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Entry, Descent, and Landing Mission Design For The Crew Exploration Vehicle Thermal Protection System Qualification Flight Test

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In support of NASA's Vision For Space Exploration, a new manned space vehicle (the Crew Exploration Vehicle or CEV) is being designed to replace the aging Space Shuttle fleet. Integral to the CEV development is the design of the systems necessary for the safe return of the crew back to Earth, especially from high speed lunar return missions. One of the many system challenges for a safe return is the design of the Thermal Protection System (TPS) necessary to protect the astronauts from the extreme thermal environments encountered during the Earth Entry, Descent, and Landing (EDL) operations. A study was established, called Test Of Reentry Capsule Heatshield (TORCH), to explore the flight system development of a sub-scale CEV capsule for the specific purpose of supporting the qualification of the TPS material (PICA) for both low Earth orbit and lunar return missions. Integral to this flight system study was the EDL mission design necessary to achieve the aerothermal test requirements while minimizing the overall cost of the flight test.

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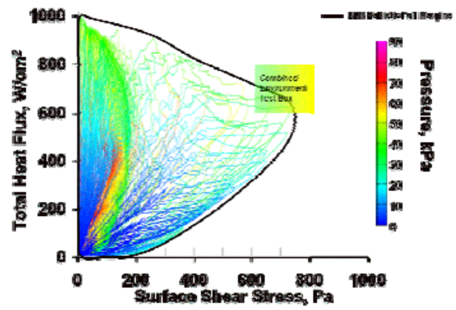
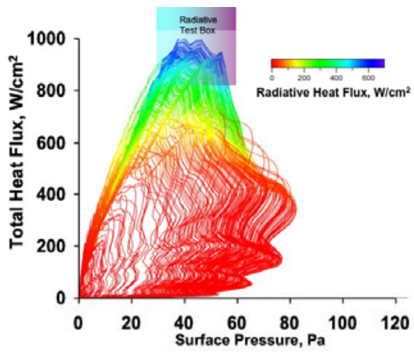
Problem Statement

The TORCH team was challenged to generate the lowest cost mission design solution that meets the CEV aerothermal test objectives on a sub-scale flight article. The test objectives resulted from producing representative lunar return missions and observing the aerothermal envelopes of select surface locations on the CEV. **From these aerothermal envelopes, two test boxes were established: one for high shear and one for high radiation.** The unique and challenging trajectory design objective for the flight test was to "fly" through these aerothermal boxes in shear, pressure, heat flux, and radiation while also not over testing. These test boxes, and the max aerothermal limits, became the driving requirements for defining the mission design.



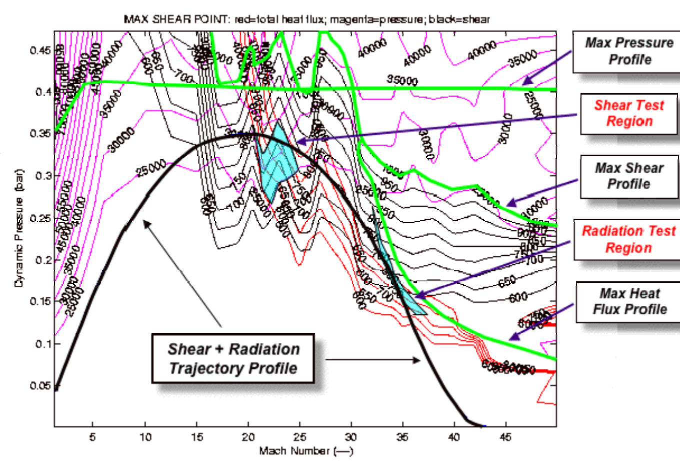


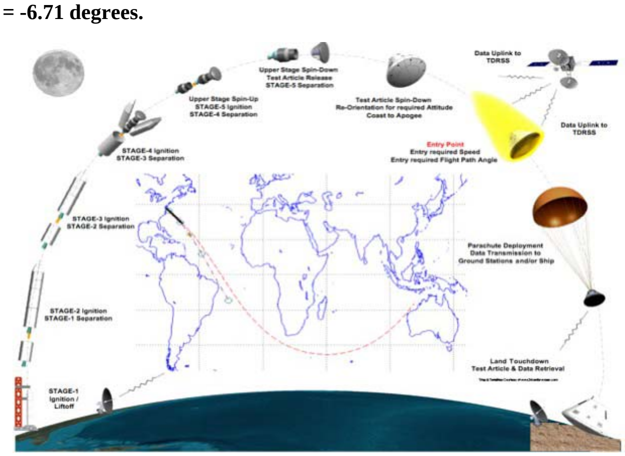
Problem Formulation

Generating the lowest cost mission design solution required finding the minimum energy entry state in terms of entry velocity and the mass of the test article. In addition, reducing the number of flights by combining the two test objectives into a single flight test as well as reducing the vehicle diameter to enable smaller launch vehicles and lower manufacturing costs was also highly desirable. An optimization process was established whereby the vehicle mass and entry velocity was parametrically varied and for each combination an optimal trajectory was determined via a gradient optimizer wrapped around JPL's EDL simulation tool: Dynamics Simulator for Entry, Descent, and Surface landing (**DSENDS**). The objective function for the optimization problem was to minimize the maximum error from the center of the aerothermal test box (computed throughout the simulation) by controlling entry flight path angle.

Results

The configurations explored included a mass range from 400 to 1200 kg and a diameter range of 1 to 2.2 m. Although able to achieve the test box conditions, it was determined that vehicles with mass below ~650 kg and diameters below 2 m were shear and heat flux limited and were eliminated. **Ultimately, an 850 kg flight test article with a 2 m diameter was established as the lightest and smallest feasible vehicle.** In addition, it was concluded that this configuration could indeed successfully fly through both test boxes in a single test flight further reducing the overall cost. The entry conditions for this single flight test would be as follows: **Entry Velocity = 12.1 km/s, Entry Flight Path Angle = -6.71 degrees.**





Flight Operations

Flight operations will be carried out from either the Wallops Island or Cape Canaveral launch facilities. The launch vehicle trajectory design would be a sub-orbital flight with either 1) a high apogee to allow gravity to enable a high velocity entry state or 2) a lower apogee with the utilization of an upper stage for a "pile drive" powered phase to achieve the desire velocity. In either case, the landing location would be on land to avoid adverse water induced alteration of the TPS material upon landing. Currently, it is expected that the landing site would be in Woomera, Australia.

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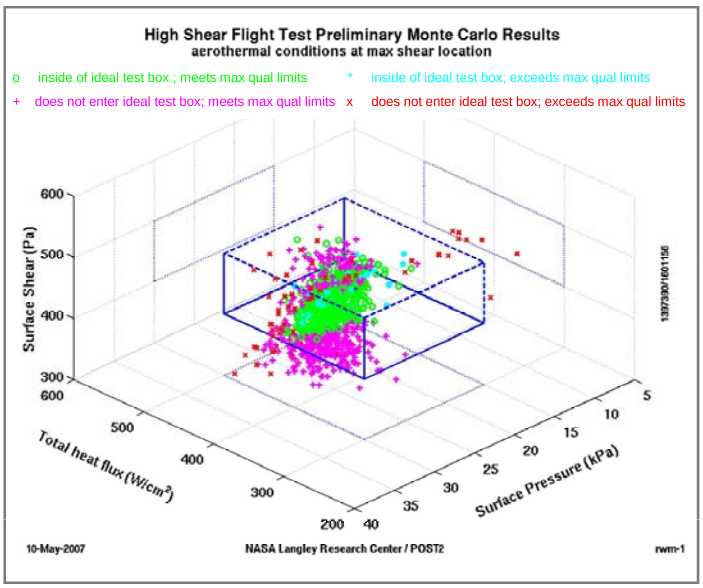
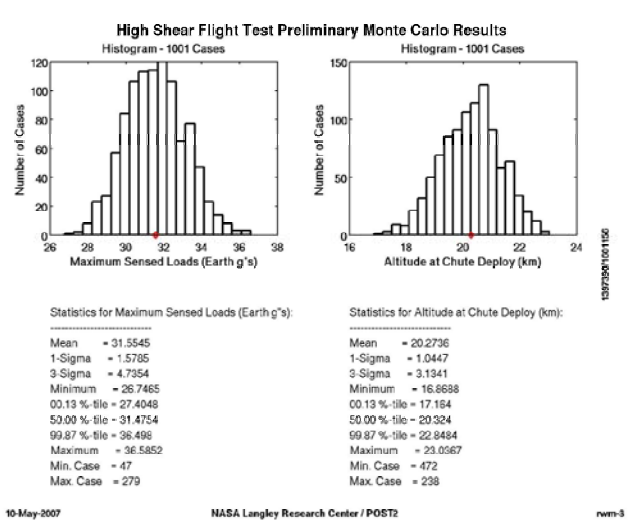
Monte Carlo Analysis

In order to verify that the aerothermal test conditions could be met when subject to varying entry, atmospheric, and aerodynamic conditions, independent Monte Carlo simulations were performed at NASA Langley Research Center and the Jet Propulsion Laboratory. Results from the Monte Carlo analysis were used to determine the amount of margin that needed to be applied to the nominal trajectory to ensure that test conditions could be satisfied under dispersed conditions. The major inputs to the Monte Carlo simulation included aerothermal uncertainties supplied by the CEV Aerosciences Project, aerodynamic uncertainties as specified in the project Orion Aerodynamic Data Book, and a set of 1000 dispersed entry states for the Minotaur IV launch vehicle provided by Orbital Sciences Corporation.



Statistical Results

Below is an example of just one type of statistical product which can be produced from a Monte Carlo analysis. This type of analysis is key in the systems design component of the flight project. It provides the necessary information to determine design requirements and the system's performance against those requirements.



Monte Carlo Inputs and Models

Input	Units	Value	Distribution Type	Dispersion 3-σ or Min/Max
Number of cases		1001		
Entry Velocity	m/s	8700.0	--	Minotaur 4 Entry states file
Entry Flight Path Angle	deg	-9.5695	--	Minotaur 4 Entry states file
Mass	kg	400.0	Uniform	+/- 1.0 %
Aeroshell diameter	m	2.0	--	none
c.g. location	cm	[0.676, 0.0, -0.0595]	Uniform	+/- 1.0
Angle of attack	deg	Trim at 147 deg	Gaussian	+/- 3.0
Initial bank angle	deg	90.0	Gaussian	+/- 5.0
Side slip	deg	0.0	--	none
Bank rate	rpm	0.0	--	none
Atmosphere		GRAM99	--	Random perturbed
Winds		GRAM99 tables	--	Random perturbed
Aerodynamics		Orion Aero Database Version 2 draft 3	Uniform	Orion Aero Database Version 2 draft 3
Aerothermal- convective		Aerothermal Database	Uniform	Multiplier 0.741/1.35
Aerothermal- radiative		Aerothermal Database	Uniform	Multiplier 0.5/2.0
Aerothermal- shear		Aerothermal Database	Uniform	Multiplier 0.8/1.25
Aerothermal- pressure		Aerothermal Database	Uniform	Multiplier 0.952/1.05
Chute deploy mach		0.7	Gaussian	+/- 0.1

Aerothermal Performance

This is an example of the summary from a Monte Carlo analysis performed using NASA Langley Research Center's POST2 (Program to Optimize Simulated Trajectories) simulation software. The box shown in blue is meant to represent this flight test's aerothermal test condition limits in total heat rate, surface pressure, and surface shear, as measured at the maximum shear location on the heat shield. The various colored data points show how each trajectory in the Monte Carlo faired in meeting these test conditions.

These results are meant to be representative. Preliminary analysis has determined that there exists a strong dependence on the the nature and level of uncertainties in the aerodynamics and aerothermal databases. These results can be used to illustrate the sensitivity to stringent test environment constraints in contrast to more flexible, or qualitative, limits. In this example, only 463 of the 1001 cases result in a flight test which achieve both the flight test aerothermal limits as well as the maximum material qualification limits. However, these limits are not exact. For example, even though the lower flight test limit for surface shear is shown here as 400 Pa, it is reasonable to expect that a test condition only achieving 399 Pa is likely to be acceptable. The challenge comes in defining these various levels of achieving the desired test conditions. The test box shown here may be "ideal", but there may be a slightly larger box that could be considered "desired", and an even larger box could be "acceptable". The same also holds true with respect to the maximum qualification limits. It is certain that with this type of consideration (which will be completed in the continuation of this work) many, if not most, of the remaining cases would be considered successful flight tests.

Dispersions at the Landing Site in Australia

The landing site selected for the test capsule is Woomera, Australia. One of the products from the Monte Carlo simulation is a dispersion in the trajectories at the landing site, which can be used to compute the size of the landing probability ellipse. Shown here is the dispersion in latitude and longitude at deployment of the subsonic parachute at Mach 0.7. The dimensions of the 99.87% probability ellipse at parachute deploy were computed to be 136 km X 62 km (major X minor axis). Preliminary estimates by NASA Johnson Space Center have predicted that the size of the dispersions at chute deploy can be reduced to approximately 10 km diameter if entry guidance is used after the test point. The size of the ellipse at landing may be larger due to drift on the parachute chute from winds and atmospheric dispersions. The information from the landing site dispersions can be used to target the Woomera test range and assess the probability of contact with populated areas.