IMPROVED AEROTHERMAL RELIABILITY ANALYSIS ENABLED BY THE MARS SAMPLE RETURN EARTH ENTRY SYSTEM AEROTHERMAL DATABASE.

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Introduction: The Mars Sample Return (MSR) campaign is a series of missions designed to retrieve Martian rock and soil samples for detailed study on Earth. The campaign is split into three primary phases: sample collection with the Mars2020 rover, retrieval with the Sample Return Lander (SRL) and Mars Ascent Vehicle (MAV), and then return to Earth with the Earth Return Orbiter (ERO) and Capture, Containment, and Return System (CCRS) [1]. The final sequence in the Earth return phase is the delivery and entry of the Earth Entry System (EES) sample return capsule. Due to unprecedented planetary protection concerns, the sample return capsule is subject to strict reliability requirements. To this end, the MSR-EES aerothermal team has implemented a flexible aerothermal database architecture capable of integration with state-of-the-art trajectory codes to provide a more rigorous aerothermal reliability analysis. The EES database enables the generation of environments at any location on the heatshield and can incorporate trajectory uncertainties to both statistically quantify aerothermal environments for arcjet testing and produce material response boundary conditions to rigorously select thermal protection system (TPS) sizing environments. This poster will not discuss the fundamental modeling assumptions included in the database, and will instead focus on the downstream reliability analyses that can be performed with a database of this architecture.

Aerothermal Database: Several methodologies exist to predict aerothermal environments for candidate entry trajectories. The simplest approach is to employ generalized stagnation point heating correlations, such as the Brandis-Johnston correlations developed for Earth entry [2]. This method can be extended off the stagnation point by fitting density-velocity scaling laws to heating estimations from computational fluid dynamics (CFD) simulations. The primary drawbacks to these fits are that they perform poorly with complex margin policies that vary both spatially and temporally, such as the margins used for the EES, and that they are not guaranteed to recover the original data used for fitting. A higher-fidelity method is the creation of an aerothermal database anchored to CFD results using a panel method code, such as CBAERO [3]. While panel method codes use more physical scaling laws and better extrapolate spatially across the vehicle than engineering correlations, these databases have poor outlier handling and are still not flexible enough to accommodate the complex EES margin policy. To meet these accuracy and flexibility needs, the EES aerothermal team uses an approach similar to the Orion aerosciences team [4] where entry trajectories are directly interpolated within a database of CFD solutions. This database architecture recovers the anchoring CFD results and is capable of both generating environments for every point across the EES heatshield as well as handling the temporally and spatially varying EES heating margins. To provide rapid aerothermal environment predictions, the EES aerothermal database has been successfully integrated with the state-of-the-art trajectory codes Program to Optimize Simulated Trajectories II (POST2) and Dynamics Simulator for Entry, Descent and Surface landing (DSENDS) [5]. Figure 1 shows the EES aerothermal database triangulated in the dynamic pressure – velocity interpolation space alongside a set of 20,000 trajectories produced by POST2.

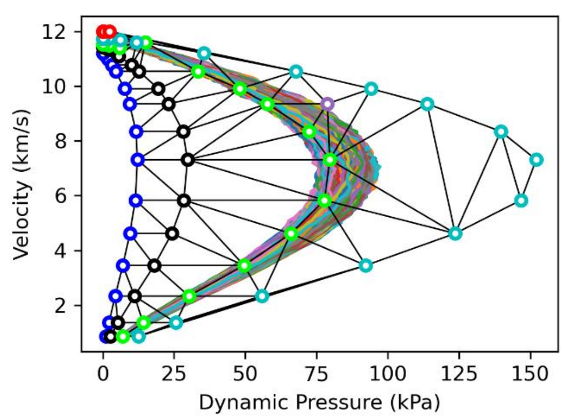

Fig. 1: *Aerothermal database triangulation in interpolation space with 20k trajectories flown through it.*

Analysis Products: The integration of the EES aerothermal database with Monte-Carlo trajectory codes allows for high trajectory throughput and captures the effects of trajectory uncertainties. Bounding aerothermal environment profiles (known as "butterfly plots") for a given probability are produced with the database by analyzing the variation in aerothermal environments across time, vehicle location, and trajectory dispersions. Figure 2 below shows the probability map from which these profiles are extracted alongside the 99.87% contour in blue and the 0.13% contour in red. A "99.87% *High*" aerothermal profile (the 0.13% contour line) represents simultaneous pressure and heat flux conditions that are more extreme than those experienced by 99.87% of likely trajectories. This profile informs arcjet testing conditions to ensure that the EES TPS materials can withstand the worst case entry environments.

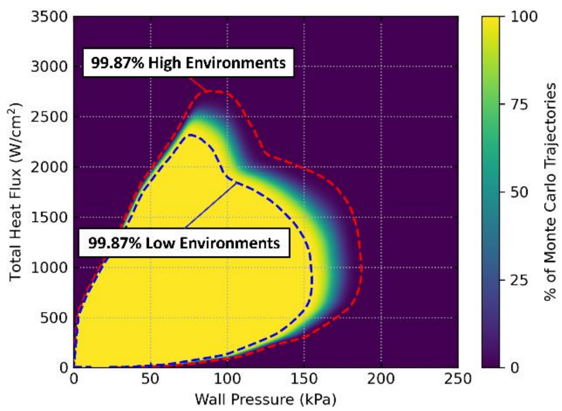

Fig. 2: *Probability map that a given aerothermal environment will be experienced by an entry trajectory within an MSR-EEV monte carlo simulation.*

Another capability of the aerothermal database is the ability to rigorously select TPS sizing trajectories using large-scale material response analysis. Entry probe heatshield thicknesses are sized to maintain operating temperatures in all material systems, such as the TPS bondline, as well as to cover the worst-case expected recession. Flight projects traditionally assume that these two cases are accounted for by sizing the TPS to the trajectories that result in the largest instantaneous heat flux and integrated heat load. For the EES, the aerothermal database is used to check this assumption by generating boundary conditions for the Fully Implicit and Ablation Thermal response code (FIAT) [6] along each trajectory within a Monte-Carlo set. Evaluating the heatshield material response for each case allows the direct selection of the trajectories that result in the highest bondline temperatures and largest TPS recession. This process guarantees that the TPS thickness accounts for the worst-case expected entry conditions. Figure 3 shows sample output from this process and highlights that for the EES, the traditionally selected "peak heat flux" and "peak heat load" trajectories are not actually the bounding material response cases.

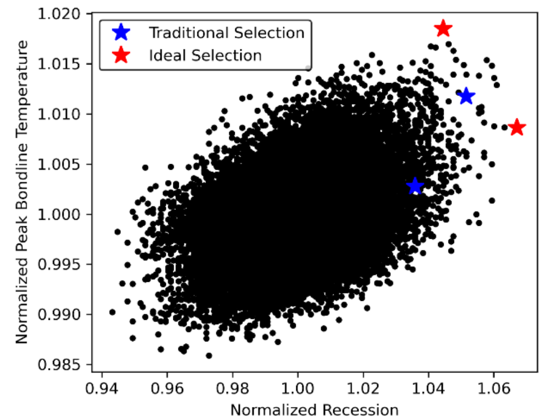

Fig. 3: *Output from a 20k trajectory material response analysis showing that the peak heat flux and heat load trajectories (blue) are not necessarily bounding in recession and bondline temperature.*

Scope: This poster will present the EES aerothermal database architecture, compare database results with alternative methods, explain the formulation aerothermal reliability metrics such as the aerothermal butterflies, and show how this database architecture can be used to more rigorously select trajectories for TPS sizing. For a higher-level overview of the EES aerothermal database, please refer to the work of G. Palmer et al being presented at IPPW 2023.

References:

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