

SHOCK-LAYER RADIATIVE HEATING FOR MSR SAMPLE RETRIEVAL LANDER WITH 8 KM/S ENTRY

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ABSTRACT

This study investigates the radiative heating environment of the Mars Sample Return (MSR) Sample Retrieval Lander (SRL), set for potential 2031 launch from Earth with a Mars entry velocity near 8 km/s. This speed presents a significant change compared to prior Mars missions, such as Mars Science Laboratory (MSL), InSight, and Mars 2020, which typically experienced entry velocities around 6 km/s. Consequently, the SRL is subjected to a markedly different radiative heating regime, where CO 4th-Positive bands emerge as the dominant radiation mechanism under these entry conditions. We quantified the nominal radiative heating environment and assessed both the parametric uncertainty in the radiative heating model and the experimentally-anchored shock-tube informed bias. The analysis revealed that parametric uncertainty can reach as high as 160% for the heatshield and 50% for the backshell. The shock-tube informed bias indicated an increase in nominal radiative heating by 10% on the forebody and 24% on the afterbody. To address the substantial uncertainties in the nonequilibrium models, we compiled the best available nominal modeling parameters along with their uncertainties. Our findings emphasize the critical role of CO dissociation rate as the primary contributor to uncertainty on the forebody, while CO₂ dissociation rate is the dominant factor on the backshell.

Index Terms— Mars Entry, Aerothermodynamics, Coupled Radiation, Hypersonic

1. INTRODUCTION

The proposed 2031 launch date for the SRL requires an entry interface velocity near 8 km/s, which results in peak radiative heating at a free-stream velocity of 7.03 km/s. This 8 km/s entry interface velocity distinguishes the radiative heating of this vehicle from that of recent MSL [1], InSight [2], Mars 2020 [3, 4], and Schiaparelli [5] vehicles, which all had entry interface velocities near 6 km/s and peak forebody radiative heating near 5 km/s. The increase in peak radiative heating velocities from 5 to 7 km/s results in a fundamentally different radiative heating environment over the vehicle forebody. We will show that such increase in entry velocity shifts the dominant radiation mechanism on the fore-

body from CO₂ Infrared (IR) bands to CO 4th-Positive and CN bands. The uncertainties in the flowfield chemistry and non-Boltzmann (Quasi-Steady State) models, which are relatively large, lead to substantial uncertainties in the radiative heating predictions. We will show that these uncertainties are anticipated to be greater than those associated with CO₂ IR bands, which are less sensitive to post-shock chemistry and non-Boltzmann effects [6].

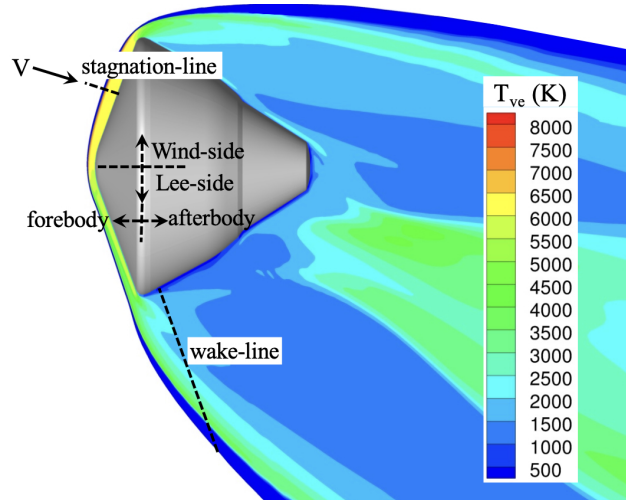


Fig. 1. Definition of the SRL geometry and surface regions, as well as the nominal vibrational temperature field.

Figure 1 presents the SRL geometry considered in this work, which consists of a 70 degree sphere-cone forebody heat shield with a maximum diameter of 4.64 m and an elongated afterbody relative to the MSL or Mars 2020 vehicles.

2. MODELING OVERVIEW

The LAURA Navier-Stokes solver [7] is applied for the flowfield simulations in this work. The two-temperature thermochemical nonequilibrium model presented by Park et al. [8] is applied, as reviewed by Johnston et al. [9]. The flowfield consists of the 16 species chemical kinetic model of Johnston and Brandis [10]: CO₂, CO, N₂, O₂, NO, C, N, O, CN, C₂, C⁺, O⁺, NO⁺, O₂⁺, CO⁺, and e⁻. Table 1 tabulates the most im-

portant rates with their associated uncertainties for modeling radiation (see Johnston and Mazaheri [11] for more detail).

Table 1. Uncertainty values for chemical rates with the largest impact on radiative heating predictions.

Reaction	Uncertainty Multiplier
$\text{CO}_2 + \text{M} \leftrightarrow \text{CO} + \text{O} + \text{M}$	0.3, 1.2 [8, 12, 13, 14, 15]
$\text{CO} + \text{M} \leftrightarrow \text{C} + \text{O} + \text{M}$	0.2, 3.5 [16, 17, 18, 19, 20]
$\text{NO} + \text{M} \leftrightarrow \text{N} + \text{O} + \text{M}$	0.2, 3.5 [10, 21, 22, 23, 24]
$\text{O}_2 + \text{M} \leftrightarrow \text{O} + \text{O} + \text{M}$	0.3, 1.3 [25, 26, 27, 28]
$\text{CO} + \text{O} \leftrightarrow \text{O}_2 + \text{C}$	0.8, 10.0 [8, 29, 30]
$\text{CN} + \text{O} \leftrightarrow \text{NO} + \text{C}$	0.5, 10.0 [31, 32]
$\text{N}_2 + \text{C} \leftrightarrow \text{CN} + \text{N}$	0.8, 1.3 [8, 33, 34]
$\text{N}_2 + \text{O} \leftrightarrow \text{NO} + \text{N}$	0.4, 1.1 [25, 35, 36, 37]

The HARA code is used for coupled radiation analyses, which incorporates the divergence of the radiative flux into the LAURA total energy equation as a source term. The tangent-slab approximation is used to solve for radiative transport and compute the divergence of radiative flux. While the tangent-slab approximation results in unacceptable errors in the surface radiative flux on afterbody regions, Johnston and Mazaheri [38] showed that it is adequate for providing the divergence of the radiative flux, which is coupled to the flowfield energy equations. The surface radiation coupling has the primary impact of lowering the temperatures in the post-shock nonequilibrium region slightly, therefore decreasing the radiative heating by 10 to 20%. The radiative heating is computed as a post-processing step to these coupled radiation flowfields using the ray-tracing approach [39], which avoids the tangent-slab approximation.

The free-stream mass fractions are set to 0.97 for CO_2 and 0.03 for N_2 , which corresponds to a free-stream gas constant R of 192 J/kg. This gas constant is convenient for converting the flight pressures to shock-tube conditions, while maintaining the free-stream density. This conversion is required because the free-stream temperatures for the EAST shock-tube conditions, discussed in Section 5, are larger than the flight value. This conversion is $p_{\text{EAST}} = \rho_{\text{flight}} R T_{\text{EAST}}$, where $T_{\text{EAST}} = 300$ K.

The uncertainties associated with the molecular band processes used in the radiation analyses are listed in Table 2 along with the non-Boltzmann rates uncertainties that are listed in Table 3.

3. RADIATIVE HEATING

The results are presented for the peak forebody radiative heating case listed in Table 4. The nominal radiative heating distributions on the forebody and afterbody for this case are shown in Fig. 2. The peak radiative heating value on the forebody, which occurs at the stagnation point, is 38 W/cm². The flowfield region that provides the dominant emission contribution to this radiative heating is the near-shock nonequilibrium region. This is shown in Fig. 3(a), where a sharp increase in the wall-directed intensity near 24 cm body normal

Table 2. Uncertainties in the molecular band processes.

Molecule	States	Band name	λ Range (nm)	Uncertainty
CO	$\text{A}^1\Pi - \text{X}^1\Sigma^+$	4th Positive	120 – 280	$\pm 40\%$ [40, 41, 42]
CO	$\text{b}^3\Sigma^+ - \text{a}^3\Pi_r$	3rd Positive	250 – 450	$\pm 50\%$ [40, 41]
CO	$\text{d}^3\Delta_g - \text{a}^3\Pi_r$	Triplet	320 – 2500	$\pm 50\%$ [41]
CO	$\text{a}^3\Sigma^+ - \text{a}^3\Pi_r$	Asundi	370 – 2500	$\pm 50\%$ [41]
CO	$\text{B}^1\Sigma^+ - \text{A}^1\Pi$	Angstrom	400 – 700	$\pm 50\%$ [41]
CO	$\text{X}^1\Sigma^+ - \text{X}^1\Sigma^+$	Infrared	1200 – 7000	$\pm 50\%$ [40, 41]
CN	$\text{A}^2\Pi_i - \text{X}^2\Sigma^+$	Red	400 – 2800	$\pm 30\%$ [40, 41, 42]
CN	$\text{B}^2\Sigma^+ - \text{X}^2\Sigma^+$	Violet	300 – 550	$\pm 15\%$ [40, 41, 42]
C ₂	$\text{d}^3\Pi_g - \text{a}^3\Pi_u$	Swan	390 – 1000	$\pm 50\%$ [40, 41, 42]
C ₂	$\text{b}^3\Sigma_g^- - \text{a}^3\Pi_u$	Ballik-Ramsay	500 – 3000	$\pm 50\%$ [40, 41, 43, 44]
C ₂	$\text{A}^1\Pi_u - \text{X}^1\Sigma_g^+$	Phillips	350 – 1200	$\pm 50\%$ [40, 41]
C ₂	$\text{D}^1\Sigma_u^+ - \text{X}^1\Sigma_g^+$	Mulliken	200 – 250	$\pm 50\%$ [40, 41]
C ₂	$\text{C}^1\Pi_g - \text{A}^1\Pi_u$	Des.-D'Aram.	280 – 700	$\pm 50\%$ [40, 41]
C ₂	$\text{e}^3\Pi_g - \text{a}^3\Pi_u$	Fox-Herzberg	200 – 500	$\pm 50\%$ [40, 41]
CO ₂	$\text{X}^1\Sigma_g^+ - \text{X}^1\Sigma_g^+$	2700 nm band	2600 – 3300	$\pm 70\%$
CO ₂	$\text{X}^1\Sigma_g^+ - \text{X}^1\Sigma_g^+$	4500 nm band	4000 – 5000	$\pm 20\%$

Table 3. Uncertainties for the Non-Boltzmann rates: $K_f[\text{cm}^3/\text{mol} - \text{s}] = AT^n \exp(-E/T)$.

Reaction	A	n	E	K_f Multiplier
$\text{CO}(\text{X}^1\Sigma^+) + \text{M} \leftrightarrow \text{CO}(\text{A}^1\Pi) + \text{M}$	1.86e-10	0.344	93669	0.3, 3.0 [45]
$\text{CO}(\text{X}^1\Sigma^+) + \text{e}^- \leftrightarrow \text{CO}(\text{A}^1\Pi) + \text{e}^-$	3.82e-09	0.12	95850	0.3, 3.0 [46]
$\text{CN}(\text{X}^2\Sigma^+) + \text{M} \leftrightarrow \text{CN}(\text{A}^2\Pi) + \text{M}$	1.29e-13	0.50	13300	0.3, 2.5 [47]
$\text{CN}(\text{X}^2\Sigma^+) + \text{M} \leftrightarrow \text{CN}(\text{B}^2\Sigma^+) + \text{M}$	1.03e-12	0.50	37000	0.1, 2.5 [48]
$\text{CN}(\text{X}^2\Sigma^+) + \text{e}^- \leftrightarrow \text{CN}(\text{A}^2\Pi) + \text{e}^-$	6.41e-09	0.20	18303	0.3, 3.0 [49]
$\text{CN}(\text{X}^2\Sigma^+) + \text{e}^- \leftrightarrow \text{CN}(\text{B}^2\Sigma^+) + \text{e}^-$	6.83e-10	0.39	40428	0.3, 4.0 [49]

Table 4. Freestream condition for the peak forebody radiative heating case.

Time (s)	Velocity (m/s)	Density (kg/m ³)	Temperature (K)	Angle of Attack (Degrees)
630	7030	4.65×10^{-4}	158	-20

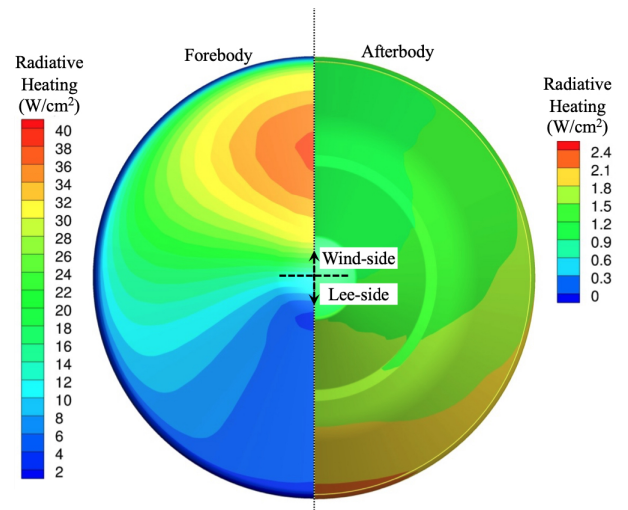
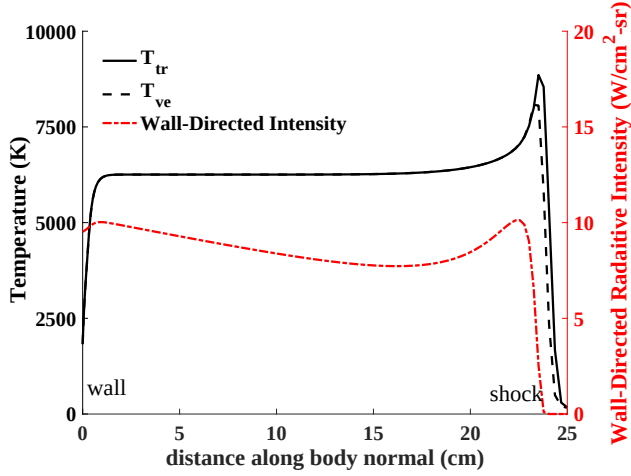


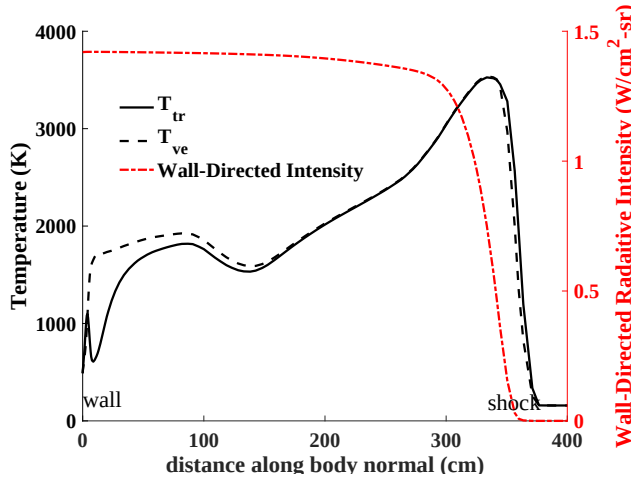
Fig. 2. Nominal radiative heating for the 630 s case.

distance is evident in the region where the temperatures are still equilibrating and the chemical nonequilibrium is strong

Considering the afterbody, the peak radiative heating of 2.2 W/cm^2 occurs near the lee-side shoulder. Figure 3(b) presents the temperatures and wall-directed radiative intensity along the wake-line defined in Fig. 1. Similar to the stagnation-line, this figure shows that the dominant emission occurs in the near-shock region.



(a) Stagnation line



(b) Wake line

Fig. 3. Temperature and wall-directed radiative intensity profiles along body normal lines defined in Fig. 1.

Figure 4 shows the contributions from individual molecular band systems to the centerline radiative heating. These values were computed by evaluating the ray-tracing radiative heating separately for each band system. This figure shows the nearly equal contribution from CO 4th-Positive and CN Violet. The remaining band systems provide the other roughly one-third of the radiative heating in the stagnation region ($z \approx 1.4 \text{ m}$). Because of the lower normal shock veloc-

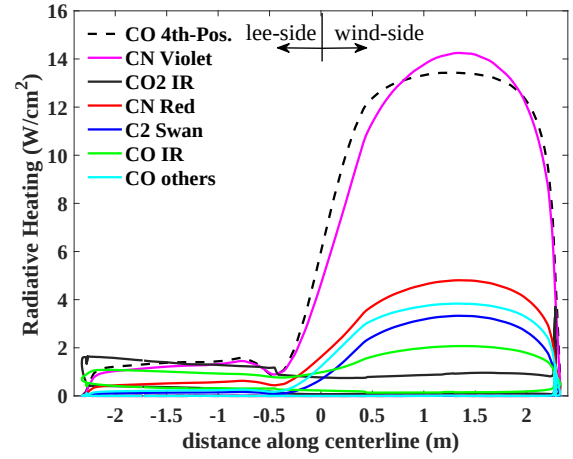


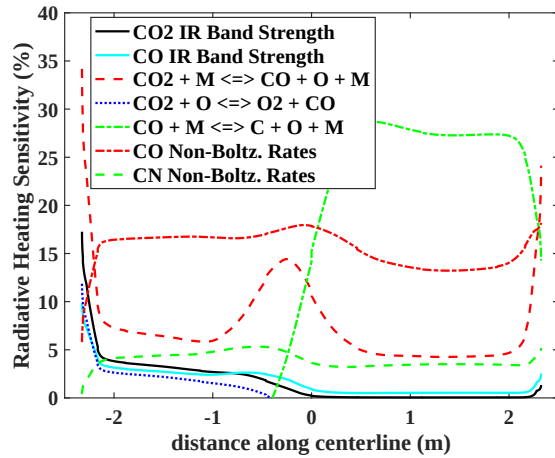
Fig. 4. Molecular band contributions to the the radiative heating along the centerline for the 630 s case.

ities on the lee-side forebody (negative z values) compared to the wind-side, the relative contribution from the CO_2 IR band is larger because of less CO_2 dissociation and therefore stronger CO_2 IR emission.

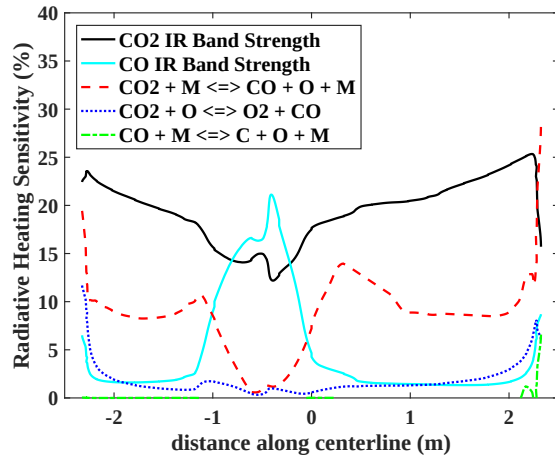
4. PARAMETRIC UNCERTAINTY

The HARA.UQ code [7] is used for the radiative heating parametric uncertainty. Each modeling parameter was changed by its uncertainty increment defined in Section 2 to obtain the associated parametric sensitivity. A major factor in this parametric uncertainty is the near-shock emission, which was shown to be a dominant contributor to the radiative heating (see Fig. 3). This is because of the relatively large uncertainties in the chemical rate and non-Boltzmann models which the radiative emission is sensitive to in near-shock nonequilibrium regions. And the large uncertainties in these models are due to the difficulty in obtaining relevant rate data.

The largest contributors to the radiative heating parametric uncertainty are presented in Fig. 5 along the forebody and afterbody centerlines, where the lee-side is on the left and the wind-side is on the right. This figure shows that the CO dissociation rate and CO non-Boltzmann rates have the largest impact on the forebody radiative heating parametric uncertainty. This is due to their strong impact on CO 4th-Positive emission (see Fig. 4) to be one of the dominant contributors to the forebody radiation. The other dominant contributor on the forebody is CN Violet, which is also influenced by the higher temperatures resulting from the decreased CO dissociation rate. The decrease in this rate is applied in the sensitivity analysis because it provides an increase in the radiative heating. For the afterbody region, this figure shows that the CO_2 and CO Infrared band strengths and CO_2 dissociation rate dominate the parametric uncertainty, due to the dominant



(a) Forebody



(b) Afterbody

Fig. 5. Sensitivity of the radiative heating along the centerline to modeling parameters for the 630 s case.

CO₂ and CO IR bands for the lower temperature wake flow-field.

The resulting upper limit parametric uncertainty values for the radiative heating, expressed as a percentage with respect to the nominal value, are shown in Fig. 6. In the stagnation region, where the radiative heating has the highest magnitude, the upper limit parametric uncertainty value is 73.9 W/cm². This corresponds to a nearly 100% parametric uncertainty, which increases to over 160% near the wind-side shoulder region. On the afterbody, where the maximum predicted parametric uncertainty is near 50%, the peak upper limit radiative heating is 2.7 W/cm².

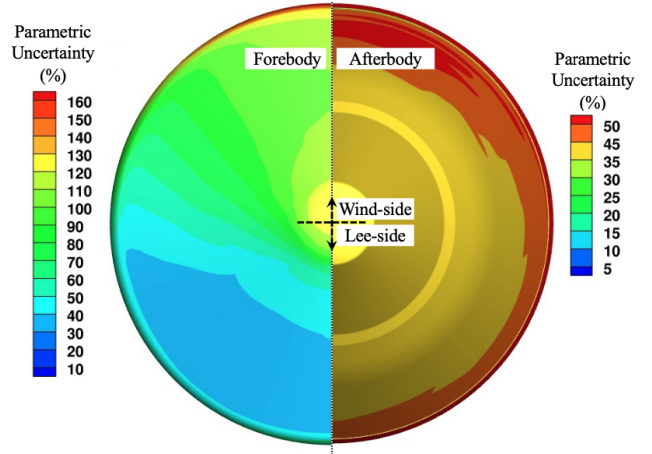


Fig. 6. Percentage of the radiative heating parametric uncertainty for the 630 s case.

5. SHOCK-TUBE INFORMED BIAS

The shock-tube informed bias (STIB) approach [50] allows differences between shock-tube measurements and their simulations to be converted into bias(model) form error in the computed surface radiative heating. To apply the STIB approach, the disagreement factors are evaluated for the relevant shock-tube measurements [51, 52, 4], which are listed in Tables 5 and 6. These measurements are for a Mars/Venus-

Table 5. EAST Measurements [51, 52] considered for the STIB analysis of CO, CN, and C₂ bands.

Velocity (km/s)	Pressure (Torr)	Test #
6.72	0.1	51-40
6.79	0.1	54-4
6.90	0.1	51-12
7.00	0.1	54-6
7.71	0.1	54-2
7.98	0.1	54-7
6.43	0.25	51-7
6.53	0.25	51-17
6.71	0.25	51-2
7.75	0.25	48-43
7.82	0.25	48-39

Table 6. EAST Measurements [4] considered for the STIB analysis of CO₂ IR bands.

Velocity (km/s)	Pressure (Torr)	Test #
5.29	0.15	55-20
5.83	0.15	55-22
4.77	0.5	55-13, 55-28
4.82	0.5	55-18, 55-27
4.91	0.5	55-29
4.93	0.5	55-15
4.98	0.5	55-16
5.24	0.5	55-14

relevant free-stream composition of 96% CO₂ and 4% N₂, by

mole. For more details on the disagreement factors, the readers are referred to the work of Johnston and Mazaheri [11].

Figure 7 shows the percent difference between the nominal surface radiative heating values and the values evaluated with the STIB correction. The impact of STIB approach is seen to be up to a 10% increase on the forebody and 24% increase on the afterbody radiative heating.

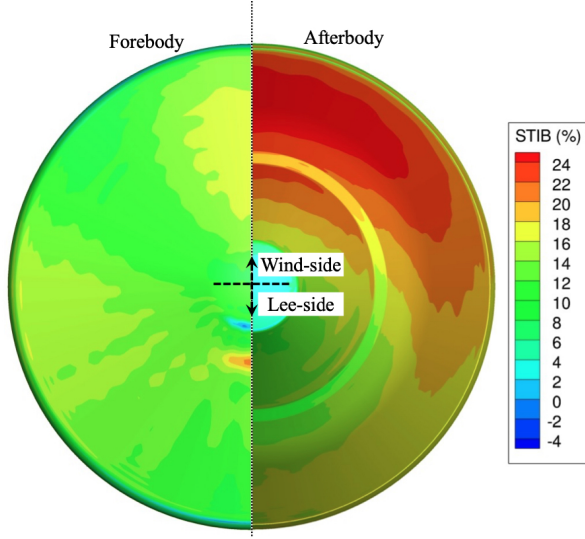


Fig. 7. Percent increase in the STIB radiative heating relative to the nominal for the 630 s case.

6. MARGIN ASSESSMENT

The total margined radiative heating is obtained by taking a pragmatic approach using the maximum between the STIB (model-form uncertainty) and parametric uncertainty (PU) at each surface location; i.e.,

$$q_{rad,margined} = q_{rad,nominal} [1 + \max(STIB, PU)] . \quad (1)$$

For the present case where the PU is larger than STIB at every surface location, the PU result defines the margin. Note that other approaches for combining uncertainty components could be considered, such as that presented by Cruden et al. [53], which is not considered in this work.

The resulting margined radiative heating for the 630 s case is shown in Fig. 8. The maximum margined radiative heating on the forebody is at the stagnation region with the value of 73.9 W/cm². On the afterbody, the maximum margined radiative heating occurs near the lee-side shoulder with a value of 2.7 W/cm².

7. SUMMARY

The nominal radiative heating environment for an 8km/s entry Mars Sample Return Sample Retrieval Lander, which

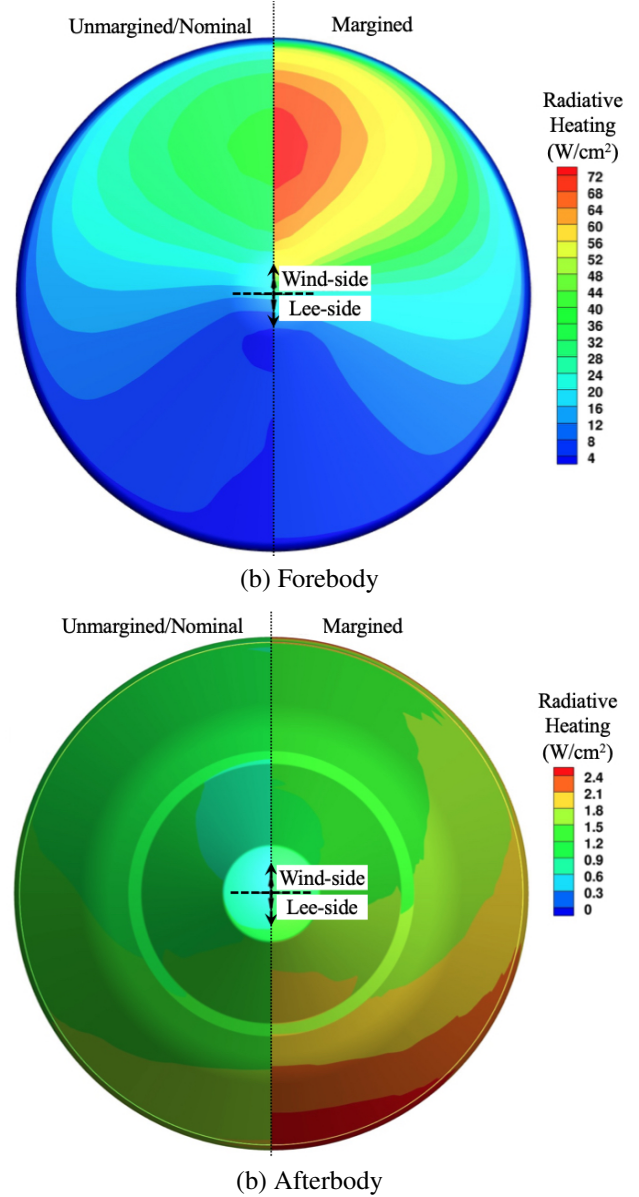


Fig. 8. Comparison between the unmargined (nominal) and margined radiative heating for the 630 s case.

resulted in a peak radiative heating velocity of 7.03 km/s, was quantified. It was shown that the CO 4th-Positive and CN Violet bands are dominant radiation mechanisms under such entry conditions. Both the parametric uncertainty in the radiative heating model and the shock-tube informed bias were assessed. The parametric uncertainty in radiative heating was found to vary from around 100% at the forebody stagnation point to 160% near the shoulder. For the afterbody, the parametric uncertainty in the radiative heating was shown to be up to 50%. The STIB analysis indicated estimated model form uncertainty bounds of 10% on the forebody and 24% on

the afterbody. As the STIB uncertainty bounds were much smaller than the parametric uncertainty bounds, the margin policy was driven by the latter. The maximum margined radiative heating on the forebody was predicted to be 73.9 W/cm², while the maximum margined radiative heating on the afterbody reached 2.7 W/cm².

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