Development of a Tool to Recreate the Mars Science Laboratory Aerothermal Environment

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The Mars Science Laboratory will enter the Martian atmosphere in 2012 with multiple char depth sensors and in-depth thermocouples in its heatshield. The aerothermal environment experienced by MSL may be computationally recreated using the data from the sensors and a material response program, such as the Fully Implicit Ablation and Thermal (FIAT) response program, through the matching of the char depth and thermocouple predictions of the material response program to the sensor data. A tool, CHanging Inputs from the Environment of FIAT (CHIEF), was developed to iteratively change different environmental conditions such that FIAT predictions match within certain criteria applied to an external data set. The computational environment is changed by iterating on the enthalpy, pressure, or heat transfer coefficient at certain times in the trajectory. CHIEF was initially compared against arc-jet test data from the development of the MSL heatshield and then against simulated sensor data derived from design trajectories for MSL. CHIEF was able to match char depth and in-depth thermocouple temperatures within the bounds placed upon it for these cases. Further refinement of CHIEF to compare multiple time points and assign convergence criteria may improve accuracy.

Nomenclature

B' = Dimensionless mass blowing rate
C_H = Stanton number for heat transfer
C_{H1} = Stanton number for heat transfer for a nonablating surface
C_M = Stanton number for mass transfer
F = View factor
h = Enthalpy, J/kg
H_r = Recovery enthalpy, J/kg
$\dot{m}$ = Mass flux, kg/m^{2}s
q_c = Conductive heat flux, W/m^2
q_r = Radiative heat flux, W/m^2
T = Temperature, K
ε = Surface emissivity
λ = Blowing reduction parameter
σ = Stefen-Boltzmann constant, W/m^{2}K^4

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Subscripts

c = Char
g = Pyrolysis gas
w = Wall

I. Introduction

WHEN comparing computational material response models against arc-jet test data, flow properties such as cold wall heat flux and enthalpy are inferred from slug calorimeters, pressure taps and measurements of the facility energy balance. By design, most arc-jet tests are at relatively constant conditions, for example, constant enthalpy, pressure, and heat flux. The aerothermal environments provided by these measurements can then be passed into a material response program and a comparison between the predicted values of parameters such as recession and surface temperature from the model and the experimental data can be made. The Fully Implicit Ablation and Thermal[1] (FIAT) response model is an example of a material response program that uses environmental inputs to predict the effects on a material exposed to that environment.

If only the in-depth effects of an aerothermal environment on the material are known, one is left to solve the inverse problem, which is not readily achievable with a program such as FIAT. There could be a wide range of enthalpy and cold wall heat fluxes that generate a certain recession rate or char depth, especially if the exposure time to the environment is very long. To determine the aerothermal environment from measured data, one would need a tool outside of the material response program that compares the predicted data with the external data and changes the environmental inputs if the discrepancy between the two data sets is outside some tolerance. A tool, called CHanging Inputs from the Environment of FIAT (CHIEF), places the material response code inside an iterative loop, automatically altering the environmental input of FIAT so predictions better match expected results, either experimentally, from flight, or from simulated flight data. For initial testing of this tool, experimental data comes from arc-jet test data and simulated aerothermal environments for the Mars Science Laboratory (MSL).

The Mars Science Laboratory mission will attempt to land the largest payload ever on the surface of Mars: a 900 kilogram rover. As a result, the MSL entry capsule was designed to have the largest entry capsule diameter at 4.5 meters, an entry mass of over 2800 kg, and a ballistic coefficient of 115 kg/m^2. It is the first Mars entry vehicle that is expected to experience turbulent heating augmentation prior to peak-heating, thus, the predicted pressure and shear stresses will be greater than what was previously experienced by Pathfinder or the Mars Exploration rovers.[2,3] The Langley Aerothermodynamic Upwind Relaxation Algorithm[4] (LAURA) and Data Parallel Line Relaxation[5] (DPLR) Navier-Stokes programs were used to predict the MSL aerothermodynamic environments. The maximum predicted hotwall heat flux[4] for the original 2009 launch of MSL was 197 W/cm^2. As a result of the new 2011 launch trajectory, the maximum margined heat flux on the heatshield is predicted as 229 W/cm^2. The actual surface heat flux upon entry into the Martian atmosphere cannot be directly measured and must be reconstructed from other measurements. CHIEF iterates upon environmental inputs and makes a comparison between FIAT's char and thermocouple predictions and simulated data of a design trajectory, where edge enthalpy, pressure, and the heat transfer coefficient are known. From this comparison, CHIEF will either change the unknown environmental inputs to better match the data sets, or move on to the next time in the trajectory if the data is sufficiently matched up to that point in time. Though FIAT is run for the entire trajectory of interest, CHIEF will only carry out comparisons and iterate at defined points in the trajectory. The use of CHIEF to perform a "post-flight" analysis prelaunch of the MSL allows for refinement of procedures and tools needed when the actual post-flight analysis is conducted.

II. The Mars Science Laboratory

A. Heatshield

The Phenolic Impregnated Carbon Ablator[6] (PICA) was chosen as the heatshield material after the original choice of SLA-561V[7] was seen to have catastrophic failure in arc-jet tests that recreated flight-like enthalpies.[2] The thickness of the PICA heatshield, 3.18 cm (1.25 inches), was chosen due to mass considerations and time constraints but it was sized based on thermal requirements.[8] The heatshield thermal protection system (TPS) thickness is constant and is the thickest for a Mars entry vehicle.[5] Though the as-built heatshield is 3.18 cm in thickness, analysis indicates that only a thickness of 2.39 cm is required to maintain a bondline temperature of 260 degrees Celsius (533 K). Reference 7 contains a detailed description of the MSL PICA heatshield margins and sizing process.

B. Instrumentation

The MSL Entry, Descent, and Landing Instrumentation (MEDLI)[9] project was initiated in the winter of 2006 to deliver an instrumentation package for the MSL flight heatshield to better characterize the aerothermodynamic environment experienced during entry to the Martian atmosphere. There are two instrumentation suites in MEDLI: MEDLI Integrated Sensor Plug (MISP), consisting of temperature and char depth sensors, and the MEDLI Entry Air Data System (MEADS) pressure sensors. Reference 9 contains schematic drawings of the sensors. The MISP will be used to reconstruct surface heat flux and contains the Hollow aErothermal Ablation and Temperature (HEAT) sensor.[10] There are seven MEDLI locations (Fig. 1) on the heatshield, including two locations where significant turbulent heating and shear augmentation is expected (T2 and T3). In the actual entry into the Martian atmosphere surface pressure will be known from the MEADS sensors and enthalpy and Mach number can be determined by the density derived from pressure, entry velocity, and atmospheric models for the Martian atmosphere. There is some noise associated with the sensors and electronics and the same numerical filters applied to ground test MISP instruments may be applied to alleviate these effects.

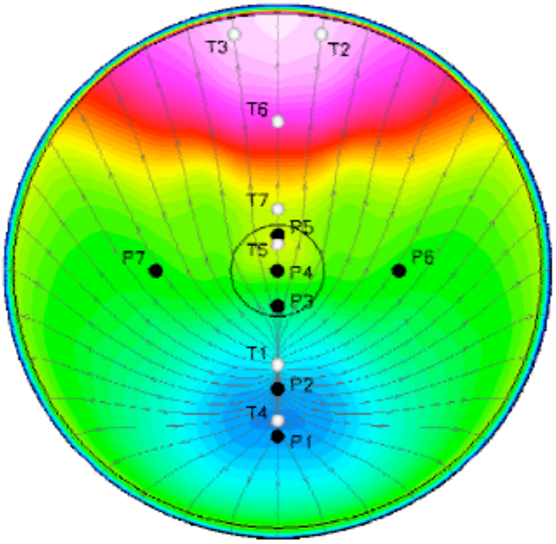


Figure 1. Heat flux distribution on the MSL aeroshell at an instant in time. The seven locations of the MISP sensors (T) and the MEADS sensors (P) are shown.

C. Environmental Reconstruction Requirements

For the MSL, there are certain requirements that are desired in what the instruments should be able to measure, the instrument location, and how accurate any computational model should come to the actual environment experienced upon entry, which is documented in the MEDLI Level 2 science requirements. Each Type K thermocouple in the MISP sensor should be able to measure the temperature range between 100-1300 Kelvin. The thermocouple depths are at 2.54, 5.08, 11.43, and 17.88 ± 0.25 millimeter below the initial surface of the heatshield. At one point in the design process, the requirement on the HEAT sensor was for it to measure the depth of a 973 K, ± 50 K isotherm through the thermal protection system (TPS) within ± 0.50 mm. The final temperature margin may differ upon completion of the calibration test program of the HEAT sensor. These bounds, 0.50 mm (0.05 cm) and 50 K, will be used in CHIEF to determine when the environment has been changed enough at a particular time point such that char or recession and thermocouple predictions match the external data set up to that point in time, allowing CHIEF to move on to the next point in the trajectory.

In recreating the environment, the heating levels are desired to be 25% of the actual levels. The recession rate estimated from near surface thermocouple and HEAT sensor data should be within 25% of the actual recession rate. One can also apply these margins to the predictions from FIAT such that the FIAT data is within 25% of some hypothetical data set. It is through both the physical margins, such as the 0.50 mm and 50 K requirements, and the percentage requirements, like 25% of the recession rate, which CHIEF uses to determine if the predicted parameters are similar to the external parameters.

III. Computational Setup

A. Fully Implicit Ablation and Thermal (FIAT) Response Program

FIAT computes the transient one-dimensional thermal response of Thermal Protection System (TPS) materials arranged in a multilayer stackup, subject to aerothermal heating on one surface, and can be loosely coupled to a Computational Fluid Dynamics (CFD) flow solver. The FIAT program is described in Ref. 1. While FIAT is able to predict material response at any point during an experiment or trajectory, from an environmental input standpoint, it does not need to have every time since it will simply linearly interpolate between the given points.

Heating may be predicted using a boundary condition that includes convection, radiation flux across the surface, heating due to chemistry, and conduction:

$$C_H(H_R - (1+B')h_w) + \dot{m}_g h_g + \dot{m}_c h_c + q_r - F\sigma\varepsilon_w T_w^4 - q_c = 0 \tag{1}$$

where C_H is the blown heat transfer coefficient and H_R is the recovery enthalpy. If the material is ablating, the blown heat transfer coefficient is derived from the corrected form of the unblown heat transfer coefficient, C_{H1}:

$$\frac{C_H}{C_{H1}} = \frac{2\lambda B'}{\exp(2\lambda B') - 1} = \frac{\ln(1+2\lambda B')}{2\lambda B'} \tag{2}$$

where

$$B_1' = \frac{\dot{m}}{C_{H1}}, B' = \frac{\dot{m}}{C_H}$$

The unblown heat transfer coefficient, which is used in nonablating cases, and the recovery enthalpy, which also may be called the edge or centerline enthalpy, both come from the environment prediction. They are used to calculate the cold wall heat flux. It is these parameters that CHIEF iterates upon, along with pressure.

To determine which of the three environmental inputs should be iterated upon first to reach a defined criteria, a sensitivity study is conducted (Table 1). The percent change is the difference between the new value and the baseline value, divided by the baseline. The test case is an arc-jet experiment (MQ08-1) run for MSL with a PICA coupon with a thickness of 2.29 cm. The slug cold wall heat flux is measured at 85 W/cm^2 with an edge enthalpy of 7.67 MJ/kg. The pressure during the test is 0.75 atmospheres (76 kilopascals). The in-depth thermocouples are placed at depths of 0.23, 0.49, 1.14, and 1.77 cm from the surface.

From the sensitivity study, it is apparent that changing pressure, going so far as to make it nearly zero, does not affect any material prediction by more than a 5%. A cursory glance at Eq. 1 would seem to explain why pressure has little affect on the material predictions, as it is not included in the surface energy balance and hence, would not play a large or direct role in determining the heating profile. From a surface chemistry standpoint, while pressure plays a role in determining the formation of char in the PICA *B'* table, charring rates are more dependent on the temperature and enthalpy upon the surface. In the hierarchy of which of the three parameters to iterate upon, pressure is the least sensitive. Like-changes in the enthalpy and heat transfer coefficient produced similar changes in the material predictions, except for the recession prediction. For recession, changing the enthalpy has little effect, but changing the heat transfer coefficient has a large effect, more than doubling the recession if the heat transfer coefficient doubles. This is due in part to the relationship between the heat transfer coefficient and the nondimensionalized ablation rate *B'* seen in Eq. 2. Thus, the order of iteration is determined to be the heat transfer coefficient first, enthalpy second, and pressure third. The relationship between the percent change in the input and the percent change in the predictions is used by CHIEF to determine what to do in case of over or underpredicitions.

FIAT is coupled to CHIEF, but FIAT is only used to provide predictions for CHIEF to compare to an external data set. FIAT is not changing its inputs. It is effectively running independently of CHIEF, using only the new environmental inputs that CHIEF provides.

Table 1. Sensitivity study using FIAT.

Percent Change in Input	Percent Change In Output					
	Char	Recession	Temp at TC 1	Temp at TC 2	Temp at TC 3	Temp at TC 4
Pressure						
-90	-0.38	0.33	2.1	-0.58	-0.33	-0.25
-50	-0.02	0.01	2.2	-0.34	-0.01	-0.01
10	0.01	-0.08	2.2	-0.33	0.0	0.0
50	0.01	-0.10	2.2	-0.33	0.0	0.0
100	0.01	-0.10	2.2	-0.33	0.0	0.0
Recovery Enthalpy						
-90	-87.21	-2.60	-41.37	-40.04	-27.02	-18.13
-50	-33.72	4.28	-14.75	-16.63	-10.50	-7.03
-10	-5.31	0.37	-0.59	-3.05	-1.71	-1.15
10	4.06	-0.41	4.76	2.20	1.56	1.06
50	17.04	-0.32	13.22	10.17	5.39	3.97
100	29.63	0.90	21.81	18.67	11.28	7.38
Heat Transfer Coeff						
-90	-99.97	-99.76	-49.50	-46.87	-31.85	-21.14
-50	-40.63	-65.36	-18.89	-20.33	-12.18	-7.72
-10	-6.12	-13.56	-1.45	-3.85	-2.02	-1.24
10	5.22	14.91	5.97	3.34	2.03	1.24
50	20.84	70.35	18.29	15.27	8.61	4.98
100	34.43	144.12	33.02	29.38	15.80	8.76

B. CHanging Inputs from the Environment of FIAT (CHIEF)

CHIEF can compare FIAT predictions of recession or char and up to four thermocouple locations to an external data set. It can also ignore any of those parameters during certain times in the analysis, either by user definition or by some iteration count. The sensitivity study provides a basis for the iteration order of the main environmental inputs but it does not provide the guidelines by which to move from one parameter to the next. In CHIEF, once a certain limit is reached when changing the heat transfer coefficient, such as the parameter is now one thousand times larger than its original guess and the predictions from FIAT do not fall within the margins assigned to that output, the coefficient is reset to its original value and the enthalpy is changed. How the enthalpy is changed depends on if the previous predictions are too large or too small when compared to the external data set and the margins. Once enthalpy is changed, iterations on the heat transfer coefficient begin again until the predictions meet the physical and percentile criteria or it reaches its limits again. For each time step, if the iterated enthalpy reaches specified limits and CHIEF still has not converged, then CHIEF alters the pressure with the enthalpy and the heat transfer coefficient reset to their original guesses and the process begins anew. The heat transfer coefficient will always be the most iterated upon parameter.

CHIEF can only make comparisons and change parameters at the time points used in the environmental input. CHIEF concentrates on the current time position and does not adjust multiple parameters over multiple time ranges at the same time. It is important then the original guess at the environment under analysis contains any areas of interest that can be determined by looking at the external data set, though the hypothetical environmental conditions that go along with that time need not be initially accurate. Also, since FIAT linearly interpolates between the conditions provided at each given time position, it is important that the points aren’t too closely grouped together or too widespread. Since CHIEF operates on one defined time location at any given moment, if the specified times are near each other over a short range and the predictions are not accurate, it is difficult to achieve accuracy due to the extreme dependency the closely packed previous time points have on the current time point owing to interpolation. Conversely, if the time points are too widespread, then it may be easier to achieve accuracy at the points explicitly defined in the input, but not in the time ranges in between those points. Time interval problems are due in part to the thermal lag for in-depth thermocouples.

Figure 2 shows the process by which CHIEF compares FIAT predictions with an external data set and how it changes the environmental parameters accordingly. If a prediction falls within the desired bounds, CHIEF moves on to the next time step using the previous time step’s heat transfer coefficient as its initial guess.

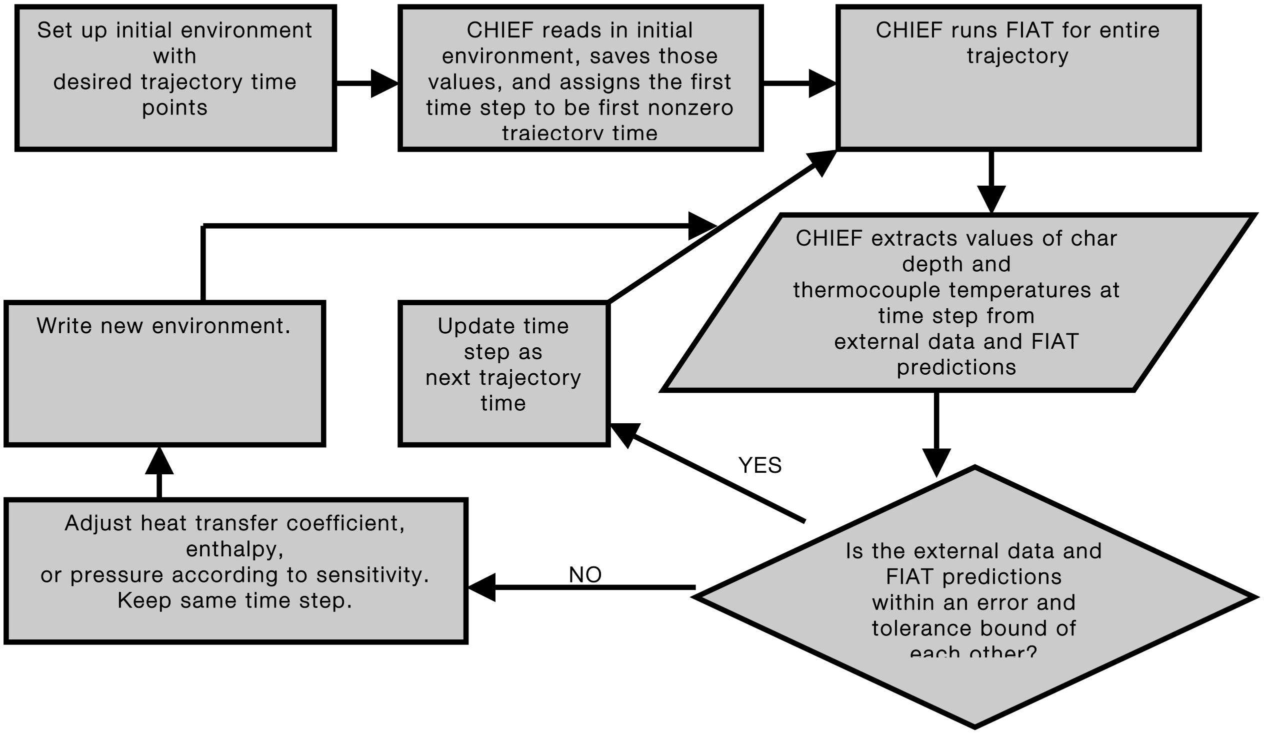


Figure 2. The flow chart of how CHIEF interacts with FIAT and how it adjusts the parameters of interest

IV. Using CHIEF to Match Data

A. MSL Arc-Jet

Data from arc-jet experiments, carried out to examine the HEAT sensor and PICA material for the purposes of MSL, are used to see if CHIEF can successfully match FIAT predictions to a measured data set. The arc-jet cases are chosen to be used first because the arc-jet environment is constant in time due to constant current and mass flow settings. Each arc-jet test coupon contains a MISP plug bonded at the center and is able to measure char depth and in-depth temperatures as a function of time. The first arc-jet experiment, MQ08-1, was exposed to the arc-jet conditions for 45 seconds, the environment is set up in FIAT with the measured edge enthalpy of 7.67 MJ/kg and pressure of 76 kPa. Each time step is 5 seconds from the previous one. The heat transfer coefficient could be calculated from the measured enthalpy and cold wall heat flux; however, during the actual descent into the Martian atmosphere, pressure will be known from measurements and enthalpy from computational flow dynamics, but not the cold wall heat flux. So for these arc-jet tests, the cold wall heat flux, while measured, is not used to compute the heat transfer coefficient, which is specified in CHIEF/FIAT as some arbitrary number to be iterated upon. Allowing the heat transfer coefficient to be some arbitrary number tests if enthalpy, a defined measured value, will significantly change in the FIAT environment through CHIEF iterations if the heat transfer coefficient does not start at the calculated value.

For MQ08-1, the bounds on matching the char data as measured by HEAT to the FIAT predictions are 0.05 cm and 20%. For the thermocouples, these values are 50 K and 20%. Starting from a completely arbitrary heat transfer coefficient, CHIEF is able to iteratively change the coefficient until FIAT recreates a char and temperature profile that seems to match the measured profile (Figs. 3 and 4). A root mean square analysis is performed to see if numerically the FIAT predictions are within the defined bounds. Root mean squared analyses[11,12] have been used before when dealing with an inverse parameter study such as the ones employed in this paper. The root mean square formula used is:

$$RMS = \left[\frac{1}{N}\sum_{i=1}^{N}\left(q_{i_{FIAT}} - q_{i_{Meas}}\right)^2\right]^{0.5} \tag{3}$$

where *N* is the number of data points being compared and *q* is the parameter being evaluated.

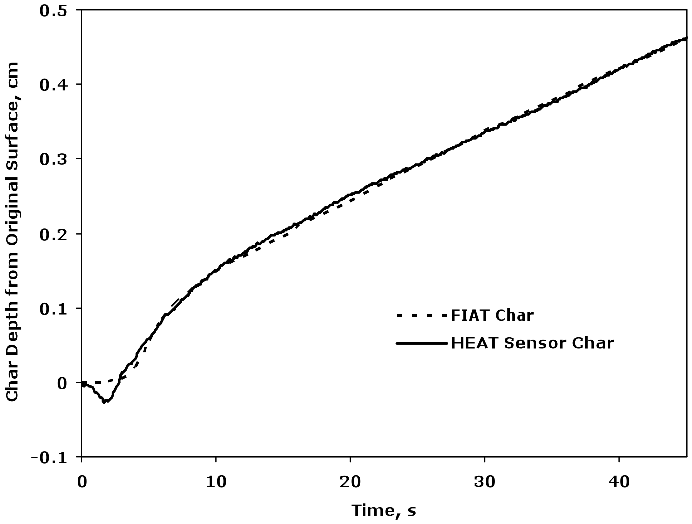


Figure 3. The char depth during the heating period measured by the HEAT sensor and predicted by FIAT through the use of CHIEF for MQ08-1

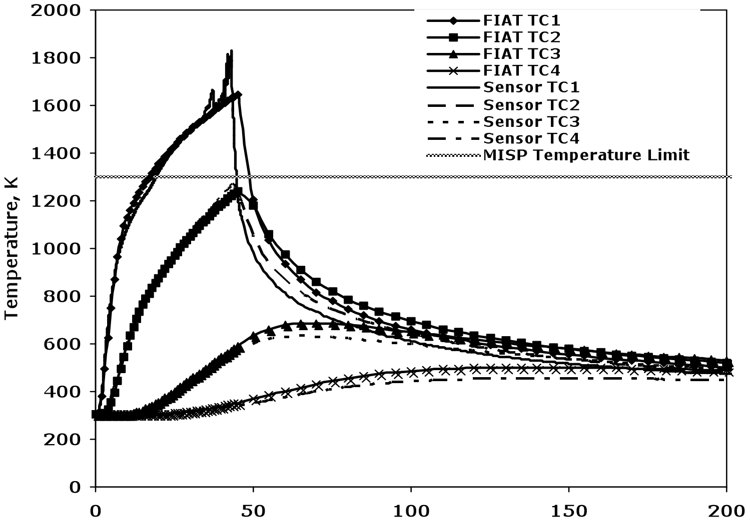


Figure 4. The in-depth temperature profile during the heating period and heat soak measured by the HEAT sensor and predicted by FIAT through the use of CHIEF for MQ08-1

The root mean square error analysis on the five predicted and measured parameters, char depth and four thermocouples, during the time of heating (where CHIEF is operating and has the greatest effect) shows that the predicted values are within the desired margins to the measured values assigned to the computation, that is, within 0.05 cm and 50 K. It should be noted the first five seconds of the measured values of char depth predicts "negative" char is due to the temperature coefficient of resistance of the platinum-tungsten wires in the HEAT increasing the initial temperature and resistance; this phenomenon is unable to be captured by FIAT calculations. The initial environmental guess for MQ08-1 ignores the initial HEAT sensor lag, with CHIEF starting iterations 5 seconds into the arc-jet conditions. It is also seen that the thermocouple data start to experience problems after the 1300 K threshold is reached. Since the sensor is only supposed to measure up to 1300 K, the data can experience fluctuations after that point, as seen in Fig. 4 for Sensor TC 1.

CHIEF's final enthalpy and pressure found in its environment recreation are constant in time and are the same values measured in the arc-jet test, whose values were used in the initial CHIEF environment guess. The heat transfer coefficient prediction reaches a constant state in time after 10 seconds, where it remains 0.073 kg/m^{2}s until 45 seconds, when FIAT considers the material out of the arc-jet. After 45 seconds, the heat transfer coefficient is set as zero. For the recession, the measured value is 0.25 cm, where FIAT with CHIEF predicts a recession of 0.20 cm, which is within the measurement error (± 0.05 cm). The cold wall heat flux is measured to be 85 W/cm^2, however, the final environment found by CHIEF predicts the cold wall heat flux to be 56 W/cm^2, which is a discrepancy of 34%. This is outside the requirement (25%) desired in recreating the heating environment. However, there may be error associated with the cold wall heat flux measurement. If the environment is actually 10% lower, at 77 W/cm^2, but the other measured values remain the same, then the CHIEF derived cold wall heat flux is within 27% of the measured heating environment, closer to the desired 25% heat flux recreation.

A second arc-jet test, MQ08-4 is recreated using CHIEF, using the same margins as for MQ08-1. For this test, the measured cold wall heat flux and the edge enthalpy are 270 W/cm^2 and 17.9 MJ/kg, respectively, and the coupon experiences arc-jet conditions for 30 seconds. The thermocouple depths are 0.24, 0.51, 1.15, and 1.76 cm. Once again, CHIEF's final enthalpy and pressure are constant in time and match the values measured in the arc-jet and used to initialize the environment. The heat transfer coefficient recreation from CHIEF is also constant in time at a value of 0.136 kg/m^{2}s until FIAT considers the material out of the arc-jet at 30 seconds, when the coefficient then goes to zero. CHIEF recreates the char depth (Fig. 5) with a root mean square error of 0.015 cm during the heating period. The thermocouple data (Fig. 6) is recreated within the 50 K margin. The cold wall heat flux constructed by CHIEF and FIAT is, again, slightly off from the measured value, with a CHIEF calculated heat flux of 243 W/cm^2. This is a more favorable result than the calculated cold wall heat flux from MQ08-1, since it is within 10% of the measured value. It is seen in the two arc-jet cases that CHIEF underpredicts the cold wall heat flux when recreating the aerothermal environment. The predicted recession, 0.24 cm, is outside the measurement error of the physical recession, which is recorded as 0.33 cm. The important result from both arc-jet recreations is that of the 5 parameters that were examined, CHIEF is able to successfully create an environment that leads to predictions that match an external data set, in this case, measured arc-jet data, within a user-defined envelope. Additionally, the values used in the environmental input that were measured were not changed by CHIEF, indicating that CHIEF does not need to iterate upon all parameters to manipulate predictions into a defined margin. This confirms that the basic function of CHIEF works and CHIEF can now be further analyzed against simulated data from MSL design trajectories.

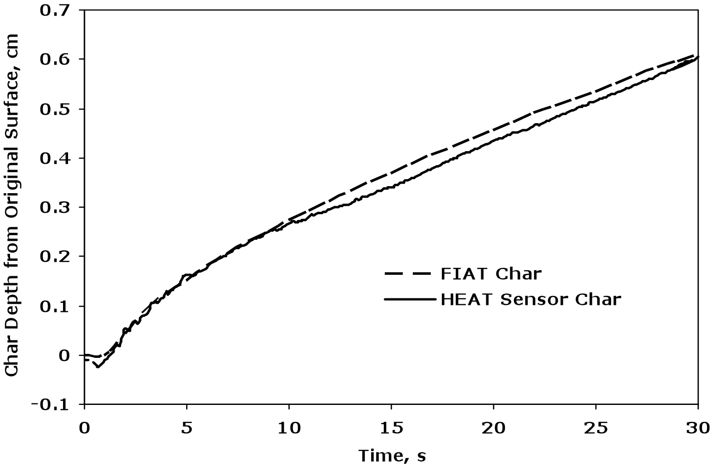


Figure 5. The char depth during the heating period measured by the HEAT sensor and predicted by FIAT through the use of CHIEF for MQ08-4

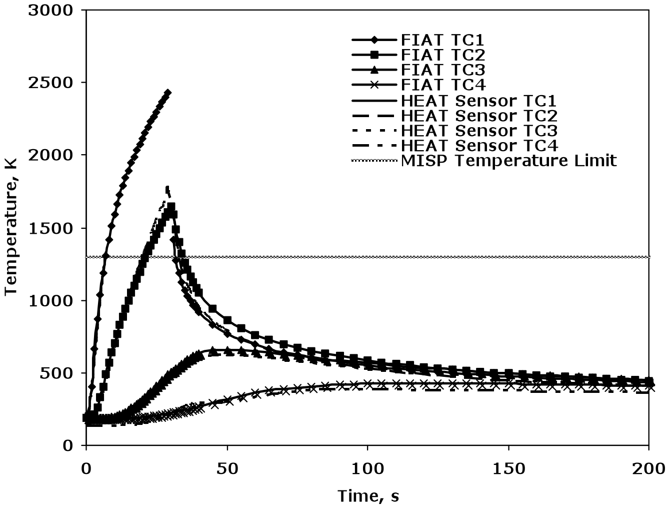


Figure 6. The in-depth temperature profile during the heating period and heat soak measured by the HEAT sensor and predicted by FIAT through the use of CHIEF for MQ08-4

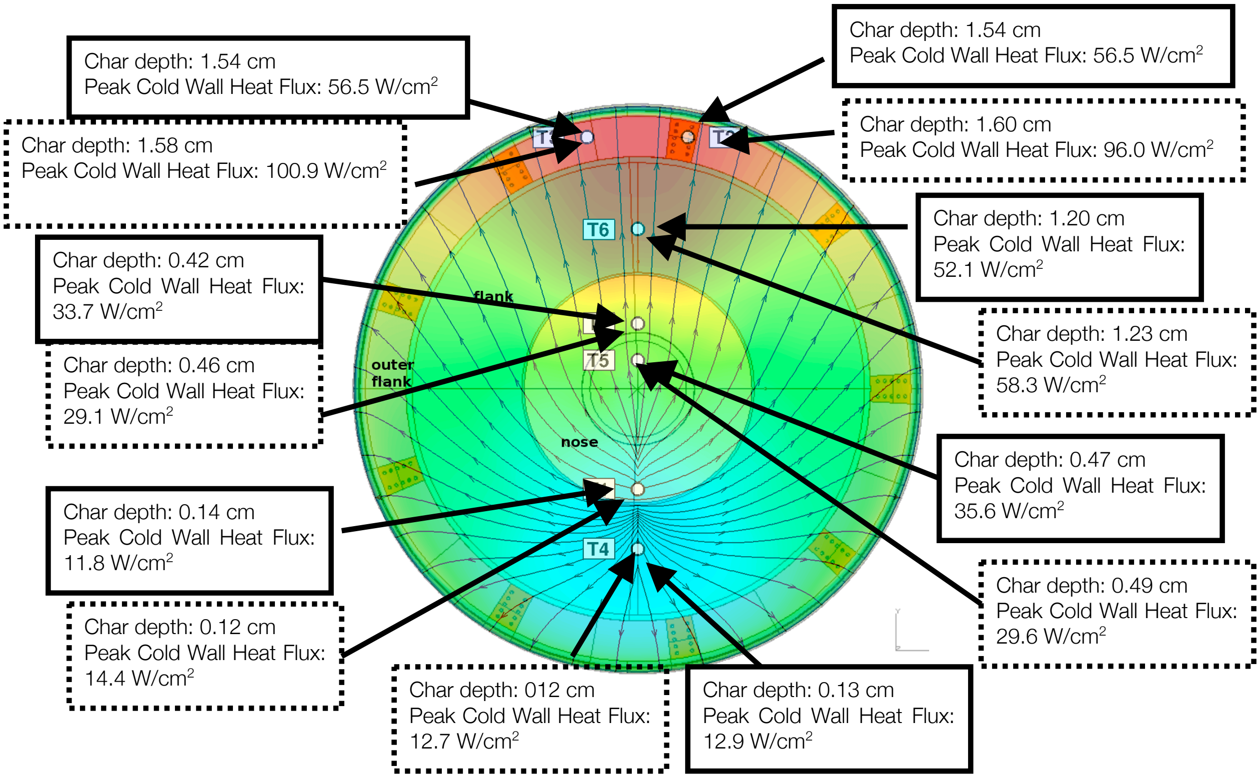
B. MSL Design Trajectory

To test CHIEF for the reconstruction of MSL entry into the Martian atmosphere, trajectory 08-TPS-01a, which includes high shear at MISP locations 2 and 3, is used as the baseline trajectory. The trajectory environment, with its design edge enthalpy, heat transfer coefficient, and pressure, is first used to generate the simulated data of char depth and in-depth temperatures by running FIAT. The simulated data that come from knowing all three design parameters are then randomized around their values to simulate noise that accompanies the instruments. This noise is then filtered out using a basic numerical filter function found in MATLAB called “filter” which uses ten data points. The filtered simulated data are used in CHIEF as the baseline case for comparison, with CHIEF only knowing the enthalpy and pressure. This simulates the MSL reentry experience from a data standpoint: enthalpy and pressure can be measured from the instrumentation on the heatshield, along with the char depth and the thermocouple data.

CHIEF is run at each MISP location, with each location having its own unique environment (enthalpy and pressure) due to its location and noise, for the entire trajectory, which lasts 280 seconds from Entry Interface (EI) until heatshield ejection. CHIEF makes a comparison every ten seconds of the trajectory. The thermocouple depths are the same as those for the arc-jet test MQ08-1 however, the TPS thickness is greater.

Table 2. The root mean square error and tolerance of each prediction at MISP locations during the heating period.

Sensor Location	Parameter				
	Char Error (cm) (%)	**TC1 Error (K) (%)**	**TC2 Error (K) (%)**	**TC3 Error (K) (%)**	**TC4 Error (K) (%)**
MISP 1	0.00789 (9.8)	20.7 (3.4)	13.3 (2.4)	5.02 (1.1)	4.96 (1.4)
MISP 2	0.0512 (5.4)	22.7 (14)	13.0 (8.4)	4.37 (3.0)	24.7 (5.9)
MISP 3	0.0384 (4.1)	25.2 (16)	20.3 (13)	10.5 (7.0)	16.9 (4.0)
MISP 4	0.0107 (16)	18.3 (3.0)	15.3 (2.8)	9.28 (2.1)	2.40 (0.67)
MISP 5	0.0337 (12)	20.7 (8.4)	21.6 (3.8)	9.62 (2.1)	3.7 (1.0)
MISP 6	0.0337 (4.6)	39.3 (22)	19.2 (11)	21.4 (10)	15.9 (3.9)
MISP 7	0.0404 (16)	28.0 (11)	17.0 (3.0)	6.21 (1.4)	2.70 (0.74)



Char depth: 1.54 cm
Peak Cold Wall Heat Flux: 56.5 W/cm^2

Char depth: 1.58 cm
Peak Cold Wall Heat Flux: 100.9 W/cm^2

Char depth: 1.54 cm
Peak Cold Wall Heat Flux: 56.5 W/cm^2

Char depth: 1.60 cm
Peak Cold Wall Heat Flux: 96.0 W/cm^2

Char depth: 1.20 cm
Peak Cold Wall Heat Flux: 52.1 W/cm^2

Char depth: 1.23 cm
Peak Cold Wall Heat Flux: 58.3 W/cm^2

Char depth: 0.42 cm
Peak Cold Wall Heat Flux: 33.7 W/cm^2

Char depth: 0.46 cm
Peak Cold Wall Heat Flux: 29.1 W/cm^2

Char depth: 0.47 cm
Peak Cold Wall Heat Flux: 35.6 W/cm^2

Char depth: 0.49 cm
Peak Cold Wall Heat Flux: 29.6 W/cm^2

Char depth: 0.14 cm
Peak Cold Wall Heat Flux: 11.8 W/cm^2

Char depth: 0.12 cm
Peak Cold Wall Heat Flux: 14.4 W/cm^2

Char depth: 012 cm
Peak Cold Wall Heat Flux: 12.7 W/cm^2

Char depth: 0.13 cm
Peak Cold Wall Heat Flux: 12.9 W/cm^2

Figure 7. The solid boxes are the simulated measured data for each MISP location, while the dashed boxes are the CHIEF predictions that try to match the data.

Table 2 shows how the CHIEF/FIAT predictions for char and temperatures at the thermocouple depths match with those of the simulated data. All parameters fall within the margins assigned to each, except for the char at location 2 and temperature at the first thermocouple at location 6. The char error at MISP 2 is outside the 0.05 cm error margin, but within the 20% tolerance desired for recession. Though the root mean square analysis has CHIEF's TC 1 at MISP 6 within 50 K over the entire trajectory, CHIEF's manipulated predictions are 22% away from the simulated data. This is 2% outside the assigned margin of 20%. These outliers may be due to CHIEF's limits on how many times it can iterate on all three parameters before a solution can be found at a time step. If CHIEF cannot reach a satisfactory result within that limit, and going back to the previous time step to improve that result does not help, the envelope for the parameter at the current time step is slightly expanded and CHIEF iterates again.

The root mean square analysis would seem to indicate that the environments used to generate the simulated data and found through CHIEF should be similar if the parameters are relatively close. Figure 7 illustrates the peak heat flux environment from the simulated data and from what CHIEF arrives at when trying to match the five parameters for each MISP location. Figure 8 shows the cold wall heat flux used to generate the comparison data and the heat flux recreated by CHIEF through the trajectory at MISP location 6. Figures 7 and 8 show that CHIEF recreates the peak heat flux (which occurs in the first half of the Mars entry trajectory) to within 25% compared to the simulated heat flux for most locations, but as the heat flux decreases and becomes negative (the enthalpy at the wall becomes negative), CHIEF does not match as well. This may be due to CHIEF overpredicting char later in the trajectory (Fig. 9). This overprediction may be caused by CHIEF using the previous time step's heat transfer coefficient as an initial guess. Although the previous time step's heat transfer coefficient causes an overprediction of char at the current time step when it may have been underpredicted at the previous time step, the char prediction still is within the margin assigned to char and CHIEF moves on to the next time step. The overprediction is then represented in the heating profile by a higher cold wall heat flux. Figure 10 compares the simulated temperatures at each thermocouple depth with those predicted by CHIEF at MISP 6. The predictions are very close to the external data set, with the predictions stopping around the same time as the simulated data indicating that the material has ablated past that depth and the thermocouple would cease to work. Similar trends are seen at other MISP locations, which are reflected in the root mean square analysis showing that the differences between the temperature prediction by CHIEF and the simulated data generally remains within the defined margin.

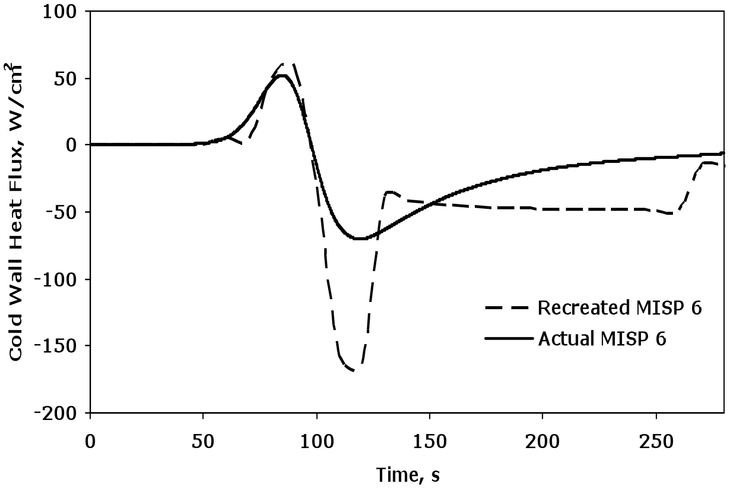


Figure 8. The cold wall heat flux for MISP 6 from both the environment used to generate the comparison data set and that created from CHIEF to match the comparison data set

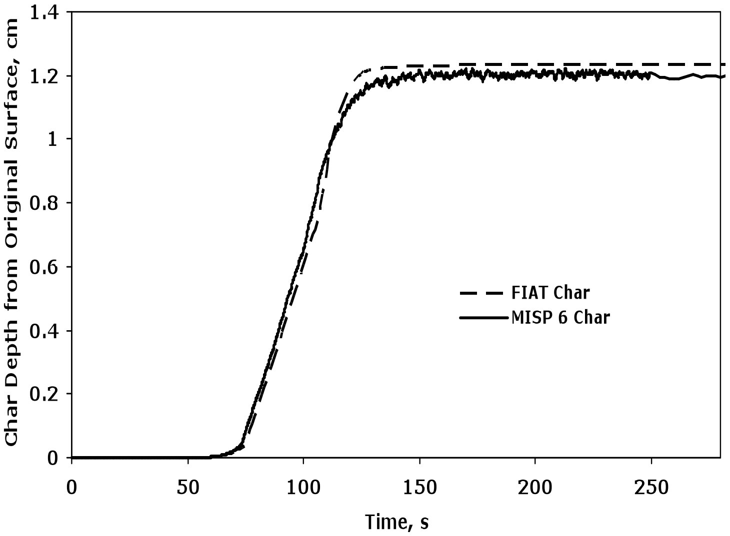


Figure 9. Simulated char and char as predicted through use of CHIEF at MISP 6.

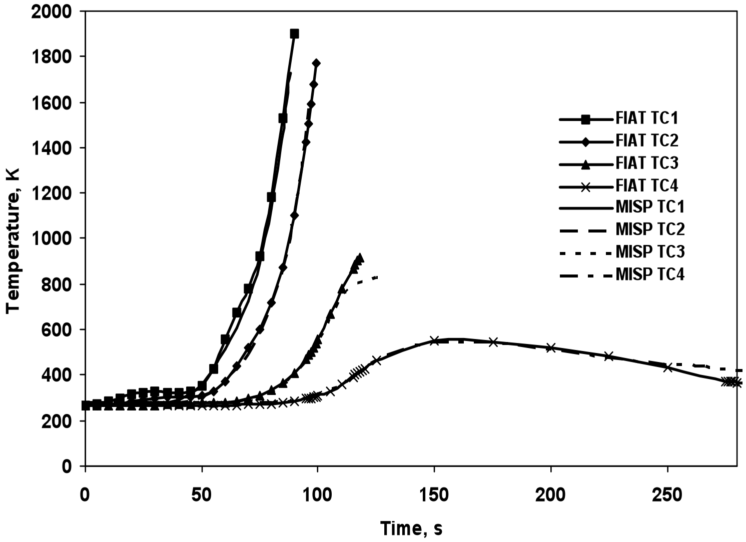


Figure 10. Simulated temperature and temperature as predicted through use of CHIEF at each thermocouple depth at MISP 6

There are two locations where CHIEF does not match the peak cold wall heat flux to within 25%: MISP 2 and MISP 3. At those locations, while char and thermocouple predictions are within the desired margins, the cold wall heat flux is overpredicted, with CHIEF predicting the peak cold wall heat flux as twice the amount of the simulated amount. This is due to a factor not included in the environment: failure rate of the heatshield material. The failure rate has a direct impact on recession and char. The higher the failure rate, the higher the recession, which means the char depth will be deeper relative the original surface. It is assumed that at all locations that the PICA heatshield experiences only 5% material failure. However, since MISP 2 and 3 will experience high shear upon entry into the Martian atmosphere, those cases are run at 150% fail when calculating the simulated data set. Since CHIEF does not iterate upon failure and ignores how any changes to failure affect predictions, the failure rate remains at 5% for MISP 2 and 3 and uses high heating rates to account for the higher char depth. When the failure rate is adjusted so it matches what is used for the comparison data, CHIEF's predictions for MISPs 2 and 3 fall more in line with the simulated parameters, with the root mean square errors decreasing and with the peak cold wall heat flux reduced to 44 W/cm^2, a 22% difference from the simulated cold wall heat flux.

All 7 locations are simulated at the same edge enthalpy and CHIEF is initialized at those values. Except for the MISP locations where failure was not taken into proper account, CHIEF did not change the edge enthalpy (Fig. 11) or pressure from the initial values. Figure 12 is the recreated heat transfer coefficients from CHIEF for each MISP location. The highest heat transfer coefficients were found in the locations where high shear is predicted to occur (MISPs 2 and 3), but failure was not increased. To match the simulated data that had the higher failure, CHIEF increased the heat transfer coefficient, which in turn increases the heat flux on the heatshield surface. Though MISP locations 2 and 3 are identified as high shear locations, MISP 6 may experience some shear which would dictate a higher than 5% fail. The simulated data may have reflected a higher shear by the implementation of some unknown failure rate. A higher failure rate for MISP 6 may have caused CHIEF to produce the third highest heat transfer coefficient and change the edge enthalpy in a similar way to those parameter for two known shear locations, MISPs 2 and 3, to make up for the lower failure assumption. The heat transfer coefficient for MISP 6 is less than the ones for known shear locations MISPs 2 and 3. Additionally, the CHIEF peak heat flux for MISP 6 is only 12% higher than the simulated peak heat flux. This difference is much lower than the discrepancies found at MISPs 2 and 3 when shear failure is not considered. If the MISP 6 simulated data is experiencing shear at a higher failure rate than 5%, it is not experiencing it as severely as the shear at MISPs 2 and 3.

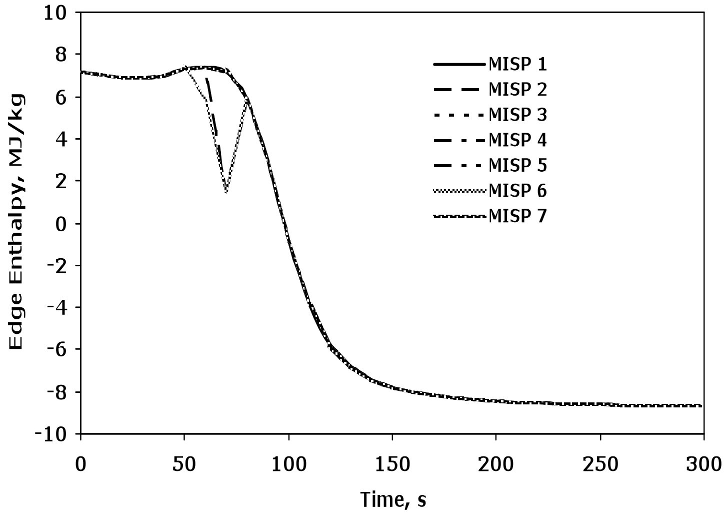


Figure 11. The final edge enthalpy for each MISP location when using CHIEF. The smoother lines indicate no change in enthalpy from the supplied values.

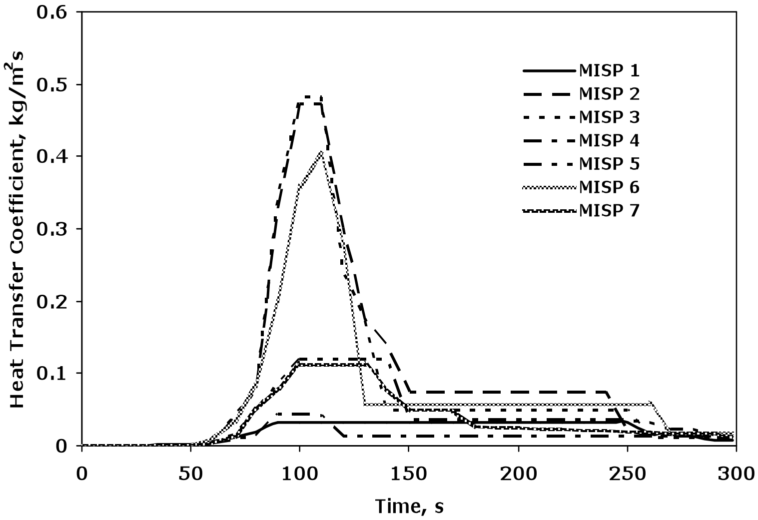


Figure 12. The heat transfer coefficient for each MISP location which was the primary parameter iterated upon by CHIEF

The Effects of Changing the Number of Time Steps

As mentioned in Section III.B, the choice of the number and frequency of time steps in both the overall environment and in certain intervals within the environment can affect the iteration process. To illustrate how the number of time steps is important, MISP locations 2 and 3 are examined. These locations are chosen due to the overprediction of the cold wall heat flux. While the overprediction is due to the unaccounted increase in failure rate, manipulating the time aspect of the environment may help decrease the error as well. All MISP environments are initially set up with a time interval of 10 seconds, uniformly spaced. In that case, the predictions for char and thermocouple temperatures for MISPs 2 and 3 all fall within the assigned envelopes, but the peak cold wall heating is double the simulated value. If the environment is only set up to check predictions every 20 seconds, it would be expected that the overall difference between the CHIEF predictions and the simulated data set would increase, due to lack of constant checking. Conversely, it would be expected that adding more time steps would increase accuracy, decreasing the difference, due to more data points being compared. Table 3 shows that the only expectation met is the decrease in accuracy when decreasing the number of time steps.

Table 3. The root mean square error and tolerance of each prediction at MISPs 2 and 3 at different uniformly spaced time step intervals

Sensor Location	**Parameter**				
	Char Error (cm)	**TC1 Error (K)**	**TC2 Error (K)**	**TC3 Error (K)**	**TC4 Error (K)**
MISP 2 (20 s interval)	0.0627	42.3	35.6	12.9	30.7
MISP 2 (10 s interval)	0.0512	22.7	13.0	4.37	24.7
MISP 2 (5 s interval)	0.0322	36.5	23.9	12.5	21.2
MISP 3 (20 s interval)	0.0327	45.1	40.0	20.0	19.8
MISP 3 (10 s interval)	0.0384	25.2	20.3	10.5	16.9
MISP 3 (5 s interval)	0.0428	30.6	18.4	7.19	23.4

When the interval between time steps decreases past a certain point, it becomes harder for CHIEF to closely match predictions to the external data set. This is due to CHIEF only analyzing predictions at one time step per iteration. If at that time step, after a certain number of iterations, the assigned error or tolerance cannot be met, CHIEF returns to the previous time step and tries to make that prediction more accurate. When it returns to the current time step, if it once again cannot match up the predictions with the comparison data set, it increases the allowable error and tolerance so it can move on. This is previously mentioned as a possible cause for MISP 6's CHIEF-driven predictions for TC 1 having a final tolerance of 22%. For time steps grouped too close together, such as those that occur at every five seconds, it is both physically and mathematically harder to affect predictions at the current time step. It is physically difficult because surface conditions are not instantly felt into the entire depth of the material due in part to the material's properties and thickness. As one gets more in depth, the conditions at that depth are a result of heating from moments before. For example, the temperature at TC 4, which is at a depth of 1.77 cm from the initial surface, is not as directly related to the surface heating at the current time as TC 1 is, which is located only 0.23 cm from the surface.

Mathematically, closely grouped time steps make it harder to interpolate between time points and leaves less room for prediction manipulation. If at the previous time step the prediction is within the margin but is near the cutoff point and the current prediction is outside that margin, manipulation of the heat transfer coefficient or enthalpy will need to be drastic because there are fewer time points to interpolate between the two times of interest in FIAT. The fewer "free" time points for FIAT to interpolate means that the change of surface conditions caused by interpolation has to be replaced by more exact conditions. The differences between CHIEF-driven predictions and the comparison set are likely to propagate as the computational environment needs to be more rigid as the time interval decreases and there are less time points for FIAT to calculate its own conditions. Because of the physical and mathematical difficulties encountered when decreasing the time interval, more time points for CHIEF to iterate upon does not mean increased accuracy.

From a heating environment standpoint, changing the time interval has many effects. For both MISP 2 and 3, having a large 20 second time interval leads to underprediction of the peak cold wall flux, which is predicted at about 36 W/cm^2. This underprediction may have led to the char predictions for this time interval being further outside the desired margin than what is found for the 10 second time interval. While the environment may more closely match, the predictions are adversely affected for the large time step. For the smaller time step, the 5 second time interval, the environment is once again overpredicted, like that of the 10 second time interval, and now the enthalpy is being changed more often by CHIEF. Previously, for the 10 second time interval, the difference between the CHIEF environment and the environment used to generate the comparison data was only in the heat transfer coefficient for each time step and the enthalpy changed at only one time point, as seen in Fig. 11. For the 5 second time interval, CHIEF changes the enthalpy at two time points to better match the char and thermocouple data. This is another sign that closely grouped time steps require more environmental changes to match data. Time interval choice should not be arbitrary and requires both knowledge of when important events in the environment occur and when one approaches too exact of a time space. Further refinement of CHIEF may improve predictions of smaller time intervals.

The Effects of Changing Pressure

The important parameters in the environment have been singled out to be the heat transfer coefficient and enthalpy, because of the sensitivity study and their role in the surface energy balance equation. In an attempt to see if pressure plays any role in the predictions, MISP 7 is given a pressure profile one hundred times less than that of what is used in the comparison case. The decrease in pressure does not greatly affect the char prediction or the temperatures at thermocouples one or two, with their root mean square error analysis being the same as the one generated with the correct pressure. However, for TCs 3 and 4, the root mean square error went from 6.2 and 2.7 K to 25.9 and 21.7 K, respectively. Figure 13 shows how changing the pressure affects the cold wall heat flux. During the period of positive enthalpy and heat flux, there is little difference between how CHIEF recreates the environment between the base pressure and the pressure that is one hundred times less. When the enthalpy becomes negative, the smaller pressure underpredicts the environment while the base case overpredicts. The much smaller pressure may have a greater effect when negative enthalpy occurs due to what state the *B'* table considers the material to be in. In the PICA *B'* table, as pressure becomes smaller and enthalpy becomes negative, there is a decreased likelihood that the material will char considering the same temperature, pyrolysis gas and char rate ranges. When enthalpy is positive and pressure small, there may be a wider range of conditions where the material will char. When the enthalpy is negative the conditions where the material may char changes and that affects how char depth is predicted and how CHIEF will iterate upon the environmental parameters. So to get similar char depths between the predicted and the simulated values, CHIEF would need to increase the absolute value of the heat flux at the smaller pressure during negative enthalpy, which in turn, may have led to the increase in root mean square error of the in-depth temperatures.

The main driver of this change is the heat transfer coefficient, with the smaller pressure profile having a different heat transfer coefficient profile in comparison to that of the simulated environment and the one derived from CHIEF under the correct pressure (Fig. 14). The sensitivity study shows that small changes in the pressure do not greatly affect predictions, however, large changes, those of many magnitudes, cannot be ignored. The readings from the MEADS pressure sensors should be within 0.5% of the actual pressure, so such a great disparity between what is being read and what is the actual pressure should not occur. However, if such an error in measurement is suspected, then the affects on the recreated environment and predictions are known.

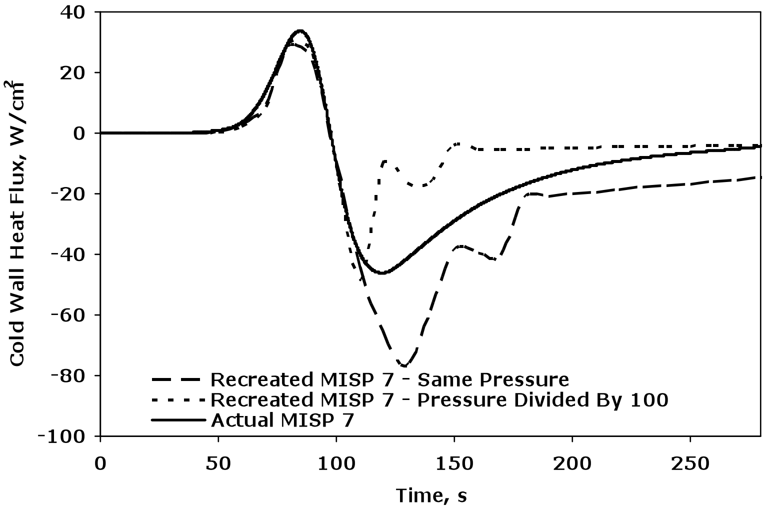


Figure 13. The cold wall heating profile for three cases dealing with the simulated environment and changes in pressure

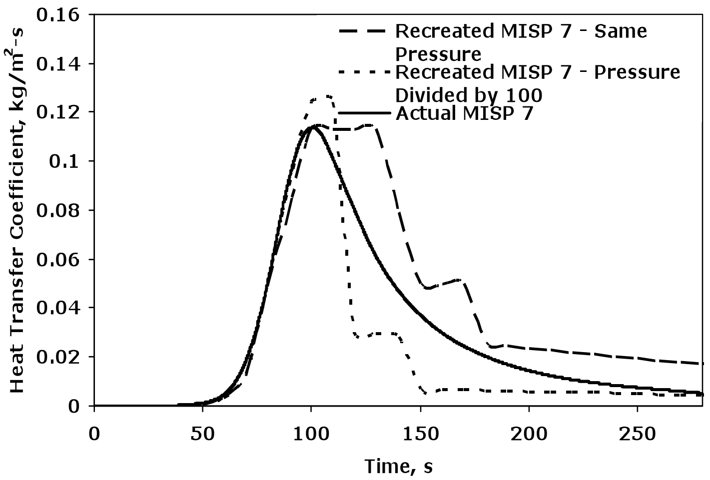


Figure 14. The heat transfer coefficient profile for three cases dealing with the actual environment and changes in pressure

V. Future Work

Currently, CHIEF does not have the capability to check predictions at multiple time steps concurrently. A logical modification to CHIEF would be to add multiple target points to minimize errors. Additionally, the error and tolerance equations used for comparison are the differences between the predictions and external data set. The root mean square analysis is used outside of CHIEF for post-processing purposes, but it can be inserted into CHIEF for more robust error and tolerance checking. Also, some parameters being checked for accuracy may be more important than others during certain periods of analysis. CHIEF has the ability to skip certain parameters if the user flags those parameters at times of interest during the analysis but cannot change the order of importance of the parameters or have the user define the allowable error or tolerance at unique times. The user defines the error and tolerance for all times, with CHIEF changing those margins on its own if it cannot iterate enough to get the predictions with those margins. A weighting system for the parameters that can focus CHIEF on one or more of the parameters during periods of interest can be developed to allow the user to implement different criteria for each point of comparison. This may help when considering smaller time intervals, especially with trying to match temperatures found at deeper thermocouple depths.

In addition to the high shear predicted to occur at MISPs 2 and 3, MISP location 6 may also undergo high shear. Analysis of a higher fail rate at MISP 6 remains to be carried out. There are also other possible trajectories developed for MSL that CHIEF has not run, including 08-TPS-02, which has the maximum allowable heat flux, shear stress and pressure of the trajectories.[5] The purpose of looking at the MSL trajectory was to begin a post-processing study before the actual entry into the Martian atmosphere. Once actual data is collected by the MISP and MEADS instruments during entry, CHIEF can be used to recreate the heating environment, as enthalpy and pressure will be known from measurements, but the heat transfer coefficient will not. The sensitivity study and how CHIEF manipulates the environmental parameters can be used in the post-processing of the MSL data.

VI. Conclusions

A tool, CHIEF, has been developed that can create FIAT environments to match sensor outputs from an external data set. By iteratively adjusting the heat transfer coefficient, and modifying the enthalpy and pressure as necessary, CHIEF can change char or recession and thermocouple temperature predictions. The user defines what is the allowable error and tolerance when matching the predictions to the external data set. Currently, it is important that the time interval for checking predictions versus the external set is chosen properly yield the best agreement, as the current implementation is strongly dependant on time-step selection of the CHIEF program.

One of the design trajectories for the Mars Science Laboratory was chosen to validate CHIEF's ability to recreate a known or measured environment. The design trajectory was used in FIAT to generate data that was simulating hypothetical data "measured" by the instruments on the MSL heatshield. With a margin of 0.05 cm for char and 50 K for temperatures, CHIEF matched the FIAT predictions, using an environment with initially unknown heat transfer coefficients, to those found by the trajectory with known heat transfer coefficients. It was seen that the char prediction is generally overpredicted during the period of the trajectory where charring has reached a steady state. It was concluded that this phenomenon occurs because CHIEF uses the previous time steps heat transfer coefficient for an initial guess. During this time, the cold wall heat flux was overpredicted as well. Additionally, it was seen that while CHIEF can match char and temperature data, if material failure is not properly taken into account, the heating profile will greatly differ between cases where there is low failure in CHIEF and high failure in actuality. This occurred when high shear was assumed at MISPs 2 and 3 in the comparison data but not within CHIEF. When the assumption of shear (high failure) was added into CHIEF, the heating profiles became more alike. CHIEF has demonstrated accuracy in recreating the heating profile when compared to the baseline case of a known design trajectory and can be used to generate a profile when measured data includes enthalpy and pressure.

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References

[1]Chen, Y.K. and Milos, Frank S., "Ablation and Thermal Response Program for Spacecraft Heatshield Analysis," *Journal of Spacecraft and Rockets,* Vol. 36, No. 3, May-June 1999. pgs 475 – 483.

[2]Beck, R.A.S., et al, "Development of the Mars Science Laboratory Heatshield Thermal Protection System," AIAA Paper 2009-4229, *41st AIAA Thermophysics Conference,* San Antonio, Texas, June 2009.

[3]Edquist, K.T., Wright, M.J., and Tang, C.Y., "Aerothermodynamic Design Conditions for the Mars Science Laboratory Heatshield," AIAA Paper 2009-4231, *41st AIAA Thermophysics Conference,* San Antonio, Texas, June 2009.

[4]Cheatwood, F.M. and Gnoffo, P.A., "User's Manual for Langley Aerothermodynamic Upwind Algorithm (LAURA)," NASA TM-4674, April 1996.

[5]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.

[6]Tran, H., et al, "Phenolic Impregnated Carbon Ablators (PICA) as Thermal Protection Systems for Discovery Missions," NASA TM-110440, April 1997.

[7]Wright, M., Beck, et al, "Sizing and Margins Assessment of the Mars Science Laboratory Aeroshell Thermal Protection System," AIAA Paper 2009-4231, *41st AIAA Thermophysics Conference*, San Antonio, Texas, June 2009.

[8]Willcockson, W. H., "Mars Pathfinder Heatshield Design and Flight Experience," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, May-June 1999.

[9]Gazaric, M., et al, "Overview of the MEDLI Project," IEEE Paper 2008-1510, IEEE Aerospace Conference, Big Sky, Montana, March 2008.

[10]Oishi, T., Martinez, E.R., and Santos, J.A., "Development and Application of a TPS Ablation Sensor for Flight," AIAA Paper 2008-1219, *46th Aerospace Meeting and Exhibit*, Reno, Nevada, January 2008.

[11]Beck, J.V., and Murio, Diego A., "Combined Function Specification-Regularization Procedure for Solution of Inverse Heat Conduction Problem," *AIAA Journal*, Vol. 24, No. 1, 1986, pgs 180-185.

[12]Dowding, K., et al, "Estimation of Thermal Properties and Surface Heat Flux in Carbon-Carbon Composite," *Journal of Thermophysics and Heat Transfer*, Vol. 9, No. 2, April-June 1995, pgs. 345-351.

[13]Kontinos, D., and Stackpoole, M., "Post-Flight Analysis of the Stardust Sample Return Capsule Earth Entry," AIAA Paper 2008-1197, January 2008.