2000

International Space Station

Meteoroid / Orbital Debris Survivability and Vulnerability

BOEING

Russell Graves
The Boeing Company
Houston, Tx
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International Space Station

Elements currently in orbit

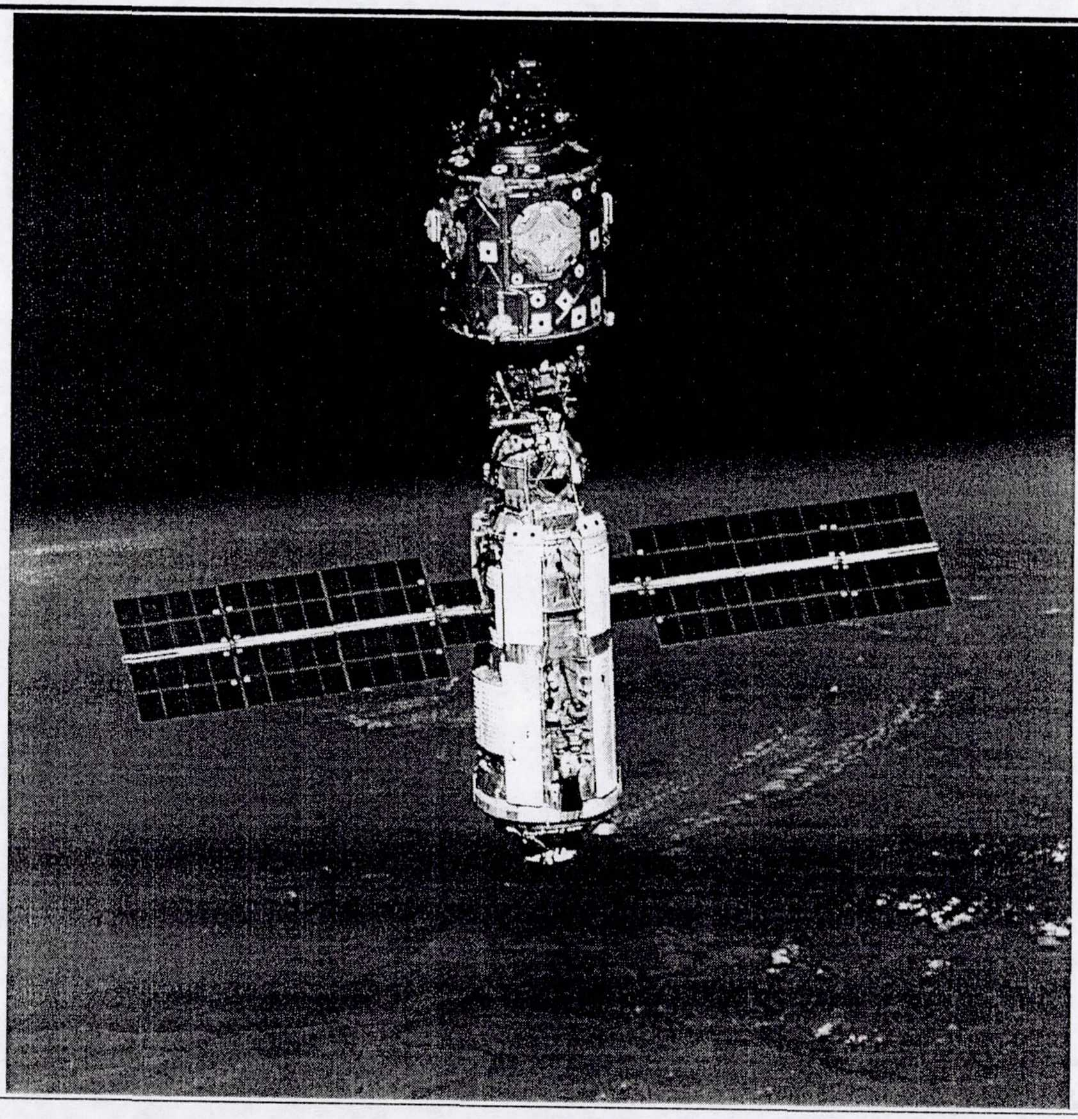


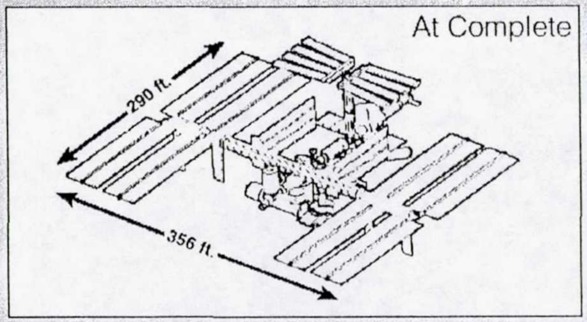
Photo courtesy NASA

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

	Today	Percent	At Complete
Weight (lbs)	74,000	7.4%	~1 Million
Volume (cf)	5,045	12.0%	43,000
Power (kw)	2	1.4%	110
Atmosphere (psi)	14.7	yes	14.7
Inclination (degrees)	51.6	yes	51.6
Altitude (miles)	220	yes	220
Crew (persons)	0	0.0%	7
Assembly Flights	3	4.3%	46



International Space Station

Data Points

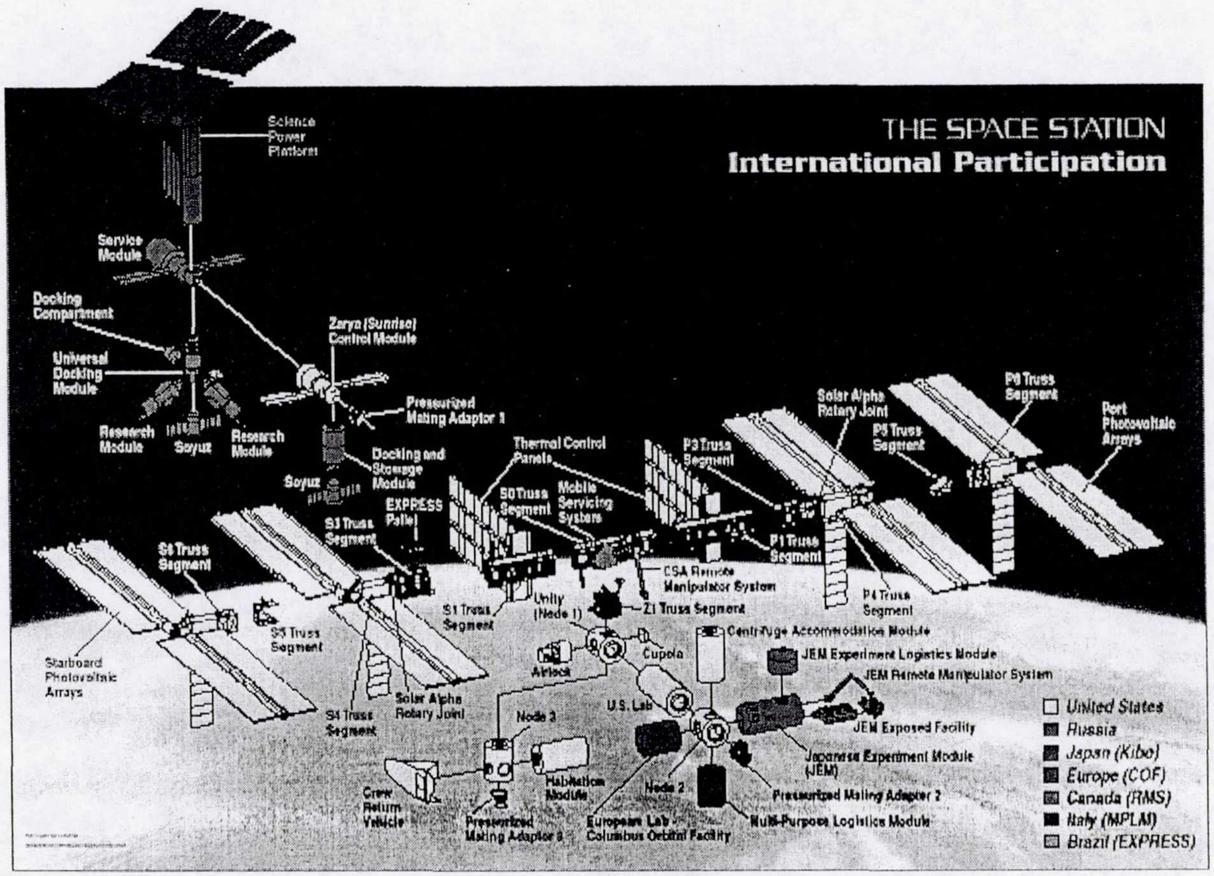
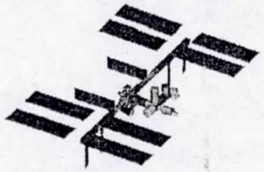


Image courtesy NASA, International Space Station Fact Book

- 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

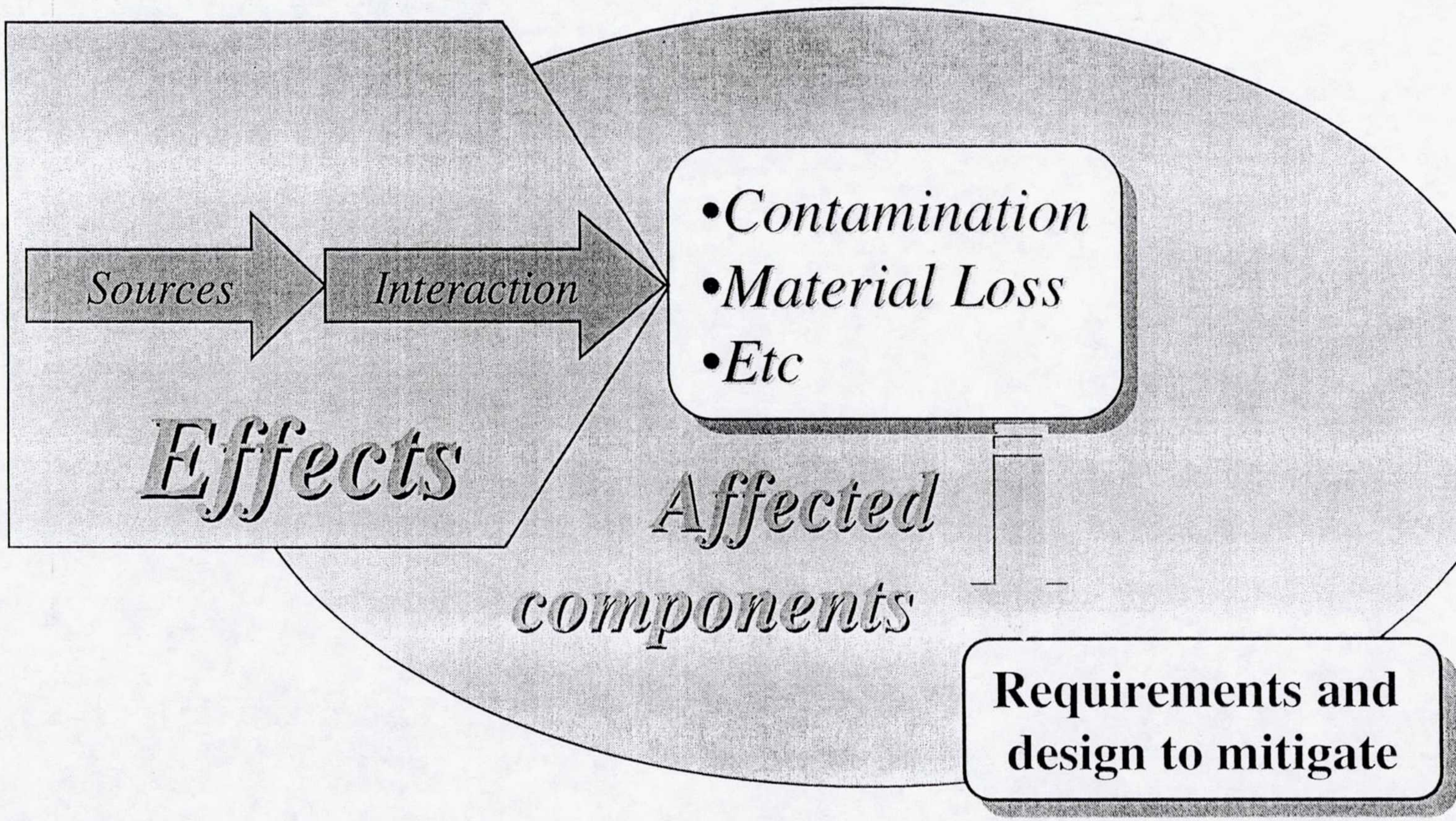
Site \ Capability	Vulnerability Analysis	Shield Design	Product Assurance	Environment Modelling	Trajectory assessment	Collision Avoidance	Tracking / observation	Shield Fabrication	Hypervelocity Impact Testing	Hypervelocity Test Method Dev.	Laser Systems
Canoga Park	X	X						X			X
Colorado Springs				X			X				
Downey	X	X	X							X	
Houston	X		X		X	X	X				
Huntington Beach	X	X	X					X			X
Huntsville	X	X	X					X			
Seattle	X	X							X		

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

- → **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



Space Environments

Neutral Atmosphere and Atomic Oxygen

Neutral Atmosphere Environment

Sources
- •Natural Atmosphere
- •Vacuum Venting
- •Transfer Vehicle Operations
- •Reboost / attitude control
- •Payload Operations
- •Off-gas / Out-gas
- •Leaks
- •EVA/Airlock

Interaction
- •Erosion
- •Ram / Wake
- •Deposition

Component
- •Structures
- •Solar Arrays
- •Surface Materials
- •Payloads

Effects
- •Contamination
  - •Reflectance
  - •Absorbtivity
  - •Emissivity
- •Material Loss
- •Coating Loss
- •Thermal Control
- •Instrumentation
  - •Accuracy
  - •Sensitivity

Atomic Oxygen Environment

Sources
- •LEO Natural Atmosphere

Interaction
- •Direct impingement
- •High Velocity Impact with ram surfaces
- •Excited species generation causing surface glow

Component
- •Surface Materials
- •Solar Arrays
- •Optical Sensors
- •Payloads
- •Lubricants
- •EVA suits

Effects
- •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

Space Environments

External Contamination and Ionizing Radiation

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External Contamination Environment

Sources
- Material outgassing and offgassing
- Ground processing and non-volatile residue

Interaction
- 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

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

Ionizing Radiation Environment

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

Interaction
- Upset
- Latchup
- Burnout
- Total dose
- Cancer induction
- MTL degradation (bond breaking)
- Create color centers

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

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

Space Environments

Plasma and Thermal

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Plasma Environment

Sources
- Natural Plasma
- UV ionizations
- Solar Arrays
- Charge exchange
- Experiments/Probes/EM sources

Interaction
- Charge balance
- Discharges: corona, arc
- Currents: conductors, dielectrics
- Fields: **V**x**B**, **E**, **B**
- Sheaths
- Sputtering
- Ram / wake
- Photoelectron emission
- Secondary electron generation

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

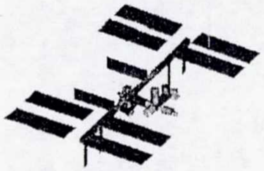
Thermal Environment

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

Interaction
- Radiation heat transfer

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



Space Environments

Thermal Vacuum and Meteoroids/Orbital Debris

Thermal Vacuum Environment

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

Interaction
- Outgassing
- Evaporation
- Sublimation

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

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

Meteoroids and Orbital Debris Environment

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

Interaction
- Impacts
  - Perforations
  - Craters
  - Ricochet

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

Effects
- Structural failure / pressure loss
- Degradation of optical properties of exposed equipment
- Component failure and degradation
- EVA threat
- Surface coating penetration

Space Station Environments

Summary

- 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

- Space station natural and induced environments
- ⇒ Meteoroid and orbital debris threat definition
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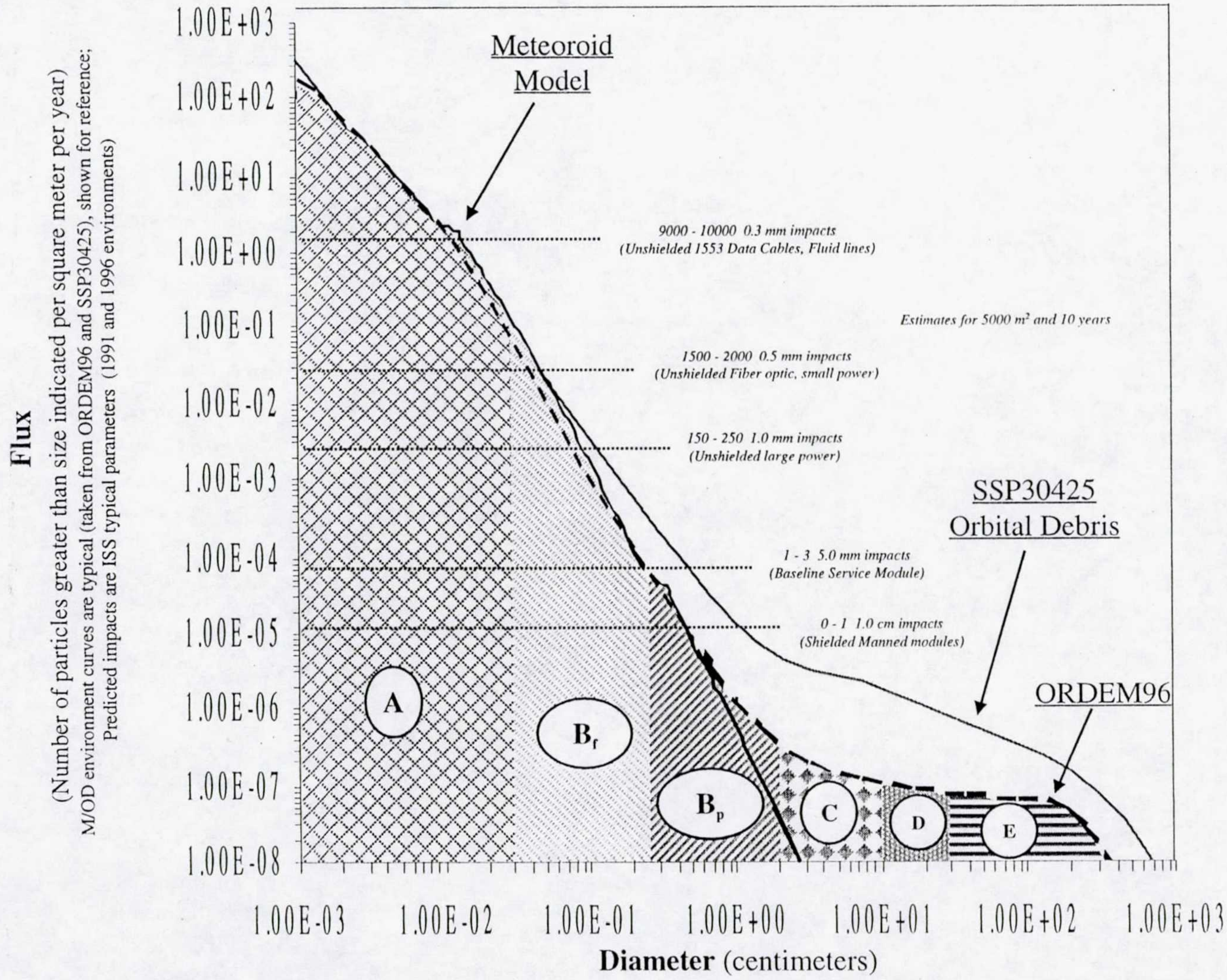

Legend:

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.

Comparative Orbital Debris and Meteoroid with SSP 30425 Orbital Debris Environment Shown

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
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- 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 $n = f * a * t$ = the expected number of perforations
      - f = penetrating flux
      - a = exposed critical area
      - t = exposure time

Similarity to Probability of no Impact

- 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

- 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 equipment loss
      - Hypoxia related losses
      - Secondary injury loss
    - Assessed but not included in catastrophic risk tally
      - Critical module depressurization
      - Non-fatal injuries

- Probability of no subcomponent penetration
  - Lesson learned
  - Partially implemented due to "pre-existing hardware" and other constraints

System-level Criticality \ MTBF (hours)	<50,000	50,000 to 872,000	>872,000
1	$(0.999898)^{area(m^2)}$	$(0.999898)^{area(m^2)}$	$(0.999898)^{area(m^2)}$
1R	0.84	$\exp^{(-\frac{365*24}{mtbf(hours)})}$	0.99
2	0.7	$\exp^{(-\frac{2*365*24}{mtbf(hours)})}$	0.98
2R	0.6	$\exp^{(-\frac{3*365*24}{mtbf(hours)})}$	0.97
3	0.5	$\exp^{(-\frac{4*365*24}{mtbf(hours)})}$	0.96

- 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:

Partial implementation

  - 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

- Space station natural and induced environments
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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

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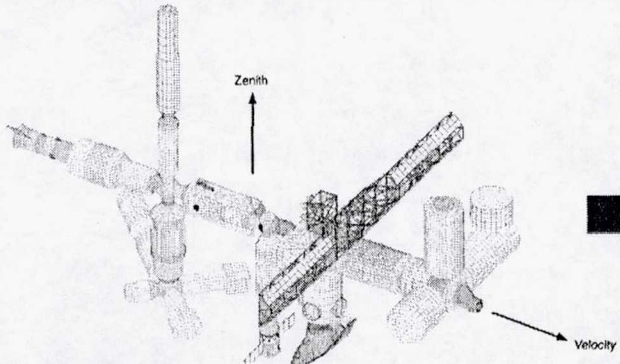
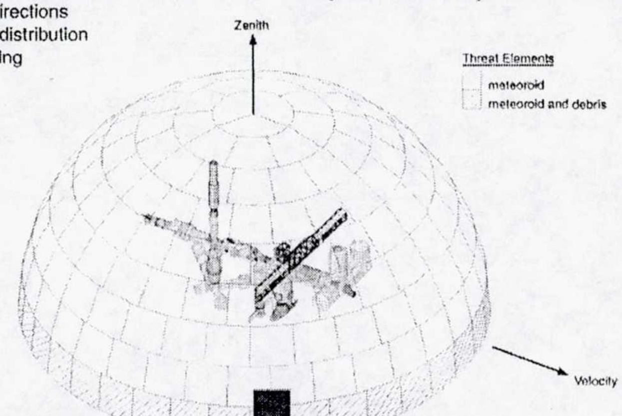
Spacecraft Configuration (I-DEAS)

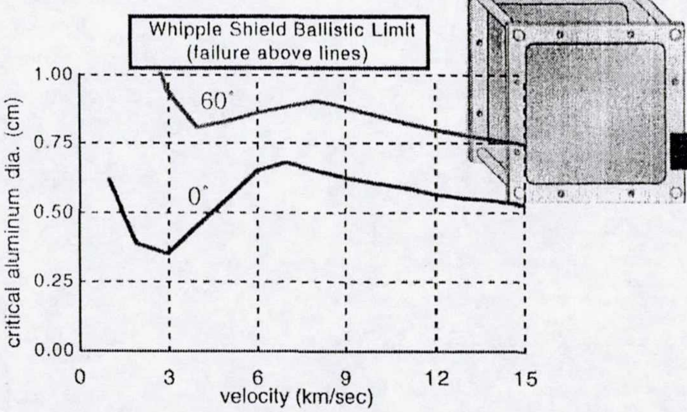


I-DEAS Finite Element Model
- Describes spatial relationships of spacecraft components
- Defines spacecraft orientation (velocity and zenith directions)
- Defines M/OD shield regions

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



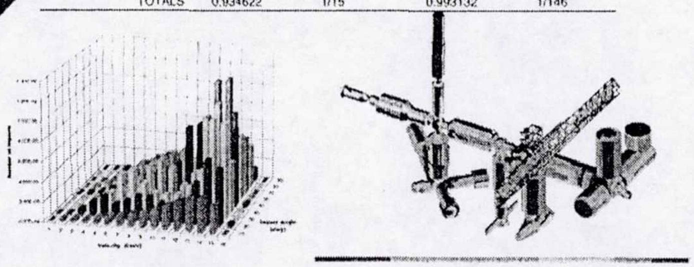
Critical Particle Diameter Calculation (RESPONSE)
- Protection capability

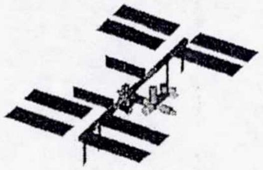


Computation of Penetrating Flux and PNP (SHIELD)
Graphical Interpretation of Results (EXCEL & I-DEAS)

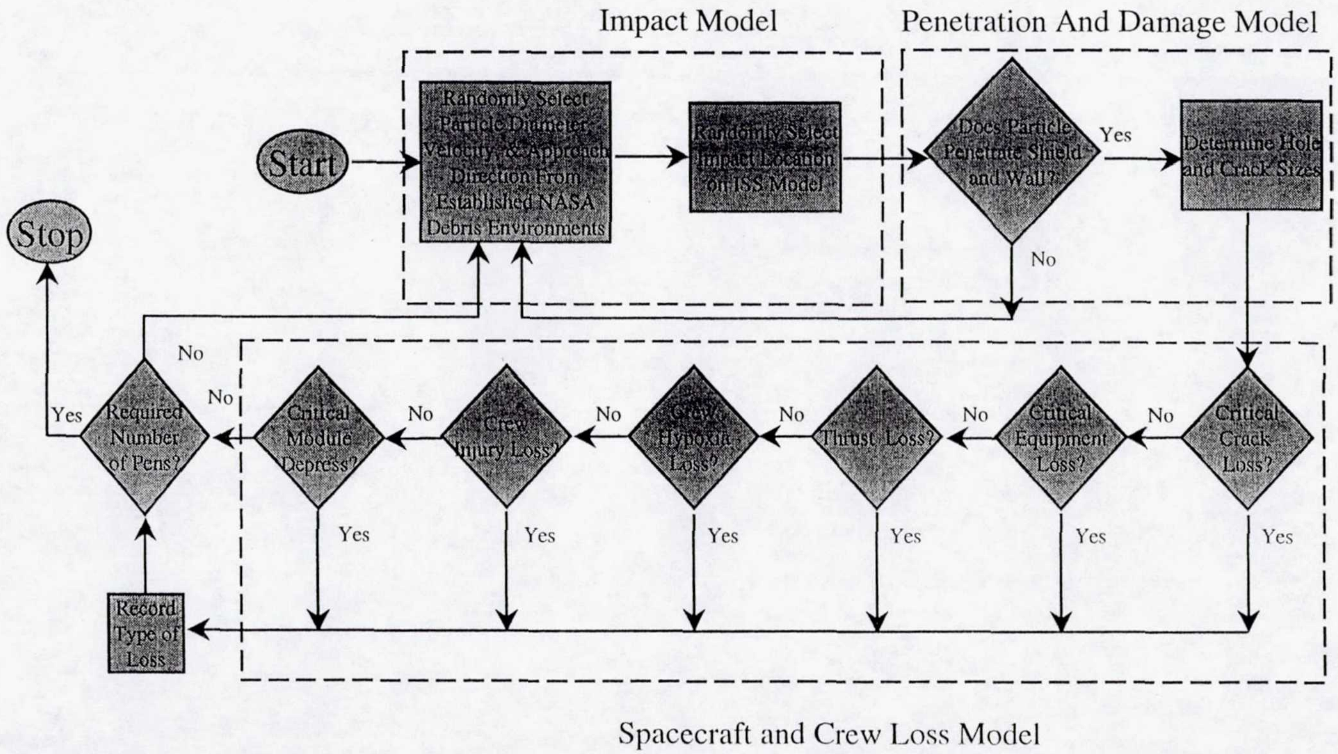
Space Station Orbital Debris Threat Assessment

Station Region	Impact Risk From 1mm Ø Debris: Probability No Impact	Impact Risk From 1mm Ø Debris: Odds of Impact	Debris Penetration Risk: Probability No Penetration	Debris Penetration Risk: Odds of Penetration
FGB	0.995338	1/214	0.995541	1/224
Service Module	0.999335	1/1505	0.999796	1/4912
Node 2	0.990465	1/105	0.999998	1/625000
Hab Module	0.965074	1/29	0.998923	1/928
Lab Module	0.985522	1/69	0.999022	1/1023
CRV	0.997443	1/391	0.999839	1/6223
TOTALS	0.934622	1/15	0.993132	1/146





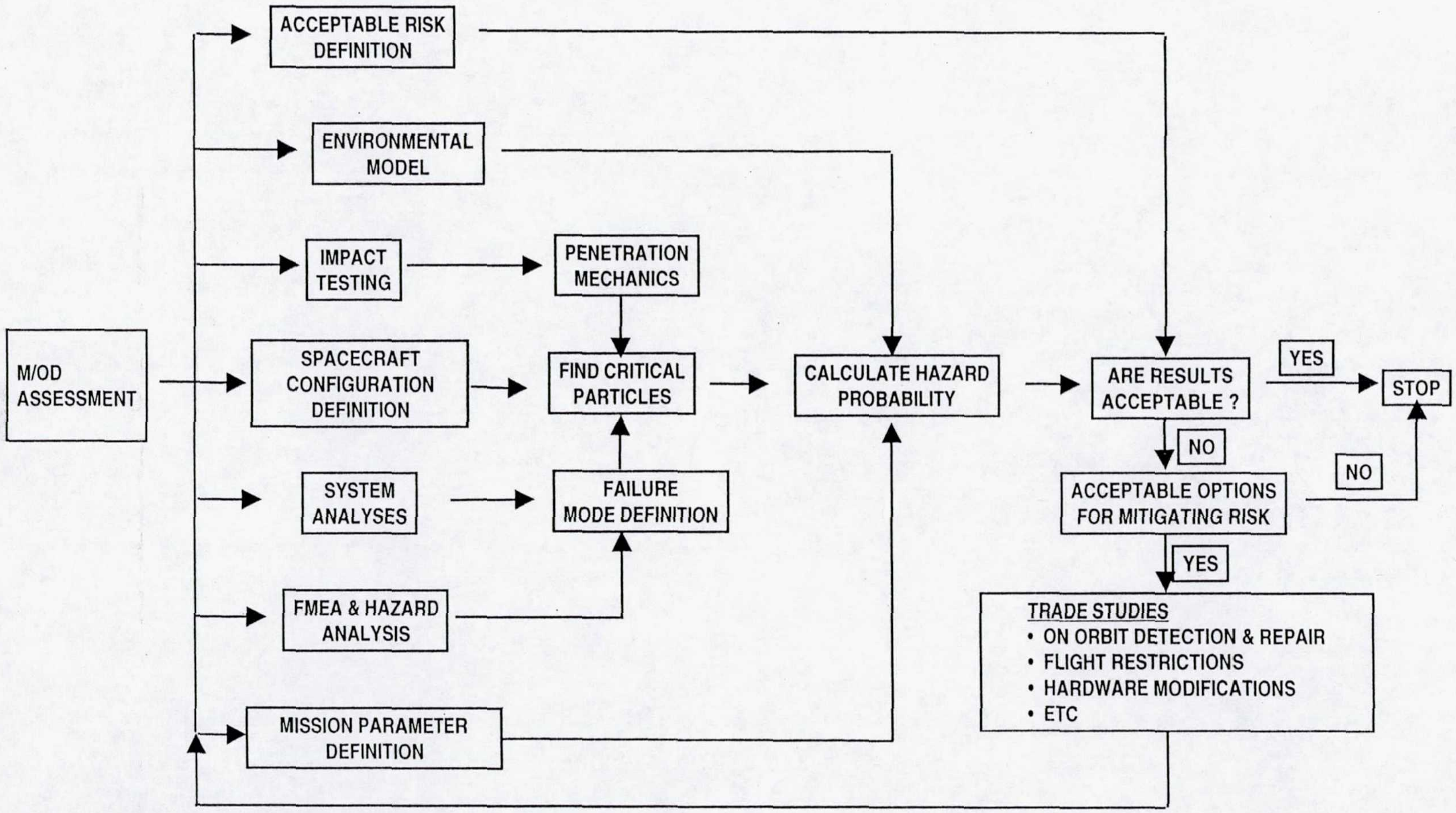
MSCSurv 4.1 FLOWCHART



• 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



- Space station natural and induced environments
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- → Shield development
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Shield Development

- Ballistic limit equation development
- Designing to a probabilistic requirement
- Shield design considerations
- Shield qualification

- 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

Approximately 50 test articles per shield configuration for performance equations for ideal case

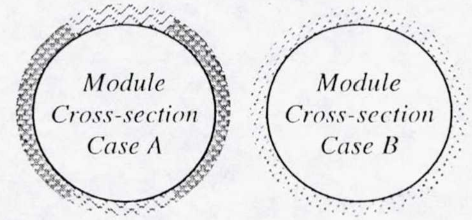
- Built starting with existing database
  - Whipple shield impact data
- Generalized shape of curve based on NASA shield concept testing
- Test types
  - Development
  - Pre-declared development
  - Certification

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

Shield Development

Top Shield Design Considerations and Issues

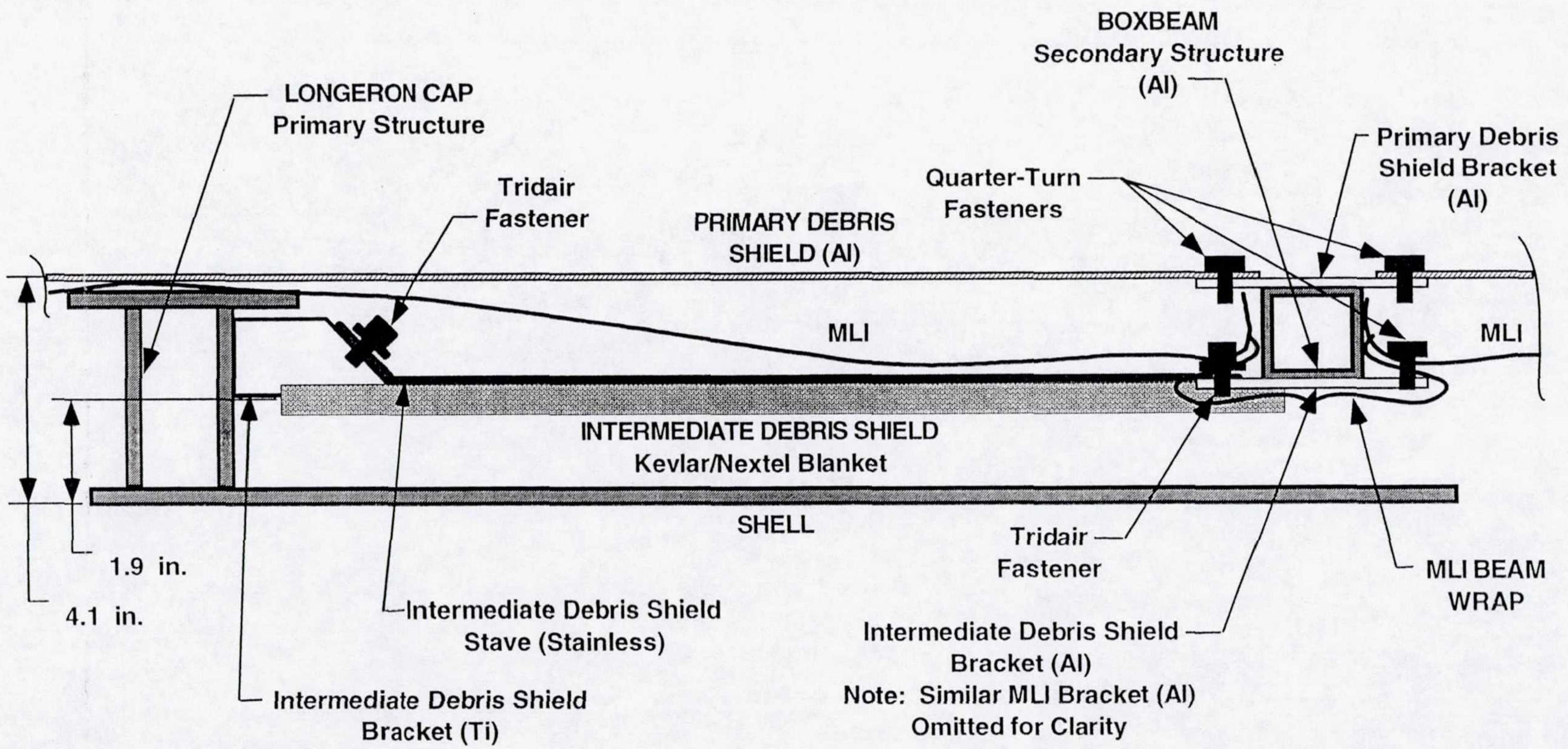
- Weight
- Static discharge
- Ascent venting
  - Blanket
  - Outer shield
- Touch temperature
- Intermediate Nextel/Kevlar blanket per "customer request"
- Contamination
  - Kevlar, Nextel sizing
- Blanket fabrication
- Brackets for intermediate shielding "anywhere" on cylinder

↑ *Design*

↓ *Program*

- 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



- 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

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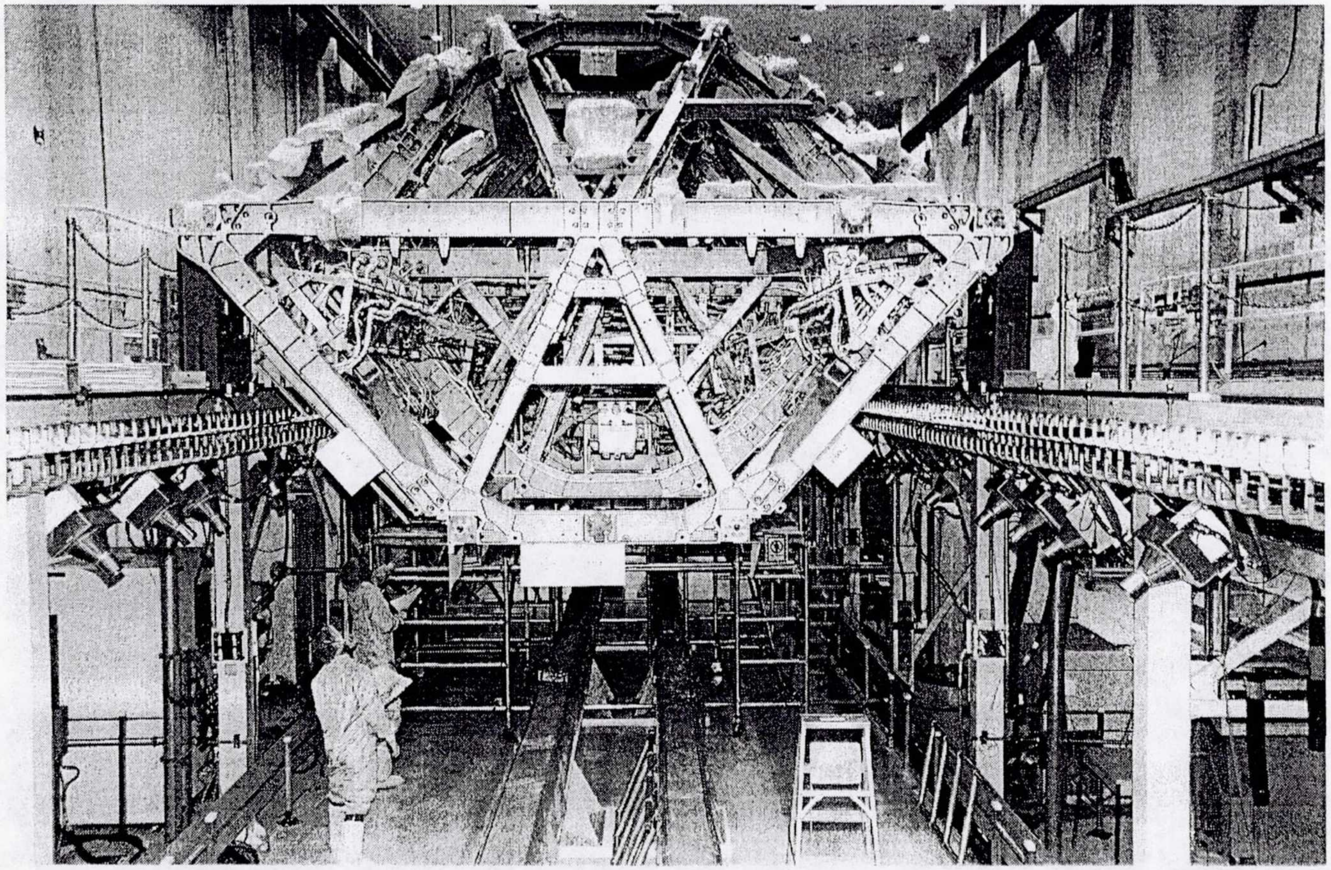
"Just tell me which (wire, tube, box, etc.) is going to break and we will shield it."



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

Powered and unpowered

- 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

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

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Boeing Space Station Survivability and Vulnerability
"Other"

- ***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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→ Concluding remarks

Concluding Remarks

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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

Supporting Material

Orbital Debris Risk Mitigation

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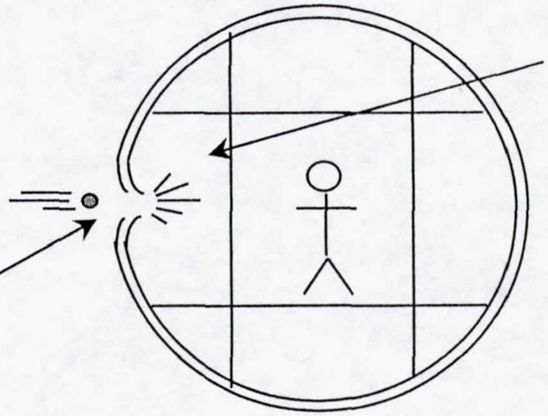


Reduce N_{impact}

- Environmental Definition

→ **Debris Reduction, Tracking, & Avoidance**

Reduce $P_{penetration/impact}$ which is to say Increase PNP

- Penetration
- Ricochet
- Spallation

→ **Augmented Shields and Materials**

Analysis Tool: BUMPER

Reduce $P_{loss/penetration}$ (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

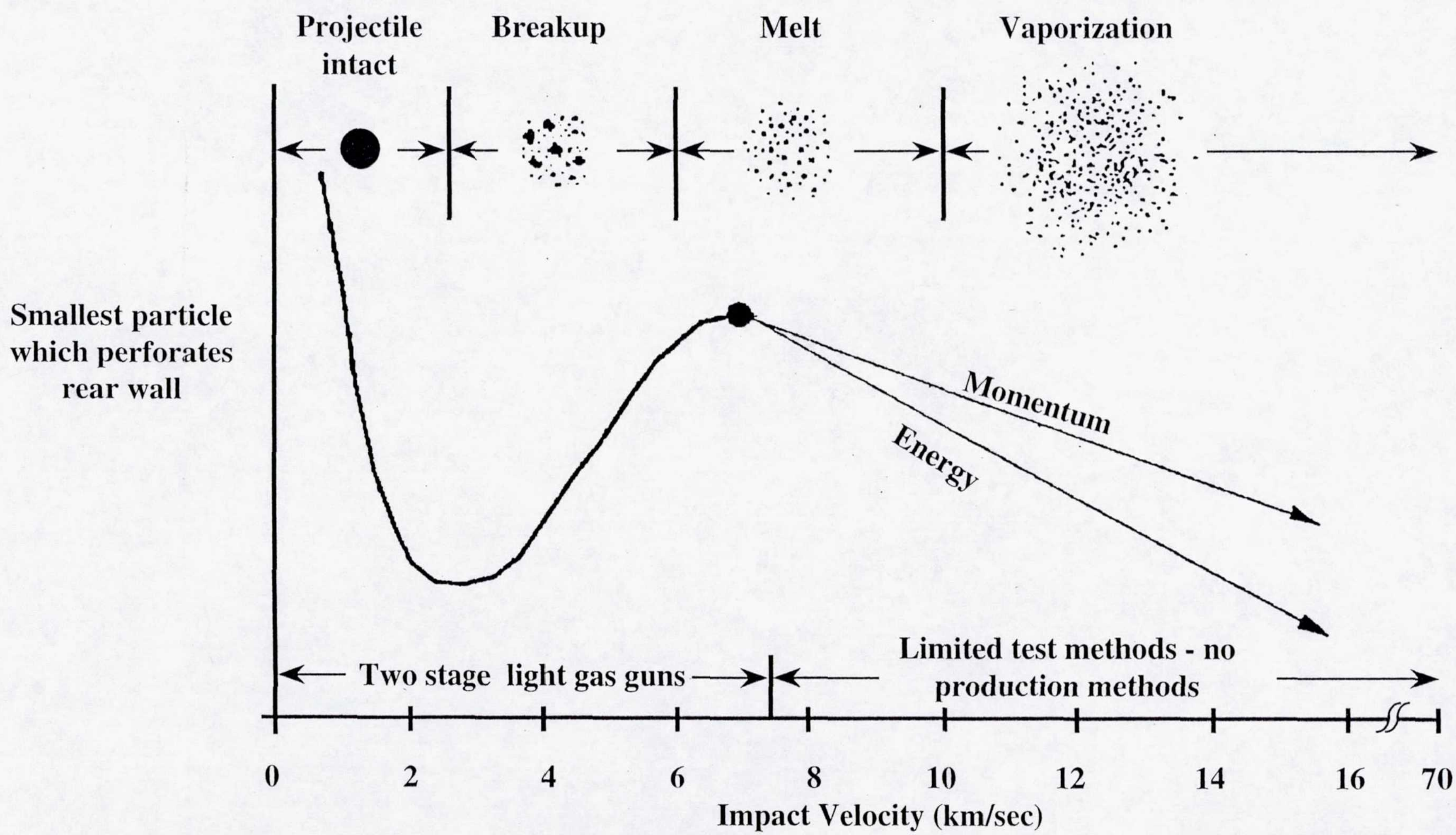
Analysis Tool: MSCSurv
(Manned Spacecraft Crew Survivability)

$$P_{loss} = 1 - \exp(-N_{impact} \times P_{\frac{penetration}{impact}} \times P_{\frac{loss}{penetration}})$$

$$= 1 - \exp(-N_{pen} \times P_{\frac{loss}{penetration}})$$

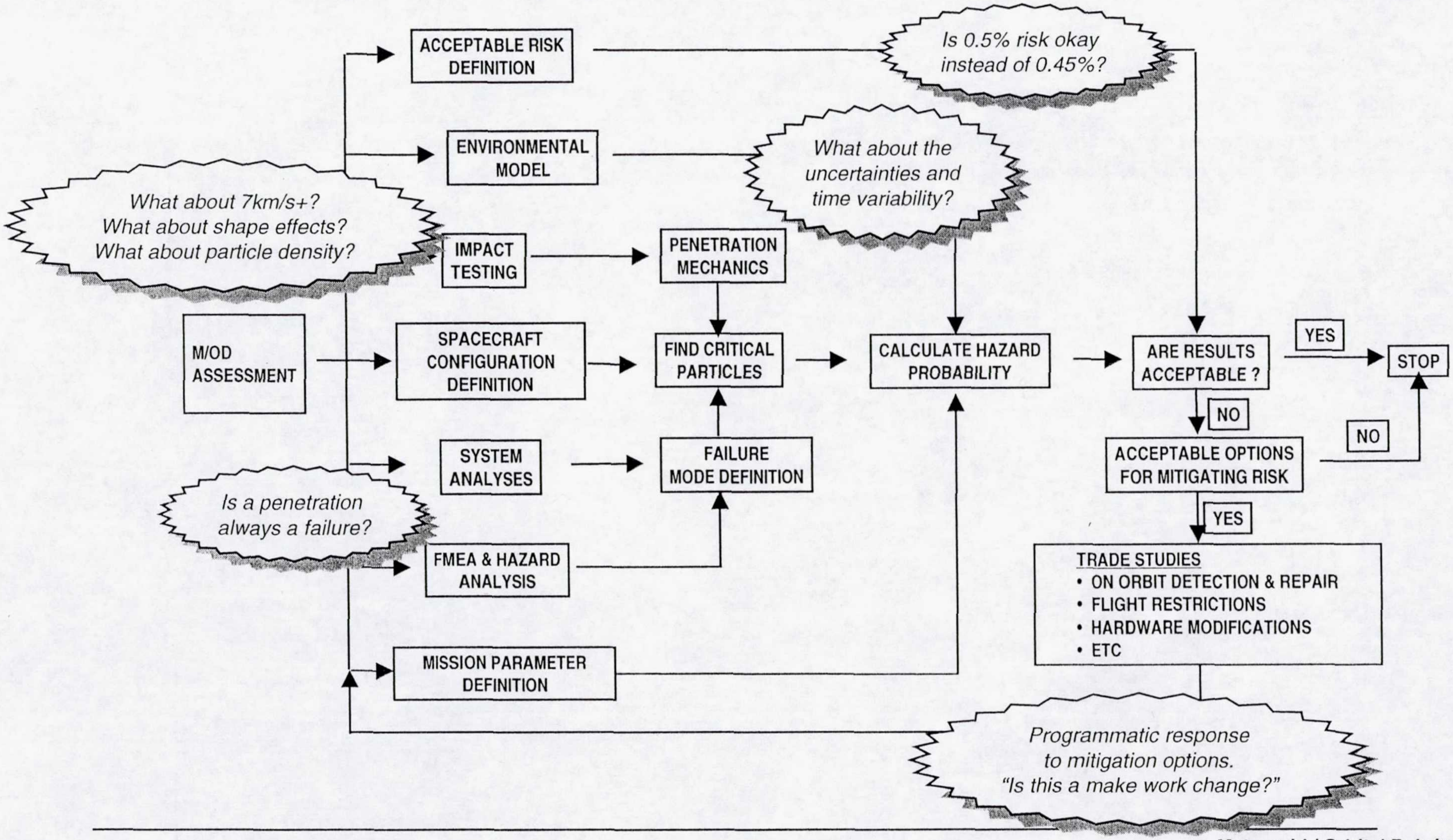
$$PNCF = PNP \wedge R \text{ (Chart 20)}$$

Typical Ballistic Limit Curve



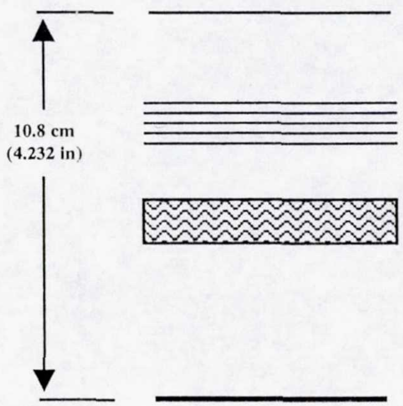
Boeing Space Station Survivability and Vulnerability

Concluding Remarks



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**

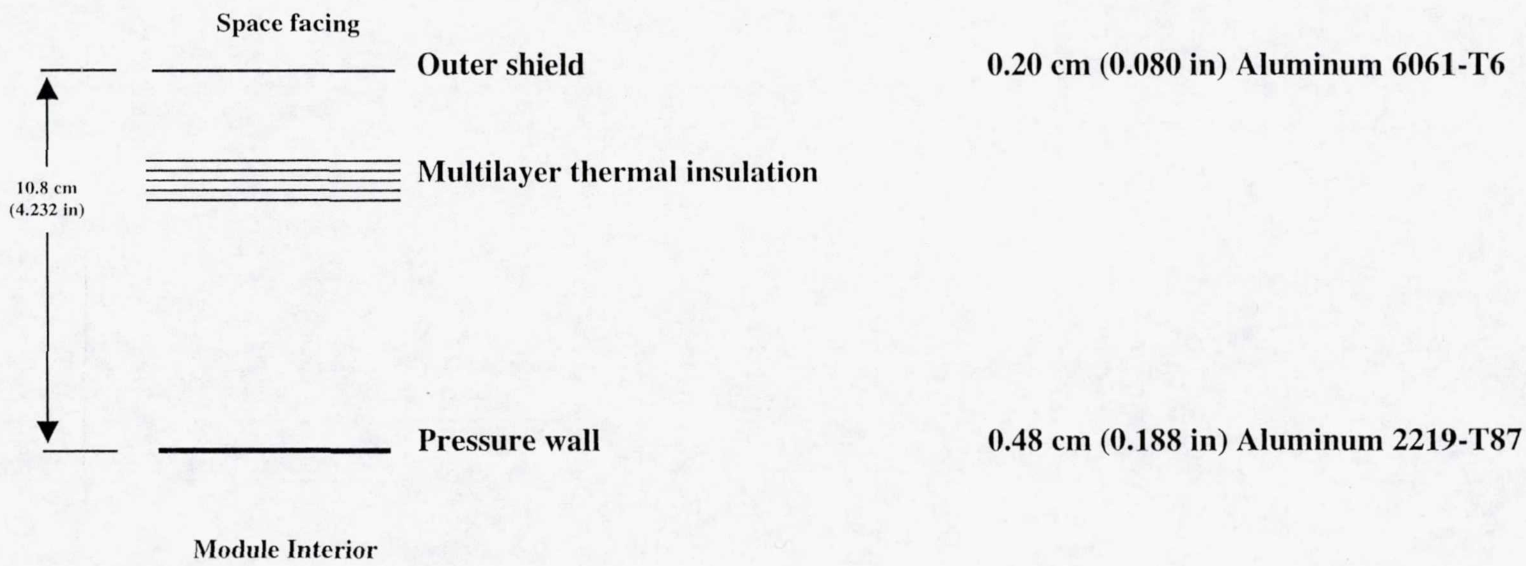
Module Interior

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.

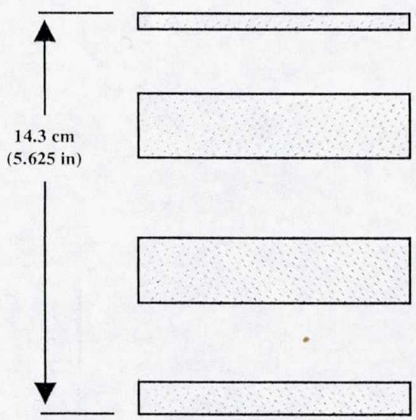
US Laboratory and Airlock
Meteoroid / Orbital Debris "Whipple" Shield



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.