EXTERNAL CONTAMINATION INTEGRATION OF VISITING VEHICLES ON THE INTERNATIONAL SPACE STATION

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ABSTRACT

The International Space Station (ISS) is an on-orbit platform for science utilization in low Earth orbit. The induced contamination environment can impact performance, mission success, and science utilization. Cargo and crew vehicles visiting the ISS represent significant sources of contamination. The Space Environments Team of the ISS Program Office has developed visiting vehicle requirements and methodologies to address the increasingly complex challenge of integrating multiple visiting vehicles while maintaining overall ISS contamination control requirements. The external contamination control requirements are summarized and the integration and verification process is described along with required data deliverables. Contamination characterization data deliverables address vacuum-exposed materials, thrusters, vacuum venting, and particulate releases. Visiting vehicle external contamination analyses are conducted by the ISS Space Environments Team to certify compliance with external contamination control requirements. Unpressurized cargo contamination analyses are also performed to characterize induced contamination to payloads while in transit to ISS. Efforts to confirm the visiting vehicle contamination modeling and analysis process based on on-orbit data are discussed.

1. INTRODUCTION

The International Space Station (ISS) external contamination environment includes contributions from ISS elements, visiting vehicles, and external payloads. External contamination can impact performance, mission success, and science utilization. This induced environment is characterized by the Space Environments Team of the ISS Program Office in Houston, Texas, U.S.A.

Visiting vehicles induce multiple types of molecular contamination on ISS, such as materials outgassing and thruster plume-induced contamination (see Figure 1).

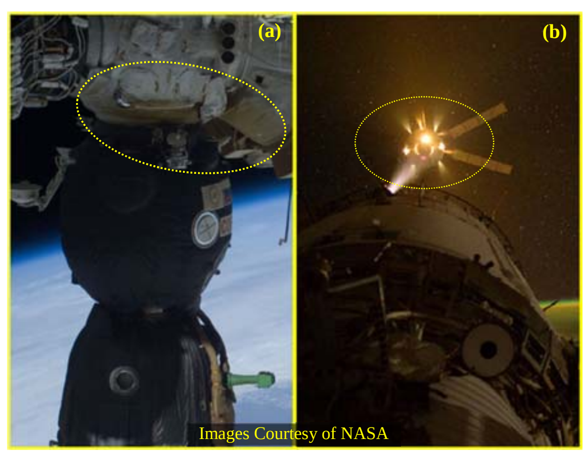

Figure 1. Visiting vehicle contamination sources
(a) Discoloration due to visiting vehicle materials outgassing
(b) Cargo Vehicle Thruster Plumes

The ISS is currently visited by commercial cargo vehicles as well as international partner spacecraft. There are also several commercial crew and cargo vehicles currently in development. Figure 2 shows example visiting vehicles mated to the various docking and berthing ports available on the U.S. Segment.

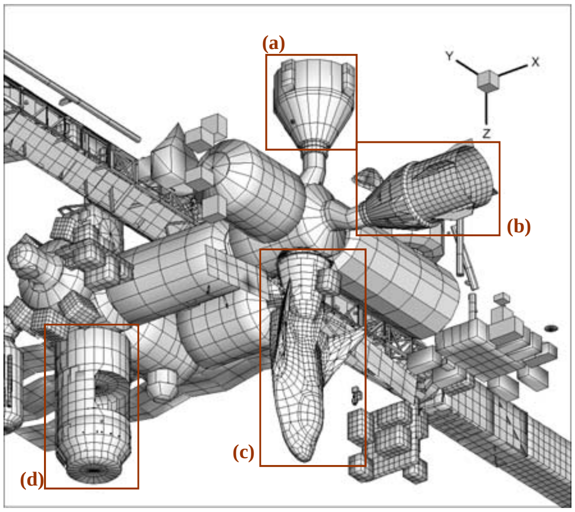

Figure 2. U.S. Segment docking and berthing ports
(a) Crew vehicle on Node 2 zenith docking port
(b) Crew vehicle on Node 2 forward docking port
(c) Cargo vehicle on Node 2 nadir berthing port
(d) Cargo vehicle on Node 1 nadir berthing port

As ISS program emphasis has shifted from assembly to science utilization, it is all the more critical to maintain ISS contamination control requirements. This is necessary to support continued ISS system performance as well as integration and operation of science payloads.[1,2] The Space Environments Team has developed visiting vehicle requirements and methodologies to address the increasingly complex challenge of integrating multiple visiting vehicles while maintaining overall ISS contamination control requirements.

2. VISITING VEHICLE CONTAMINATION OVERVIEW

During ISS assembly, the Space Shuttle Orbiter was a significant contamination source due to use of high outgassing materials in the thermal protection system. However, the shuttle missions were typically short (~ 2 weeks) and there were relatively few external ISS payloads to be affected compared to the current payload complement occupying U.S and international partner platforms.[2]

In the current ISS configuration, materials outgassing from visiting vehicles is a significant concern. This is especially true for reentry vehicles since thermal protection system materials can have high outgassing rates. Unlike the Orbiter, commercial visiting vehicles can utilize multiple docking or berthing locations and for much longer missions (from approximately one month up to six months in duration). All ISS visiting vehicles have new hardware each mission (in part or the whole vehicle), which means the decay in outgassing rate is not as significant compared to permanent ISS elements.

Another consideration with visiting vehicles is outgassing of materials located in interstitial volumes (i.e., internal areas that are not pressurized). Outgassing products from equipment located in interstitial volumes (e.g., avionics, cabling, propellant tanks) can be released at vent path openings. Discoloration due to materials outgassing has been observed on surfaces that are adjacent to interstitial volume openings (see Figure 3).

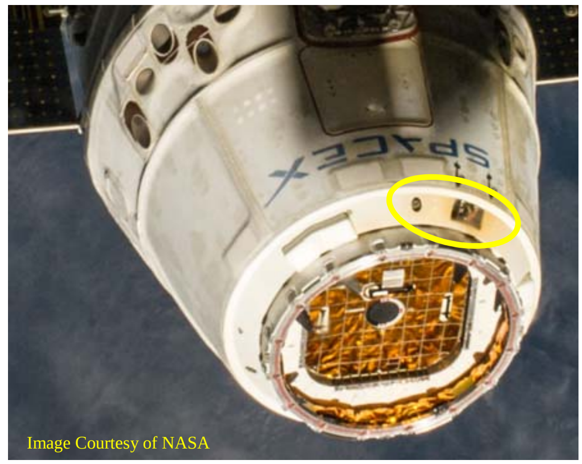

Figure 3. Discoloration near interstitial vent openings observed during Dragon cargo vehicle departure from ISS.

Visiting vehicle thruster firings during approach and departure proximity operations with ISS are another potential source of contamination. External ISS surfaces can also be mechanically damaged (eroded/pitted) when impacted by high velocity unburned liquid propellant drops present in thruster plumes. In the case of monopropellant thrusters, mechanical damage due to catalyst ejecta must also be considered. Optical surfaces and surfaces with thin coatings, such as windows, camera lenses, and solar cells, are of primary concern for erosion/pitting. Thruster plume-induced contamination and erosion/pitting have been observed on Space Shuttle flight experiments.[3,4]

Other potential visiting vehicle contamination sources include vacuum venting/leakage and particulates. Visiting vehicle-induced contamination to unpressurized cargo during transit to ISS due to materials outgassing, thruster plumes, or other sources is also an important consideration, since many external payloads utilize contamination-sensitive equipment/sensors. Figure 4 shows unpressurized cargo integrated with the Dragon cargo vehicle during ground processing and in flight (following stage separation).

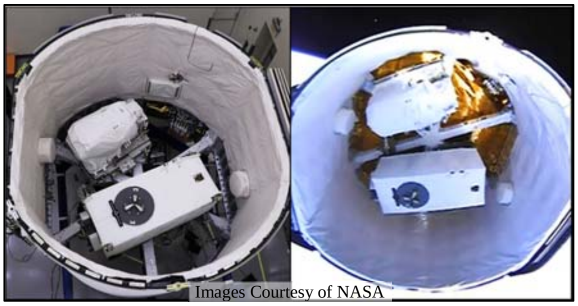

Figure 4. Unpressurized cargo integrated with Dragon cargo vehicle

In addition to being sources of contamination, visiting vehicles are also receivers of induced contamination. If visiting vehicles utilize contamination-sensitive equipment, they must be compatible with the ISS external contamination environment, including materials outgassing and thruster plumes. Visiting vehicle thruster firings during proximity operations may need to be assessed for pitting/erosion effects on other visiting vehicles. Given the number of vehicles and berthing/docking ports, vehicle-to-vehicle thruster plume impacts can involve a significant number of combinations. The Space Environments Team has performed special studies to evaluate vehicle-to-vehicle thruster plume-induced erosion concerns.[5]

Addressing these contamination issues to maintain a controlled contamination environment at ISS requires in-depth understanding of visiting vehicle hardware and high-fidelity contamination modelling and analyses. Early coordination with visiting vehicle providers on external contamination requirements and data deliveries is essential for early identification of potential issues and successful integration with ISS.

3. REQUIREMENTS

The ISS system level requirements are contained in the System Specification for the International Space Station (SSP 41000).[6] In turn, the system level specification calls on specific sections of the Space Station Contamination Control Requirements document, SSP 30426 (sections 3.4, 3.5 and 3.6).[7] Of special note, the system level requirements specify an induced contaminant deposition limit equivalent to 130 Å/year on contamination-sensitive surfaces from all ISS sources of contamination combined.

The system level contamination requirement must be met for performance (all hardware must perform within the specified system level environment) and for contaminant releases. Hence, the induced contamination contribution from a visiting vehicle, when combined with all other sources of contamination, must not lead to a violation of the system level requirement.

SSP 50808, which is the ISS to Commercial Orbital Transportation Services (COTS) Interface Requirements Document (IRD), identifies the applicable ISS requirements that commercial visiting vehicles must meet and the methods of verification.[8] External contamination requirements detailed in SSP 50808 were developed to ensure compatibility with the system level requirements:

- Section 3.3.1.3.6.B specifies cleanliness requirements for exterior (i.e., vacuum-exposed) surfaces of COTS vehicles to be maintained during ground processing. (Note: Cleanliness requirements are jointly addressed with the ISS Materials and Processes organization)
- Section 3.3.9.2 specifics the on-orbit quiescent and non-quiescent contamination environments that the visiting vehicle must operate in.
- Section 3.3.10.2.A limits materials outgassing-induced contamination/deposition from a cargo COTS vehicle to contamination-sensitive ISS surfaces to 2.5 Å/mission.
- Section 3.3.10.2.B limits thruster plume-induced contamination/deposition to contamination-sensitive ISS surfaces due to COTS vehicle approach and departure proximity operations to 2 Å/mission.
- Section 3.3.10.2.C prohibits COTS vehicle venting or release of chemically reactive substances that can degrade or damage ISS surfaces.
- Section 3.3.10.2.D limits materials outgassing-induced contamination/deposition from a crewed COTS vehicle to contamination-sensitive ISS surfaces to 15 Å/mission.
  (Note: The contamination requirement allocation was increased to 15 Å/mission for crewed vehicles to allow for longer mission durations compared to cargo vehicle missions.)
- Section 3.3.10.3 prohibits COTS vehicle venting or release of liquid water/waste during ISS proximity operations or while mated to ISS. However, venting of water vapor for thermal/humidity control is permitted.

The contamination allocations specified in 3.3.10.2 A and D were defined based on detailed system trade studies such that the contamination contribution from a visiting vehicle – when added with all other ISS contamination sources – would stay within the ISS system level contamination limit on all contamination-sensitive ISS surfaces. It is possible that some ISS contamination-sensitive surfaces could accept higher deposition levels from a visiting vehicle and still stay within the system level limit, depending on the other contamination sources affecting that surface. In this case, exceptions may be granted for a visiting vehicle to exceed the contamination allocation, provided that an integrated ISS system level analysis demonstrates no contamination issues. However, during development, visiting vehicle providers should make every effort to meet the SSP 50808 allocations, because ISS integrated analyses to evaluate margin for exceptions are not finalized until a few months prior to launch. Ultimately, the ISS Program strives to give visiting vehicles as much flexibility as possible while still controlling contamination levels to support system performance and science utilization.

JAXA's HTV (or H-II Transfer Vehicle) is not part of the Commercial Orbital Transportation Services program. However, the external contamination requirements captured in the HTV segment specification (SSP 50273) are very similar to those described above. Likewise, the external contamination requirements for JAXA's next generation cargo vehicle (HTV-X), captured in the ISS to HTV-X IRD (SSP 51070), are similar to those in the SSP 50808 COTS IRD.[9,10]

It should be noted that visiting vehicle-to-cargo/payload interfaces are addressed in a separate requirements document. The International Space Station Program Cargo Transport IRD (SSP 50833) identifies the requirements that COTS vehicle providers must meet for cargo transportation to and from the ISS.[11] This includes ground processing/cleanliness requirements that a visiting vehicle provider must maintain while processing ISS cargo. This document also includes a limit for visiting vehicle-induced contamination during transit to ISS (i.e., prior to payload installation) due to materials outgassing, thruster plumes, or other sources (e.g., pyrotechnics).

4. VERIFICATION DATA DELIVERABLES

Verifications of external contamination requirements are conducted via analysis. These analyses are performed by the ISS Space Environments Team since external contamination requirements are verified at the ISS system level in addition to the element level. The verification analysis addresses visiting vehicle-induced contamination to ISS systems, payloads, and other visiting vehicles.

Detailed characterization of contamination sources on the visiting vehicle and identification of contamination-sensitive surfaces are the responsibility of the visiting vehicle provider. The required contamination source characterization data must address vacuum-exposed materials (all non-metallic materials outside of a pressurized or hermetically sealed environment), thrusters, vacuum venting, and particulate releases.

The ISS Program coordinates with each visiting vehicle provider to capture data item deliverables in a joint integration, verification, and test plan document. Typical data item deliverables required for external contamination integration are summarized herein. Preliminary data deliveries are required approximately 1.5 to 2 years prior to launch (no later than Critical Design review) to allow for early resolution of contamination concerns. Final data deliveries are typically required approximately 6 months prior to launch for final analyses and verification purposes.

4.1 Materials Outgassing

All non-metallic vacuum-exposed materials are sources of molecular contamination. This includes all materials outside of a pressurized or hermetically sealed environment. The following data is required for all non-metallic vacuum-exposed materials (including interstitial materials):

- Material identification
- Location of application on vehicle
- Vacuum-exposed surface area
- Nominal operating temperature data
- Outgassing rate data from ASTM E1559 testing

Acceptability of a particular material application depends on several factors such as vacuum-exposed area, operating temperature, pre-processing (vacuum baking) conditions, location, and geometry of the application (line-of-sight to ISS sensitive surfaces). Geometric definition of the vehicle surface is required to support modeling and analysis (e.g., NASTRAN, CAD). Figures/cross-sections demonstrating material locations and layups may also be needed for complicated configurations.

The on-orbit thermal environment of a material is a critical input to contamination analyses. Condensable outgassing rates increase with the operating temperature of a material and this phenomenon typically has a non-linear behavior. Small increases in operating temperatures can produce significant increases in condensable outgassing rates if new species are released.

The required format for the definition of operating temperature data for visiting vehicle materials is one that specifies the percentage of time spent under 30°C, between 30° and 60°C, between 60°C and 100°C, and between 100°C and the maximum operating temperature. This type of definition removes excessive conservatism from the analysis when compared to an analysis using only maximum operating temperature data.

Solar beta conditions can be a significant factor in operating temperatures of thermal protection system materials and other gross acreage external materials that receive direct illumination. Thermal data corresponding to discrete solar beta cases may be required to characterize material outgassing impacts due to external material 'hot spots' at solar beta conditions for a given mission window.

Outgassing rate data from ASTM E1559 testing is used in the analysis. Testing for the ISS Program is based on Method B of the ASTM E1559 standard.[12] The minimum test duration is 144 hours. Four Thermoelectric (i.e., thermally-controlled) Quartz Crystal Microbalances (TQCMs) are used for condensable outgassing rate measurements. The TQCMs are held at 80K, -40°C, -10°C and +25°C. The selection of these temperatures was based on the operating temperatures of ISS contamination-sensitive surfaces which include active and passive thermal control system radiators, laser retro-reflectors, windows, sensors, and science payloads.

ASTM E1559 test sample configuration and preparation is critical to accurate characterization of an outgassing source. Preparation, application, and processing of samples should be to flight specification. Clean room gloves and cloths should be used during sample processing to avoid transfer of skin oils and other contaminates to the samples. Non-metallic materials (e.g., adhesives, stitching) that are not intended to be part of the test article should not be used to prepare or bind samples. Test samples should be configured as flight-like as possible, especially when used in a layup as with panels or surfaces with primers/coatings (i.e., to account for attenuation of the outgassing signal from substrates). Special consideration should be given to materials that are intended to be reused for multiple missions, especially if additional processing or coatings will be applied between missions.

Visiting vehicle providers often rely on ASTM E595 Total Mass Loss and Collected Volatile Condensable Materials data[13] to support material selection. Although ASTM E595 may be considered helpful as a screening test in determining whether a material will function in the space vacuum, one cannot assume that a passing material will be acceptable from an ISS external contamination perspective. ASTM E595 data does not characterize condensable outgassing rates and is not accepted in lieu of the specified ASTM E1559 test data.

Visiting vehicle material outgassing-induced contamination is calculated using an analytical model developed by the Space Environments Team. This model is based on physical models of molecular transport and is coded into Boeing's NASAN contamination computer tool. NASAN is an integrated computer model, utilizing NASTRAN 3-D geometric models, view factor calculations, and transport routines to analyze induced contamination on an ISS configuration, with results available in tabular or graphical formats.

To perform a materials outgassing calculation for a visiting vehicle, the compiled materials are matched to outgassing rate test data at corresponding on-orbit temperature estimates. A time decay scale factor is applied to outgassing rate source terms based on experimental data and diffusion theory.[14]

Visiting vehicle providers often do not have a sense of how materials being selected will perform in an integrated external contamination analysis. The ISS Program request for early delivery of preliminary materials and thermal data is typically at odds with the visiting vehicle provider's design process, since it must first be determined if materials meet functional requirements. Nevertheless, early coordination is critical to begin ASTM E1559 testing – which can be a long-lead effort spanning many months – and identify potential issues while there is still flexibility to adjust the design. The Space Environments Team performs preliminary outgassing analyses based on preliminary data deliveries to give providers feedback. Parametric outgassing studies have also been used to assist visiting vehicle providers in determining outgassing rate targets ahead of preliminary data and analyses.

4.2 Thruster Plume Contamination

Thruster plume contamination occurs in the liquid phase (i.e., unburned/partially burned propellant) in the plume. Liquid phase releases primarily occur during thruster start-up and shut-down.[15] Therefore, contamination analyses of visiting vehicle thruster firings involve characterization of thruster exhaust plumes as well as thruster firings (timing and duration) during proximity operations with ISS. The following is a typical list of required thruster parameters for chemical thrusters:

- Location
- Direction vector
- Propellant composition including trace components
- Propellant mass flow rate
- Thrust
- Specific Impulse (I_{sp})
- Nozzle length
- Nozzle exit radius
- Nozzle area ratio
- Minimum pulse width
- Thruster performance test data showing thrust/I_{sp} vs. pulse width.
- Reaction efficiency (i.e., estimated mass fraction of unburned propellant).
- Characterization of catalyst ejecta (mass, size, velocity, plume/particle dispersion model; i.e., for monopropellant thrusters).

Use of electric or other types of thrusters could require a more complicated modelling and analysis effort, if for instance the exhaust plume contains ionized constituents. In this case, additional characterization data may be required to evaluate sputtering effects and impacts to the ISS charging environment.

In addition to thruster characterization data, a database of thruster firing histories for visiting vehicle approach and departure proximity operations with ISS are required. Histories should include a timeline of thrusters fired (number of pulses and pulse width) with corresponding distance and orientation with respect to ISS, typically for a range of at least 200 meters. The database should contain a statistically significant set of simulated thruster firing histories for nominal approach and departure scenarios including dispersions for atmospheric conditions, controller performance, vehicle loading, thruster performance, etc. Thruster firing histories are also needed for addressing other effects (e.g., plume loads, plume heating, and controllability), so data requirements are coordinated across multiple disciplines and organizations within the ISS Program.

The Space Environments Team bipropellant thruster plume model is a semi-empirical model that uses flight experiment and chamber test data for contamination characterization.[15] The model describes the number density and velocity distribution of unburned fuel droplets (particles) in a thruster plume with respect to particle size and angle from plume centerline. The thruster plume particle sizes and respective velocities are based on a model developed by Hernandez Engineering that specifies unburned propellant droplets and limiting velocities.[16,17]

The thruster plume particle distribution is adapted for each visiting vehicle engine type depending on thrust, propellant mass flow rate, and nozzle length. The plume contamination and erosion models are coded into Boeing's NASAN contamination computer tool to analyse a given thruster's effect on an ISS configuration. Thruster firing histories are processed to simulate thruster firings and calculate thruster plume-induced contamination and erosion effects to ISS.

The Space Environments Team performs preliminary thruster plume contamination and erosion analyses based on preliminary data deliveries to give providers feedback. Preliminary analyses and early coordination are important for identifying any missing thruster data prior to engine qualification testing.

4.3 Vacuum Venting

Vacuum venting is a source of molecular contamination and can impact molecular column density. (Note: the ISS contamination control requirements specify molecular column densities of up to 1.0×10^{14} molecules/cm^2 for unobstructed lines-of-sight during quiescent periods[7]). The following data is required for all sources of vacuum venting (nominal and contingency use):

- Vent location
- Orientation
- Vent geometry/configuration
- Composition (including trace elements)
- Mass flow rate
- Operational frequency and duration
- Exit conditions (pressure, temperature, velocity)

Visiting vehicle propellant purges or other types of liquid venting can produce frozen particulates that can be a source of damage through direct contact or orbital recontact. Liquid phase releases that can damage ISS surfaces are prohibited by SSP 50808 requirements.

4.4 Particulates

Characterization data is required if a visiting vehicle will release particulates or other sources of contamination (e.g., pyrotechnics). Input data may include operational timelines, geometry, direction of releases, plume/exhaust composition, and plume/particle dispersion models. Use of external materials that degrade in the natural environment (i.e., due to atomic oxygen/solar ultraviolet radiation exposure) and subsequently release particulates would be a contamination concern for ISS.

4.5 Contamination-sensitive surfaces

A description of visiting vehicle contamination-sensitive surfaces, their location, orientation, and operating temperature data is required so that ISS induced contaminant accumulation may be tracked on these surfaces. If a visiting vehicle has surfaces that may be sensitive to thruster-induced pitting/erosion, material and coating information is also needed, since impact damage is material dependent. Special consideration should be given to any contamination-sensitive equipment that will be reused for multiple ISS missions.

5. UNPRESSURIZED CARGO INTEGRATION

Some ISS visiting vehicles are capable of transporting unpressurized (i.e., external) payloads/cargo. After the visiting vehicle arrives at ISS, these external cargo are robotically extracted from the carrier and installed on ISS. The Space Environments Team performs unpressurized cargo contamination integration analyses to characterize the contamination environment of payloads/cargo while in transit. The results are used to characterize the accumulation of contaminant levels on payload/cargo sensitive surfaces to support assessment of thermo-optical degradation of sensitive surfaces.

Materials outgassing-induced contamination during the period from visiting vehicle launch to payload installation on ISS can be a significant for unpressurized payloads. Material outgassing rates upon initial vacuum exposure have been observed to be much higher compared to rates even a few hours later (see Figure 5). In addition, visiting vehicles and unpressurized payloads may experience more extreme temperature gradients while in free-flight compared to the ISS thermal environment (depending on free-flight attitudes), which can result in elevated outgassing/deposition rates.

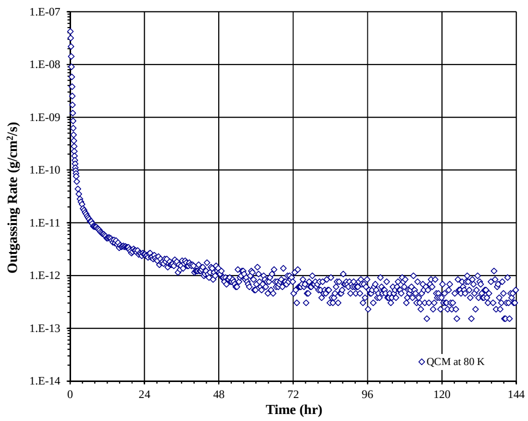

Figure 5. Example ASTM E1559 outgassing rate data.

The Space Environments Team performs a baseline materials outgassing analysis addressing visiting vehicle-induced contamination to generic payload envelopes. This baseline analysis is readily available to support contamination assessments far ahead of a given mission. A flight-specific analysis can also be performed upon request, including actual payload configurations and payload-to-payload contamination contributions. Such analyses depend on flight-specific integrated thermal analysis data for the visiting vehicle and payloads, which is typically not available until approximately 10 months prior to launch. Figure 6 depicts an example visiting vehicle cargo volume with a generic configuration (i.e., payload envelopes) versus a flight-specific configuration.

Unpressurized payloads/cargo may be exposed to other contamination sources while in transit to ISS, including visiting vehicle thruster plumes, upper stage thruster plumes, particulates due to pyrotechnics/fairing separation/stage separation, and venting/leaking from the visiting vehicle or upper stage. Visiting vehicle providers must deliver contamination characterization data to support the unpressurized cargo integration effort.

It should be noted that the visiting vehicle-induced contamination contribution prior to payload deployment is not included in the 130 Å/year ISS system level requirement. The Space Environments Team works in close coordination with visiting vehicle providers and payload developers to assess potential concerns for contamination-sensitive equipment/sensors. If a payload is highly sensitive to molecular or particulate contamination, protective measures (e.g., retractable covers) may be warranted.

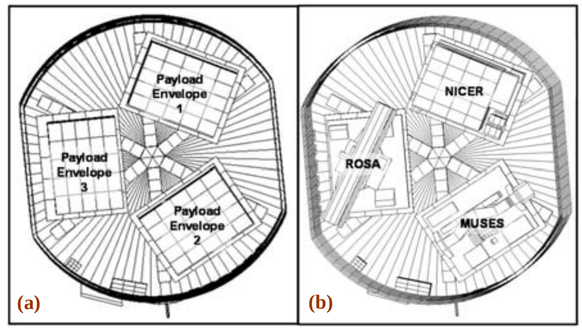

Figure 6. Example visiting vehicle cargo volume models used for materials outgassing analyses
(a) Generic payload envelopes for baseline analysis
(b) Actual payload geometric models for flight-specific analysis

6. PERFORMANCE VS. EXPECTATIONS

Prior to 2017, ISS had no active monitoring of the induced contamination environment. However, contaminant deposition measurements were made on returned hardware and compared to analysis predictions to assess performance against expectations.

The Materials International Space Station Experiment (MISSE) program provided one opportunity to compare contamination measurements with analysis predictions. MISSE has been deploying materials experiment trays on ISS since 2001. MISSE 2 was deployed for 4 years on ISS, during which it was exposed to multiple contamination sources including the Space Shuttle and Russian visiting vehicles. Two MISSE 2 gold mirror samples were analyzed with X-Ray Photoelectron Spectroscopy (XPS) to determine the composition and thickness of the contaminant layer. A comparison with analysis predictions showed excellent agreement in contaminant deposition values (within a factor of 1.6 of predictions).[2] The Micro-Particles Capturer and Space Environment Exposure Device (MPAC&SEED) flown by the Japanese Space Exploration Agency (JAXA) provided another opportunity to compare induced contamination predictions with measurements from flight hardware with similar findings.[2,18]

The Space Environments Team has also utilized on-orbit imagery of contamination to corroborate visiting vehicle contamination analysis predictions. For example, localized areas of discoloration were identified during a 2015 video survey of the ISS Node 2 nadir common berthing mechanism (CBM), which is used for visiting vehicle mating to ISS. The locations of discoloration were assessed to be associated with materials outgassing-induced contamination from Dragon vehicle interstitial vent openings. Although precision measurements of the deposition are not available, the predicted contamination levels in this area are consistent with the observed discoloration (see Figure 7). The observed darkening indicates a significant increase in the solar absorptance of the affected areas; fortunately, these areas are not considered to be contamination-sensitive and can receive levels of contamination in excess of the ISS specification of 130Å/year.

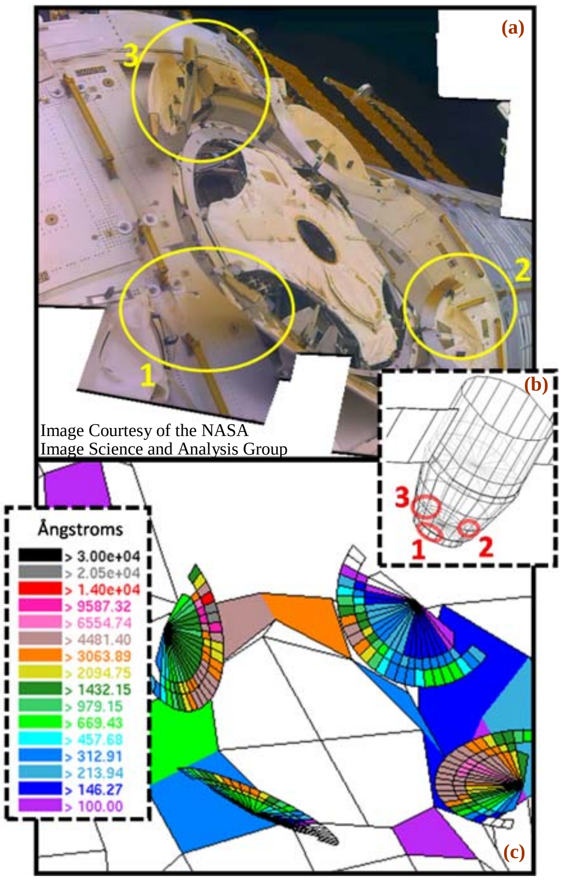

Figure 7. Discoloration of the Node 2 nadir CBM due to visiting vehicle materials outgassing
(a) Composite image of the Node 2 nadir CBM
(b) Dragon vehicle interstitial vent openings
(c) Dragon materials outgassing analysis results for the Node 2 nadir CBM

In February 2017, the NASA Langley Research Center (LaRC) Stratospheric Aerosol and Gas Experiment III (SAGE III) arrived at ISS. SAGE III measures solar radiation transmitted through the limb of the Earth's atmosphere to determine vertical profiles of various atmospheric constituents. It also utilizes eight Thermoelectric Quartz Crystal Microbalances (TQCMs) as part of a sophisticated contamination monitoring package.[19] With the SAGE III TQCM data, ISS now has active monitoring of the induced contamination environment. This new capability is being actively evaluated in collaboration with the NASA LaRC SAGE III Team and is expected to be examined at length in future publications. However, some initial observations that are pertinent to this work will be discussed in brief.

The SAGE III TQCMs have consistently measured higher than expected contamination levels while the Dragon cargo vehicle is present at ISS. Fortunately, the SAGE III payload has seen no significant degradation in any of the critical wavelengths for the SAGE III science project.[19] Nevertheless, the TQCM data indicates that there is a Dragon material outgassing source that needs to be identified and evaluated for impacts to other ISS payload sites and hardware. The Space Environments Team has been assigned responsibility to review and interpret the TQCM data and develop an understanding of the cause of the high contamination levels being detected. Figure 8 shows the SAGE III location on ISS.

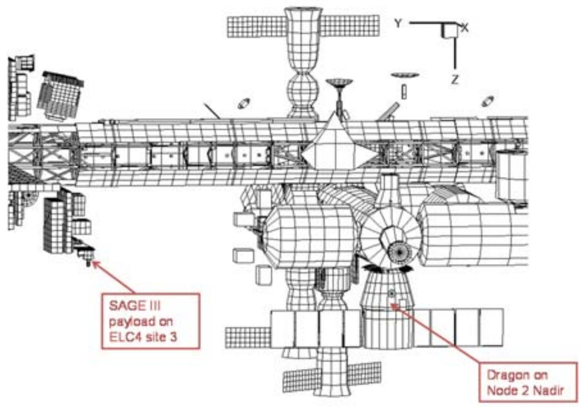

Figure 8. SAGE III and the Dragon cargo vehicle on ISS

QCMs consist of a pair of quartz crystals, one kept isolated from and one exposed to the environment. The difference in resonant frequency between the two crystals can then be correlated to the amount of molecular contaminant mass accreted on the exposed crystal. Figure 9 shows an example plot of SAGE III TQCM frequency data for a period covering three Dragon missions. The solar beta angle is also shown. The increase in QCM frequency is more pronounced with each mission, corresponding to increasingly negative solar beta peaks.

There are two factors tied to solar beta that could affect material outgassing rates:

1) Material heating/operating temperature
   Note: Space Environments has assessed via a parametric study that increasing material operating temperatures could account for the observed deposition.

2) Ultraviolet (UV) illumination
   Note: Ground testing and satellite data have shown that UV illumination can impact material optical properties and contaminant layers.[20]

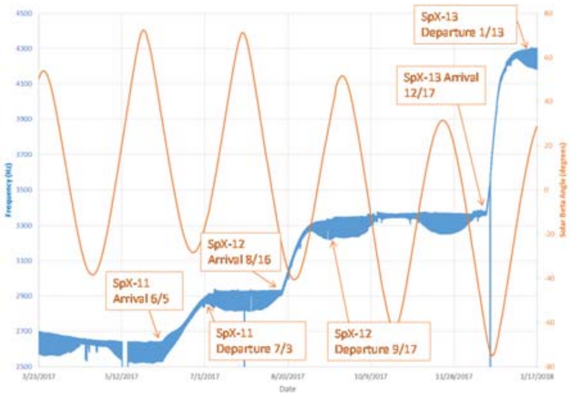

Figure 9. Example SAGE III QCM Frequency Data

The Space Environments Team has developed a resolution plan to address the possibility of elevated Dragon material operating temperatures and/or UV illumination affecting deposition. The resolution plan involves material outgassing rate testing at elevated temperatures and UV illumination/outgassing testing to evaluate effects on material optical properties and deposition. The resolution plan has been implemented by the ISS Program and is part of an ongoing activity to identify the primary material outgassing source of contamination and candidate corrective actions.

In parallel with this investigation, the Space Environments Team performed an external contamination assessment of Dragon materials outgassing-induced contamination to ISS hardware and payload sites using an empirical model based on SAGE III QCM measurements. The empirical analysis showed only 7 of the 56 U.S. hardware and active payload sites sensitive to induced contamination could experience exceedances of the system level requirement (130 Å/year). The empirical data is useful in supporting hardware impact assessments, payload placement studies, and other system integration activities.

One important and encouraging finding from the SAGE QCM data is that the rest of the ISS permanent modules and visiting vehicles have had a minimal contribution to contamination at the SAGE III site thus far. Nevertheless, this investigation has highlighted the importance of well-characterized vacuum-exposed materials and operating temperature data for visiting vehicles.

7. CONCLUSIONS

Visiting vehicles introduce complex induced contamination environment interactions that must be addressed to support continued ISS system performance as well as integration and operation of science payloads. The Space Environments Team has developed visiting vehicle requirements and methodologies to address the increasingly complex challenge of integrating multiple visiting vehicles while maintaining ISS contamination control requirements.

Visiting vehicle providers supply the required contamination source characterization data addressing vacuum-exposed materials (all non-metallic materials outside of a pressurized or hermetically sealed environment), thrusters, vacuum venting, and particulate releases. Visiting vehicle external contamination analyses are conducted by the ISS Space Environments Team to certify compliance with external contamination control requirements. The verification analyses address visiting vehicle-induced contamination to ISS systems, payloads, and other visiting vehicles. The Space Environments Team also performs unpressurized cargo contamination integration analyses to characterize the contamination environment of payloads/cargo while in transit. These integration and verification activities help ensure success of ISS as a platform for scientific experiments in low Earth orbit.

Historically, on-orbit contaminant deposition measurements made on returned hardware or observed in on-orbit imagery have been used in comparison to analysis predictions to confirm the contamination modeling and analysis process used for visiting vehicle integration. Recent capability of the SAGE III payload to actively monitor the ISS induced contamination environment shows the vast majority of ISS permanent modules and visiting vehicles as having minimal contributions to contamination. However, higher than expected contamination levels have been observed while the Dragon cargo vehicle is present at ISS. The Space Environments Team is actively investigating to identify the primary material outgassing source of contamination and candidate corrective actions. This investigation has highlighted the importance of well-characterized vacuum-exposed materials and operating temperature data for visiting vehicles.

Addressing visiting vehicle contamination issues to maintain a controlled contamination environment at ISS requires in-depth understanding of visiting vehicle hardware and high-fidelity contamination modelling/analyses. Early and close coordination with visiting vehicle providers on external contamination requirements and data deliveries is essential for early identification of potential issues and ultimately successful integration with ISS.

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