Physics-based Entry, Descent and Landing Risk Model

Ken Gee*[a], Loc Huynh[b], and Ted Manning[a]
[a] NASA Ames Research Center, Moffett Field, USA
[b] Science and Technology Corporation, Moffett Field, USA

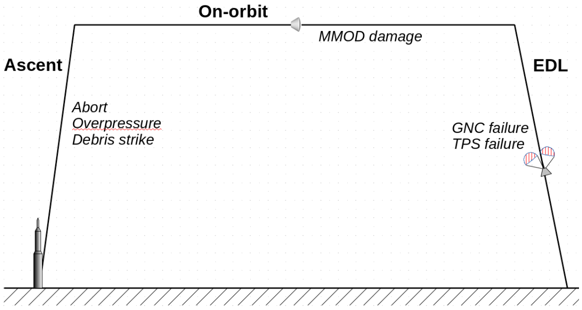
Abstract: A physics-based risk model was developed to assess the risk associated with thermal protection system failures during the entry, descent and landing phase of a manned spacecraft mission. In the model, entry trajectories were computed using a three-degree-of-freedom trajectory tool, the aerothermodynamic heating environment was computed using an engineering-level computational tool and the thermal response of the TPS material was modeled using a one-dimensional thermal response tool. The model was capable of modeling the effect of micrometeoroid and orbital debris impact damage on the TPS thermal response. A Monte Carlo analysis was used to determine the effects of uncertainties in the vehicle state at Entry Interface, aerothermodynamic heating and material properties on the performance of the TPS design. The failure criterion was set as a temperature limit at the bondline between the TPS and the underlying structure. Both direct computation and response surface approaches were used to compute the risk. The model was applied to a generic manned space capsule design. The effect of material property uncertainty and MMOD damage on risk of failure were analyzed. A comparison of the direct computation and response surface approach was undertaken.

Keywords: EDL, physics-based risk model, TPS, Monte Carlo, response surface.

1. INTRODUCTION

The Engineering Risk Assessment Team at NASA Ames is currently developing a High Fidelity Mission Risk (HFMR) model to assess the overall mission risk of manned space systems [1]. The HFMR model evaluates risk for the ascent, on-orbit and entry, descent and landing (EDL) phases of a space system mission. In a nominal mission, shown schematically in Figure 1, a launch vehicle is used to place a manned space vehicle into Earth orbit. The manned vehicle remains in orbit for some mission duration and then returns to Earth in the EDL phase. In the EDL phase, the vehicle must slow from its orbital velocity to its landing velocity at the end of the entry trajectory. Atmospheric drag is used to slow the vehicle down during the entry trajectory. However, friction between the vehicle and the a*tmosphere creates high aerothermodynamic heating that the can destroy the vehicle if not for its thermal protection system (TPS). The TPS of the vehicle is typically composed of a stack-up of materials that can withstand the expected high heating rates and temperatures during the entry. At the end of the entry trajectory, the vehicle can deploy parachutes or use retro-rockets to further reduce its velocity. Landings can occur in water or on land.

Figure 1. Schematic of manned space mission analyzed by HFMR model.



*Ken.Gee-1@nasa.gov

In each phase there are failure scenarios that can lead to a loss of mission and possibly a loss of crew. Failure scenarios in each phase may include loss of control of the launch vehicle or catastrophic failures of the engines during ascent, damage due to micrometeoroid/orbital debris impacts while in orbit and TPS failures in the EDL phase. One possible failure of the TPS occurs when the temperature at some point in the system exceeds a given limit. For example, if the maximum allowable temperature of the adhesive used to bond the TPS material to the underlying structure is exceeded, the TPS material may separate, exposing the structure to the aerothermodynamic heating environment. This can lead to structural failure and a loss of crew. TPS failures can also result from the damage caused by MMOD impacts while on-orbit, higher-than-expected heating due to trajectory and/or atmospheric uncertainties, or larger-than-expected variations in the material properties of the TPS itself.

Physics-based models are used to evaluate the crew risks associated with failure scenarios and the resulting failure environments. To date, models have been developed to assess the risk of blast overpressure [2,3] and debris strike [4,5] on the crew module resulting from a catastrophic failure of the launch vehicle. The failure scenarios are modeled using a level of fidelity necessary to resolve the physics involved. For example, the debris strike model defined the debris field in terms of the number of pieces and the mass, reference area, drag coefficient and imparted velocity of each piece. The model then computed the trajectory of each debris piece using a three degree-of-freedom trajectory tool. The probability of at least one piece of debris striking the crew vehicle was computed by comparing the relative position of the debris field and crew vehicle during an ascent abort. The conservative approach assumed that any debris strike resulted in a loss of crew. A vulnerability criterion was developed that related the penetration velocity as a function of the debris mass. Applying the criterion, only debris pieces that had a relative velocity greater than the penetration velocity were counted in the strike probability. The probability of loss-of-crew due to these failure scenarios are computed using the physics-based models in a Monte Carlo simulation. The Monte Carlo approach has been used to analyze the effect of dispersions or uncertainties on the entry trajectories for Apollo [5] through to Stardust [6]. Monte Carlo methods have been used to determine the effect of TPS material property uncertainties on the thermal response [7].

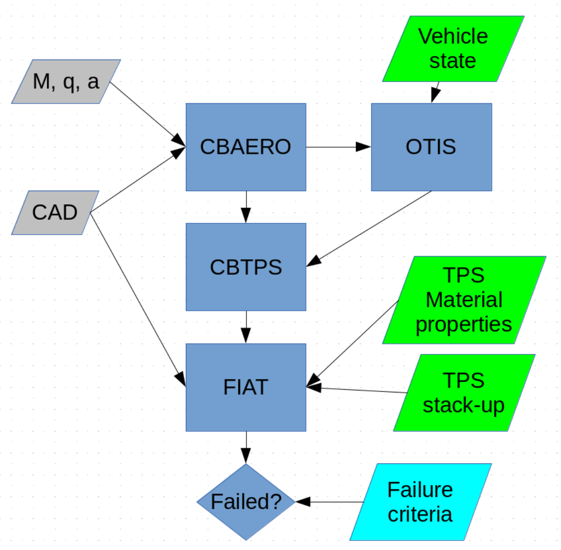
A physics-based model has been developed to assess some of the risks associated with the EDL phase. The model included modules to compute the entry trajectory, the aerothermodynamic environment during entry and the thermal response of the TPS to the heating environment. The model also included the capability to model the effects of MMOD damage on the TPS response. The Monte Carlo approach was used to account for dispersions and uncertainties in the vehicle state at the start of the entry phase, the aerothermodynamic environment and the TPS material properties. Failure criteria based on bondline temperature were used to determine the success or failure of each Monte Carlo sample. The following sections describe the EDL risk model in more detail and an application of the model to assess the EDL risks for a generic capsule-based manned vehicle design.

The purpose of the TPS was to protect the underlying structure and crew from the heating environments encountered during the reentry. Without the TPS in place, the heating environment would cause structural failure and loss of crew. Potential failure scenarios for the TPS include manufacturing defects resulting in materials that did not have the expected thermal properties, entry trajectories resulting in heating environments more severe than expected and damage to the TPS from mishandling or MMOD impacts. The risk model was developed to assess the effects of the dispersions in material properties and vehicle state and the damage due to MMOD impacts on the ability of the TPS to protect the crew. The probability of failure is dependent upon the criteria used to measure success or failure of the system.

2. EDL RISK MODEL

The physics-based portions of the EDL risk model computed the aerodynamic and aerothermodynamic database for a given vehicle design, the entry trajectories and the TPS thermal response to the heating environments. The physics-based tools are integrated with an algorithm to perform the Monte Carlo analysis and manage the resulting data sets. The analysis data flow of the physics-based portion of the model is shown in Figure 2.

Figure 2. Flowchart of EDL risk model.



CBAERO [8], an engineering level aerothermodynamics tool, was used to predict the aerodynamic and aerothermodynamic environment about the spacecraft during entry. Input data include a surface grid of the vehicle being analyzed and a range of values for Mach number, dynamic pressure and angle of attack to define the parameter space encompassing the entry trajectories. A component of CBAERO called CBTPS was used to determine the aerothermodynamic heating time history at specific points on the vehicle, given a particular trajectory.

The trajectories were computed using OTIS, a three-degree-of-freedom trajectory optimization tool [9,10], starting from entry interface (EI) and ending at the designated landing site. Lift and drag data for the vehicle were obtained from the CBAERO database. Optimized solutions were obtained using distance to a specified landing site as the objective function. Constraints were used to ensure that dynamic pressure, heat flux and total acceleration were within design limits. The optimization procedure may at times fail to find an optimized or feasible solution given the initial vehicle state and constraints. Currently, only successfully optimized trajectories are used in the risk analysis.

The heating time history computed from the trajectory and aerothermodynamic database was used as input to compute the thermal response of the TPS stack-up. The thermal response of the TPS material stack-up was computed using FIAT, a one-dimensional transient analysis tool [11]. FIAT also required definitions of the TPS stack-ups and a database file containing the TPS material properties. FIAT computed the thermal response of the stack-up to the heating environment, generating output in the form of time histories of temperature and heat flux at specified locations in the stack-up.

The risk of failure of the TPS was computed by comparing the data obtained from the FIAT analysis against a set of failure criteria, such as temperature limits at a specific depths or layers. Probabilities were computed using a Monte Carlo simulation. Dispersions in the vehicle state at the start of the entry trajectory, material properties of the TPS, the heating environment and TPS stack-up thickness were used to define the parameter space of the Monte Carlo simulation.

A representation of a TPS stack-up is shown in Figure 3. The stack-up can be composed of multiple layers of materials, such as high-emissivity coatings, toughened materials to withstand impact damage, substrate layers and adhesive layers that attached the TPS stack-up to the underlying structure. The stack-up was defined within a FIAT input file and included the thickness of each material layer.

Figure 3. Schematic of TPS stack-up in heat shield.

The damage due to an MMOD strike was modeled by modifying the TPS stack-up to reflect the loss of material, as shown schematically in Figure 4. The damage was modeled as an hemisphere with radius equal to the cavity depth. To model the effect of damage on the bondline temperature using FIAT, an area-weighted average of the conduction heat flux, accounting for the regions of undamaged and damaged tile, was used. Failure risk was computed for two impact scenarios. The conservative approach assumed that all MMOD strikes occurred at the point of maximum heating. A more realistic approach randomly selected the point of impact in each Monte Carlo sample.

Figure 4. Schematic of TPS stack-up damage due to MMOD strike.

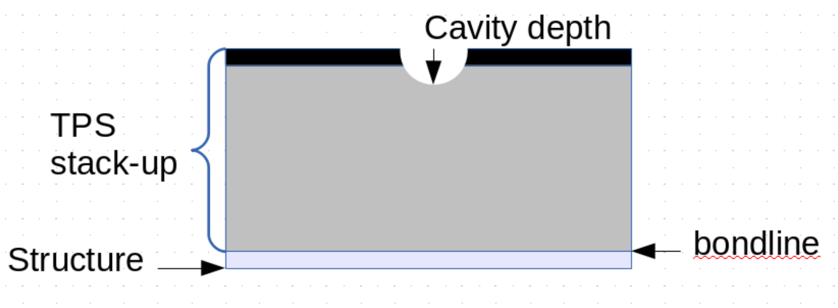
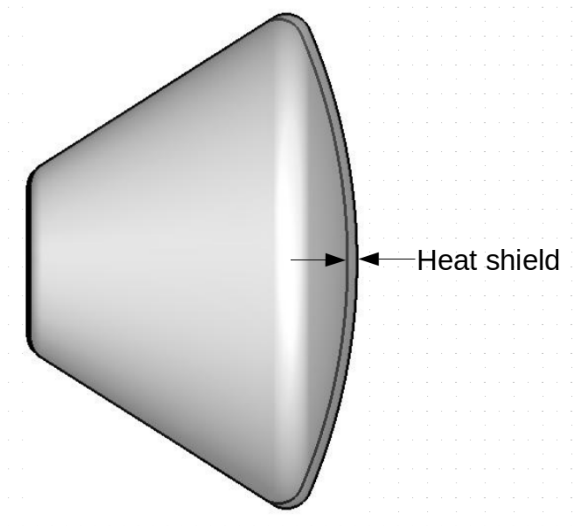


Figure 5. Side view of generic manned capsule.

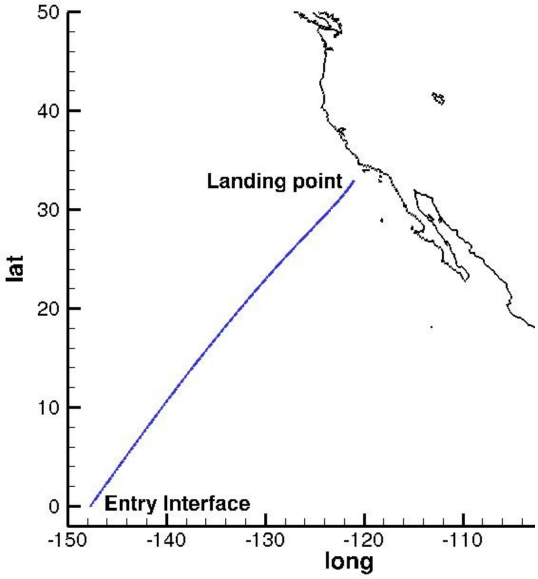


3. EXAMPLE APPLICATION OF THE RISK MODEL

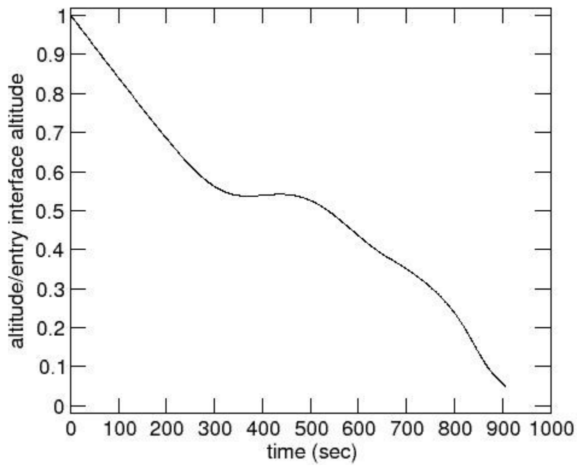
The EDL risk model was applied to the analysis of a manned capsule designed for missions to low Earth orbit (LEO). The generic capsule design, shown in Figure 5, utilized a heat shield consisting of a reusable TPS material similar to that used on the Space Shuttle [12]. The TPS stack-up consisted of a high-emissivity coating, a toughened material layer, a substrate layer and an adhesive layer to attach the TPS stack-up to the structure. In this example, the failure criterion was set as the maximum temperature that the adhesive used to attach the TPS material to the structure could withstand before debonding occurred. If this temperature was exceeded, it was assumed that the TPS debonded from the structure, causing failure of the TPS. A conservative assumption was made that any failure of the TPS would lead to a loss of crew, either through subsequent failure of the vehicle structure due to the direct exposure to the heating environment or through loss of aerodynamic control due to changes in the outer mold line of the vehicle.

Figure 6. Nominal entry trajectory of generic capsule returning from LEO.

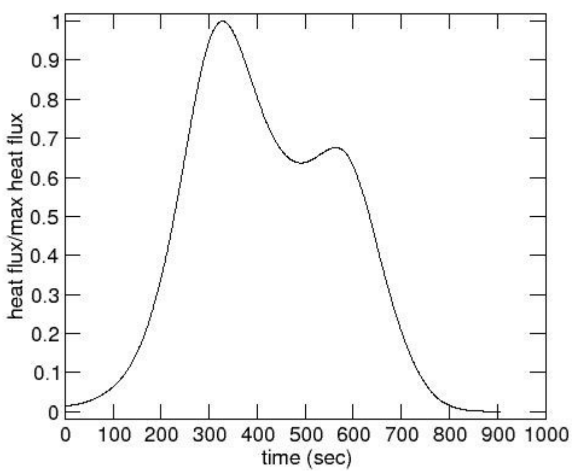
a) Position track of nominal entry trajectory



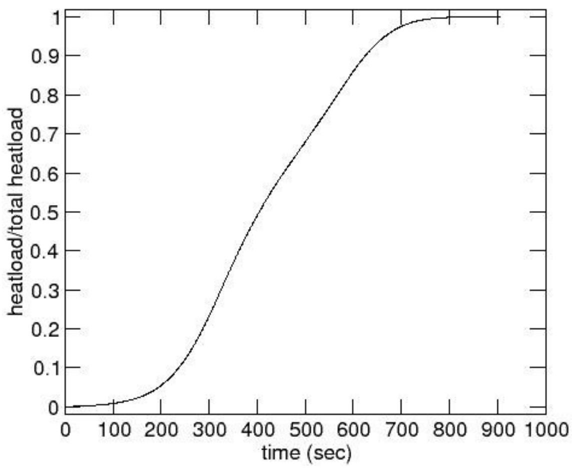
b) altitude time history



c) Heat flux time history



d) Total heatload time history



CBAERO was used to compute lift and drag coefficients of the capsule assuming a center of gravity offset from the centerline of the vehicle. A nominal entry trajectory was computed using OTIS assuming a return from the low Earth orbit (LEO) and a landing in the San Clemente Water Landing Area off the coast of California [13], as shown in Figure 6a. The nominal altitude, heat flux and total heat load time histories are plotted in Figure 6b through 6d, respectively. Typical of this type of entry, peak heating occurred early in the trajectory and decreased to near zero at the end of the trajectory as the vehicle velocity decreased. Since heat load was the time integral of the heat flux, the maximum occurred at the end of the trajectory.

Monte Carlo simulations were computed using the uncertainty bounds for the vehicle state at entry interface listed in Table 1 and the TPS material properties listed in Table 2. Uniform distributions were assumed for all parameters. The risk model was used to assess the failure probability as a function of the design thickness of the heatshield. Given a nominal heatshield design, the risk model was used to assess the failure probability due to MMOD impact damage. In addition, the feasibility of using a response surface approach to reduce the computational expense of the Monte Carlo simulations was assessed.

Table 1. Uncertainty bounds in vehicle state at entry interface.

Parameter	Range
velocity	±0.1%
azimuth	±0.05 deg
FPA	±0.25 deg
longitude	±0.2 deg
latitude	±0.2 deg
mass	±3%

Table 2. Uncertainty bounds in TPS material properties.

Parameter	Range
Heating augmentation factor	1.0 – 1.25
Density	±4%
Specific heat	±5%
Thermal conductivity	±5%
Cavity depth	0 – 1.5 in

3.1. Risk Assessment of the Heatshield Design Thickness

The need to account for uncertainty and dispersions in the design can be illustrated in the following example. Using the nominal entry trajectory and nominal material property values, a minimum thickness for the heatshield, for which the temperature at the bondline no longer violated the maximum allowable value, can be obtained, as shown in Figure 7. Applying the risk model to include the effects of entry state and material property uncertainties on the bondline temperature indicated that additional thickness was required to reduce the failure probability to acceptable levels, as shown in Figure 8.

The failure probabilities in Figure 8 were obtained using Monte Carlo simulations consisting of 2000 samples. As the failure probability decreased to zero, additional samples were required to fully resolve the probability of failure. Results from Monte Carlo simulations consisting of 10000 samples are listed in Table 3 and indicate that a thickness of 2.6 in. was required to reduce the bondline temperature failure probability to a 1 in 10000 level.

Figure 7. Bondline temperature as function of heatshield thickness for nominal conditions.

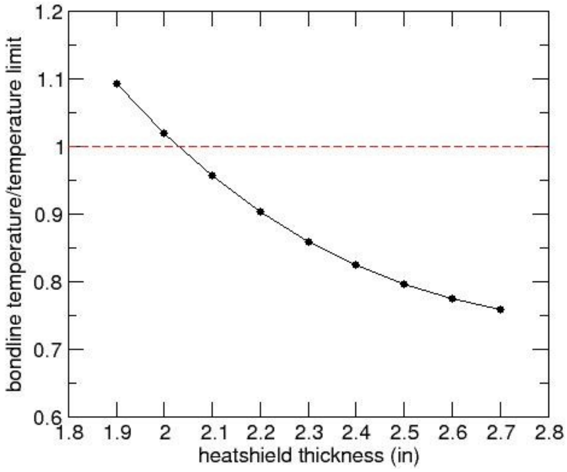


Figure 8. Bondline temperature failure probability as a function of heatshield thickness

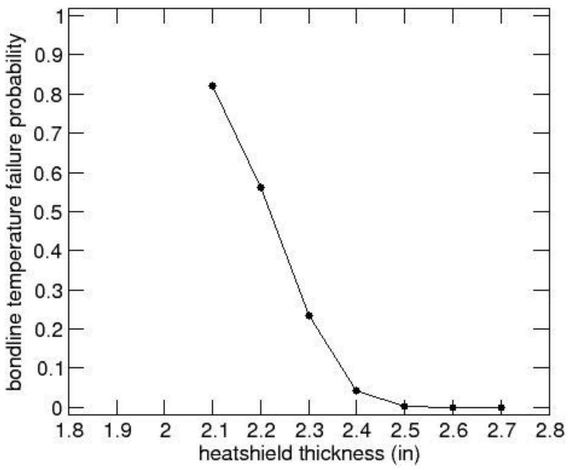


Table 3. Bondline temperature failure probabilities as function of heatshield thickness and number of MC simulation samples

Thickness (in)	Failure probability using 2000 samples	failure probability using 10000 samples
2.5	0.001	0.0044
2.6	0	0.0001
2.7	0	0

3.2. Risk Assessment of MMOD Impact Damage

Assuming that a failure probability on the order of 1e-4 was an acceptable risk, the nominal heatshield design was set to a thickness of 2.6 in. The risk model was then used to assess the failure probability of the heatshield design due to MMOD impact damage. The model assumed that an MMOD impact caused a hemispherical divot in the TPS stack-up with the penetration depth equal to the radius of the divot, as shown in Figure 4. For each Monte Carlo sample, the vehicle state at entry interface and the

TPS material properties were randomly generated based on the bounds listed in Tables 1 and 2. Bondline temperatures were computed using this set of values for penetration depths ranging from 0.1 to 1.5 in. for the two impact scenarios discussed in Section 2. There were 10000 samples in each Monte Carlo simulation. Failure probabilities for MMOD impacts that always occurred at the point of highest heating are listed in Table 4. Failure probabilities for MMOD impacts at randomly selected points on the heatshield are listed in Table 5. Assuming that all MMOD impacts occurred at the point of maximum heating yielded higher failure probabilities, confirming the conservatism of this assumption. In this example, the additional local heating in the damage cavity and the growth of the cavity during reentry were not modeled.

Table 4. Probability of exceeding bondline temperature limit for MMOD impacts at point of maximum heating.

cavity depth (in)	0	0.1	0.2	0.3	0.4	0.5	0.75	1.0	1.25	1.5
failure probability	0.0001	0.0001	0.0001	0.0002	0.0004	0.0005	0.0094	0.2421	0.9338	1.0000

Table 5. Probability of exceeding bondline temperature limit for MMOD impacts at randomly selected points on heatshield.

cavity depth (in)	0	0.1	0.2	0.3	0.4	0.5	0.75	1.0	1.25	1.5
failure probability	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0057	0.4929

The choice of a bondline temperature limit as the failure criterion was appropriate for assessing the reliability of the system. A reusable TPS system would need to retain its integrity over a number of missions. This would not be possible if the TPS material did not remain attached to the vehicle. However, using the bondline temperature limit to assess the probability of TPS failures leading to a loss of crew may be too conservative. Typically, the maximum bondline temperature for each sample was reached at or near the end of the trajectory, mirroring the heatload time history shown in Figure 6c.. Even if the adhesive were to fail, causing the TPS material to debond and exposing the structure to the environment, the heat flux near the end of the trajectory, as shown in Figure 6b, was low enough that structural failure due to heating would be a remote possibility. Loss of aerodynamic control due to changes to the outer mold line may not be an issue, either, especially if the capsule was under parachutes when the bondline temperature limit was reached. The development of appropriate failure criteria for loss of crew assessments is an area of active research.

3.3. Response Surface Approach

Each of the Monte Carlo simulations discussed in the previous section used the direct computation approach and required about 1800 CPU hours to complete on the NASA Pleiades supercomputer [14] using its Ivy Bridge nodes. A less computationally intensive approach was to generate a response surface defining the relationship between the bondline temperature and the input parameters in the parameter space. Once defined, the response surface was used to generate the values for the Monte Carlo sampling. The parameter space was defined by the variables listed in Tables 1 and 2. Kriging [15] was selected as the multivariate interpolation scheme used to create the response surface. Kriging required a training data set to determine the interpolation coefficients used in the scheme. A Latin hypercube design was used to populate the parameter space with the training data points. A total of 2000 data points were used in the training set, requiring about 300 CPU hours to compute. The response surface generated from the training data was used to predict the bondline temperature in Monte Carlo simulations consisting of 10000 samples. MATLAB was used to generate the response surface and perform the Monte Carlo simulation. This took about 10 minutes on a single CPU. Table 6 lists the failure probabilities as a function of penetration depth predicted using the response surface and the direct computation approach for the nominal heatshield thickness, assuming all impacts were at the point of maximum heating. For small penetration depths (< 0.5 in.), the response surface was not able to resolve the low failure probabilities. The response surface was better able to resolve the higher failure probabilities for the larger penetration depths. Since the response surface method was faster, used less computational resources and provided reasonable estimates of the failure probabilities, the method would be useful in quickly providing risk information about early vehicle designs. Once the design matured, the direct computation method would be used to generate more refined risk data.

Table 6. Probability of bondline temperature failure due to MMOD strike damage predicted using response surface.

Cavity depth (in)	0	0.1	0.2	0.3	0.4	0.5	0.75	1	1.25	1.5
Response surface	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0082	0.4232	0.9613	0.9987
Direct computation	0.0001	0.0001	0.0001	0.0002	0.0004	0.0005	0.0094	0.2421	0.9338	1.0000

4. CONCLUSION

A physics-based model was developed to predict the probability of a loss of crew due to failure scenarios that can occur during the entry, descent and landing phase of a manned space mission. The model integrated an engineering-level aerothermodynamics tool to compute the lift, drag and heating coefficients for a given vehicle, a three-degree-of-freedom trajectory tool to compute the entry trajectory and a one-dimensional transient response code to predict the thermal response of the vehicle thermal protection system. The model accounted for damage to the TPS due to MMOD impacts. Monte Carlo simulations were used to predict the effects of dispersions and uncertainties in the vehicle state at the start of the entry trajectory, the heating environment during the trajectory and the material properties of the TPS on the ability of the vehicle to operate within its design limits. Both direct computation and response surface methods were used in the Monte Carlo simulations.

The model was used to analyze a generic manned capsule designed for missions to low Earth orbit. A temperature limit at the bondline between the TPS and the underlying structure was used as the failure criterion. Exceeding the temperature limit would cause the TPS material to debond from the structure. The model was used to determine the nominal heatshield thickness based on the failure probabilities due to the dispersions in trajectory, aerothermodynamic heating and material properties. For the nominal heatshield design, the model was used to predict the failure probabilities due to MMOD damage. Conservative values were obtained by assuming the MMOD impact always occurred at the point of maximum heating. More realistic values were obtained by assuming the impacts occurred at random locations on the heatshield.

A response surface approach was also developed to predict the failure probabilities in a less computationally intensive manner. The response surface was built using Kriging as the interpolation scheme and a Latin hypercube design to populate the parameter space. The response surface provided results that compared well with the data obtained using the direct computation method and certainly can be used in the preliminary design phase to quickly provide risk information.

The selection of a bondline temperature limit was appropriate for assessing the reliability of the TPS design. Using the criterion to predict the probability of loss of crew due to TPS failures may be too conservative for the sample problem, since bondline temperature failures typically occurred late in the trajectories, when heating may not be significant enough to cause structural damage. The development of appropriate failure criteria for the assessment of loss of crew probabilities during the EDL phase is an ongoing research topic.

References

[1] Go, S., Mathias, D., Lawrence, S. and Gee, K., "An Integrated Reliability and Physics-based Risk Modeling Approach for Assessing Human Space Launch Systems," 12th International Conference on Probabilistic Safety Assessment and Management (PSAM12), Honolulu, HI, June, 2014.

[1] Lawrence, S. L., Mathias, D., Gee, K. and Olsen, M., "Simulation Assisted Risk Assessment: Blast Overpressure Modeling," PSAM-0197, 8th International Conference on Probabilistic Safety Assessment and Management (PSAM8), New Orleans, LA, May, 2006.

[2] Lawrence, S. L. and Mathias, D., "Blast Overpressure Modeling Enhancements for Application to Risk-Informed Design of Human Space Flight Launch Abort Systems," RAMS 06B-3, 2008 Reliability and Maintainability Symposium, Las Vegas, NV, January, 2008.

[3] Gee, K. and Mathias, D., "Assessment of Launch Vehicle Debris Risk During Ascent Aborts," RAMSRM-312, The 54th Annual Reliability and Maintainability Symposium, Las Vegas, NV, January, 2008.

[4] Gee, K. and Lawrence, S. L., "Launch Vehicle Debris Models and Crew Vehicle Ascent Abort Risk," Reliability and Maintainability Symposium (RAMS), Orlando, FL, January, 2013.

[5] Marx, M. H., "A Computer Program to Predict the Impact Dispersions of Debris Resulting From the Forced Entry of Apollo Vehicles," NASA-TM-X-69808, October, 1968.

[6] Desai, P. N., Lyons, D. T., Tooley, J. and Kangas, J., "Entry, Descent, and Landing Operations Analysis for the Stardust Re-Entry Capsule," AIAA Paper 2006-6410, 2006.

[7] Sepka, S. A. and Wright, M., "A Monte Carlo Approach to FIAT Uncertainties – Improvements and Applications for MSL," AIAA Paper 2009-4234, 41st AIAA Thermophysics Conference, San Antonio, TX, June, 2009.

[8] Kinney, D. J. and Garcia, J. A., "Predicted Convective and Radiative Aerothermodynamic Environments for Various Reentry Vehicles Using CBAERO," AIAA Paper 2006-659, 44th AIAA Aerospace Sciences Meeting and Exhibit, January, 2006.

[9] Hargraves, C. R. and Paris, S. W., "Direct Trajectory Optimization Using Nonlinear Programming and Collocation," AIAA Journal of Guidance, Control and Dynamics, Vol. 10, No. 4, 1987, pp. 338-342.

[10] Riehl, J., Paris, S. and Sjauw, W., "Comparison of Implicit Integration Methods for Solving Aerospace Trajectory Optimization Problems," AIAA Paper 2006-6033.

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

[12] Rodriguez, A. C. and Snapp, C. G., "Orbiter Thermal Protection System Lessons Learned," AIAA Paper 2011-7308, AIAA SPACE 2011 Conference & Exposition, Long Beach, CA, September, 2011.

[13] Tigges, M. A., Bihari, B. D., Stephens, J., Vos, G., Bilimoria, K. D., Mueller, E. R., Law, H. G., Johnson, W., Bailey, R. E., and Jackson, B., "Orion Capsule Handling Qualities for Atmospheric Entry," AIAA Paper 2011-6264, AIAA Guidance, Navigation and Control Conference, Portland, OR, August, 2011.

[14] http://www.nas.nasa.gov/hecc/resources/pleiades.html#url

[15] Lophaven, S. N., Nielsen, H. B., and Sondergaard, J., "DACE: A MATLAB Kriging Toolbox," Technical Report IMM-TR-2002-12, Informatics and Mathematical Modelling, Technical University of Denmark, 2002