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Independent Review of U.S. and Russian Probabilistic Risk Assessments for the International Space Station Mini Research Module #2 Micrometeoroid and Orbital Debris Risk

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Langley Research Center, Hampton, Virginia

March 2011

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Independent Review of United States and Russian Probabilistic Risk Assessments (PRAs) for the International Space Station (ISS) Mini Research Module #2 (MRM-2) Micrometeoroid and Orbital Debris (MMOD) Risk

February 3, 2011

Approval and Document Revision History

NOTE: This document was approved at the February 3, 2011, NRB. This document was submitted to the NESC Director on February 10, 2011, for configuration control.

Approved Version:	*Original Signature on File*	2/10/11
1.0	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Mr. Michael Squire, NESC Back-up Principal Engineer	2/3/2011

Table of Contents

Volume I: Consultation Report

Volume II: Appendices

List of Figures

List of Tables

1.0 Notification and Authorization

Mr. Michael Suffredini, International Space Station (ISS) Program Manager, requested an independent review of the separate micrometeoroid and orbital debris (MMOD) catastrophic risk assessments for the Mini-Research Module-2 (MRM-2) performed by both the Russian Federal Space Agency and NASA. The risk assessments produced by the two organizations differed by roughly one order of magnitude.

This NESC assessment was approved as an out-of-board activity on November 2, 2009 by the NESC Director. Mr. Michael Squire, Back-up Principal Engineer at the NASA Langley Research Center (LaRC), was selected to lead this assessment. The stakeholder requested a short duration for this activity, so the requirement for an assessment plan was waived. The results of the assessment were presented to the stakeholders on December 17, 2009. The final report was presented and approved by the NESC Review Board on February 3, 2011.

The stakeholders for this assessment were Mr. Michael Suffredini and the ISS Program.

2.0 Signature Page

Submitted by:

Team Signature Page on File – 3/10/11

Mr. Michael Squire Date

Significant Contributors:

Dr. Joel Williamsen Date

Mr. Dana Lear Date

Dr. William Schonberg Date

Dr. Fayssal Safie Date

Signatories declare the findings and observations compiled in the report are factually based from data extracted from Program/Project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

Name	Discipline	Organization
Core Team		
Michael Squire	Lead/NESC Principal Engineers Office	LaRC/NESC
Dana Lear	MMOD	JSC/Human Exploration Science Office
Hank Rotter	Technical Fellow for Life Support and Active Thermal Control	JSC/NESC
Fayssal Safie	Technical Fellow for Reliability and Maintainability	MSFC/NASA Safety Center
William Schonberg	MMOD Protection System Design	Independent Consultant
Joel Williamsen	MMOD Survivability	Institute for Defense Analysis
Pamela Throckmorton	MTSO Program Analyst	LaRC/NESC
Administrative Support		
Pamela Sparks	Project Coordinator	LaRC/ATK
Donna Gilchrist	Planning and Control Analyst	LaRC/ATK
Christina Williams	Technical Writer	LaRC/ATK

4.0 Executive Summary

The Mini-Research Module-2 (MRM-2), a Russian module on the International Space Station (ISS), does not meet its requirements for micrometeoroid and orbital debris (MMOD) probability of no penetration (PNP). To document this condition, the primary Russian Federal Space Agency ISS contractor, S.P. Korolev Rocket and Space Corporation-Energia (RSC-E), submitted an ISS non-compliance report (NCR), NCR-RS-MRM2-01 (Appendix E), which was presented at the 5R Stage Operations Readiness Review (SORR) in October 2009. In the NCR, RSC-E argued for waiving the PNP requirement based on several factors, one of which was the risk of catastrophic failure was acceptably low at 1 in 11,100 (0.009 percent). However, NASA independently performed an assessment of the catastrophic risk resulting in a value of 1 in 1380 (0.07 percent) and believed that the risk at that level was unacceptable. The NASA Engineering and Safety Center (NESC) was requested to evaluate the two competing catastrophic risk values and determine which was more accurate.

Because the outcome of this activity was requested to be complete within approximately 6 weeks, the analysis of the risk assessments of each organization was necessarily performed at a high level. The sources of divergence between RSC-E and NASA catastrophic risk assessments were identified as were further areas of analysis that would likely result in a convergence of risk assessment values. During the course of the activity, RSC-E and NASA refined their assessments and produced risk values that were within a factor of 2 of each other instead of the factor of 10 that was initially observed, so determining which assessment was more accurate became less urgent.

The MMOD catastrophic risk is calculated using the risk factor (R or R-factor), which is defined as the ratio of catastrophic[1] MMOD impacts to total MMOD impacts. The probability of no catastrophic failure (PNCF) is defined as PNCF = PNP^R. The catastrophic risk as a percentage is defined as 1-PNCF. To explore the influence PNP and R have on catastrophic risk, the NESC team performed a rudimentary sensitivity study varying PNP and R in PNCF calculations. The results show that while both PNP and R affects the PNCF, the effect of PNP is more pronounced. One source of disparity in PNP values (and catastrophic risk) was the MRM-2 finite element models (FEM) used by the MMOD risk assessment application Bumper II (*Bumper*). The FEM used by RSC-E was an older version and contained differences from the FEM used by NASA.

Differing values for R was another contributor to the disparate risk assessments. The RSC-E and NASA R-factors used in initial risk assessments were 0.010 and 0.090, respectively. Each R-factor is the summation of individual R-factors for each identified risk, and when the individual R-factors were compared, differences between NASA and RSC-E became evident. For example, RSC-E considered the loss of crew due to hypoxia and a docking unit failure to be higher risks

[1] A catastrophic failure is one that causes the loss of a crew member or loss of the spacecraft.

than NASA (i.e., the RSC-E R-factors for each of those risks are greater than NASA's). Similarly, NASA considered the risks due to fragmentation and internal equipment penetration to be higher than RSC-E, and those corresponding R-factors were greater for NASA than RSC-E.

For NASA, R-factors are calculated using the Manned Spacecraft and Crew Survivability (*MSCSurv*) program. In *MSCSurv*, the effects of impact velocity are incorporated into the hole diameter and crack length predictions using a momentum scaling factor for hole diameter and an energy scaling factor for crack length. In contrast, no velocity effects are evident in the hole diameter and crack length equations used by RSC-E, so the equations are valid only for a single impact velocity (6.5 km/s) from which the equations were empirically derived. In addition, there is some ambiguity as to the origin of the values for two of the coefficients used in the RSC-E crack length equation, where the values given in one reference do not match those provided in another. This may be another source of divergence between risk assessments.

Although the PNCF values converged during the course of this assessment, both the NASA and RSC-E PNCFs indicate that additional shielding should be installed on the MRM-2 to bring the PNP into compliance and reduce the catastrophic risk. In addition, because the PNCFs are still different by a factor of 2, the NESC team recommends that the two agencies continue to collaborate and decrease the discrepancy. As a part of this, the uncertainties associated with the R-factors and PNCFs should be defined. Finally, NASA's plans to reevaluate *MSCSurv* will provide R-factors that are a more accurate reflection of the current ISS configuration and operation.

5.0 Assessment Plan

The NESC team relied on documentation review (see References and the Appendices for specific documents) and interviews with NASA and Russian MMOD organizations to arrive at findings, observations and NESC recommendations. Information from NASA was provided by the NASA Astromaterials Research and Exploration Systems/Human Exploration Science (HES) Office. Questions for the primary Russian Federal Space Agency ISS contractor, RSC-E, were relayed through the HES to their RSC-E counterparts.

6.0 Problem Description and Background

6.1 MMOD Risk Assessment Methodology and Requirements

The PNP is used to assess the ability of a spacecraft to resist MMOD impacts. PNP for a given spacecraft is a function of the shield properties, the MMOD environment (flux, directionality, mass, size), configuration (e.g., the deployed position of radiators and solar panels may shadow areas of the spacecraft), flight attitude, and failure criteria. Bumper II (*Bumper*) is the tool used by NASA for calculating PNP. While the PNP gives the probability that an MMOD particle will inflict damage exceeding defined failure criteria, it does not describe the potential for the loss of life or the loss of the vehicle. The PNCF gives the probability that an MMOD penetration will not cause the loss of a crew member or the loss of the vehicle.

The ratio of catastrophic impacts to total impacts is the risk factor (R-factor or R). The PNCF, PNP, and R are related as shown in the equation:

$$\text{PNCF} = (\text{PNP})^{R} \qquad \text{Eq. 6.1-1}$$

Like PNP, PNCF is expressed as a decimal numeral with a value less than 1. The catastrophic risk is typically expressed as a percentage and is defined as:

$$\text{Catastrophic Risk} = 1 - \text{PNCF} \qquad \text{Eq. 6.1-2}$$

The R-factor for a spacecraft (or module) is achieved by summing the individual R-factors for each failure mode. This summative R-factor is then used to determine the PNCF and catastrophic risk for the overall spacecraft or module.

The MMOD environment models used for the PNP calculation will affect the resultant PNP. The Russian ISS requirements, specified in the Space Station Natural Environment Definition for Design (SSP-30425) [ref. 1], state that the orbital debris model used for calculation of PNP is the NASA 1991 Orbital Debris Model. A newer model, ORDEM2000, is available and can also be used for PNP calculations, but is not used to meet requirements. The micrometeoroid model specified by Reference 1 used for MMOD risk analysis is the 1991 Meteoroid Model. The newest meteoroid model is called the Meteoroid Engineering Model (MEM) but also is not used to meet requirements.

The NASA-desired PNP requirement for the MRM-2 is PNP ≥ 0.995 based on an exposure duration of 15 years. This is the value specified in the Russian Segment Specification [ref. 2] for the Docking Compartment #2 (DC-2), which is structurally identical to the MRM-2. A notification of document change (NDC) has been submitted (NDC-41163-52 Revision B) to change “DC-2” to “MRM-2.” However, RSC-E rejected this change and countered with a proposal that the MRM-2 PNP requirement should reflect as-launched MMOD capability (i.e., a PNP requirement of 0.9734 for 15 years). The MMOD requirement for MRM-2 has not been resolved, but for this assessment, the requirement of PNP ≥ 0.995 was assumed.

6.2 MRM-2 Risk Assessment

The MRM-2 (Figure 6.2-1) was launched aboard a modified Progress spacecraft in November 2010. It provides a docking port for Progress and Soyuz spacecraft, adds additional space for experiments, and contains data-transmission interfaces for external payloads. It is attached to the Russian ISS Segment at the zenith port of the Service Module Transfer Compartment, and extends in the zenith direction 4 m (see Figures 6.2-2 and 6.2-3). The maximum hull diameter is 2.5 m. Two EVA hatches oriented 180 degrees apart are on the forward and rear faces of the module. Also located on the MRM-2 exterior is a Strela extendable cargo boom, an equipment box, a multipurpose work station, and EVA handrails. The orientation of the module exposes the forward face, including most of the forward hatch, to the highest MMOD risk.

Separate risk assessments performed by RSC-E and NASA concluded that the MRM-2 MMOD PNP was less than the requirement of PNP ≥ 0.995. Using the 1991 meteoroid and orbital debris environments, RSC-E assessed the PNP as 0.985. Similarly, NASA independently assessed the PNP as 0.983 using the same environment models. The violation was documented in the noncompliance report (NCR), NCR-RS-MRM2-01 [Appendix E]. Within the NCR and the discussions it generated, there was agreement between RSC-E and NASA that the MRM-2 PNP was not in compliance with a PNP ≥ 0.995 requirement. In the NCR, RSC-E proposed waiving the requirement based on several factors, one being that the catastrophic risk for the MRM-2 was at an acceptable value of 0.009 percent (1 in 11,100/PNCF = 0.9999). NASA calculated the catastrophic risk as 0.0725 percent (1 in 1380/PNCF = 0.9993) and judged this to be unacceptable (there is no requirement for catastrophic risk or PNCF at the module level). NASA further recommended a risk mitigation strategy that included augmenting the MRM-2 MMOD shielding. This catastrophic risk disparity is what the NESC team was requested to evaluate.

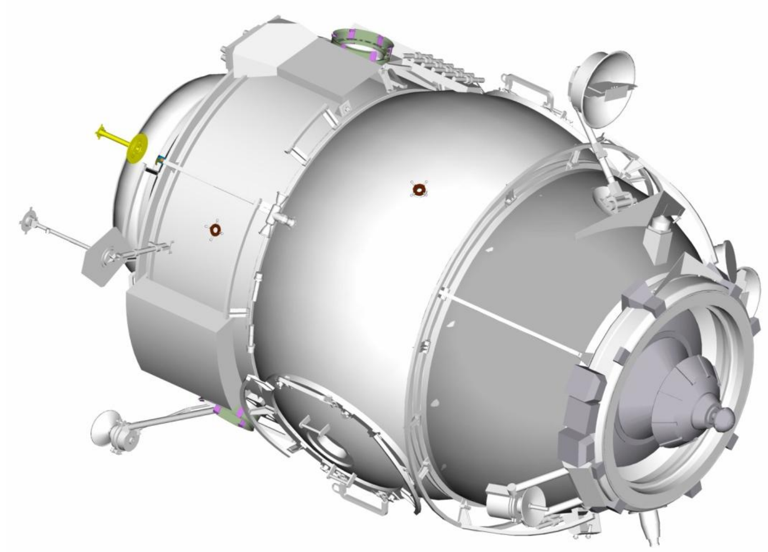

Figure 6.2-1. MRM-2

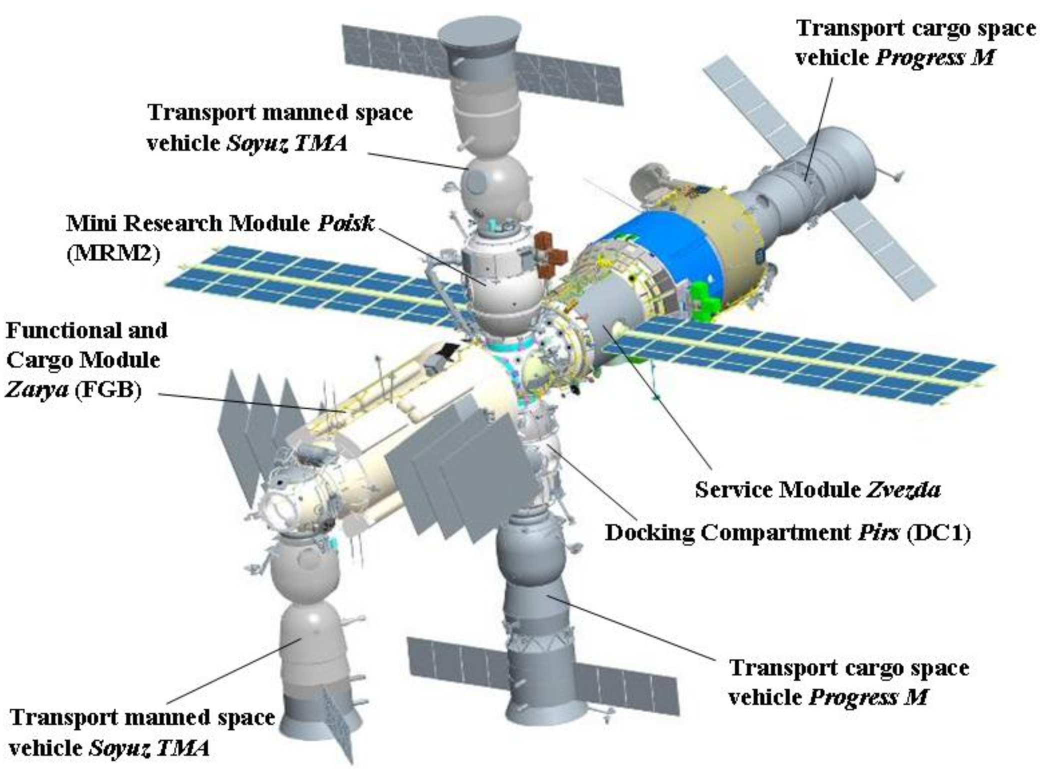

Figure 6.2-2. Location of MRM-2 on the ISS Russian Orbital Segment

Figure 6.2-3. MRM-2 on Orbit

7.0 Data and Evaluation

7.1 Risk Estimates

The purpose of this NESC assessment was to quickly provide the ISS Program with an opinion regarding the Russian and NASA risk assessments performed for the MRM-2. Time constraints limited the NESC team to a high-level review of the methods used by RSC-E and NASA and to understand how both parties arrived at their results. Further study would result in an increased understanding of the results.

The PNP and catastrophic risk values originally presented to the NESC team were those from the October 26, 2009 5R SORR (see Appendix A) and are shown in Table 7.1-1.

Table 7.1-1. Risk Comparison from October 2009

Agency	PNP	R-factor	**Catastrophic Risk**	Odds	Models
RSC-E	0.991	0.010	**9.0×10^{-5}**	1 in 11,111	ORDEM2000/1991 meteoroid
NASA	0.992	0.090	**7.2×10^{-4}**	1 in 1385	ORDEM2000/MEM

As the understanding of the MRM-2 MMOD risk matured, the PNP and PNCF evolved from the values in contention at the beginning of the assessment. By December 4, 2009, reassessments showed that the difference between the RSC-E and NASA catastrophic risk had decreased from a roughly tenfold difference to a difference closer to a factor of two (see Table 7.1-2).

Table 7.1-2. Risk Comparison from December 2009

Agency	PNP	R-factor	**Catastrophic Risk**	Odds	Models
RSC-E	0.9955	0.0512	**$2.3x10^{-4}$**	1 in 4347	2000 debris/1991 meteoroid
NASA	0.994	0.077	**$4.8x10^{-4}$**	1 in 2083	2000 debris/1991 meteoroid

One reason RSC-E's PNP increased from 0.991 to 0.9955 is because earlier RSC-E PNP calculations used estimated stand-off distances between the outer shield (bumper) and the pressure wall that were smaller than the actual configuration. Also, the older PNP runs used 1998 as the starting year for the debris and meteoroid models, instead of the actual year of MRM-2's launch (2009). Similarly, an increased understanding of the MRM-2 configuration increased the NASA PNP from 0.992 to 0.994.

7.2 Impact of Divergent PNP and R-Factors on Assessed Risk

A simple sensitivity study was performed to assess the relative impact PNP and R-factor values had on the assessed risk. Table 7.2-1 presents the most recent values of PNP, R-factor, assessed risk, and risk odds for the MRM-2 module, and includes the RSC-E-to-NASA risk ratio. As seen in this table, the assessed risk value calculated by the RSC-E is ~50 percent of the value calculated by NASA.

Table 7.2-1. Risk Values Uses as Baseline for Sensitivity Study

Agency	PNP	R-Factor	Risk	Odds	RSC-E to NASA Risk Ratio
RSC-E	0.9955	0.0512	2.31E-04	1 in 4331	**0.50**
NASA	0.994	0.077	4.63E-04	1 in 2159	----

This sensitivity study considered two scenarios. In Case I, the R-factor was held constant at the value equal to the average of the most recent RSC-E and NASA R-factors, while the PNP was varied between the most recent RSC-E and NASA values. In Case II, the PNP was held constant at the value equal to the average of the most recent RSC-E and NASA PNPs, while the R-factor was varied between the most recent RSC-E and NASA values. Tables 7.2-2 and 7.2-3 present the results of this study. It is important to note that since PNP and R-factor are interrelated, treating them as independent variables will allow only qualitative conclusions regarding their relative effect on assessed risk values.

Table 7.2-2. Case I: Effect of PNP Values on Risk Assuming a Constant R-factor

Agency	PNP	Average R-Factor	Risk	Odds	RSC-E to NASA Risk Ratio
RSC-E	**0.9955**	0.0641	2.89E-04	1 in 3460	0.75
NASA	**0.994**	0.0641	3.86E-04	1 in 2593	----

Table 7.2-3. Case II: Effect of R-factor Values on Risk Assuming a Constant PNP

Agency	Average PNP	R-Factor	Risk	Odds	RSC-E to NASA Risk Ratio
RSC-E	0.99475	**.0512**	2.69E-04	1 in 3711	0.66
NASA	0.99475	**0.077**	4.04E-04	1 in 2468	----

As illustrated in Tables 7.2-2 and 7.2-3, increasing the PNP from the NASA value of 0.994 to the RSC-E value of 0.9955, while assuming a constant average R-factor would result in an assessed risk by RSC-E that is 75 percent of what would be NASA's assessed risk. Also, decreasing the R-factor from the NASA value of 0.077 to the RSC-E value of 0.0512, while assuming a constant average PNP would result in an assessed risk by RSC-E that is 66 percent of what would be NASA's assessed risk. This shows that the assessed risk is more sensitive to PNP changes than changes to R.

7.3 Causes of PNCF Disparity: Finite Element Model (FEM)

Both NASA and RSC-E use *Bumper* to perform MMOD risk assessments and to calculate the PNP. An FEM that describes the spacecraft geometry is created in Integrated Design and Engineering Analysis Software (IDEAS) and used by *Bumper*. The FEM is separated into different elements, each identified with a property identifier (PID). During the course of this activity, it was verified that the FEM used by NASA for their ISS *Bumper* risk assessment was different than the one used by RSC-E. The FEM was provided by RSC-E, but RSC-E was using an older version for their risk assessments. Figures 7.3-1 and 7.3-2 graphically illustrate the differences between the two FEMs in question.

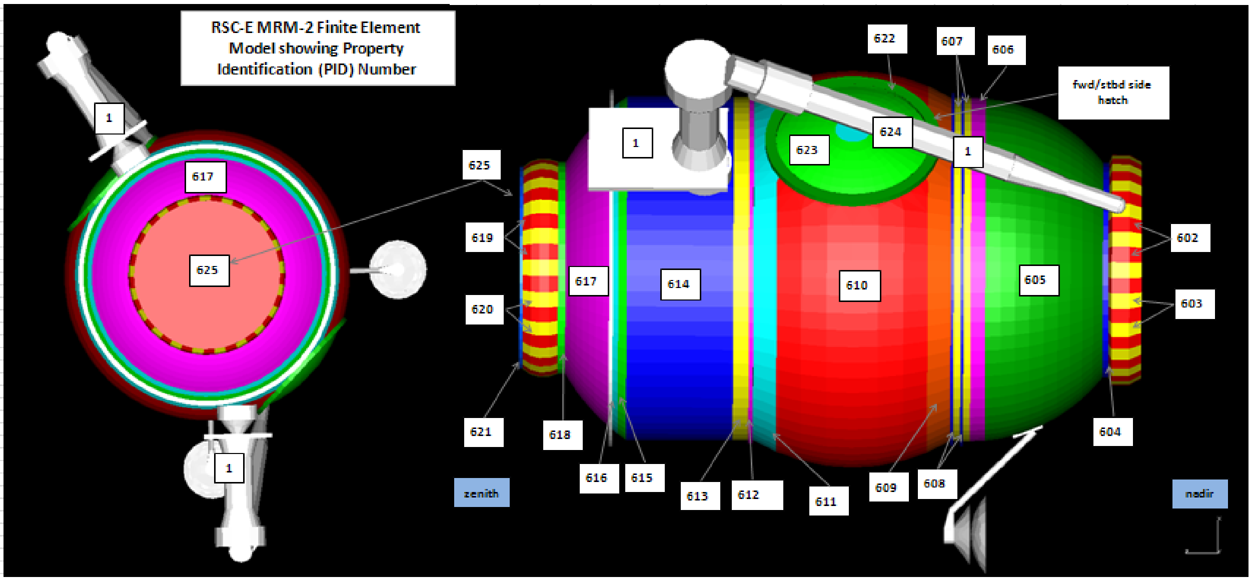

Figure 7.3-1. FEM used by RSC-E in Bumper Assessment Showing PID Assignments

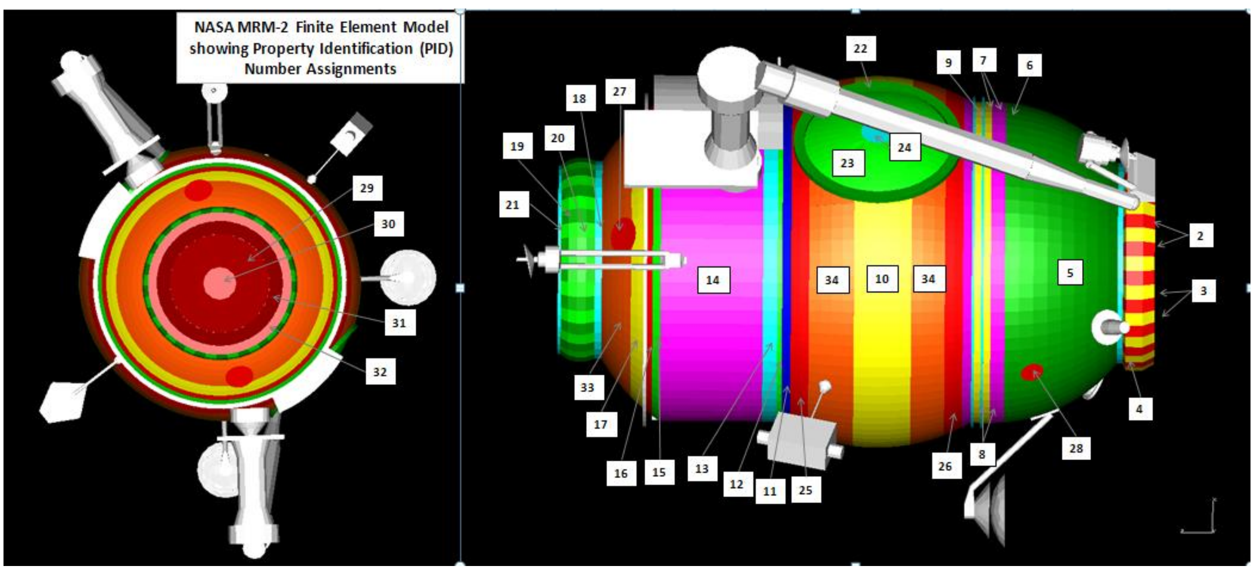

Figure 7.3-2. FEM used by NASA in Bumper Assessment Showing PID Assignments

7.4 Causes of PNCF Disparity: R-factor

Another reason for differences in PNCF is disparity in R-factors chosen by RSC-E and NASA. The R-factor used by RSC-E in the PNCF estimate presented in the October 2009 NCR was 0.010, resulting in a catastrophic risk of 9.0×10^{-5}. However, NASA used an R-factor of 0.090 to arrive at a catastrophic risk of 7.2×10^{-4} (see Table 7.1-1). Like the PNPs, R-factors also changed from October to December 2009. RSC-E's reassessment of catastrophic risk changed the R-factor from 0.010 to 0.0512, causing an increase in catastrophic risk. The NASA catastrophic risk actually decreased because the R-factor of 0.090 used in the October assessment was changed to 0.077 in the December assessment.

Table 7.4-1 illustrates the individual risk factors and the assumptions that led to the respective R-factors for NASA and RSC-E. In general, the differences can be summarized as:

- NASA does not include docking unit failure as a risk,
- RSC-E considers the loss of crew due to hypoxia to be a higher risk factor than NASA,
- NASA considers the risk due to fragmentation to be higher than RSC-E, and
- RSC-E does not consider the risk due to the catastrophic destruction of internal pressurized tanks.

Table 7.4-1. R-factor Comparison (N/C = Not Calculated in Analysis Provided)

NASA R	RSC-E R	Risk Description	Comments
0	N/C	Critical crack (unzipping) causes loss of ISS	
0	N/C	External equipment penetration causes loss of ISS	
0.063	N/C	Internal systemic equipment penetration causes loss of ISS	NASA assumption is the presence of internal pressurized tanks.
0	0.02435	Docking unit failure	
0.004	0.02519	Hypoxia causes loss of crew	Depends on hole size and time it takes crew to egress ISS. RSC-E assumes time of 9.5 minutes, while NASA uses a distribution relating to crew position and amount of time spent in different areas of the station.
0.010	0.00168	Fragmentation causes loss of crew	NASA probably assumed a higher occupancy that RSC-E.
0	N/C	Thrust induced angular velocity causes loss of crew	

To further examine the differences between the Russian and NASA risk assessments requires a closer examination of the Russian and NASA probability risk assessment (PRA) processes. The ISS MMOD PRA process is described in Appendix C, with details pertaining to RSC-E in Reference 3 and NASA in References 4 and 5. Due to the short timeline and high-level review, many questions remained unanswered that, if addressed, would result in an increased understanding of the respective PRA processes and their differences.

NASA PRA Process – Hole Diameter and Crack Length Calculations

The NASA PRA process is based on the application Manned Spacecraft and Crew Survivability (*MSCSurv)*, which provides as an output the R-factor. In the version of *MSCSurv* [ref. 5] used for these assessments, hole diameter and crack length resulting from an MMOD impact are calculated using empirical equations that were developed for 14 common ISS wall configurations [ref. 6]. These equations are based on impact test data obtained at an impact velocity of ~6.5 km/s. The effects of impact velocity are incorporated into the hole diameter and crack length predictions by NASA using a momentum scaling factor for hole diameter and an energy scaling factor for crack length [ref. 7].

RSC-E PRA Process – Hole Diameter and Crack Length Calculations

With respect to the RSC-E PRA process, the equations for module wall hole diameter and maximum tip-to-tip crack length (Equations 7.4-1 and 7.4-2) presented in Section 2.2.2 of Reference 3 appear to be based on the empirical equations provided in Reference 6 that were developed in 1995 using data collected from high speed impact tests performed at impact velocities near 6.5 km/s.

$$D_h = Acos^B\theta \left[1 - e^{-C(\frac{d_p}{d_{BL}}-1)}\right] \quad \text{Eq. 7.4-1}$$

$$L_h = Acos^B\theta \left[1 - e^{-C(\frac{d_p}{d_{BL}}-1)}\right] \quad \text{Eq. 7.4-2}$$

where:

D_h = effective hole diameter (cm)
L_h = maximum crack length (cm)
d_p = diameter of a spherical particle (cm)
θ = incidence angle
d_{BL} = ballistic diameter limit for an impact velocity of 6.5 km/s and angle of incidence θ
A, *B* and *C* = factors that vary with hole diameter and crack length. For hole diameters in a typical Russian module shield: A = 4.323 cm, B = 0.416 cm, and C = 1.474 cm. For a pressurized hull crack length, A = 4.89 cm, B = 0.633 cm, and C = 1.44 cm.

No velocity effects are evident in the RSC-E hole diameter and crack length equations. Therefore, these equations are strictly valid at a single impact velocity of 6.5 km/s. RSC-E is apparently aware of this restriction and their PRA process and catastrophic risk calculations ignore velocity effects (see Appendix B). As such, the RSC-E risk and PNCF values are obtained without considering impact velocity effects.

RSC-E presented a method for incorporating impact velocity effects for very large projectiles ($d_p/h_b > 20$) in Reference 3, pages 4-5 (shown in equations 7.4-3 and 7.4-4), but not for smaller projectiles.

$$D_h = 0.45 \cdot d_p \left\{ \left[\left(h/d_p \right)^{2/3} \cdot V \right] + 2.0 \right\} \qquad \text{Eq. 7.4-3}$$

where:

D_h = effective hole diameter (cm)
d_p = diameter of a spherical particle (cm)
h = barrier thickness (aluminum equivalent)
V = impact velocity (km/s)

$$m_p V_{p0} = m_p V_p + \tfrac{1}{4}\pi D_h^2 h_b \rho_b V_p \quad \rightarrow \quad V_p = V_{p0} \frac{1}{1+\left(\frac{\pi D_h^2 h_b \rho_b}{4 m_p}\right)} \qquad \text{Eq. 7.4-4}$$

where:

m_p= particle mass (units not given)
V_{p0} = particle velocity before impact (km/s)
V_{p0} = particle velocity after impact (km/s)
D_h = effective hole diameter (cm)
h_b = shield thickness (cm)
ρ_b = shield material density (units not given)

Equations 7.4-3 and 7.4-4 for the larger projectiles are based on the conservation of momentum. The RSC-E PRA predictions might change if an energy balance were used (i.e., energy losses due to shock heating, etc. would be subtracted out). It would also be instructive to compare the predictions of the momentum-based approach (or a combined energy-and-momentum-based approach) against actual data, and against the predictions of empirical hole size and crack length equations for the particle size regime considered.

Empirical Equation Coefficient Issues

Inspection of the values of the coefficients A, B, and C in Equation 7.4-1 (from Reference 3) for hole diameter reveals that all three values match the values of A, B, and C in Reference 6 for the Research Module hole diameter equation. However, the values of B and C for crack length as given in Reference 3 (Equation 7.4-2) do not match the values of B and C in Reference 6 for the

Research Module crack length equation (Table 7.4-2, in blue). The value of A for the crack length equation in Reference 3 does match the value of A in Reference 6, indicating that the asymptotic value of crack length according to Reference 3 will eventually match that of Reference 6.

$$L_h = \boldsymbol{A} cos^{\boldsymbol{B}}\theta \left[1 - e^{-\boldsymbol{C}(\frac{d_p}{d_{BL}}-1)}\right] \qquad \text{Eq. 7.4-2}$$

Table 7.4-2. Coefficients for Equation 7.4-2

Coefficient	Value for Hole Diameter from Ref. 3 (cm)	Value for Hole Diameter from Ref. 6 (cm)	Value for Crack Length from Ref. 3 (cm)	Value for Crack Length from Ref. 6 (cm)
A	**4.323**	4.323	**4.89**	4.89
B	0.416	0.416	**0.633**	**0.498**
C	1.474	1.474	**1.44**	**9.518**

When RSC-E was queried regarding the source of the values of B and C for the crack length equation in Reference 3, their reply was that they are based on the "experimental results obtained in MSFC [where] the crack length = 1.5 x penetration hole." From the form of equation 7.4-2, it is evident that coefficient B factors in the effects of impact obliquity, while coefficient C governs the rate at which the equation's asymptotic value is reached. However, the values of B and C given for the crack length equation do not appear to cause the crack length values calculated using that equation to be 1.5 times the pressure wall hole diameter. If that were the desired end result, then it would appear that the value of coefficient A for the crack length equation would need to be 1.5 times the value of the coefficient A for the hole diameter equation. However, those two values as given in Reference 3 are within approximately 10 percent of each other (Table 7.4-2, in pink). Hence, the explanation provided by RSC-E regarding how the values of B and C for the crack length equation are obtained is not clear and should be revisited to more fully understand the role of these coefficients in affecting the outcomes of the RSC-E PRA process. A review of the Research Module pressure wall hole diameter and maximum tip-to-tip crack length data obtained at impact test velocities near 6.5 km/s reveals that crack lengths are, on average, approximately 1.33 times larger than corresponding hole diameters [ref. 8] over all of the impact obliquities and projectile diameters tested. Therefore, the RSC-E contention that the crack length = 1.5 x penetration hole diameter appears to be reasonable and should yield more conservative (i.e. higher) values of assessed risk if implemented in a PRA process.

Figure 7.4-1 compares predictions of pressure wall tip-to-tip crack length for normal 6.5 km/s impacts on a Research Module wall target as given by Equation 7.4-2 using the values of the coefficients B and C given in Reference 3 (the RSC-E equation), and in Reference 6 (the NASA-equivalent equation). Empirical crack length data for this type of impact on this wall system are also shown. As can be seen in Figure 7.4-1, crack-length predictions can vary significantly depending on the values of the coefficients B and C. Specifically, using the values of B and C identified by RSC-E results in predictions of crack length that are smaller than if the coefficients generated by the NASA-equivalent equation were used.

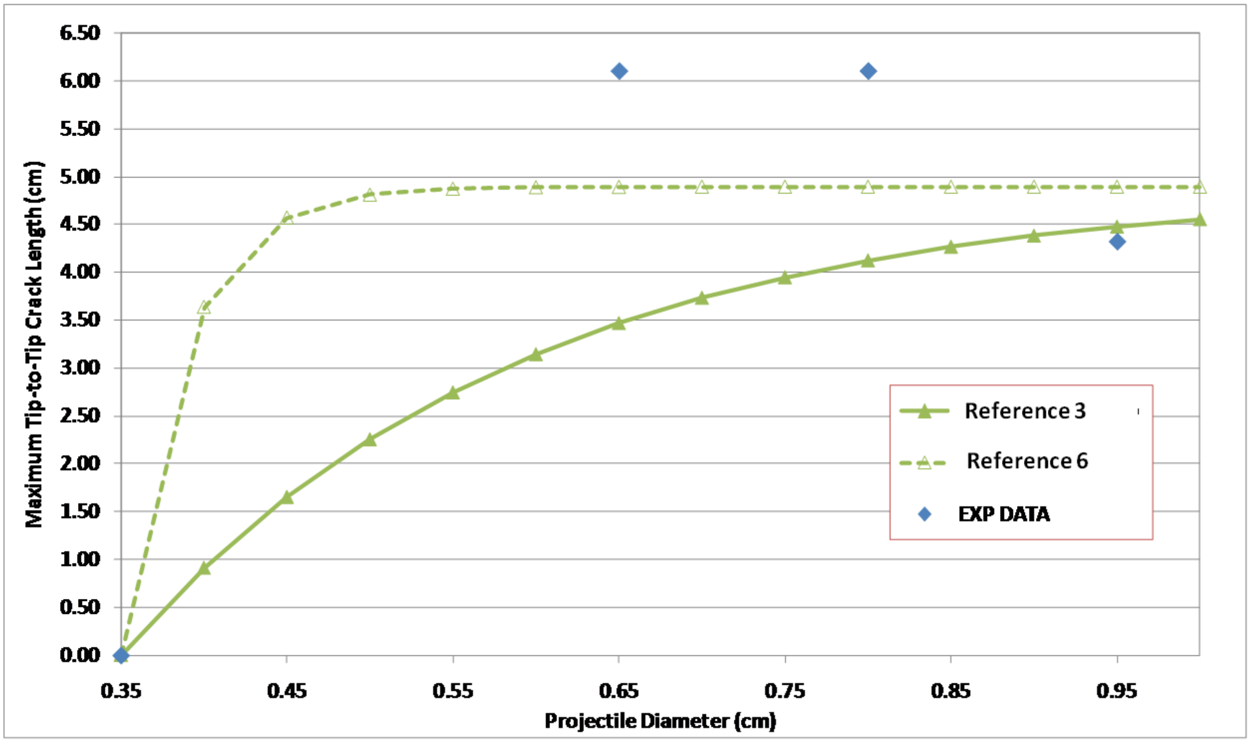

Figure 7.4-1. Comparison of RSC-E Empirical Predictions of Tip-to-Tip Crack Length for the Russian Research Module, Normal Impact at 6.5 km/s

8.0 Findings, Observations, and NESC Recommendations

8.1 Findings

The following findings were identified:

F-1. Based on the risk assessment for either source, augmented MMOD shielding for MRM-2 is warranted for MRM-2.

F-2. According to the most recently produced values, the discrepancy between NASA and RSC-E risk is approximately a factor of 2, instead of the factor of 10 displayed at the 5R SORR.

F-3. The planned NASA and RSC-E tasks are appropriate to close the gap between the MMOD risk assessments.

F-4. Variations in PNCF between NASA and RSC-E may be caused by:

- RSC-E using older FEM than NASA,
- PNP calculations using different property identification mapping, and
- Differing assumptions resulting in different R-factors.

F-5. The components of the individual R-factors are different, and this may cause a larger variation in PNCF than either NASA or RSC-E are currently accounting for. Variations in R-factor between NASA and RSC-E may be caused by:

- RSC-E assuming no risk due to pressurized tanks within the module while NASA does,
- NASA not accounting for docking mechanism failure,
- RSC-E assuming higher risk of hypoxia,
- RSC-E assuming lower risk from fragmentation (function of time spent in module), and
- Differences between how NASA and RSC-E calculate rear wall hole diameter and crack length, including an apparent lack of velocity effects in the RSC-E approach across the entire impact velocity spectrum (i.e., 1-16 km/s) and the use of empirical equation coefficients of unknown origin.

F-6. With the information available, the two PNCFs cannot be adequately evaluated.

F-7. Different uncertainty assumptions may contribute to different risk assessments.

F-8. There is no NASA mechanism for incorporating changes in the R-factor due to model changes, shield changes, and operational changes.

8.2 Observations

O-1. It is unclear how NASA and RSC-E take into account the differences in construction between the actual MRM-2 and the Research Module wall system as tested in 1995 in their hole diameter and crack length equations.

O-2. Some of the empirical coefficients used by RSC-E in its empirical crack length equation do not match corresponding coefficients in the original reference for the equation, and the explanation provided by RSC-E does not appear to fully explain the differences.

O-3. Using the RSC-E equation for crack length could lead to values of assessed risk that are lower as compared to those that might be obtained using the NASA-equivalent equation, assuming no other variations between the RSC-E and NASA PRA processes.

O-4. Considering the magnitudes of the changes in PNP and R-factor values and the resulting corresponding changes in assessed risk values, it is evident that assessed risk value is more sensitive to changes in PNP value than it is to changes in R-factor value.

8.3 NESC Recommendations

The following NESC recommendations were identified and directed towards the ISS Program unless otherwise identified:

R-1. Install additional MMOD shielding on the MRM-2 to reduce the PNP to the level specified in the requirements. ***(F-1 and F-3)***

R-2. Continue NASA and RSC-E collaboration to narrow the gap between R-factors and PNCF for MRM-2. ***(F-2, F-3, F-5, F-6, and F-7)***

R-3. Define uncertainties in PNCFs and the terms factored into their calculation. ***(F-5, F-6, and F-7)***

R-4. Proceed with current NASA plans to update R-factors in risk assessments. ***(F-7 and F-8)***

9.0 Alternate Viewpoints

There were no alternate viewpoints identified during the course of this assessment by the NESC team or the NRB quorum.

10.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this assessment.

11.0 Lessons Learned

No applicable lessons learned were identified for entry into the NASA Lessons Learned Information System (LLIS).

12.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. Alternatively, an observation could be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its

occurrence and, if eliminated or modified, would have prevented the undesired outcome.

Recommendation	An action identified by the NESC to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.

13.0 Acronyms List

DC-2	Docking Compartment #2
FEM	Finite Element Model
IDEAS	Integrated Design and Engineering Analysis Software
ISS	International Space Station
LaRC	Langley Research Center
MEM	Meteoroid Engineering Model
MEO	Meteoroid Environment Office
MMOD	Micrometeoroid and Orbital Debris
MOD	Mission Operations Directorate
MRM-2	Mini-Research Module 2
MSFC	Marshall Space Flight Center
MTSO	Management and Technical Support Office
NCR	Noncompliance Report
NDC	Notification of Document Change
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
PID	Property Identifier
PNCF	Probability of No Catastrophic Failure
PNP	Probability of no Penetration
PRA	Probabilistic Risk Assessment
R	Risk Factor
RSC-E	S.P. Korolev Rocket and Space Corporation – Energia
SORR	Stage Operations Readiness Review

14.0 References

1. SSP-30425, revision B, Space Station Natural Environment Definition for Design, February 8, 1994.

2. SSP-41163, Russian Segment Specification, Revision J, 28 November 2008.

3. Anon., A Study of the Probability of Catastrophic MMOD Penetration of the Docking Compartment Pressurized Hull, Technical Report No. П-38332-311 / SS40950, Russian Space Agency, 2005.

4. J.E. Williamsen, Vulnerability of Manned Spacecraft to Crew Loss from Orbital Debris Penetration, NASA–TM–108452, 1994.

5. Evans, H., Blacklock, K., and Williamsen, J.; Manned Spacecraft & Crew Survivability (MSCSurv) Version 4.0 User's Guide; Sverdrup Technology, Inc., NASA-MSFC; Report no. 651-001-97-006; September, 1997.

6. W.P. Schonberg, Pressure Wall Hole Size and Maximum Tip-to-Tip Crack Length Following Orbital Debris Penetration, Final Report, NASA/ASEE Summer Faculty Fellowship Program, Marshall Space Flight Center, Alabama, 1995.

7. J.E. Williamsen, D.J. Grosch, and W.P. Schonberg, "Empirical Prediction Models for Hole and Crack Size in Space Station Shielding from 6 to 12 km/s," *in* Proc. SPIE Symposium on Orbital Debris, Impact Modeling, and Penetration Effects, Paper No. 2813-20, Denver, Colorado, 1996.

8. Schonberg, W. and Williamsen, J. Empirical Hole Size and Crack Length Prediction Models for Dual Wall Systems Under Hypervelocity Impact, International Journal of Impact Engineering, Vol. 20, pp 711, 1997.

Volume II: Appendices

Appendix A. 5R Stage Operations Readiness Review

The documents presented in Appendix A, while pre-decisional when created, are now considered to be post-decisional due to events that have transpired since the date of the presentation.

National Aeronautics and Space Administration

MRM-2 MMOD NCR

Presented to the 5R Stage Operations Readiness Review (SORR)

KX/Dana M. Lear
KX/Eric L. Christiansen
ES/Kornel Nagy
NA/George K. Gafka

26 October 2009

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I-1

National Aeronautics and Space Administration

Purpose of Presentation

- To present RSC-Energia's micro-meteoroid orbital debris (MMOD) non-compliance report (NCR) for Mini-Research Module 2 (MRM-2) to the 5R SORR
  - MRM-2 NCR is for 6 months starting at flight 5R (Nov 2009)
  - RSC-Energia does not plan to add additional MMOD protection to MRM-2
- Discuss dissenting opinion:
  - Unacceptable to leave MRM-2 configuration as-is for the life of ISS
  - Risk mitigation strategy must be developed over the next 6 months. The risk mitigation strategy will likely involve on-orbit augmentation.

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I-2

National Aeronautics and Space Administration

MRM-2 MMOD Risk

- **MRM-2 MMOD protection is non-compliant**
  - MRM-2 module has same structure as Docking Compartment 1 (DC-1)
  - DC-1 was also non-compliant
  - MRM-2 assessed PNP is 0.985 for 15years versus 0.995 requirement
    - In the NCR, RSC-Energia compares MRM-2 PNP to 0.996 DC-1 requirement, because MRM-2 PNP requirement (0.995) was not agreed to by RSC-Energia
    - MMOD requirements based on 1991 debris model
- **MMOD risk terminology for MRM-2**
  - *"Penetration"* risk is defined as complete penetration of pressure shell (crew cabin leak) or complete penetration of the glass windows that endangers crew/ISS survivability
  - "*Catastrophic*" risk is defined as a penetration that results in loss of crew and includes three failure modes:
    1. Death of crew from hypoxia due to rapid depressurization (9.5 minutes is required for crew to egress Soyuz without deactivating ISS per SSP 50506)
    2. Rupture of pressure shell due to dynamic crack growth caused by penetration
    3. Death or injury of crew as result of high-speed debris caused by penetration

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I-3

National Aeronautics and Space Administration

Penetration Risk Assessment Results

- **Penetration Risk Requirement (SSP 41163 Russian Segment Spec):**
  - 1991 Debris and 1991 Meteoroid Model (SSP-30425, Rev. B)
  - 15-year exposure Penetration Risk <= **0.5%** (PNP>=**0.995**) Odds 1 in 200
- **RSC-E Penetration Risk Assessment Results:**
  - **1991 Debris (SSP-30425, Rev. B) and 1991 Meteoroid model (SSP-30425, Rev. B)**
  - Penetration Risk = **1.5%** (PNP=**0.985**) Odds 1 in 66 (does not meet requirement)
  - **2000 Debris (ORDEM2000) and 1991 Meteoroid model (SSP-30425, Rev. B)**
  - Penetration Risk = **0.9%** (PNP=**0.991**) Odds 1 in 117 (does not meet requirement)
- ***NASA and RSC-E PNP results are comparable.***

MRM-2 MMOD Risk Assessment Results (15 year exposure)

	Assessment Source	Environments	PNP	Risk	Odds	Assessed vs. Requirement
	RSC-Energia	2000 debris & 1991 meteoroid	0.991	0.9%	1 in 117	172%
	NASA		0.992	0.8%	1 in 125	160%
NCR>	RSC-Energia	1991 debris & 1991 meteoroid	0.985	1.5%	1 in 66	304%
	NASA		0.983	1.7%	1 in 60	337%

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I-4

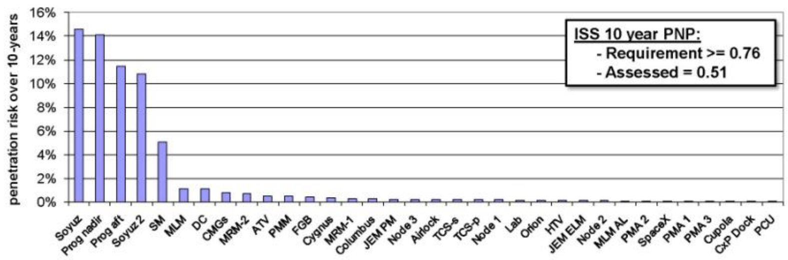
National Aeronautics and Space Administration

ISS MMOD Protection Status

(updated with latest RSC-Energia results)

- The majority of ISS elements meet MMOD protection requirements
- Most ISS MMOD risk associated with a few elements not meeting protection requirements (non-compliant)
  - Service Module (SM)
  - Soyuz and Progress
  - Docking Compartment 1(DC-1) and MRM-2

MMOD risk for pressure shell leak and critical damage to external pressure vessels & stored energy items (CMGs)
Over 10-years (2010 – 2020)



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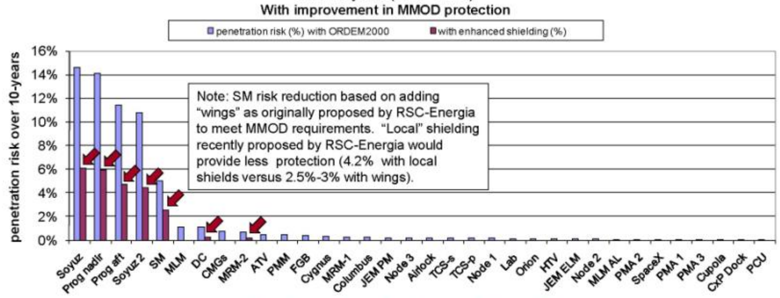
I-5

National Aeronautics and Space Administration

Expected improvement in MMOD penetration risk given changes in RS hardware

- Changes in Soyuz, Progress, Service Module, DC and MRM-2 MMOD protection
  - RSC-Energia proposal to add bumper and standoffs to Soyuz/Progress orbital module
  - RSC-Energia proposal to add local shielding and/or deployable "wings" to Service Module
  - RSC-Energia proposal to augment MRM-2

MMOD risk for pressure shell leak and critical damage to external pressure vessels & stored energy items (CMGs)
Over 10-years (2010 – 2020)
With improvement in MMOD protection



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I-6

National Aeronautics and Space Administration

Consequences of MRM-2 Penetration

15-year catastrophic and evacuation risk assessment

- Loss-of-crew due to depress, internal effects (fragments), catastrophic rupture of pressure shell, secondary failures of pressurized equipment
  - NASA MRM2 as-is assessment: **1 in 1,380** = 0.07% catastrophic risk
  - NASA MRM2 compliant assessment: **1 in 2,450** = 0.04% catastrophic risk
  - RSC-E MRM2 as-is assessment: **1 in 11,100** = 0.009% catastrophic risk
    - This value has changed from 1 in 2,500 to 1 in 222 to 1 in 11,100 in recent months
- Loss-of-mission: ISS evacuation without loss of crew due to depress of MRM-2 and SM
  - NASA calculation: 1 in 151 = 0.66% evacuation risk
  - RSC-E assessment: (not provided)
- Loss-of-function: depress MRM-2 results in loss of a Soyuz/Progress docking port and potential reduction of ISS crew capability from 6 to 3
- Resource costs:
  - Replace air lost during depress event
  - Crew time required to find and repair penetration through pressure shell
  - Replace internal damaged components

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I-7

National Aeronautics and Space Administration

Rationale for Risk Acceptance in current MRM-2 NCR

1. In the event of MRM-2 penetration, ISS crew action scenarios have been developed with the goal of ensuring crew safety and the integrity of the station (SSP 50506).

2. The RSC-E probability of a catastrophic penetration for MRM2 (probability of crew death as a result of penetration) over 10 years does not exceed $6*10^{-5}$ ($9*10^{-5}$ over 15 years). The NASA calculated probability of a catastrophic penetration for MRM2 over 10 years is $5*10^{-4}$ (odds of 1 in 2,070), and for 15 years is $7*10^{-4}$ (odds of 1 in 1,380). RSC-E calculations were performed with the following assumptions:
   - ORDEM 2000 was used;
   - Three possible consequences of penetration of the pressurized hull leading to catastrophic consequences in less than 9.5 minutes (the time stipulated in SSP 50506 needed for the crew to egress to the Soyuz without deactivating the station) were considered:
     - destruction of the pressurized hull as a result of the dynamic growth of the crack caused by the penetration;
     - Injury or death of crewmembers as a result of waves caused by high-velocity debris formed during penetration.
     - Death of the crew as a result of hypoxia brought on by rapid depressurization of the ISS.

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I-8

National Aeronautics and Space Administration

Rationale for Risk Acceptance in current MRM-2 NCR (continued)

3. The following functions are retained during MRM-2 depressurization:
   - MRM-2 thermal control;
   - Docking of Progress vehicles and undocking of Soyuz vehicles;
   - Refueling of ISS RS fuel tanks via the MRM2 ТМДТ (refueling transport lines)

4. The volume of air lost during MRM-2 depressurization, taking into account the time required to isolate the module from the station (16 minutes) is estimated to be 30 m^3. If a re-pressurization is required, these losses may be compensated for either by equalizing pressure with the rest of the ISS (volume is approximately 500 m^3) as is done after nominal EVA, or by using the portable repress tanks (БНП) (there are three located permanently on the ISS RS, which are sufficient to pressurize MRM-2).

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I-9

National Aeronautics and Space Administration

Rationale for Risk Acceptance in current MRM-2 NCR (continued)

5. There are the following measures for detecting and isolating a leak (see hazard report RSCE-103-MRM2):
   - Upon depressurization of the MRM-2 pressurized compartment, a pressure drop emergency signal is generated. This emergency signal is displayed on the MRM-2 panel and relayed throughout RS and USOS modules.
   - The drop in pressure is monitored by pressure sensors installed in MRM2.
   - The depressurized compartment in RS modules, including MRM2, is identified via the actuation of air flow sensors installed near ISS RS module docking assemblies.

6. The PNP estimate according to ORDEM2000 is 0.991 over 15 years.

7. The capability exists for the ISS to perform an avoidance maneuver for orbital debris tracked by a space monitoring system by changing attitude.

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I-10

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Dissenting Opinion

- RSC-Energia recommends keeping MRM-2 shielding as-launched for remaining life of program.

- U.S. MMOD team and the ISS Chief Safety and Mission Assurance Officer (SMA Technical Authority) believe:
  - it is unacceptable to leave the MRM-2 configuration as-is for the long-term life of ISS
  - future risk mitigation strategy should be developed by RSC-E within 6 months of MRM-2 launch, to include MMOD shielding augmentation, to reduce ISS MMOD risk

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I-11

National Aeronautics and Space Administration

Backup Charts

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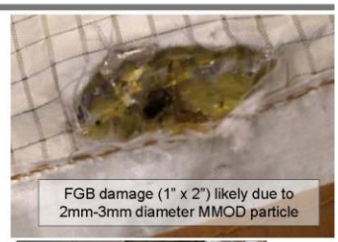
I-12

National Aeronautics and Space Administration

MMOD Damage to ISS

- Several recently identified damages appear to be due to MMOD strikes with sufficient energy to cause significant damage (i.e., pressure shell and/or window failure) to lightly protected areas of ISS such as Progress & Soyuz Orbital Module, Service Module, MRM-2 & DC
  - FGB compressor damage due to 2mm-3mm particle
  - P6 radiator damage due to 3mm-5mm particle
  - SM solar array damage due to >2mm particle
  - STS-118 radiator damage due to 1.5mm particle
- Good agreement between actual damage and predicted damage for ISS Pressurized Logistics Module and Shuttle (damage identified after return to ground and analyzed via Scanning Electron Microscope)



FGB damage (1" x 2") likely due to 2mm-3mm diameter MMOD particle

P6 radiator damage noted during STS-118 (0.75" diameter) likely due to 3-5mm diameter MMOD particle

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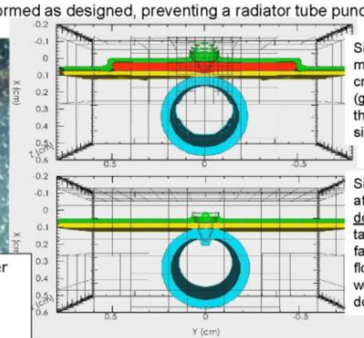
I-13

National Aeronautics and Space Administration

STS-128 Shuttle Radiator Impact shows why adding protection to vulnerable areas of spacecraft is a good thing

- During STS-128, an impact occurred on center-line of a radiator doubler, which protects the Shuttle radiator flow tubes from MMOD
  - Impact crater penetrated through the thermal tape, completely through the 0.02" thick doubler, and damaged the facesheet below the doubler
  - Analysis indicates this impact would have penetrated the flow tube if the doublers were not present
  - Doublers added in 1997-1999 time period, to provide additional protection for ISS missions
  - Conclusion: Doublers performed as designed, preventing a radiator tube puncture

MMOD impact into Radiator LH1 doubler protecting flow-tubes
Crater diameter = 0.8 mm
Crater depth = 0.58 mm
Doubler thickness = 0.51 mm



Simulation of impact after 2 micro-seconds with doubler: crater through thermal tape (green) and penetration nearly through doubler (red)…i.e., similar to actual damage.

Simulation of same impact after 2 micro-seconds without doubler: crater through thermal tape (green), through facesheet (yellow) and through flow tube wall (blue)…i.e., leak would have occurred without doubler.

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I-14

National Aeronautics and Space Administration

What can be said about MRM-2 MMOD risk from past history of DC-1

- DC-1 was launched Sep 2001: no penetration over 8.1 years ago
- **Best Case**: No penetration of DC-1 for next 8.1 years
  - Implies (at best) a penetration every 16.2 years (i.e., 8.1 years + another 8.1 years before a penetration occurs)
  - 1 penetration every 16.2 years = **46% risk of penetration over 15 years**
- **Worst Case**: Penetration in the immediate future
  - Implies (at worst) a penetration every 8.1 years = **71% risk of penetration over 15 years**
- Both the best and worst case risks are much higher than our current MRM-2 risk calculations
- Surviving ~8 years without a penetration of DC-1 does not mean that MMOD risk is small for MRM-2
- Lack of a penetration event of DC-1 since launch (8.1 years) should NOT be used as part of the basis of acceptance of MRM-2 MMOD risk.

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National Aeronautics and Space Administration

History of Docking Compartment and MRM-2 Catastrophic Risk by RSC-E

- **August 4, 2006 (MMOD TIM Protocol):**
  - Docking Compartment 10 year catastrophic risk:
    - 2E-03 (0.2%) to 5E-03 (0.5%), odds 1 in 200 to 1 in 500
    - Depends on evacuation time assumptions
- **July 15, 2009 (RSC-E MRM-2 NCR):**
  - 10 year catastrophic risk: 4E-04 (0.04%), odds 1 in 2,500
- **September 24, 2009 (RSC-E MRM-2 NCR):**
  - 10 year catastrophic risk: 3E-03 (0.3%), odds 1 in 333
  - 15 year catastrophic risk: 4.5E-03 (0.45%), odds 1 in 222
    - Is 6% of the total ISS catastrophic risk, but only 2% of ISS surface area
    - NASA commented that this risk seemed too high
- **October 6, 2009 *(current RSC-E estimate from MRM-2 NCR)*:**
  - 10 year catastrophic risk: 6E-05 (0.006%), odds 1 in 16,700
  - 15 year catastrophic risk: 9E-05 (0.009%), odds 1 in 11,100
    - RSC-E updated estimate after receiving feedback from NASA regarding September 24, 2009 catastrophic results
    - 50x risk reduction from value provided in previous NCR
    - Based on reduced time (9.5minutes) to evacuate crew without isolating modules

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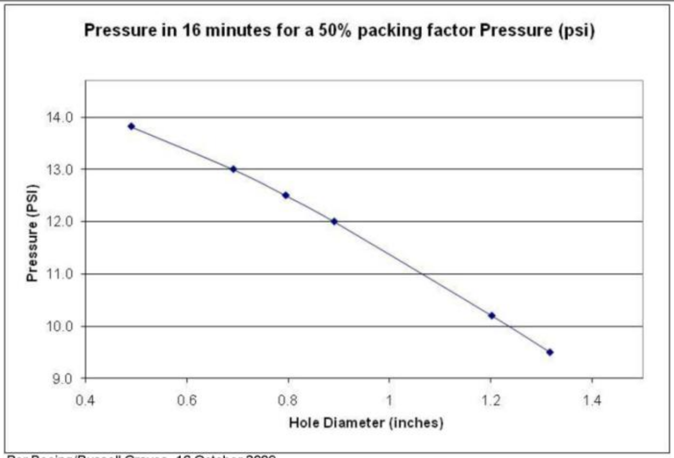
Hole diameter versus ISS Pressure Drop



Per Boeing/Russell Graves, 16 October 2009

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I-17

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MMOD Risk Uncertainties

	Lower	Nominal	Upper
15-year Penetration Risk (odds) **2000 Debris model & Meteoroids**	0.59% 1 in 171	0.80% 1 in 125	1.06% 1 in 95
15-year Penetration Risk (odds) **1991 Debris model & Meteoroids**	1.23% 1 in 81	1.68% 1 in 60	2.22% 1 in 45

- Uncertainty estimates for MRM-2 were scaled from results of study conducted for S&MA of Shuttle MMOD uncertainty (Uncertainty factor of 1.35)
    - *Hyde, J., Christiansen, E., Bumper-II Micrometeoroid and Orbital Debris Threat Assessment Code: Estimation of Orbiter Uncertainty Bounds v2.0, JSC Report 63999, Rev. A, October 2007*
- Lower and upper bound represent the 5% and 95% model output; center is the mean
- Risk assessment uncertainties to the following variable were considered:
    - MM and OD flux
    - OD velocity
    - MM and OD density
    - MMOD ballistic limit equations
- Did not consider uncertainties associated with damage criteria

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I-18

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Comparison of ISS MMOD Risk with and without MRM-2 Shielding Enhancement
(with ISS meeting MMOD requirements)

Assuming ISS meets MMOD requirements (i.e., 0.76 PNP over 10years) due to changes in Russian Segment MMOD protection

Case	MRM-2 PNP	ISS PNP	Risk	Odds
MRM-2 compliant shielding	0.997	0.757	24.3%	1 in 4.1
MRM-2 "as-is" shielding	0.994	0.755	24.5%	1 in 4.1
Total ISS risk increase (relative risk):			0.8%	

- Analysis assumptions:
  - 10 year exposure
  - 2000 debris (ORDEM2000) environment
  - 1991 meteoroid (SSP-30425, Rev.B) environment
- Non-compliant MRM-2 increases ISS MMOD penetration risk by **0.8%**

Pre-decisional - Internal Use Only

I-19

National Aeronautics and Space Administration

Comparison of ISS MMOD Risk with and without MRM-2 Shielding Enhancement
(with no changes to RS MMOD protection)

Assuming no change to Russian Segment MMOD protection (i.e., no improvement in SM, Progress, or Soyuz)

Case	MRM-2 PNP	ISS PNP	Risk	Odds
MRM-2 compliant shielding	0.997	0.430	57.0%	1 in 1.8
MRM-2 "as-is" shielding	0.994	0.428	57.2%	1 in 1.7
Total ISS risk increase (relative risk):			0.2%	

- Analysis assumptions:
  - 10 year exposure
  - 2000 debris (ORDEM2000) environment
  - 1991 meteoroid (SSP-30425, Rev.B) environment
- Non-compliant MRM-2 increases ISS MMOD penetration risk by **0.2%**

Pre-decisional - Internal Use Only

I-20

National Aeronautics and Space Administration

Comparison of MMOD Catastrophic Risk with and without MRM-2 Shielding Enhancement (with no changes to RS MMOD protection)

Assuming no change to Russian Segment MMOD protection (i.e., no improvement in SM, Progress, or Soyuz)

Case	MRM-2 PNCF	Catastrophic Risk	Catastrophic Odds
MRM-2 compliant shielding	0.9996	0.04%	1 in 2,489
MRM-2 "as-is" shielding	0.9993	0.07%	1 in 1,380

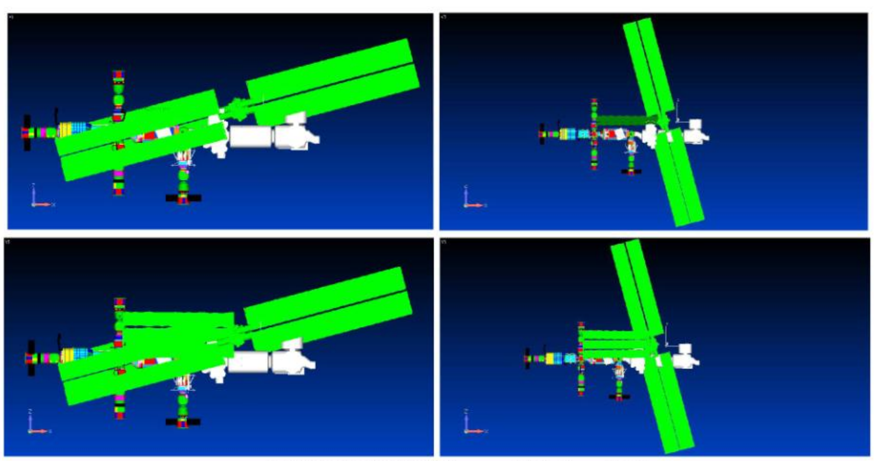
- Analysis assumptions:
  - 15 year exposure
  - 2000 debris (ORDEM2000) environment
  - 1991 meteoroid (SSP-30425, Rev.B) environment

Pre-decisional - Internal Use Only

I-21

National Aeronautics and Space Administration

MRM-2 NCR Assessment RSC-E Finite Element Model



MRM-2 NCR RSC-E MMOD Risk Assessment Finite Element Model

Pre-decisional - Internal Use Only

I-22

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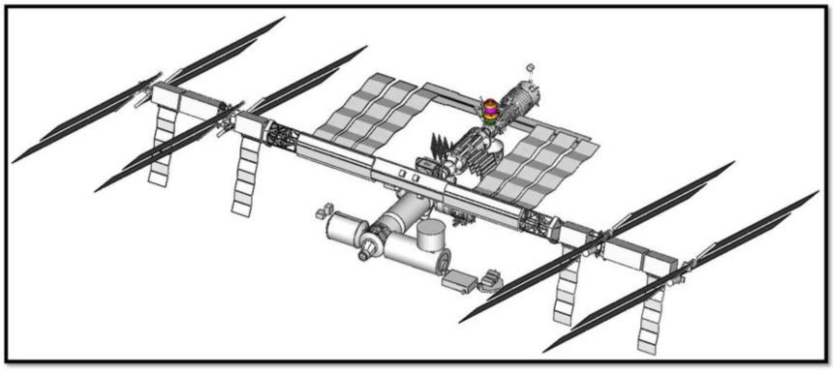
MRM-2 NCR Assessment NASA Finite Element Model



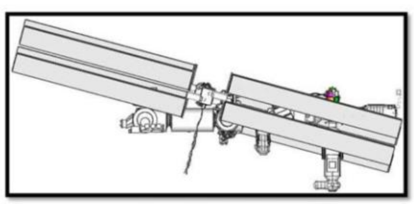
MRM-2 NCR NASA MMOD Risk Assessment Finite Element Model

Pre-decisional - Internal Use Only

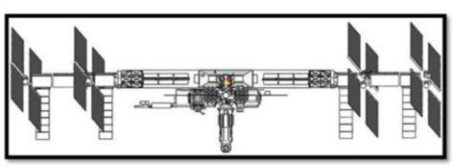
I-23

National Aeronautics and Space Administration

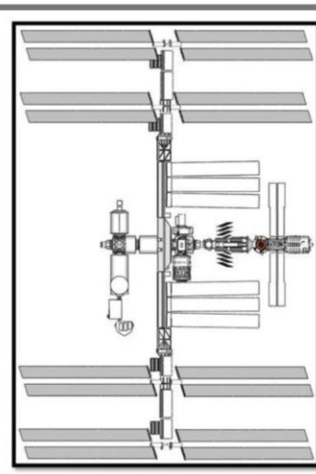
MRM-2 NCR Assessment NASA Finite Element Model



Looking ISS Starboard



Looking ISS Forward

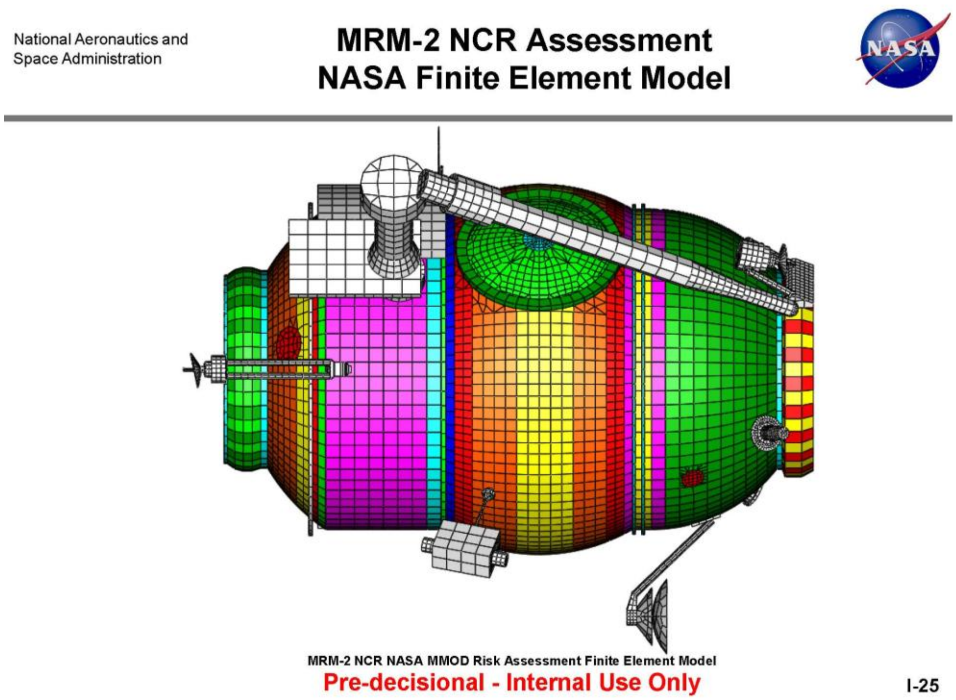


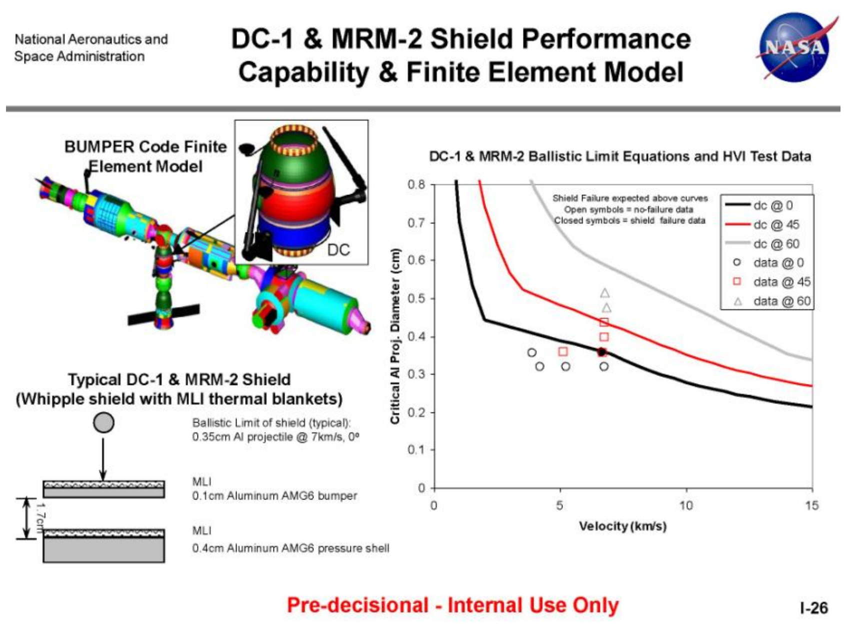
Looking ISS Nadir

MRM-2 NCR NASA MMOD Risk Assessment Finite Element Model

Pre-decisional - Internal Use Only

I-24


National Aeronautics and Space Administration
MRM-2 NCR Assessment
NASA Finite Element Model
MRM-2 NCR NASA MMOD Risk Assessment Finite Element Model
Pre-decisional - Internal Use Only
I-25


National Aeronautics and Space Administration
DC-1 & MRM-2 Shield Performance
Capability & Finite Element Model
BUMPER Code Finite Element Model
DC
Typical DC-1 & MRM-2 Shield
(Whipple shield with MLI thermal blankets)
Ballistic Limit of shield (typical): 0.35cm Al projectile @ 7km/s, 0°
MLI
0.1cm Aluminum AMG6 bumper
1.7cm
MLI
0.4cm Aluminum AMG6 pressure shell
DC-1 & MRM-2 Ballistic Limit Equations and HVI Test Data
Shield Failure expected above curves
Open symbols = no-failure data
Closed symbols = shield failure data
dc @ 0
dc @ 45
dc @ 60
data @ 0
data @ 45
data @ 60
Critical Al Proj. Diameter (cm)
Velocity (km/s)
Pre-decisional - Internal Use Only
I-26

Appendix B. Questions to RSC-E with Replies

NESC Questions for RSC-E with responses from RSC-E:

Note: RSC-E responses are shown here as received (unedited)

1. Do threaded holes exist on the frames of Service Module windows #1 and #2 (on the Service Module Working large diameter cylinder)? If so, could these be used to attach a window cover?
   - RSC-E 01/30/10 reply: "To be studied with SME in a weeks time (TBS)."
2. Can you e-mail or bring to the TIM any structure or materials information you have regarding the Service Module MMOD wings?
   - RSC-E 01/30/10 reply: "Information to be delivered on TIM."
3. Are there two hatches on MRM-2?
   - RSC-E 01/30/10 reply: "Yes"
4. What are the clearance requirements for the MRM-2 antennas, particularly those around the zenith cylinder and central sphere?
   - RSC-E 01/30/10 reply: "TBS"
5. Is the MRM-2 MLI grounded? If so, are all areas grounded or just some areas?
   - RSC-E 01/30/10 reply: "TBS"
6. Do you have any information regarding outgassing from the Russian Kevlar?
   - RSC-E 01/30/10 reply: "TBS"
7. What is the areal density of the Russian Kevlar and strength?
   - RSC-E 01/30/10 reply: "0.160g/cm^2, for fiber band 25x200mm – 3500N"
8. What are the kick load requirements for the MRM-2 exterior thermal blanket?
   - RSC-E 01/30/10 reply: "TBS"
9. What is the range of motion of the MRM-2 Strela arm?
   - RSC-E 01/30/10 reply: "TBS"
10. What is the range of motion of the MRM-2 hatches?
    - RSC-E 01/30/10 reply: "TBS"
11. Where on MRM-2 can't we add shielding due to interferences or keep-out zones?
    - RSC-E 01/30/10 reply: "TBS"
12. Does RSC-E have any ideas on how we could add MMOD protection to MRM-2?
    - RSC-E 01/30/10 reply: "to be delivered on TIM and included in the presentation to be send for you before TIM."
13. For the catastrophic risk calculations as outlined in SS40950 ("A Study of the Probability of Catastrophic MMOD Penetration of the Docking Compartment Pressurized Hull", Technical Report П38332-311), how are the effects of impact velocity factored into the predictions of hole diameter and crack length (page 4)?
    - RSC-E 01/30/10 reply: "the velocity factor in catastrophic risk calculations was ignored (fixed at 6.5 km/s) because of lack of experimental data"
14. How would the predictions of the RSC-E probabilistic risk assessment as outlined in SS40950 for very large projectiles change if an energy balance were used as well?
    - RSC-E 01/30/10 reply: "to be discussed on TIM"
15. Are you using the hole diameter and crack length equations from the "Research Module" wall system for MRM-2? If yes,

a. how are differences in construction between MRM-2 and the "Research Module" accounted for?
- RSC-E 01/30/10 reply: "Yes ->a) the differences in construction between MRM-2 and RM were not accounted for. So the calculation results were conservative in our estimates."

b. where do the values of B and C for the crack length equation given on page 4 in SS40950 come from?
- RSC-E 01/30/10 reply: "b) according to experimental results obtained in MSC the crack length=1.5 x penetration hole."

16. NCR-RS-MRM2-01 lists three possible consequences of a penetration of the pressurized hull of the MRM-2 module that might lead to a catastrophic end-state (module rupture, crew injury or death from impact-induced fragments or shock waves, and hypoxia), and lists three functions that would not be affected by such an impact (thermal control, docking / undocking functions, and refueling). The most recent PCF values for MRM-2 (19-Oct-09) are:
    1. Module rupture = 0.0
    2. Docking failure = 2.9x10e-05
    3. Hypoxia = 3.0x10e-05
    4. Crew injury = 0.2x10e-05

a. Why is the PCF of module rupture given as 0.0 if it is listed as a possible consequence that could lead to catastrophic end-state?
- RSC-E 01/30/10 reply: "a) this catastrophic consequence was found to be practically zero because MRM_2 critical crack length is estimated to be caused by debris of size over 20cm that is beyond particle size range under consideration."

b. Why is the PCF of docking failure non-zero if it is listed as a function that would not be affected by a potentially catastrophic impact?
- RSC-E 01/30/10 reply: "b) these are two different docking mechanisms involved: 1) in NSR – docking function of MRM-2 docking mechanism 2) in catastrophic risk calculations – docking mechanism of some joint between two ISS modules which fails as the result of torque caused by air flow through MRM-2 penetration hole."

17. Are there any constraints to adding shielding over the MLI from a passive thermal standpoint?
    a. RSC-E 01/30/10 reply: "TBS"

Appendix C. ISS Probabilistic Risk Assessment: MMOD Assessment

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PROGRAM INTEGRATION AND CONTROL CONTRACT
NNJ04AA01C

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER

ARES DRD-A-SA-05
Probabilistic Risk Assessment (PRA) Report

Assembly Complete Model Micrometeoroid & Orbital Debris (MMOD)

PRA Report No.: ISSPRA-MMOD-001

February 4, 2008

Prepared by:

Tiffany Wilson
Warren Grant
ARES Corporation

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TYPE 3 DOCUMENT – FINAL NASA COMMENTS INCLUDED

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ISS PROBABILISTIC RISK ASSESSMENT
Micro Meteoroid Orbital Debris (MMOD) Assessment

February 4, 2008

Prepared by: Tiffany Wilson, ARES Corporation
Warren Grant, ARES Corporation

Reviewed by: Roque Haines, ARES Corporation
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Approved by:

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Project Manager, ISS PRA

TABLE OF CONTENTS

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List of Tables

List of Figures

ACRONYMS and ABBREVIATIONS

ATV	Automated Transfer Vehicle
CMG	Control Moment Gyro
DC	Docking Compartment
EF	Error Factor
ESD	Event Sequence Diagram
EVAC	Evacuation
FGB	Functional Cargo Block
HR	Hazard Report
HTV	H-II Transfer Vehicle
ISS	International Space Station
JEM	Japanese Experiment Module
JEM-ELM	JEM Experiment Logistics Module
JEM-PM	JEM Pressurized Module
LOC	Loss of Crew
LOCV	Loss of Crew and Vehicle
LOM	Loss of Module
MLM	Multipurpose Laboratory Module
MLM AL	Multipurpose Laboratory Module Airlock
MMOD	Micro Meteoroid Orbital Debris
MPLM	Multi-Purpose Logistics Module
PCU	Plasma Contactor Unit
PMA	Pressurized Mating Adaptor
PNP	Probability of No Penetration
PNCF	Probability of No Catastrophic Failure
PRA	Probabilistic Risk Assessment
SM	Svezda Service Module
TCS	Thermal Control System

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1 Introduction

The purpose of this notebook for the International Space Station (ISS) Micro Meteoroid Orbital Debris (MMOD) Probabilistic Risk Assessment (PRA) is to document the model assumptions, Event Sequence Diagrams (ESDs) and any other directly pertinent information that will allow an informed PRA practitioner to review or recreate the ISS MMOD models. This model is to be used as part of the integrated model of the Station PRA. As such, it should be pointed out that quantification of this model separately may not be meaningful in terms of assessing the contribution of MMOD to the overall risk to the Station. The MMOD related Hazard Reports (HRs) that were used to determine that all possible hazards accounted for during the modeling phase are listed in Appendix A. The MMOD ESDs included in the integrated SAPHIRE model are shown graphically in Appendix B. The fault tree models used are shown in Appendix C.

The overall objective of the ISS MMOD protection program is to develop and deploy the ISS to safely operate in the MMOD environment by protecting the crew, protecting critical hardware, and minimizing degradation of subsystems. The ISS MMOD protection requirements should comply with the ISS protection principle:

- Probability of no catastrophic failure (PNCF) requirement for 10 years is to meet/exceed 0.95
- Risk of catastrophic failure for 10 years to not exceed 5%

2 Assumptions

- All orbital debris larger than 10 cm is tracked by a ground station, and trajectory of this debris can be plotted accurately to determine if a potential collision with ISS is likely.
- ISS debris shielding will prevent penetration by orbital debris smaller than from 0.2 cm to 1.3 cm depending on the module or element (and assuming orbital debris is aluminum).
- ISS is vulnerable to penetration by orbital debris between the capability of the shielding and the collision avoidance limit. Risk mitigation in event of penetration includes crew procedures to locate and isolate the leak, or evacuate the ISS if there is insufficient time to isolate the leak.
- ISS avoids collision with orbital debris by performing a reboost maneuver, using the Service Module (SM) reboost engines or the Progress main engines.
- If penetration of an ISS module pressure shell occurs, and the hole is small enough, the module can be isolated by the crew by closing the hatches to other modules, to prevent loss of atmosphere for the entire Station.
- If the crew must isolate a leaking module from the rest of the ISS, there is a rapid means to remove drag-through cables and ducts that would otherwise prevent hatch closure.
- Hatch mechanism failure which would prevent module isolation was considered to be very low probability and was not included in the MMOD PRA models.
- Propulsion system failure which would prevent tracked debris avoidance was considered very low probability, and was not included.

3 Tracked and Untracked Orbital Debris Risks

Based on the size of the debris, the Space Station MMOD risk analysis was divided into two categories: tracked orbital debris (OD) and untracked MMOD. If a tracked OD particle was predicted to have greater than a 1E-4 probability of impacting the ISS, the Operational Flight Rules require a debris avoidance maneuver to be performed by the ISS. The untracked MMOD risk was based on NASA's meteoroid and orbital debris integrated threat assessment (see Ref. 2) which uses the most current hardware design and flight information available. Central to the MMOD risk assessment is the computer code "BUMPER-II" (see Ref. 3), which calculates the probability of no penetration (PNP) for a spacecraft based on the spacecraft geometry, shielding configuration and flight parameters.

3.1 Tracked OD Risk

Debris that is tracked is generally greater than ~10cm in size. Debris avoidance maneuvers use the reboost thrusters to move the Station out of the 1E-4 probability debris path. The Station is prepared for the reboost maneuver when ground flight support personnel determine that the Station needs to perform an OD avoidance maneuver. If preparation of the Station for OD avoidance or execution of the maneuver commands fails, the OD avoidance maneuver will not be performed. Failure to move out of the predicted path of the debris could result in OD hitting the Station. This is considered a very low likelihood event, and is not included in the PRA model.

3.2 Untracked MMOD Risks

Debris that is too small to track, but large enough to cause damage to the ISS is considered "untracked MMOD". All micrometeoroids, of any size large enough to penetrate the shielding of ISS modules and critical elements, are considered "untracked MMOD". In this situation, there will be no debris avoidance maneuver to move the Station out of the debris path, resulting in MMOD hitting the Station. The severity of the impact is modeled in three event sequence diagrams (ESD).

It should be noted that "penetration" at a minimum causes a pressure leak in a habitable module or external pressure vessel or propellant tank. A module penetration can cause crew loss or injury from the internal fragments and secondary effects of the penetration, and would be counted as a catastrophic failure even if the leak is isolated and ISS is not lost. Catastrophic failure is loss of ISS or crew if MMOD penetration of the pressure shell occurs. Catastrophic failure does not include injury of crew, evacuation of crew, loss/isolation of parts of ISS, or depress of the entire ISS, if the crew is evacuated successfully. Catastrophic failures are a subset of penetrations. Loss modes included in the catastrophic failure group are: crew injury/death, hypoxia, module/tank leakage thrust induced failures, critical equipment loss and module unzipping.

3.2.1 Evacuation due to MMOD (EVAC-MMOD)

If MMOD damage to the ISS is severe enough to cause loss of a critical system necessary for ISS survival, or if a MMOD penetration causes depressurization at a rate that does not leave enough time to isolate the leak[1], then crew evacuation is necessary. Evacuation due to MMOD penetration (EVAC-MMOD) is defined as ISS crew evacuating, leaving the ISS unmanned. The ISS may be able to maintain a stable orbit altitude and attitude, and maintain module atmosphere with ground commanding for a long period, to permit docking and reinhabiting the ISS later. This endstate includes the following scenarios:

1. SM depressurization
2. Crew non-fatal injury from penetrating particle impact
3. Loss of ISS attitude control

This is depicted in Figure 3-4 as the blue circle.

If an Orbiter is docked to the ISS, it will be used for evacuation. If not, then the Soyuz will be used to evacuate the crew. The mean probability used for each of these pivotal events was calculated as shown in Section 4, to model the probability that the crew can evacuate. Failure to undock and failure of the vehicles to return the crew to earth after undocking was considered out of scope of the PRA, and is not included in the model. If evacuation via either vehicle is not possible, the event sequence ends in Loss of Crew (LOC).

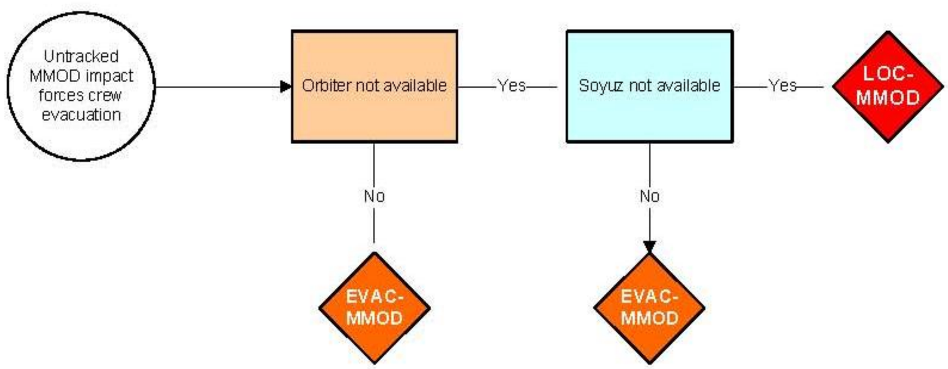

Figure 3-1. Event Sequence Diagram: MMOD-Untracked-EVAC

3.2.2 Loss of Crew due to MMOD (LOC-MMOD)

If MMOD penetration of the ISS pressure shell occurs, then crew loss may occur as a result of the internal fragments and secondary effects of the penetration, and would be counted as a catastrophic failure even if the leak is isolated and ISS is not lost.

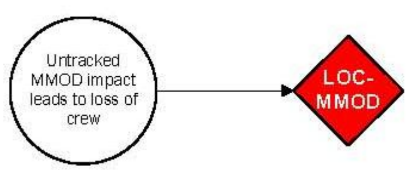

Figure 3-2. Event Sequence Diagram: MMOD-Untracked-LOC

Loss of Crew due to MMOD penetration (LOC-MMOD) is defined as loss of one or more crewmembers *without* loss of the ISS. The endstate includes the following scenarios:

1. Module unzip
2. External equipment catastrophic failure
3. Internal equipment catastrophic failure
4. Large hole in module (hypoxia)
5. Crew fatal injury from penetrating particle impact
6. Gas release thrust causes collision during departure

This is depicted in Figure 3-4 as the yellow circle.

3.2.3 Loss of Crew and Vehicle due to MMOD (LOCV-MMOD)

If MMOD damage to the ISS is severe enough to cause rapid depressurization of the ISS or external pressurized tank explosion and fragmentation, there would be insufficient time for crew evacuation. This would be due to a large debris impact hole in a module or pressurized tank. This scenario would result in complete loss of ISS and loss of the crew.

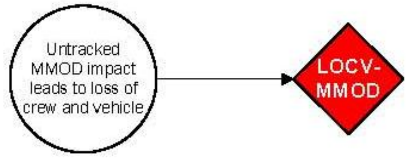

Figure 3-3. Event Sequence Diagram: MMOD-Untracked-LOCV

Loss of Crew and Vehicle due to MMOD penetration (LOCV-MMOD) is defined as loss of crew *and* loss of vehicle. The event happens so rapidly that the ISS crew has insufficient time to evacuate or perform corrective action to mitigate the hazard. This endstate includes the following scenarios:

1. Module unzip
2. Gas release thrust causing collision during departure

This is depicted in Figure 3-4 as the orange circle.

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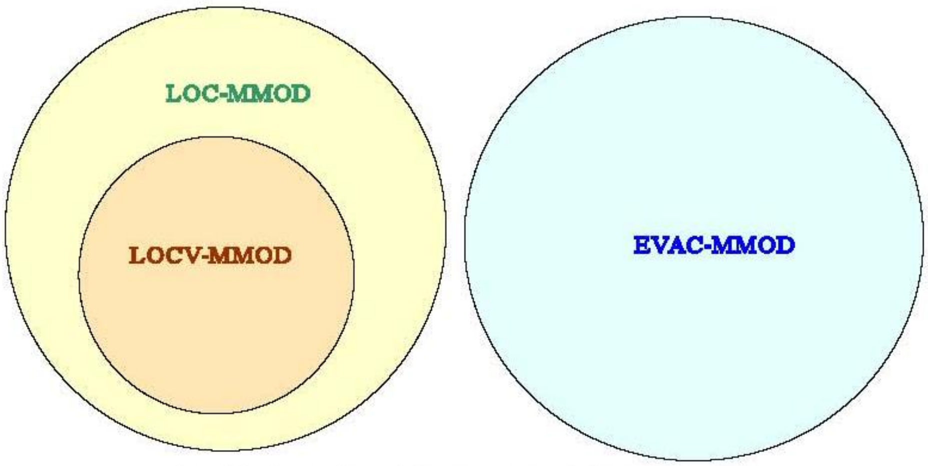

Figure 3-4. Venn diagram showing relationship of MMOD endstates.

4 Evacuation Vehicle Availability Quantification

4.1 Soyuz Evacuation Vehicle

The Russian-provided Soyuz vehicle is always present while the ISS is manned, so the probability of Soyuz unavailability for evacuation was the complement of the vehicle availability.

$$P_S = 1 - (R) \qquad \text{(Equation 4-1)}$$

Where,

P_S = Unavailability of Soyuz for ISS evacuation
R = Reliability of Soyuz vehicle

4.2 Orbiter Evacuation Vehicle

The Orbiter is not always present for ISS crew evacuation. It was assumed that the Orbiter can evacuate any ill or injured ISS crew. One distinct advantage with the Orbiter is that only the ill or injured ISS crewmember would have to leave. The Orbiter crew could tend to the ill crewmember during the return flight, and the Soyuz would remain docked as a lifeboat for the remainder of the ISS crew. Mean probability of Orbiter availability to perform an evacuation was determined by the total hours expected during the mission for an Orbiter to be docked at the Station divided by the total ISS mission hours.

$$P_O = 1 - (O/T) \qquad \text{(Equation 4-2)}$$

Where,

P_O = Unavailability of Orbiter for ISS evacuation
T = Total mission time (6 months)
O = Time on orbit (2 docked missions at 14 days each) (Ref. 8)

This event used a normal probability distribution, based on expert judgment.

5 MMOD Penetration Analysis

MMOD risks are subject to change based on:

- Modification of ISS assembly sequence
- Time exposed to MMOD
- Changes in MMOD environment models
- Refining of ballistic limit equations
- Extent and timing of MMOD augmentation shields added to ISS elements
- Changes in Soyuz/Progress protection
- Updated PNP or R-factor assessments

5.1 Assumptions

1. The MMOD penetration analysis is based on the 10-year PNP & PNCF assessment during the time period of 2007-2016 (Ref. 2).
2. Environment models used include: ORDEM2000 orbital debris, SSP30425B micro-meteoroid
3. SM augmentation completed over 4 years: 12A.1 conformal panels, SM solar arrays vertical in 2007, SM deployable wings by 2010 (ULF4 or ULF5).
4. No Soyuz or Progress MMOD enhancement will be performed.
5. The Russian MLM module and MLM airlock meet the PNP requirements in the RS specification.
6. One Progress is docked continuously to ISS, and a second Progress 70% of the ISS mission time.
7. One Soyuz is docked to the ISS throughout the mission.
8. An Orbiter will be docked to the ISS for 14 days per mission every three months (Ref. 8).
9. The PRA assessment is based on an assembly complete configuration.

It should be noted that there was no uncertainty distribution available in the current ISS PNP & PNCF results obtained from the ISS MMOD Protection Subsystem Manager. Unless otherwise noted, a lognormal distribution with Error Factor (EF) of 5.0 was used in the MMOD PRA events.

5.2 Definitions

5.2.1 Probability of No Penetration (PNP)

PNP is the probability that no part of the ISS will be penetrated by MMOD. PNP is calculated by the computer code "BUMPER-II" (Ref. 2) and the R-factor is derived by the computer code "MSC-Surv" (Ref. 3).

5.2.2 R-factor

The R-factor is used to calculate Probability of No Catastrophic Failure (PNCF) for catastrophic risks. The R-factor was derived from assessment of all system and structural failures caused by MMOD penetration which would result in catastrophic internal effects for the crew and/or the ISS. These catastrophic failure modes include: unzipping of crew module wall, hypoxia of crew, fragmentation of external pressure vessels, fragmentation/release of hazardous materials from damage of internal hardware, and venting/loss of attitude control during evacuation. It should be noted that penetration of a habitable module results in external atmospheric leakage.

5.2.3 Probability of No Catastrophic Failure (PNCF)

The Probability of No Catastrophic Failure (PNCF) due to penetration was calculated using PNP and R-factor:

$$PNCF = (PNP)^{R} \qquad \text{(Equation 5-1)}$$

Where:

PNP = Probability of No Penetration of MMOD shielding
R = Reduce Loss Factor R (the ratio of catastrophic penetrations to all penetrations)

5.3 MMOD Critical Elements on ISS

The locations of internal and external critical equipment assumed in the R-factor study are presented in Figure 5.1 below. This equipment is broken out by type:

- Russian cooling equipment
- Russian GN&C equipment
- External critical equipment
- Internal payloads (17.8% critical)
- Internal stowage (10% critical)
- Rack close-out (non-critical)
- Critical internal systems (100%)
- Internal non-critical systems

Note that several modules have significant portions of their exterior covered by critical external equipment. The large percentage of exposed external critical equipment elements for these modules, compared to the total elements, is reflected in Appendix D (Table D-D-1, Table D-D-2, Table D-D-3).

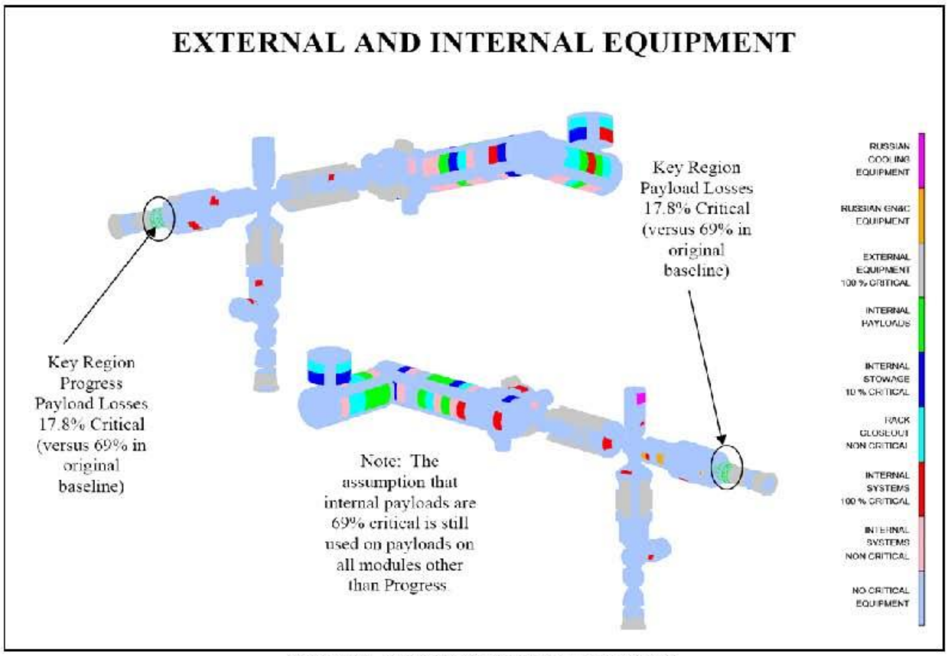

Figure 5-1. MMOD Critical Elements on ISS

5.3.1 Determining the R-factor

Within MSC-Surv, all critical external elements are marked with a “flag” (identifier used by the MSC-Surv program). The characteristics and failure conditions for the external tanks and tank lines modeled in the assessment is shown in Appendix D, Table D-D-1. The program calculates the likelihood that a Criticality 1 internal system element is impacted by debris spray from the penetration of the pressure wall. To perform these calculations accurately, the analyst must identify all Critical 1 and integral (dangerous producing) internal system elements aboard ISS manned modules. The analyst then must associate each of these internal systems with one or more external elements in MSCSurv’s data files. The percentage of critical internal systemic equipment elements for these modules, compared to the total elements are reflected in Appendix D, Table D-D-2 and Table D-D-3. In the current assessment, only those internal systems racks identified as being Critical 1 can result in critical failure if penetrated.

5.3.2 Crew Location

The crew location by day was determined by drawing random numbers for each penetration to determine where each crewmember was when the penetration occurred based on a specified crew frequency. The estimated time spent in each module by an individual crewmember in an average day is shown in Appendix D, Table D-D-4.

5.4 MMOD Calculation for Each Loss Mode

The MMOD calculation for catastrophic impacts for each catastrophic loss mode, as well as evacuation impacts for each evacuation loss mode is presented in the following table. This data was provided by the JSC Orbital Debris Program Office.

Catastrophic Impacts (N/hr) for each catastrophic loss mode						Evacuation Impacts (N/hr) for each evacuation loss mode		
Unzip (depress)	External Equip catastrophic failure (depress)	Internal Equip catastrophic failure (depress or crew loss from toxic release)	Large hole in module cause hypoxia (depress)	Internal effects (fragments, other) causes loss of crew (LOC)	Thrust induced angular velocity causes LOC during departure	Uncontrolled depress causing Service module depressur-ization	Crew non-fatal injury from internal fragments and other penetration effects	Loss of ISS attitude control
7.39E-08	5.30E-07	8.38E-08	1.81E-07	7.96E-08	6.91E-10	7.03E-07	3.37E-07	3.52E-08

Table 5-1. MMOD Calculation for Catastrophic and Evacuation Impacts.

6 MMOD Event Tree Initiator Probabilities

The probability of each initiating event occurring was determined utilizing data from the JSC Orbital Debris Program Office. This data provided totals for EVAC, LOC and LOCV based on a weighted average of the probability with respect to time on orbit for the individual module/component. Failure rates for the PRA model were weighted in a similar fashion in order to accurately reflect the result totals from the JSC Orbital Debris Program Office.

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	Unzip (depress)	Thrust induced angular velocity causes LOC during departure	LOCV
FGB	2.75E-10	0.00E+00	2.75E-10
MLM	2.24E-10	0.00E+00	2.24E-10
MLM AL	0.00E+00	0.00E+00	0.00E+00
DC	0.00E+00	0.00E+00	0.00E+00
SM	3.36E-10	2.02E-09	2.35E-09
Prog aft	0.00E+00	0.00E+00	0.00E+00
Prog nadir	0.00E+00	0.00E+00	0.00E+00
Soyuz	0.00E+00	0.00E+00	0.00E+00
Node 1	3.75E-10	0.00E+00	3.75E-10
PMA 1	2.09E-11	0.00E+00	2.09E-11
PMA 2	8.24E-12	0.00E+00	8.24E-12
PMA 3	4.95E-12	0.00E+00	4.95E-12
CMGs	0.00E+00	0.00E+00	0.00E+00
PCU	0.00E+00	0.00E+00	0.00E+00
Lab	5.15E-10	0.00E+00	5.15E-10
Airlock	2.28E-09	0.00E+00	2.28E-09
TCS-s	0.00E+00	0.00E+00	0.00E+00
TCS-p	0.00E+00	0.00E+00	0.00E+00
Orbiter	3.94E-09	0.00E+00	3.94E-09
Node 2	1.96E-09	0.00E+00	1.96E-09
Columbus	3.07E-09	0.00E+00	3.07E-09
Node 3	1.30E-09	0.00E+00	1.30E-09
Cupola	5.33E-11	0.00E+00	5.33E-11
MPLM	1.37E-10	0.00E+00	1.37E-10
ATV	1.37E-09	0.00E+00	1.37E-09
JEM ELM	1.39E-09	0.00E+00	1.39E-09
JEM PM	2.20E-09	0.00E+00	2.20E-09
HTV	3.43E-10	0.00E+00	3.43E-10
	1.98E-08	2.02E-09	**2.18E-08**

Table 6-1. LOCV Totals Based on Weighted Averages

	Unzip (depress)	Thrust induced angular velocity causes LOC during departure	External Equip catastrophic failure (depress)	Internal Equip catastrophic failure (depress or crew loss from toxic release)	Large hole in module cause hypoxia (depress)	Internal effects (fragments, other) causes loss of crew (LOC)	LOC
FGB	2.75E-10	0.00E+00	4.46E-08	8.24E-10	4.08E-08	2.75E-10	8.68E-08
MLM	2.24E-10	0.00E+00	3.64E-08	6.72E-10	3.33E-08	2.24E-10	7.08E-08
MLM AL	0.00E+00	0.00E+00	0.00E+00	5.98E-10	3.80E-11	9.49E-11	7.31E-10
DC	0.00E+00	0.00E+00	0.00E+00	1.56E-08	9.87E-10	2.47E-09	1.90E-08
SM	3.36E-10	2.02E-09	4.70E-09	1.01E-08	8.18E-08	2.86E-09	1.02E-07
Prog aft	0.00E+00	0.00E+00	6.73E-08	5.51E-08	0.00E+00	1.38E-08	1.36E-07
Prog nadir	0.00E+00	0.00E+00	9.20E-08	7.52E-08	0.00E+00	1.88E-08	1.86E-07
Soyuz	0.00E+00	0.00E+00	3.77E-08	0.00E+00	8.33E-08	1.19E-08	1.33E-07
Node 1	3.75E-10	0.00E+00	0.00E+00	2.46E-09	9.90E-10	2.90E-10	4.11E-09
PMA 1	2.09E-11	0.00E+00	0.00E+00	0.00E+00	4.49E-10	1.46E-10	6.17E-10
PMA 2	8.24E-12	0.00E+00	0.00E+00	0.00E+00	2.09E-10	1.07E-11	2.28E-10
PMA 3	4.95E-12	0.00E+00	0.00E+00	0.00E+00	1.26E-10	6.43E-12	1.37E-10
CMGs	0.00E+00	0.00E+00	7.94E-08	0.00E+00	0.00E+00	0.00E+00	7.94E-08
PCU	0.00E+00	0.00E+00	1.43E-10	0.00E+00	0.00E+00	0.00E+00	1.43E-10
Lab	5.15E-10	0.00E+00	0.00E+00	1.64E-09	3.57E-09	1.63E-09	7.36E-09
Airlock	2.28E-09	0.00E+00	0.00E+00	1.11E-10	4.99E-09	1.11E-10	7.49E-09
TCS-s	0.00E+00	0.00E+00	9.14E-09	0.00E+00	0.00E+00	0.00E+00	9.14E-09
TCS-p	0.00E+00	0.00E+00	9.14E-09	0.00E+00	0.00E+00	0.00E+00	9.14E-09
Orbiter	3.94E-09	0.00E+00	2.75E-08	0.00E+00	3.94E-09	3.94E-09	3.94E-08
Node 2	1.96E-09	0.00E+00	0.00E+00	7.45E-11	1.85E-09	1.36E-10	4.02E-09
Columbus	3.07E-09	0.00E+00	0.00E+00	3.17E-09	5.79E-09	7.81E-10	1.28E-08
Node 3	1.30E-09	0.00E+00	0.00E+00	1.82E-10	3.83E-09	2.43E-10	5.55E-09
Cupola	5.33E-11	0.00E+00	0.00E+00	0.00E+00	5.68E-10	1.32E-10	7.54E-10
MPLM	1.37E-10	0.00E+00	0.00E+00	1.41E-10	2.58E-10	3.48E-11	5.71E-10
ATV	1.37E-09	0.00E+00	9.61E-09	0.00E+00	1.37E-09	1.37E-09	1.37E-08
JEM ELM	1.39E-09	0.00E+00	0.00E+00	6.18E-10	4.20E-09	9.62E-11	6.31E-09
JEM PM	2.20E-09	0.00E+00	0.00E+00	1.62E-09	5.36E-09	5.93E-10	9.77E-09
HTV	3.43E-10	0.00E+00	2.40E-09	0.00E+00	3.43E-10	3.43E-10	3.43E-09
	1.98E-08	2.02E-09	4.20E-07	1.68E-07	2.78E-07	6.03E-08	**9.48E-07**

Table 6-2. LOC Totals Based on Weighted Averages

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	Uncontrolled depress causing Service module depressurization	Crew non-fatal injury from internal fragments and other penetration effects	Loss of ISS attitude control	EVAC
FGB	3.00E-08	2.76E-10	0.00E+00	3.03E-08
MLM	2.45E-08	2.25E-10	0.00E+00	2.47E-08
MLM AL	7.53E-09	3.65E-11	0.00E+00	7.56E-09
DC	1.96E-07	9.50E-10	0.00E+00	1.97E-07
SM	4.39E-07	2.22E-07	4.61E-08	7.07E-07
Prog aft	3.03E-09	1.21E-08	0.00E+00	1.51E-08
Prog nadir	4.13E-09	1.65E-08	0.00E+00	2.07E-08
Soyuz	0.00E+00	1.52E-08	0.00E+00	1.52E-08
Node 1	4.52E-09	1.88E-10	0.00E+00	4.71E-09
PMA 1	1.08E-09	2.74E-11	0.00E+00	1.11E-09
PMA 2	2.83E-10	1.71E-12	0.00E+00	2.85E-10
PMA 3	1.70E-10	1.03E-12	0.00E+00	1.71E-10
CMGs	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PCU	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Lab	2.80E-09	1.42E-09	0.00E+00	4.22E-09
Airlock	4.55E-09	7.31E-11	0.00E+00	4.62E-09
TCS-s	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TCS-p	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Orbiter	2.46E-09	2.46E-09	0.00E+00	4.92E-09
Node 2	3.59E-09	1.38E-10	0.00E+00	3.73E-09
Columbus	4.40E-09	8.05E-10	0.00E+00	5.20E-09
Node 3	5.74E-09	2.26E-10	0.00E+00	5.96E-09
Cupola	7.97E-10	3.65E-11	0.00E+00	8.33E-10
MPLM	1.14E-10	1.14E-10	0.00E+00	2.28E-10
ATV	5.49E-09	5.49E-09	0.00E+00	1.10E-08
JEM ELM	2.77E-09	2.74E-11	0.00E+00	2.80E-09
JEM PM	4.52E-09	6.95E-10	0.00E+00	5.21E-09
HTV	1.37E-09	1.37E-09	0.00E+00	2.74E-09
	7.48E-07	2.81E-07	4.61E-08	**1.08E-06**

Table 6-3. EVAC Totals Based on Weighted Averages

7 MMOD Model Results

7.1 Mean and Distributions for End States

Results from the MMOD PRA models are shown in Table 7-1.

	5th percentile	Mean	95th percentile
LOC-MMOD	2.128E-03	4.104E-03	7.233-03
LOCV-MMOD	4.944E-05	9.421E-05	1.655E-04
EVAC-MMOD	1.491E-03	4.607E-03	1.133E-02

Table 7-1. MMOD endstate results.

7.2 Error Factor

Basic events were assigned failure rates based upon the information given for each module. As noted in section 5.1, there was no uncertainty distribution available in the current ISS PNP & PNCF results obtained from the ISS MMOD Protection Subsystem Manager.

It is recognized that some amount of uncertainty is inherent to any estimated failure rate. In order to establish an error factor for the ISS PRA MMOD model basic events the following considerations were evaluated.

1. The *Bumper-II Micrometeoroid and Orbital Debris Threat Assessment Code: Estimation of Orbiter Uncertainty Bounds v2.0* report was reviewed.
2. A review of the Shuttle PRA (SPRA) methodology was useful since the MMOD analysis for the Shuttle included a detailed uncertainty analysis. In addition, the Shuttle PRA modeled MMOD events separately, in fault trees, similar to what is done in the ISS PRA.
3. A paper by Bruce Reistle discussing the effect on error factor by combining basic event distributions titled "Shrinkage."

The *Bumper-II* report gives a final result for the Shuttle MMOD risk with 90% confidence bounds and a nominal value. Although the inputs to the simulation have various distributions, the result closely approximates a lognormal distribution with an error factor of 1.3. Since a similar uncertainty analysis has not yet been completed for the ISS MMOD PNP and PNCF information, it is reasonable to expect like results in the absence of other data. For this reason we would expect an error factor of 1.3 (or higher to be conservative) in the ISS PRA results.

The SPRA utilized data provided in the MMOD risk analysis in the form of fault trees and event trees representing different vehicle sections and their associated risk in lieu of one overall result. This provided a higher level of fidelity in the SPRA model. Error factors for basic events were chosen such that the mean and distribution results from the SPRA model matched closely to the overall result provided by the MMOD analysis data. If an error factor of 1.3 were chosen for each basic event for example, the resulting error factor for the results would be much lower than 1.3 due to shrinkage (Reistle, 2007) thus providing an unacceptable result. An error factor of 5 for the MMOD related basic events was ultimately chosen for the SPRA.

The ISS PRA team considered using summary information from the ISS PNP & PNCF results. Since the information included results by individual module, it was decided to include the module level of detail in the SAPHIRE model. Probabilities for module penetration by MMOD are included in the model as basic events. This provides increased fidelity for the model such that individual modules can be easily added or removed and the results recalculated. It is anticipated that this will be helpful as plans for the ISS evolve and when specific trade studies may be required. The mean values obtained from the SAPHIRE model results (Table 7-1) are also a match to the summary values in the ISS PNP & PNCF results.

A sensitivity study was performed for the ISS PRA to determine the effect of different error factors for the MMOD related basic events. The error factor that would result from an assumed lognormal distribution for the end states was then compared against the expected error factor from the *Bumper II* report. The results are shown in Table 7-2. The error factors for the end state results were obtained by moment matching to a lognormal distribution using Equation 7-1.

$$EF = \sqrt{\frac{95th(percentile)}{5th(percentile)}}$$

Equation 7-1

		EF for Basic Events		
		3	5	10
		EF Result (Lognormal)		
End State	LOC-MMOD	1.49	1.84	2.55
	LOCV-MMOD	1.47	1.83	2.55
	EVAC-MMOD	2.05	2.76	3.94

Table 7-2

An error factor of 5 with a lognormal distribution was chosen for the ISS PRA MMOD model basic events. This establishes consistency with the SPRA methodology and provides appropriately conservative results for error factor when compared to the 1.3 error factor in the *Bumper-II* study.

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References

1. JSC-48512, International Space Station Complex Operations Emergency Procedures All Expedition Flights, 1.3 Response to Depress Alarm Signals.

2. "MMOD risk assessment results for ISS elements", Email from Eric Christiansen to Peng & Lutomski, dated 9/2/06.

3. "BUMPER-II", computer code to perform spacecraft meteoroid and orbital debris (MMOD) risk analysis.

4. "MSC-Surv", Manned Spacecraft Crew Survivability is a Monte-Carlo simulation to assess the effects of debris penetrations of ISS critical elements and determine R-factor for each ISS module.

5. Liou, Jer-Chyi et al, NASA/TP-2002-210780, The New NASA Orbital Debris Engineering Model ORDEM2000, May 2002.

6. Evans, Hilary; William Bohl and Joel Williamsen, "Hazard Assessment for Manned Modules Following Orbital Debris Penetration: Results for ITA-9 Stage 1J Configuration Using ORDEM2000", January 3, 2003.

7. Evans, Hilary; William Bohl and Joel Williamsen, "Hazard Assessment for Manned Modules Following Orbital Debris Penetration: Results for ITA-9 Stage 1J Configuration Using ORDEM2000", July 22, 2002.

8. "Space Shuttle Manifest", http://sspweb.jsc.nasa.gov/webdata/pdcweb/sspdocs/NSTS07700_VolumeIII_Tbl41.pdf.

9. James L. Hyde and Dr. Eric L. Christiansen, JSC-63999, Bumper-II Micrometeoroid and Orbital Debris Threat Assessment Code: Estimation of Orbiter Uncertainty Bounds v2.0, October, 2007

10. Shrinkage, Bruce Reistle, November 1, 2007

A. Appendix A

HR Number	Title
KhSC-004	Depressurization of the body of the FGB
KhSC-0011	Failure of high-pressure tanks, spheric bottles, elements, fittings, or lines.
KhSC-0023	Depressurization of the body of the FGB and its systems as a result of impact of meteoroids and space debris.
RSCE-0022-03	Hazards associated with the use of windows
RSCE-0041-02	Explosion in the SM
RSCV-0006-03	Inadvertent depressurization of Progress-M modules
RSCV-0021-03	Penetration of pressurized compartments and damage to on-board systems of Progress-M as a result of MMOD impact
RSCE-C103	Depressurization of DC1 pressurized compartments as a result of impact with a micrometeoroid or orbital debris.
ISS-STR-1005-9A	Loss of ISS Due to Micrometeoroid/Orbital Debris (MMOD) Impacts.
RSTV-0009 version 9	Depressurization of pressurized compartments as a result of MMOD.

Table A-1. MMOD Related Hazard Reports

B. Appendix B

Name	Description	Probability	Unc Type	Unc Value 1
MMOD-UNTRACKED-EVAC-G1	Untracked MMOD impact leads to crew evacuation	1.580E-002	N	5.000E+000
MMOD-UNTRACKED-LOM-G1	Untracked MMOD impact leads to loss of a module	1.100E-002	N	5.000E+000
MMOD-UNTRACKED-LOS-G1	Untracked MMOD leads to loss of ISS or crew	4.090E-003	N	5.000E+000
ORBITER	Orbiter not available for evacuation	8.466E-001	L	1.000E+001
SOYUZ	Soyuz not available for evacuation	3.750E-003	L	1.000E+001

Table B-1. Event Tree Initiating and Pivotal Event Data Used in SAPHIRE Model.

C. Appendix C

mmod-untracked-evac OR Untracked MMOD impact forces crew evacuation
- EVAC-MMOD-AIRLOCK (1.996E-005) Untracked MMOD impact to Airlock leads to evacuation of ISS
- EVAC-MMOD-ATV (4.752E-005) Untracked MMOD impact to ATV leads to evacuation of ISS
- EVAC-MMOD-COL (2.246E-005) Untracked MMOD impact to Columbus leads to evacuation of ISS
- EVAC-MMOD-CUP (3.599E-006) Untracked MMOD impact to Cupola leads to evacuation of ISS
- EVAC-MMOD-DC (8.507E-004) Untracked MMOD impact to DC leads to evacuation of ISS
- EVAC-MMOD-FGB (1.309E-004) Untracked MMOD impact to FGB leads to evacuation of ISS
- EVAC-MMOD-HTV (1.184E-005) Untracked MMOD impact to HTV leads to evacuation of ISS
- EVAC-MMOD-JEM-ELM (1.210E-005) Untracked MMOD impact to JEM ELM leads to evacuation of ISS
- EVAC-MMOD-JEM-PM (2.251E-005) Untracked MMOD impact to JEM PM leads to evacuation of ISS
- EVAC-MMOD-LAB (1.823E-005) Untracked MMOD impact to Lab leads to evacuation of ISS
- EVAC-MMOD-MLM (1.067E-004) Untracked MMOD impact to MLM leads to evacuation of ISS
- EVAC-MMOD-MLM-AL (3.266E-005) Untracked MMOD impact to MLM AL leads to evacuation of ISS
- EVAC-MMOD-MPLM (9.850E-007) Untracked MMOD impact to MPLM leads to evacuation of ISS
- EVAC-MMOD-NODE1 (2.035E-005) Untracked MMOD impact to Node 1 leads to evacuation of ISS
- EVAC-MMOD-NODE2 (1.611E-005) Untracked MMOD impact to Node 2 leads to evacuation of ISS
- EVAC-MMOD-NODE3 (2.575E-005) Untracked MMOD impact to Node 3 leads to evacuation of ISS
- EVAC-MMOD-ORB (2.125E-005) Untracked MMOD impact to Orbiter leads to evacuation of ISS
- EVAC-MMOD-PMA1 (4.795E-006) Untracked MMOD impact to PMA 1 leads to evacuation of ISS
- EVAC-MMOD-PMA2 (1.231E-006) Untracked MMOD impact to PMA 2 leads to evacuation of ISS
- EVAC-MMOD-PMA3 (7.387E-007) Untracked MMOD impact to PMA 3 leads to evacuation of ISS
- EVAC-MMOD-PROG-AFT (6.523E-005) Untracked MMOD impact to Progress Aft leads to evacuation of ISS
- EVAC-MMOD-PROG-NDR (8.942E-005) Untracked MMOD impact to Progress nadir leads to evacuation of ISS
- EVAC-MMOD-SM (3.050E-003) Untracked MMOD impact to SM leads to evacuation of ISS
- EVAC-MMOD-SOYUZ (6.566E-005) Untracked MMOD impact to Soyuz leads to evacuation of ISS

Figure C-C-1. EVAC Fault Tree

mmod-untracked-loc OR MMOD loss of crew due to untracked MMOD
- LOC-MMOD-AIRLOCK (3.236E-005) Untracked MMOD impact to Airlock leads to loss of crew
- LOC-MMOD-ATV (5.918E-005) Untracked MMOD impact to ATV leads to loss of crew
- LOC-MMOD-CMG (3.430E-004) Untracked MMOD impact to CMGs leads to loss of crew
- LOC-MMOD-COL (5.529E-005) Untracked MMOD impact to Columbus leads to loss of crew
- LOC-MMOD-CUP (3.257E-006) Untracked MMOD impact to Cupola leads to loss of crew
- LOC-MMOD-DC (8.208E-005) Untracked MMOD impact to DC leads to loss of crew
- LOC-MMOD-FGB (3.749E-004) Untracked MMOD impact to FGB leads to loss of crew
- LOC-MMOD-HTV (1.482E-005) Untracked MMOD impact to HTV leads to loss of crew
- LOC-MMOD-JEM-ELM (2.726E-005) Untracked MMOD impact to JEM ELM leads to loss of crew
- LOC-MMOD-JEM-PM (4.221E-005) Untracked MMOD impact to JEM PM leads to loss of crew
- LOC-MMOD-LAB (3.180E-005) Untracked MMOD impact to Lab leads to loss of crew
- LOC-MMOD-MLM (3.058E-004) Untracked MMOD impact to MLM leads to loss of crew
- LOC-MMOD-MLM-AL (3.158E-006) Untracked MMOD impact to MLM AL leads to loss of crew
- LOC-MMOD-MPLM (2.467E-006) Untracked MMOD impact to MPLM leads to loss of crew
- LOC-MMOD-NODE1 (1.776E-005) Untracked MMOD impact to Node 1 leads to loss of crew
- LOC-MMOD-NODE2 (1.737E-005) Untracked MMOD impact to Node 2 leads to loss of crew

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- LOC-MMOD-NODE3 (2.398E-005) Untracked MMOD impact to Node 3 leads to loss of crew
- LOC-MMOD-ORB (1.702E-004) Untracked MMOD impact to Orbiter leads to loss of crew
- LOC-MMOD-PCU (6.178E-007) Untracked MMOD impact to PCU leads to loss of crew
- LOC-MMOD-PMA1 (2.665E-006) Untracked MMOD impact to PMA 1 leads to loss of crew
- LOC-MMOD-PMA2 (9.850E-007) Untracked MMOD impact to PMA 2 leads to loss of crew
- LOC-MMOD-PMA3 (5.918E-007) Untracked MMOD impact to PMA 3 leads to loss of crew
- LOC-MMOD-PROG-AFT (5.874E-004) Untracked MMOD impact to Progress aft leads to loss of crew
- LOC-MMOD-PROG-NDR (8.032E-004) Untracked MMOD impact to Progress nadir leads to loss of crew
- LOC-MMOD-SM (4.405E-004) Untracked MMOD impact to SM leads to loss of crew
- LOC-MMOD-SOYUZ (5.744E-004) Untracked MMOD impact to Soyuz leads to loss of crew
- LOC-MMOD-TCS-P (3.948E-005) Untracked MMOD impact to TCS-p leads to loss of crew
- LOC-MMOD-TCS-S (3.948E-005) Untracked MMOD impact to TCS-s leads to loss of crew

Figure C-2. LOC Fault Tree

mmod-untracked-locv OR Loss of crew and vehicle due to untracked MMOD

- LOCV-MMOD-AIRLOCK (9.850E-006) Untracked MMOD impact to Airlock leads to loss of crew and ISS
- LOCV-MMOD-ATV (5.918E-006) Untracked MMOD impact to ATV leads to loss of crew and ISS
- LOCV-MMOD-COL (1.326E-005) Untracked MMOD impact to Columbus leads to loss of crew and ISS
- LOCV-MMOD-CUP (2.303E-007) Untracked MMOD impact to Cupola leads to loss of crew and ISS
- LOCV-MMOD-FGB (1.188E-006) Untracked MMOD impact to FGB leads to loss of crew and ISS
- LOCV-MMOD-HTV (1.482E-006) Untracked MMOD impact to HTV leads to loss of crew and ISS
- LOCV-MMOD-JEM-ELM (6.005E-006) Untracked MMOD impact to JEM ELM leads to loss of crew and ISS
- LOCV-MMOD-JEM-PM (9.504E-006) Untracked MMOD impact to JEM PM leads to loss of crew and ISS
- LOCV-MMOD-LAB (2.225E-006) Untracked MMOD impact to Lab leads to loss of crew and ISS
- LOCV-MMOD-MLM (9.677E-007) Untracked MMOD impact to MLM leads to loss of crew and ISS
- LOCV-MMOD-MPLM (5.918E-007) Untracked MMOD impact to MpLM leads to loss of crew and ISS
- LOCV-MMOD-NODE1 (1.620E-006) Untracked MMOD impact to Node 1 leads to loss of crew and ISS
- LOCV-MMOD-NODE2 (8.467E-006) Untracked MMOD impact to Node 2 leads to loss of crew and ISS
- LOCV-MMOD-NODE3 (5.616E-006) Untracked MMOD impact to Node 3 leads to loss of crew and ISS
- LOCV-MMOD-ORB (1.702E-005) Untracked MMOD impact to Orbiter leads to loss of crew and ISS
- LOCV-MMOD-PMA1 (9.029E-008) Untracked MMOD impact to PMA 1 leads to loss of crew and ISS
- LOCV-MMOD-PMA2 (3.560E-008) Untracked MMOD impact to PMA 2 leads to loss of crew and ISS
- LOCV-MMOD-PMA3 (2.138E-008) Untracked MMOD impact to PMA 3 leads to loss of crew and ISS
- LOCV-MMOD-SM (1.015E-005) Untracked MMOD impact to SM leads to loss of crew and ISS

Figure C-3. LOCV Fault Tree

D. Appendix D

Tank PID	Module	Item	Explosive Flag	Max. Thrust	Critical Crack Length (in)	Tank Characterization
16	Service	N2 Tank	0	1000 lbs	1.00	3556psi, Ti BT3-1 , 3.75 mm thick, 340mm Dia. sphere
17	Service	UDMH Prop. Tank 1 & 2	1	1000 lbs	0.48	338psi, SS301, 1.2mm thick, 600mm, cylinder
18	Service	N2O4 Oxidizer Tank 3 & 4	0	1000 lbs	0.48	338psi, SS301, 1.2mm thick, 600mm, cylinder
15	FGB	N2 Tank	0	1000 lbs	1.76	3556psi, Ti BT14, 6.6 mm thick, 426mm Dia. sphere
3	FGB	UDMH Propellant Tank	1	1000 lbs	1.81	328psi, AMG6, 2.45mm thick, 690mm, cylinder
11	FGB	N2O4 Oxidizer Tank	0	1000 lbs	1.81	328psi, AMG6, 2.45mm thick, 690mm, cylinder
5	FGB	Propellant Tank Lines	1	1000 lbs	7.74	233psi, SS301, 2mm thick, 1cm OD
6	FGB	Oxidizer Tank Lines	0	1000 lbs	7.74	233psi, SS301, 2mm thick, 1cm OD
7	Progress	Air Tanks	0	1000 lbs	0.94	5264psi, Ti, 5.4mm thick, 338mm Dia. sphere
8	Progress	Forward He Tank	0	1000 lbs	0.62	5264psi, Ti, 5.4mm thick, 338mm Dia. sphere
13	Progress	Forward Propellant Tank	1	1000 lbs	1.64	398psi, AMG6, 3.7mm thick, 754mm Dia, cylinder
14	Progress	Forward Oxidizer Tank	0	1000 lbs	1.64	398psi, AMG6, 3.7mm thick, 754mm Dia, cylinder
9	Progress	AFT Propellant Tank	1	1000 lbs	0.97	384psi, AMG6, 2.5mm thick, 750mm Dia, cylinder
8	Progress	AFT He Tank	0	1000 lbs	0.62	5264psi, Ti, 5.4mm thick, 338mm Dia. sphere
10	Progress	AFT Oxidizer Tank	0	1000 lbs	0.97	384psi, AMG6, 2.5mm thick, 750mm Dia, cylinder
7	SOYUZ	Forward Air Tank	0	1000 lbs	0.94	5264psi, Ti, 5.4mm thick, 338mm Dia. sphere
9	SOYUZ	AFT Propellant Tank	1	1000 lbs	0.97	384psi, AMG6, 2.5mm thick, 750mm Dia, cylinder
8	SOYUZ	AFT He or N2 Tank	0	1000 lbs	0.62	5264psi, Ti, 5.4mm thick, 338mm Dia. sphere
10	SOYUZ	AFT Oxidizer Tank	0	1000 lbs	0.97	384psi, AMG6, 2.5mm thick, 750mm Dia, cylinder
3	UDM	UDMH Propellant Tank	1	1000 lbs	1.81	328psi, AMG6, 2.45mm thick, 680mm, cylinder
11	UDM	Oxidizer Tank	0	1000 lbs	1.81	328psi, AMG6, 2.45mm thick, 680mm, cylinder
4	UDM	N2 Tank	0	1000 lbs	0.41	4879psi, Ti BT3-1, 5.4 mm thick, 426mm Dia, sphere
12	HPGC	N2 & O2 Tanks	0	1000 lbs	0.65	4875psi, .066" Inc. 718, 1" E-Glass, 38.64" Dia. sphere

Table D-D-1. External Critical Elements by Type

Module	Flag	Flag Description	# of Elements	% of Elements	Total Elements
FGB	0	Non-critical Internal Equipment or No Equipment	1970	40.53	4860
	1	Internal Pres bottles, 100% critical	18	0.37	
	3	External UDMH Prop. Tank	1216	25.02	
	5	External Propellant Tank	80	1.65	
	6	External Oxidizer Tank	40	0.82	
	11	External N_2O_4 Oxidizer Tank	1216	25.02	
	15	External Nitrogen Tank	172	3.54	
	30	External Compressor	148	3.05	
Service (Aft)	0	Non-critical Internal Equipment or No Equipment	6762	78.44	8621
	1	Internal Systems, 100% critical	158	1.83	
	16	External NO_2 Tank	64	0.74	
	17	External Propellant Tank	24	0.28	
	18	External Oxidizer Tank	24	0.28	
	30	External Compressor	120	1.39	
	95	Critical GN&C Equipment	71	0.82	
	96	Coolant Loops Critical for GN&C	1398	16.22	
UDM	0	Non-critical Internal Equipment or No Equipment	2729	75.76	3602
	1	Internal Pres bottles, 100% critical	25	0.69	
	3	External UDMH Prop. Tank	300	8.33	
	4	External Nitrogen Tank	248	6.89	
	11	External N_2O_4 Oxidizer Tank	300	8.33	
SSP 1	0	Non-critical Internal Equipment or No Equipment	2636	95.58	2758
	1	Internal Pres bottles, 100% critical	12	0.44	
	96	Coolant Loop Components (GN&C Crit)	110	3.99	
Docking Comp	0	Non-critical Internal Equipment or No Equipment	388	96.04	404
	1	Internal Pres bottles, 100% critical	16	3.96	
Progress	0	Non-critical Internal Equipment or No Equipment	1424	38.44	3704
	2	Internal Payload, 69% critical	540	14.58	
	7	External Air Tank	1152	31.10	
	8	External AFT Helium or N_2 Tank	152	4.10	
	9	External AFT Prop. Tank	144	3.89	
	10	Exteranl AFT Oxidizer Tank	84	2.27	
	13	External Forward Prop. Tank	120	3.24	
	14	External AFT Prop. Tank	72	1.94	
	20	External Batteries	16	0.43	
Service (Fwd)	0	Non-critical Internal Equipment or No Equipment	334	93.30	358
	96	Coolant Loops Critical for GN&C	24	6.70	
Soyuz	0	Non-critical Internal Equipment or No Equipment	3804	85.68	4440
	7	External Air Tank	288	6.49	
	8	External AFT Helium or N_2 Tank	102	2.30	
	9	External AFT Prop. Tank	144	3.24	
	10	External AFT Oxidizer Tank	86	1.94	
	20	External Batteries	16	0.36	

Table D-D-2. Internal and External Critical Elements by Type (RSA Modules)

Module	Flag	Flag Description	# of Elements	% of Elements	Total Elements
Node 2	0	Non-critical Internal Equipment or No Equipment	2576	92.53	2784
	1	Internal systems, non-critical	76	2.73	
	1	Internal systems, 100% critical	28	1.01	
	2	Internal Stowage, 10% critical	104	3.74	
JEM PM	0	Non-critical Internal Equipment or No Equipment	556	75.14	740
	1	Internal systems, non-critical	56	7.57	
	1	Internal systems, 100% critical	8	1.08	
	2	Internal Payload Closeout, 0% critical	64	8.65	
	2	Internal Payload, 69% critical	56	7.57	
JEM ELM	0	Non-critical Internal Equipment or No Equipment	160	71.43	224
	1	Internal systems, 100% critical	8	3.57	
	2	Internal Payload Closeout, 0% critical	32	14.29	
	2	Internal Stowage, 10% critical	24	10.71	
US LAB	0	Non-critical Internal Equipment or No Equipment	1128	66.20	1704
	1	Internal systems, non-critical	264	15.49	
	1	Internal systems, 100% critical	24	1.41	
	2	Internal Payload Closeout, 0% critical	72	4.23	
	2	Internal Stowage, 10% critical	48	2.82	
	2	Internal Payload, 69% critical	168	9.86	
Node 1	0	Non-critical Internal Equipment or No Equipment	2888	96.52	2992
	1	Internal systems, 100% critical	24	0.80	
	2	Internal Stowage, 10% critical	80	2.67	
HP Tanks	12	External High Pressure Tanks	252	100.00	252
Airlock	0	Non-critical Internal Equipment or No Equipment	1521	92.46	1645
	1	Internal systems, non-critical	92	5.59	
	1	Internal systems, 100% critical	32	1.95	
PMA 1	0	Non-critical Internal Equipment or No Equipment	880	100.00	880
PMA 2	0	Non-critical Internal Equipment or No Equipment	884	100.00	884
PMA 3	0	Non-critical Internal Equipment or No Equipment	964	100.00	964

Table D-D-3. Internal and External Critical Elements by Type (NASA Modules)

ARES CORPORATION Booz | Allen | Hamilton SPACEHAB

Very Low Occupancy				Low Occupancy			
Module	Factor	Ave. hours per day	Ave. minutes per day	Module	Factor	Ave. hours per day	Ave. minutes per day
AIRLOCK	0.25	0.301887	18	NODE_1	1	1.207547	72
DK COMP	0.25	0.301887	18	NODE_2	1	1.207547	72
JEM ELM	0.25	0.301887	18	UDM	1	1.207547	72
PMA_2	0.1	0.120755	7	FGB	1	1.207547	72
PMA_3	0.1	0.120755	7	PMA_1	0.5	0.603774	36
PROG	0.1	0.120755	7	SERVFWD	0.5	0.603774	36
SOYUZ	0.1	0.120755	7				
SPP_1	0.1	0.120755	7				

High Occupancy				Very High Occupancy			
Module	Factor	Ave. hours per day	Ave. minutes per day	Module	Factor	Ave. hours per day	Ave. minutes per day
US_LAB	2	2.415094	145	SERVAFT	3.5	4.226415	254
JEM PM	1.5	1.811321	109				
					Total per day	16	960

Table D-D-4. Estimated Time Spent in Each Module by an Individual Crewmember in an Average "Day" (Note: This does not include sleeping period during crew "night")

E. Appendix E

	Catastrophic Impacts (N/hr) for each catastrophic loss mode					
	Unzip (depress)	External Equip catastrophic failure (depress)	Internal Equip catastrophic failure (depress or crew loss from toxic release)	Large hole in module cause hypoxia (depress)	Internal effects (fragments, other) causes loss of crew (LOC)	Thrust induced angular velocity causes LOC during departure
FGB	2.75E-10	4.46E-08	8.24E-10	4.08E-08	2.75E-10	0.00E+00
MLM	3.20E-10	5.20E-08	9.61E-10	4.75E-08	3.20E-10	0.00E+00
MLM AL	0.00E+00	0.00E+00	8.54E-10	5.42E-11	1.36E-10	0.00E+00
DC	0.00E+00	0.00E+00	1.56E-08	9.87E-10	2.47E-09	0.00E+00
SM	3.36E-10	4.70E-09	1.01E-08	8.18E-08	2.86E-09	2.02E-09
Progress aft	0.00E+00	6.73E-08	5.51E-08	0.00E+00	1.38E-08	0.00E+00
Progress nadir	0.00E+00	1.31E-07	1.07E-07	0.00E+00	2.69E-08	0.00E+00
Soyuz	0.00E+00	3.77E-08	0.00E+00	8.33E-08	1.19E-08	0.00E+00
Node 1	3.75E-10	0.00E+00	2.46E-09	9.90E-10	2.90E-10	0.00E+00
PMA 1	2.09E-11	0.00E+00	0.00E+00	4.49E-10	1.46E-10	0.00E+00
PMA 2	8.24E-12	0.00E+00	0.00E+00	2.09E-10	1.07E-11	0.00E+00
PMA 3	4.95E-12	0.00E+00	0.00E+00	1.26E-10	6.43E-12	0.00E+00
CMGs	0.00E+00	7.94E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PCU	0.00E+00	1.43E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Lab	5.15E-10	0.00E+00	1.64E-09	3.57E-09	1.63E-09	0.00E+00
Airlock	2.28E-09	0.00E+00	1.11E-10	4.99E-09	1.11E-10	0.00E+00
TCS-s	0.00E+00	9.14E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TCS-p	0.00E+00	9.14E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Orbiter	1.50E-07	1.05E-06	0.00E+00	1.50E-07	1.50E-07	0.00E+00
Node 2	2.18E-09	0.00E+00	8.27E-11	2.05E-09	1.52E-10	0.00E+00
Columbus	3.41E-09	0.00E+00	3.53E-09	6.44E-09	8.68E-10	0.00E+00
Node 3	1.62E-09	0.00E+00	2.28E-10	4.79E-09	3.04E-10	0.00E+00
Cupola	6.67E-11	0.00E+00	0.00E+00	7.10E-10	1.65E-10	0.00E+00
MPLM	4.16E-08	0.00E+00	4.30E-08	7.84E-08	1.06E-08	0.00E+00
ATV	4.64E-09	3.25E-08	0.00E+00	4.64E-09	4.64E-09	0.00E+00
JEM ELM	1.54E-09	0.00E+00	6.87E-10	4.67E-09	1.07E-10	0.00E+00
JEM PM	2.44E-09	0.00E+00	1.81E-09	5.95E-09	6.59E-10	0.00E+00
HTV	4.17E-09	2.92E-08	0.00E+00	4.17E-09	4.17E-09	0.00E+00
ISS Total	**7.39E-08**	**5.30E-07**	**8.38E-08**	**1.81E-07**	**7.96E-08**	**6.91E-10**

Table E-E-1. Catastrophic Impacts (N/hr) for Each Catastrophic Loss Mode

	Evacuation Impacts (N/hr) for each evacuation loss mode		
	Uncontrolled depress causing Service module depressurization	Crew non-fatal injury from internal fragments and other penetration effects	Loss of ISS attitude control
FGB	3.00E-08	2.76E-10	0.00E+00
MLM	3.50E-08	3.21E-10	0.00E+00
MLM AL	1.08E-08	5.22E-11	0.00E+00
DC	1.96E-07	9.50E-10	0.00E+00
SM	4.39E-07	2.22E-07	4.61E-08
Progress aft	3.03E-09	1.21E-08	0.00E+00
Progress nadir	5.90E-09	2.36E-08	0.00E+00
Soyuz	0.00E+00	1.52E-08	0.00E+00
Node 1	4.52E-09	1.88E-10	0.00E+00
PMA 1	1.08E-09	2.74E-11	0.00E+00
PMA 2	2.83E-10	1.71E-12	0.00E+00
PMA 3	1.70E-10	1.03E-12	0.00E+00
CMGs	0.00E+00	0.00E+00	0.00E+00
PCU	0.00E+00	0.00E+00	0.00E+00
Lab	2.80E-09	1.42E-09	0.00E+00
Airlock	4.55E-09	7.31E-11	0.00E+00
TCS-s	0.00E+00	0.00E+00	0.00E+00
TCS-p	0.00E+00	0.00E+00	0.00E+00
Orbiter	9.35E-08	9.35E-08	0.00E+00
Node 2	3.99E-09	1.54E-10	0.00E+00
Columbus	4.89E-09	8.94E-10	0.00E+00
Node 3	7.17E-09	2.83E-10	0.00E+00
Cupola	9.96E-10	4.57E-11	0.00E+00
MPLM	3.47E-08	3.47E-08	0.00E+00
ATV	1.86E-08	1.86E-08	0.00E+00
JEM ELM	3.08E-09	3.05E-11	0.00E+00
JEM PM	5.02E-09	7.72E-10	0.00E+00
HTV	1.67E-08	1.67E-08	0.00E+00
ISS Total	**7.03E-07**	**3.37E-07**	**3.52E-08**

Table E-E-2. Evacuation Impacts (N/hr) for Each Evacuation Loss Mode

Appendix D. MRM-2 Ballistic Limit Equation Inputs

NASA MRM-2 Ballistic Limit Equation Inputs

Region	Start ID	End ID	# of Elements	PID#	Color	area (m2)	Shield Type	bumper (cm)	bumper mat'l	standoff (cm)	rear wall (cm)	rear wall mat'l	Debris Dcrit @7 km/s, 0-deg (cm)	PNP 15 year (2000d+1991m)
nadir docking mechanism	1	69	69	2	red	0.60	NNO	0.20	AMg6	4.0	2.50	AMg6	1.5833	0.999999
nadir docking mechanism	70	138	69	3	yellow	0.60	NNO	0.20	AMg6	10.0	0.40	AMg6	0.6333	0.999952
nadir docking mechanism frame	139	182	44	4	cyan	0.16	NNO	0.02	AMg6	1.5	4.80	AMg6	1.7638	1.000000
nadir sphere	183	832	650	5	dark green	5.26	DC1	0.10	AMg6	3.0	0.40	AMg6	0.4682	0.999515
plate 5 (nadir sphere)	5,777	5,804	28	28	red	0.02	NNO	0.13	AMg6	3.0	1.20	AMg6	0.8819	1.000000
nadir sphere (zenith ring)	833	902	70	6	magenta	0.67	DC1	0.10	AMg6	3.5	0.40	AMg6	0.5057	0.999919
nadir sphere (short cylinder)	903	1,042	140	7	yellow	0.64	DC1	0.10	AMg6	5.5	0.40	AMg6	0.634	0.999964
nadir sphere frames	1,043	1,474	432	8	cyan	1.22	NNO	0.13	AMg6	3.0	4.50	AMg6	2.1286	1.000000
central sphere - low standoff	1,547	1,896	350	10	yellow	2.18	DC1	0.10	AMg6	[illegible]	0.40	AMg6	0.3525	0.998825
central sphere - high standoff	1,897	2,438	542	34	orange	3.16	DC1	0.10	AMg6	3.5	0.40	AMg6	0.5057	0.999463
central sphere (zenith ring)	5,233	5,476	244	25	red	0.87	NNO	0.13	AMg6	3.5	0.43	AMg6	0.4684	0.999652
central sphere (zenith ring)	2,439	2,510	72	11	blue	0.47	DC1	0.10	AMg6	3.5	0.40	AMg6	0.5057	0.999886
central sphere (nadir ring)	5,477	5,720	244	26	red	0.87	NNO	0.13	AMg6	3.5	0.43	AMg6	0.4684	0.999844
central sphere (nadir ring)	1,475	1,546	72	9	magenta	0.47	DC1	0.10	AMg6	3.5	0.40	AMg6	0.5057	0.999969
zenith cylinder frame	2,511	2,720	210	12	green	0.55	NNO	0.13	AMg6	3.5	2.70	AMg6	1.5941	0.999999
zenith cylinder (nadir ring)	2,721	2,790	70	13	cyan	0.69	DC1	0.10	AMg6	4.0	0.40	AMg6	0.5407	0.999873
zenith cylinder	2,791	3,280	490	14	magenta	4.81	DC1	0.10	AMg6	4.0	0.40	AMg6	0.5407	0.999125
zenith sphere under skirt (short standoff)	3,281	3,350	70	15	green	0.44	NNO	0.02	AMg6	4.0	2.30	AMg6	1.4977	0.999998
zenith sphere under skirt (long standoff)	3,351	3,420	70	16	red	0.43	NNO	0.02	AMg6	1.5	5.70	AMg6	1.9779	0.999999
zenith sphere - low standoff	3,421	3,566	146	17	yellow	0.79	DC1	0.10	AMg6	[illegible]	0.40	AMg6	0.3525	0.999234
plate 4 (zenith sphere)	5,721	5,776	56	27	red	0.10	NNO	0.13	AMg6	[illegible]	1.20	AMg6	0.8299	0.999997
zenith sphere - high standoff	3,567	3,918	352	33	orange	1.57	DC1	0.10	AMg6	[illegible]	0.40	AMg6	0.4274	0.999346
zenith sphere frame	3,919	3,960	42	18	cyan	0.20	NNO	0.02	AMg6	1.5	4.80	AMg6	1.7638	0.999999
zenith docking mechanism	3,961	4,044	84	19	dark green	0.53	NNO	0.20	AMg6	4.0	2.50	AMg6	1.5833	0.999996
zenith docking mechanism	4,045	4,128	84	20	green	0.53	NNO	0.20	AMg6	10.0	0.40	AMg6	0.6333	0.999898
zenith docking mechanism frame	4,129	4,168	40	21	cyan	0.09	NNO	0.20	AMg6	1.5	4.80	AMg6	1.7638	1.000000
fwd/stbd hatch central cover ring	4,169	4,296	128	22	dark green	0.47	NNO	0.02	AMg6	1.5	5.30	AMg6	1.8842	1.000000
aft/port hatch central cover ring	4,297	4,424	128	22	dark green	0.47	NNO	0.02	AMg6	1.5	5.30	AMg6	1.8842	0.999999
fwd/stbd hatch central cover	4,425	4,760	336	23	green	0.79	DC1	0.10	AMg6	2.5	0.40	AMg6	0.4274	0.999946
aft/port hatch central cover	4,761	5,096	336	23	green	0.79	DC1	0.10	AMg6	2.5	0.40	AMg6	0.4274	0.999523
fwd/stbd hatch central window	5,097	5,164	68	24	cyan	0.04	FS	-	-	-	1.40	SiO_2	0.253	0.999990
aft/port hatch central window	5,165	5,232	68	24	cyan	0.04	FS	-	-	-	1.40	SiO_2	0.253	0.999913
zenith hatch - thin wall	5,805	5,972	168	29	red	1.06	NNO	0.02	AMg6	1.5	5.00	AMg6	1.8124	0.999999
zenith hatch - circle	5,973	6,008	36	30	pink	0.07	NNO	0.20	AMg6	4.0	2.50	AMg6	1.5833	1.000000
zenith docking mech inside	6,009	6,128	120	31	dark red	0.89	NNO	0.20	AMg6	4.0	2.50	AMg6	1.5833	0.999997
zenith docking mech frame	6,129	6,176	48	32	pink	0.30	NNO	0.02	AMg6	1.5	4.80	AMg6	1.7638	0.999999
shadowing	6,177	13,965	7,789	1	white	16.88	-	-	-	-	-	-	20	1.000000

From MRM-2_MMOD_Risk_Results_History_v3.xlsx, 12-04-2009

RSC-E MRM-2 Ballistic Limit Equation Inputs

region	Start ID	End ID	# of Elements	PID#	Color	area (m2)	Shield Type	bumper (cm)	bumper mat'l	standoff (cm)	rear wall (cm)	rear wall mat'l
nadir docking mechanism	260,000	260,137	138	602	red	0.60	NNO	0.20	AMg6	4.0	2.50	AMg6
nadir docking mechanism				603	yellow	0.60	NNO	0.20	AMg6	10.0	0.40	AMg6
nadir docking mechanism frame	260,138	260,181	44	604	blue	0.16	NNO	0.02	AMg6	1.5	4.80	AMg6
nadir sphere	260,182	260,811	630	605	dark green	5.28	DC1	0.10	AMg6	3.0	0.40	AMg6
nadir sphere (zenith ring)	260,812	260,881	70	606	magenta	0.67	DC1	0.10	AMg6	3.5	0.40	AMg6
nadir sphere (short cylinder)	260,882	261,021	140	607	yellow	0.64	DC1	0.10	AMg6	5.5	1.00	AMg6
nadir sphere frames	261,022	261,453	432	608	blue	1.22	NNO	0.13	AMg6	3.0	4.50	AMg6
central sphere	264,852	265,235	384	610	red	5.82	DC1	0.10	AMg6	[illegible]	0.40	AMg6
central sphere (zenith ring)	265,236	265,321	87	611	cyan	1.13	DC1	0.10	AMg6	3.5	0.40	AMg6
central sphere (nadir ring)	264,764	264,851	87	609	orange	1.13	DC1	0.10	AMg6	3.5	0.40	AMg6
zenith cylinder frame	261,454	261,663	210	612	magenta	0.55	NNO	0.13	AMg6	3.5	2.70	AMg6
zenith cylinder (nadir ring)	261,664	261,733	70	613	yellow	0.69	DC1	0.10	AMg6	4.0	0.40	AMg6
zenith cylinder	261,734	262,223	490	614	blue	4.81	DC1	0.10	AMg6	4.0	0.40	AMg6
zenith sphere under skirt (short standoff)	262,224	262,293	70	615	green	0.44	NNO	0.02	AMg6	1.5	2.30	AMg6
zenith sphere under skirt (long standoff)	262,294	262,363	70	616	cyan	0.43	NNO	0.02	AMg6	1.5	5.70	AMg6
zenith sphere	262,364	262,853	490	617	magenta	2.46	DC1	0.10	AMg6	[illegible]	0.40	AMg6
zenith sphere frame	262,854	262,895	42	618	green	0.20	NNO	0.02	AMg6	1.5	4.80	AMg6
zenith docking mechanism	262,896	-	84	619	red	0.53	NNO	0.20	AMg6	4.0	2.50	AMg6
zenith docking mechanism	-	263,063	84	620	yellow	0.53	NNO	0.20	AMg6	10.0	0.40	AMg6
zenith docking mechanism frame	263,064	263,103	40	621	grey blue	0.09	NNO	0.02	AMg6	1.5	4.80	AMg6
fwd/stbd hatch central cover ring	263,934	264,061	128	622	dark green	0.47	NNO	0.02	AMg6	1.5	5.30	AMg6
aft/port hatch central cover ring	263,104	263,231	128	622	dark green	0.47	NNO	0.02	AMg6	1.5	5.30	AMg6
fwd/stbd hatch central cover	264,062	264,481	420	623	green	0.78	DC1	0.10	AMg6	2.5	0.40	AMg6
aft/port hatch central cover	263,232	263,651	420	623	green	0.78	DC1	0.10	AMg6	2.5	0.40	AMg6
fwd/stbd hatch central window	264,482	264,763	282	624	cyan	0.04	FS	-	-	-	1.40	glass
aft/port hatch central window	263,652	263,933	282	624	cyan	0.04	FS	-	-	-	1.40	glass
zenith port cover	265,322	265,489	168	625	red	1.32	NNO	0.10	AMg6	10.0	0.50	AMg6
shadowing	265,490	268,841	3,352	1	white	11.45	-	-	-	-	-	-

From MRM-2_MMOD_Risk_Results_History_v3.xlsx, 12-04-2009

MRM-2 Ballistic Limit Equation Inputs – NASA/RSC-E Comparison

Region	RSC-E PNP 15 year (2000d+1991m)	NASA PNP 15 year (2000d+1991m)	NASA:RSC-E N-Ratio	NASA:RSC-E Risk Delta Contribution %	Comments
nadir docking mechanism nadir docking mechanism	0.999954	0.999951	1.1	0.2%	Inputs match, result nearly match
nadir docking mechanism frame	1.000000	1.000000	2.2	0.0%	Inputs match, result nearly match
nadir sphere plate 5 (nadir sphere)	0.999530	0.999515	1.0	1.0%	Inputs nearly match, NASA model more refined.
nadir sphere (zenith ring)	0.999922	0.999919	1.0	0.2%	Inputs match, result nearly match
nadir sphere (short cylinder)	0.999997	0.999964	13.2	2.2%	RSC-E rearwall thickness (1.0 cm) does not match NASA rearwall thickness (0.40 cm)
nadir sphere frames	1.000000	1.000000	0.8	0.0%	Inputs match, result nearly match
central sphere - low standoff central sphere - high standoff	0.998802	0.998289	1.4	33.4%	RSC-E used area-weighted average standoff; major difference in results.
central sphere (zenith ring) central sphere (zenith ring)	0.999819	0.999539	2.5	18.2%	Inputs similar, results different, NASA model refined into 2 regions
central sphere (nadir ring) central sphere (nadir ring)	0.999922	0.999813	2.4	7.1%	Inputs similar, results different, NASA model refined into 2 regions
zenith cylinder frame	1.000000	0.999999	2.4	0.0%	Inputs match, results match
zenith cylinder (nadir ring)	0.999928	0.999873	1.8	3.6%	Inputs match, result nearly match (difference probably due to shadowing differences)
zenith cylinder	0.999309	0.999125	1.3	12.0%	Inputs identical, but results are different (shadowing differences)
zenith sphere under skirt (short standoff)	0.999994	0.999998	0.4	-0.3%	Inputs slightly different, results nearly match (small area, shadowing differences?)
zenith sphere under skirt (long standoff)	0.999999	0.999999	1.1	0.0%	Inputs match, result nearly match
zenith sphere - low standoff plate 4 (zenith sphere) zenith sphere - high standoff	0.998856	0.998578	1.2	18.1%	Inputs similar, but NASA model refined into 3 separate regions
zenith sphere frame	0.999999	0.999999	1.0	0.0%	Inputs match, result nearly match
zenith docking mechanism zenith docking mechanism	0.999900	0.999996	0.0	-6.2%	Inputs identical, but results are different, probably due to shadowing differences.
zenith docking mechanism frame	1.000000	1.000000	1.2	0.0%	Inputs similar, results match
fwd/stbd hatch central cover ring	1.000000	1.000000	2.9	0.0%	Inputs similar, results match
aft/port hatch central cover ring	0.999999	0.999999	2.0	0.0%	Inputs similar, results match
fwd/stbd hatch central cover	0.999963	0.999946	1.5	1.1%	Inputs similar, results nearly match
aft/port hatch central cover	0.999677	0.999523	1.5	10.1%	Inputs similar, results different.
fwd/stbd hatch central window	0.999992	0.999990	1.4	0.2%	Inputs similar, results nearly match
aft/port hatch central window	0.999896	0.999913	0.8	-1.1%	Inputs similar, results nearly match
zenith hatch - thin wall zenith hatch - circle zenith docking mech inside zenith docking mech frame	1.000000	0.999996		0.3%	Regions mapped differently, but are mostly covered by Soyuz docked to zenith port
shadowing	0.999997	1.000000	0.0	-0.2%	Inputs similar, areas slightly different

From MRM-2_MMOD_Risk_Results_History_v3.xlsx, 12-04-2009

Appendix E. ISS Noncompliance Report NCR-RS-MRM2-01

Record Number: NCR-RS-MRM2-01		ISS Non-Compliance Report	Page	1	of	
2. Date: 10/~~06~~23~~2~~/09			3. NCR Number			

4. NCR Title: Protection of MRM2 from Meteoroids and Orbital Debris		
5. Hazard Report: RSCE-103-MRM2		
6. Originator:	Organization:	Telephone:
7. Safety Engineer:	Organization:	Telephone:
8. Extends to (Flight): 5R		
9. Date Activities Completed: 5R plus 6 months~~from November 2009 (flight 5R) to November 2011 (2 years)~~ (10 Nov 2009 to 10 May 2010)		
10. ISS Element Designation: MRM2		

11. Requested Review:

In Nominal Sequence	Urgent (basis needs to be given below)

12. Applicable Requirement:

SSP 41163, Russian Segment Specification: paragraph 3.3.12.1.1 "Estimated Life of Structure for Meteoroid and Space Debris Analysis"; paragraph 3.3.12.1.1.1.1 "Penetration of Structure" and paragraph 3.2.6.1.8 "Meteoroids and Orbital Debris."

13. Non-Compliance Description:

The probability of no penetration (PNP) for MRM2 docked to the SM zenith port, which was calculated with the BUMPER program using meteoroid environment model SSP30425B and ORDEM 1991 and which accounts for the actual situation on the ISS as regards MRM2 including USOS movable radiators, is 0.985 over 15 years. This value is less than the value stipulated in SSP 41163 for DC1, the analogue module of MRM2 (0.996).

14. Cause as to Why the Requirement cannot be Fulfilled:

In order to increase MRM2 protection to the required level, it is necessary to install additional shielding. This implies a change in its design, an increase in mass (to the extent of not being able to launch MRM2 as part of the Progress vehicle), an increase in cost, and a need for experimental confirmation of changes in the thermal balance and structural integrity.

15. Acceptance Rationale:

1. In the event of MRM2 penetration, ISS crew action scenarios have been developed with the goal of ensuring crew safety and the integrity of the station (SSP 50506).
2. According to the estimate of RSC Energia, ~~T~~the probability of a catastrophic penetration for MRM2 (probability of crew death as a result of penetration) over 10 years does not exceed $6*10^{-5}$ ($0.9*10^{-4}$ over 15 years). The estimate of the probability of a catastrophic penetration for MRM2 conducted by NASA is (5~~6~~*10$^{-4\cancel{5}}$ over 10~~5~~ years (1 in 2070) and $7*10^{-4}$ over 15 years (1 in 1380). The RSC Energia ~~C~~calculations were performed with the following assumptions:

- ORDEM 2000 was used;
- Three possible consequences of penetration of the pressurized hull leading to catastrophic consequences in less than 9.5 minutes (the time stipulated in SSP 50506 needed for the crew to egress to the Soyuz without deactivating the station) were considered:

- destruction of the pressurized hull as a result of the dynamic growth of the crack caused by the penetration;
- Injury or death of crewmembers as a result of waves caused by high-velocity debris formed during penetration.
- Death of the crew as a result of hypoxia brought on by rapid depressurization of the ISS.

3. The following functions are retained during MRM2 depressurization:
   - MRM2 thermal control;
   - Docking of Progress vehicles and undocking of Soyuz vehicles;
   - Refueling of ISS RS fuel tanks via the MRM2 ТМДТ.
4. The volume of air lost during MRM2 depressurization, taking into account the time required to isolate the module from the station (16 minutes) is estimated to be 30 m^3. If a re-pressurization is required, these losses may be compensated for either by equalizing pressure with the rest of the ISS (volume is approximately 500 m^3) as is done after nominal EVA, or by using the portable repress tanks (БНП) (there are three located permanently on the ISS RS, which are sufficient to pressurize MRM2).
5. There are the following measures for detecting and isolating a leak (see hazard report RSCE-103-MRM2):

- Upon depressurization of the MRM2 pressurized compartment, a pressure drop emergency signal is generated. This emergency signal is displayed on the MRM2 panel and relayed throughout RS and USOS modules.
- The drop in pressure is monitored by pressure sensors installed in MRM2.
- The depressurized compartment in RS modules, including MRM2, is identified via the actuation of air flow sensors installed near ISS RS module docking assemblies.

~~6. There have been no penetrations of the MRM2 analogue, DC1, that has been mated to the ISS since 2001.~~

~~7.~~6. The PNP estimate according to ORDEM2000 is 0.991 over 15 years.

~~8.~~7. The capability exists for the ISS to perform an avoidance maneuver for orbital debris tracked by a space monitoring system by changing attitude.

~~9.~~8. The US MMOD community and the ISS Chief Safety and Mission Assurance Officer believe that the as-is MRM-2 configuration represents an unacceptable long term MMOD risk to the ISS Program. Therefore, an agreed to long term risk reduction strategy must be developed and implemented within reasonable constraints to appropriately mitigate this risk. For example, it is believed that feasible options exist to later augment MRM-2 shielding on-orbit, and these options should be fully pursued as part of that long term strategy. This NCR has a limited effectivity to intentionally decouple the MRM-2 launch decision from the long term risk management issue. This effectivity also recognizes the on-going high-level discussions with respect to overall ISS MMOD risk, of which this MRM-2 issue is a part, and allows time for those discussions to mature. Success criteria for managing this NCR at Level II through final risk reduction implementation is prior to expiration of this NCR revision, an agreed to plan/schedule is developed, and future NCR revisions track agreed to plan/schedule.

Подписной лист к отчету о несоответствии NCR-RS-MRM2

Имя, фамилия	Подпись	Дата
Михаил Агафонов		
Вячеслав Соколов		
Виталий Айнулов		
Михаил Шутиков		
Александр Диденко		
Павел Воробьев		
Валерий Рюмин		

Signature Page for Non-Compliance Report NCR-RS-MRM2

First Name, Last Name	Signature	Date
Vyacheslav Sokolov		
Alexander Telegin		
Boris Ryadinsky		
Konstantin Grigoriev		
Alexey Bideyev		
Vitaly Ainulov		
Mikhail Shutikov		
Alexander Didenko		
Pavel Vorobiev		
Valery Ryumin		

1. Tracking Number:	INTERNATIONAL SPACE STATION SAFETY NONCOMPLIANCE REPORT (NCR)	Page: of
2. Date:	3. NCR Number: NCR-RS-MRM2-01	

19. Shuttle Signatures:	
19a. Safety & Mission Assurance Panel - *Shuttle* Print Name: Signature: N/A	Phone: Date:
19b. Engineering Technical Authority - *Shuttle* Print Name: N/A Signature:	Phone: Date:
19c. Health and Medical Technical Authority - *Shuttle* Print Name: Signature: N/A	Phone: Date:
19d. Safety & Mission Assurance Technical Authority - *Shuttle* Print Name Signature: N/A	Phone: Date:
19e. Program Manager - *Shuttle* Print Name: Signature: N/A	Phone: Date:
20. Concurrence Signatures:	
20a. Affected AIT/SPRT/FIT Print Name: Signature:	Phone: Date:
20b. Affected AIT/SPRT/FIT Print Name: Signature:	Phone: Date:
20c. Flight Equipment Safety and Reliability Review Panel (FESRRP) Print Name: N/A Signature:	Phone: Date:
20d. ISS Safety Review Panel (SRP/PSRP/GSRP) Print Name: Signature:	Phone: Date:
20e. ISS Safety & Mission Assurance Panel: Print Name: Signature:	Phone: Date:
20f. Other Concurrence (as required) Print Name: Signature:	Phone: Date:
20g. Other Concurrence (as required) Print Name: Signature:	Phone: Date:

1. Tracking Number:	INTERNATIONAL SPACE STATION SAFETY NONCOMPLIANCE REPORT (NCR)	Page: of
2. Date:	3. NCR Number: NCR-RS-MRM2-01	

21. Approval Signatures:	
21a. Engineering Technical Authority - ISS	
Print Name:	Phone:
Signature:	Date:
21b. Health and Medical Technical Authority - ISS	
Print Name:	Phone:
Signature:	Date:
21c. Safety & Mission Assurance Technical Authority - ISS	
Print Name:	Phone:
Signature:	Date:
21d. ISS Program Office	
Print Name:	Phone:
Signature:	Date:

1. Tracking Number:	INTERNATIONAL SPACE STATION SAFETY NONCOMPLIANCE REPORT (NCR)	Page: of
2. Date:	3. NCR Number: NCR-RS-MRM2-01	

22. International Partner Signatures	
22a. ASI	
Print Name:	Phone:
Signature:	Date:
22b. CSA	
Print Name:	Phone:
Signature:	Date:
22c. ESA	
Print Name:	Phone:
Signature:	Date:
22d. JAXA	
Print Name:	Phone:
Signature:	Date:
22e. Roscosmos/RSC-E	
Print Name:	Phone:
Signature:	Date:

Appendix F. Stakeholder Briefing for Independent Review of US and Russian PRAs for MRM2 MMOD Risk

	Presenter **Mike Squire**
	Date **December 2009**

Stakeholder Briefing

Independent Review of US and Russian PRAs for MRM2 MMOD Risk
NESC Request # TI-00592

Mike Squire

December 2009

NESC Request No: TI-00592 1

Charter

Charter	Presenter: Mike Squire
	Date: December 2009

- **NESC Request**
  - Review MMOD catastrophic risk assessments for NASA and RSC-Energia for the Mini-Research Module 2 (MRM-2)
- **NESC Team**
  - Mike Squire/NESC
  - Dana Lear/NASA JSC (KX)
  - Hank Rotter/NASA Technical Fellow for Life Support and Active Thermal
  - Dr. Fayssal Safie/NASA Safety Center
  - Dr. William Schonberg/Missouri University of Science and Technology
  - Dr. Joel Williamsen/Institute for Defense Analysis

NESC Request No: TI-00592 2

Background

Background	Presenter: Mike Squire
	Date: December 2009

- **MMOD probability for catastrophic failure assessments between NASA and RSC-Energia presented at the 5R Stage Operations Readiness Review (SORR) differed considerably**
  - NASA: 1 in 1380 (0.07%) vs
  - RSC-E: 1 in 11,100 (0.009%)
  - *Both are for 15 years*
- **Low probability for catastrophic failure risk presented as acceptance rationale for ISS NCR-RS-MRM2-01**
  - NCR documented probability of no penetration (PNP) for MRM-2 violating requirement
    - 0.985 for 15 years (requirement is PNP >= 0.996 for 15 years)

NESC Request No: TI-00592 3

Background (cont'd)

Presenter: Mike Squire
Date: December 2009

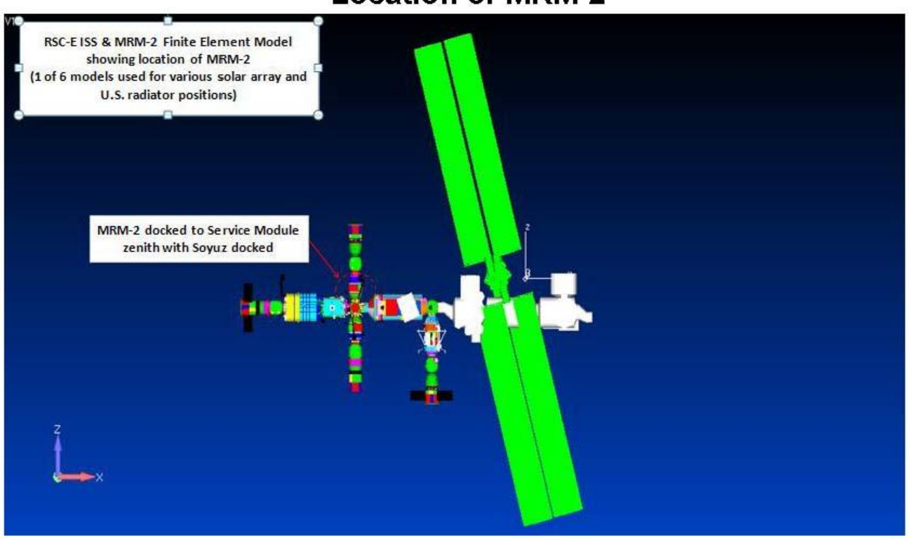
- **Recommendations presented at 5R SORR**
  - RSC-Energia:
    - Keep MRM-2 MMOD shielding as is for life of the program
  - NASA MMOD and ISS Chief of SMA:
    - Current MMOD shielding for MRM-2 unacceptable for long-term
    - Risk mitigation strategy should be developed by RSC-E to include MMOD shielding augmentation to reduce ISS MMOD risk

NESC Request No: TI-00592 4

Background

Presenter: Mike Squire
Date: December 2009

Location of MRM-2



NESC Request No: TI-00592 5

Calculation of Catastrophic Risk

Presenter: Mike Squire
Date: December 2009

- **Probability of no penetration (PNP)**
  - SORR PNP's were in agreement and not source of divergence between NASA and RSC
    - 15 year: 0.992 (NASA) vs. 0.991 (RSC) using 2000 debris model
- **Reduce Loss Factor (R-factor)**
  - Ratio of catastrophic penetrations to all penetrations
  - Total R-factor is sum of all R-factors for individual risk modes
- **Probability of no catastrophic failure (PNCF)**
  - $PNCF = (PNP)^R$
  - Catastrophic Risk = 1-PNCF

NESC Request No: TI-00592 6

Updated Risk Estimates

Presenter: Mike Squire
Date: December 2009

- **RSC-E Risk Estimates have evolved since the SORR**
  - Most recent values show ~2x difference between NASA and RSC-E rather than ~10x difference observed at SORR and the NCR

RSC-Energia

Date	PNP	R-Factor	Risk	Odds	Comments
10/6/09	0.991	0.010	9.0e-05	1 in 11,111	Values presented in NCR and SORR, PNP uses 2000 debris/1991 meteoroid
12/4/09	0.9955	0.0512	2.3e-04	1 in 4294	Most recent values as of 12/4/09, PNP uses 2000 debris/1991 meteoroid

NASA

Date	PNP	R-Factor	Risk	Odds	Comments
8/25/09	0.992	0.090	7.2e-04	1 in 1385	Values presented in NCR and SORR, PNP uses 2000 debris/MEM
12/2/09	0.992	0.077	6.2e-04	1 in 1619	Most recent values as of 12/4/09, PNP uses 2000 debris/MEM
12/2/09	0.994	0.077	4.8e-04	1 in 2101	Most recent values as of 12/4/09, PNP uses 2000 debris/1991 Meteoroid

NESC Request No: TI-00592 7

NASA and RSC-Energia's R-factors

Presenter: Mike Squire
Date: December 2009

- R-factor Comparison (N/C = not calculated in analysis provided)

NASA R	RSC-E R	Risk Description	Comments
0	N/C	Critical Crack (unzipping) causes loss of station	
0	N/C	External equipment penetration causes loss of station	
0.063	N/C	Internal systemic equipment penetration causes loss of station.	NASA assumption is the presence of internal pressurized tanks.
0	0.02435	Docking unit failure.	
0.004	0.02519	Hypoxia causes loss of crew.	Depends on hole size and time it takes crew to egress ISS. RSC-E assumes time of 9.5 minutes, NASA uses a distribution relating crew position and amount of time spent in different areas of the ISS.
0.010	0.00168	Fragmentation causes loss of crew.	NASA probably assumed a higher occupancy rate than RSC-E
0	N/C	Thrust induced angular velocity causes loss of crew.	

NESC Request No: TI-00592 8

R-factors (cont'd)

Presenter: Mike Squire
Date: December 2009

- **NASA R-factor (using numbers from previous chart)**
  - 0.063+0.004+0.01 = 0.077
- **RSC-E R-factor (using numbers from previous chart)**
  - 0.02435+0.02519+0.00168 = 0.05122
- **For MRM-2 R-factors are not equal but close**
  - NASA R-factor = 0.077
  - RSC-E R factor = 0.05122
- **An upper bound for R-factor may be approximated by adding the worst case values from NASA and RSC-E**
  - 0.063 (internal system failure) + 0.02435 (docking system failure) + 0.02519 (hypoxia) + 0.01 (fragmentation) = 0.123

NESC Request No: TI-00592 9

Possible Reasons for Differences from October to December

Presenter: Mike Squire
Date: December 2009

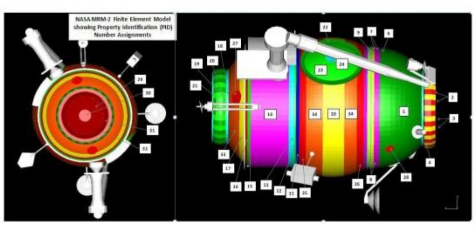
- **Known factors affecting RSC-E increase in risk**
  - PNP calculations now use actual stand-off distance between outer shield and pressure wall (larger than previous)
  - Starting year for debris and meteoroid models changed from 1998 to 2009
  - R-factor updated from 0.010 to 0.0512
- **Factors affecting NASA decrease in risk**
  - Incorrect initial R-Factor of 0.090 corrected to 0.077

NESC Request No: TI-00592 10

Possible Reasons for Remaining Difference between NASA and RSC-Energia

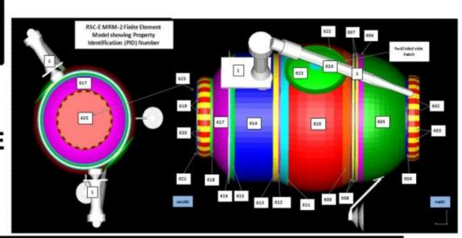
Presenter: Mike Squire
Date: December 2009

- **Suspect that RSC-E may be using older FEM than NASA, which affects the PNP.**
- **PNP calculations use different property identification (PID) mapping (see back-up charts for enlarged views)**



NASA

RSC-E



NESC Request No: TI-00592 11

Differences between NASA and RSC-Energia

Presenter: Mike Squire
Date: December 2009

- **Differing assumptions result in different R-factors 0.077 (NASA) vs. 0.0512 (RSC-E)**

NASA R	RSC-E R	Risk Description	Comments
0	N/C	Critical Crack (unzipping) causes loss of station	
0	N/C	External equipment penetration causes loss of station	
0.063	N/C	Internal systemic equipment penetration causes loss of station.	NASA assumption is the presence of internal pressurized tanks.
0	0.02435	Docking unit failure.	
0.004	0.02519	Hypoxia causes loss of crew.	Depends on hole size and time it takes crew to egress ISS. RSC-E assumes time of 9.5 minutes, NASA uses a distribution relating crew position and amount of time spent in different areas of the ISS.
0.010	0.00168	Fragmentation causes loss of crew.	NASA probably assumed a higher occupancy rate than RSC-E
0	N/C	Thrust induced angular velocity causes loss of crew.	

NESC Request No: TI-00592 12

Additional possible reasons to explain R-factor differences

Presenter: Mike Squire
Date: December 2009

- **NASA calculates R-factor using MSCSurv**
  - Some empirical equations for pressure wall hole diameter and crack length believed being used are based on data from testing at 6.5 km/s only, some based on data at 6.5 and at 11.3 km/s.
    - If single-velocity equations are being used, how are other impact velocities accounted for?
  - Equations believed being used derived from testing on targets with different configuration than MRM-2 wall geometry
    - Bumper stand-off distances for MRM-2 less than test configuration
    - One of the MLI blankets on MRM-2 not present in test configuration
    - How are configuration differences accounted for?

NESC Request No: TI-00592 13

Additional possible reasons to explain R-factor differences	Presenter Mike Squire
	Date December 2009

- **RSC uses empirical equations for pressure wall hole diameter and crack length developed in a 1995 NASA/ASEE study**
  - Equations are derived from testing at 6.5 km/sec only
    - How are other impact velocities accounted for? Same technique as NASA or somehow else?
  - Equations derived from testing on targets with different ~~in~~ configuration than MRM-2 wall geometry
    - Bumper stand-off distances for MRM-2 less than test configuration
    - One of the MLI blankets on MRM-2 not present in test configuration
    - How are configuration differences accounted for? Same technique as NASA or somehow else?

NESC Request No: TI-00592 14

Findings	Presenter Mike Squire
	Date December 2009

- **F-1: Based on the risk assessment for either source, augmented MMOD shielding is warranted for MRM-2.**
- **F-2: According to the most recently produced values, the discrepancy between NASA and RSC-Energia's risk is now approximately a factor of 2 instead of the factor of 10 displayed at the 5R SORR.**
- **F-3: The work NASA and RSC-E have planned is appropriate to close the gap between the MMOD risk assessments.**
- **F-4: Variations in PNP between NASA and RSC-E may be caused by**
  - RSC-E may be using older FEM than NASA.
  - PNP calculations use different property identification mapping.
  - Differing assumptions result in different R-factors.

NESC Request No: TI-00592 15

Findings

Presenter: Mike Squire
Date: December 2009

- **F-5: The components of the individual R-factors are different, and this may cause a larger variation in PNCF than either NASA or RSC-E are currently accounting for. Variations in R-factor between NASA and RSC-E may be caused by:**
  - RSC-E assumes no risk due to pressurized tanks within the module while NASA does.
  - NASA does not account for docking mechanism failure.
  - RSC-E assumed higher risk of hypoxia.
  - RSC-E assumes lower risk to fragmentation (function of time spent in module).

NESC Request No: TI-00592 16

Findings (cont'd)

Presenter: Mike Squire
Date: December 2009

- **F-6: With the information available, there is no way to judge which of the two current PNCFs is *more* appropriate – the assumptions going into the two PNCFs are not yet aligned with one another.**
- **F-7: Different uncertainty assumptions may also contribute to different risk assessments**
  - This was not explored in depth in this study.
- **F-8: Currently, there is no NASA mechanism for incorporating changes in the R-factor due to model changes, shield changes, operational changes, etc.**
  - NASA is working on rectifying this

NESC Request No: TI-00592 17

Recommendations

Presenter: Mike Squire
Date: December 2009

- **R-1: Install additional MMOD shielding to reduce the PNP to the level specified in the requirements.**
- **R-2: NASA and RSC-Energia should continue to work to further narrow the gap between R-factors and PCF for MRM-2.**
  - NASA plans to run Bumper using RSC-E's FEM and ballistic limit equation inputs.
- **R-3: Define uncertainties in PCFs and the terms going factored into their calculation.**
- **R-4: Proceed with current NASA plans to update R-factors in risk assessments.**

NESC Request No: TI-00592 18

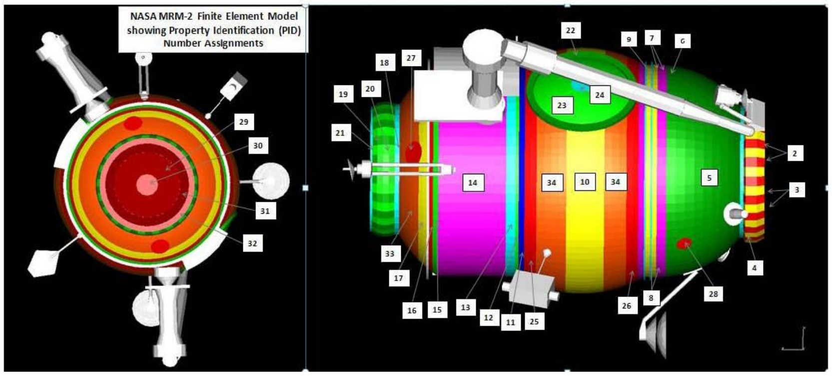
Back-up

Presenter: Mike Squire
Date: December 2009

NESC Request No: TI-00592 19

PID Differences	Presenter **Mike Squire** Date **December 2009**

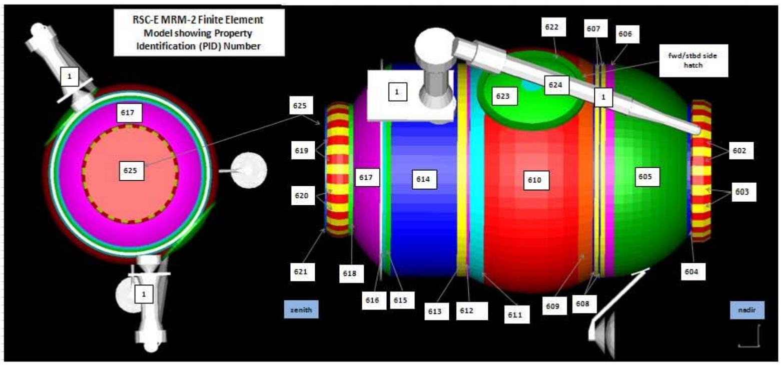
NASA FEM showing PID assignments



NESC Request No: TI-00592 20

PID Differences	Presenter **Mike Squire** Date **December 2009**

RSC-Energia FEM showing PID assignments



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14. ABSTRACT
The Mini-Research Module-2 (MRM-2), a Russian module on the International Space Station, does not meet its requirements for micrometeoroid and orbital debris probability of no penetration (PNP). To document this condition, the primary Russian Federal Space Agency ISS contractor, S.P. Korolev Rocket and Space Corporation-Energia (RSC-E), submitted an ISS non-compliance report (NCR) which was presented at the 5R Stage Operations Readiness Review (SORR) in October 2009. In the NCR, RSC-E argued for waiving the PNP requirement based on several factors, one of which was the risk of catastrophic failure was acceptably low at 1 in 11,100. However, NASA independently performed an assessment of the catastrophic risk resulting in a value of 1 in 1380 and believed that the risk at that level was unacceptable. The NASA Engineering and Safety Center was requested to evaluate the two competing catastrophic risk values and determine which was more accurate. This document contains the outcome of the assessment.

15. SUBJECT TERMS
International Space Station; Micrometeoroid and orbital debris; Probability of no penetration; NASA Engineering and Safety Center; Mini-Research Module-2

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