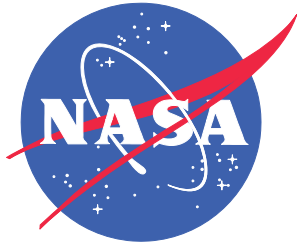


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NESC-RP-13-00921



International Space Station (ISS) External Thermal Control System (ETCS) Loop A Pump Module (PM) Jettison Options Assessment

*Daniel G. Murri/NESC
Langley Research Center, Hampton, Virginia*

*Alicia Dwyer Cianciolo
Langley Research Center, Hampton, Virginia*

*Jeremy D. Shidner and Richard W. Powell
Analytical Mechanics Associates, Hampton, Virginia*

October 2014

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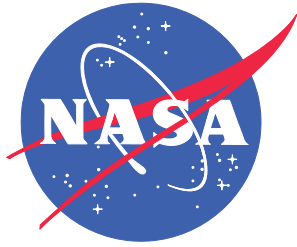
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*Alicia Dwyer Cianciolo
Langley Research Center, Hampton, Virginia*

*Jeremy D. Shidner and Richard W. Powell
Analytical Mechanics Associates, Hampton, Virginia*

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

October 2014


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September 18, 2014

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NOTE: This document was approved at the September 18, 2014, NRB. This document was submitted to the NESC Director on September 22, 2014, for configuration control.

Approved:	<i>Original Signature on File</i>	9/26/14
	_____ NESC Director	_____ Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Daniel Murri, NASA Technical Fellow for Flight Mechanics, LaRC	9/18/14


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Technical Assessment Report

1.0 Notification and Authorization

The NASA Engineering and Safety Center (NESC) received a request to support the International Space Station (ISS) Pump Module (PM) Jettison Assessment on December 16, 2013.

Mr. Daniel Murri, NASA Technical Fellow for Flight Mechanics at the NASA Langley Research Center (LaRC), was selected to lead this assessment. Mrs. Alicia Dwyer Cianciolo (LaRC) was selected as the technical lead.

The key stakeholder for this assessment was the ISS Program.

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2.0 Signature Page

Submitted by:

Team Signature Page on File - 10/2/14

Mr. Daniel Murri

Date

Significant Contributors:

Ms. Alicia Dwyer Cianciolo

Date


Mr. Jeremy D. Shidner

Date

Mr. Richard Powell

Date

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


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3.0 Team List

Name	Discipline	Organization
Core Team		
Daniel Murri	Lead, NASA Technical Fellow for Flight Mechanics	LaRC
Alicia Dwyer Cianciolo	Technical Lead, Flight Mechanics and Trajectory Design	LaRC
Jeremy Shidner	Flight Mechanics and Trajectory Design	LaRC/AMA
Richard Powell	Flight Mechanics and Trajectory Design	LaRC/AMA
Scott Angster	Flight Animation	LaRC/AMA
Sarah Rieger	Flight Mechanics and Trajectory Design	JSC
Christopher Cerimele	Branch Chief	JSC
Consultants		
Joe Pascucci	DM33/ISS Trajectory Operations	JSC/ULA
Yared Mesfin	Senior Technical Lead, Boeing ISS Guidance, Navigation, and Control (GN&C)	JSC/Boeing
Charles Gray	VIPER Systems Analysis & Integration	JSC/ Booz Allen Hamilton
Neil Dennehy	NASA Technical Fellow for GN&C	GSFC
Dave Schuster	NASA Technical Fellow for Aerosciences	LaRC
Administrative		
Stephanie Hamrick	MTSO Program Analyst	LaRC
Erin Moran	Technical Writer	LaRC/AMA

3.1 Acknowledgements

The team would like to acknowledge Forrest Lumpkin, Randy Thurman, Ryan Eastand, and James Fenner for their contributions.

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4.0 Executive Summary


On December 11, 2013, the International Space Station (ISS) experienced a failure of the External Thermal Control System (ETCS) Loop A Pump Module (PM). To minimize the number of extravehicular activities (EVA) required to replace the PM, jettisoning the faulty pump was evaluated. The objective of this study was to independently evaluate the jettison options considered by the ISS Trajectory Operations Officer (TOPO) and to provide recommendations for safe jettison of the ETCS Loop A PM.

The simulation selected to evaluate the TOPO options was the NASA Engineering and Safety Center's (NESC) version of Program to Optimize Simulated Trajectories II (POST2) developed to support another NESC assessment¹. The objective of the jettison analysis was twofold: (1) to independently verify TOPO posigrade and retrograde jettison results, and (2) to determine jettison guidelines based on additional sensitivity, trade study, and Monte Carlo (MC) analysis that would prevent PM recontact. Recontact in this study designates a propagated PM trajectory that comes within 500 m of the ISS propagated trajectory. An additional simulation using Systems Tool Kit (STK) was run for independent verification of the POST2 simulation results.

Ultimately, the ISS Program removed the PM jettison option from consideration. However, prior to the Program decision, the retrograde jettison option remained part of the EVA contingency plan.

The jettison analysis presented showed that, in addition to separation velocity/direction and the atmosphere conditions, the key variables in determining the time to recontact the ISS is highly dependent on the ballistic number (BN) difference between the object being jettisoned and the ISS.

¹ Development of Verification Data for Flight Simulation (NESC #TI-12-00770)

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5.0 Jettison Options and Assumptions

The jettison options include posigrade (i.e., in the direction of ISS motion) or retrograde (i.e., in the opposite direction of ISS motion). To ensure continuous separation of the jettisoned ETCS Loop A PM and the orbiting ISS, there must be a minimum BN difference between the objects. The BN is given by equation 1:

$$BN = M/(C_D * A) \quad (\text{EQ. 1})$$

where M is the vehicle mass, C_D is the vehicle drag coefficient, and A is the area exposed to the flow.

Posigrade jettison is advantageous for cases where the PM BN is greater than the ISS BN. Examples are provided in Section 6. A posigrade PM jettison would be performed at the EVA worksite.

Retrograde jettison is better for PM BNs less than the ISS BN. For the faulty PM, the retrograde jettison would be done using the robotic arm from the nadir side truss below the worksite. The EVA crew preferred the retrograde option because it provided a better viewing angle during initial release.

Other jettison assumptions included the ISS jettison policy² of a minimum separation speed of 0.05 m/s. This speed is considered worst-case and represents a “drift away” scenario. Although past experience has shown that 0.2 m/s is reasonable, EVA performance is based on a braced and pushed case. Additionally, the ISS jettison policy requires the assessment of a 30-degree half cone angle from the nominal jettison direction, the starboard solar array rotary joint (SARJ) at 195 degrees, and the PM recontact time (i.e., the time it takes for a propagated PM trajectory to come within 500 m of the propagated ISS trajectory) has to be greater than 10 days. This time requirement is to accommodate an ISS reboost to avoid recontact.

6.0 Data Analysis

6.1 Independent Trajectory Simulation


The simulation tool selected to evaluate the TOPO options was the NESC’s version of POST2, which was developed to support another NESC assessment³. The simulation was developed to model the ISS orbit propagation using the Distributed Space Exploration Simulation Test Plan [ref. 1]. The simulation has been demonstrated to provide comparable results to the Johnson Space Center (JSC) Trick simulation framework [ref. 2] and was configured with the states and models needed to perform the jettison analysis.

The POST2 simulation models include:

- Lunar and Solar point mass 3rd body perturbations (i.e., SPICE toolkit using the Jet Propulsion Laboratory (JPL) DE405 ephemeris).

² <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080047307.pdf>

³ Development of Verification Data for Flight Simulation (NESC #TI-12-00770)

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- Goddard Earth Model (GEM-T1) Gravity Field (8×8).
- Marshall Engineering Thermal (MET) Model Atmosphere.
- 3-Degree of Freedom Aerodynamic Drag Only.
- Non-varying BN (i.e., PM was not tumbling).

The reference frame used to initialize orientation is the ISS-defined local orbital (i.e., local vertical, local horizontal (LVLH)) coordinate system [ref. 3]. The LVLH frame defines the +Z-axis as the radial vector toward Earth and the +Y-axis as normal to the orbit plane, as shown in the left side of Figure 6.1-1. The ISS Design Reference Frame (DRF), or the Space Station Analysis Coordinate System [ref. 3] shown in right side of Figure 6.1-1, has +X-axis (i.e., red arrow) initially aligned with +X_{LVLH}, and +Z-axis (i.e., blue arrow) initially aligned along the radial vector, +Z_{LVLH}. For purposes in this analysis, the DRF and LVLH frame were assumed to be coincident. However, these reference coordinate systems are offset on the order of 5 degrees as detailed at the ISS attitude planning website [ref. 4]. The jettison direction is calculated as a 3(yaw)-2(pitch) Euler angle sequence from the ISS DRF, where the positive yaw direction will rotate the jettison object to the right of the ISS, and a positive pitch direction will rotate the jettison object above the ISS.

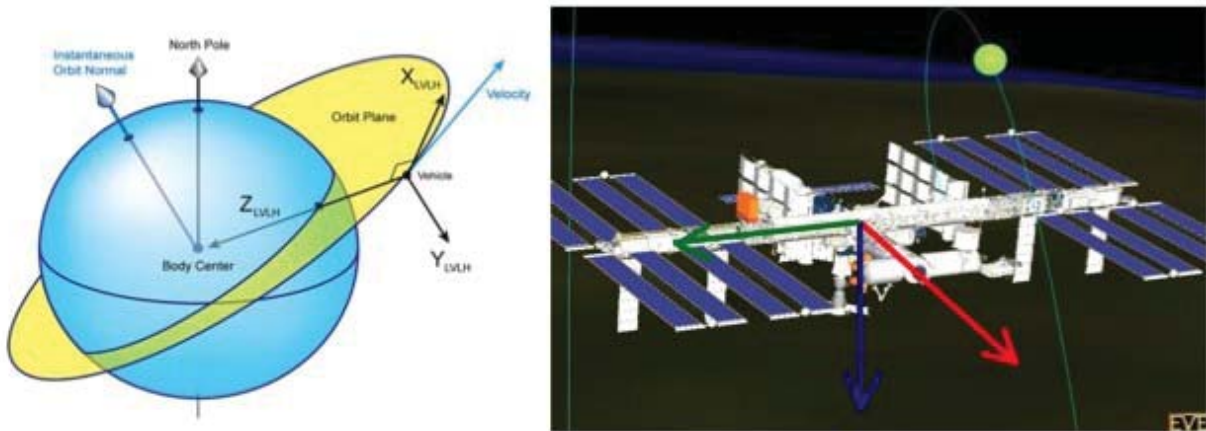


Figure 6.1-1. Reference Frames
(Left) LVLH and (Right) Station DRF depictions.

The nominal simulation assumptions listed in Table 6.1-1 were derived from various sources, including: the TOPO assumptions for atmosphere inferred to use max MET values from the model, TOPO values for ISS and PM mass, website queries from operational assessments of ISS location [ref. 5], and locations of jettison from ISS model inquiries using Exploration Visualization Environment (EVE). EVE is a simulation, visualization, and analysis tool developed to integrate potentially disparate time-based data with detailed graphical models in a real-time virtual environment. Details of the animation tool and its application to this study are described in Section 6.2.4.


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Table 6.1-1. Simulation Assumptions

Category	Parameter	Value
Initial State	Epoch	2013-352/12:00:00.000 UTC'
	J2000 Position	3414153.57, 3560080.97, 4670109.53 m
	J2000 Velocity	-2847.347311, 6505.836888, -2871.765151 m/s
MET Atmosphere	F10.7 (Max)	250
	Geomagnetic Index (Max)	25
	F10.7 (Mean)	118.0
	Geomagnetic Index (Mean)	1.827
Mass Properties	PM Mass	360.25 kg
	PM Reference Area (Mean)	1.6 m ²
	ISS Mass	413,309.469 kg
	ISS Reference Area (Mean)	1836.8 m ²
Planet Parameters	Gravitational Constant	3.98600436e14 kg/m ³
	Rotation Rate	7.29211514670638e-5 rad/s
	GEM-T1 Gravity Field	8 x 8 order
	Equatorial Radius	6,378,137.0 m
	Polar Radius	6,356,755.38082467 m
Aerodynamics	PM Drag Coefficient	2.0
	ISS Drag Coefficient	2.07
Pushoff Location	Posigrade (DRF)	2, 14, 0 m
	Retrograde (DRF)	0, 14, 10 m

6.2 Analysis

The simulation described in Section 6.1 was used to evaluate the PM jettison options. The objective of the jettison analysis was twofold: (1) to independently verify TOPO posigrade and retrograde jettison results, and (2) to determine general jettison guidelines based on additional sensitivity, trade study, and MC analysis that would prevent PM recontact (i.e., approaching within 500 m) with the ISS for at least 10 days. The major consideration to determine the time to recontact was the BN difference between the PM and the ISS. The analysis accuracy depended on the PM and ISS BN accuracy. The ISS BN could be varied with solar array actuation.

6.2.1 Determining BN for ISS and PM

This section presents the determination and effect of ISS and PM BNs, and a summary of the sensitivity, trade studies, and MC analysis performed.

It became evident early in this study that characterizing the PM and ISS BNs would be critical to determine the time to recontact. This section summarizes what is known about the PM mass and volume and the characterization of and mitigation options for the ISS BN.

6.2.1.1 PM Mass

The team received two sets of ISS and PM mass and dimension values. The first set included values from the Vehicle Integrated Performance Environments and Resources (VIPER) [ref. 6] and are provided in Table 6.2-1. The second set was provided by the TOPO and is shown in Table 6.2-2.


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Table 6.2-1. VIPER PM Mass and Area Values [ref. 7]

Object	Mass (kg)	Dimensions (m)	Area (m ²)	BN (kg/m ²)
ISS			2013	100.0
Pump Module	360.25	1.750 × 1.270 × 0.910		
Minimum Area			1.16	155.1
Average Area			1.60	112.4
Maximum Area			2.23	80.9

Table 6.2-2. TOPO PM Mass and Area Values [ref. 7]

Object	Mass (kg)	Dimensions (m)	Area (m ²)	BN (kg/m ²)
ISS	413,309.5		1836.8	108.7
Pump Module	413.7	1.524 × 1.245 × 0.787		
Minimum Area			0.6	344
Average Area			1.159	178
Maximum Area			1.897	109

To resolve the PM mass and dimension differences, Randy Thurman, and Charlie Gray (JSC-ISS Operations) [Barrios Technology, Ltd.], were consulted. Both Thurman and Gray confirmed that the PM dimensions were 68.1 × 50.0 × 35.7 in (1.73 × 1.27 × 0.91 m) and consistent with the VIPER data. Thurman commented the PM dimensions were accurate to about ±1 inch [refs. 8, 9].

Thurman stated the dry mass of the PM was 919 lbm (417.2 kg). However, because loop system pressure was reduced prior to removal, the PM accumulator to mostly empty and the PM wet mass would be 935 lbm (424.5 kg), including approximately 16 lbm (7.3 kg) of residual ammonia. Gray indicated the 358.9 kg wet mass number was correct, and indicated the 935-lbm number included the flight support equipment (FSE), which weighs 182.93 lbs (83 kg). The FSE would not be jettisoned with the PM. However, there is a credible contingency scenario that a 75-lbm (34-kg) grapple bar would be attached to the PM and should be included in total jettison mass. Table 6.2-3 attempts to capture the PM mass components to identify which should be included in the calculation of the BN. By accounting for the residual ammonia and grapple bar as part of the jettison mass, the estimated PM mass was between 357.4 and 368.2 kg. It is noted the margined VIPER (±10 lbm) mass falls between the range.

Table 6.2-3. PM Mass Inconsistencies

VIPER Wet Mass	TOPO Mass	Wet mass from Thurman	Component
	413.7 kg	424.5 kg	
	-83.0 kg	-83.0 kg	FSE - not jettison
	+34.0 kg	+34.0 kg	Grapple bar is jettison
	364.7 kg	375.5	WET MASS
	-7.3 kg	-7.3 kg	Residual Ammonia
	357.4 kg	368.2 kg	DRY MASS
358.9 kg ±4.54 kg			


There was an inconsistency recognized with the minimum area provided with the TOPO values provided in Table 6.2-2. The stated 0.6-m² does not correspond to the area of the minimum TOPO dimensions (1.245 × 0.787 = 0.979 m²). Likewise, it is unclear how the average area was determined in the TOPO and VIPER data. Assuming a $C_D = 2$ in the BN calculation, the average PM area in the VIPER data should be approximately 1.69 m². This area results in an average BN of approximately 106 kg/m² versus the VIPER value of 112 kg/m². This difference, shown in Section 6.2.2, is important when determining the recontact time and deciding whether to perform a posigrade or retrograde jettison.

6.2.1.2 ISS BN

The TOPO develops orbit averaged frontal array areas for each ISS configuration involving five ranges of solar beta angles, with and without drag reduction enabled. The orbital averaging takes into account alpha joints motion (e.g., SARJs), which go through one "cycle" per orbit. In the "no drag reduction" mode, the SARJs go through one rotation at a constant rate for the orbit. The drag reduction mode is the normal ISS operational mode. This joint rotation with the use of the beta gimbals, which account for the effect of the angle of the Sun to the orbital plane, keep the arrays pointed at the Sun when not in eclipse. With drag reduction enabled, strategies were employed to reduce the drag. This includes feathering the arrays when in eclipse, and trading power production by off pointing from the Sun. The strategy is repeated every orbit producing periodic array operations with orbital frequency. The specific strategies vary depending on the beta angle.

The TOPO computes the expected projected areas for the next several years, which is updated quarterly. Using these projections, examples of the ISS BN effects resulting from changes in assumed array orientations are obtained.

The 1836.8-m² in the "nominal case" (Table 6.2-2) corresponds to the ISS configuration for a beta angle (i.e., absolute value) range of 0 to 15 degrees. As the absolute value of beta increased over a 2-week period, the solar beta magnitude exceeded 60 degrees on December 30, 2013. The projected area will decrease as the beta gimbals angles point the arrays more into the ISS Y-direction to direct them at the Sun. This orientation feathers the arrays with respect to the ISS velocity vector, which is nearly aligned with the ISS X-axis. For example, for the beta range of 60 to 75 degrees (i.e., the maximum range in the TOPO tables), the projected area reduces to

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1299.3 m². Alternatively, if drag reduction is disabled for the 0 to 15 degree beta range, the projected area increases to 2321.9 m².

Along with changes to the ISS projected area, the vehicle experiences variations in drag coefficient that range between 2.04 and 2.2 [ref. 10].

Therefore, the BNs for these three cases are:

Nominal case	108.7 kg/m ²
High beta, drag reduction	153.7 kg/m ²
Low beta, no drag reduction	86.0 kg/m ²

If the jettison option is selected, then a retrograde release is the best option, allowing for efforts to lower ISS drag. It could also be desirable to combine a retrograde jettison with a preemptive debris avoidance maneuver (i.e., in effect a re-boost) to reduce the likelihood of PM recontact.

6.2.2 Results

Using the simulation described in Section 6.1, the PM mass, and PM and ISS BN uncertainties, the analysis for comparison with the TOPO provided nominal trajectories utilizes following assumptions:

- **BN**
 - ISS – 108.7 kg/m²
 - PM minimum – 80.9 kg/m²
 - PM average – 112.4 kg/m²
 - PM maximum – 155.1 kg/m²
- **Pushoff velocity for 0.05 and 0.20 m/s**
- **Posigrade pushoff attitude**
 - Pitch = 30 degrees, Yaw = -15 degrees
- **Retrograde pushoff attitude**
 - Pitch = -30 degrees, Yaw = 160 degrees

6.2.2.1 Results – Posigrade PM Jettison

For each pushoff attitude, a nominal set of dispersed trajectories was considered. The trajectories, obtained by taking a sweep of clock angles from 0 to 360 degrees in 30-degree increments with a constant 30-degree cone angle from the nominal 30-degree pitch and -15-degree yaw angles, are shown in Figure 6.2-1.



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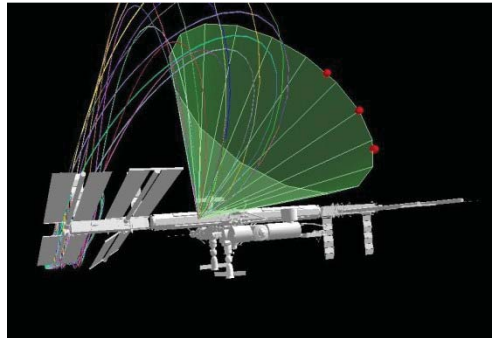


Figure 6.2-1. Posigrade Jettison Cone [ref. 7]

The results of the posigrade jettison dispersed trajectories are shown in Figure 6.2-2. This figure illustrates the difference in range, or distance between the PM and the ISS, for a posigrade separation using two different pushoff velocities. The left side of Figure 6.2-2 illustrates the range after 10 days using the minimum pushoff velocity of 0.05 m/s. If the PM has a BN near 80 kg/m² (shown in green), which is less than the assumed average ISS BN of 108 kg/m², then it could recontact the ISS in less than 1 day. However, if the PM BN is greater than the ISS BN, then recontact will take longer than 10 days. Recontact designates a propagated PM trajectory that comes within 500 m of the ISS propagated trajectory. The right side of Figure 6.2-2 illustrates the effect of increasing the pushoff velocity to 0.2 m/s. In this case, the possibility of PM recontact, for PM BNs less than the ISS, is extended to almost 3 days.

Therefore, in the cases of posigrade jettison, the jettison object must have a BN greater than that of the ISS to maximize the time to recontact.

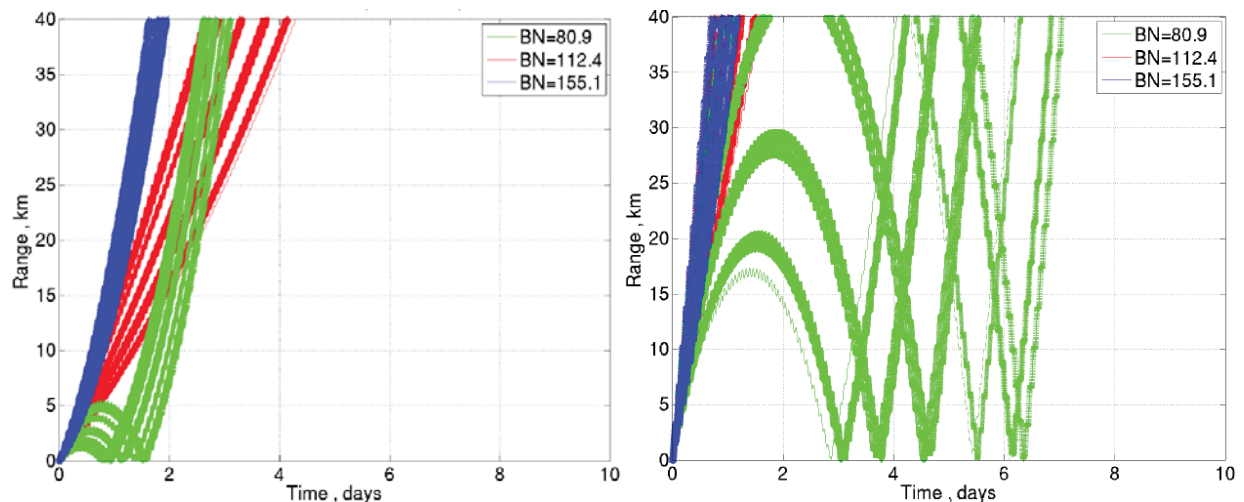



Figure 6.2-2. Separation Distances of PM from ISS - Posigrade Jettisons

Figures on the left and right show results using 0.05 and 0.2 m/s separation velocity, respectively.

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6.2.2.2 Results – Retrograde PM Jettison

Figure 6.2-3 shows the range between the ISS and PM after 10 days for the case of retrograde jettison with the pushoff velocities (left: 0.05 m/s, right: 0.2 m/s) considered in the posigrade analysis. The sweep of clock angles (i.e., 0 to 360 degrees in 30-degree increments) is the same as those used in the posigrade analysis. However, the nominal retrograde pitch angle is -30 degrees and the nominal yaw angle is 160 degrees. In this case, the PM BN near 155 kg/m² predicts recontacts in just over 1 day. Therefore, to ensure positive separation of a retrograde jettison, the PM BN must be less than the ISS BN to prevent recontact in 10 days. However, similar to posigrade jettison analysis, the increase in separation velocity does delay the time to recontact. This analysis highlights the substantial effect that a BN mismatch and, to a lesser extent, the effect of jettison velocity can have on ISS recontact time.

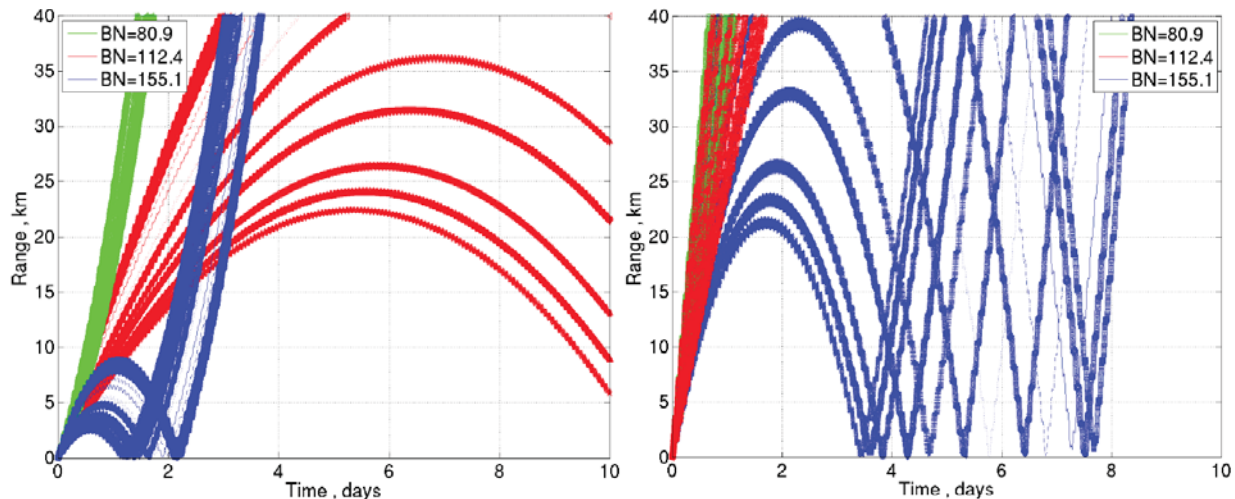


Figure 6.2-3. Separation Distances of PM from ISS - Retrograde Jettisons

Figures on the left and right show results using 0.05 and 0.2 m/s separation velocity, respectively.

One purpose of the analysis was to verify TOPO trajectories for similar trajectory conditions. Figure 6.2-4 is an example of the TOPO provided trajectory results for retrograde jettison analysis using the 0.05-m/s separation velocity and similar PM BN range. Though the plots are on different scales, Figure 6.2-4 and the left side of Figure 6.2-3 show the PM returning for particular cases in just over 1 day, while lower PM ballistic trajectories maintain positive separation during the same time period.



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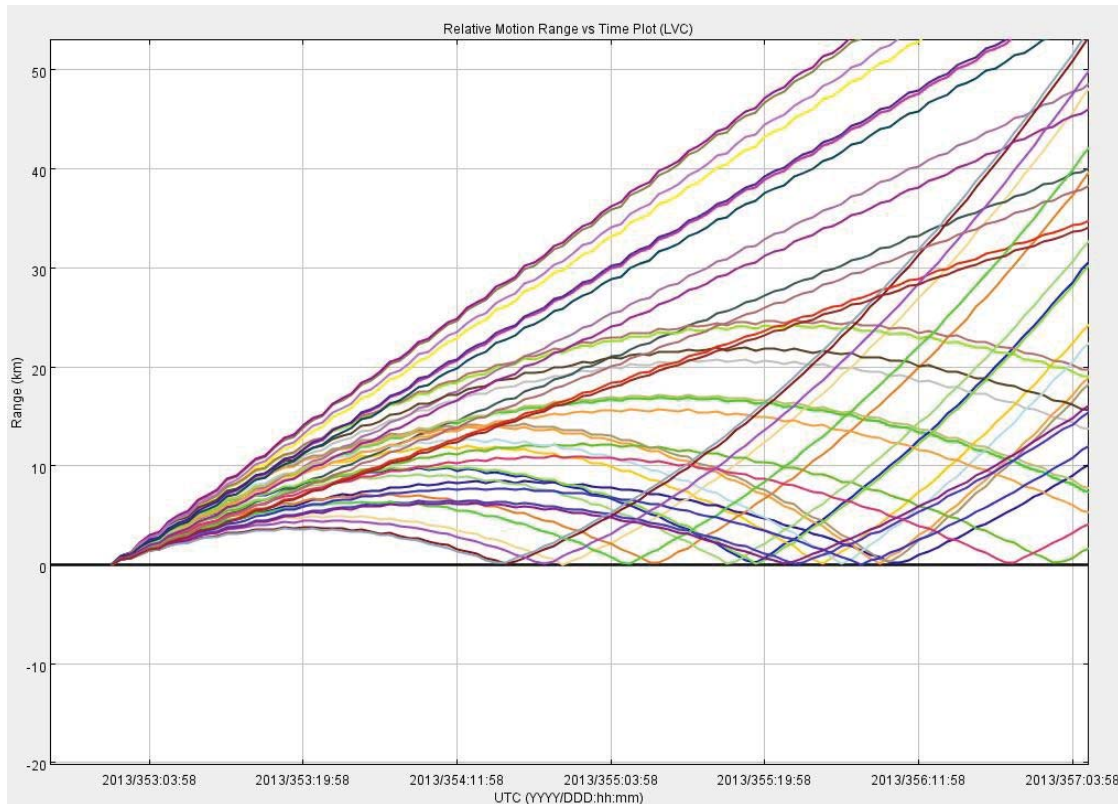



Figure 6.2-4. TOPO Retrograde Jettison Trajectory Ranges for Separation Velocity of 0.05 m/s

Having validated TOPO results, and with the retrograde jettison option remaining as part of the contingency, additional analyses were performed using only retrograde jettison.

Recognizing the significant impact of the BN difference on time to recontact, a study was performed to determine the BN difference required to prevent recontact for 10 days using a 0.2-m/s separation velocity. The retrograde case with a 0.2-m/s jettison velocity and a BN of 155 kg/m^2 that returned in the shortest time (~ 3.5 days) had a pitch angle of -30 degrees, a yaw of 160 degrees, a clock angle of 30 degrees, and a cone angle of 210 degrees. This case is shown in blue in Figure 6.2-5. To delay recontact to 10 days, PM BN must be less than 120 kg/m^2 . This case is shown in red in Figure 6.2-5. Since BN is a function of mass and area, and assuming a constant drag coefficient $C_D = 2$, the PM would require an area increase of approximately 0.34 m^2 , or a mass reduction of 82 kg to achieve the a BN of 120 kg/m^2 . Though some mass reduction could be gained by draining the remaining ammonia, it is not likely the PM mass could be reduced to this level. The more likely mitigation technique would be to add a drag device (e.g., inflatable, tethered balloon, etc.).

Currently, there are no simple solutions available on the ISS to increase a jettison objects drag area. One recommendation from this study (i.e., R-6) is to consider development and crew training to use some type of deployable decelerator specifically for these situations.

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In addition to drag mitigation features for the jettison object, there are ISS BN drag mitigation options (see Section 6.2.1.2) that should be considered if the jettison options are exercised. Further work is needed to characterize how much ISS drag mitigation would be needed on each orbit and for how many orbits. The result will likely be jettison case-specific.

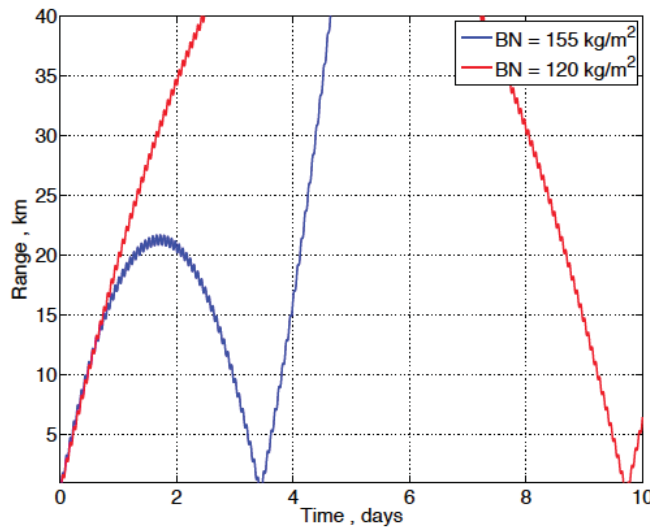


Figure 6.2-5. Comparison of PM with Different BN

The BN of the object was reduced from 155 kg/m² to 120 kg/m² to illustrate the effect BN number has on the time to recontact.

6.2.2.3 Results – Sensitivity Studies

To understand simulation sensitivities, additional analyses were performed to characterize the PM/ISS range at 10 days to the effects of simulation integration step size, gravity model, and atmosphere. The analysis considered effects on the nominal trajectory defined in Section 6.2.2 (i.e., ISS BN = 108.7 kg/m²; PM BN = 112.4 kg/m², pushoff pitch angle = -30 degrees, pushoff yaw angle = 160 degrees, pushoff velocity = 0.05 m/s). The results are provided in the following three subsections.

Sensitivity to Simulation Integration Step Size

Due to the time being considered for orbit propagation (i.e., 10 days), it was important to understand the effect of and differences in propagated trajectories due to the simulation integration type and step size. Three integrators were evaluated in the POST2 simulation: Runge-Kutta 4, Runge-Kutta 8, and Enche using a Runge-Kutta 4 at start up. Additionally, three time steps were considered: 0.1 s, 1.0 s, and 10 s. The ISS-to-PM range difference after 10 days is shown in Table 6.2-4. Note the Runge-Kutta 8 simulation with a 0.1-s time step took the longest to complete. As the results indicate, integration type and step size do not have a substantial effect on the propagation results. Therefore, the Runge-Kutta 4 with a 1-s time step was used for the remaining analyses.


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Table 6.2-4. Results of Integration and Time Step Sensitivity Study

Integrator with time step	Resulting difference in PM to ISS distance after 10 days (m)
Range (RK4, dt = 0.1) – Range (RK4, dt = 1.0)	0.003
Range (RK4, dt = 10) – Range (RK4, dt = 1.0)	0.4
Range (RK8, dt = 0.1) – Range (RK8, dt = 1.0)	0.03
Range (RK8, dt = 10) – Range (RK8, dt = 1.0)	0.09
Range (Enche + RK4, dt = 0.1) – Range (Enche + RK4, dt = 1.0)	0.006
Range (Enche + RK4, dt = 10) – Range (Enche + RK4, dt = 1.0)	0.3

Sensitivity to Gravity Model


A second sensitivity study compared the ISS and PM propagated range after 10 days considering gravity models of different resolution. The three resolutions considered were 4×4 , 8×8 , and 36×36 order fields. The GEM-T1 gravity model was used for the analysis as it extends to a 360×360 order field resolution. The highest resolution currently available in the POST2 simulation was the 36×36 . Should longer propagation periods be considered, higher order gravity models may be necessary. The nominal simulation was run changing only the gravity resolution. The difference in PM and ISS distance at the end of 10 days was compared with the results shown in Table 6.2-5. The effect of increasing the gravity model resolution was a difference in propagated range at the end of 10 days of only about 50 m. Therefore, only the 4×4 model was used for the study.

Table 6.2-5. Results of the Gravity Field Resolution Sensitivity Study

Gravity Models	Resulting difference in PM to ISS distance after 10 days (m)
Range (8×8) – Range (4×4)	40.3
Range (36×36) – Range (8×8)	7.3

Sensitivity to Atmosphere

The atmosphere model used in the POST2 simulation was the MET model, which is a modified Jacchia 1970 model [ref. 11]. In this model, the daily solar flux 10.7 cm can be varied (i.e., minimum = 70, mean = 128.8, maximum = 250.0) as can the geomagnetic index (i.e., minimum = 0.0, mean = 15.7, maximum = 25.0). Therefore, the atmosphere sensitivity study considered the effect of the maximum, minimum, and mean atmosphere settings on the PM and ISS separation range trajectories for posigrade and retrograde jettison simulations assuming a PM BN of 112.4 kg/m^2 and a ISS BN of 108.7 kg/m^2 . The plots in Figure 6.2-6 show the difference in range at the end of 10 days for both cases. The minimum atmosphere settings (i.e., generating the least atmospheric density and drag) result in posigrade jettison encountering the ISS sooner. In this case, since the BN of the PM is higher than the ISS, the lower density slows the separation as compared to higher density atmosphere. The maximum atmosphere settings (i.e., highest density) stress the retrograde jettison because the higher drag allows the PM, with a higher BN than the ISS, to overtake the ISS more quickly and results in potential recontact sooner than a low-density (i.e., low-drag) atmosphere. It is expected that these results

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would be reversed if the PM BN were lower than the ISS BN. The atmosphere conditions at the time of the study recorded the F10.7 to be near 118.0, and a geomagnetic index of approximately 1.827 [ref. 5].

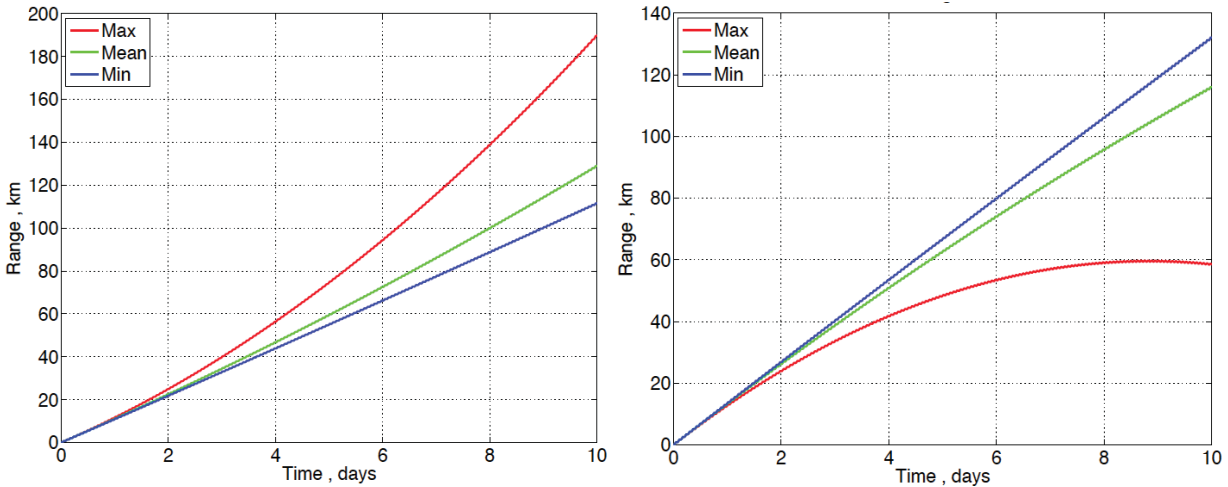



Figure 6.2-6. Separation Distance of PM from ISS for Different Atmospheric Settings
ISS versus PM range using different atmosphere settings for (left) posigrade jettison and (right) retrograde jettison.

It is important to note the “stress” case atmosphere is different for posigrade jettison than for retrograde jettison scenarios and should be considered when evaluating jettison options.

6.2.2.4 MC Analysis Results

Simplified analysis can reveal the initial implications of the mass, area, and drag coefficient dispersions. Figure 6.2-5 illustrated that a 30-percent decrease in BN can increase the recontact time from 3.5 to almost 10 days. Throughout this study, it was evident the PM mass, mean projected area, and drag coefficient are not consistently defined. The uncertainty in PM mass, area and drag coefficient effect the BN and the calculation of recontact time. Consider a 10-percent variation in the PM mass, area, and drag coefficient. A 10-percent change in any single PM BN quantity while the others remain at their nominal value would result in a 10-percent BN change. However, a 10 percent increase in mass with area and drag dispersions that are 10 percent lower than the nominal result in a 35-percent difference in PM BN. Likewise, a 10 percent decrease in mass dispersion with area and drag dispersions that are 10 percent high result in a 25 percent difference in PM BN from the nominal. This simplified BN sensitivity analysis demonstrates the impact of parameter variations on calculating time to recontact. It highlights the importance of obtaining a precise knowledge of the ISS BN and drag mitigations options that factor into time to recontact calculations.


To assess the impact of additional dispersions affecting the ISS-to-PM range after 10 days in more detail, relevant MC parameters were identified. The primary parameters with their considered nominal values, perturbations, and dispersions are provided in Table 6.2-6. The

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purpose of the MC analysis was to review the nominal values and dispersions to determine optimal PM jettison options.

Table 6.2-6. Suggested PM MC Parameters

Parameter	Nominal	Perturbation	Distribution	Rationale
Mass Properties				
PM Mass (kg)	424.49	417.23 to 429.03	Uniform	Randall Thurman email 12/15/13: "dimensions should be good to within 5-10 lbm... Weight/Mass 919 lbm dry; 935 lbm with ammonia when removed from system (only 16 lbm residual ammonia because loop system pressure is reduced prior to removal, causing the PM accumulator to mostly empty)."
PM Area: in (m ²)	4	1.10 to 2.28	Uniform	Randall Thurman email 12/15/13: "dimensions should be good to about +/- one inch...Envelope dimension (inches): 68.1 x 50.0 x 35.7"
PM BN (kg/m ²)		91.62 to 195.55		Not explicitly dispersed
Aerodynamics				
PM Drag Coefficient C _D	2	1.8:2	Uniform	If drag coefficient goes down, then need more area and less mass to keep PM BN > ISS BN
Jettison Velocity				
Velocity (m/s)	0.2	0.1 to 0.25	Uniform	0.05 m/s policy min is unrealistically low
Initial Attitude				
Posigrade cone angle (degrees)	0	-30:30	Uniform	30 degree half angle cone – Jettison Policy
Posigrade clock angle (degrees)	0	0:360	Uniform	
Retrograde cone angle (degrees)	0	-30:30	Uniform	30 degree half angle cone – Jettison Policy
Retrograde clock angle (degrees)	0	0:360	Uniform	
Gravity				
Gravity Model	8 × 8	40 × 40, 65 × 65, or 360 × 360		Truncated GEM-T1 Only single version used per MC
Atmosphere				
MET Model	250	±10 percent	Uniform	Solar Flux 10.7 cm setting; Nominal MC value set equal to the maximum, therefore, resulting densities are higher than the maximum expected for this analysis

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During the course of this study, the ISS Program removed the retrograde jettison from the EVA PM contingency options, so MC analysis was performed on only a subset of the dispersions. Selected MC results are shown in Figures 6.2-7 and 6.2-8. For these cases, the average ISS BN was 108.7 kg/m^2 . As mentioned, to ensure continuous positive separation for posigrade jettison, the PM BN value and difference compared to the ISS BN is important. The plot in the left of Figure 6.2-7 shows the ISS/PM range versus time for the 8001 simulated trajectories. Of those cases, 6780 show continuous positive separation for 10 days following jettison. Of the remaining 1221 posigrade trajectories, all but 136, or total of 1085 of the trajectories, showed recontact (i.e., within 500 m of the ISS) in the following 10 days. All of the recontact cases had PM BN less than 108.7 kg/m^2 . The BN of the posigrade trajectories were plotted as a function of pushoff velocity and days to recontact, as shown in the right side of Figure 6.2-7. Note that the maximum BN of the returning trajectories was 103.8 kg/m^2 , and establishes the lower limit on the PM BN necessary to ensure no recontact for a posigrade jettison.

More retrograde jettison cases showed ISS recontact in 10 days (i.e., almost 1400) compared to the 1085 cases in the posigrade jettison MC results. As mentioned, to ensure continuous positive separation for retrograde jettisons, the PM BN needs to be lower than the ISS BN. The cases that most often predict recontact is when the PM and ISS BNs are similar (i.e., within $\sim 5 \text{ kg/m}^2$), and there is a lower pushoff velocity. The retrograde jettison MC results are shown in Figure 6.2-8.

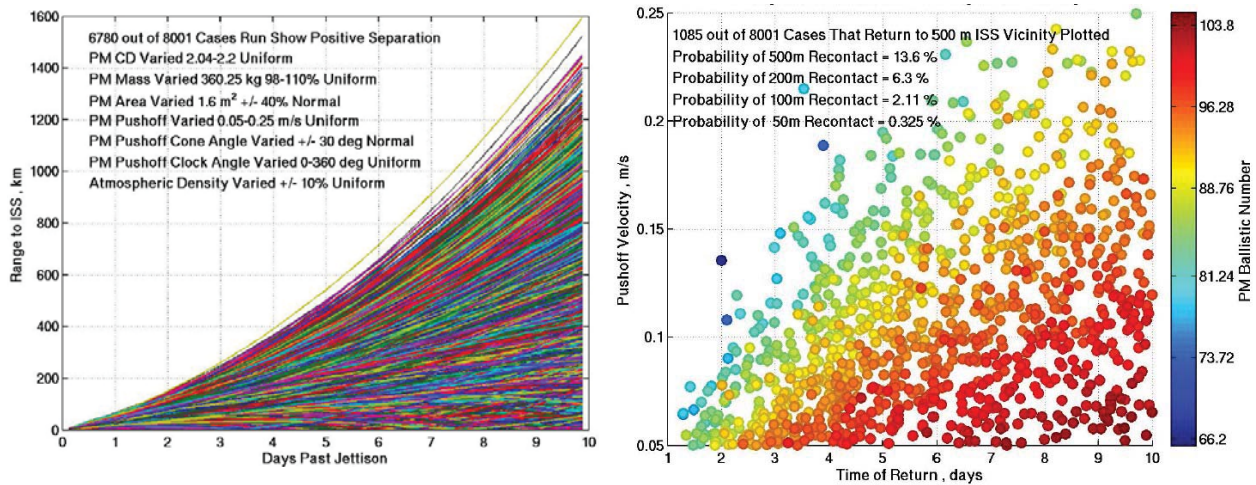


Figure 6.2-7. Posigrade MC Results

(Left) Plots of MC trajectories of posigrade jettison PM to ISS range over 10 days. (Right) BN and pushoff velocities of the cases that returned to within 500 m of the ISS in the same time period.

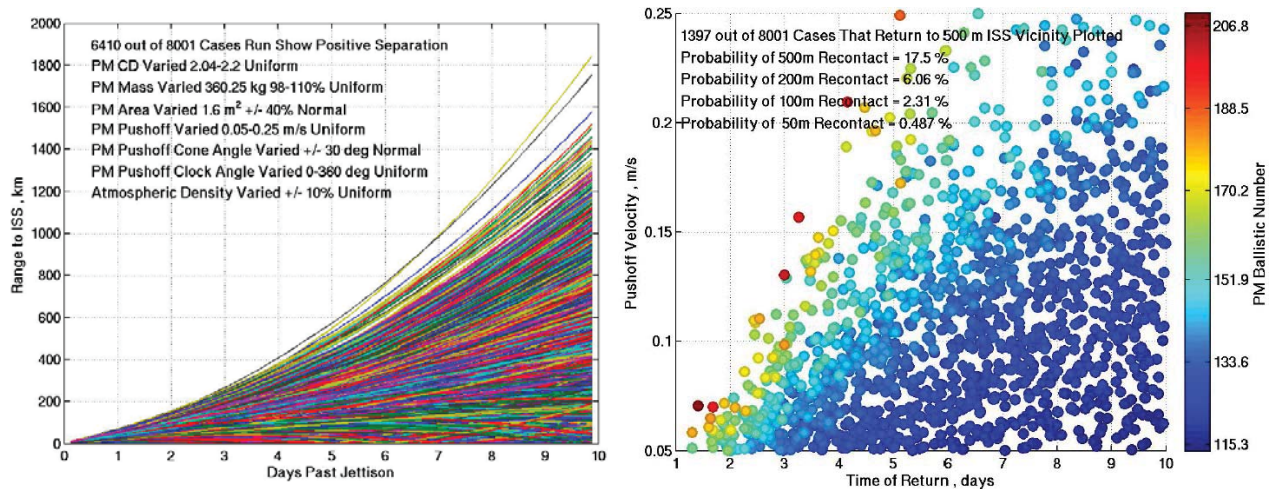


Figure 6.2-8. Retrograde MC Results

(Left) Plots of MC trajectories of retrograde jettison PM to ISS range over 10 days. (Right) BN and pushoff velocities of the recontact cases in the same time period.

For this particular jettison object, under the assumptions made for the MC analysis, the results indicate that to prevent recontact in 10 days, the PM must have a BN greater than 103.8 kg/m² for a posigrade jettison and a BN less than 115.3 kg/m² for a retrograde jettison.

6.2.3 Verification

To verify the analysis performed using the POST2 simulation, STK was used to recreate the nominal cases. The cases run in STK used the following assumptions:

- **BN**
 - ISS – 108.7 kg/m²
 - PM minimum – 80.9 kg/m²
 - PM average – 112.4 kg/m²
 - PM maximum – 155.1 kg/m²
- **Pushoff velocity for 0.05 and 0.20 m/s**
- **Posigrade pushoff attitude**
 - Pitch = 30 degrees, Yaw = -15 degrees
- **Retrograde pushoff attitude**
 - Pitch = -30 degrees, Yaw = 160 degrees

Cases run in STK were sample cases intended to verify the results of POST2, but not to recreate the entire POST2 analysis. These cases were run using Astrogator with Runge-Kutta-Fehlberg integration. The Earth gravitational parameter was set to 3.986004418e14 m³/s² and the initial state was set using the same vector used in POST2.

While some initial differences were seen between the STK and POST2, it was determined different pushoff locations were used for the retrograde jettison, and different notations were



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used for geomagnetic index. After the retrograde pushoff location was changed and the geomagnetic index notations were reconciled, the results agreed. Therefore the cases run using STK verify the results of the POST2 analysis. Figures 6.2-9 and 6.2-10 show the POST and STK results for the posigrade jettison with a 0.05 and 0.20 m/s pushoff velocities, respectively for the three PM BNs. Figures 6.2-11 and 6.2-12 show the simulation results for the retrograde jettison with a 0.05- and 0.2-m/s pushoff velocities, respectively.

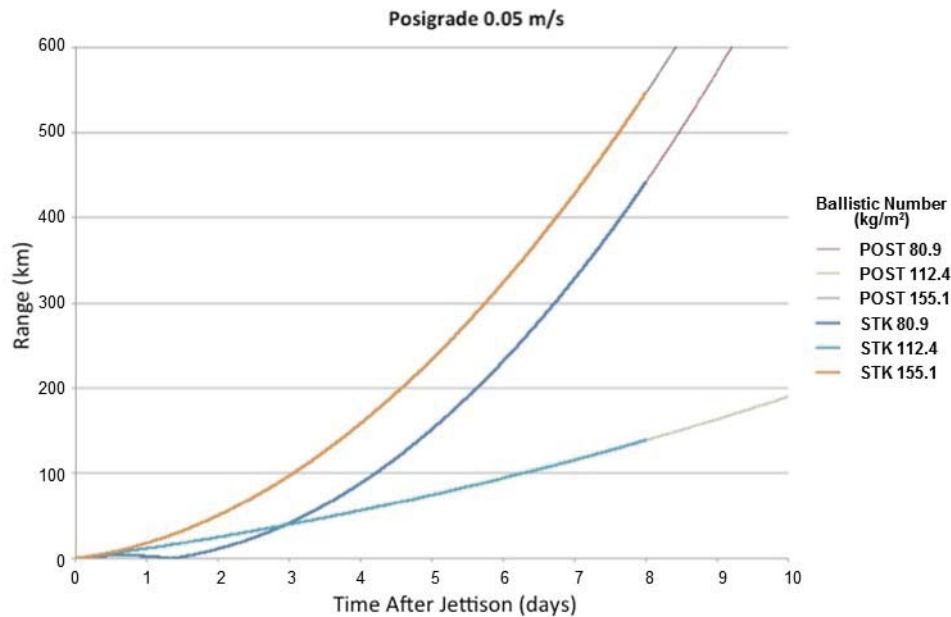


Figure 6.2-9. Comparison of STK and POST2 - Posigrade 0.05 m/s Jettison



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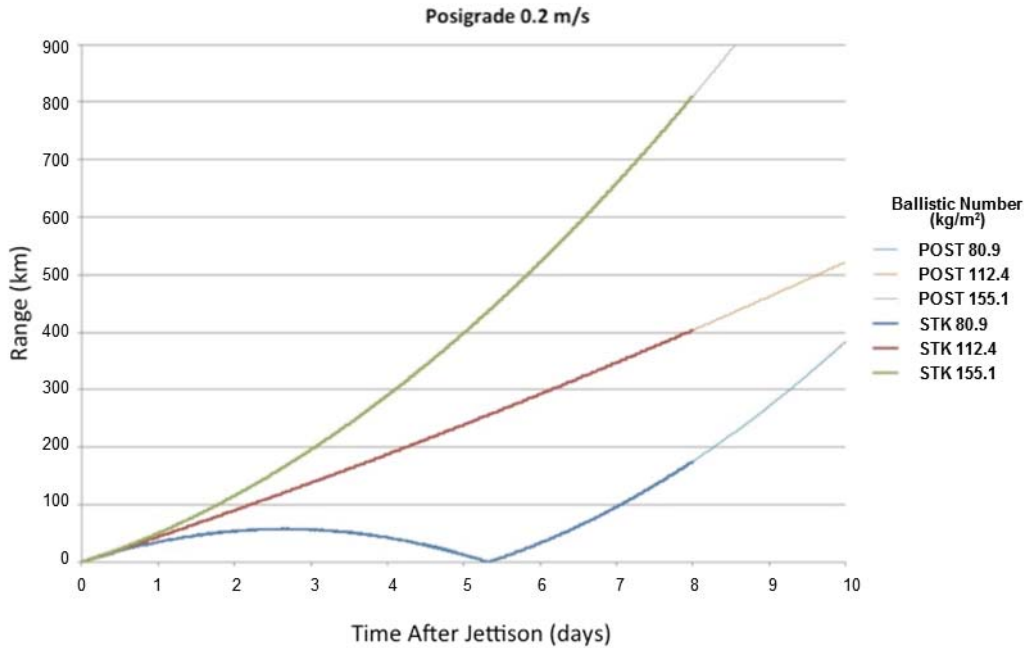


Figure 6.2-10. Comparison of STK and POST2 - Posigrade 0.2 m/s Jettison

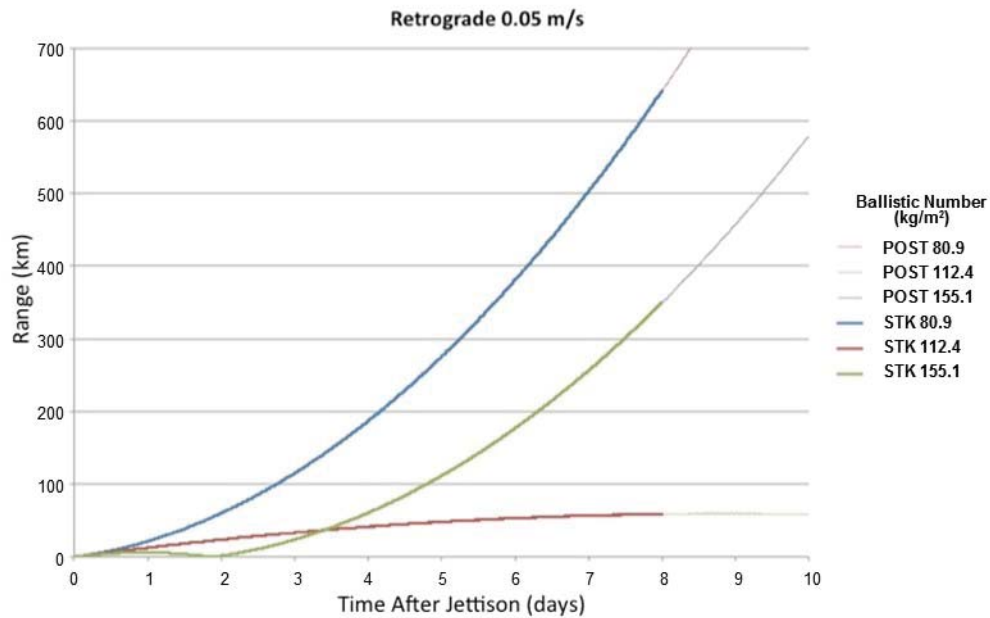



Figure 6.2-11. Comparison of STK and POST2 - Retrograde 0.05 m/s Jettison

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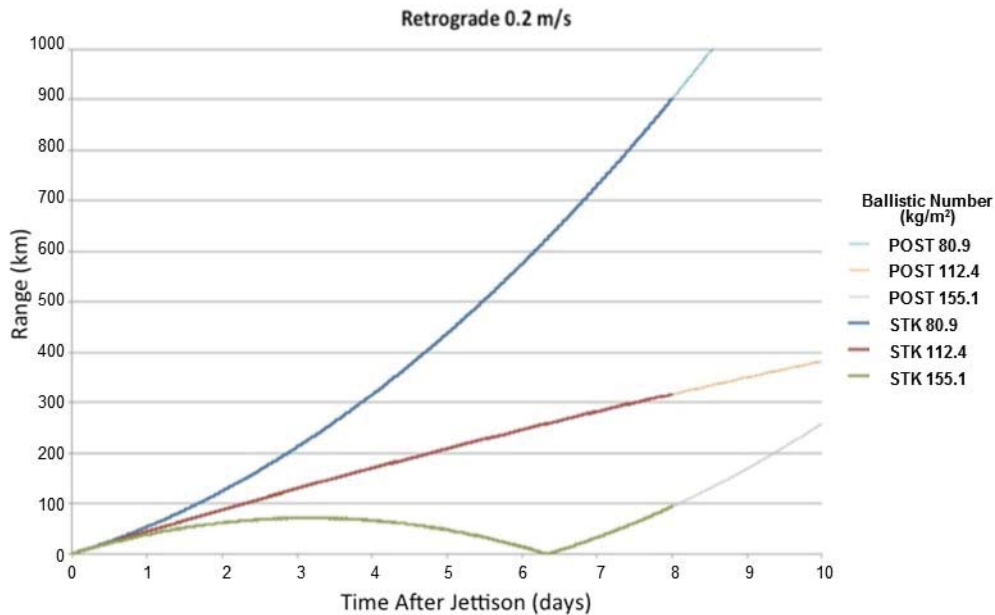



Figure 6.2-12. Comparison of STK and POST2 - Retrograde 0.2 m/s Jettison

6.2.4 Animation

EVE was used to assist in the visualization of the PM jettison analysis results generated using POST2. EVE enables a user to gain better understanding of the system by exploring data in time and space within the context of the mission, rather than only in plots and charts. EVE has an established history of supporting NASA missions, programs, and projects, including the ISS within the VIPER team’s engineering efforts and the mission operations team activities. In addition, many NASA missions supported by the EVE team have included data generated from POST2. The EVE and POST2 communities have been working to better facilitate data exchange between these two systems. Therefore, EVE was ideally situated to assist in the visualization of the PM jettison analysis.

The development of a mission within EVE requires the engineering data and the graphical models for incorporation into the scene. As a base, EVE provides the context of the solar system, including planetary and moon graphical models and SPICE-based trajectory data. Spacecraft are added to the scene using the orbital body reference frames as a basis. For the ISS graphical model, a representative configuration was used based on historical Revision Q ISS assembly complete models. The ISS was placed in a baseline orbit around Earth using a Kepler® propagation model (see Figure 6.2-13). The ISS was put in a nominal 0,0,0 attitude in an LVLH flight mode. The PM was added to the ISS as a child element, using a scaled sphere to model the PM size. All POST2 time-based PM position data was provided relative to the ISS DRF, which was output at 5-second intervals.

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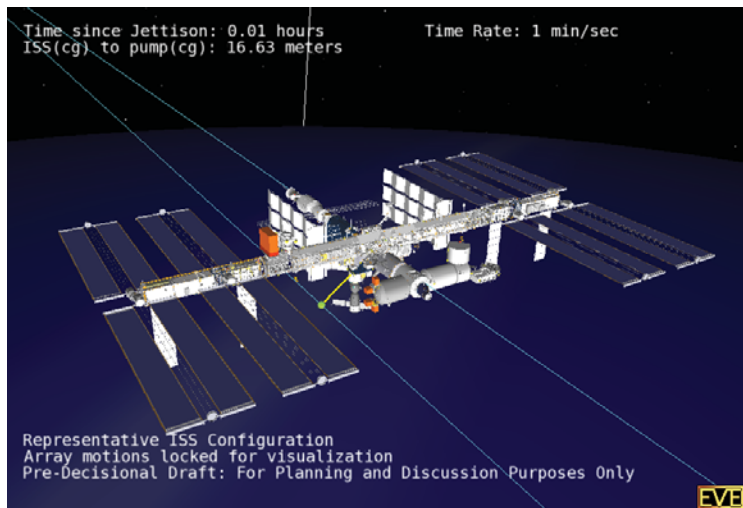
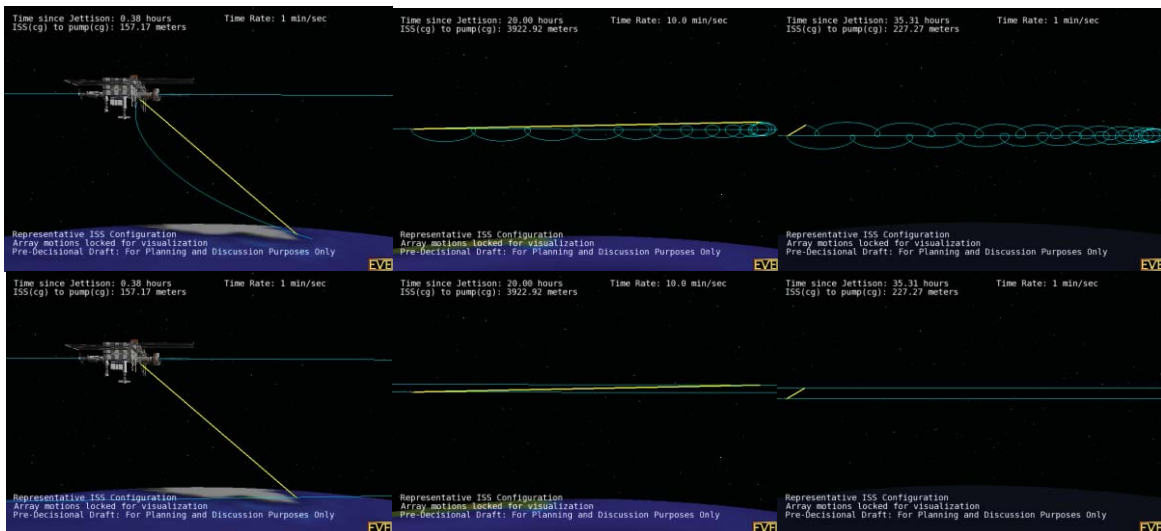



Figure 6.2-13. ISS Representation in EVE

Two different animations utilizing the same data set, but different perspectives, were created to help visualize the PM motion. Each animation showed the ISS, the PM motion, a line between the ISS and PM for reference, and a real-time calculation of the ISS-to-PM separation distance. This distance was displayed with the simulation time. The first animation displayed the PM relative to the ISS DRF, as provided by POST2. However, this perspective provided a non-intuitive display of the motion, showing the PM first moving away from the ISS, then returning towards the ISS in spiraling motion (see the top of Figure 6.2-14). The second animation displayed the same data in the Earth-centered inertial frame, which provided a more intuitive view of the PM orbit, and highlights the difference in orbit eccentricity between the PM and the ISS, as shown in the bottom of Figure 6.2-14.



**Figure 6.2-14. EVE Animations of the PM Motion Relative to ISS
(Top) ISS DRF; (Bottom) Earth-Centered Inertial Frame.**


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7.0 Findings, Observations, and NESC Recommendations

Several findings, observations, and NESC recommendations emerged as a result of the PM jettison option study. The determination to do a retrograde or posigrade jettison was not as straightforward as initially thought. The analysis showed that in addition to separation velocity, attitude, and the atmosphere conditions, the key to determining the time to recontact the ISS was highly dependent on the ISS and jettisoned object BNs.

7.1 Findings

- F-1.** A BN mismatch is needed between the PM and ISS to provide the best separation characteristics over subsequent orbits.
- For posigrade PM jettisons, the best separation characteristics are obtained when the PM has a BN higher than the ISS.
 - For retrograde PM jettisons, the best separation characteristics are obtained when the PM has a BN lower than the ISS.
- F-2.** The minimum BN mismatch is determined by the requirements on minimum time to recontact.
- F-3.** Considerations for achieving a desired BN mismatch:
- To increase the BN mismatch for posigrade jettison where the ISS BN is lower than jettison object, efforts to increase the drag area of the ISS for subsequent orbits is preferred.
 - To increase the BN mismatch for retrograde jettison, the ISS drag should be minimized on subsequent orbits, where the number of orbits and duration of drag mitigations efforts can be determined by analysis and operational considerations on a case-by-case basis.
 - Adding a drag device to the jettison object (e.g., an inflatable) can increase the BN mismatch.
 - Adding or removing mass from a jettison object (i.e., draining fluids, attaching extra mass, etc.) can increase BN mismatch.
- F-4.** The preferred jettison direction is retrograde because it results in continuous altitude degradation of the jettison object and may reduce the long-term likelihood of an ISS reboost to avoid collision.
- F-5.** Higher jettison velocity increases time to recontact for posigrade and retrograde jettisons.
- F-6.** The "stress" case atmosphere resulting in the shortest recontact times is different for posigrade and retrograde jettison options. For the case where the BN of the PM is higher than the BN of the ISS:
- The maximum atmosphere (e.g., highest density) results in the shortest recontact times for retrograde jettison.

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- The minimum atmosphere (e.g., lowest density) produces shortest recontact times for posigrade jettison.

7.2 Observations

- O-1.** Having the NESC version of the POST2 simulation, developed to support another NESC assessment, made it possible to complete the PM jettison analysis in a timely manner (i.e., initial analysis in 3 days).
- O-2.** The EVE animation capability was helpful in understanding and visualizing the simulation results.
- O-3.** Low jettison tip-off rates are preferred to allow the object to achieve a trim condition sooner thereby reducing it BN dispersions.

7.3 NESC Recommendations


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

- R-1.** Perform unique jettison analyses based in case specific assumptions. *(F-1 through F-6)*
- R-2.** Optimize the difference between ISS to jettison object BNs (e.g., change ISS drag, or change drag and/or mass of jettisoned object) to maximize recontact interval. *(F-1, F-2, F-3)*
- R-3.** Ensure jettison objects have a BN higher than ISS for posigrade jettison, or jettison objects have a BN lower than ISS for retrograde jettison. *(F-1)*
- R-4.** Utilize retrograde jettison when possible as it results in continuous altitude degradation of the jettison object and may reduce the long-term likelihood of ISS reboost to avoid recontact. *(F-4)*
- R-5.** Employ high jettison velocities and low tip-off rates. *(F-5, O-3)*
- R-6.** Consider developing attachable drag devices to jettison objects to guarantee positive ISS separation and object deorbit. *(F-3)*
- R-7.** Consider development methods and procedures to add or remove jettison object mass to optimize ISS to jettison object BN mismatch. *(F-3)*

8.0 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 relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation.

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Lessons Learned	Knowledge, understanding, or conclusive insight gained by experience that may benefit other current or future NASA programs and projects. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure.
Observation	A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Posigrade	In the same direction as the velocity vector of the ISS.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk.
Retrograde	In the opposite direction of the velocity vector of the ISS.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.
Supporting Narrative	A paragraph, or section, in an NESC final report that provides the detailed explanation of a succinctly worded finding or observation. For example, the logical deduction that led to a finding or observation; descriptions of assumptions, exceptions, clarifications, and boundary conditions. Avoid squeezing all of this information into a finding or observation

9.0 Acronyms List

BN	Ballistic Number
DRF	design reference frame
ETCS	External Thermal Control System
EV	Extravehicular
EVE	Exploration Visualization Environment
FSE	Flight Support Equipment
GEM	Goddard Earth Model

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GN&C	Guidance, Navigation, and Control
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Flight Center
LaRC	Langley Research Center
LVLH	Local Vertical, Local Horizontal
MC	Monte Carlo
MET	Marshall Engineering Thermal
MTSO	Management Technical Support Office
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
PM	Pump Module
POST2	Program to Optimize Simulated Trajectories
SARJ	Solar Array Rotary Joint
STK	Systems Tool Kit
TOPO	Trajectory Operations Officer
V&V	Validation and Verification
VIPER	Vehicle Integrated Performance Environments and Resources

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14. ABSTRACT On December 11, 2013, the International Space Station (ISS) experienced a failure of the External Thermal Control System (ETCS) Loop A Pump Module (PM). To minimize the number of extravehicular activities (EVA) required to replace the PM, jettisoning the faulty pump was evaluated. The NASA Engineering and Safety Center (NESC) received a request to support the International Space Station (ISS) Pump Module (PM) Jettison Assessment on December 16, 2013. The objective of this study was to independently evaluate the jettison options considered by the ISS Trajectory Operations Officer (TOPO) and to provide recommendations for safe jettison of the ETCS Loop A PM. This document contains the outcome of the NESC assessment.					
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