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International Space Station/Shuttle "Flip" Maneuver for Thermal Protection System Repair Consultation Report

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April 2009

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Consultation Report

July 21, 2005

TABLE OF CONTENTS

VOLUME I: CONSULTATION REPORT

List of Figures

List of Tables

VOLUME II: APPENDICES

Volume 1: Technical Consultation Report

1.0 Authorization and Notification

Michael Gilbert, the NESC Chief Engineer at LaRC, was the initiator of this activity. David Hamilton, the NESC Chief Engineer at JSC, performed the initial evaluation of this item. Per the official minutes, the NESC Review Board (NRB) approved this activity as a technical consultation on 27 April 2004. The key stakeholders for this consultation report are the Space Shuttle Program (SSP) and the International Space Station (ISS) Program.

2.0 Signature Page

NESC Team Members

Cornelius Dennehy	Frank Bauer
Karl Bilimoria	Dennis Dillman
Michael Gilbert	Michael Hagopian
Tuyen Hua	Dexter Johnson
Jay Leggett	Peiman Maghami
David Mangus	Scott Starin

3.0 Team Members

Several members of the NESC Guidance, Navigation and Control (GN&C) Super Problem Resolution team (SPRT) have been providing high-level oversight of the technical and programmatic activities surrounding the ORM since July 2004. This small group of GN&C specialists was augmented with additional NESC personnel to form a diverse ORM Peer Review Team capable of performing both an overall system-level assessment of the ORM and a detailed technical interrogation in key identified areas of interest. The following individuals comprised the June 2005 NESC ORM Peer Review Team:

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4.0 Executive Summary

The intent of this Technical Consultation Report is to document the finding and recommendations of the NESC Orbiter Repair Maneuver (ORM) Peer Review conducted at NASA's Johnson Space Center (JSC) with the ORM Working Group (WG) over the period 8-10 June 2005.

Background

The ORM is a complex, untested, and hazardous human/robotic contingency operation spread over three (3) days. It has been developed by JSC to support the repair of entry critical Thermal Protection System (TPS) tile and Reinforced Carbon-Carbon (RCC) damage at locations that cannot be reached, with the Orbiter docked to ISS, by either the Shuttle Remote Manipulator System (SRMS) or the Space Station Remote Manipulator System (SSRMS). As depicted in Figure 4.0-1 the ORM has been designed and developed to position the Orbiter such that 100 percent of the TPS tile is within reach of an EVA astronaut on the SSRMS. The ORM entails undocking the Orbiter from the ISS using the SRMS, followed directly by the SRMS maneuvering of the Orbiter through a series pre-planned (and auto-sequenced) trajectory waypoints, in close proximity to the ISS, to a repair orientation accessible by Extravehicular Activity (EVA) astronauts positioned on the SSRMS.

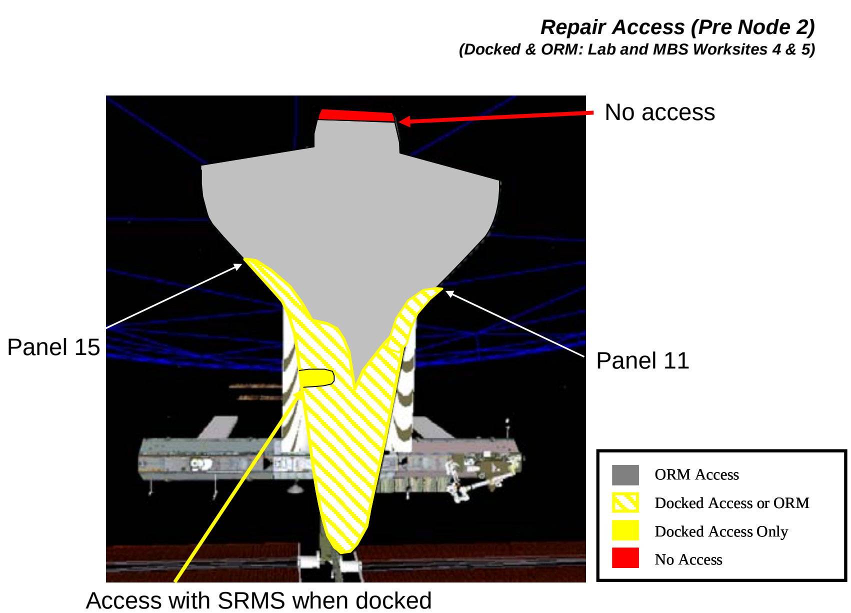


Figure 4.0-1. Orbiter Repair Access Diagram

The Space Shuttle Project (SSP) considers the ORM to be a contingency operation for flights LF1-10A. There is no plan for the Project to certify the ORM. The initial ORM plan called for all analyses to be complete and the operational procedures to be ready for STS-114. That initial plan has been overcome by events. While much progress has been made over the last several months in many of the analytical areas, especially the characterization of the repair worksite dynamics, the complete technical solution for the ORM is still being developed at JSC on a "best efforts" basis by multiple engineering and operational organizations.

The NESC team's position is that, compared to the Orbiter/ISS/SRMS/SSRMS experience base, the ORM has a high-degree of complexity, uncertainty and therefore risk to crew and the flight structures. It involves close proximity movements of the Orbiter, ISS, the SRMS, the SSRMS structures and requires split-crew astronaut operations inside the Orbiter and ISS as well as EVA astronauts on the SSRMS to perform the repairs.

<u>Peer Review Approach and Objectives</u>

The motivation for the Peer Review was derived from NESC's concern that ORM represents new and unfamiliar operations that are complex and pose risks (both know and unknown) to the crew and flight systems. The team's approach to performing this most recent ORM peer review was twofold. The team first reviewed the ORM from a "big picture" systems-level viewpoint to determine, to the extent a short duration review such as this would permit, if the ORM WG missed any key aspects of the problem. The team then investigated a few key technical areas to evaluate the depth and completeness of some of the ORM WG's analysis, modeling and simulation work.

Specific objectives of the NESC ORM Peer Review were:

1) To assess the breadth of the ORM technical solution at a systems–level.

2) To assess the status, depth, and completeness of the ORM pre-launch modeling, simulation and analysis work performed to date.

3) To determine what ORM work remains to be completed.

4) To assess the ORM operational readiness for STS-114.

5) To understand the risks associated with performing the ORM and determine if there are any "showstoppers."

6) To determine if the ORM WG was proceeding down the path towards a successful ORM.

ORM Operations

The ORM is a complex contingency operation that cannot be fully validated on the ground prior to first use. Moreover the ORM is a "first of a kind" operation whose execution will require both the flight hardware and the crew to operate in a non-standard manner that is significantly outside the nominal operational experience regime. If invoked the ORM would be the first SRMS "Heavy Payload" operation and would also be the first use of the SRMS for undocking the Orbiter from the ISS. The heaviest SRMS payload to date has been the Functional Energy Block (known as FGB), which had a mass of approximately 48,000 pounds. Note also that SRMS-assisted docking operations have not been done since STS-88/2A, which was the first ISS assembly mission, in 1998.

It is important to recognize that "ORM" is a broad term that covers the end-to-end operation of first undocking the Orbiter, SRMS maneuvering of the Orbiter via multiple prescribed trajectory waypoints to the repair position, the subsequent Orbiter/EVA astronaut dynamic (relative motion) interactions at the repair worksite and the maneuvering and redocking of the Orbiter following completion of the repairs.

During the ORM, as mentioned above, the Orbiter is maneuvered by the SRMS through multiple pre-determined trajectory waypoints in an auto-sequenced manner. There are in fact a total of thirteen (13) maneuver waypoints during this operation. Early on in the ORM dynamics and controls analysis process the JSC GN&C team concluded that the existing as-is ISS CMG-based attitude control system did not have sufficient capability/authority to stabilize the various stack configurations during the SRMS maneuvering of the Orbiter through the multiple waypoints. During the ORM the ISS GN&C system alone is used to control the attitude of the entire ISS/Orbiter stack. The Orbiter GN&C system is in a passive state (with its control actuators not enabled) and it is not used to control the dynamics of the stack. In order to provide adequate attitude control of the ORM stack configurations from Waypoints 1-13, a new ORM-specific controller and operational mode was designed by the JSC GN&C team to provide stable operational performance. This new GN&C operational mode, referred to as the United States (US) Thruster-Only (USTO) mode, uses the existing US CMG Proportional-Derivative (PD) control law algorithm to only command Russian Segment (RS) Service Module (SM) thrusters in a Pulse Width Modulation (PWM) mode. The JSC GN&C team selected thrusters (instead of the CMG's) as the ORM control actuators in order to provide good attitude control performance while achieving acceptable Orbiter relative motion with respect to the ISS. The CMG's are not used at all, during ORM maneuvering of the Orbiter, to generate attitude control torques.

The ORM is a relatively long duration (3 days) multi-step process that begins with the Orbiter docked to the ISS and, from a dynamics and control perspective, includes the following specific events:

1) Grappling of ISS by the SRMS (with ISS under normal CMG MM control).

2) SRMS controlled undocking of the Orbiter from ISS and subsequent maneuvering to Waypoint 1 (with ISS under normal CMG MM control).*

3) Transition of ISS GN&C from normal Control Moment Gyro (CMG)-based MM control mode to the US Thrusters Only (USTO) thruster-based attitude hold control mode. The CMG's are placed in a free drift mode.*

4) Maneuvering of the Orbiter, via auto-sequenced SRMS motion, from Waypoint 1 to the Overnight Park Position (Waypoint 8) with the ISS under USTO thruster-based attitude hold control.*

5) Transition of ISS GN&C from USTO thruster-based attitude hold control back to normal CMG-based MM control at the Overnight Park Position. *

6) Maintaining the Orbiter/ISS stack in a Torque Equilibrium Attitude (TEA) at the Overnight Park Position (Waypoint 8) under normal CMG MM control.*

7) Transition of ISS GN&C from normal CMG-based MM control to USTO thruster based attitude hold control. The CMG's are placed in a free drift mode.

8) Maneuvering of the Orbiter, via auto-sequenced SRMS motion, from the Overnight Park Position (Waypoint 8) to the Repair Position (Waypoint 13) with the ISS under USTO thruster-based attitude hold control.*

9) Transition of ISS GN&C from USTO thruster-based attitude hold control back to normal CMG-based MM control at the Repair Position. *

10) Providing a sufficiently stable repair worksite dynamic environment, with the ISS under CMG-based MM control, to permit the required TPS tile or RCC repair by EVA astronauts positioned on the SSRMS affixed to ISS.*

11) Post-repair maneuvering and re-docking of the Orbiter, by performing Step 9 through Step 1 in reverse order.*

- Note: The * indicates a first time operational occurrence.

Figure 4.0-2 depicts the Orbiter at the ORM overnight park position while Figures 4.0-3 and 4.0-4 illustrate the Orbiter at the ORM repair position.

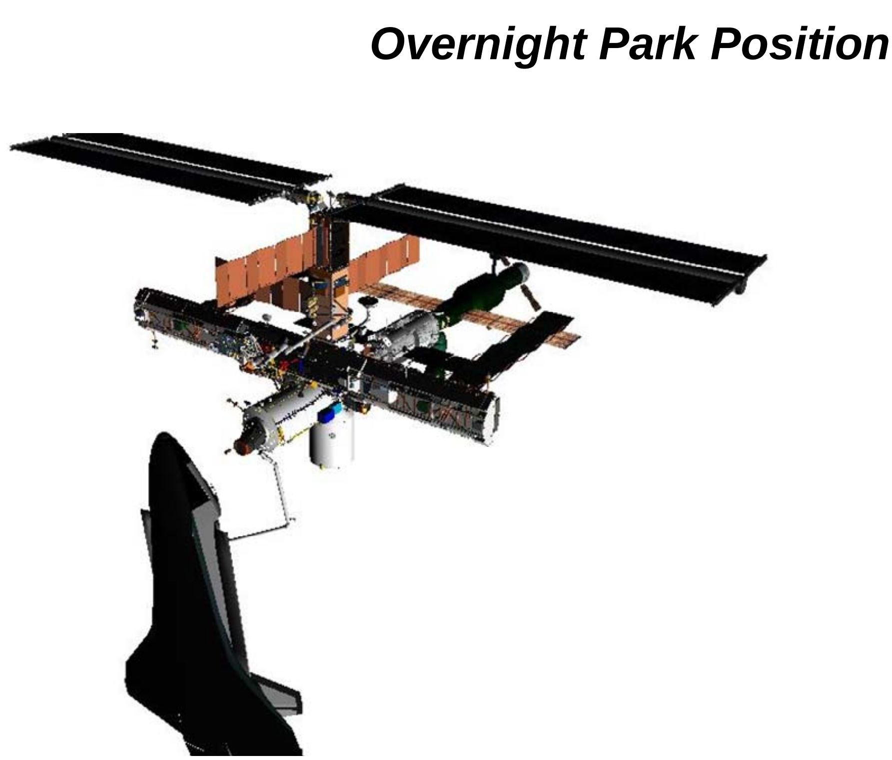


Figure 4.0-2. Orbiter at the ORM Overnight Park Position

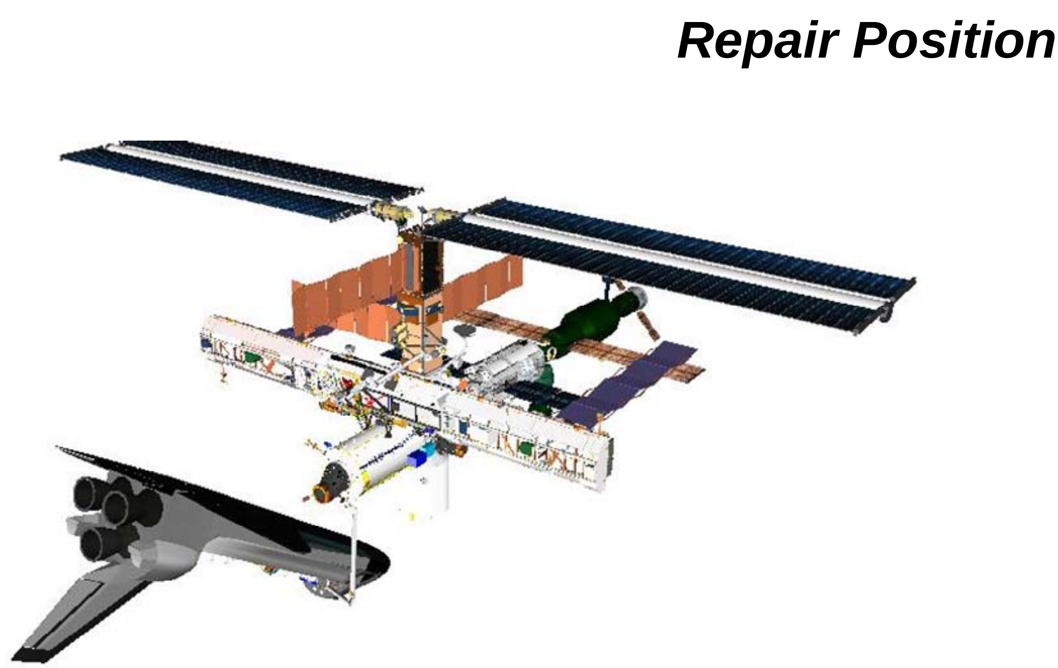


Figure 4.0-3. Orbiter at the ORM Repair Position (with respect to ISS)

ORM Repair Position

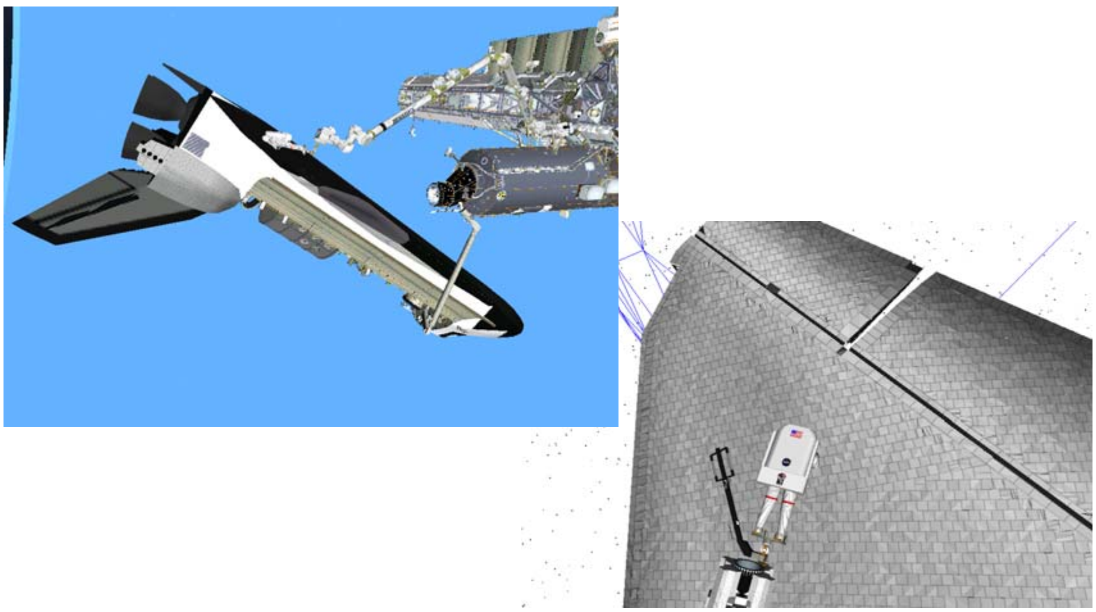


Figure 4.0-4. Orbiter at the ORM Repair Position (Side View)

<u>Summary of Key Findings and Recommendations</u>

The NESC team had ten (10) findings and five (5) recommendations coming from the limited (2.5 day) "snapshot" pre-RTF review of the ORM status. Some of these findings and recommendations address known technical concerns with specific aspects of the GN&C system design and performance. Others relate to system level concerns with the quantity of known open work, the need to integrate and prioritize activities across organizations, and the strategic implementation of on-orbit checks into the operational plan to account for remaining ORM uncertainties.

The team found that that while the ORM WG structure was a useful way to share information between multiple organizations there apparently is no single person tasked with coordinating/managing the overall effort, from an end-to-end system perspective, on a full-time dedicated basis. It is the team's position that the lack of a dedicated full-time ORM Lead Engineer has impacted, and continues to impact, the integration and prioritization of open ORM analytical and operational planning work. A full-time ORM Lead Engineer, with a system-wide perspective, is critically needed to both prioritize and schedule completion dates for all remaining ORM open work based upon negotiated agreements with appropriate resource managers. This ORM engineering lead could be positioned to efficiently identify and complete remaining work in preparation for launch, to authoritatively communicate ORM status and capability to the SSP, and to support real time on-orbit analysis and decision-making should the ORM be invoked.

One of the team's primary technical concerns focuses on low reported stability margins for the ISS USTO attitude control system. In particular, the team was very concerned with low reported phase margins - as low as 4.5 degrees in one specific case. Specifically "phase margin" is defined as the amount of additional phase lag (at the gain crossover frequency) that is required to bring the system to the verge of instability Therefore, these low phase margins indicate that, under certain operating conditions, the ISS attitude control system could be operating very near the boundary of stability.

In classical linear control system theory gain and phase margins are typically used as figure-of-merit measures indicating the degree of stability in a closed-loop feedback system. Control system designers gain important insights into a control system's robustness to uncertainty by computing and evaluating the gain and phase margins. Uncertainty can manifest itself in a control system in several ways such as un-modeled plant dynamics (that perhaps could be excited by the control system), and/or non-linearities that were not included in the plant model (or perhaps not known to exist) and/or unknown/unanticipated variations in plant parameter values. Standard engineering best practice guidelines suggest that a control system possess both a minimum of 30 degrees of phase margin, and a minimum of 6 dB of gain margin to adequately provide robustness to uncertainty.

The team's position is that the low reported phase margins are not acceptable given that:

a) the ORM is a first-of-a-kind maneuver,

b) there is limited experience with a USTO type controller that combines the US CMG control law algorithm with the RS SM thrusters,

c) the on/off control of the thrusters is implemented via the PWM such that the exact time for the execution of a thruster firing is variable and depends on the command levels, and

d) effects of sensor dynamics, as well as some discretization effects, do not seem to have been included in the GN&C ORM analyses. The belief/posture that these low phase margins, which are based on a linear model of the SRMS, are overly conservative is not a sufficient basis to proceed with the current USTO controller design.

It is the position of the team that the critical importance of maintaining controller stability is paramount in the case of the ORM where the Orbiter-to-ISS maneuver clearances are tight. Controller instability could directly lead to collision and damage/loss of the Orbiter/ISS stack.

It is also the position of the team that potentially low controller margins coupled with remaining (both known and unknown) uncertainties dictate that deliberate ORM steps with engineering checks be embedded into the operations plans/procedures to evaluate ORM performance and gain confidence prior to these key activities. This philosophy should be extended to address other areas of uncertainty like the dynamic worksite environment. Astronauts can excite the complex control-structure system stack from a safe position near the repair site, by dry running the nominal repair steps, to gain confidence prior to the actual repair. It may be possible that previous work, including early planning for the ORM Demonstration Task Objective (DTO), can be leveraged to determine what is feasible and appropriate.

Summary Remarks

Based upon cursory review, the team recognizes that the majority of the analysis work has already been performed by the ORM WG to prepare for the eventuality where the ORM is needed to provide accessibility for Orbiter repairs. It is equally clear that several critical items of analytic open work, the execution of which reduces ORM uncertainty, will need to be completed prior to safely invoking the ORM operationally. In addition to the known list of open analysis work, recommendations have been formulated, and captured in this report, for specific additional analyses and model/simulation validations steps to be performed before the first use of the ORM is undertaken.

Equally clear to the team is that the definition and implementation of critically needed operational on-orbit safeguards/checks for the ORM are lagging the analysis. These operational safeguards/checks would support the necessary real time on-orbit analysis, performance monitoring, and dynamic behavior during both the maneuver of the Orbiter and during the repair process. The team has therefore formulated a set of operationally related recommendations that, when completed, will also have the positive effect of reducing ORM uncertainty.

It is the team's position that the above set of five NESC prioritized recommendations represents the minimum set of ORM analytical and operational planning tasks, needed to be implemented, in order for the ORM to be considered as a viable contingency for the STS-114 mission. Furthermore, the team's position is that ORM contingency operations should not be invoked until, at a minimum, all five of the above prioritized recommendations have been addressed by the SSP.

Taken together, team's analytical and operational recommendations represent the best set of the "necessary conditions" needed to reduce ORM uncertainty prior to first use. Given that the Peer Review team performed only a cursory review of the ORM status it would be inappropriate and presumptuous to claim that our recommendations represent the complete set of "sufficient conditions" for a successful ORM. Along these lines the team recommends that a full-time ORM WG Lead Engineer be named to prioritize the known open work prior to launch and to be in a position to identify unknown issues/problems as they emerge.

Comment on the Project's OBSS Alternative to the ORM

Note that JSC has also identified, and is currently investigating, the feasibility of using the Orbiter Boom Sensor System (OBSS) 50-foot boom extension to the SRMS as an alternative method of accessing 100 percent of the TPS tiles. The NESC team did not assess the details of this OBSS alternative as part of this 8-10 June 2005 peer review. The team was however exposed to some of the OBSS Project approach to assessing the OBSS alternative and its pros/cons relative to the ORM.

Based upon only the limited information presented, the team's viewpoint is, provided the EVA astronaut on the end of the OBSS boom has sufficient dynamic stability to effect repairs, this OBSS alternative intrinsically appears to be a significantly lower risk contingency operation compared to the ORM. The team observed that many of the same individuals supporting the ORM are also supporting the OBSS feasibility assessment activity and many of the same analytical tools, models, and simulation techniques are being employed. It is likely, therefore, that many of the NESC's ORM recommendations may be applicable to the OBSS alternative.

The team would like to thank the entire ORM WG and the ORM leads, Ladonna Miller and Curt Larsen from the SSP and Bill Spetch from the ISS Program, for their openness

and frank dialog throughout our consultation activity. This was much appreciated and was crucial in NESC getting a good understanding of the ORM analyses, plans and potential risks.

5.0 Consultation Plan

The NESC initially became involved in the ORM in March 2004 when LaRC engineers expressed concerns over the complex dynamics and control of the Orbiter and ISS during the proposed ORM operation. The NESC Review Board (NRB) acted to formally authorize a Peer Review Consultation on the ORM (04-034-E - ISS/Shuttle Flip Maneuver for TPS Repair) and the GN&C NESC Discipline Expert (NDE) conducted an initial Peer-Review of the ORM WG modeling and analysis efforts at JSC in August 2004. Since that time members of the NESC GN&C SPRT have maintained oversight of ORM development progress via the weekly ORM WG telecons. In April 2005, a detailed NESC status report of the ORM was presented to the NRB by Frank Bauer (see Appendix D). Subsequently the ORM was added to the NESC's "STS-114 Return to Flight (RTF) Constraints – Open Work" list as a Red item (which is defined as "Technical Solution in Development") to be tracked and reported on as part of NESC's RTF pre-launch presentations at the SSP Flight Readiness Review (FRR), Shuttle Safety and Mission Assurance Readiness Review (SMARR), and other related reviews. The NRB also agreed upon the SPRT's recommendation to perform another Peer Review Consultation prior to the launch of STS-114. Planning and negotiation meetings were held between the SSP and NESC in May 2005 to define the scope/content of the Peer Review and to set a mutually agreeable date for holding this review (June 8-10 2005).

The motivation for the peer review was derived from NESC's concern that ORM represents new and unfamiliar operations that are complex and pose risks (both known and unknown) to the crew and flight systems. The team's approach to performing this most recent ORM peer review was twofold. The team first reviewed the ORM from a "big picture" systems-level viewpoint to determine, to the extent a short duration review such as this would permit, if the ORM WG missed any key aspects of the problem. Then as a follow-up, the team investigated key technical areas to evaluate the depth and completeness of some of the ORM WG's analysis, modeling and simulation work.

Specific objectives of the NESC ORM Peer Review were:

1) To assess the breadth of the ORM technical solution at a systems–level.

2) To assess the status, depth, and completeness of the ORM pre-launch modeling, simulation and analysis work performed to date.

3) To determine what ORM work remains to be completed.

4) To assess the ORM operational readiness for STS-114.
5) To understand the risks associated with performing the ORM and determine if there are any "showstoppers."

6) To determine if the ORM WG was proceeding down the path towards a successful ORM.

The purpose of the ORM Peer Review Team was to investigate the models, methodology, and overall use of the ORM as a safe repair method. The specific topics covered during the NESC ORM Peer Review Process, over the period 8-10 June 2005, are identified in the review agenda provided for reference in Appendix B.

6.0 Description of Problem, Proposed Solutions, and Risk Assessment

The JSC driver for developing the ORM contingency capability is unambiguous. The ORM represents one possible solution to the problem that the majority (approximately 60 percent) of the TPS tile acreage is unreachable by the SRMS alone, or even in combination with the SSRMS, when the Orbiter is docked to ISS. (See Figure 4.0-1) The ORM has been designed and developed to position the Orbiter such that 100 percent of the TPS tile is within reach of an EVA astronaut on the SSRMS.

The ORM is a complex contingency operation that cannot be fully validated on the ground prior to first use. Moreover, the ORM is a "first of a kind" operation whose execution will require both the flight hardware and the crew to operate in a non-standard manner that is significantly outside the nominal operational experience regime. For example, consider that normally, the SRMS lifts and deploys payloads with mass and inertias much less than the Orbiter. In all operational cases to-date, the Orbiter can be thought of as an "infinite mass" that reacts against the much smaller payload mass. The SRMS uses this "infinite" reactive mass to help move the payload in the proper position (translation and orientation). However, for the ORM, the Orbiter effectively becomes the payload that reacts against the more massive ISS. It should be noted that the largest payload manipulated by the SRMS to-date has been the 48,000 pound FGB. The FGB mass is approximately an order of magnitude less than the Orbiter's mass of approximately 240,000 pounds. Extending SRMS robotic operations from a FGB-class payload to the Orbiter, as the payload, is a significant extrapolation. In December 2004, the SRMS was certified for Heavy Payload mass operations, following an extensive series of low-speed robotic joint ground tests and associated servo-loop model updates. If invoked the ORM would be the first SRMS "Heavy Payload" operation. The ORM would also be the first use of the SRMS for undocking the Orbiter from the ISS.

It is important to recognize that "ORM" is a broad term that covers the end-to-end operation of undocking/maneuvering the Orbiter, via the SRMS, to the repair position, the subsequent Orbiter/EVA astronaut dynamic (relative motion) interactions at the repair worksite, and the maneuvering and redocking of the Orbiter following completion of the repairs. The ORM is a relatively long duration (3 days), multi-step process that begins with the Orbiter docked to the ISS and, from a dynamics and control perspective, entails the following specific events:

1) Grappling of ISS by the SRMS.

2) SRMS controlled undocking of the Orbiter from ISS.

3) Transitioning ISS from nominal CMG-based momentum management control to thruster-based attitude hold control.

4) Maneuvering of the Orbiter, via the SRMS, to an interim Overnight Park Position.

5) Transitioning ISS from thruster-based attitude hold control to CMG-based momentum management control.

6) Maintaining the Orbiter/ISS stack in the Overnight Park Position.

7) Maneuvering of the Orbiter, via the SRMS, from the Overnight Park Position to the repair position with the ISS under Thruster-based attitude hold control.

8) Providing a sufficiently stable repair worksite environment, with the ISS under CMG based momentum management control, to permit the required tile or RCC repair by EVA astronauts positioned on the SSRMS affixed to ISS.

9) Post-repair maneuvering and re-docking of the Orbiter.

Figure 4.0-2 depicts the Orbiter at the ORM overnight park position while Figures 4.0-3 and 4.0-4 illustrate the Orbiter at the ORM repair position.

Early on in the ORM dynamics and controls analysis process, the JSC GN&C team concluded that the existing as-is ISS CMG-based attitude control system did not have sufficient capability/authority to stabilize the various stack configurations during the SRMS maneuvering of the Orbiter through the multiple waypoints. During the ORM, the ISS GN&C system alone is used to control the attitude of the entire ISS/Orbiter stack. The Orbiter GN&C system is in a passive state (with its control actuators not enabled), and it is not used to control the dynamics of the stack. In order to provide adequate attitude control of the ORM stack configurations from Waypoints 1-13, a new ORM-specific controller and operational mode was designed by the JSC GN&C team to provide stable operational performance. This new GN&C operational mode, referred to as the USTO mode, uses the existing US CMG PD control law algorithm to only command, using a pulse width modulated implementation, the Russian thrusters. Thrusters were selected over the CMG's, as the desired ORM control actuators in order to provide good attitude control performance, while achieving acceptable Orbiter relative motion with respect to the ISS.

Effectively, the normal control torque command, generated by the CMG PD controller is converted to a momentum change command (by multiplying it with the PWM period) and then sent to the RS SM, where specific thrusters are fired for specific on-times in order to achieve the requested momentum change. At the same time the CMG actuator torque command is set to zero. Hence, the CMG's are not used during ORM maneuvering of the Orbiter to generate attitude control torques. Functionally, this mode is mechanized in the ISS GN&C flight software, by enabling the existing CMG Thruster Assist (TA) mode with its CMG control torque limit parameter set to zero, and by setting the parameter defining the minimum time between CMG desaturations (i.e., CMG momentum unloading via thruster firings) equal to the PWM period.

The ORM is an operation with high levels of uncertainty involving close proximity movements of flight structures, limited back-out opportunities and visibility, and high potential for adverse Control-Structure Interaction (CSI) between control systems, possibly resulting in large or unstable relative motion between the Orbiter repair worksite, the EVA Astronauts positioned on the SSRMS, and the ISS.

The ORM presents a very challenging system-level modeling, simulation and problem - a multi-disciplinary ORM WG and operations organization at JSC. The ORM WG provides a much needed forum for coordination and exchange of information between the various organizations performing analysis. Although no new hardware is being developed for the ORM, the analyses required to ensure the feasibility and safety of this repair option present a tremendous analysis integration challenge

Note that JSC has also identified and is currently investigating the feasibility of using the OBSS 50-foot boom extension to the SRMS as an alternative method of accessing 100 percent of the TPS tiles. The NESC team did not assess the OBSS option but, provided the EVA astronaut on the end of the OBSS boom has sufficient dynamic stability to effect repairs, this OBSS alternative intrinsically appears to be a significantly lower risk contingency operation compared to the ORM.

7.0 Data Analysis

The NESC team did not perform any independent analysis, modeling, or simulation of the ORM dynamics and controls as part of this peer review process.

8.0 Findings and Recommendations

8.1 Findings

Based upon the data/information conveyed during our meetings at JSC over the period 8-10 June 2005 the ORM Peer Review Team compiled the following findings:

F-1 There is a considerable amount of critical open work, in both the ORM analytical and operational planning areas, that absolutely must be completed prior to first use of ORM. These key pieces of open work, not in priority order, are listed in Table 8.1-1.

F-2 While many of the ORM technical analyses appear to be quite comprehensive with sufficient depth/rigor, it is not apparent that all the results of these analyses have been very well integrated and used to systematically drive the development of all the necessary ORM flight/ground operations plans and procedures. The most likely reason for this situation is that there appears to be no single person tasked with coordinating/managing the overall effort on a full-time dedicated basis. It is the team's position that the lack of a dedicated full time ORM Lead Engineer has impacted, and continues to impact, the integration and prioritization of open ORM analytical and operational planning work. A full-time ORM Lead Engineer, with a system-wide perspective, is critically needed to both prioritize and schedule completion dates for all remaining ORM open work based upon negotiated agreements with appropriate resource managers.

F-3 The ORM is an operation that the SSP recognizes as complex and risky. The SSP is actively studying the risk trades for accessing a repair worksite using ORM as well as other access methods. Currently, the SSP is considering, in descending hierarchical order, three alternative methods of gaining access to TPS tile and RCC repair worksites:

1) access by use of SRMS/ SSRMS robotic arms,

2) access by use of the SRMS with the OBSS 50-foot boom attached, and

3) ORM access. The on orbit contingency decision flow process/policy defining specifically when the ORM will be operationally invoked was pending on the results of the previously mentioned risk trades and had not been finalized by the SSP at the time of the peer review.

F-4 GN&C ORM analyses indicate that the smallest phase margins for the ISS USTO controller can go as low as 4.5 degrees. This very low phase margin occurs at the Waypoint 9 position using the "perturbed" dynamic model, where a 20 percent uncertainty is included for both modal frequencies and modal amplitudes, with a 2-second delay in execution of the thruster commands. Likewise, the phase margin for the overnight parking configuration is at 5.5 degrees. The frequency associated with these margins is at 0.016 Hz, which is close to the Nyquist frequency (0.025 Hz). The proximity of the flexible mode to the Nyquist frequency, as well as the fact that in this particular control system design the flexible modes below 0.04 Hz are phase stabilized, raise stability robustness issues in view of model uncertainties in modal frequencies, damping, etc. Moreover, aliasing effects may become a problem and need to be considered. The team's position is that these very low phase margins are not acceptable given that:

a) the ORM is a first-of-a-kind maneuver,

b) there is limited experience with a USTO type controller that combines a US controller with the Russian thrusters,

c) the on/off control of the thrusters is implemented via a Pulse Width Modulator (PWM) such that the exact time for the execution of a thruster firing is variable and depends on the command levels, and

d) that effects of sensor dynamics, as well as some discretization effects, do not seem to have been included in the GN&C ORM analyses.

The belief that these low phase margins, which are based on a linear model of the SRMS, are overly conservative is not a sufficient basis to proceed with the current USTO controller design. It is the position of the team that the ISS controller stability margins must either be re-computed with a high fidelity model (which includes the 20 percent variation in modal frequencies of the SRMS as well as appropriate modal damping/amplitude uncertainties), and shown to be adequate, or a new/modified ISS attitude controller design must be developed and incorporated.

F-5 The ability of the rate-damping controller to recover the stack from a free drift (at maximum nominal angular velocities) at either of the parking positions (both the overnight park and repair waypoints), is not fully clear to the team. This is equally the case for any of the waypoints for which the analysis has indicated that direct recovery without reorienting the SRMS, is not possible. Additionally, there are some maneuver waypoints for which the analysis has indicated the direct recovery from free drift rate buildup (resulting from a loss of ISS attitude control) is not possible without a reorientation of the SRMS. For example, analysis has shown it is not possible for the ISS rate-damping controller to recover the stack, from maximum free drift angular velocities, at either of the overnight park position waypoint or the repair position waypoints. The general finding here is, therefore, if the ISS loses attitude control during the ORM the Orbiter may, depending on which maneuver waypoint it is at or which two waypoints it is between, have to be reoriented with the SRMS back to a recoverable waypoint before ISS attitude control can be restored. The implication is that failure of the SRMS during ORM such that the Orbiter cannot be reoriented, depending on the orientation at the time of failure, could preclude

a) rebirthing of the Orbiter to the ISS and recovery of the Orbiter ORM crew,

b) establishment of a favorable Torque-Equilibrium-Attitude (TEA) ISS attitude control with the Orbiter attached,

c) re-establishment of ISS attitude control From free-drift if the ISS attitude control goes off-line, and/or

d) Orbiter separation from the ISS for redocking.

F-6 The ORM WG's ability to reuse models from their legacy TRICK simulation library environment, and their incremental "build-then-test" approach for the ORM simulation development, were both viewed by the team as being very positive and impressive. Their use of heritage models, recognizing that they are operating well out of the experience range and used Kane's equations to independently verify the work, were all very positive. The matching results from the independent comparison check of the newly developed (by the ER Robotics Engineering organization) integrated ORM simulation (which represents a rigid Orbiter, a flexible SRMS and a rigid ISS model) in the TRICK simulation environment against the functionally equivalent Station/Orbiter Multibody Berthing Analysis Tool (SOMBAT)-based simulation (which is an existing simulation developed by the EG GN&C engineering organization) is a major step in verifying the newly developed ER ORM simulation. However, another critical independent simulation cross-check remains to be performed between the ER-developed Worksite Dynamics (WSD) Simulation (which represents the complete end-to-end system dynamics including ISS flexible dynamics and the EVA astronaut on the SSRMS) and the functionally equivalent EG-developed SOMBAT-based simulation.

F-7 No Contingency Action Plan has been developed for the on-orbit real-time ORM WSD analysis.

F-8 The ORM planned implementation relies heavily on the human-in-loop approach to fault detection, isolation, and recovery (FDIR) at the system level. Although each element of the stack (ISS, Shuttle, SRMS, and the SSRMS) has their respective FDIR systems, the stack as whole will have to rely on the situational awareness of the astronauts on the ISS, and on the Orbiter, to assure the health and safety of the system. This requires extensive training, and well-defined protocols for the astronauts, so that they may act prudently and quickly to unforeseen anomalies that may affect this maneuver. The team also found that, given the continuous auto-sequenced nature of the SRMS maneuvering of the Orbiter, there are no "hold and monitor" steps planned for each SRMS maneuver trajectory waypoints beyond Waypoint 1. No clearly defined realtime "Go/No Go" ORM maneuver criteria have been developed based upon the collection, analysis and monitoring of telemetry/camera video data.

F-9 Separation of the Orbiter from the ISS during ORM, if required, must be performed passively, using orbital dynamics from the overnight park position, with the Shuttle/ISS stack pitched down 45 degrees and no Orbiter thruster firings.

F-10 There has been considerable progress in the area of work site dynamics stability analysis and modeling. The loads and training testbeds should help greatly to characterize the expected loads during the repairs as well as to train the astronauts. Preliminary limits on the force level, time duration of the force application, and time separation between discrete force applications of the various repair loads have been identified for the TPS tile repairs. However, there is a lack of detailed understanding on the possibility of repair-induced motions that potentially may result in the crew getting injured at the work site or additional damage to the hardware.

Table 8.1-1. List of ORM Open Work (as of 10 June 2005)

a) Final and complete definition and agreement on all the worksite dynamics forcing functions (force versus time profiles) due to the EVA astronaut repair operations on tile and RCC.

b) Inclusion of the ISS flexible dynamics in the ER-developed Worksite Dynamics simulation used to predict relative motion between the Orbiter and the EVA astronauts.

c) Independent cross-check comparisons between the ER-developed Worksite Dynamics simulation and the functionally equivalent EG-developed SOMBAT-based simulations for a representative set of common benchmark test cases.

d) Simulation, using the ER-developed Worksite Dynamics simulation tool, of the relative motion between the Orbiter and the EVA astronauts using the final defined set of repair forcing functions.

e) Analysis and evaluation of the relative motion dynamics to assess repair feasibility.

f) Additional ORM stability margin simulation and analysis.

g) Nominal SRMS clearance analysis.

h) The definition and performance of a common test case, as part of the overall ORM verification process, to be used across the 1) VR Lab repair dynamics testbed, 2) the 3-DOF PBAF repair dynamics testbed and 3) the end-to-end integrated system dynamics simulation. Common test case results from each of the three environments should be compared and any major differences reconciled.

i) Development of an ORM Contingency Action Plan for performing on-orbit realtime ORM analysis of specific TPS tile or RCC repair contingencies.

j) Development of an on-orbit realtime ORM monitoring strategy, plans and procedures. Such procedures would be used during the course of actually maneuvering the Orbiter to its repair position using the SRMS to evaluate the overall system state-of-health and to do realtime assessments of the ORM performance. They will define what specific sensor data will be collected and processed to support the realtime monitoring of the ORM performance and the health of the combined dynamic stack.

k) Finalization of the decision flow policy of the repair "access" options that would be employed prior to invoking the Contingency Shuttle Crew Support/Launch on Notice (CSCS/LON) contingency activity.

8.2 Recommendations

The ORM Peer Review team has developed the following prioritized set of recommendations which represents the minimum set of ORM analytical and operational planning tasks needed to have the ORM in place as a viable contingency for STS-114. These prioritized recommendations are summarized, in a top-level fashion, in the STS-114 Flight Readiness Review (FRR) ORM chart package which is provided for reference in Appendix C.

R-1 Re-assess the ISS attitude control system design, employed for ORM operations, for both stability and performance

The use of the high-fidelity SOMBAT-based time-domain simulation is recommended to show that the current ISS controller design has adequate stability robustness margins (i.e. gain and phase margins). Also use the high-fidelity simulation to demonstrate performance of ISS rate damping controller to recover the ISS/Orbiter stack from free drift rates, on the order of 0.18 degrees/second, at either the overnight park position or the repair position

High fidelity simulations, using the flight-proven SOMBAT, should be used to demonstrate that the system, in free drift in each of these configurations, can be recovered by moving the SRMS to the nearest recoverable safe point, and implementing the rate damping controller. The high fidelity simulation model should include the damping and frequency uncertainties associated with the SRMS.

R-2 Complete the independent validation of the ORM integrated end-to-end dynamic simulation, to include benchmarking with Virtual Reality (VR) laboratory dynamics simulation

The planned, but as yet unexecuted, independent cross-check comparison runs between the ES/ER integrated WSD Simulation and EG-developed SOMBAT tool needs to be completed, using a set of common benchmark test cases. This particular item is also captured as Open Work item c), but its fundamental importance to reducing uncertainty and increasing confidence in the ORM modeling merits it being citied as a specific high-priority recommendation. Some comparisons already exist, but common end-to-end runs, using the same load inputs, are needed. This work should preferably be completed prior to launch of STS-114.

The ORM WG should define a common benchmark test case, as part of a unified approach to the overall ORM modeling/simulation verification process, to be performed/conducted across the following three elements: 1) VR Laboratory repair dynamics testbed, 2) the 3-Degree of Freedom (DOF) Precision Air Bearing Facility (PBAF) repair dynamics testbed and 3) the new ER-developed end-to-end integrated system dynamics simulation. Common test case results from each of these three environments should be compared and any major differences reconciled prior to the first use of the ORM.

R-3 Complete ORM contingency planning to include definition and development of detailed procedures and protocols, especially for ORM abort scenarios.

ORM contingency planning is critically needed to define:

a) the ORM state-of-health/dynamic behavior monitoring procedures and protocols,

b) the specific Contingency Action Plan for performing on-orbit analysis of worksite dynamic interactions,

c) and, on-orbit pre-repair dynamic checks in the worksite environment and d) FDIR checks/tests.

Develop a contingency action plan that defines the real-time, on-orbit ORM analysis tasks that need to be completed, the people and phone numbers required, and the facilities that are necessary to support the ORM realtime analysis. Also, prior to launch the ORM realtime Contingency Action Plan needs to be simulated with appropriate personnel. Each of the real time models has been run, but there is not a case in which the team was asked about specific damage at an arbitrary location and then run the tools from beginning to end. This simulation would allow Mission Control Center (MCC)/Mission Evaluation Room (MER) users to see this process and understand what limitations exist and also understand the resulting outputs. At a minimum, a table-top paper simulation should be performed, by the ORM WG, of these realtime repair assessments.

The SSP should consider implementing a hold at each maneuver waypoint to allow for realtime assessment of the integrated stack's dynamics behavior and performance. There needs to be a clear plan and procedure to do realtime assessment on how the ORM is progressing from a dynamics perspective. Define how, during the course of actually maneuvering the Orbiter to its repair position using the SRMS, the flight operations team will determine the overall system state-of-health and perform real-time assessments of the ORM performance. Define what specific sensor data will be collected and processed to support the monitoring of the ORM performance and the health of the combined dynamic stack.

The FDIR systems in the ISS, shuttle, SRMS, and SSRMS need to be examined for any potential conflicts in exercising this maneuver

Fault scenarios, which describe potential loss of system's stability, need to be identified from the moment of the Orbiter separation, at the start of the maneuver, and throughout the maneuver, including at all 13 waypoints. Particular attention must be given to the two parking positions. These scenarios include, but are not limited to, loss of attitude control due to instabilities as well as hardware failure, and excessive and unstable motion of SRMS arms and joint angles.

Metrics must be developed for assessing the health and safety of the system during the overall maneuver and repair. It is advisable to have these metrics at a system level and not simply rely on the existing fault detection systems on the ISS and SRMS, individually. However, if that is not possible, procedures for identifying system level faults must be developed and astronauts must be trained to properly implement these procedures. These procedures must support the decentralized nature of the fault detection approach.

Protocols must be developed for each configuration of the stack, during the ORM, to define mode switching logic (from USTO to rate damping, for example) as well as to define feasible schemes to maneuver to the nearest waypoint for safe recovery. These protocols should be implemented as soon as possible once a fault/instability is identified. It is best that these protocols are implemented with software within an FDIR system. However, if that is not possible, astronauts should be trained to implement these protocols in a timely and proper manner.

Given uncertainties in the worksite dynamics, close clearances, and a general inability to undo repair mistakes, on-orbit checks of the worksite environment in a safe (not likely to lead to impact/damage) location prior to initiating an actual repair are recommended. For example, the astronaut can be positioned near the repair site and survey motion relative to the site while sitting quiet, performing a layback maneuver, and touching the wing with a mock execution of the repair steps. These actions could refine repair operations and optimize likelihood of success.

R-4 Complete the analysis and simulation of the repair worksite dynamic interaction (i.e. assess relative motions between the EVA astronaut and Orbiter).

The ORM WG needs to finalize the complete definition and agreement on all the worksite dynamics forcing functions (force versus time profiles) due to the EVA astronaut repair operations on both TPS tile and the RCC locations.

The ORM WG should take the steps necessary to include the modal-significant ISS flexible dynamics in the ER-developed Worksite Dynamics simulation used to predict relative motions between the Orbiter and the EVA astronauts. While some preliminary work has been performed to assess the impact of ISS flexibility, it is clear to the team that those results do not provide a sufficient basis to ignore the potential impact of ISS dynamic flexibility on relative motions between the Orbiter and the EVA astronauts.

R-5 Fully document and communicate all ORM operational constraints and hazards to Astronaut Office and mission control center staff.

The SSP should define and communicate (or re-communicate, as the case may be) an up-to-date summary of all ORM operational constraints, hazards, and risks to the flight crew, the Astronaut Office and the mission operations team to ensure all those parties are fully aware of the operational implications of loss of ISS attitude control during the ORM.

For example, there is a need to document and communicate the fact that, if required during the ORM, an emergency Orbiter separation must be performed passively, using orbital dynamics with no thruster firings, from the overnight park position with the entire ISS/Orbiter stack attitude pitched down by 45 degrees.

The SSP should, prior to launch, finalize the decision flow policy of the repair “access” options that would be employed prior to invoking the CSCS/LON contingency. The SSP should complete its assessment of the feasibility of employing the OBSS boom to effect repairs (i.e., primarily to determine if the OBSS provides a sufficiently stable base from which to perform the repairs), in a time frame to support the establishment of the repair access decision flow policy prior to launch of STS-114.

It is the team's position that the above set of five NESC prioritized recommendations, represents the minimum set of ORM analytical and operational planning tasks, needed to be implemented in order for the ORM to be considered as a viable contingency for the STS-114 mission. Furthermore, the team's position is that ORM contingency operations should not be invoked until, at a minimum, all five of the above prioritized recommendations have been addressed by the SSP.

9.0 Lessons Learned

This NESC Consultation presented no lessons learned.

10.0 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 during the assessment/inspection 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/inspection 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.
Problem	The subject of the independent technical assessment/inspection.
Recommendation	An action identified by the assessment/inspection team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible C/P/P/O in the preparation of a corrective action plan.
Root Cause	Along a chain of events leading to a mishap or close call, the first causal action or failure to act that could have been controlled systemically either by policy/practice/procedure or individual adherence to policy/practice/procedure.

11.0 List of Acronyms

CMG	Control Moment Gyroscope
CSCS	Contingency Shuttle Crew Support
CSI	Control-Structure Interaction
dB	Decibel
DOF	Degree of Freedom
EG	Aeroscience and Flight Mechanics Engineering Division at JSC
ER	Robotics Engineering Division at JSC
EVA	Extra Vehicular Activity
FDIR	Fault, Detection, Isolation, and Recovery
FGB	Functional Energy Block
FRR	Flight Readiness Review
GN&C	Guidance, Navigation & Control
Hz	hertz
ISS	International Space Station
JSC	Johnson Space Center
LON	Launch-on-Need
MCC	Mission Control Center
MER	Mission Evaluation Room
MM	Momentum Management
NDE	NESC Discipline Expert
NESC	NASA Engineering & Safety Center
NRB	NESC Review Board
OBSS	Orbiter Boom Sensor System
ORM	Orbiter Repair Maneuver
PABF	Precision Air Bearing Facility

PD	Proportional-Derivative
PWM	Pulse Width Modulation
RCC	Reinforced Carbon-Carbon
RS	Russian Segment
RTF	Return-to-Flight
SM	Service Module
SMARR	Safety & Mission Assurance Readiness Review
SOMBAT	Station/Orbiter Multibody Berthing Analysis Tool
SPRT	Super Problem Resolution Team
SRMS	Shuttle Remote Manipulator System
SSP	Space Shuttle Project
SSRMS	Space Station Remote Manipulator System
TEA	Torque Equilibrium Attitude
TPS	Thermal Protection System
USTO	United States Thruster-Only
VR	Virtual Reality
WG	Working Group
WSD	Worksite Dynamics

12.0 Minority Report

There are no dissenting opinions in this report.

Volume 2: Appendices

Appendix A. NESC ITA/I Request Form (NESC-003-FM-01)

NASA Engineering and Safety Center Request Form

Submit this ITA/I Request, with associated artifacts attached, to: nrbexecsec@nasa.gov, or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681

Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt		
Received (mm/dd/yyyy h:mm am/pm) 3/26/2004 6:30 PM	Status: New	Reference #: 04-034-E
Initiator Name: M. Gilbert (LaRC: H. Bush, W. Doggett, J. Dorsey, J. Watson, T. Collins)	E-mail: Michael.G.Gilbert@nasa.gov	Center: LARC
Phone: (757)-864-2839, Ext _____	Mail Stop: 105	
Short Title: ISS / Shuttle "Flip" Maneuver for TPS Repair		
Description: The primary contingency operation under consideration for EVA inspection and repair of Shuttle TPS surfaces while at ISS involves grapple of the ISS by the Shuttle RMS (SRMS), undocking the Shuttle from ISS, reorienting (flip-over of) the Shuttle using the SRMS, and an Astronaut on the end of the ISS RMS (SSRMS) positioned over the underside of the Shuttle for the inspection and repair. This is a complex operation with potential for adverse dynamic interactions between control systems (ISS attitude, SRMS, SSRMS), mechanical systems (SRMS & SSRMS motors/brakes), structure (flexible SRMS & SSRMS components, ISS structure), and the EVA Astronaut(s) performing the repair. The maneuver requires that STS flight structure pass within close proximity of various ISS components. Repeated requests through multiple paths for information from the STS and ISS programs on the modeling, simulation, and analysis of these interacting systems from a system-of-systems perspective has been largely unsuccessful. It is known that the ISS GNC community has been analyzing the extremely low-frequency structural mode effects on the ISS attitude control laws during the "flip," and have determined that notch filters in the ISS attitude control laws will be required, but this analysis is not an integrated system-of-systems analysis. It has also been reported that this maneuver is considered too risky to ISS/STS vehicles and crews to be practiced or demonstrated before contingency use. The risks to the ISS/STS vehicles and crews inherent in this contingency operation are high. Analysis of this contingency operation requires coordination, integration, and shared responsibility by the STS and ISS programs, and thus the potential for critical work to fall-through-the-cracks exists. Independent assessment of the ISS and STS program sponsored modeling, simulation, and analysis approaches and efforts to determine if all the physics, dynamics, mechanical, controls, interactions, and system-of-system effects for the "flip" maneuver have been captured and accounted for is warranted. In addition, an independent second-look integrated modeling, simulation, and analysis effort to independently verify results and evaluate the consequences of potential failure modes is also warranted.		
Source (e.g. email, phone call, posted on web): Phone, E-Mail, Meetings		
Type of Request: Assessment		
Proposed Need Date: 7/1/2004		
Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):		
Section 2: Systems Engineering Office Screening		
Section 2.1 Potential ITA/I Identification		

NESC Request Form
NESC-PR-003-FM-01, v1.0

Page 1 of 3

Received by SEO: (mm/dd/yyyy h:mm am/pm): 3/25/2004 12:00 AM			
Potential ITA/I candidate? ☒ Yes ☐ No			
Assigned Initial Evaluator (IE): Dave Hamilton			
Date assigned (mm/dd/yyyy): 3/30/2004			
Due date for ITA/I Screening (mm/dd/yyyy): 4/29/2004			
Section 2.2 Non-ITA/I Action			
Requires additional NESC action (non-ITA/I)? ☐ Yes ☐ No			
If yes:			
Description of action:			
Actionee:			
Is follow-up required? ☐ Yes ☐ No If yes: Due Date:			
Follow-up status/date:			
If no:			
NESC Director Concurrence (signature):			
Request closure date:			
Section 3: Initial Evaluation			
Received by IE: (mm/dd/yyyy h:mm am/pm):			
Screening complete date:			
Valid ITA/I candidate? ☐ Yes ☐ No			
Initial Evaluation Report #: NESC-PN-			
Target NRB Review Date:			
Section 4: NRB Review and Disposition of NCE Response Report			
ITA/I Approved: ☐ Yes ☐ No	Date Approved:		Priority: - Select -
ITA/I Lead: , Phone ( ) - , x			
Section 5: ITA/I Lead Planning, Conduct, and Reporting			
Plan Development Start Date:			
ITA/I Plan # NESC-PL-			
Plan Approval Date:			
ITA/I Start Date	Planned:	Actual:	
ITA/I Completed Date:			
ITA/I Final Report #: NESC-PN-			
ITA/I Briefing Package #: NESC-PN-			
Follow-up Required? ☐ Yes ☐ No			
Section 6: Follow-up			
Date Findings Briefed to Customer:			
Follow-up Accepted: ☐ Yes ☐ No			
Follow-up Completed Date:			
Follow-up Report #: NESC-RP-			
Section 7: Disposition and Notification			
Notification type: - Select -	Details:		
Date of Notification:			
Final Disposition: - Select -			
Rationale for Disposition:			
Close Out Review Date:			

NESC Request Form
NESC-PR-003-FM-01, v1.0

Page 2 of 3

Form Approval and Document Revision History

Approved:	______________________ NESC Director	________ Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04

Appendix B. NESC ORM Peer Review Agenda (8-10 June 2005)

NESC ORM Peer Review Agenda (6 June 2005)

All personnel listed are the team leads and responsible for assuring other team members, as appropriate, are in attendance.

Day1 - Wednesday, June 8th
Meeting Location: Building 16, Room 1123A

8:45 am to 9:00 am
Introductions & Review Objectives/Guidelines
(Frank Bauer)

9:00 am to 11:00am
ORM Status Update, Technical Overview, Analysis Approach and Open Work
(Curt Larsen/MO2 and Bill Spetch/OM5)

11:00 am to 12 noon
Discussion of the Integrated Simulation architecture (aka the "Common Sim")
(Les Quiocho/ER7) ** subject to move**

1pm to 2:30 pm
Worksite Dynamics
(Sean Cupitt/Lora Bailey/Kwun Siu (Ki)/Dina Barclay

2:30 pm to 5:00 pm
Discussion of SRMS and SSRMS Dynamic Analysis Results
(Liz Bains/ER7)
5:00 pm to 6 pm
NESC Team Caucus: Recap of Day 1 and Re-Plan for Day 2

Day 2 - Thursday, June 9th
Meeting Location: Building 4S, Room 1200

9:00 am to 10:30 am
Discussion of ISS GN&C (MM/AH) ORM Analysis Results
(Louis Nguyen/EG3)

10:30 am to 12:00 noon
Discussion of Independent Modeling and Simulation Plans/Results
(Louis Nguyen/EG3)

1:00 pm to 3:00 pm
SRMS/APAS Operations
(Tim Briscoe/ES2)

Note: This portion of the Peer Review did not take place.

3:00 pm to 5:00 pm
Discussion of ORM Risks/Fault Tolerance (Probability vs. Impact)
(Todd Miller/NC)

5:00 pm to ?pm
NESC Team Caucus: Recap of Day 2 and Wrapup. *(Also planning for Day 3 meetings)*

Day 3 - Friday, June 9th

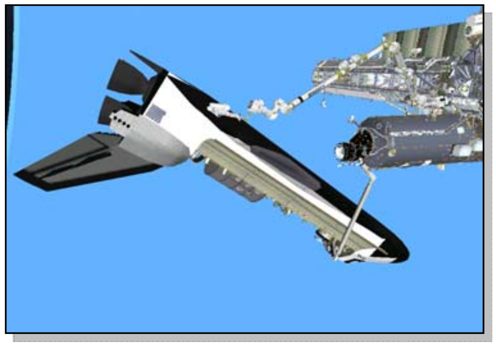
8:00 am to 10:00 am
Meeting Location - Building 1, Room 720
Question and Answer session for all ORM WG members
(all WG members)

10:00 am to 12:00 noon (IF NEEDED)
Meeting Location - Building 1, Room 715F

Wrapup
(Curt Larsen and Bill Spetch)

Appendix C. ORM STS-114 FRR Chart Package (dated 27 June 2005)

Shuttle/ISS Orbiter Repair Maneuver	28-29 June 05
	Dennehy



- **Description and Scope:**
  - In response to concerns over the complex dynamics and control of the Orbiter and ISS during the Orbiter Repair Maneuver (ORM) the NESC GN&C SPRT conducted a pre-RTF Peer Review of the ORM Working Group's modeling and analysis efforts at JSC on 8-10 June 2005
- **Background**
  - ORM is a complex contingency operation with close proximity movements of flight structures, limited back-out opportunities and visibility, and high potential for adverse dynamic interactions between control systems, SRMS, SSRMS, and structure, possibly resulting in large or unstable relative motion between the Orbiter, the EVA Astronauts, and the ISS

04-051-E This briefing is for status only and does not represent complete engineering data analysis 1

Shuttle/ISS Orbiter Repair Maneuver	28-29 June 05
	Dennehy

- **Background (continued)**
  - **ORM consists of new and unfamiliar operations that are complex and pose risks (both know and unknown) to the crew and flight systems.**
  - **ORM is a "first of a kind" operation whose execution will require both the flight hardware and the crew to operate in a non-standard manner in regimes that are significantly outside the nominal operational experiences.**
- **Results:**
  - **NESC White Paper Report developed summarizing ORM Peer Review findings and recommendations**
  - **Peer review team consensus is that there remains critical open work that absolutely must be completed prior to first use of ORM**
  - **The team also found that that lack of a dedicated full time ORM Lead System Engineer has impacted, and continues to impact, the integration and prioritization of open ORM analytical and operational planning work**
  - **The team found that the on-orbit contingency decision flow process/policy defining specifically when the ORM will be invoked had not been finalized**
  - **The team has developed the following prioritized set of recommendations which represents the minimum set of ORM analytical and operational planning tasks needed to have the ORM in place as a viable contingency for STS-114**

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Shuttle/ISS Orbiter Repair Maneuver

28-29 June 05

Dennehy

- **Results (continued):**
  - **Prioritized set of NESC recommendations on the ORM:**
    - #1 Priority: Re-assessment of ISS attitude control system design and performance. Use high-fidelity simulation to show current design has adequate stability robustness margins. Also use high-fidelity simulation to demonstrate performance of ISS rate damping controller to recover stack from free drift rates at either the overnight park position or the repair position
    - #2 Priority: Complete the independent validation of the ORM integrated end-to-end dynamic simulation, to include benchmarking with Virtual Reality (VR) laboratory dynamics simulation
    - #3 Priority: Complete ORM contingency planning to include definition of: a) the ORM state-of-health/dynamic behavior monitoring procedures and protocols, b) the specific Contingency Action Plan for performing on-orbit analysis of worksite dynamic interactions, c) on-orbit pre-repair dynamic checks in the worksite environment and d) Failure Detection, Isolation and Recovery (FDIR) checks/tests

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Shuttle/ISS Orbiter Repair Maneuver

28-29 June 05

Dennehy

- **Results (continued):**
  - #4 Priority: Complete the analysis and simulation of the repair worksite dynamic interaction (i.e. assess relative motions between the EVA astronaut and Orbiter)
  - #5 Priority: Fully document and communicate all ORM operational constraints and hazards to Astronaut Office and mission control center staff
    - For example, need to document and communicate the fact that, if required during the ORM, an emergency Orbiter separation must be performed passively, using orbital dynamics with no thruster firings, from the overnight park position with the entire stack pitch down 45 degrees
- **Issues/constraints/open work:**
  – The set of five NESC prioritized recommendations, representing the minimum set of ORM analytical and operational planning tasks, need to be implemented in order for the ORM to be considered as a viable contingency for STS-114
- **Flight Rationale/ Risk Assessment:**
  - ORM contingency operations should not be invoked until, at a minimum, all NESC prioritized recommendations have been addressed

04-051-E This briefing is for status only and does not represent complete engineering data analysis 4

Appendix D. April 2005 ORM Status Report

Status Report

Orbiter Repair Maneuver (a.k.a. Orbiter "Flip" Maneuver)
Frank H. Bauer, NESC GN&C SPRT
3/31/05

The intent of this report is to provide a status on the NASA JSC initiative to perform a series of re-orientation maneuvers on the Space Shuttle using the Space Shuttle Remote Manipulator to support Orbiter Repair. The primary requirement for this very challenging maneuver is to inspect remote portions of the RCC and ceramic tile for damage and, if damage is observed, to enable vehicle repair. Repair would be accomplished by undocking from the ISS using the Shuttle RMS, reorienting the Shuttle using the Shuttle RMS and then allowing astronauts on the Space Station Remote Manipulator to complete the repair. It should be noted that this specific maneuver will only be required for a small subset of the RCC and ceramic tile repair scenarios.

<u>Executive Summary</u>

Several members of the NESC Guidance, Navigation and Control SPRT have been providing high-level oversight of the technical and programmatic activities surrounding the Orbiter Repair Maneuver since July 2004. Members of the SPRT attended a comprehensive NESC review at NASA JSC on August 31-Sept 2, 2004. In addition, as time permits, SPRT team members participate in the ORM weekly teleconferences, get periodic status updates from JSC-resident SPRT members Louis Nguyen and Tuyen Hua, they review material on the ORM web site, and Frank Bauer, the out-going GN&C NDE, has performed face-to-face status discussions with the ORM Shuttle Program Office leads Ladonna Miller and Curt Larsen.

The ORM activity represents a challenging control-structure interaction problem. Normally, the Shuttle RMS lifts and deploys payloads with mass and inertias much smaller than the Shuttle. In all cases to-date, the Shuttle can be thought of as an "infinite mass" that reacts against the much smaller payload. The Shuttle RMS uses this "infinite" reactive mass to help move the payload in the proper position (translation and orientation). However, for the ORM, the Shuttle becomes the payload that reacts against the ISS. It should be noted that the largest payload attached to the Shuttle RMS to-date is the FGB. The FGB mass is approximately an order of magnitude less than the Shuttle mass. So extrapolation from an FGB payload to the Shuttle as a payload is a quite daunting challenge.

It is the NESC team's opinion that the ORM team are currently on the right path to analytically validate the viability of whether this end-to-end system can successfully perform an ORM; however, the initiative is proceeding much slower than anticipated. The primary cause of this delay resulted from the engineering community (i.e. EG, ER and ES) needing to prioritize their human resources on primary Shuttle Return to Flight (RTF) initiatives. Now that sufficient resources are available to move forward, ORM end-to-end analysis has begun in earnest to assess the stability of the system (Shuttle, SRMS, etc.) while under the influence of worksite dynamic interaction (crew motion and vehicle repair).

Specific major ORM-related activities performed to date, with NESC team recommendations on these follow:

1) **ISS Russian Segment Maneuver Control System Modification**---requires a new thruster control system (phase plane parameter changes and development of "cyclogram") to minimize Shuttle RMS brake slip. ISS controller modifications have been developed and have been tested on-orbit. NESC GN&C SPRT comments: Good first step in ORM development

2) **ORM Detailed Test Objective (DTO)**---a DTO was planned for STS-121 (2nd flight of shuttle after return to flight) while docked to the ISS. The intent of this DTO was to validate some aspects of the ORM activity, particularly specific Shuttle RMS orientations with the Shuttle acting as the payload. This DTO was not approved by the Joint Shuttle/ISS Program Office due to concerns regarding mission risk and analytic maturity. The NESC team was following this initiative quite closely. The NESC team was quite concerned about proceeding forward with this DTO, given the analytic maturity and mission (ISS and Shuttle) risk. They concur with the Program Office decision on this matter.

3) **Worksite stability**---models of crew member dynamics and repair dynamics are currently being developed. The end-to-end analysis of the entire system (Shuttle Controller, ISS Controller, Shuttle RMS controller, Station ISS controller and worksite dynamics) has not been completed to date. NESC reaction: Obviously, these analyses need to be completed before the ORM can be contemplated for use. Once the analyses are complete, the NESC team would like to have a second comprehensive review of the analysis efforts, similar to the depth provided at the August 2004 meeting. Given that this maneuver and subsequent repair have the

potential for catastrophic loss of the Shuttle and ISS, plans to independently validate these models are recommended by the NESC prior to their use.

4) **Contingency decision to use of ORM during future Shuttle missions**---given that the ORM has yet to be validated, there is significant concern within the NESC GN&C SPRT that, in the event that a Shuttle tile problem is observed, a go-ahead to proceed with the ORM may be operationally invoked. The NESC GN&C team does not support this given the immature state of the analyses. Further, we have recently learned that ORM contingency procedures are in place for STS-114. It is our recommendation to the NESC Review Board that the ORM contingency operations procedures not be invoked until the system validation is complete and the NESC has concurred with the validation and contingency operations plan.

The above represents an executive summary of the ORM plans and NESC GN&C SPRT thoughts and recommendations to date. This team will continue to monitor the progress of the ORM activities and report back to the NESC as appropriate. If more detailed discussions on this topic are required, please contact Frank Bauer at frank.bauer@nasa.gov or 202-358-0897. Additional background material is shown on the next few pages.

The NESC GN&C SPRT would like to thank the entire ORM team and the ORM leads, Ladonna Miller and Curt Larsen from the Shuttle Program Office and Bill Spetch from the ISS Program Office, for their openness and frank dialog throughout our oversight activity. This was much appreciated and was crucial in getting a good understanding of the ORM analyses, plans and potential risks.

<signed>
Frank H. Bauer
NESC GN&C SPRT

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	NESC Director	Date

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14. ABSTRACT
The intent of this Technical Consultation Report is to document the finding and recommendations of the NESC Orbiter Repair Maneuver (ORM) Peer Review conducted at NASA's Johnson Space Center (JSC) with the ORM Working Group (WG) over the period 8-10 June 2005.

15. SUBJECT TERMS
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