

STATUS OF SHOCK LAYER RADIATION VALIDATION STUDIES

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ABSTRACT

This paper presents a status update for the shock layer radiation validation studies conducted at NASA. A review of the present capability for the simulation and validation of shock layer radiation is presented as well as providing an overview of the data obtained from the Electric Arc Shock Tube (EAST). The paper will include details covering updated convective and radiative heating correlations, provide an overview of the development of new kinetics for Mars entry and detail some recent work calculating after-body radiation. Furthermore, the paper will highlight conditions where there is high confidence in the validation of EAST data (e.g. Earth entry for speeds greater than approximately 10 km/s and for many Mars entry conditions) and where further experimental data would be highly beneficial (e.g. lower speed Earth entry around 7.5 to 10 km/s and higher speed CO₂ entries relevant to Venus). Nominal test conditions for both Earth and Mars are provided for future potential facility-to-facility comparisons.

Key words: shock layer radiation; Entry Systems Modeling; shock tubes.

1. INTRODUCTION

Modeling of radiative heating of a vehicle entering an atmosphere can be an experimentally challenging and computationally expensive task. The research conducted for the Shock Layer Radiation Testing and Radiation Modeling and Validation tasks of NASA's Entry Systems Modeling project aim to provide better understanding of the radiation encountered during entry into a variety of atmospheres. With an improved understanding of shock layer radiation, the uncertainty in thermal protection system (TPS) design can be reduced for cases where radiation is a significant component of the total heat flux. For cases where radiation is the dominating heat flux, the improvements in the understanding of radiative heating may be required to enable a mission to proceed. In order to reduce the uncertainty in shock layer radiation, experiments to measure the radiation for various atmospheric entries are conducted in the EAST facility combined with

simulations from NASA's radiation codes, NEQAIR and HARA.

2. DESCRIPTION OF EAST

The EAST facility at NASA Ames Research Center was developed to simulate high-enthalpy, real gas phenomena encountered by hypersonic vehicles entering planetary atmospheres. This enables experiments to be performed with flow parameters, such as velocity, static pressure, and atmospheric composition close to actual flight conditions. The basic principle behind testing in the EAST facility is that the shock-heated test gas in a shock tube simulates conditions along the stagnation line of an atmospheric entry vehicle. It has the capability of producing super-orbital shock speeds (shock speeds of up to 46 km/s have been obtained in H-He mixtures) using an electric arc driver with a driven tube diameter of 10.16 cm [1, 2]. The region of valid test gas lies between the shock front and the contact surface that separates the driver and driven gases. For some of the conditions presented in this paper, experiments in the EAST facility have utilized a buffer gas section to obtain test time at higher speeds (> 10.5 km/s). The purpose of the buffer is to act as a barrier to reduce penetration of driver gas jets into the driven (test) gas, thus increasing the test time. As the shocked gas arrives at the test section in the tube, spectrometers attached to Intensified Charge Coupled Devices (ICCDs) or a Focal Plane Array (FPA) are gated and the volume of shock-heated gas is analyzed with both spectral and spatial resolution. In each shot, EAST utilizes four spectrometers, each associated with a different wavelength range. These spectrometers/cameras are set to obtain data in one of the following wavelength regions, which are referred to as VUV (~ 120 nm – 215 nm), UV/Vis (~ 190 nm – 500 nm), Vis/NIR (~ 480 nm – 900 nm), IR (~ 700 nm – 1650 nm) and MWIR (~ 1900 nm – 5500 nm).

3. EAST TEST CONDITIONS

The following subsections will detail the EAST test conditions for Earth, Mars and Venus. A summary of all

the shots conducted in EAST since the facility upgrade in 2008, is provided at the end of this paper in Table 1. The table includes all EAST shots where at least one of the spectrometers collected usable data.

3.1. Earth

The nominal Earth entry test condition, which has been used as a verification of the facility set up in several campaigns, is 10 km/s at 0.2 Torr. However, due to the EAST data providing results across a large shock speed range, conditions of relevance are available for a variety of entry scenarios. Figure 1(a) shows a comparison of EAST test conditions with various proposed and actual flight missions entering Earth's atmosphere. The flight conditions have been scaled in pressure to match density by accounting for the difference in ambient temperature in the upper atmosphere versus the laboratory. Three sets of EAST data are shown, denoted Test 47 [3], 50 [4, 5] and 52 [6].¹ The level of validation for different ranges of these test conditions is shown in Fig. 1(b). The high speed return conditions, and the conditions relevant to the higher end of lunar return are those with the best level of validation, which have been labelled as "Well Characterized". These conditions encompass shock speeds greater than 10 km/s at pressures of 0.1 and 0.2 Torr. "Well characterized" has been defined as the conditions that have been extensively studied, with generally very good agreement between simulations and experimental results. Furthermore, the level of agreement has been quantified between simulations and experiment, and therefore, the radiative heating component for a design margin is readily available for this regime [6]. "Well characterized" does not indicate that all aspects have been completely resolved. For instance, in the "Well Characterized" regime, there is only a limited number of deep-VUV (< 145 nm) spectra, and this is a spectral region where radiation is very significant. This lack of deep-VUV data will be addressed in the upcoming Test 57 campaign for the higher end of lunar return relevant velocities, i.e. between 10 and 12 km/s.

Previous analyses of EAST data for shock speeds below 10 km/s at 0.1 and 0.2 Torr have shown that the experiment does not reach an adequate level of equilibrium as electron number density measurements can be up to a factor of three higher than expected based on shock conservation (i.e. Rankine-Hugoniot) equations [4]. This leads to a substantial under-prediction of the experimental data by simulation codes. Thus, this region has been labelled as "Observed Discrepancies". As these conditions are relevant to a recent flight test performed by NASA where radiative heating was measured, EFT-1, obtaining more experimental data in this regime could be highly beneficial.

There have been several comparisons between experiment and simulations made in the region labelled as "Par-

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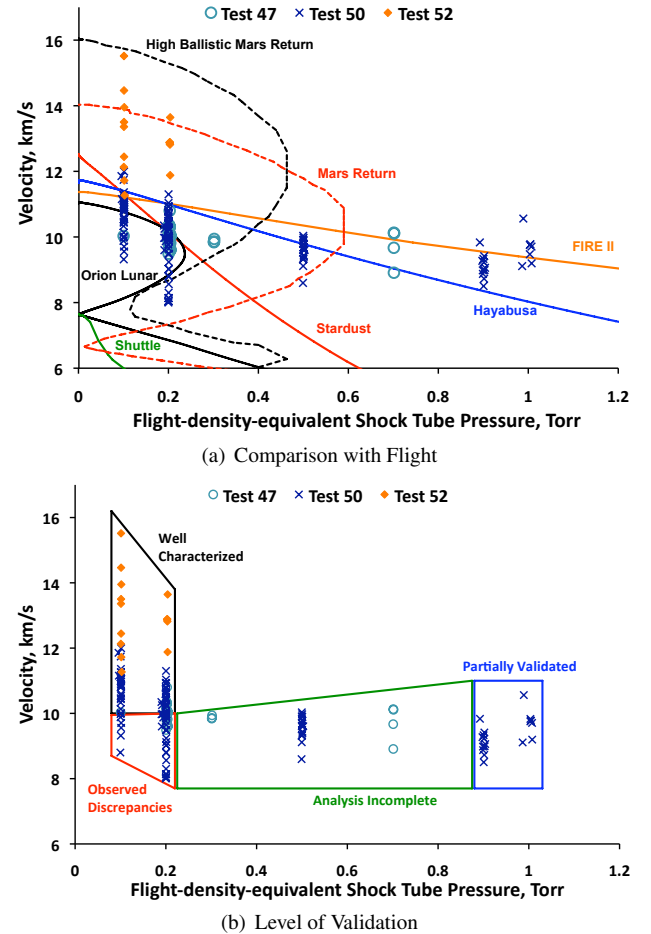


Figure 1. Map of EAST Earth test conditions.

tially Validated". These comparisons have generally focused on individual comparisons of equilibrium spectra due to the high pressure of 0.9 and 1.0 Torr. However, there has been no dedicated analysis to cover all spectral regions while calculating an overall level of agreement for all shots in this range. For the shots with pressures greater than 0.2 Torr and less than 0.9 Torr, the analysis is largely incomplete, and has been labelled as such.

3.2. Mars/Venus

As both Mars and Venus have similar atmospheric compositions, dominated by CO_2 (approximately 96%), with the remainder mostly N_2 and parts of Ar, the experiments will be discussed together. The nominal Mars entry conditions for EAST have typically been 6.5 km/s at 0.25 Torr and 7 km/s at 0.1 Torr, where the dominating radiation is emitted from the VUV spectral region from CO. However, with recent testing measuring the radiation emitted from CO_2 in the Mid-Wave Infrared (MWIR) spectral region at slower speeds [7], another test condition to complement this is suggested to be 3 km/s and 1.0 Torr. As with the Earth entry campaigns, experiments have been conducted across a wide range of

conditions relevant for a variety of entry scenarios. Figure 2(a) shows a comparison of EAST testing conditions with various proposed and actual flight missions entering the atmospheres of Mars and Venus. The flight conditions have again been scaled in pressure to match density by accounting for the difference in ambient temperature in the upper atmosphere versus the laboratory. Six sets of EAST data are shown, denoted Test 48 [8], 49 [8], 51 [9], 53 [9], 54 [10] and 55 [7].² The level of validation for different ranges of these test conditions is shown in Fig. 2(b). The “Well Characterized” conditions include pressures from 0.05 Torr to 1.55 Torr, with shock speeds less than 9 km/s [11, 12]. As with Earth entry, this “Well Characterized” region has been extensively studied, with the level of agreement quantified between simulations and experiment, and therefore, the radiative heating component for a design margin is readily available for this regime [7]. These experiments have been used extensively for the validation of CO 4th Positive spectral databases [13] and for the development of new kinetic models for Mars entry [10, 12]. “Well characterized” does not indicate that all aspects have been completely resolved. Even though these experiments have been used for the development of new rates, and to validate spectroscopic databases, some discrepancies still remain. These discrepancies predominantly stem from the fact that a previous equilibrium analysis identified a departure in the temperature calculated from the Plank limited portion of the spectra compared to the theoretical equilibrium value by a few 100 K [13]. Furthermore, discrepancies between experiment and simulations have been identified for the $2.6 \mu\text{m}$ band of CO_2 for conditions relevant to MSL [7].

The region labelled as “Incomplete Analysis/Data” corresponds to conditions relevant to Venus entry. Radiation from carbon continuum in the VUV is one of the dominating mechanisms for radiation at such conditions. This region has been listed as incomplete due to only limited data being available in the VUV spectral region at such high velocities. Therefore, a comprehensive validation of the simulation capability has not been possible. Obtaining new shock tube data for such regimes could provide significant insights into the understanding of radiation relevant to Venus entry. Once a number of VUV experiments at Venus entry conditions are obtained, the validation of the relevant physics pertaining to carbon VUV continuum can take place. This would entail comparisons with NASA’s radiation codes, and would possibly require an update to the TOPbase database [14] for some of the relevant carbon energy levels.

4. DESCRIPTION OF PREDICTIVE CODES

This section will briefly detail the two main radiation codes used by NASA; NEQAIR and HARA. Non-Equilibrium AIR (NEQAIR) is a line-by-line radiation code which computes spontaneous emission, absorption

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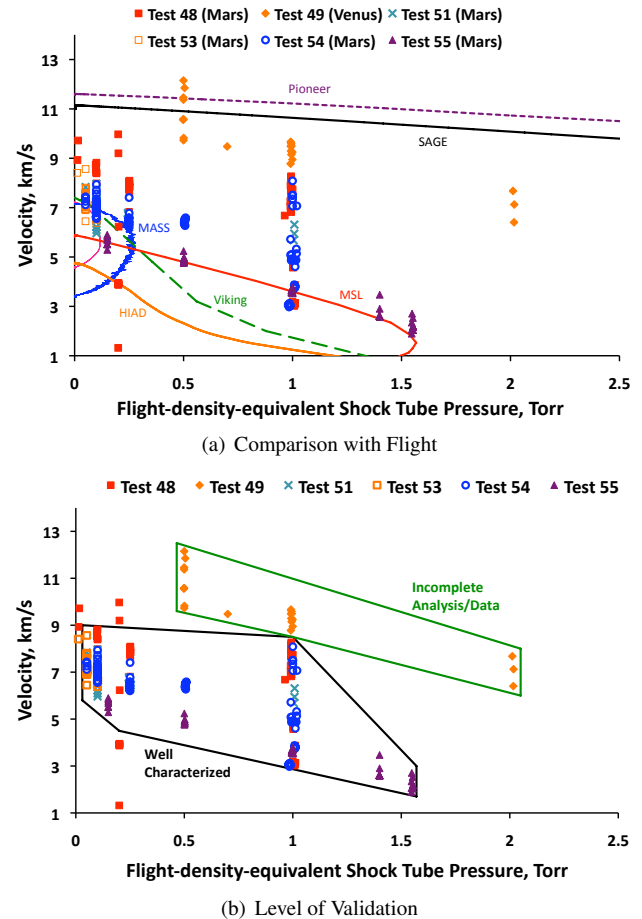


Figure 2. Map of EAST CO_2/N_2 test conditions.

and stimulated emission due to transitions between various energy states of chemical species along a line-of-sight [15]. Individual electronic transitions are considered for atoms and molecules, with the molecular band systems being resolved for each rotational line. Since the report of Whiting et al. [15], numerous updates have been incorporated into NEQAIR, such as: parallelization of the code, using the latest version of the National Institute of Standards and Technology (NIST) atomic database (version 5.0) [16], using the bound-free cross sections from TOPbase [14] and improvements to the mechanics of QSS (including adding the ability to run QSS for CO and CN). This latest version of NEQAIR is known as v14.0. NEQAIR uses the tangent-slab as the default option for calculating the wall-directed radiative heat flux.

The High-temperature Aerothermodynamic Radiation (HARA) model is discussed in detail by Johnston et al. [17, 18]. A line-by-line approach is used for atoms and optically thick molecules, while a smeared band model is used for optically thin molecules. HARA is based on a set of atomic levels and lines from NIST [19] and Opacity Project databases [20]. The atomic bound-free model is composed of cross sections from the Opacity project’s online TOPbase [14], which were curve fit by Johnston [17]. As with NEQAIR, HARA uses the tangent-

slab approximation as the default option for radiation transport.

While NEQAIR and HARA share many common features, there are some important differences between the two codes. These differences being the inclusion of the radiative attachment mechanism [21] and TOPbase atomic lines [17] in HARA, both of which are currently not implemented in NEQAIR. Different sources of data are also used for the CO 4th Positive database, which is important when inferring rates from the EAST data. NEQAIR uses the database of da Silva and Dudeck [22], while HARA uses the database of Babou et al [23].

5. RECENT SHOCK LAYER RADIATION WORK

This section will detail some of the recent work that has been conducted as part of the Radiation Modeling and Validation task at NASA.

5.1. After-Body Radiation

5.1.1. Earth

Radiative heating was identified as a major contributor to after-body heating for Earth entry capsules at velocities above 10 km/s [24]. Because of rate-limited electron-ion recombination processes, many of the electronically excited N and O atoms produced in the high temperature/pressure fore-body are continually created by electron-ion recombination as they expand into the after-body region, which results in significant after-body radiation. In addition, ablation products from a representative heatshield TPS were shown to increase the after-body radiation by nearly 40% [24]. The larger radiative intensity for the ablating case is not the result of emission from ablation products, such as CO, but rather the influence of the ablation products on the vibrational-electronic energy equation. This analysis showed that the increased intensity for the ablating case comes from increased emission from the VUV lines identified previously for air, whereas no new molecular bands from ablation products are noticeable. The commonly used one-dimensional tangent-slab radiation transport approach was shown to over-predict the radiative flux by as much as 50% in the after-body, therefore making the more computationally expensive full angular integration approach (or a fully 3D radiative transport method) necessary for more accurate radiative flux predictions [24]. Using this approach, comparisons with FIRE II measurements showed improved agreement with the addition of after-body radiation.

A parameter was defined, ϕ , to be the logarithm of the Saha-Boltzmann population divided by the Boltzmann population. Evaluating this parameter throughout an after-body flowfield for N allows the strongly radiating regions to be identified, an example of which is

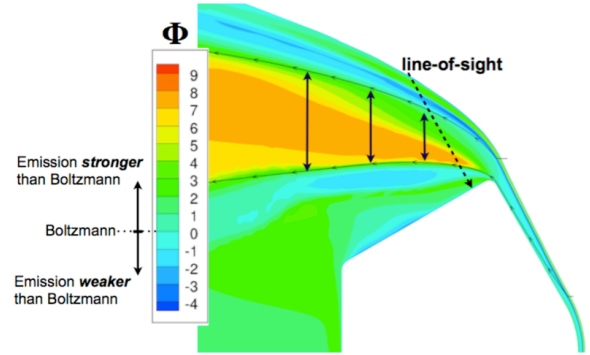


Figure 3. Values of ϕ for Stardust at $t = 46$ s.

shown in Fig. 3. The observation that after-body radiation is significant does not contradict the negligible FIRE II and Apollo radiometer measurements for two reasons. First, these measurements did not capture the VUV region of the spectrum, which was shown to contribute up to 7 times the non-VUV radiative flux. Second, these measurements had a lower sensitivity limit of roughly 2 W/cm^2 , below which the radiometer read a value of zero. Therefore, a radiometer location that encountered just under 2 W/cm^2 of non-VUV radiative flux, and therefore produced a negligible radiometer reading, could have actually encountered up to 14 W/cm^2 of VUV and 16 W/cm^2 of total radiative flux [24]. This value may be nearly equal to, if not greater than, the convective heating for most after-body flows, and therefore should be included in heating estimates. These comparisons provided confirmation that after-body radiation is a valid heating mechanism and one that requires consideration in future vehicle designs.

5.1.2. Mars

Simulations of the radiative heat flux on the after-body of vehicles entering the Martian atmosphere have also been performed. The radiation is dominated by CO_2 bands emitting in the MWIR spectral region. This mechanism has not previously been considered in the design of Mars entry vehicles. However, recent analysis has shown that the CO_2 radiation can be greater than convective heating in the wake. With several upcoming and proposed missions to Mars potentially affected, an investigation of the impact of this radiation is warranted. An upcoming paper will provide a better understanding of the impact to flight thermal protection systems and to quantify the uncertainty in the simulations [25].

5.2. Heating Correlations

There have been several attempts to provide relatively simple correlations to describe the convective and radiative heat fluxes in terms of general parameters, such

as freestream pressure/density, shock speed, gas composition and vehicle size [26, 27, 28]. For appropriate conditions, these correlations have been shown to accurately predict convective and radiative heat flux. However, several simplifications were made in the development of these correlations, such as assuming the shock layer is in equilibrium and that radiation has no effect on the flowfield. The new correlations, which do not rely on these assumptions, have been developed based on an extensive suite of simulations. To increase confidence in the updated correlations, the results of several previous analyses that validated NASA's radiation codes for high speed Earth entry are utilized [6, 29, 30, 31], such as was discussed in Section 3.1. These works showed that the radiation models provided excellent agreement with the shock tube data under equilibrium conditions.

Updated convective and radiative stagnation-point heating correlations were evaluated for a variety of Earth entry conditions [32]. The correlations were based on the characterization of stagnation-point convective and radiative heat flux to an entry vehicle over a range of velocities, densities and nose radii. The simulations were compared with the established correlations of Fay-Riddell and Sutton-Graves for convective heating and Tauber-Sutton for radiative heating. Both the radiative and convective heating values were computed using state-of-the-art coupled LAURA/HARA simulations. The treatment of thermochemical non-equilibrium effects in the LAURA flowfield solution and non-Boltzmann modeling in the HARA radiation solution represented significant modeling improvements over the previous Sutton-Graves convective heating correlation and the Sutton-Hartung radiative heating tables (which were used for the Tauber-Sutton correlations). As flowfield-radiation coupling becomes more significant at higher shock speeds (i.e. $> \sim 11$ km/s), the present work extends the range of validity by including non-adiabatic effects. The coupling of the radiation and flowfield not only affects the radiative heat flux to the vehicle's surface, but also the convective heat flux. Coupling removes energy from the flow, reducing enthalpy available to drive convective heating. At the same time, however, radiation absorbed in the boundary layer may increase heating by increasing the boundary layer temperature and energy. A total of 648 LAURA/HARA solutions were used in the analysis in order to provide correlations that covered densities from 1×10^{-5} to 5×10^{-3} kg/m³ and vehicle radii from 0.2 to 10 m and velocities of 3 to 17 km/s for convective and 9.5 to 17 km/s for radiative heating. A comparison between the Tauber-Sutton correlation and the updated correlations [32], as a fraction of the total heat flux, is shown in Fig. 4. The updated correlations provide an estimate of the total heat flux for any given mission entering Earth's atmosphere, and show improved agreement with the LAURA/HARA solutions compared to previous correlations in terms of the mean, standard deviation and maximum error. Furthermore, the parameter space of the fit is expanded, reducing the reliance on extrapolation for almost any conceivable air entry scenarios.

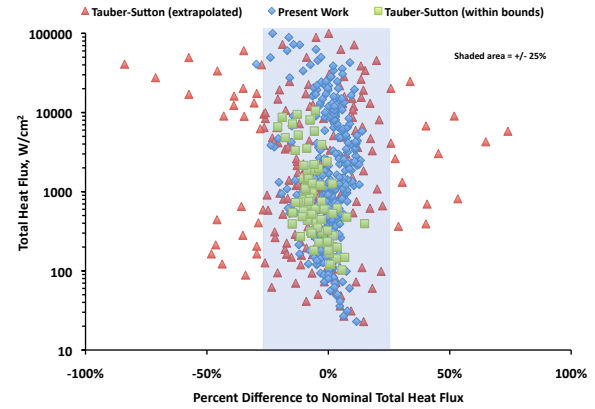


Figure 4. Comparison of CFD results with the updated radiative heating correlation and the Tauber-Sutton relation.

5.3. New Kinetic Model for Mars Entry

The influence of radiative heating on the aerothermal environment of future NASA missions to Mars is potentially significant [33]. Concepts such as hypersonic inflatable aerodynamic decelerators (HIADs) [34] may consist of a geometry similar to a 70 degree sphere cone with a diameter as large as 20 m. This large diameter will result in radiative heating that is a significant fraction of the convective heating, if not larger. Proposed materials for the inflatable structure have relatively low heat flux limits (≈ 40 W/cm²) [34]. The accurate prediction of the radiative and convective heating at these low magnitudes, which will likely occur at high altitudes with strong shock-layer thermochemical non-equilibrium, presents a significant challenge for NASA's present aerothermodynamic simulation capability. An outstanding issue in the determination of kinetic models from EAST is due to the assumptions that must be made about the physical models required to infer the rates. The derived rates depend on assumptions regarding both the CO QSS model and the CO spectroscopic constants used in the simulation, neither of which are understood to great accuracy at present. If either one of these is determined to be substantially in error, then the kinetics would need to be reformulated.

Prior to EAST Test campaign 54, all Mars tests used a mixture of 96% CO₂ : 4% N₂ by volume. However, the major constituents of the Martian atmosphere are actually 95.7% CO₂ : 2.7% N₂ : 1.6% Ar by volume. Therefore, Test 54 examined the influence of changing from the approximate Mars composition to a more accurate composition. Electronic temperatures were extracted from Planck-limited portions of the spectrum and analyzed for fast and slow relaxation times which are associated with the decomposition of CO₂ and CO, respectively. Analysis of CN relaxation was performed via the CN Violet radiation. Relaxation times, found to be weakly dependent upon composition [10], were compared to times extracted from stagnation line calculations performed with reaction rates recommended by Johnston et al in 2012 [11]. Disagreements in experimentally inferred relaxation times

and those from stagnation line computations prompted a re-examination of rates of certain reactions, which led to an alternate reaction rate set being proposed by Cruden et al [10].

The study by Cruden et al [10] identified that the fast dissociation of NO, which provided an important pathway for CO dissociation through a two-step process, was of particular importance. Therefore, in order to provide good agreement with EAST, the NO dissociation rate was decreased by using the work of Tsang and Herron [35] and the CO dissociation rate increased based on the work of Hanson [36]. These new rates were found to give a better match to relaxation times for pure CO₂ [10]. The relaxation rate of CN was found to closely follow the temperature relaxation and is reasonably well matched with the 2012 Johnston model [10, 11]. The impact of the 2012 Johnston [11] model and the Cruden model [10] was further investigated by calculating the non-equilibrium radiation as a function of position at 0.25 Torr [10]. Predictions at 0.1 Torr were not attempted due to the lack of a non-Boltzmann model in NEQAIR at the time. These predictions were found to generally match the peak radiance better primarily due to an increase in peak vibrational temperature [10]. Additionally, the non-equilibrium radiance, integrated over ± 2 cm, was found to be in better agreement with the Cruden model [10] than the 2012 Johnston model [11]. Even though the NO dissociation rate was found to be important in the work of Cruden et al [10], the rate was not used in the optimization performed as a part of the Johnston 2012 model [11].

Published at the end of 2014, a baseline simulation approach for Mars entry radiative heating predictions and associated uncertainty was developed [12]. Using recent EAST shock tube measurements of non-equilibrium CO 4th Positive and CN Violet emission at pressures and velocities ranging from 0.10 to 1.0 Torr and 6 to 8 km/s, the rate model was developed through an optimization procedure that minimizes the disagreement between the measured and simulated non-equilibrium radiance profiles. Unlike the model of Cruden et al [10], which specifically considered interactions between different reactions and used various literature sources for new rates, Johnston et al [11, 12] used an optimization procedure to minimize discrepancies between simulations and experiment.

There were two main differences between the analyses of Johnston et al in 2012 and 2014, which had significant impacts to the rates that were determined by the optimization. One difference being that the 2014 analysis incorporated the effect of the EAST Spatial Resolution Function (SRF) [37]. The SRF is applied to account for the smearing due to the optics, the charge spread of the CCD and the fact that the shock is moving during the exposure time. Therefore, the SRF is an important component for simulating non-equilibrium radiance. The other main difference being that more reaction rates were treated as unknown in the optimization routine due to the results of the analysis of Cruden et al [10], e.g. NO dissociation. As such, the 2014 Johnston optimization treated the dissociation rates of CO₂, CO and NO, along with CN + O and

CN + N, as unknown in the optimization procedure. The other rates were set to recent values from the literature. Due to the different constraints applied to the optimization, the rates determined were significantly different to what was previously published in 2012.

The end result of the optimization found that a factor of 5.2 increase in the CO dissociation rate relative to the previously widely used value provided the best agreement with measurements, while the CO₂ rate was not changed. Several other reactions were modified, with the new rates detailed in the paper by Johnston et al [12]. The developed model is found to capture the measured non-equilibrium radiance of CO 4th Positive and CN Violet within error bars of $\pm 30\%$ [12].

6. CONCLUSION

This paper has presented a summary of all the experiments showing useful data performed in EAST since the facility upgrade in 2008. In particular, the paper has highlighted conditions where well characterized data is available (e.g. high speed Earth entry and Mars entry conditions), and where obtaining more experimental data from other facilities would be highly beneficial (e.g. VUV measurements for Venus entry and Earth entry conditions below 10 km/s). An overview of recent work from the Radiation Modeling and Validation task at NASA has also been provided. Details were shown on three separate research areas: 1) after-body radiation for Mars and Earth entries, 2) new radiative and convective heating correlations for Earth entry and 3) new kinetic models for Mars entry.

ACKNOWLEDGMENTS

The authors would like to thank the NASA Space Technology Mission Directorate (STMD) Entry Systems and Modeling (ESM) project for their support of this work, in particular, Drs Michael Wright and Michael Barnhardt. Drs Aaron Brandis and Brett Cruden are supported through the NNA10DE12C contract between NASA Ames Research Center and ERC Inc.

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Atmosphere	Test Campaign No.	Pressure, Torr	Average, km/s	Min, km/s	Max, km/s	No. of Shots
Earth (Lunar Return)	47	0.1	10.0	10.0	10.0	1
		0.2	10.8	9.5	10.8	34
		0.3	9.9	9.8	9.9	3
		0.7	9.7	8.9	10.1	4
		Total Shots:				
Mars	48	<0.02	9.3	8.9	9.7	2
		0.1	8.5	8.0	8.8	6
		0.2 (slow)	3.4	1.3	3.9	5
		0.2 (mid)	6.2	6.2	6.2	1
		0.2 (fast)	9.6	9.2	10.0	2
		0.25	7.3	6.5	8.1	14
		1 (slow)	3.1	3.0	3.2	11
		1 (mid)	4.4	3.9	4.6	3
		1 (fast)	7.5	6.7	8.3	14
Total Shots:					58	
Venus	49	0.5	10.9	9.7	12.2	8
		0.7	9.5	9.5	9.5	1
		1.0	9.3	8.8	9.7	9
		2.0	7.1	6.4	7.7	3
		Total Shots:				
Earth (Lunar Return)	50	0.1	10.6	8.8	12.0	28
		0.2	9.8	8.0	11.3	49
		0.5	9.6	8.6	10.0	16
		0.9	9.1	8.5	9.8	11
		1.0	9.7	9.1	10.6	7
		Total Shots:				
Mars	51	0.05	7.4	7.2	7.8	4
		0.1	6.9	6.0	8.0	20
		0.25	6.5	6.3	6.8	10
		1.0	6.0	5.7	6.3	3
		Total Shots:				
Earth (High Speed)	52	0.1	13.4	11.3	15.5	8
		0.2	12.8	11.9	13.6	5
		Total Shots:				
Mars (High Altitude) 24" Tube	53	0.01	8.4	8.4	8.4	1
		0.05	7.2	6.4	8.6	24
		0.1	6.7	6.4	7.2	11
		Total Shots:				
Mars	54	0.05	7.3	7.1	7.4	4
		0.1	7.0	6.6	7.9	23
		0.25	6.5	6.2	7.4	14
		0.5	6.4	6.3	6.6	7
		1 (slow)	3.5	3.0	3.9	13
		1 (mid)	5.1	4.6	5.7	10
		1 (fast)	7.4	7.1	8.1	6
		Total Shots:				
Mars (Mars Science Lab)	55	0.15	5.6	5.3	5.9	7
		0.5	4.9	4.8	5.2	9
		1.0	3.6	3.5	3.8	11
		1.4	2.7	2.6	3.5	8
		1.55	2.2	1.9	2.7	10
		Total Shots:				
Outer Planets	56	0.1	26.2	23.2	28.7	7
		0.2	27.1	25.6	28.7	9
		0.5	25.4	20.3	29.6	11
		Total Shots:				

Table 1. Summary of EAST test conditions since facility upgrade