First Stage Solid Propellant
Multi Debris Thermal Analysis

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The crew launch vehicle considered for the Constellation (Cx) Program utilizes a first stage solid rocket motor. If an abort is initiated in first stage flight the Crew Module (CM) will separate and be pulled away from the launch vehicle via a Launch Abort System (LAS) in order to safely and quickly carry the crew away from the malfunction launch vehicle. Having aborted the mission, the launch vehicle will likely be destroyed via a Flight Termination System (FTS) in order to prevent it from errantly traversing back over land and posing a risk to the public. The resulting launch vehicle debris field, composed primarily of first stage solid propellant, poses a threat to the CM. The harsh radiative thermal environment induced by surrounding burning propellant debris may lead to CM parachute failure. A methodology, detailed herein, has been developed to address this concern and quantify the risk of first stage propellant debris leading to radiative thermal demise of the CM parachutes. Utilizing basic thermal radiation principles, a software program was developed to calculate parachute temperature as a function of time for a given abort trajectory and debris piece trajectory set. Two test cases, considered worst-case aborts with regard to launch vehicle debris environments, were analyzed using the simulation: an abort declared at Mach 1 and an abort declared at maximum dynamic pressure (Max Q). For both cases, the resulting temperature profiles indicated that thermal limits for the parachutes were not exceeded. However, short duration close encounters by single debris pieces did have a significant effect on parachute temperature, with magnitudes on the order of 10's of degrees Fahrenheit. Therefore while these two test cases did not indicate exceedance of thermal limits, in order to quantify the risk of parachute failure due to radiative effects from the abort environment, a more thorough probability-based analysis using the methodology demonstrated herein must be performed.

Nomenclature

A_1	= Area of Nylon
A_2	= Area of spherical debris
C	= Specific heat of nylon
CM	= Crew Module
Cx	= Constellation
$\vec{D}$	= Vector of distance between parachutes and a debris piece
D	= Magnitude of $\vec{D}$
F_{12}	= View factor
FS	= First Stage
LAS	= Launch Abort System
LOC	= Loss Of Crew
LOX	= Liquid Oxygen
MET	= Mission Elapsed Time
q	= Heat flux
Q	= Energy
r	= Radius of a spherical debris piece
T	= Temperature
ε	= Emissivity of parachutes
σ	= Stefan-Boltzmann Constant
ρ_N	= Mass to Area ratio of the parachute nylon.

θ_1 = Angle between normal vector of A_1 and the vector $\vec{D}$

θ_2 = Angle between normal vector of A_2 and the vector $\vec{D}$

I. Introduction

The crew launch vehicle for the Cx Program is designated Ares I. The propulsion system of Ares I consists of a first stage solid rocket motor and a LOX/Hydrogen liquid upper stage. If an abort is initiated during first stage flight, the Launch Abort System (LAS) is fired to quickly pull the Crew Module (CM) away from the launch vehicle in an effort to save the crew. During this abort there is an option to detonate the "headless" launch vehicle for public safety. Detonation of the Ares I results in thousands of fragments thrown outward from the destruct location. In such a scenario, there is a risk that launch vehicle debris could strike the CM and lead to a Loss-Of-Crew (LOC) event. The majority of these resultant fragments originate from the first stage propulsion system and are comprised of burning solid rocket propellant. The risk of debris strikes in first stage abort scenarios have been studied in-depth by the Cx Program. However, a secondary debris concern exists on the thermal effects of burning solid rocket propellant on the CM, specifically the parachute system.

An abort trajectory analysis on Ares I was performed using a first stage debris catalog, which utilizes a vehicle specific debris database to generate propellant debris characteristics. This debris database is a heritage-based/First Stage (FS) hybrid debris catalog. From this analysis it was observed that aborts at Mach 1 (~44 sec MET) and max dynamic pressure (~60 sec MET) could result in the CM being surrounded by debris for a significant portion of the abort trajectory. This brought up a concern that when the parachutes are deployed there is a possibility of failure from burn through of the parachute system due to the harsh thermal environment induced by the close-proximity of flaming debris. A methodology was developed to calculate the CM parachute temperature profile for a given abort trajectory.

II. Assumptions/Limitations

To develop and test the validity of the methodology discussed in this paper, several assumptions were made to simplify the problem. The assumptions listed below were used in this analysis, since they represent conservative conditions for the problem.

- The debris pieces are spherical and radiate as black bodies.
- Ambient temperature (T_{amb}) is 50°F (283°K).
- The debris burns ($T_{fireball}$) at a constant 4000°F (2478°K) thru entire abort trajectory.
- There is no heat transfer between debris; therefore all debris pieces are at the same temperature.
- Only radiative heating is analyzed; convective cooling is ignored.

The next set of assumptions is based on Ares I and Orion data, which were obtained from the Constellation program. The assumptions detailed below are accurate as of June 2010.

- The nylon parachutes have an emissivity (ε) of 0.899.
- The parachutes failure temperature is 150°F (339°K).
- Debris density is 1811.1 kg/m^3 (used to determine debris size).
- A_1 = 1.0 [m^2]
- σ = 5.669e-9 [W/(m^{2*}K^4)]
- C = 1.7 [J/(g*K)]
- ρ_N = 33.9049 [g/m^2]

III. Methodology

The foundation of this methodology will be based on the Stefan-Boltzmann Law, in order to analyze the parachutes for thermal failure:

$$q = \varepsilon \sigma T^4 \text{ (Ref. 3)} \quad (1)$$

The problem is constructed as a three body system, as depicted in Figure 1. The fireball (body 2) is the collection of burning debris. The nylon (body 1) is a section of the parachute. The third body is the portion of the sky that is not obscured by the fireball. The approach taken was to analyze the heat flux that is absorbed and expelled by the nylon. This was accomplished by writing the Stefan-Boltzmann Law into equations that represent the heat flux imparted to the nylon from the fireball and the heat flux radiated out from the nylon to the sky:

$$q_{in} = \varepsilon\sigma\left(T_{fireball}^4 - T_{nylon}^4\right) \tag{2}$$

$$q_{in} = \varepsilon\sigma\left(T_{nylon}^4 - T_{amb}^4\right) \tag{3}$$

Equation (2) assumes all of the radiated heat from the fireball is directed at the nylon. This is not the case, since the fireball is a 3D object that radiates in all directions. Equation (3) has the same assumption, but corresponds to the relationship between the nylon and sky. To account for this fact Equations (2) and (3) will need to be multiplied by a view factor. The view factor is defined as “the fraction of radiation leaving one surface that is intercepted by a second surface.”When relating several bodies the *summation rule* applies: $F_{12}+F_{13}=1$. Applying the view factor and summation rule on Equations (2) and (3) results in:

$$q_{in} = \varepsilon\sigma\left(T_{fireball}^4 - T_{nylon}^4\right)F_{12} \tag{4}$$

$$q_{out} = \varepsilon\sigma\left(T_{nylon}^4 - T_{amb}^4\right)F_{13} \rightarrow$$

$$q_{out} = \varepsilon\sigma\left(T_{nylon}^4 - T_{amb}^4\right)\left(1 - F_{12}\right) \tag{5}$$

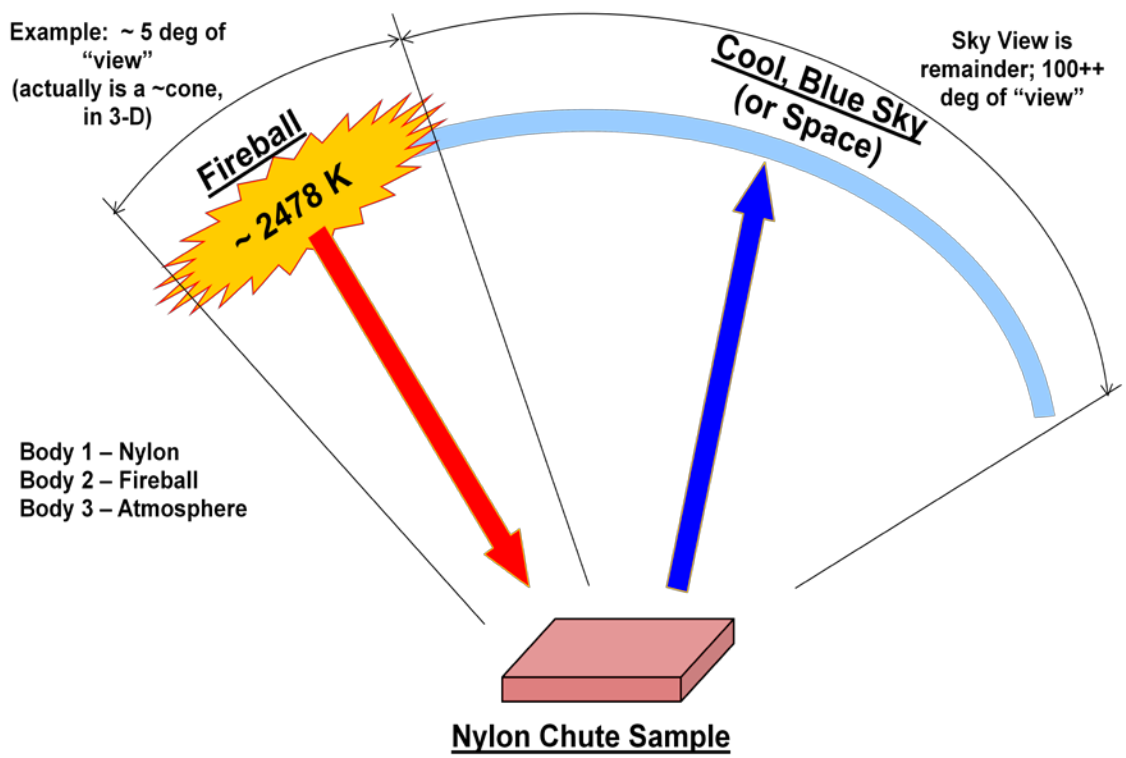

Figure 1: Diagram of Thermal Problem

The system has two equations and 4 unknowns, q_{in}, q_{out}, T_{nylon}, and F_{12}. Since the goal is to create a temperature profile of the nylon, T_{nylon} will have an initial condition applied based on the situation. This leaves 3 unknowns, which means F_{12} will have to be solved for outside the heat flux equations. This is accomplished by starting with the generic equation for a two body view factor:

$$F_{12} = \frac{1}{A_1} \iint \frac{\cos\theta_1 \cos\theta_2}{\pi D^2} dA_1 dA_2 \quad \text{(Ref. 4)} \tag{6}$$

Here A_1 is the surface area of body 1, A_2 is the surface area of body 2, θ_1 is the angle between normal vector of A_1 and $\vec{D}$, θ_2 is the Angle between normal vector of A_2 and $\vec{D}$, and D is the magnitude of the distance between A_1 and A_2. An illustration supporting Equation (6) can be seen in Figure 2.

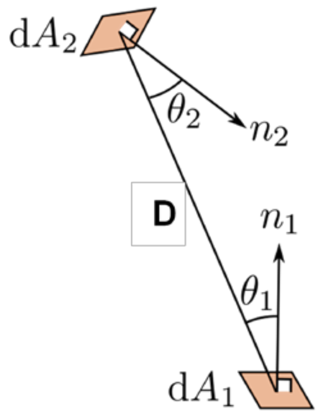

Figure 2: Illustration of F_{12}

Equation (6) can be integrated to:

$$F_{12} = \frac{1}{A_1} \left(\frac{\cos\theta_1 \cos\theta_2}{\pi D^2} \right) A_1 A_2 \tag{7}$$

Assume that A_1 is a parachute segment with the normal vector pointed toward A_2. A parachute segment is analyzed since if only one section is degraded then the entire parachute system is considered failed. Assume A_2 is the cross section or projected area of a spherical propellant debris piece of radius r. Figure 3 is an illustration of the set up of F_{12} with the above assumptions applied.

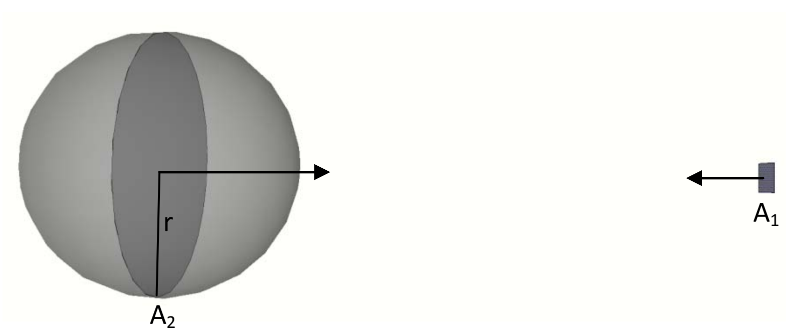

Figure 3: Illustration of F_{12} with Assumptions

Equation (**7**) will then reduce to:

$$F_{12} = \frac{\cos 0 \cos 0}{\pi D^2} \pi r^2 = \frac{r^2}{D^2} \tag{8}$$

Equation (8) reduction means that the view factor is based only on the size of the debris and the distance of the debris from the parachutes. F_{12} is the view factor of only one debris piece to the parachutes; the view factor of all the debris pieces to the parachutes is needed. It was assumed that all of the propellant burns at the same temperature of 4000 °F and the temperature will remain constant throughout the trajectory. Since the debris temperatures do not change, this means that there will be no heat transfer between the debris pieces. This assumption means that we can use the *summation rule*: (F_{1d1}+F_{1d2}+F_{1d3}+F_{1d4}+ …) + F_{13} = 1, where F_{1d1} is the view factor of body 1 to debris piece 1, F_{1d2} is the view factor of body 1 to debris piece 2, etc. The summation of the individual view factors adds up to the F_{12} variable in Equations (4) and (5).

Now that the view factors can be calculated, Equations (4) and (5) can be used to calculate the net energy acted on the nylon. Multiply Equations (4) and (5) by the area of nylon (A_1) to create energy equations for the nylon. The net energy on the nylon is calculated by taking the energy emitted by the nylon and subtracting it from the energy absorbed by the nylon:

$$Q_{in} = \varepsilon\sigma\left(T_{fireball}^4 - T_{nylon}^4\right)F_{12}A_1 \tag{9}$$

$$Q_{out} = \varepsilon\sigma\left(T_{nylon}^4 - T_{amb}^4\right)\left(1 - F_{12}\right)A_1 \tag{10}$$

$$Q_{net} = Q_{in} - Q_{out} \tag{11}$$

The net energy can then be utilized to calculate the change in temperature:

$$\Delta T = \frac{Q_{net}}{c\rho_N A_1} \text{ (Ref. 4)} \tag{12}$$

For each time step, the delta temperature is applied to the previous parachute temperature. The result is a parachute temperature profile along the trajectory.

IV. Simulations

The methodology was written into a MATLAB script. The script inputs were the distance from the CM and mass of the debris pieces at different time steps. The initial temperature of the parachute was conservatively set to 70 °F (294 °K).

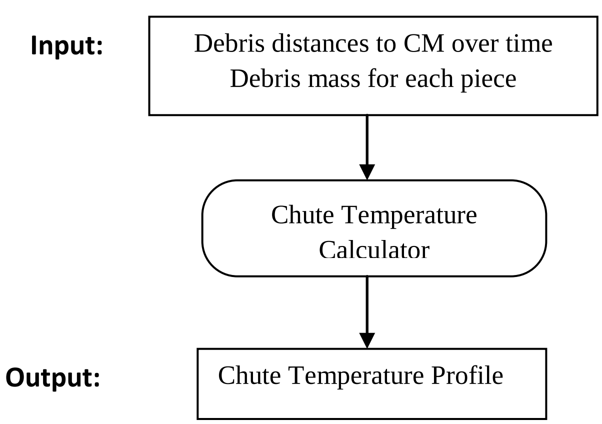

Figure 4: Simulation Flow Chart

Figure 4 displays the basic process of the simulation. The first input is a list of distances between each debris piece and the CM over a time profile. The section input is the mass of each debris piece, which is used to calculate the spherical dimensions of the debris piece. The Chute Temperature Calculator employs the methodology detailed in Section III. The output is a parachute temperature profile.

V. Results

Two cases were run with the Chute Temperature Calculator, one with an abort when the launch vehicle reaches Mach 1 (~44 sec MET) and one at Max Dynamic Pressure (~60 sec MET). Figure 5 below displays the temperature and minimum distance profile for an abort at Mach 1:

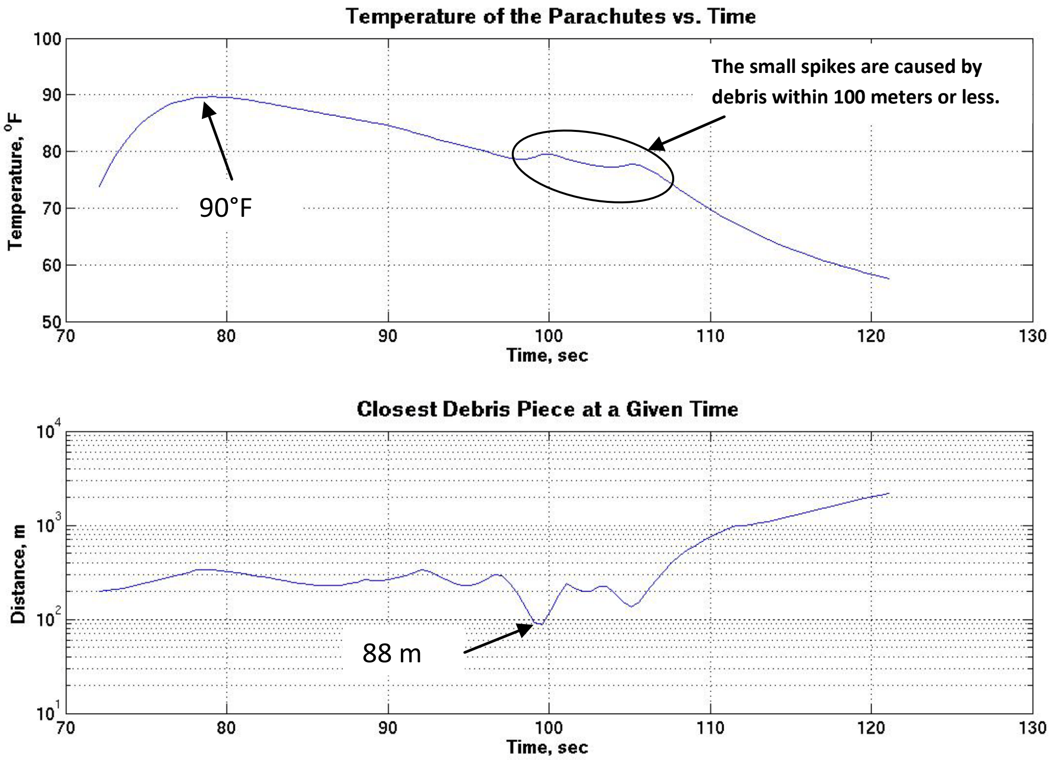

Figure 5: Abort at Mach 1

The first temperature increase in Figure 5, the slow ramp up from 72 sec to 80 sec, was caused by a large number of debris pieces passing between ~200 m to ~2500 m of the CM. The two temperature spikes circled above were caused by one or more debris pieces passing within 100 m of the CM. This relation between pieces passing close to the CM and a temperature spike can be seen by looking at the closest debris piece profile. Anytime that a large downward spike is seen in the closest debris piece profile correlates to an upwards spike in the temperature profile. The closest debris piece throughout the trajectory was 88 m. For this case the nylon failure temperature limit of 150°F was not reached. Figure 6 below shows the results for the abort at max dynamic pressure.

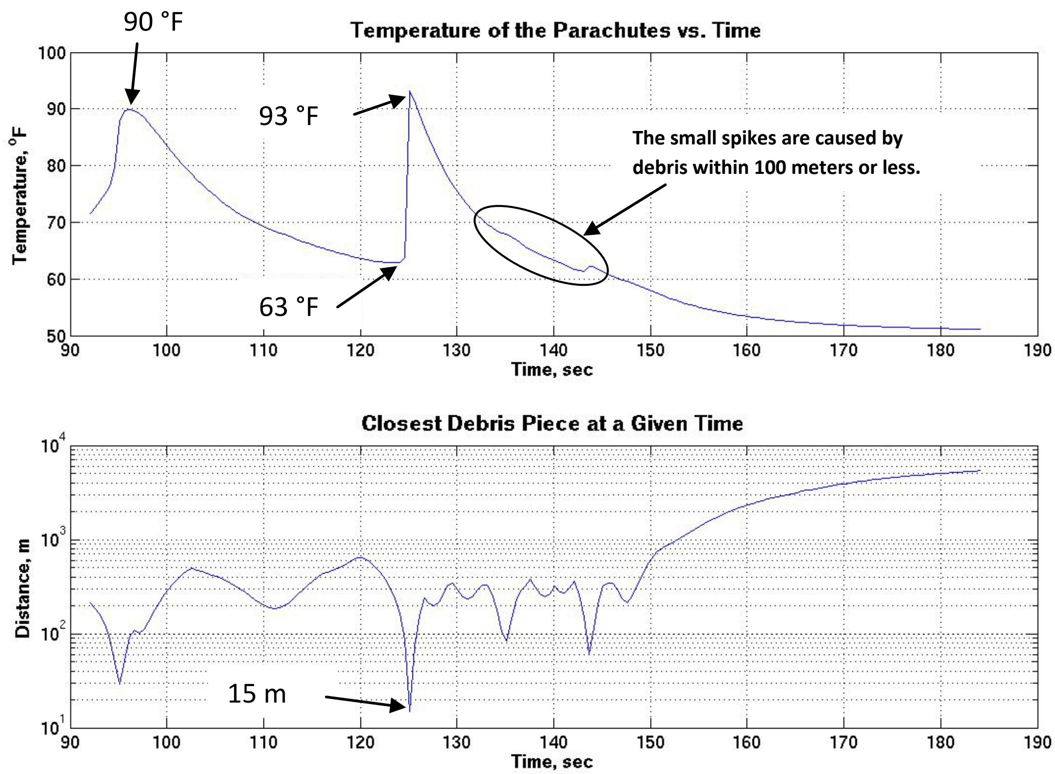

Figure 6: Abort at Max Dynamic Pressure

The first temperature increase in Figure 6, the ramp up from 92 sec to 97 sec, was caused by a large number of debris pieces in the range of distances ~200 m to ~4000 m. The first temperature spike, at 125 sec, was caused by a single debris piece flying within 14.8 m of the CM and only took about 1 sec to occur. The other smaller spikes were caused by a few pieces getting within 100 m of the parachute. For this case the nylon failure temperature limit of 150°F was not reached.

Even though the Mach 1 and Max Dynamic Pressure cases evaluated did not result in a thermal failure of the parachutes, there still exists a probability of the parachutes temperature reaching the nylon failure limit for other debris configurations. These two cases also demonstrate the risk for large temperature increases to occur in a short amount of time.

VI. Conclusions

These two cases raise a concern as to the probability of the temperature profile reaching the nylon failure temperature. Only two cases were run and the results do not represent the full spectrum of possible debris field configurations. From the two cases it has been observed that the possibility exists for large temperature increases in a short amount of time. For a different debris field configuration and dispersed abort trajectory, then a failure could take place. A set of dispersed abort trajectories with dispersed debris field configurations should be analyzed using the developed thermal methodology. A Monte Carlo of this scale is very computationally intensive. Due to the limited computational resources available to the author, a Monte Carlo was not performed. This additional work would be used to calculate the probability of a thermal limit violation for the parachutes.

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