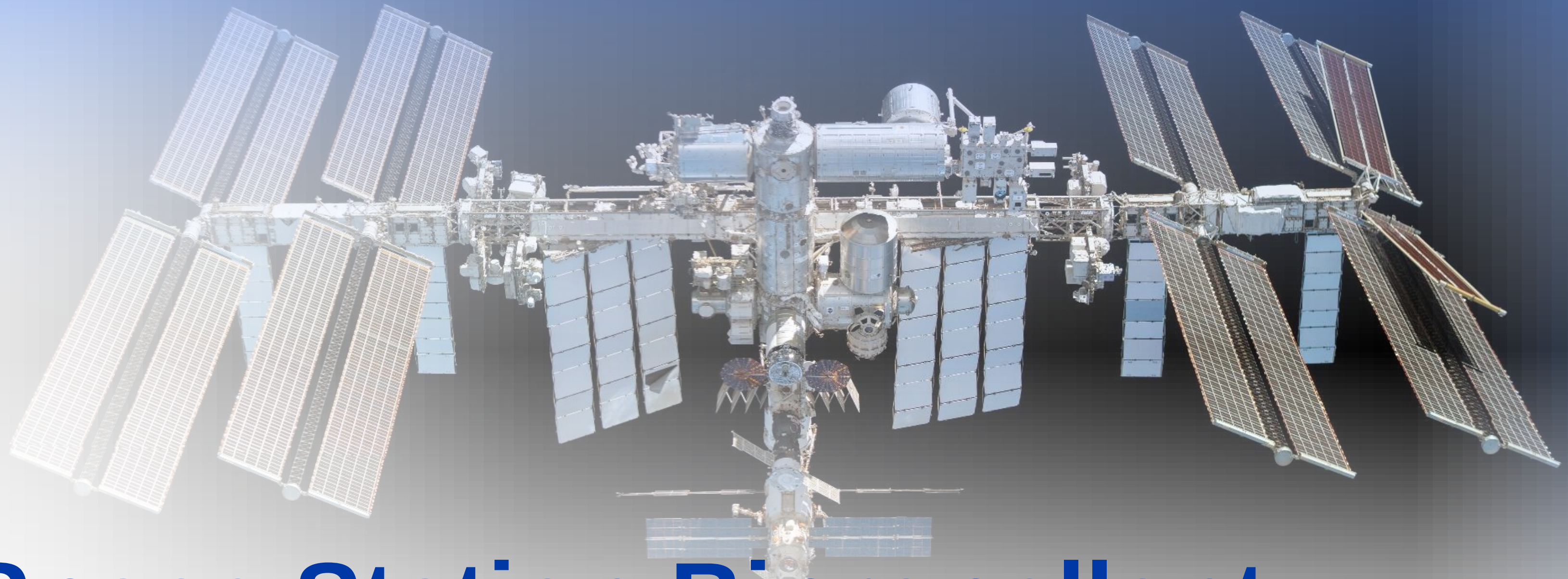

International Space Station Bipropellant Plume Contamination Model Update for Short Thruster Pulse Widths

15th International Symposium on Materials in the Space Environment (ISMSE)

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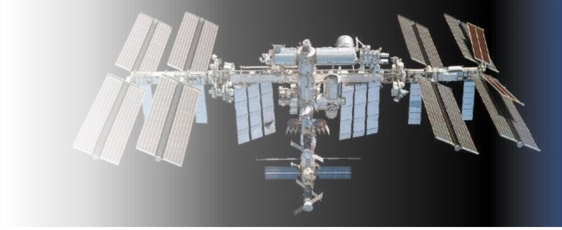
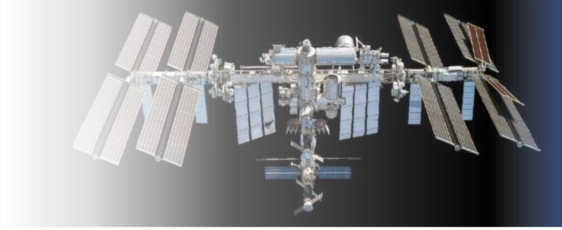


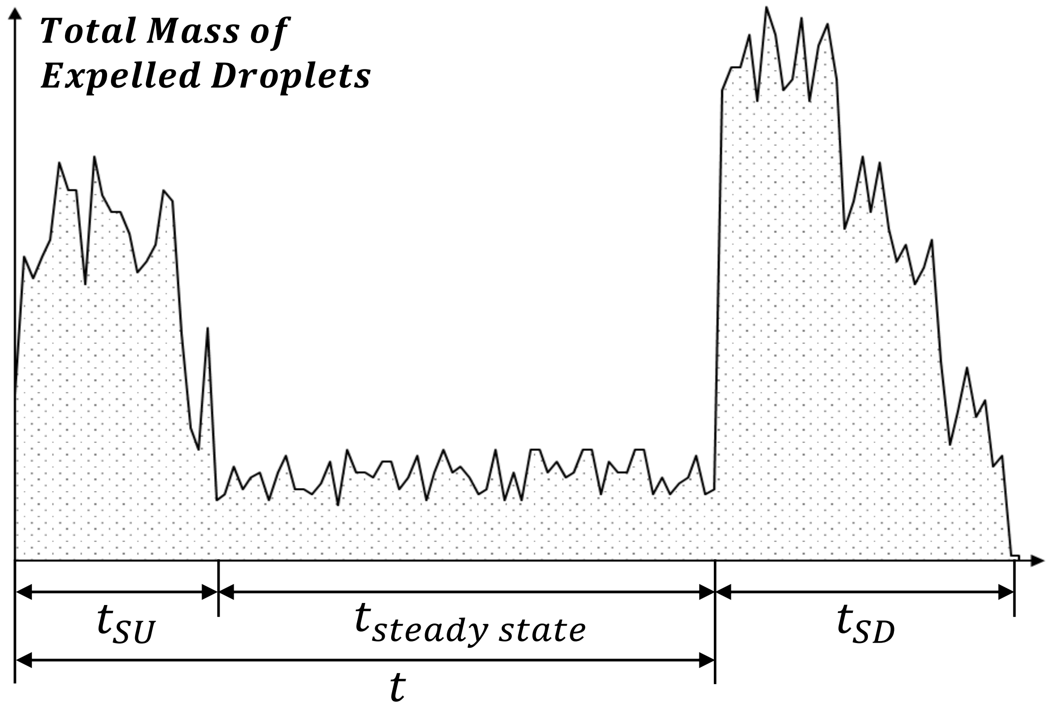
Purpose

- **Provide an update to the International Space Station (ISS) Bipropellant Plume Contamination Model developed by ISS Space Environments to account for short thruster pulse widths.**
- **Outline**
  - Introduction: Thruster Plume-Induced Contamination at ISS
  - Current ISS Bipropellant Plume Contamination Model
  - Updated ISS Bipropellant Plume Contamination Model
  - Implementation Approaches for Updated ISS Bipropellant Plume Contamination Model
  - Comments on Plume Contamination Model Selection for a New Thruster
  - Conclusion

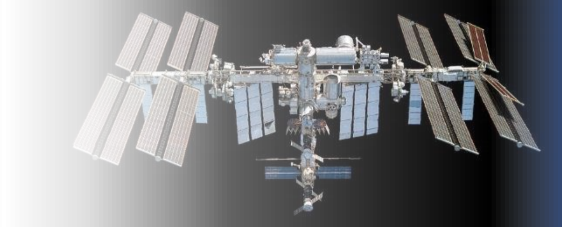


Introduction

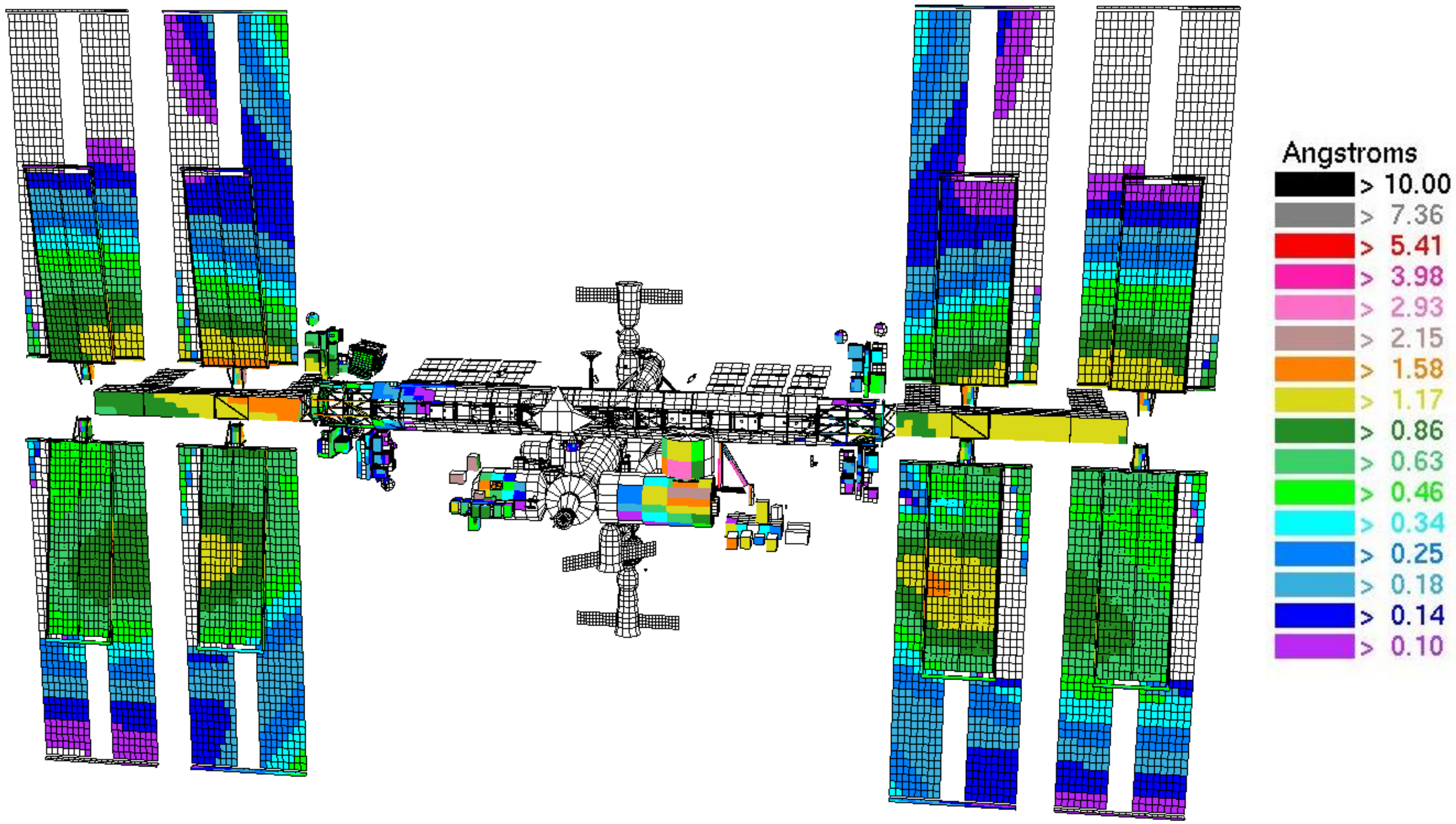
- **Thruster plume contamination occurs in the liquid phase (i.e., unburned or partially burned propellant in the plume), primarily during start-up and shut-down phases.**
  - Liquid phase releases during thruster steady state phase contribute a small amount relative to total contaminant mass released during thruster firing.



Thruster Plume-Induced Contamination at ISS



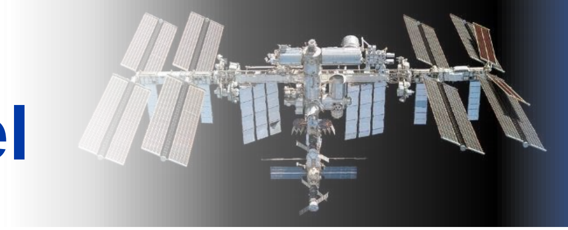
- **Thruster plume contamination impacts ISS operations in a variety of ways:**
  - Science payload operations
  - USOS radiator and solar array performance (the latter due to plume-induced erosion impacts)
  - Safety impacts due to toxic fuel-oxidizer reaction products (FORP) deposits on crew surfaces



Example thruster-plume induced contamination results from NASAN, Boeing Space Environments' external contamination analysis code.

It is vital for ISS operational planning to have an accurate model for predicting thruster plume-induced contamination

Current ISS Bipropellant Plume Contamination Model



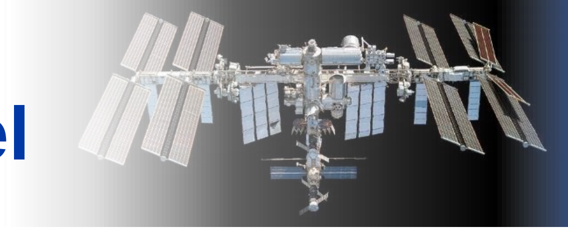
- **ISS Bipropellant Plume Contamination Model developed by ISS Space Environments is a semi-empirical model anchored in flight experiment data.**
  - Available flight experiment data from Plume Impingement Contamination (PIC) and Shuttle Plume Impingement Flight Experiment (SPIFEX) studies includes Orbiter 3870 N PRCS and Russian 130 N thrusters operating in pulse mode with 80 – 100 ms pulse widths.

$$\dot{m}_c(r,\theta) = f(T) \cdot f(r) \cdot f(\theta)$$

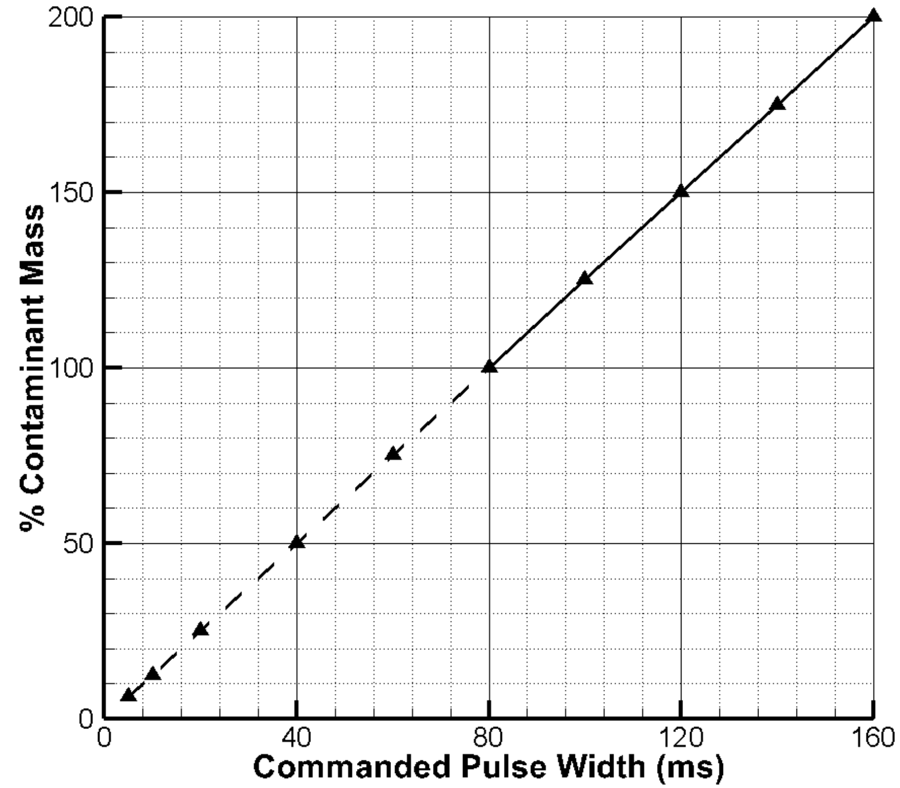
$$\dot{m}_c(r,\theta) = KT^{-\beta} \cdot \frac{\dot{M}_T}{R_{exit}^2} \cdot \left(\frac{r + l_{noz}}{R_{exit}}\right)^{-2} \cdot \left(2e^{-\frac{\theta}{\theta_0}} - e^{-2\frac{\theta}{\theta_0}}\right)$$

$\dot{m}_c$	Contaminant mass flux, g/cm^2/s	K	CR curve fit coefficient	r	Distance from nozzle exit plane, cm
		T	Engine thrust, N	l_{noz}	Nozzle length, cm
		β	Slope of CR curve fit	R_{exit}	Nozzle exit radius, cm
		$\dot{M}_T$	Propellant total mass flow, g/s	θ	Angle off plume centerline, deg
		R_{exit}	Nozzle exit radius, cm	θ_0	Angular dispersion coefficient, 5°

Current ISS Bipropellant Plume Contamination Model

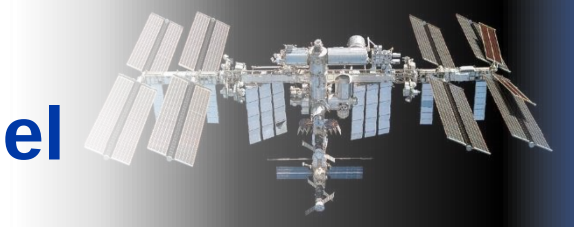


- Predicted contaminant mass scales linearly with commanded pulse width.
- The next generation of visiting vehicles arriving at ISS have thrusters capable of operating at pulse widths much shorter than 80 ms.
- Using the current ISS Bipropellant Plume Contamination Model at very short pulse widths can lead to severely under-predicting plume-induced contamination and erosion impacts during visiting vehicle proximity operations with ISS.



Current ISS Bipropellant Plume Contamination Model is not intended to be used for short thruster pulse widths.

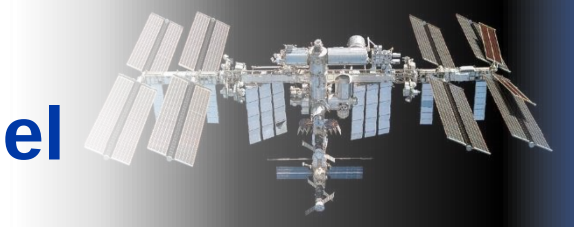
Updated ISS Bipropellant Plume Contamination Model



- ISS Space Environments has added a functional dependency on pulse width to the existing ISS Bipropellant Plume Contamination Model.
- The non-dimensional scale factor f(pw) would ensure a full start-up and shut-down cycle is modeled for each thruster firing.

$$\dot{m}_c(r,\theta) = \boxed{f(T)} \cdot \boxed{f(r)} \cdot \boxed{f(\theta)} \cdot \boxed{f(pw)}$$

Updated ISS Bipropellant Plume Contamination Model



- **Value of f(pw) is dependent on commanded pulse width, t, thruster start-up time, t_{SU}, and thruster shut-down time, t_{SD}. The reference on-time, t', is interpreted as the thruster on-time required to model an entire start-up plus shut-down sequence.**
  - Factor of 2 is empirically derived from Orbiter PRCS total start-up and shut-down time of 40 ms compared to minimum pulse width of 80 ms used.
  - If total thruster start-up and shut-down time is not available (t_{SU} + t_{SD}), Orbiter PRCS total start-up and shut-down time of 40 ms will be used as default.

$$f(pw) = \frac{t'}{t}$$

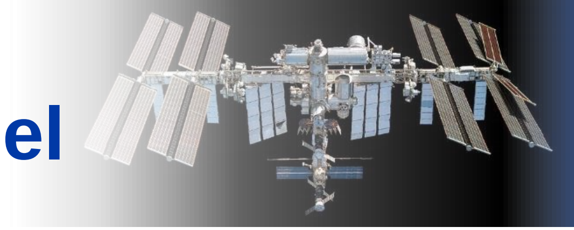
where t' is defined as:

$$t' = \begin{cases} 2 \cdot (t_{SU} + t_{SD}) & if\ t < 2 \cdot (t_{SU} + t_{SD}) \\ t & if\ \ t \geq 2 \cdot (t_{SU} + t_{SD}) \end{cases}$$

t_{SU}	Thruster start-up time, s
t_{SD}	Thruster shut-down time, s
t	Commanded pulse width, s

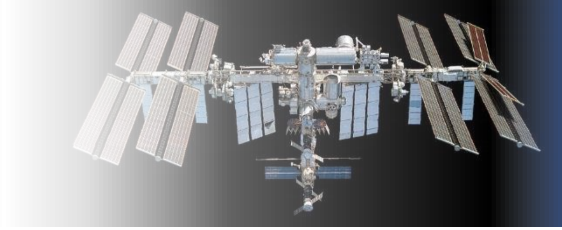
Updated ISS Bipropellant Plume Contamination Model ensures a full start-up and shut-down cycle is modeled for each thruster firing

Updated ISS Bipropellant Plume Contamination Model



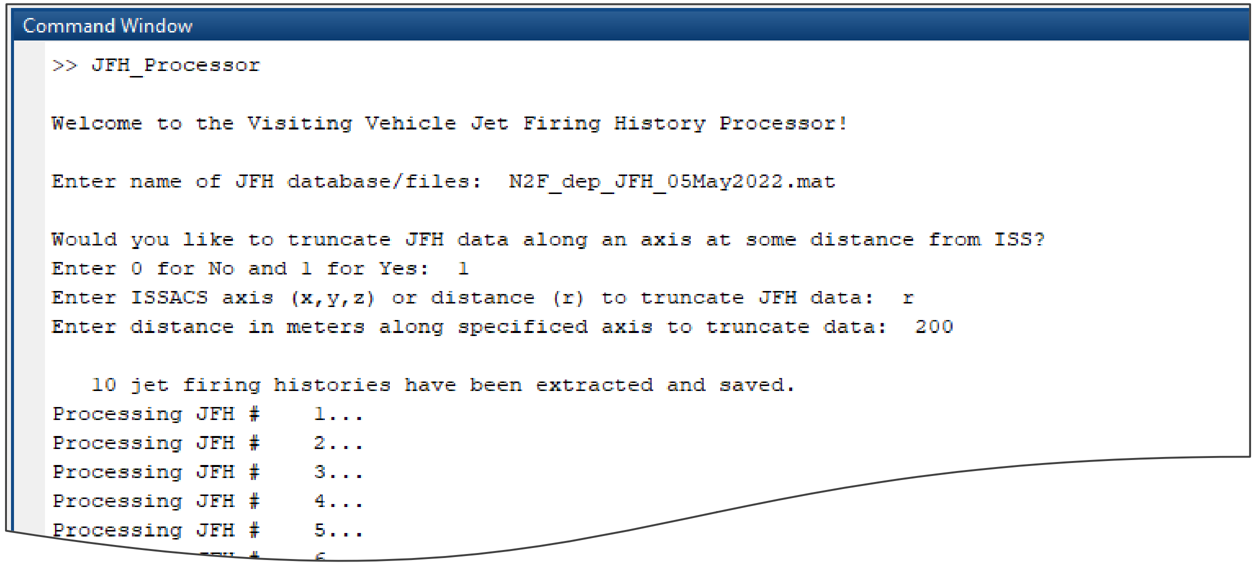
- **Practically, when thruster start-up and shut-down times are not available, the updated ISS Bipropellant Plume Contamination Model has the effect of forcing all commanded thruster on-times less than 80 ms to be equal to 80 ms.**

	Example 1			Example 2		
Commanded On-Time (ms), t	**Start-up / Shut-down time (ms), $t_{SU} + t_{SD}$**	**$f(pw)$**	**Reference On-Time (ms), t'**	**Start-up / Shut-down time (ms), $t_{SU} + t_{SD}$**	**$f(pw)$**	**Reference On-Time (ms), t'**
5	40	16	80	20	8	40
10	40	8	80	20	4	40
20	40	4	80	20	2	40
40	40	2	80	20	1	40
60	40	1.33	80	20	1	60
80	40	1	80	20	1	80
100	40	1	100	20	1	100
150	40	1	150	20	1	150



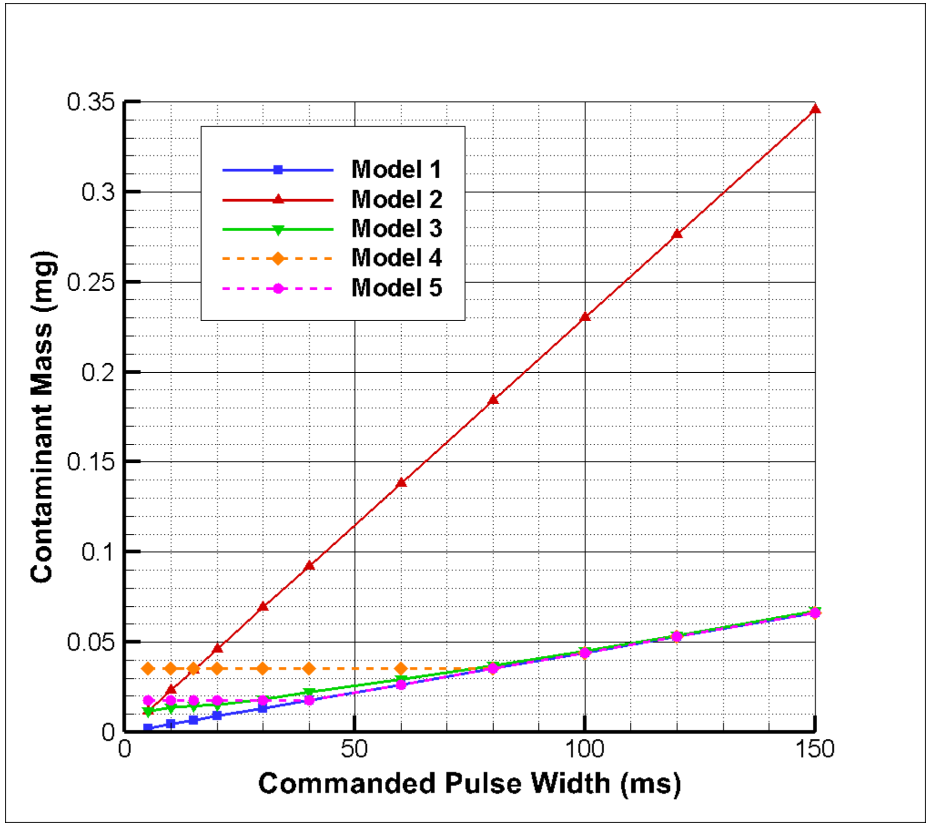
Implementation Approaches

- **Short-term and long-term options exist for implementing the updated ISS Bipropellant Plume Contamination Model into the existing ISS Space Environments' plume contamination analysis process.**
  - **Short-term:** Modify vehicle-specific jet firing history data pre-processers to replace commanded thruster on-times with reference on-times in generic-format jet firing history files readable by NASAN, the Space Environments' external contamination analysis code.
  - **Long-term:** Update NASAN to require user to enter thruster start-up and shut-down times or select the Orbiter PRCS thruster total start-up and shut-down time as default.



Selecting a Thruster Plume Contamination Model

- **Developing the plume contamination model for a specific thruster using the current or updated ISS Bipropellant Plume Contamination Model must be done in consideration of all available thruster performance data.**

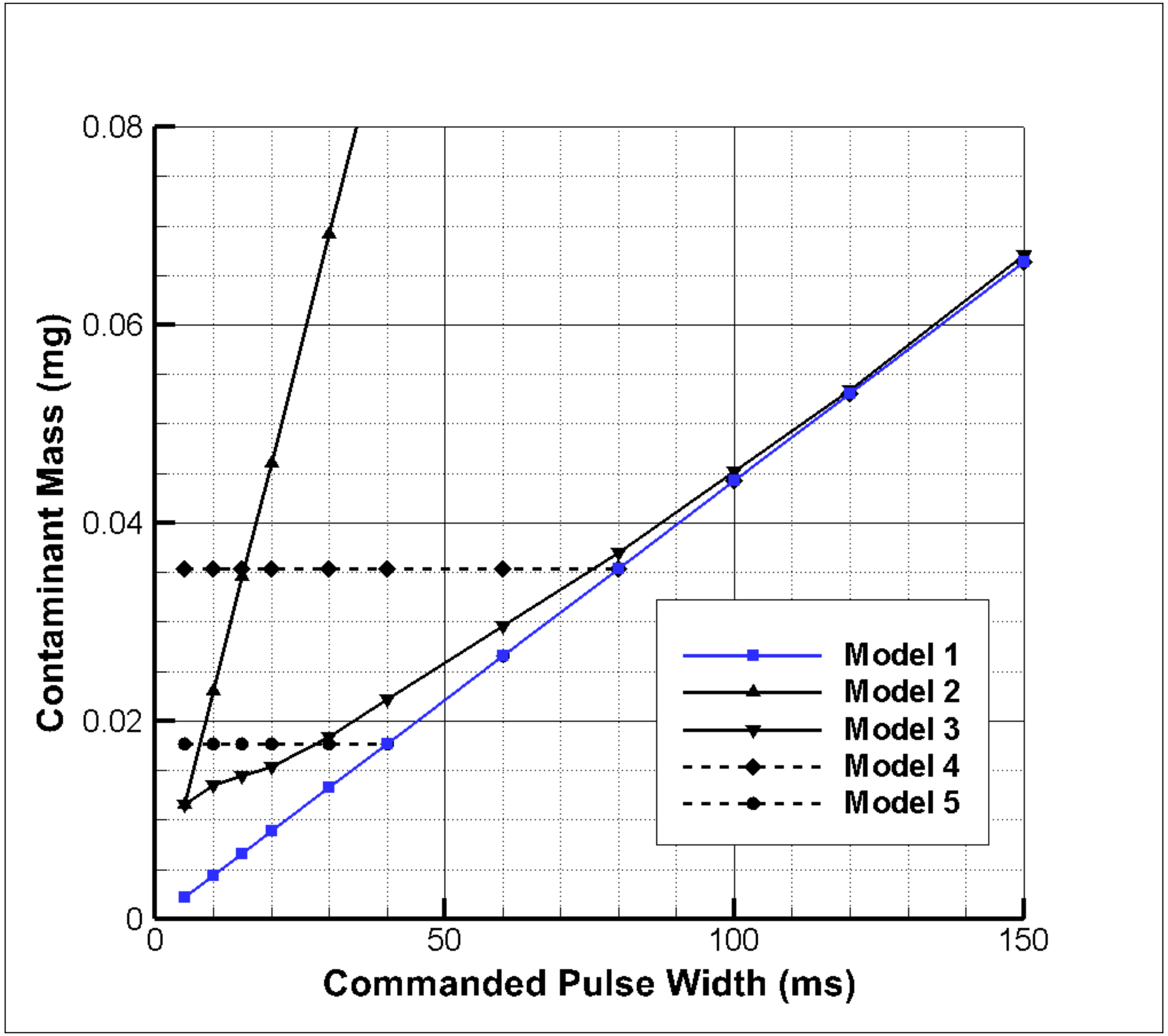


- **Following examples demonstrate the advantages and disadvantages of five potential plume contamination models for a small thruster.**
  - Thrust: 10 lbf (44.48 N)
  - Steady State I_{sp}: 280 s
  - I_{sp} vs. Pulse Width data beginning at 5 ms
  - Nozzle Length: 20 cm
  - Contaminant mass calculated on 1 m^2 receiver surface 5 m from thruster on plume centerline

Note: All thruster parameters are manufactured for demonstration purposes and do not represent thrusters on existing ISS visiting vehicles.

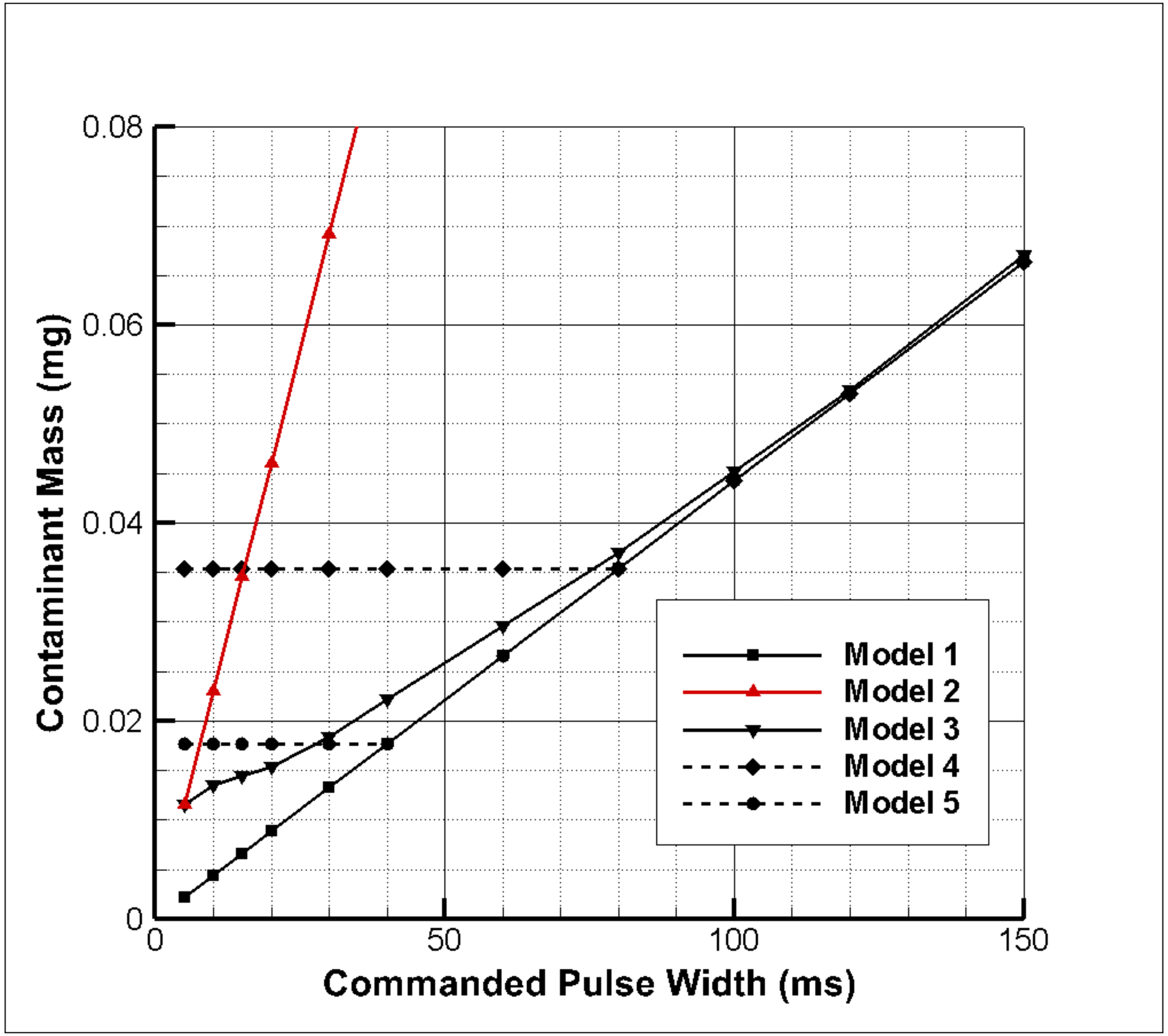
Selecting a Thruster Plume Contamination Model

- **Model 1: <u>Current</u> ISS Bipropellant Plume Contamination Model using steady state thruster parameters**
  - Model likely under-predicts contaminant mass released at short pulse widths

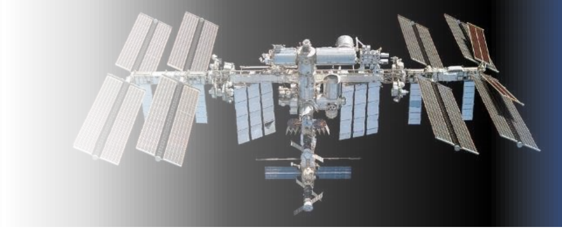


Selecting a Thruster Plume Contamination Model

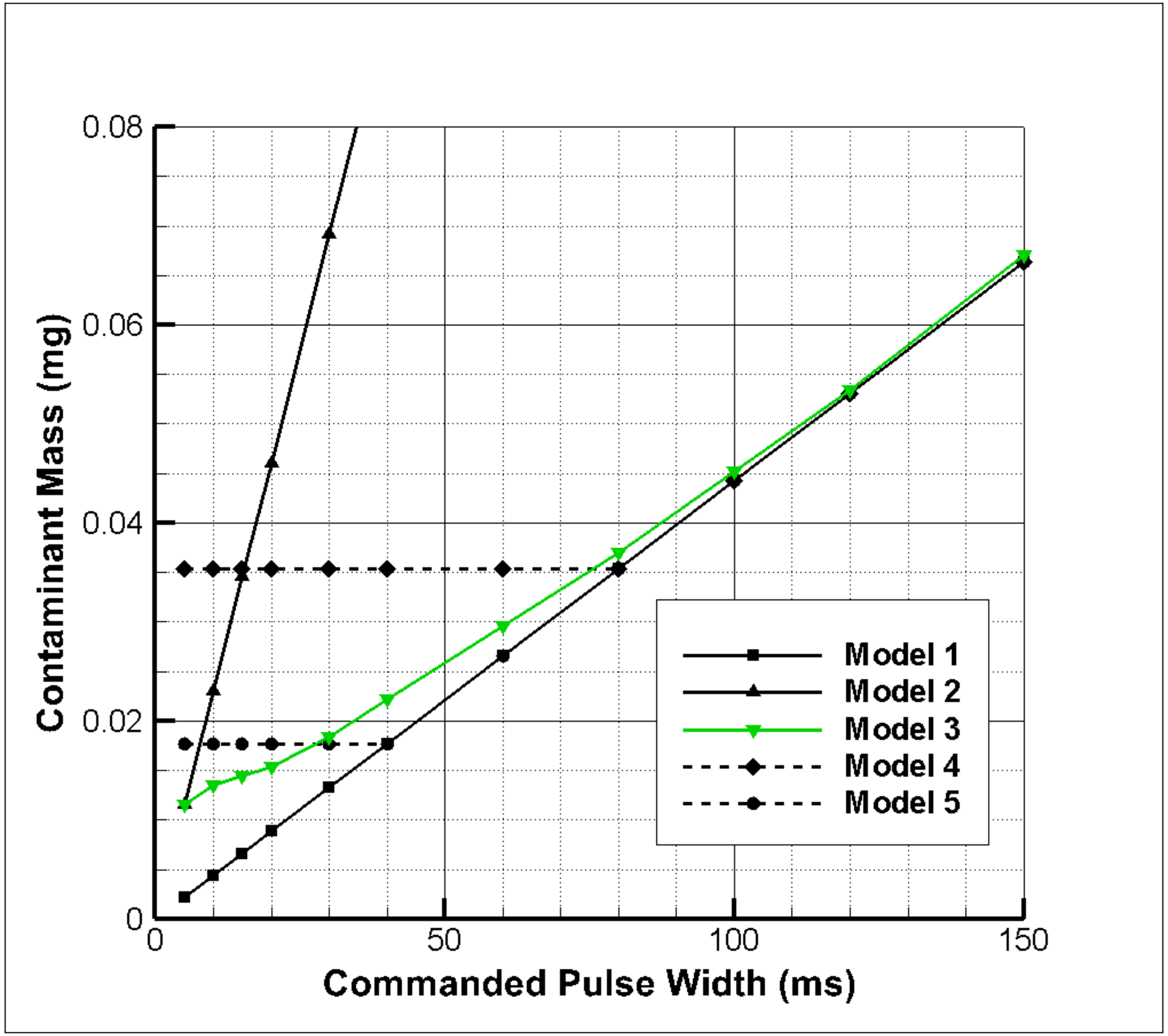
- **Model 2: <u>Current</u> ISS Bipropellant Plume Contamination Model using thruster parameters at minimum pulse widths**
  - This model approach has been used for visiting vehicle thrusters with minimum pulse widths of 60 ms.
  - When pulse mode data at much shorter minimum pulse widths is used (5-10 ms), model likely significantly over-predicts contaminant mass released at longer pulse widths



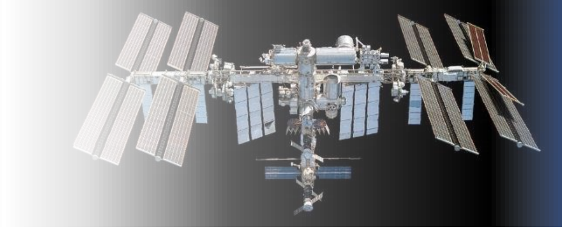
Selecting a Thruster Plume Contamination Model



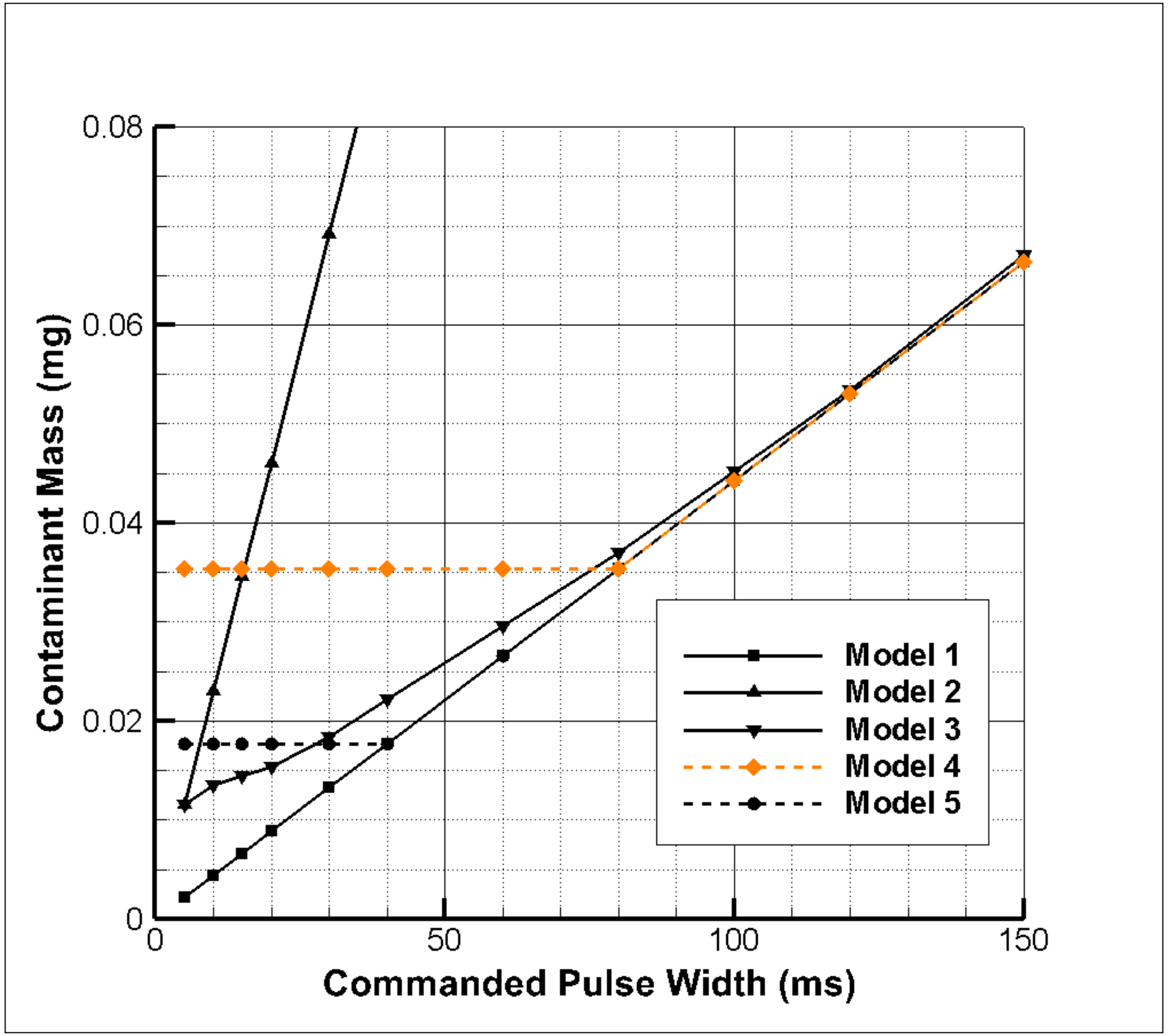
- **Model 3: <u>Current</u> ISS Bipropellant Plume Contamination Model using specific impulse (I_{sp}) versus pulse width data**
  - A step function plume contamination model can be designed but it is difficult to obtain reliable pulse mode data from ground based testing.



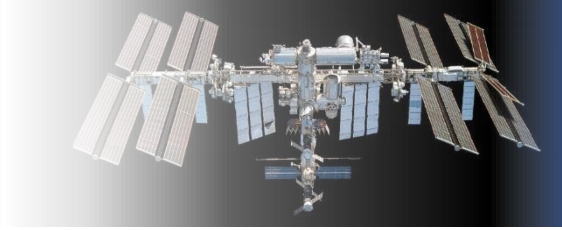
Selecting a Thruster Plume Contamination Model



- **Model 4: <u>Updated</u> ISS Bipropellant Plume Contamination Model assuming default total start-up and shut-down time of 40 ms.**
  - Steady state thruster parameters, not pulse mode parameters, should continue to be used.
  - Model ensures a full start-up and shut-down cycle is modeled for each thruster firing, based on existing flight experiment data.

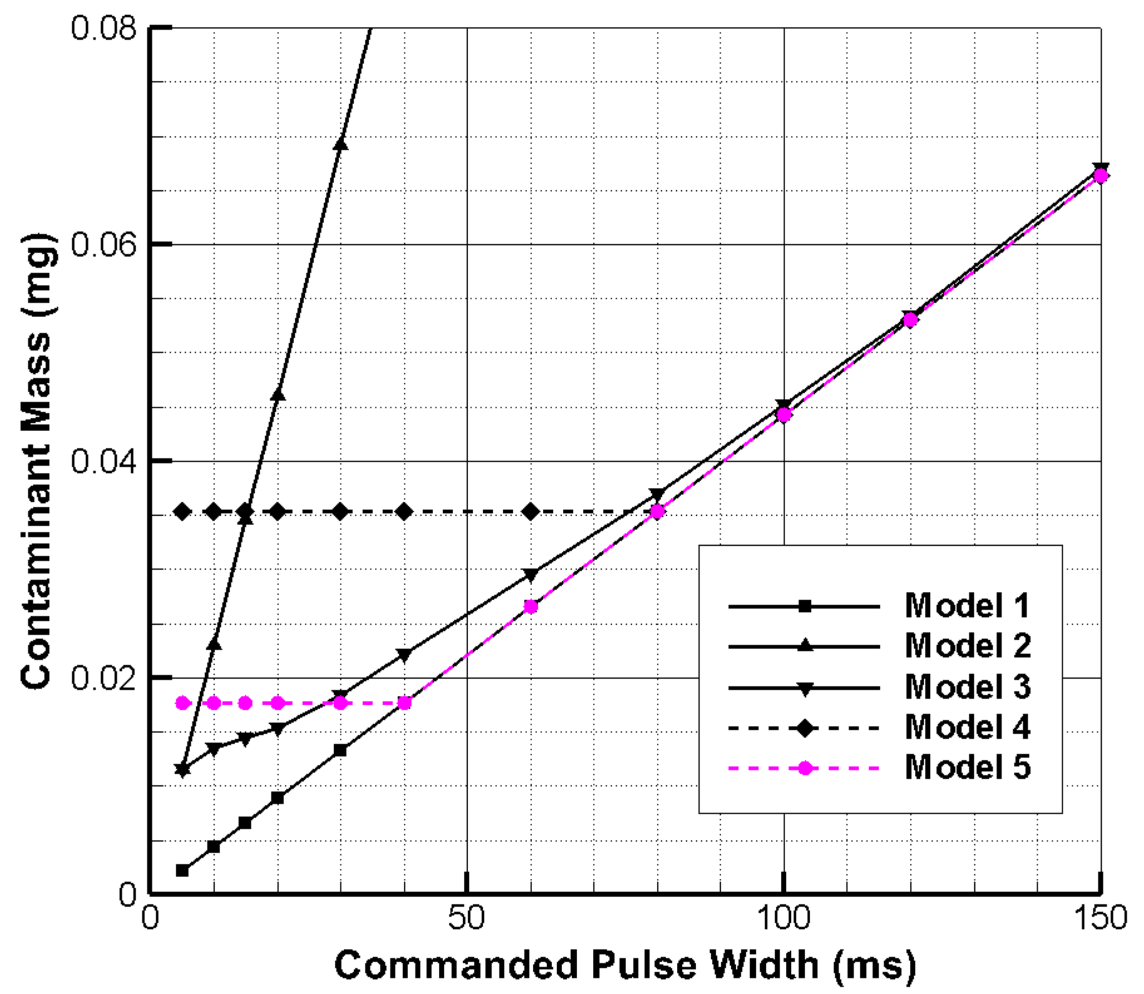


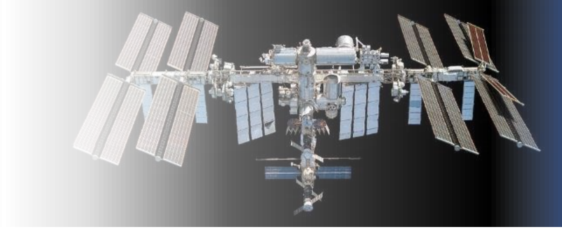
Selecting a Thruster Plume Contamination Model



- **Model 5: <u>Updated</u> ISS Bipropellant Plume Contamination Model assuming total start-up and shut-down time of 20 ms.**
  - Steady state thruster parameters continue to be used.
  - Potential for over-conservatism in predicting contaminant mass levels at very short pulse widths using default total start-up and shut-down time can be mitigated when reliable thruster start-up and shut-down times are available.

Thruster plume contamination models must be developed in consideration of all available data.



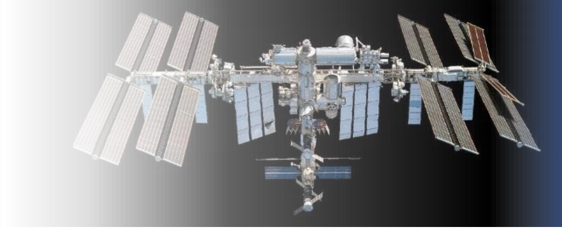


Conclusions

- The updated ISS Bipropellant Plume Contamination Model by ISS Space Environments introduces a functional dependency on thruster pulse width, which ensures a full thruster start-up and shut-down cycle is modeled.
- The update allows for the continued use of the ISS Bipropellant Plume Contamination Model for predicting thruster plume-induced contamination and erosion at ISS, even when a thruster commanded on-time is extremely short.
- The updated model prevents under-prediction of thruster plume-induced contamination due to visiting vehicle proximity operations while providing a way to take advantage of thruster start-up and shut-down data gathered during test programs, if available.

The updated ISS Bipropellant Plume Contamination Model gives flexibility so that all available thruster data can be considered in the analysis approach.

References

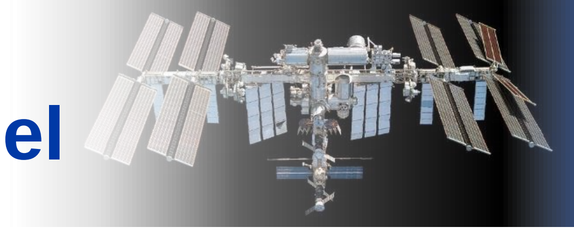


1) Soares C, Mikatarian R, Barsamian H and Rauer S 2002 International Space Station Bipropellant Plume Contamination Model *Proc. of the 8th AIAA/ASMT Joint Thermophysics and Heat Transfer Conf.* AIAA Paper 2002-3016, St. Louis, MO USA, June 2002
2) Soares C, Barsamian H and Rauer S 2002 Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments *Optical System Contamination: Effects, Measurements, and Control VII* {\bf 4774} 199-209
3) Trinks H 1987 Experimental investigation of the exhaust plume flow fields of various small bipropellant and monopropellant thrusters *Proc. of the 22nd AIAA Thermophysics Conf.* AIAA Paper 87-1607, Honolulu, HI USA, June 1987
4) Soares C, Olsen R, Steagall C, Schmidl W, Myers B, Mikatarian R, Koontz S and Worthy E 2015 Improvements in modeling thruster plume erosion damage to spacecraft surfaces *Proc. of the 13th Int. Symp. on Materials in a Space Environment* Pau, France, June 2015
5) Kubiak E and Martin M 1983 Minimum impulse limit cycle design to compensate for measurement uncertainties *Journal of Guidance, Control, and Dynamics* {\bf 6:6} 432-5
6) Hattis P 2016 A Short History of the Space Shuttle Orbit Flight Control System Development and Application Evolution *Proc. of the 39th Annual AAS Rocky Mountain Section Guidance and Control Conf.* AAS Paper 16-095 Breckenridge, CO USA, February 2016
7) Steagall C, Mikatarian R, Huang A, Fox K, Olsen R, Koontz S, Worthy E and Soares C 2018 External contamination integration of visiting vehicles on the International Space Station *Proc. of the 14th Int. Symp. on Materials in a Space Environment* Biarritz France, October 2018
8) Larin M, Lumpkin F and Rauer S 2001 Standardization of rocket engine pulse time parameters *Proc. of the 25th AIAA Thermophysics Conf.* AIAA Paper 2001-2817, Anaheim, CA USA, June 2001

Figures

1) NASA Image and Video Library. iss066e125277 (Dragon 2 undock). January 23, 2022. Available from: https://images.nasa.gov/details-iss066e125277
2) NASA Image and Video Library. jsc2021e064216_alt (ISS). December 9, 2021. Available from: https://images.nasa.gov/details-jsc2021e064216_alt

Updated ISS Bipropellant Plume Contamination Model



- **Value of f(pw) is dependent on commanded pulse width, t, thruster start-up time, t_{SU}, and thruster shut-down time, t_{SD}.**
  - Factor of 2 is empirically derived from Orbiter PRCS total start-up and shut-down time of 40 ms compared to minimum pulse width of 80 ms used.
  - If total thruster start-up and shut-down time is not available (t_{SU} + t_{SD}), Orbiter PRCS total start-up and shut-down time of 40 ms will be used as default.

$$f(pw) = \begin{cases} 2 \cdot \dfrac{t_{SU} + t_{SD}}{t_{SU}} & if\ t < t_{SU} \\ 2 \cdot \dfrac{t_{SU} + t_{SD}}{t} & if\ t_{SU} \leq t < 2 \cdot (t_{SU} + t_{SD}) \\ 1 & if\ \ t \geq 2 \cdot (t_{SU} + t_{SD}) \end{cases}$$

t_{SU}	Thruster start-up time, s
t_{SD}	Thruster shut-down time, s
t	Commanded pulse width, s

Updated ISS Bipropellant Plume Contamination Model ensures a full start-up and shut-down cycle is modeled for each thruster firing