42nd AIAA Thermophysics Conference
27 - 30 June 2011, Honolulu, Hawaii

AIAA 2011-3141

# Uncertainty Assessment of Hypersonic Aerothermodynamics Prediction Capability

Deepak Bose,* James L. Brown,#
*NASA Ames Research Center, Moffett Field, CA 94035, USA*

Dinesh K. Prabhu,§
*ERC Inc., NASA Ames Research Center, Moffett Field, CA 94035, USA*

and

Peter Gnoffo,† Christopher O. Johnston,‡ and Brian Hollis¶
*NASA Langley Research Center, Hampton, VA 23681, USA*

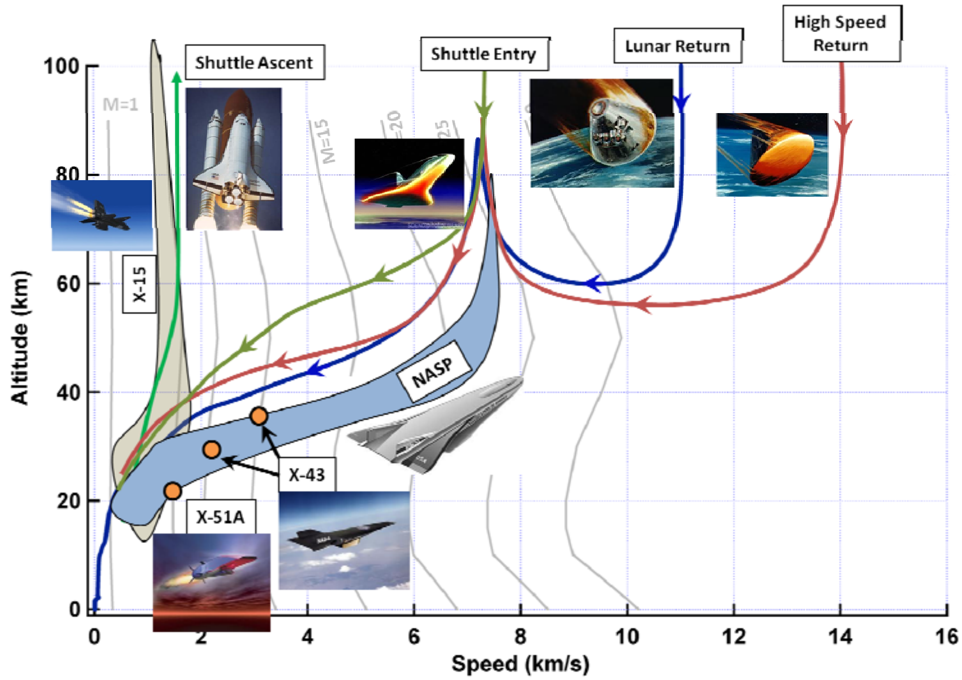
**The present paper provides the background of a focused effort to assess uncertainties in predictions of heat flux and pressure in hypersonic flight (airbreathing or atmospheric entry) using state-of-the-art aerothermodynamics codes. The assessment is performed for four mission relevant problems: (1) shock turbulent boundary layer interaction on a compression corner, (2) shock turbulent boundary layer interaction due to an impinging shock, (3) high-mass Mars entry and aerocapture, and (4) high speed return to Earth. A validation based uncertainty assessment approach with reliance on subject matter expertise is used. A code verification exercise with code-to-code comparisons and comparisons against well established correlations is also included in this effort. A thorough review of the literature in search of validation experiments is performed, which identified a scarcity of ground based validation experiments at hypersonic conditions. In particular, a shortage of useable experimental data at flight like enthalpies and Reynolds numbers is found. The uncertainties for the four mission relevant problems were quantified using metrics that measured discrepancy between model predictions and experimental data. The discrepancy data are statistically analyzed and investigated for physics based trends in order to define a meaningful quantified uncertainty. The detailed uncertainty assessment of each mission relevant problem is found in four companion papers.**

## 1. Introduction

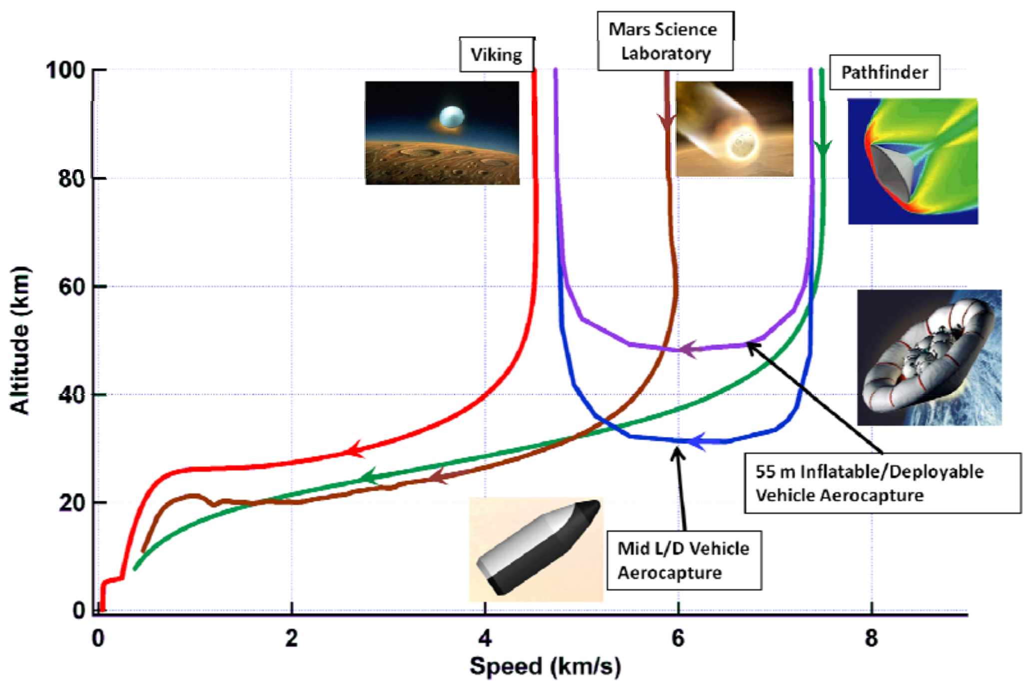
A hypersonic vehicle encounters an aerothermodynamic environment characterized by strong shocks and high temperatures that result in heating of the vehicle.[1,2] The severity of the environment strongly depends on the mission profile and the vehicle configuration. Figure 1 shows representative hypersonic flight profiles and conditions of interest to NASA in Earth and Mars atmospheres. It is noted that the hypersonic flight regime covers a large range of speed and altitude. As an example, airbreathing vehicles, such as X-43 and X51A, fly at low altitude and high dynamic pressure where the aerothermal environment is dominated by fluid dynamics effects. The vehicle heating is highest at leading edges, in the regions with shock interactions, and in downstream locations where the flow transitions to turbulence. On the other hand, a high speed planetary entry blunt vehicle, such as the Galileo probe entering Jupiter or a high speed Earth return capsule, encounters an aerothermal environment dominated by high enthalpy effects. A high enthalpy flow in planetary entry is characterized by elevated levels of ionization, and may result in significant radiative heating and high heat shield ablation rates.

---

* Aerospace Engineer, AIAA Associate Fellow
# Research Scientist, AIAA Member
§ Senior Research Scientist, AIAA Associate Fellow
† Senior Research Engineer, AIAA Fellow
‡ Aerospace Engineer, AIAA Member
¶ Aerospace Engineer, AIAA Associate Fellow




(a)




(b)

Figure 1. Representative hypersonic flight trajectories in (a) Earth and (b) Mars atmospheres

The aerodynamic and aerothermodynamic loads on a hypersonic vehicle set the performance requirements for various sub-systems, such as the thermal protection system (TPS), the control system, and if applicable, the airbreathing propulsion system. The design and safe operation of these vehicles, therefore, require adequate definition of the aerodynamic and aerothermodynamic environment (thermal and mechanical loads, and stability characteristics). As in most flight regimes, these design loads cannot be solely obtained from ground test facilities, as no facility can reproduce all aspects of the flight environment. This limitation is particularly true for the hypersonic flight due to a very high energy requirement to create a true hypersonic environment at a reasonable scale on the ground. The designers, therefore, rely on computational predictive capability. The computational predictions are generally made using computational fluid dynamics (CFD) codes that use a suite of thermo-physical models, to account for various physical phenomena occurring in hypersonic flows. The thermo-physical models are mostly derived from a combination of theoretical and empirical assessments based on perhaps a limited amount of experimental data. The applicability and importance of a particular model is dependent on the state of the flow as represented by enthalpy, gas mixture, Reynolds number, Mach number, Knudsen number, etc. The physical models and numerical techniques have error and uncertainties in their results. These uncertainties are caused by a variety of factors that include inherent assumptions, lack of knowledge/data, application of physical models beyond the validated range, and other errors accepted in the interest of developing a practical design tool. The net result is often a large prediction uncertainty which could be as high as a factor of two in heat flux. In many cases the uncertainties are simply unknown and overly conservative estimates become necessary. It is therefore critical that an uncertainty assessment of the aerothermodynamic predictions is made in order to provide a measure of confidence and apply it to design margins.

The Aerodynamics, Aerothermodynamics, and Plasmadynamics (AAP) Discipline[3] of NASA's Hypersonics Project within the Fundamental Aeronautics Program has undertaken an effort to make quantitative uncertainty assessments of the state-of-the-art CFD predicted aerothermal environments. The primary objectives of this effort are:

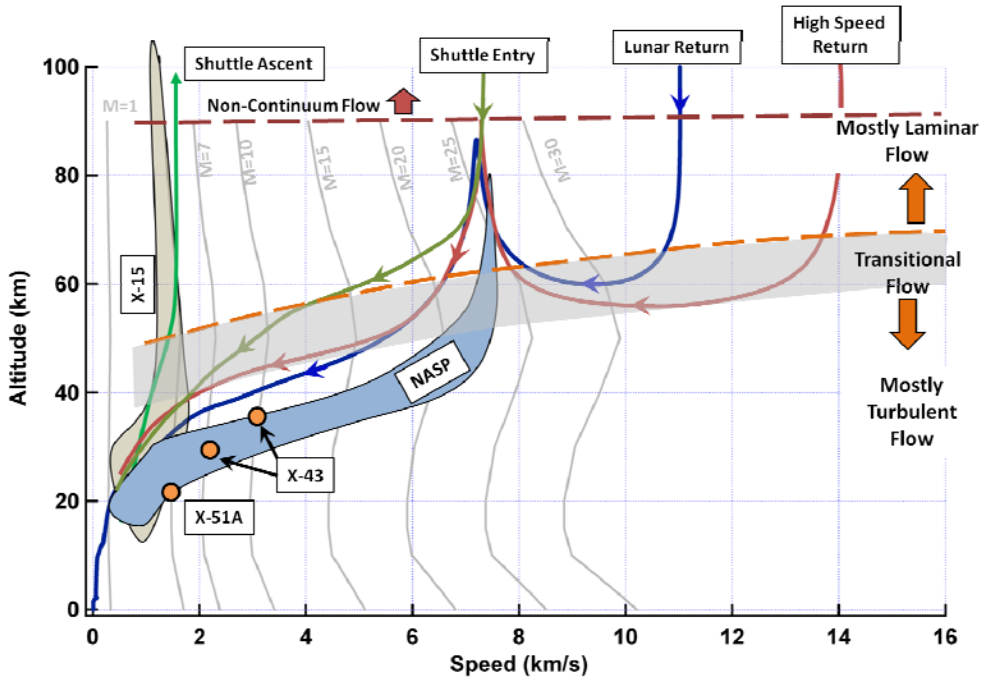
1. To establish the baseline state-of-the-art (SOA) in hypersonic aerothermodynamics modeling capability
2. To define quantified uncertainty metrics in order to gage advancement in the SOA
3. To identify the primary drivers of uncertainty and help define research priorities
4. To provide baseline aerothermal uncertainties for future system studies and flight project margin assessments

Given the wide range of flow conditions encountered in hypersonic flight, as discussed before, a meaningful aerothermal prediction uncertainty can only be defined for a specific flight condition. Even for a given flight condition, the aerothermal prediction uncertainty varies significantly depending on the location on the vehicle. For example, our predictive capability of the stagnation point heating may be significantly more mature than the ability to predict heating in a separated flow region with shock interactions. Similarly, our ability to predict heating in an attached laminar flow is significantly better than that in a transitional or turbulent flow. The scope of this uncertainty assessment effort is defined by four mission relevant problems (MRPs). These MRPs are selected at a variety of flight conditions relevant for airbreathing as well as planetary entry vehicles. The flight conditions are chosen near the maximum heating point on a representative trajectory. The details of the MRPs are given in Sec. 3.

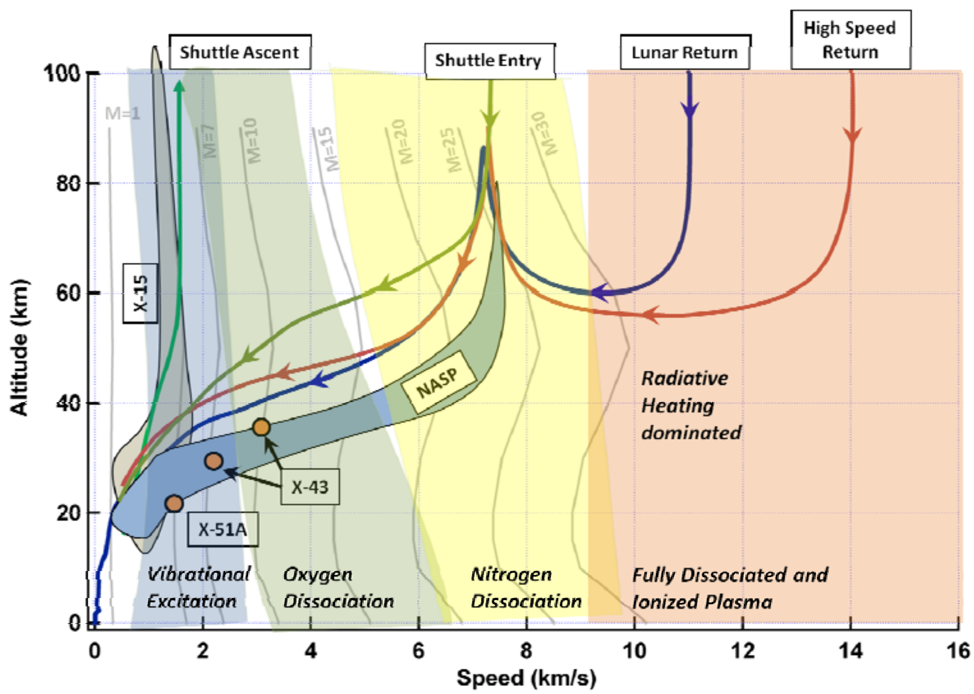
There exists a significant body of literature on uncertainty assessment techniques.[4,5] In this effort, a suitable approach was used by considering various factors such as the model complexity, availability of validation quality data, the level of effort, and the final objectives of the study. Section 4 discusses the uncertainty assessment approach. The uncertainty assessment was performed by a team of subject matter experts with background in the computational/theoretical as well as experimental aspects. Our approach is based on model validation of physical models and computational tools that relies substantially on expert judgment. The uncertainty assessment for each of the MRPs is presented in a separate paper[6-9] to be presented in this Special Session titled Hypersonic Aerothermodynamics Uncertainty Assessment. In Sec. 5, we briefly discuss the results of the uncertainty assessment.

## 2. Hypersonic Flight Regimes and Sources of Modeling Uncertainty

Hypersonic flight, as shown in Fig. 1, spans a wide range of altitude and speed, and occurs in different planetary atmospheres. The critical aerothermodynamic phenomena also vary widely as these conditions change. Fig. 2 shows the regions on the altitude-speed map where various physical phenomena become important. This section discusses a few different classes of hypersonic vehicles and the associated aerothermodynamic phenomena that cause modeling uncertainties.




(a)




(b)

Figure 2. Map of physical phenomena occurring at different flight conditions (a) fluid dynamics effects (laminar to turbulence transition is estimated using a simple Reynolds number correlation at 10 m scale) and (b) real gas/high enthalpy effects.

We begin with an airbreathing hypersonic cruise vehicle capable of sustained flight at Mach 5-7 in a high dynamic pressure trajectory. The aerothermodynamic environment on these vehicles will be dominated by turbulence, and shock-shock and shock-boundary layer interactions. The shock interactions typically occur at the scramjet inlet and isolator sections, and also on external aerodynamic surfaces. These interactions may not only lead to localized heating that is much higher than the surrounding areas, but may also influence the aerodynamics of the vehicle. The predictive capability in this environment is governed by inadequacies in turbulence models, especially in the regions with shock interactions and flow separation. A detailed discussion on the assessment Reynolds Averaged Navier Stokes (RANS) turbulence models in hypersonic flows, which is used in design, is available in Ref. 10. Over portions of the vehicle, the flow may also be transitional, which would bring another source of uncertainty.  A prediction of boundary layer transition is well recognized as one of the most difficult challenges in fluid dynamics. In terms of real gas effects, there is some vibrational excitation possible in this flight regime; however, its impact on aerothermal prediction *uncertainty* would be small, except maybe in the prediction of the extent of flow separation.

For airbreathing access-to-space vehicles, the Mach number and maximum altitude is higher depending on the staging mach number for a two-stage system. In general, for access-to-space vehicles the real gas effects would be significant as vibrational excitation and some dissociation of oxygen will occur due to strong shocks at leading edges and due to viscous dissipation in the boundary layer. NASA's X-43 flight at Mach 9.8 falls in this category. The single-stage-to-orbit National AeroSpace Plane (NASP)[11] trajectory, studied in 1990s, involved airbreathing flight at high mach numbers and speed, where complete oxygen dissociation is possible and even some nitrogen dissociation. Also, an access-to-space vehicle flies through a transitional flow regime resulting in more uncertainty due to difficulties in the prediction of boundary layer transition.

The entry vehicles of interest to NASA generally encounter higher speeds/mach numbers and fly at lower dynamic pressures than airbreathing hypersonic vehicles. The trajectory of an entry vehicle is dependent on the entry speed, flight path angle, the ballistic coefficient, atmospheric properties, and the lift-to-drag (L/D) ratio. A winged entry vehicle, like the Space Shuttle Orbiter, enters from the low earth orbit at a speed around 7.5 km/s and flies at a higher altitude with lower dynamic pressure (relative to an airbreathing vehicle). The arothermodynamic environment during the Orbiter entry is dominated by shock interactions (on the leading edge of the wing), surface catalycity due to recombination of dissociated species, and boundary layer transition. The boundary layer transition generally occurs at Mach number below 6-7 in a nominal Orbiter entry. However, unusual surface roughness on the thermal protection system can cause a premature boundary layer transition as oberserved by the HYHIRM observation campaign.[12]

An entry on a lunar return trajectory, such as the Apollo Command Module entry, occurs at 10-11 km/s.[13] At these conditions the heat flux is high enough that a blunt vehicle with an ablative heat shield is used. The vehicle flies through laminar, transitional, and turbulent environments. The transition to turbulence is expected to occur sooner than smooth-wall predictions due to surface roughness of an ablating heat shield. The design of these vehicles are generally done using a fully turbulent aerothermal environment.[14] At the peak heating point in the trajectory, there is significant high enthalpy effect where the flow is almost fully dissociated into atomic species and a considerable portion of the flow is in thermal and chemical nonequilibrium. This occurs as the flow encounters a strong bow shock in front of the vehicle and loses much of its kinetic energy. The ionization levels are generally substantial (~10%) with significant radiative heating. Much of the uncertainty in this flow regime comes from the ability to model turbulence over a rough ablating surface in a high enthalpy environment with thermochemical nonequilibrium. Radiative heating also contributes significantly to prediction uncertainty.[15]

An even higher speed entry at Earth is possible when a vehicle returns on a hyperbolic trajectory.[16] The speed of such an entry can be as high as 12-16 km/s. This would be the case for a sample return mission (Stardust and Genesis) and a human return mission from Mars or an asteroid. The harsh aerothermal environment around the vehicle is dominated by strong ionization, high radiative heating, and high blowing rates of the ablating TPS.[17] In fact, the blowing rates at the surface under this condition can be large enough to push the boundary layer away from the vehicle and reduce the convective heating to near zero. The envronment is dominated by a strong coupling of flow, radiation and ablation. The uncertainty in this extreme entry is due to very high temperature phenomena and the interaction of radiation with ablation. Turbulent mixing of the ablation and atmospheric gases at the blowing boundary layer also has an impact.

While planetary entry into many solar system bodies is of interest to NASA, we only discuss entries into atmspheres of Earth and Mars in this paper. Typical entry profiles at Mars for aerocapture and entry trajectories are shown in Fig. 1b. These speeds are generally high enough to cause significant dissociation of $CO_2$, a main constituent of Martian atmosphere. The aerothermal heating is dominated by gas-surface interaction at the vehicle surface in addition to possible nonequilibrium radiative heating. Diatomics such as CO and CN that are formed in this environment have strong radiative properties. Much of the catalytic properties are material dependent and cause significant uncertainty in predictions. A conservative prediction is usually made using a supercatalytic model which ensures a full conversion of chemical enthalpy into heat at the surface. Recently, Edquist et al.[18] assessed the aerothermal uncertainty for the Mars Science Labortaory entry scheduled to occur in 2012.

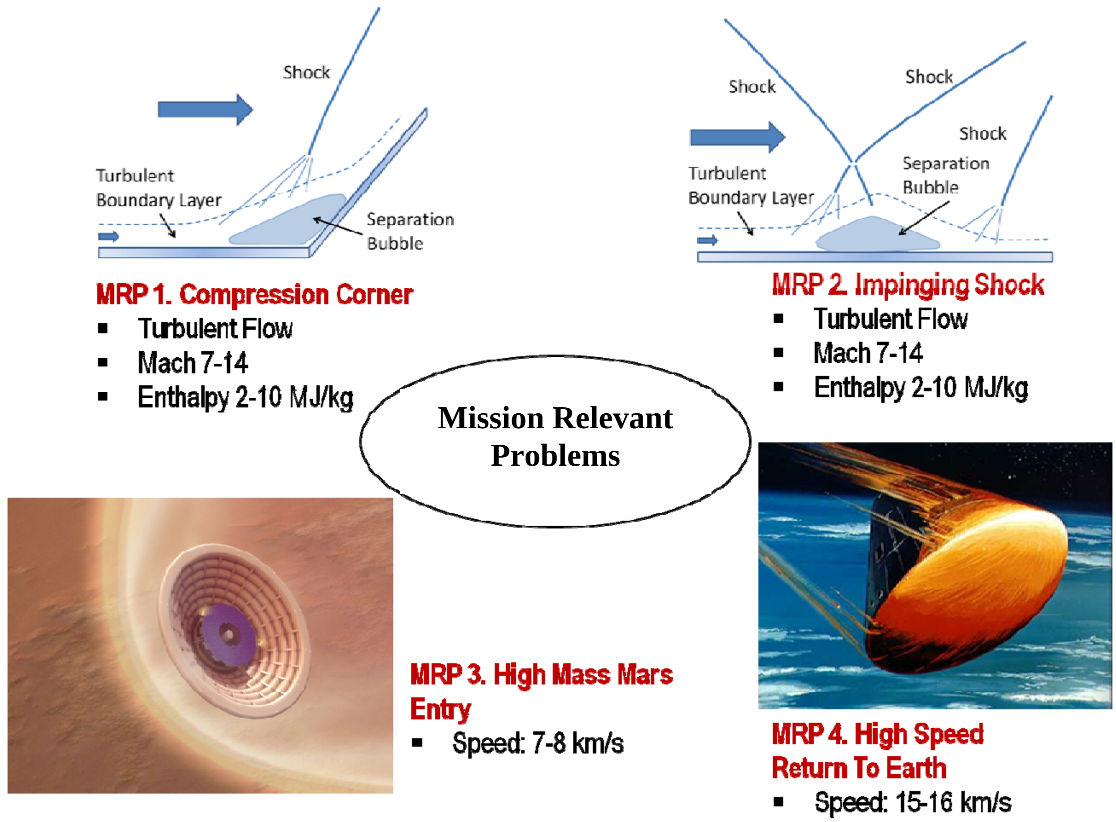
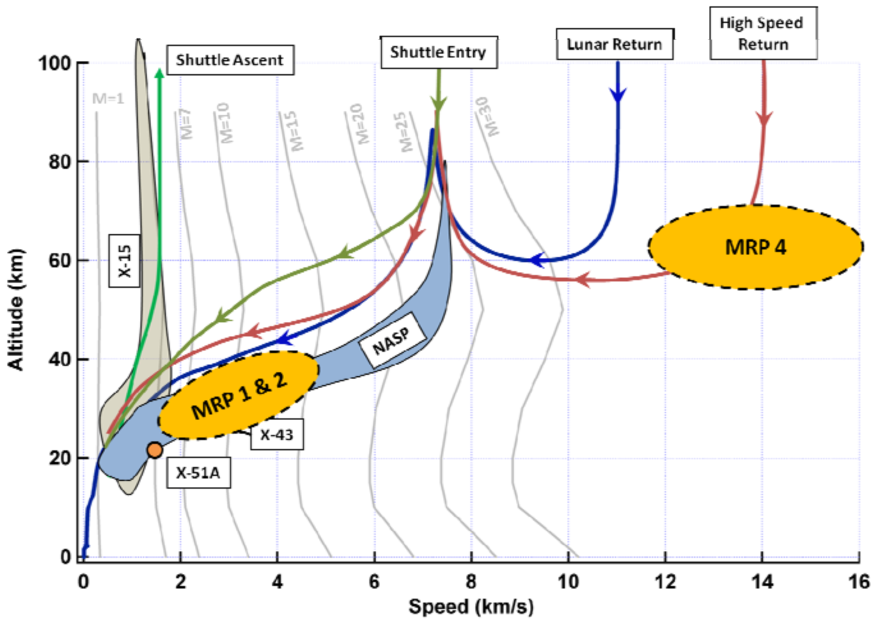



Figure 3. Mission relevant problems (MRPs) considered in this uncertainty assessment effort

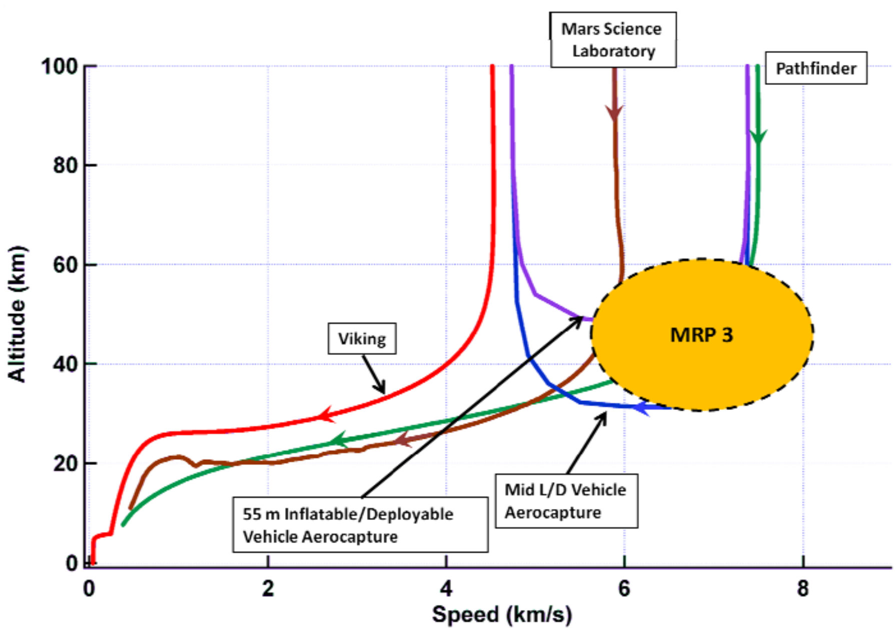
## 2. Mission Relevant Problems and Scope

The scope of the present effort is to assess aerothermodynamic modeling uncertainty for four mission relevant problems (MRPs) defined in this section. The MRPs are chosen from flight profiles of both airbreathing and entry vehicles. Before we define the MRPs, a few observations on the importance of boundary layer transition is appropriate. Although we recognize the significance of boundary layer transition in many hypersonic flows, we have excluded this factor from our uncertainty assessment. The flows in our MRPs are considered either fully laminar or fully turbulent. Given the relatively immature state-of-the-art in boundary layer transition modeling, its contribution to aerothermodynamic modeling uncertainty may be significant. Much of the uncertainty in the prediction of boundary layer transition is likely from poor definition of factors that trigger transition, such as surface roughness and blowing, and freestream noise. On a vehicle with ablative TPS, the surface roughness and blowing evolves throughout the flight. Moreover, the transition mechanisms, especially when it is caused by surface roughness, are generally poorly understood. Boundary layer transition also suffers from the lack of clean validation quality data. However, the recent use of quiet hypersonic tunnels has begun to change that.[19,20] Many of the transition predictions for design are still made using empirical correlations with limited validity. This difficult subject requires a separate consideration, and is not included in the scope of the present effort.

The MRPs are schematically shown in Fig. 3 with nominal conditions. The relevance of the MRPs and how they map on to hypersonic flight profiles are shown in Fig. 4. The highlighted MRP regions in Fig. 4 represent the region of peak heating in their respective vehicle trajectories.




(a)




(b)

Figure 4. Nominal conditions of the mission relevant problems selected for the uncertainty assessment

*MRP 1. Shock-Turbulent Boundary Layer Interaction on a Compression Corner (Mach 7-14)*

A hypersonic flow over a compression corner occurs in a scramjet inlet and on control surfaces. Under the flight conditions highlighted in Figs. 3 and 4, a shock interaction will occur with a turbulent boundary layer that may lead to flow separation and localized peaking of pressure, shear, and heating. The shock interaction also has implications on vehicle drag, scramjet mass capture, and the effectiveness of a control surface. There is considerable uncertainty in CFD predictions of shock induced separation and the distribution of heating and shear profile. In addition there are very limited data available to validate turbulence models in flight relevant Mach numbers under real gas conditions. This MRP is studied in detail in the companion paper titled, "Uncertainty Assessments of 2D and Axisymmetric Hypersonic Shock Wave-Turbulent Boundary Layer Interactions Simulations at Compression Corners" by Gnoffo et al.[6]

*MRP 2. Impinging Shock on a Turbulent Boundary Layer (Mach 7-14)*

Impinging oblique shocks on turbulent boundary layers are encountered in scramjet inlets and isolators following the initial compression. The impinging shock also tends to separate the boundary layer and result in a sharp rise in heat flux at the reattachment point. The interaction of the shock has implications on vehicle drag and irreversible losses that impact engine performance. The flow conditions chosen are shown in Figs. 3 and 4. Similar to the compression corner case, there is only a limited set of validation data available in flight relevant enthalpy and Mach numbers. This MRP is studied in the companion paper titled, "Shock Wave Impingement on Boundary Layers at Hypersonic Speeds: Computational Analysis and Uncertainty" by Brown.[7]

*MRP 3. High Mass Mars Entry and Aerocapture*

A NASA entry, descent, and landing systems analysis (EDL-SA) team has recently defined candidate entry vehicle configurations and flight conditions for high mass (~40 metric tons) Mars landers.[21] Two specific configurations were studied for hypersonic aerocapture and entry: a larger deployable/inflatable blunt configuration and a mid L/D rigid configuration. An aerocapture maneuver uses atmospheric drag in a single-pass to capture a vehicle into an orbit around the planet. Their nominal aerocapture trajectories are shown in Figure 1(b). This MRP concerns only with blunt configurations. A mid L/D vehicle will be studied in future. At 7.4 km/s, the vehicle aerothermodynamics will be dominated by high enthalpy effects, such as gas phase chemistry and gas-surface interaction. In ground testing, which is done on non-ablative surfaces, catalytic properties of the model and instrumentation surfaces are important. Surface catalycity releases heat as dissociated species recombine at the surface. Ground test data are also mostly available in low to moderate enthalpy conditions where catalycity is only moderately active.[22] In addition to gas-surface interaction, vehicle heating due to nonequilibrium radiation from CN, CO, and other species will also be significant for large diameter configurations. This MRP is studied in the companion paper titled, "Assessment of Laminar Convective Aeroheating Predictions Uncertainties for Mars Entry Vehicles", by Hollis and Prabhu.[8]

*MRP 4. High Speed Return to Earth*

A high speed return vehicle from an interplanetary trip or a sample return mission would enter Earth atmosphere at speeds in the range of 12-16 km/s. These high speeds of a large vehicle would cause extreme amount of radiative heating, and a large mass blowing due to ablation on the surface. Unlike in other MRPs, the aerothermodynamics at this condition is less dominated by fluid mechanics effects and more governed by high temperature physics such as strong ionization, radiation, interaction of radiation and ablation species, etc. Ground testing that captures this extreme environment is not yet possible. Much of the model validation occurs in very small scale laboratory devices such as arcs and shock tubes. The MRP conditions are shown in Figs. 3 and 4, and are studied in detail in the companion paper titled, "Assessment of Radiative Heating Uncertainty for Hyperbolic Earth Entry", by Johnston et al. [9]

## 3. Uncertainty Assessment Approach and Challenges

A suitable approach to use for uncertainty assessment is dependent on various factors. Many approaches are available with varying degree of applicability. A number of papers by Oberkampf and co-workers[4,5] outline the necessary steps involved in an uncertainty assessment and discuss their pros and cons. In our study we consider uncertainty of two types: parametric and structural (also called model-form uncertainty). Uncertainty can be further classified into reducible (epistemic) and irreducible (aleatory) type. In this work we consider only reducible uncertainties that can, in principle, be continually reduced with increased knowledge. In our case these are generally fundamental physics properties whose uncertainty can be reduced by additional measurements. The irreducible uncertainty such as trajectory variabilities due to natural variation in atmospheric properties, and guidance and control are considered beyond the scope of this study. We also do not address uncertainties that arise from manufacturing and operational aspects of a vehicle.

A parametric uncertainty analysis approach assigns uncertainty intervals, and in some cases, probability distribution functions, to all relevant model input parameters based on the level of knowledge.[23,24] These uncertainties are then propagated through the computational model using a variety of techniques, such as a linear sensitivity analysis, a Monte Carlo technique, or another approach. The output uncertainties are then analyzed and characterized. This approach, however, is only sufficient if the physical model form is correct and the only unknowns in the model are the values of the input parameters. This is almost never the case in hypersonic aerothermodynamics.

Much of the uncertainty is aerothermodynamics originates from inadequacies in physical models, i.e. uncertainties are structural. Physical models, by definition, are attempted mathematical representation of physical phenomena that cannot be (or are not) directly simulated. For example, a turbulence model is an attempted mathematical representation and not a direct simulation of turbulence. Another example is a chemistry model, which is an attempted mathematical representation constructed using phenomena observed in experiments aided with theoretical insight, empiricism, and hypotheses. The models are only approximations of truth since they rely on simplifications and assumptions. Therefore, the only reasonable approach to assess the uncertainty in these models is via validation against experimental measurements at relevant conditions, which forms the basis of our effort.

A validation based approach, while preferred, also has its limitations. The impact of these limitations on uncertainty assessment must be assessed by a subject matter expert on a case specific basis. Following are some of the challenges well recognized in hypersonic aerothermodynamics.

1) *A general lack of validation quality data:* Experimental data in hypersonics is generally sparse due to high costs involved in acquiring flight data, testing in ground facilities, and developing instrumentation. As an example, Settles and Dodson[25] in 1991 conducted an extensive literature review of hypersonic shock boundary layer interaction for model validation. As they filtered the available experiments in the literature through necessary criteria for hypersonic code validation, they found only five validation quality experiments; one fin generated shock experiment, three compression corner experiments, and one impinging shock case. Two decades later, as part of this study, Brown identified only three impinging shock experiments for validation.[7] The general lack of data is even more evident in high enthalpy flows. In the case of high speed Earth return, for example, Johnston et al. did not find any spectrally resolved radiation data above 12 km/s.[9] The data they did find was for integrated intensity and needed careful use of physics based scaling law. In the case of Mars entry, no useable data at high enthalpy under turbulent flow conditions was found. It is also commonplace to find datasets with incomplete information that prevent its use for model validation. A small experimental dataset, while extremely useful for point-wise validation, is generally unable to validate the trends predicted by a computational model which is key to estimating structural problems with a model. An expert judgment that is vetted by peers is critical to making reasonable conclusions from such validation studies.

2) *A general lack of flight relevant data:* It is well known that hypersonic ground facilities cannot reproduce all aspects of a flight environment.[26] While it is not within the scope of this paper to critically evaluate hypersonic ground test facilities, a few general observations about ground to flight traceability must be made. It is generally known that obtaining flow conditions that simultaneously replicate the most critical aspects of the flight environment is not possible. For example, it is generally very difficult to produce flight relevant enthalpies (> 10-20 MJ/kg) in a turbulent flow environment. All of the shock turbulent boundary layer interaction data identified in study are obtained in low enthalpy facilities. The direct consequence in this case is that the turbulence models remain un-validated at elevated enthalpies where real gas and chemistry effects are present. Turbulence, clearly,

has a significant role in the transport of chemical species (which also carry chemical enthalpy) in addition to momentum and heat. The investigation in this study also showed that very high enthalpy data (>50 MJ/kg), relevant for hyperbolic earth entry, are not generally available at scales larger than a few mm to a cm. While high enthalpy data is precious at any scale, physics based scaling laws must be used to justify relevance to flight. An example of the use of high pressure constricted arc data is demonstrated by Johnston et al.[9] using a pressure-length scaling. The judgment of a subject matter expert is necessary to correctly interpret the data in order to perform validation. In Sec. 5 we discuss the gaps that exist between conditions where we test and the conditions where we fly. The ground to flight traceability challenge for each MRP is also discussed in individual papers.

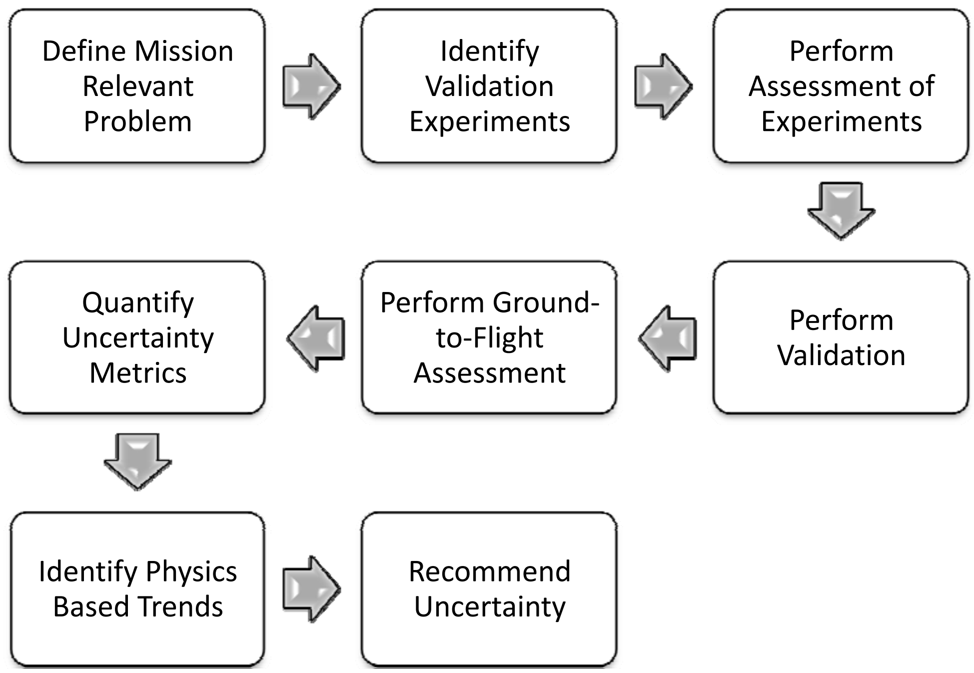


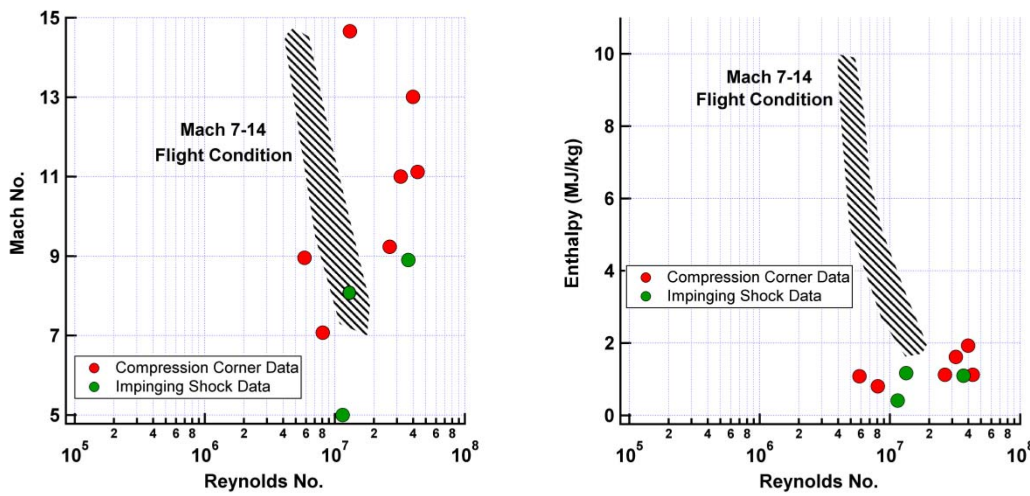

Figure 5. Uncertainty assessment approach

3) *Uncertainty in ground tests data:* All measurements have associated uncertainty, however, in hypersonics the uncertainty is further amplified by the fact that conditions in the test facility is often inadequately defined.[27] This, of course, poses a key challenge in model validation where predictions are compared against data that are uncertain themselves. Neither model predictions nor measurements give truth values. This is particularly true in high enthalpy flows where temperatures are high and test times are generally short and conventional instrumentation cannot be used. The measurements that are made are indirect and may require use of complex and uncertain models. There are several approaches that may be used to incorporate experimental uncertainty into an overall model uncertainty assessment. One of the approaches used here is to assess the overlap between error bars associated with measurements to that associated with model predictions. Another approach is to simply stack measurement uncertainty in the assessment. This area obviously need further work and will be subject of future uncertainty assessments. An example of how inadequate facility freestream definition can lead to significant disagreement between model and measurements is found in MacLean.[28]

Our uncertainty assessment approach, schematically represented in Fig. 5, uses relevant information from validation with experiments and recognizes ground-to-flight traceability issues. Expert judgment is used throughout to evaluate experiments, define uncertainty metrics for a given problem, and quantify uncertainty values.

## 4. Uncertainty Assessment Results

In this section we summarize the uncertainty assessment results obtained for each MRP. It is emphasized that the uncertainty assessment study for each MRP was led by a subject matter expert and the computational codes and tools used were not treated as black-box. Although the uncertainty assessment technique used for each MRP was slightly different, they were all based on validation against ground based experiments in hypersonic conditions. The quantitative uncertainty obtained in this study for each MRP must be understood in the context of the scope of the study and various assumptions that has been made.[6-9] The reader is strongly recommended to review the relevant paper associated with each MRP uncertainty assessment effort.




(a) (b)

Figure 6. Conditions where validation data are available for MRP 1 and 2 and how they relate to airbreathing flight conditions (a) Mach number vs. Reynolds number, and (b) enthalpy vs. Reynolds number

*MRP 1. Shock-Turbulent Boundary Layer Interaction on a Compression Corner*

The uncertainty assessment for the flow over a compression corner involved several steps that included evaluation of a suite of turbulence models against validation data at hypersonic conditions, a grid convergence study, verification using code-to-code comparisons, and an assessment of ground-to-flight differences. The detailed assessment is presented in Ref. 6. Six commonly used RANS eddy-viscosity turbulence models, implemented in NASA's LAURA code,[29] were evaluated against experimental data on compression corners and flat plates at conditions shown in Fig. 6. The code-to-code comparisons were made using solutions from NASA's DPLR[30] and VULCAN[31] codes, also used for hypersonics flow simulations. In addition, past simulations available in literature were also included. It was found that computational predictions depend heavily on how the turbulence model was implemented. It was also noted that no turbulence model among the five that were chosen stood out as the superior one. As shown in Fig. 6 (b), there is a lack of shock-turbulent boundary layer interaction data on compression corners at flight like enthalpy. The study performed additional evaluation of high enthalpy effects, namely variable specific heats and chemistry, although no validation against experimental data could be made.

A set of coarse grained uncertainty metrics were defined to quantify computational predictive capability. These metrics focused on predictions of pressure, heat flux, and shear at locations before and after the interaction. The uncertainty metrics also captured the separation bubble size. A combined computational prediction uncertainty of ±55%, based on the median disagreement with data, is recommended for shock turbulent boundary layer interactions with flow separation. A conservative estimate of 64% uncertainty was recommended when experimental measurement uncertainty was also included.

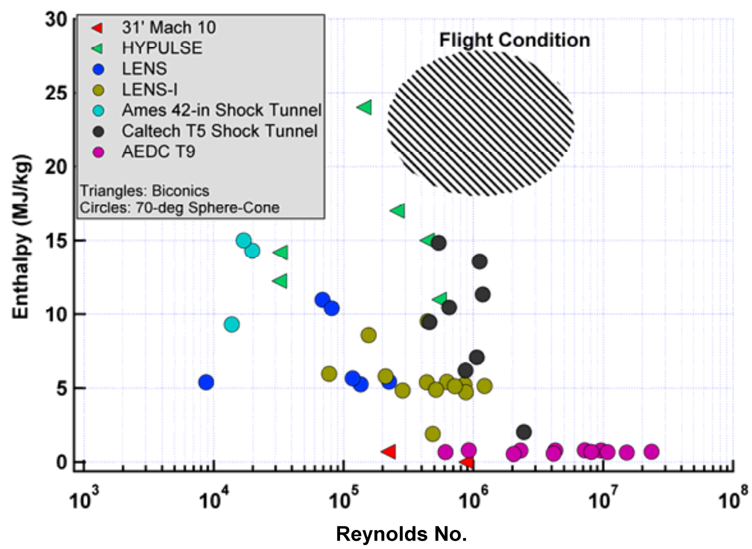



Figure 7. Conditions where validation data are available for MRP 3 and how they relate to flight conditions in an enthalpy vs. Reynolds number space

*MRP 2. Impinging Shock on a Turbulent Boundary Layer*

The uncertainty assessment of aerothermal predictions of impinging shock turbulent boundary layer interaction phenomena is presented in Ref. 7. The uncertainty metrics were defined for post interaction pressure and heat flux peaks, and a few parameters related to the separation zone. Only three sets of experimental conditions were found in hypersonic conditions as shown in Fig. 6. Each experiment had runs with and without flow separation. Three different RANS turbulence models: Spalart-Allmaras, Menter SST and Wilcox k-ω, as implemented in NASA DPLR code,[30] were considered. The implementation details and various model corrections can be found in Ref. 7. The uncertainty was quantified using a model versus experiment discrepancy factor, which was analyzed statistically to provide confidence intervals. The prediction uncertainty with 95% confidence in the post interaction region was found to be as high as ±55% for heating and ±15% for pressure. The uncertainties were much higher for predictions of the size of the separation zone and heating and pressure within this zone. Additionally, sensitivity of these parameters on real gas effects at flight conditions was also studied. The real gas effects were shown to increase peak heating by as much as 20% and reduce the extent of separation.

*MRP 3. High Mass Mars Entry and Aerocapture*

A high mass entry into Mars will occur at high enthalpy conditions (~20-25 MJ/kg) with regions of turbulent flow over the vehicle. Hollis and Prabhu[8] performed the uncertainty assessment for this MRP, and found that computational predictions are very sensitive to wall catalytic efficiency. The bounding limits due to catalycity can be obtained by implementing a non-catalytic and a supercatalytic (forcing full recombination of dissociated species) condition at the surface. The uncertainty assessment was based on comparisons of model predictions of heat flux on a blunt body with various experimental datasets from shock and expansion tunnels available at conditions shown in Fig. 7. It is found that model validation is particularly challenging because of poor definition of facility freestream characterization and an unknown catalytic efficiency of the test model/instrumentation surface. The low enthalpy data, which did not suffer from either of those effects, compared very well with model predictions. The discrepancy between model and data became progressively worse as the enthalpy increased, so much so that even the shock stand-off distances were not predicted well. The non-catalytic heat flux significantly under predicted the data, while a supercatalytic prediction fell consistently above. The uncertainty based on the discrepancy between model and data is found to be about ±15% in low enthalpy cases (<5 MJ/kg) and ±60% at high enthalpy cases (> 10 MJ/kg). It was also identified that high enthalpy turbulent flow experiments, which were available from the shock tunnels, suffered from inconsistency and high uncertainty.

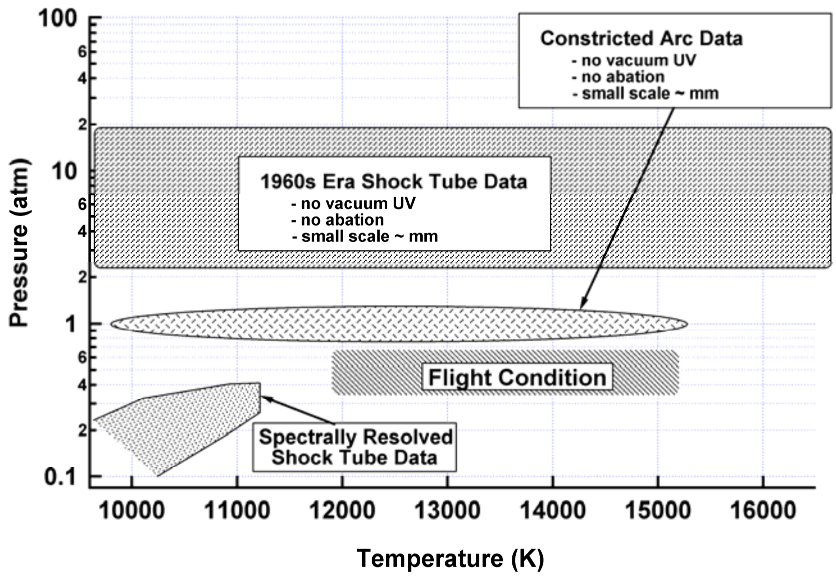



Figure 8. Post-shock pressure and temperature conditions where validation data are available for MRP 4 and how they relate to flight conditions.

<u>MRP 4. High Speed Return to Earth</u>

An uncertainty assessment in high speed entry is difficult due to extreme high temperature effects (T~16000 K) that challenge many fundamental assumptions made in a conventional aerothermodynamics model. High temperature effects are also difficult to produce in ground experiments at a reasonable scale which prevents adequate validation. Also, in such extreme entry speeds, the physical process such as fluid dynamics, radiation and ablation become strongly coupled, whereas their validation can only be done on a piecewise basis. Johnston et al.[9] performed a detailed uncertainty assessment for this MRP. The uncertainty assessment approach used here differed from the approaches used in other MRPs. A detailed parametric uncertainty analysis was performed with coupled CFD, ablation, and radiation codes, LAURA+HARA.[32] Additional uncertainty was added to account for structural uncertainties arising from turbulent mixing in the ablating boundary layer, precursor ionization and absorption upstream of the bow shock, three dimensional radiation transport, and grid convergence. The assessment effort included an extensive validation with shock tube and constricted arc data that reproduced flight like temperatures, but were at a much smaller scale. A physics based scaling law was used to justify flight relevance of the data. A detailed spectral validation of the radiation model was also performed, although only at lower speeds (<11.5 km/s). The conditions where validation data are available are shown in Fig. 8. A code-to-code comparison was also made using two radiations codes HARA[32] and NEQAIR.[33] Considerable expert judgment guided by modeling was used to assess the effect of radiation absorption by ablation products. The overall uncertainty was determined to be +78%/-53% at 15 km/s for stagnation point heating.

## 5. Concluding Remarks

An assessment of aerothermodynamics prediction uncertainty is performed for four mission relevant hypersonic airbreathing and entry flights. The objective of this effort was to establish quantitative metrics to define the state-of-the-art in hypersonic aerothermodynamics modeling. It is realized that the physical models included in aerothermodynamics CFD tools carry significant uncertainty and have been subject to limited validation in hypersonic conditions. Our effort employed a validation based uncertainty assessment approach with considerable use of subject matter expertise. The subject matter expertise was necessary because of a sparse set of validation data that was available, which in many cases came with incomplete information and inadequate documentation. In addition, subject matter expertise was required to use complex physical models and to assess implications due to ground-to-flight differences.

A thorough literature search found a critical shortage of validation experimental data in hypersonic conditions. It was especially challenging to find data that captured important flight relevant effects, like high enthalpy and turbulence occurring simultaneously, $CO_2$ chemistry with defined surface catalycity, radiation interacting with ablation, etc. A few cases of inadequate definition/documentation of the experimental conditions was also identified, such as incomplete information on geometry, flow unsteadiness, incoming state of the boundary layer, freestream thermochemical state, etc. Despite these challenges, assessment of uncertainty in the prediction of heat transfer, pressure and other MRP relevant quantities were made. The detailed study for each MRP is presented in a separate companion paper, although a short summary of the results is presented in this paper.

It is our belief that while these uncertainty values are not perfect, they provide a reasonable assessment of the state-of-the-art, which is supported by extensive analysis of existing data. The recommended uncertainty values also provide initial estimates for aerothermal margins for future flight projects or systems analysis studies. This study also highlights gaps that exist in modeling as well as validation experiments that will help mitigate these uncertainties.

**Acknowledgements**

We would like to thank Drs. Scott Berry, Bil Kleb, and Brett Cruden for providing insights into experimental measurements and uncertainty assessment techniques. We would especially like to thank Dr. Joe Marvin for his critical reviews and expert judgment during this assessment process. We acknowledge several discussions with Drs. Jeffery White, Chris Rumsey, Michael Olsen, and Robert Baurle on appropriate use of turbulence models. Special thanks are due to Drs. Amy Cassady, Karl Edquist, and Brian Andersen who provided us with aerothermal uncertainty assessment of Orion (Crew Exploration Vehicle), Mars Science Laboratory, and Space Shuttle Orbiter flights respectively. We are grateful to Dr. Gary Allen and Dr. Jeff Robinson for providing flight trajectory information. We also thank Dr. Jim Pittman, NASA Hypersonics Project Manager, for his suggestions and support during this activity, and Michael Wright, Todd White, and Charles Smith for reviewing this manuscript.

**References**

1. Bertin, J. J., *Hypersonic Aerothermodynamics*, AIAA Education Series, Washington DC, 1994.
2. Park, C., *Nonequilibrium Hypersonic Aerothermodynamics*, Wiley, New York, 1990.
3. Bose, D., “Hypersonic Aerodynamics, Aerothermodynamics, and Plasmadynamics Research Activities within NASA’s Fundamental Aeronautics Program,” AIAA Paper No. 2009-7278, Oct. 2009.
4. Roy, C.J. and Oberkampf, W.L., “A Comprehensive Framework for Verification, Validation, and Uncertainty Quantification in Scientific Computing,” Comput. Methods Appl. Mech. Engrg. Vol. 200, 2011, pp 2131-2144.
5. Oberkampf, W.L., Helton, J.C., and Sentz, K., “Mathematical Representation of Uncertainty,” AIAA Paper No. 2001-1645, Apr. 2001.
6. Gnoffo, P.A., Berry, S.A., Van Norman, J.W., “Uncertainty Assessments in Simulations of 2D/Axisymmetric Hypersonic Shock Wave-Turbulent Boundary Layer Interactions at Compression Corners”, AIAA Paper (*to be presented at the 42$^{nd}$ AIAA Thermophysics Conference, Jun 27-30, 2011*)
7. Brown, J.L., “Shock Wave Impingement on Boundary Layers at Hypersonic Speeds: Computational Analysis and Uncertainty,” AIAA Paper (*to be presented at the 42$^{nd}$ AIAA Thermophysics Conference, Jun 27-30, 2011*)

8. Hollis, B.R. and Prabhu, D.K., "Assessment of Laminar Convective Aeroheating Predictions Uncertainties for Mars Entry Vehicles," AIAA Paper (*to be presented at the 42nd AIAA Thermophysics Conference, Jun 27-30, 2011*)
9. Johnston, C.O., Mazaheri, A., Gnoffo, P.A., Kleb, B., Sutton, K., Prabhu, D.K., Brandis, and Bose, D., "Assessment of Radiative Heating Uncertainty for Hyperbolic Earth Entry," AIAA Paper (*to be presented at the 42nd AIAA Thermophysics Conference, Jun 27-30, 2011*)
10. Roy, C., and Blottner, F.G., "Review and Assessment of Turbulence Models for Hypersonic Flows", Progress in Aerospace Sciences, Vol. 42, 2006, pp. 469-530.
11. Thomas, J. and Powell, W., "The NASP Program – A Status Report," AIAA Paper No. 1192-1417
12. Horvath, T., et al., "The Hythirm Project: Flight Thermography of the Space Shuttle During Hypersonic Re-entry," AIAA Paper No. 2010-241, Jan. 2010.
13. Lee, D.B., Bertin, J.B., and Goodrich, W.D., "Heat Transfer Rate and Pressure Measurements Obtained During Apollo Orbital Entries," NASA TN D-6028, Oct. 1970.
14. Kinney, D.J., " Development of the Orion Crew Exploration Vehicle's Aerothermal Database Using a Combination of High Fidelity CFD and Engineering Level Methods," AIAA Paper No. 2009-1100, Jan 2009.
15. Bose, D., McCorkle, E., Bogdanoff, D.B., and Allen, G., "Comparisons of Air Radiation Model with Shock Tube Measurements," AIAA Paper No. 2009-1030, Jan 2009.
16. Robinson, J., Wurster, K., and Mills, J., "Entry Trajectory and Aeroheating Environment Definition for Capsule Shaped Vehicles," JSR, vol. 46, no. 1, 2009.
17. Johnston, C., Gnoffo, P., and Sutton, K., "Influence of Ablation on Radiative Heating for Earth Entry," JSR, Vol. 46, No. 3, 2009.
18. Edquist, K.T., Dyakonov, A.A., Wright, M.J., and Tang, C.Y., "Aerothermodynamic Design of the Mars Science Laboratory Heatshield," AIAA Paper No. 2009-4075, Jun 2009.
19. Schneider S. P., "The Development of Hypersonic Quiet Tunnels," AIAA Paper No. 2007-4486, Jun. 2007.
20. Kegerise, M.A., Owens, L.R., and King, R.A., "High-Speed Boundary Layer Transition Induced by an Isolated Roughness Element," AIAA Paper No. 2010-4999, Jun 2010.
21. Dwyer-Ciancolo, A.M., et al., "Entry, Descent and Landing Systems Analysis Study: Phase 1 Report," NASA TM-2010-216720, Jul. 2010.
22. Wright, M.J., Tang, C.Y., Edquist, K.T., Hollis, B.R., Krasa, P., and Campbell, C.A., "A Review of Aerothermal Modeling for Mars Entry Missions," AIAA Paper No. 2010-0443, Jan. 2010.
23. Bose, D., Wright, M.J., Gokcen, T., "Uncertainty and Sensitivity Analysis of Thermochemical Modeling for Titan Atmospheric Entry," AIAA Paper No. 2004-2455, Jun. 2004.
24. Kleb, B, and Johnston, C.O., "Uncertainty Analysis of Air Radiation for Lunar Return Shock Layers," AIAA Paper No. 2008-6388.
25. Settles, G.S. and Dodson, L.J., "Hypersonic Shock/Boundary layer Interaction Database," NASA CR 177577, April 1991.
26. Lukasiewicz, J., *Experimental Methods of Hypersonics*, Marcel Dekker, Inc., New York 1973.
27. MacLean, M., Candler, G.V., and Holden, M., "Numerical Evaluation of Flow Conditions in the LENS Reflected Shock Tunnel Facilities," AIAA Paper No. 2005-903, Jan. 2005.
28. MacLean and Holden, M., "Numerical Assessment of Data in Catalytic and Transitional Flows for Martian Entry," AIAA Paper No. 2006-2946, Jun. 2006.
29. Mazaheri, A., Gnoffo, P.A., Johnston, C.O., and Kleb, B., "LAURA Users Manual," NASA TM 2010-216836, 2010.
30. Wright, M.J., Candler, G.V., and Bose, D., "Data-Parallel Line Relaxation Method for the Navier-Stokes Equations," *AIAA Journal*, Vol. 36, No. 9, 1998, pp. 1603-1609.
31. White, J.A. and Morrison, J.H., "A Pseudo-Temporal Multi-Grid Relaxation Scheme for Solving Parabolized Navier-Stokes Equations," AIAA Paper No. 99-3360, Jun 1999.
32. Johnston, C.O., Hollis, B.R., and Sutton, K., "Spectrum Modeling for Air Shock-Layer Radiation at Lunar Return Conditions," *J. of Spacecraft and Rockets*, Vol. 45, Sep.-Oct. 2008, pp 865-878.
33. Whiting, E.E., Yen, L., Arnold, J.O., and Paterson, J.A., "NEQAIR96, Nonequilibrium and Equilibrium Radiative Transport and Spectra Program: User's Manual," NASA RP-1389, Dec. 1996.