Space Shuttle Program Dual Docked Operations

Joel W. Sills Jr[1]
National Aerospace and Space Administration (NASA)/ Johnson Space Center, Houston, TX, 77058

Erica E. Bruno[2]
MRI Technologies, Houston, TX, 77058

Due to the ever-increasing visiting vehicle traffic to and from the International Space Station (ISS) during mated Orbiter/ISS missions, it became apparent to both the ISS Program (ISSP) and the Space Shuttle program (SSP) that there would arise occasions where a visiting vehicle docking and/or undocking could overlap when the Space Shuttle Orbiter was docked to the ISS, referred to as Dual Docked Operations (DDO). The primary concerns were that plumes from the visiting vehicles would cause contamination, corrosion, and erosion to Space Shuttle surfaces and present a toxicity hazard to ground personnel when processing the Space Shuttle after landing. This potential conflict provided the genesis for evaluating risk mitigations to gain maximum flexibility for managing potential visiting vehicle traffic to and from the ISS and to maximize launch and landing opportunities for all visiting vehicles. The overarching goal of this effort was to assess the viability and readiness of the SSP to protect for DDO on any given mission. To assess the viability of performing DDO, the ISSP delivered plume particle fluence (i.e., number of particles per unit area) and contamination deposition based on the visiting vehicle's proximity operations to the SSP for evaluation. This paper summarizes the concept definition, studies, and analysis results generated by the SSP, ISSP, and Mission Operations Directorate (MOD) for implementing DDO involving the Orbiter and Russian vehicles (RVs). Discussion and results presented herein represent a generic assessment of the SSP and ISSP integrated safety and technical evaluations of DDO involving the Orbiter and RVs. Mission-specific analysis and operational impacts were conducted flight-by-flight as they arose.

I. Nomenclature

C&T	Communications and Tracking
CCTV	Closed Circuit Television
CoFR	Certificate of Flight Readiness
DC1	Docking Compartment 1
DDO	Dual Docked Operations
ECLSS	Environmental Control and Life Support System
EVA	Extravehicular Activity
FGB	Functional Cargo Block

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[1] NASA Engineering Safety Center Chief Engineer, Johnson Space Center, and AIAA Associate Fellow.
[2] Section Manager, Structural Loads and Dynamics on the Johnson Space Center (JSC) Engineering, Technology and Science (JETS) Contract

FO&I	Flight Operations and Integration
FRSI	Felt Reusable Surface Insulation
ICD	Interface Control Document
IDD	Interface Definition Document
ISS	International Space Station
ITVC	Intensified (Black and White) Television Camera
JSC	Johnson Space Center
JTWG	Joint Technical Working Group
KSC	Kennedy Space Center
LDRI	Laser Dynamic Range Imager
LDT	Loads and Dynamics Team
MOD	Mission Operations Directorate
MMH	Monomethylhydrazine
MMOD	Micrometeoroid and Orbital Debris
MRM1	Multi-Purpose Research Module 1
MRM2	Multi-Purpose Research Module 2
MSDS	Material Safety Data Sheet
NCR	Nonconformance Report
NDMA	N-nitrosodimethylamine
NTO	Nitrogen Tetroxide
NVR	Non-Volatile Report
OBSS	Orbiter Boom Sensor System
PLB	Payloads Bay
PLBD	Payload Bay Door
PPE	Personal Protective Equipment
PRT	Problem Resolution Team
psi	Pound per square inch
RCC	Reinforced Carbon-Carbon
RMS	Remote Manipulator System
RS	Russian Segment
RSC	RMS Sideview Camera
RV	Russian Vehicle
S&MA	Safety and Mission Assurance
SM	Service Module
SSP	Space Shuttle Program
STS	Space Transportation System
TCS	Thermal Control System
TPS	Thermal Protection System
UFORP	UDMH Fuel Oxidizer Reaction Products
UDMH	Unburned Unsymmetrical Dimethylhydrazine
VLA	Verification Loads Analysis
VRCS	Vernier Reaction Control System
μm	micron

II. Introduction

Due to the ever-increasing visiting vehicle traffic to and from the International Space Station (ISS) during mated Orbiter/ISS missions, it became apparent to both the ISS Program (ISSP) and the Space Shuttle program (SSP) that there would arise occasions where a visiting vehicle docking and/or undocking could overlap when the Space Shuttle Orbiter was docked to the ISS, referred to as Dual Docked Operations (DDO). The primary concerns were that plumes from the visiting vehicles would cause contamination, corrosion, and erosion to Space Shuttle surfaces and present a toxicity hazard to ground personnel when processing the Space Shuttle after landing. This potential conflict provided the genesis for evaluating risk mitigations to gain maximum flexibility for managing potential visiting vehicle traffic to and from the ISS and to maximize launch and landing opportunities for all visiting vehicles. This paper chronicles the concept definition studies and analysis results generated by both the SSP and the ISSP for DDO involving the Orbiter and Russian vehicles (RVs) (i.e., Soyuz or Progress)[1]. The studies, analyses, and results presented herein summarize the work conducted for the Space Transportation System (STS)-130 (February 2010) through STS-134 (May/June 2011) flights by a cadre of SSP, ISSP, and Mission Operations Directorate (MOD) teams. Further details and results can be found in reference 1 along with detail references from the contributing personnel and organizations.

To manage this wide-ranging issue, the program teams decided to approach this study in a piece-wise manner, focusing on the greatest portion of the visiting vehicle traffic and their potential overlap with Space Shuttle missions. For the purposes of this paper, both the ISSP and the SSP defined DDO as the capability to perform a RV docking or undocking during a mated SSP mission to ISS. H-II Transfer Vehicle (HTV), Automated Transfer Vehicle (ATV), and commercial resupply vehicles were not considered, and ground ruled out.

III. Requirements and Ground Rules

From the outset, a set of requirements and ground rules were established to set the framework for the study. The ISSP and SSP teams jointly agreed that DDO shall occur only at the following ISS Ports (Fig. 1):

1. Service Module (SM) Aft for docking and undocking
2. Docking Compartment One (DC1) Nadir for docking and undocking
3. Functional Cargo Block (FGB) Nadir for undocking only (prior to STS-132)
4. Multi-Purpose Research Module One (MRM1) (STS-132 through STS-134)
5. Multi-Purpose Research Module Two (MRM2) Zenith for docking and undocking

RV docking or undocking is prohibited while a cargo element is on the Shuttle Remote Manipulator System (SRMS). RV docking or undocking during extravehicular activity (EVA), robotics, or during Orbiter dock/undock day is prohibited.

During RV dockings, the ISS shall be under Russian Segment (RS) control, and the Orbiter system shall remain passive. For undocking, two options shall be considered for mated stack control:

1. Undocking shall be performed with ISS mated stack under RS control only.
2. Undocking shall be performed with ISS mated stack under Orbiter Vernier reaction control system (VRCS) jet control only. There shall be no consideration given to mixed Russian segment and Orbiter control due to the complexity associated with the ISS solar array plan for either set of jets.

For docking of the Soyuz, DDO shall occur only during indirect Soyuz crew rotations. Indirect Soyuz crew rotation means that there will be no more than 13 crew members onboard the ISS at a single time. RV undock/dock shall occur only over Russian ground track and during crew awake periods.

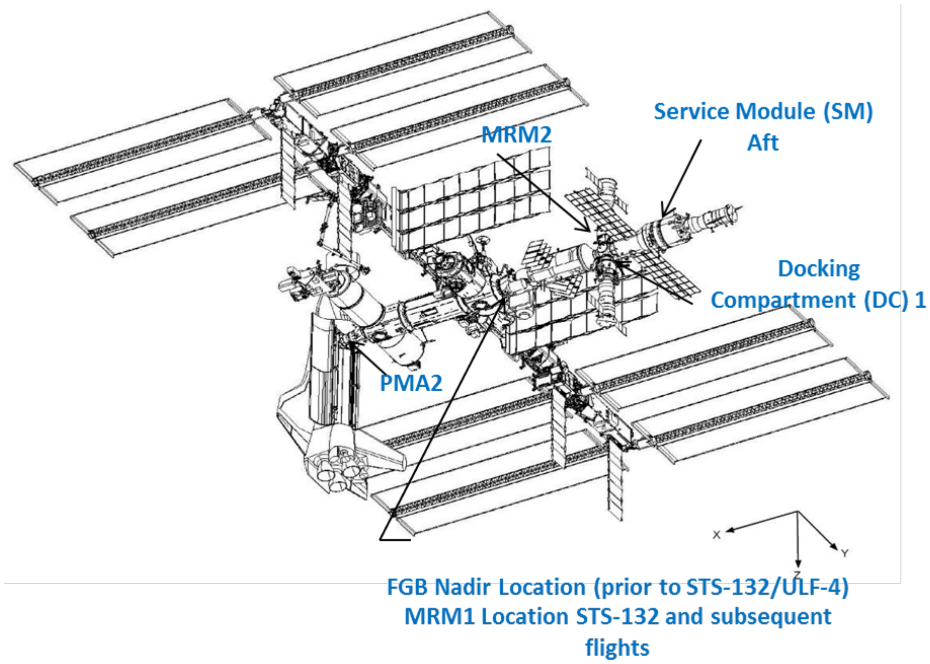

Fig. 1 Representation of joint docked SSP/ISS mission configuration

IV. Thruster Contamination and Particle Fluence

To assess the viability of performing DDO, the ISSP delivered plume particle fluence and contamination deposition based on RV proximity operations to the SSP for evaluation. These environments will cause thruster plume contamination and erosion/pitting to Orbiter surfaces. The contamination is due to the deposition of unburned or partially burned propellant droplet material, while the erosion/pitting is mechanical damage due to high velocity impacts of unburned propellant droplets. Initial contaminant deposit includes unburned unsymmetrical dimethylhydrazine (UDMH) and nitrogen tetroxide (NTO), monomethyl hydrazine (MMH)-nitrates, N-nitrosodimethylamine (NDMA), and non-volatile residue (NVR), which includes impurities in the propellant.

Particle fluence and contamination results were provided by ISSP for the following Orbiter surfaces: crew cabin windows, Orbiter boom sensor system (OBSS) sensors, cameras on payload bay (PLB) bulkheads, keel, and SRMS, payload bay door (PLBD) thermal control system (TCS) radiators, and general PLB surfaces.

Environments include particle fluence results for MRM2-based RV proximity operations to allow consideration of plume impingement on Orbiter wing reinforced carbon-carbon (RCC) due to an MRM2 event. For each RS docking port, the ISS Space Environments team simulated six approaches, one separation, and one Soyuz thruster test per the available data. These scenarios were developed using as-flown data. In all simulations, the RV centerline was coaxial throughout with the docking port centerline and with the vehicle maintaining a constant attitude. No translation or attitude dispersions were modeled. This technique was used because sufficient information for accurate modeling of translation or attitude dispersions is not available from RV flight simulations.

An additional analysis case involving a more conservative RV approach trajectory and attitude was provided by the ISS Space Environments team for assessment. RV approach proximity operations to the MRM2 docking port was selected for an alternative analysis case. The vehicle approach trajectory and attitude were selected to maximize particle fluence/contamination results for the front Orbiter windows (Fig. 2).

For this more conservative case, nominal RV lateral misalignment was limited to a 10° cone along the approach vector. The 10° cone is a specification value for the approaching vehicle. The 4° RV pitch results in higher particle fluence/contamination levels to the front Orbiter windows. The 4° pitch was selected to place the thrusters closest to the windows within the limits of the nominal approach. Results for this case indicate that particle fluence to front windows for the more conservative RV approach trajectory and attitude was higher than predictions in a NASA study using a 5° corridor by a factor of ~2.2, and contamination levels to front windows for this more conservative RV approach trajectory and attitude were higher than predictions in the original NASA study by a factor of ~2.1.

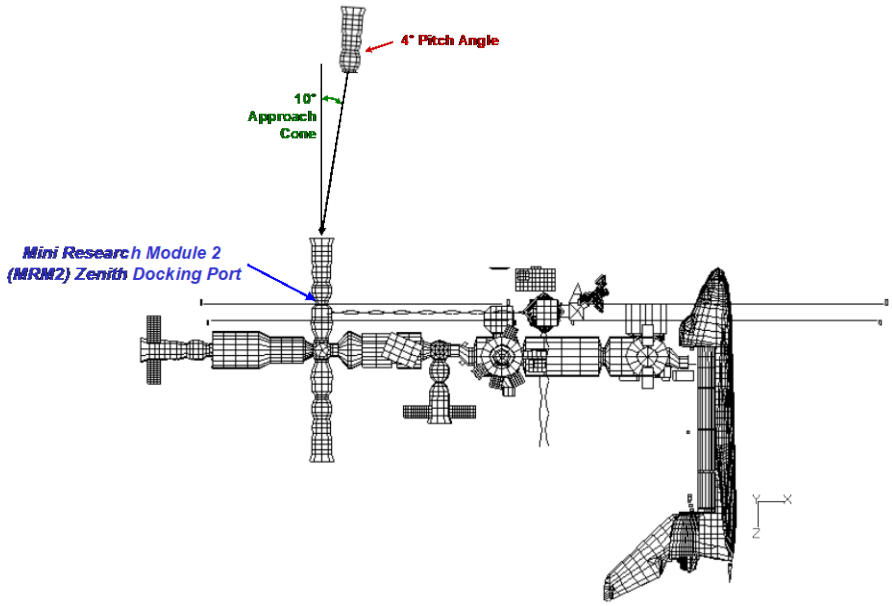

Fig. 2 Approach trajectory and attitude for alternative approach analysis case

A RV abort scenario for vehicle proximity operations to the MRM2 docking port was assessed and environments were provided to SSP personnel. The abort scenario was synthesized from nominal approach jet firing data. The RV proximity operations to the MRM2 docking port was selected for the abort scenario. The scenario involves an approach and backout, both of which were modeled using available jet firing data for nominal RV approach proximity operations. The range offset was applied such that the last lateral engine thruster firing occurs at the minimum range for Orbiter window exposure (Fig. 3).

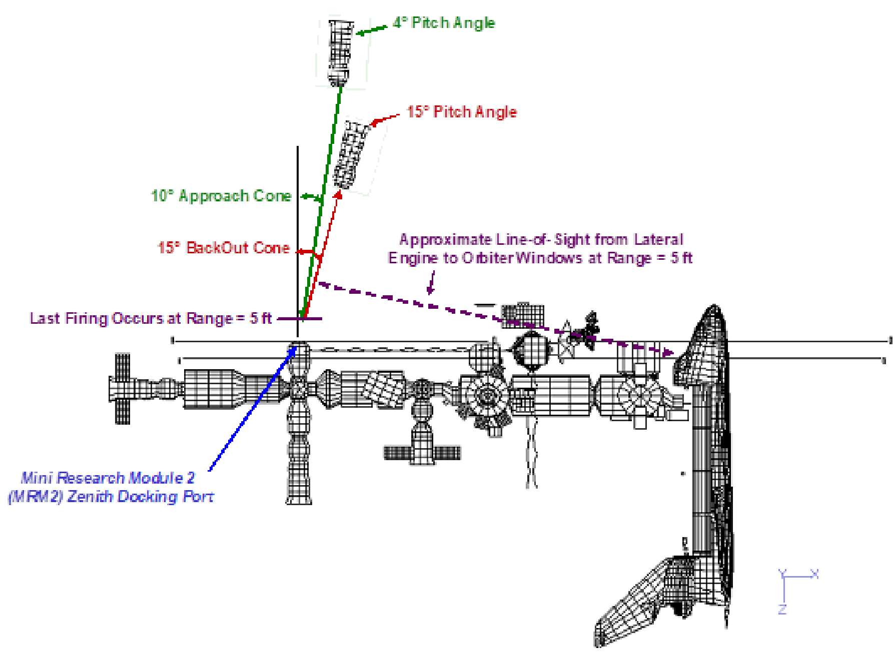

Fig. 3 RV trajectory and attitude assumptions for the abort scenario

Table 1 summarizes the particle fluence for the Orbiter windows, considered the most sensitive vehicle surface when exposed to the particle fluence. In addition, separate particle fluence results were generated from the abort scenario case for 1 to 5 microns (µm), 6 to 10 µm, and 11 to 12 µm diameter particle groups to support planned SSP ground hypervelocity impact tests as shown in Fig. 4.

Table 1. Analysis Case Summary for Orbiter Windows

	Nominal Approach	Bounded Nominal Approach	Abort Scenario - Approach	Abort Scenario - Backout	Abort Total
Approach Cone Half-Angle *degrees*	0	10	10	15	-
Russian Vehicle Pitch Angle *degrees*	0	4*	4*	15**	-
Offset Applied (to fix last firing at range = 5 ft)	N	N	Y	Y	-
Particle Fluence to Fwd-Stbd Fuselage Window (Front) *particles/cm²*	2279	5006	6580	30754	37335
Particle Fluence to Fwd-Port Fuselage Window (Front) *particles/cm²*	2274	5047	6501	30678	37179

*Pitch angle held at 4 degrees to maximize particle fluence to Orbiter front windows.

**Pitch angle of up to 15 degrees. Pitch angles less than 15° selected as needed to maximize particle fluence to Orbiter front windows.

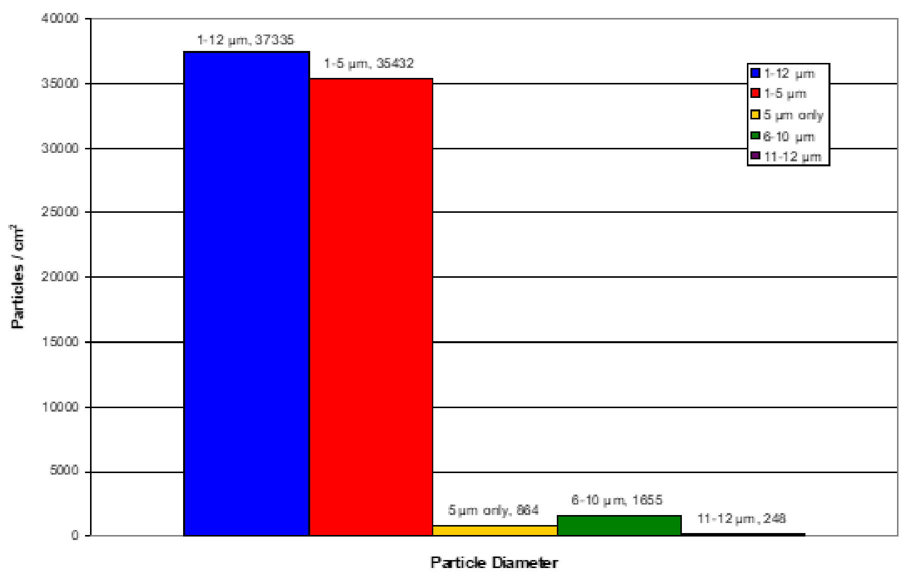

Fig. 4 Particle fluence by diameter to the Orbiter starboard front window for the RV abort scenario

V. Proximity Operations Environments

The ISS Loads and Dynamics Team (LDT) provided RV proximity operation loads when approaching the SM aft port, DC-1 nadir port, FGB nadir port, and MRM2 zenith port. These loads are based on post-flight reconstructions of RV approach trajectories to the ISS. A Monte Carlo analysis of the data were used to develop the models. For the analysis, the plume flow field uncertainty factor was set to its maximum value for all jet firings to ensure conservatism in the model. For off-nominal plume pressure cases, a dual jet plume amplification factor of 1.634 was implemented. The 1.634 amplification factor addresses superposition of two-jets and provides additional conservatism.

RV undocking force time histories were generated for the RVs using dynamic analyses that are based on the stiffness characteristics of the Probe and Cone mechanism's plunger system. There are four plungers, located symmetrically about the interface, activated after the hooks and latches are released, that separated the RV from ISS. It was assumed that the mass of the ISS was sufficiently larger than the undocking vehicle to justify modeling the RV as a rigid body mass system and the four plungers as a grounded spring, and the undocking forces were therefore calculated from a simple mass-spring system. No other external forces are included in the model.

VI. Approach and Separation Trajectory Assessments

Approach and separation clearances to ISS, as well as abort trajectories, were assessed during this study. Separation and docking analyses are required to confirm compliance with on-orbit Interface Control Document (ICD) requirements. From over 500 cases that were run, only 12 of the worst cases were selected for detailed vehicle clearance analysis. Cases include both RV failed motion control system and nominal separation scenarios. The FGB-nadir port separation for DDO provides a close clearance between a RV on the DC1 port. The FGB-nadir port was ruled out for DDO due to Orbiter tail impingement within the 45° half-angle Kurs antenna signal cone, which keeps the approaching vehicle from communicating with the ISS. For the same reason, the MRM1 at the FGB-nadir point was ruled out for DDO.

The NASA safety community and the Russian Space Agency conducted extensive reviews of these trajectories. The two-fault tolerant guidelines were applied to RVs, with the implicit understanding that NASA would never receive complete documentation.

However, over the course of detailed technical discussions concerning the architecture and docking operations, to include flight histories, agreement was achieved. In cases where the vehicles were not two-fault tolerant, nonconformance reports (NCRs) were written by the Russians, and the risks were accepted by the SSP and ISSP using the rationale of flight history to explain these situations.

A. Orbiter Assessment Results

The Orbiter Project Office, responsible for all the Orbiter systems and subsystems, reviewed all ISSP-provided induced environments and performed assessments of all their subsystems. Regarding particle impingement, the threat posed to the RCC hardware would be taken seriously, and inspections for surface damage would be included as appropriate to ensure the "Late Mission" micrometeoroid and orbital debris (MMOD) inspection was performed in accordance with operational flight rules. However, no damage to RCC was predicted, even if the late inspection constraint could not be met.

For the thermal protection system (TPS), post-flight MMOD inspections demonstrated that damage to tiles/blankets/felt reusable surface insulation (FRSI) from light fast particles was generally less severe than the damage of light fast particles to the RCC. Since the detailed Soyuz docking evaluation has determined there was no issue for RCC, no issue would be expected for tiles/blankets/FRSI. Therefore, there were no constraints for TPS.

Camera lenses are the closed-circuit television (CCTV) system's greatest vulnerability. The forward and aft bulkhead cameras and the SRMS Elbow camera must be pointed away from the plume flow to avoid direct contact by the plume particles. The SRMS wrist camera and the Orbiter RMS Sideview camera (RSC) should be protected from direct contact by the plume particles. If these constraints are not met, damage would result in degraded video pictures both by unwanted glints from pits camera lens and/or blurring from the residue.

Regarding SRMS/OBSS positioning, the OBSS receives particle impacts to some degree for all port locations. To mitigate this, the intensified television camera (ITVC)/laser dynamic range imager (LDRI) optics are constrained to not to be in the line of sight of the source of particle fluence. The OBSS constraint is to place it out of the line of sight of the plume. These positions have already been developed.

Particle impingement on the Orbiter windows was analyzed, and the Windows Problem Resolution Team (PRT) assessment was that the pane strength test of laboratory-created specimens shows no adverse degradation to thermal pane strength as a result of the nominal and bounded nominal environments for DDO. A 3-sigma (σ) strength value of 6,212 pounds per square inch (psi) stress was used, which exceeds the minimum entry/descent certification strength minimum value of 5,010 psi stress for thermal pane fused silica glass.

The Orbiter window testing did not encompass the abort scenario environment, and the Windows PRT was not comfortable extrapolating their results to this environment. The Windows PRT tried to insert as much potential scatter as possible with the available 17 specimens from 8 windows. The testing was performed at the edge of the bounded nominal environment. The PRT used 5 μm particles of a certain fluence, and 10 μm particles of a certain fluence. The strength of the glass was not sensitive to the two particle sizes nor the fluence prescribed for the nominal and bounded nominal cases. For the nominal and bounded cases, the strength of the glass was adequate for launch and landing; however, a determination on whether the strength of the glass was adequate for aborts could not be made based on the data set.

Toxicity concerns for ground processing primarily center on the NDMA residue from the UDMH fuel oxidizer reaction products (UFORP). A secondary consideration is the nonvolatile salts that may accumulate in the PLB since these do not liberate in a vacuum environment. The UFORP components evaporate within 45 minutes from a surface at 25° C. The nonvolatile particulate salts are eye and skin irritants per the Material Safety Data Sheet (MSDS) and use of personal protective equipment (PPE) will mitigate these concerns. Therefore, there are no constraints pertaining to toxicity. The NASA/Kennedy Space Center (KSC) industrial hygiene group has been engaged in this study, and no issues are foreseen. As an additional precaution, EVA is not allowed as per ground rules during a DDO, and the only exposure risk to the UFORP is in the area immediately around the engine bells of the SM.

B. SSP Flight Operations and Integration (FO&I) Assessment Results

All FO&I areas of responsibility assessed the viability for DDO. FO&I was responsible for the Orbiter payload bay cargo and middeck cargo, proximity operations and docking with ISS, and co-lead the Joint Technical Working Groups (JTWGs) with ISS. The Space Transportation System (STS)-130 mission was used as the pathfinder for this study. Existing certifications were applied generically where possible. All JTWGs assessed the ISSP-provided environments for viability to perform DDO. Power/Avionics, Environmental Control and Life Support System (ECLSS), Power/Avionics, and Communication and Tracking (C&T), and electromagnetic effects panels completed generic assessments with no issues identified. The Thermal Control System (TCS), Vehicle Configuration , Loads and Dynamics, and Flight Control and Structures panels requested mission-specific analyses and documentation updates.

Peak docking/undocking loads for both STS-130 and STS-131 demonstrated no limit load exceedances, with the peak load at 37 percent and 35 percent of the ICD limit loads, respectively. There were no constraints to DDO identified.

Flight Control DDO results showed that Orbiter maintains control within attitude deadbands, and propellant usage was as expected, with all Shuttle Operations Data Book constraints satisfied. The constraint was that DDO is certified using VRCS only ISS attitude control, and only for RV undocking. There was no consideration given to mixed Russian segment and Orbiter control for ISS attitude control due to the complexity associated with the ISS solar array plan for either set of jets. No analysis or consideration was given for Orbiter VRCS jet fail cases that lead to Alt-Primary Reaction Control System (PRCS) jet control selection for ISS attitude control.

The C&T Panel used the Soyuz/Progress System Data Book, the Space Shuttle Circuit Margin Data Book, and the NASA/Johnson Space Center Avionics Systems Engineering and Integration Branch radio frequency Data Base to ensure compatibility between RV and Orbiter communication systems. All ports were evaluated. Results indicated that the Orbiter Ku-band requires restriction, either by masking or by placing the system in standby mode. There were no other constraints on either the Orbiter communication system or the Russian communication system, pending Russian concurrence. However, reflections from the RV could cause damage to Space Station Operations , the ISS Ku-band system, and the RV.

The ISSP-provided Orbiter/ISS interface acceleration time histories for STS-131 were used to verify that RV docking/undocking loads and frequencies do not adversely affect the Orbiter/ISS interface and payloads. This configuration was selected to generate worst-case responses for STS-132 and subsequent flights. The STS-134 manifest was selected based on payload frequency content. Resulting payload maximum (max)/minimum (min) load factors were compared to verification loads analysis (VLA) max/min load factors, and each DDO payload max/min was enveloped over all docking cases. All Orbiter/ISS interface loads were within ICD allowables. For the docking ports that were examined, there were no constraints for DDO for STS-132 and subs.

FO&I completed all required assessments to determine viability for performing DDO for all technical areas of responsibility. These assessments were based on formally delivered ISS environments documented in the ISS on-orbit ICDs. Assessments and evaluations for each flight where the possibility of DDO could occur were incorporated into the Certificate of Flight Readiness (CoFR) process. The new environments were vetted when additional data was received.

C. Safety and Mission Assurance (S&MA) Assessments

The integrated S&MA team members (ISSP, NASA/ Johnson Space Center (JSC), and SSP) met many times over the course of the DDO analysis period. Joint S&MA discussions and efforts included: reviewing the affected integrated hazard and risk baseline for docked operations; many hours of detailed background on the content development and rationale for the hazard reports; exchange of corporate knowledge; and identification of potential areas where engineering analysis might be needed to obtain a thorough review of the risk baseline. ISS S&MA evaluated hazards associated with visiting vehicles and incorporated their findings into their hazard reports and controls.

Recommendations from the SSP S&MA office include the following:

1. Concurrence with the hazard analyses and risk characterization contained in the NASA/JSC S&MA analysis.
2. No show-stoppers were identified that preclude DDO, although there is a high level of uncertainty concerning the hazard analyses.
3. Risks associated with DDO should be carefully considered against the requirements mandating DDO and, if possible, the ISSP and SSP should reconsider scheduling and other constraints to avoid DDO.
4. Risk mitigations such as development of operational responses, however extensive, or further engineering analysis (including Russian-generated engineering analysis), should be pursued to reduce the potential risk(s) that the current limited and high-level assessment presents.

NASA/JSC S&MA stated that the DDO assessment showed that this operational condition represents an increase in risk to the Orbiter. Docking/undocking aborts present a higher risk than normal, but quantifying the risk was difficult because of a lack of data, open causes, and undeveloped operational impacts. The primary hazards were collision, ISS structural overload, and Orbiter structural overload.

The probability of an off-nominal scenario involving a RV dynamic operation remained high (about 1 in 20), although there was not a consensus in the S&MA community or an agreed-to methodology for computing the probability. However, because the joint ISS/Orbiter/Russian operational response to an off-nominal scenario was undeveloped, an off-nominal scenario may increase risk to the Orbiter.

SSP Safety Panel chairs reviewed the approach to DDO safety assessment and had no additional concerns.

VII. Flight STS-134 DDO

The DDO became a realistic event on flight day 8 (May 2011) during the STS-134 mission. As mentioned previously, mission-specific analysis and operational impacts were conducted flight-by-flight as DDO was defined. The DDO generic assessments were completed in Summer 2010 and the mission specific analyses for non-generically cleared technical disciplines were completed for the STS-134 fly about in April 2011. Normal planned assessments were completed when updated Attitude Timelines were made available. Table 2 provides a summary of areas of emphasis requiring mission specific analyses.

Table 2. Mission and Generis STS-134 DDO Assessments

Area Of Emphasis	Impacted By DDO	Analysis Performed: Mission Specific	Analysis Performed: Generic
Flight Operations and Integration			
Loads and Dynamics JTWG	Yes	✓	
Flight Control Structures WG	Yes	✓	
C&T Panel	Yes		✓
Vehicle Configuration	Yes		✓
ECLSS JTWG	No		✓
Power/Avionics JTWG	No		✓
Cargo On-orbit Loads	Yes		✓
Cargo Thermal Control	Yes	✓	
Cargo EME	Yes		✓
Cargo Integration Hardware	Yes		✓
Cargo Reconfiguration Eng.	No		✓
Cargo Safety and Reliability	No		✓
Cargo Avionics	No		✓
OMRSD	No		✓

Area Of Emphasis	Impacted By DDO	Analysis Performed: Mission Specific	Analysis Performed: Generic
Orbiter Project Office			
Windows	Yes	✓	
Cameras	Yes		✓
OBSS Sensors	Yes	✓	
RMS	Yes		✓
Trajectory Control Sensor	Yes		✓
Orbiter Loads (ODS)	Yes	✓	
TPS	Yes		✓
RCC	Yes		✓
PLBD and Radiators	Yes		✓
Star Trackers	Yes		✓
Ku Antenna	Yes		✓
TCS - Passive Thermal Control System	Yes	✓	
Toxicology - Payload Bay	Yes		✓
RFI/EMI	Yes		✓
IGNC	Yes	✓	

The following is a summary of the STS-134 mission specific assessments.

- SSP/ISS mated Soyuz dynamic un-dock and docking loads analysis
  - Overall peak loads (docking and undocking) at Orbiter/ISS interface: ~ 40% limit
  - Soyuz thruster firing test loads are bounded by RS Maneuver loads (~6% of limit at Orbiter/ISS interface)

- C&T
  - Evaluated generically and no issues between Soyuz to Shuttle Radio Frequency Compatibility
  - For STS-134, MOD/Shuttle moded Shuttle Ku to standby during the Soyuz fly-about unless needed by ISS

- On Orbit Integrated GN&C analysis – Contingency VRCS control analysis
  - Evaluated for STS-133 and applicable to subsequent missions, VRCS capable of maneuvers and holds except for Orbiter Mated Control during the Soyuz re-docking

- Thermal analysis
  - No Orbiter passive thermal issues
    - Orbiter has an “any attitude” capability of 3 to 5 hours depending on beta
    - The attitude timeline was continuously screened to assure no Orbiter thermal constraints were violated
  - OBSS was stowed on ISS given current operational timeline scenario

- Contamination assessment
  - OBSS/sensor packages position moved to handoff (undock) position for Soyuz Thruster testing
  - For Fly-about, OBSS/sensor packages were stowed on ISS
  - Trajectory Control System, payload bay cameras, elbow camera and RSC camera were sufficiently shielded from, and/or pointed away from, the RV plume environment
  - Star Tracker doors closed

- Post-flight contamination assessment
    - NASA/JSC Toxicology and NASA/KSC ground personnel reviewed possible deposition to determine level of post-flight sampling and assessment
        - Less than one angstrom detected after landing

- Soyuz Plume Fluence – Completed with an example particle fluence shown in Fig. 5
    - ISSP defined STS-134 mission specific fluence data as 2 times "Bounded" nominal docking
        - Envelopes both an undock and docking of RV in manual mode
        - Conservatively bounds and protects for Russian Segment 10 degree specification approach cone and for crew piloting uncertainties
        - ~2 x 5000 particles/cm2 (from Bounded Nominal Approach case) = 10,000 particles/cm2
    - Orbiter Windows
        - Mission specific environment represents no increase in risk to the mission
        - Previous window specimens tested did not violate certification strength
        - Negligible sensitivity of strength to the fluence range tested
        - An increase in fluence due to a fly-about is not expected to have a detrimental effect on strength for entry

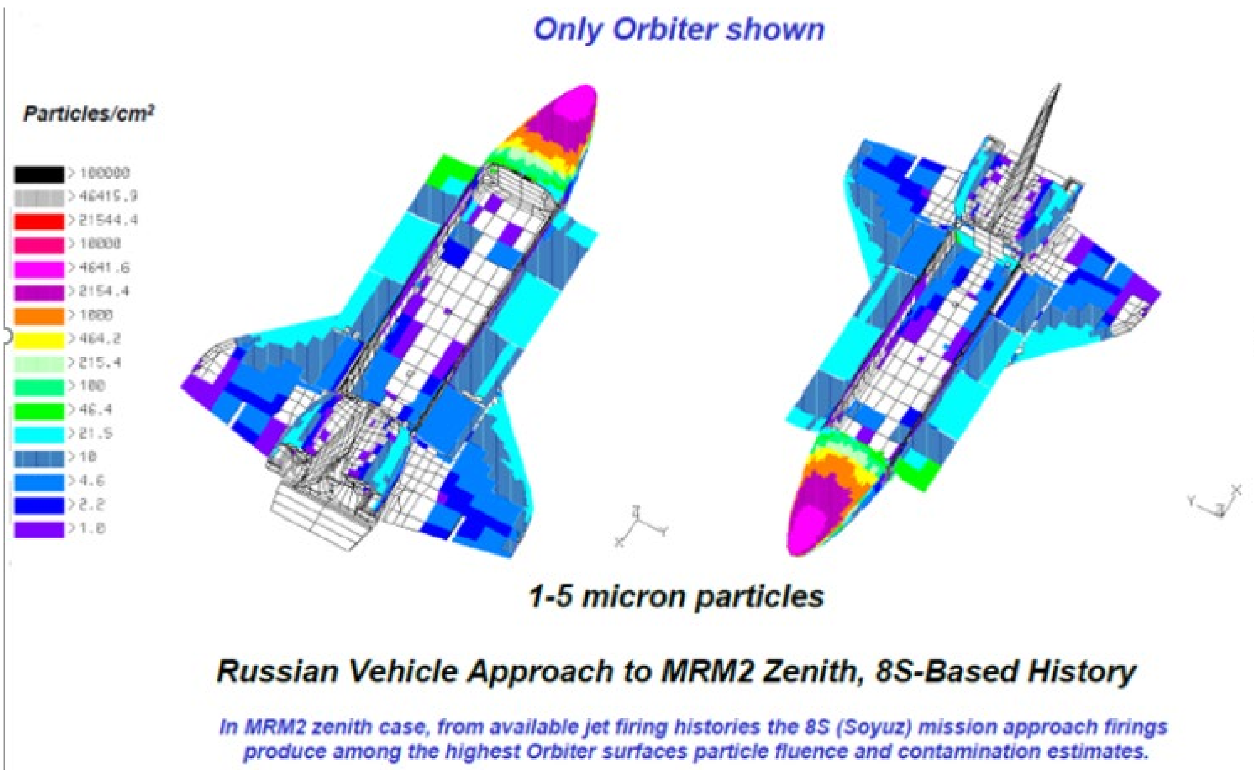

Fig. 5 Example Particle Fluence Results for MRM2 zenith Russian Vehicle Proximity Operations

The RV Soyuz undocked during the STS-134 Shuttle crew sleep period. Once Soyuz achieved a separation distance of 200 meters, ISS maneuvered to create a unique imagery opportunity that showed ISS with four visiting vehicles, including Endeavour. Imagery of ISS from the Soyuz orbital module (Fig. 6 and7) was taken as the Soyuz performed station-keeping burns.

Fig. 6 ISS and Space Shuttle (STS-134) with OBSS in protected position

Fig. 7 ISS and Space Shuttle (STS-134) During Soyuz Fly-about

VIII. Conclusion

This paper provides a summary of the concept definition, studies, and both generic and mission specific analysis results generated by the Space Shuttle Program (SSP), International Space Station (ISS) Program (ISSP), and Mission Operations Directorate for implementing Dual Docked Operations (DDO) during mated Orbiter/ISS missions. Due to the increasing visiting vehicle traffic to and from the ISS, it became apparent to both the ISSP and the SSP that there would arise occasions where conflicts between a visiting vehicle docking and/or undocking could overlap with a planned Space Shuttle launch and/or during docked operations. This potential conflict provided the genesis for evaluating risk mitigations to gain maximum flexibility for managing potential visiting vehicle traffic to and from the ISS and to maximize launch and landing opportunities for all visiting vehicles. This work was performed over several years with implementation occurring during the STS-134 mission. This work provides a roadmap of both subsystem and system analyses that need to be considered when dealing with multiple visiting vehicles (e.g., commercial crew, commercial resupply, etc.) and is directly applicable to managing the current ISS visiting vehicle traffic and traffic for the emerging Gateway program.

Acknowledgments

This study, results, and flight execution presented herein would not have been possible without the combined integrated efforts of multiple teams across many disciplines and programs. This effort reflects the hard work and dedication of individuals representing the SSP, ISSP, and their contractor community. The contributions of this team have contributed to the Agency's understanding of DDO and are greatly appreciated. The teams and their leads who contributed to this effort are as follows:

Space Shuttle Program Flight Operations and Integration Office - Joel Sills
Space Shuttle Program Orbiter Project Office - Malise Fletcher
Space Shuttle Program Safety and Mission Assurance Office - Sally Davis
ISS Requirements and Integration Office – Sean Fuller
ISS Vehicle Integrated Performance, Environments, and Resources - William Spetch and Evgeny Menkin
ISS Environments - Courtney Steagall
ISS Safety and Mission Assurance Office - Nathan Vassberg
ISS Safety and Mission Assurance Risk Office - Mike Lutomski
NASA/Johnson Space Center Safety and Mission Assurance - Brian Rochon
NASA/Johnson Space Center Proximity Operations Environments - Quyen Jones

The contributions of this diverse team have contributed to the Agency's understanding of DDO and are greatly appreciated. The work described within this paper has direct transference to the Agency's developing Gateway program that will have multiple vehicles docking during its operational life-time.

References

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