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Modeling Solid Propellant Shielding Phenomena for Launch Accident Analysis

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INTRODUCTION

Launch of a radioisotope power system requires an extensive safety analysis. [1] The launch accident environment is harsh and complex. Accidents are generally initialized by an explosion at which time both the liquid rocket propellant and the solid rocket boosters (SRBs) are intentionally destructed to prevent them from descending in one large mass. Large pieces of solid propellant can still remain however, and a concern is that they could impact or land near the radioisotope power system (RPS) that is part of the rocket payload. In the past, the designated code which is used to evaluate the radiological release ("source term") for launch accidents, Launch Accident Sequence Evaluation Program (LASEP) [2], assumed that there was nothing inhibiting the effects of the solid propellant fire. This was conservative because there could potentially be large amounts of debris between the propellant piece and the RPS. This debris could include a large amount of aluminum from the launch vehicle (LV) and space vehicle (SV) as well as both the heat shield and backshell that make up the aeroshell (for missions that include an aeroshell). This work is aimed at trying to better model that solid propellant fire environment in order to more accurately characterize the risk associated with the launch.

LASEP WORKFLOW DESCRIPTION

LASEP attempts to evaluate all potential threats to the RPS during the launch accident. The simulation starts with an Accident Initiating Condition (AIC) and continues through in-air blast environments, fragment fields, ground impact, subsequent debris and fragment insults, and solid propellant fragment fires. There are currently 27 insult types modeled in LASEP that can be invoked for any particular mission. This paper focuses on solid propellant fire in the presence of launch debris.

LASEP is a Monte Carlo code which randomly samples many of its parameters to arrive at one particular result. It is then run for multiple trials in order to get a distribution of the potential event outcomes. With a large number of calculations that need to be performed, it is not feasible to incorporate many large physics models to evaluate each insult. Therefore, LASEP uses simplified physics models as well as interpolation of tables that are created by detailed physics codes to arrive at a solution. This solution set, the source term, is then used by a consequence analysis code to determine the overall mission risk.

SOLID PROPELLANT FIRE PHENOMENA

Many launches incorporate SRBs and the high-temperature fires from the SRB fragments can vaporize some of the RPS fuel and increase mission risk. The current solid propellant fire model in LASEP evaluates the effects of SRB fragments that land within a defined distance from the RPS. This distance is typically five fragment radii. So the larger a fragment is, the further away it can be and still be evaluated as a threat. The previous model also assumed unimpeded access to the RPS by the solid propellant fire. There was no credit taken for the many phenomena that could reduce the effects of the fire. Some of these phenomena have been incorporated into the solid propellant fire model through this work, while others have not yet been addressed. All relevant phenomena are described below.

Phenomena Addressed: Debris Shielding

Debris shielding includes the effects of launch vehicle debris (e.g. Centaur upper-stage remnants), the backshell, and the heat shield. All of these materials will reduce or delay the effects of the fire on the RPS. A mechanistic model for these effects has been added into the LASEP code and is described in a later section.

Phenomena Not Addressed

There is potential that one side of the propellant fragment could have the SRB titanium casing still attached. If this casing is on the side of the exposed RPS, the heat flux and temperature could be greatly reduced.

The SRB fragment field currently defined in LASEP is the initial fragment field from the SRB destruct at altitude. It does not incorporate any secondary fragmentation that would be seen upon impact. It has been observed and would be expected that there is significant fragmentation due to the high velocity ground impacts. This will result in smaller propellant fragments, but it will also result in more fragments that could potentially threaten the RPS.

There are also aluminum droplets formed by the SRB burning process that oxidize in air. These alumina droplets might result in an alumina coating forming around the exposed fuel pellet. This will act as a heat resistant barrier to fuel vaporization. There is insufficient data to quantify this phenomenon at this time.

Another effect of the debris that will not be addressed in this model is the potential for the debris to create a substantial gap between the ground and the propellant fragment. This would likely reduce the temperature of the fire environment for any fuel located beneath the propellant fragment.

Models for these phenomena may be looked at in future LASEP development, but would only serve to reduce the source term and therefore the mission risk.

SOLID PROPELLANT FIRE SHIELDING MODEL

This model was developed in an attempt to better define and evaluate the solid propellant fire environment. The three main shielding components present are the launch vehicle debris, heat shield, and backshell. Each of these materials affects the heat flux and temperature that the RPS fuel is exposed to. The configuration of the system will also be very important. The propellant mass can be under, above, or beside the RPS. This propellant mass location and the orientation on impact will determine the aluminum debris mass between the RPS and the propellant that is available to provide shielding.

Heat Shield and Backshell

For some launch configurations the payload is housed in an aeroshell, which is composed of a heat shield and backshell. These materials are specifically designed to withstand high thermal loading. If they remain intact following the ground impact, they will offer a large amount of protection to the RPS. This will include both a delay before the heat is able to penetrate and an overall reduction in the heat flux to a point where the iridium clad surrounding the RPS fuel pellets may no longer melt.

Two thermal protection systems (TPS) were looked at in some initial calculations, Phenolic Impregnated Carbon Ablator (PICA) and Super Light Weight Ablator (SLA). PICA was first used as a heat shield material in 1999 on the Stardust mission and SLA has been used extensively in Mars missions. Because these materials are designed to withstand high temperatures, they survive for the duration of the solid propellant fire. However, heat could still be transferred through the TPS to the debris or RPS fuel on the other side.

An analysis was done to estimate the heat flux that would be seen on the other side of the PICA or SLA during the fire. It was assumed that there would be some compression of the material on impact. The two compression states looked at were fully crushed (100% dense) and half crushed (thickness decreased by 50%). Figure 1 shows the resulting fraction of the heat flux that would be emitted on the other side of a PICA layer initially 31.75 mm thick and a SLA layer initially 12.7 mm thick.

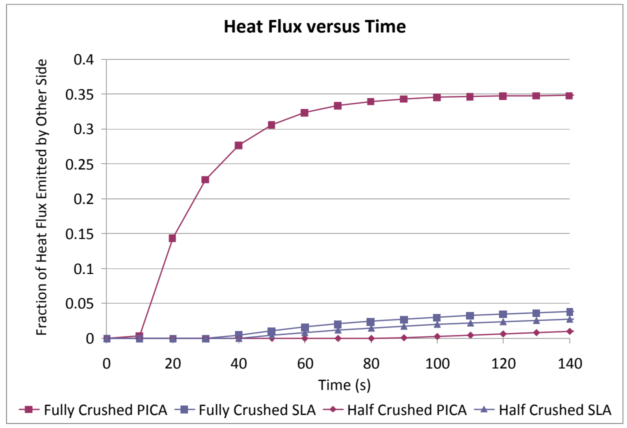

Fig. 1. Fraction of Heat Flux Emitted by Other Side of Various TPS Materials

These results show that if the heat shield and backshell material remain intact, the heat flux to the debris and RPS fuel will not be high enough to cause any significant amount of vaporization. However, if the material is cracked or fragmented in the ground impact the material may provide little protection. This is being investigated with a continuum mechanics model.

Preliminary impact results from continuum mechanics modeling suggest that while the materials remain largely intact there is potential for cracking, making the effectiveness of the shielding hard to quantify with a high level of confidence. Shielding by the TPS material will continue to be looked at. It is has not been implemented at this time, but will be incorporated when an accurate model can be developed.

Launch Vehicle and Space Vehicle Debris

Burn Geometry

The LV and SV debris is composed mainly of aluminum, which melts at 933 K. As it melts it will quickly re-solidify as it comes into contact with surrounding aluminum because of its high thermal conductivity. In the process it will deposit its heat into the large mass of debris, slowly heating it while the propellant fragment melts its way through. At the end of the melt, the gas flow field from the burn will sweep any remaining molten aluminum away from the fragment. Figure 2 shows the progression of melt through the debris for a fragment-on-top configuration.

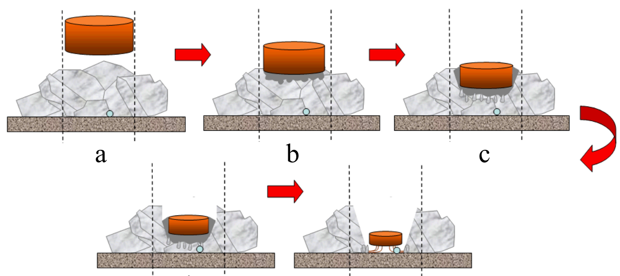

Fig. 2. Progression of Solid Propellant Fragment Melting through Aluminum Debris.

As the propellant fragment melts through the debris, its radius is decreasing. This phenomenon is currently being implemented into the code, but is not part of the results presented in this paper. The effect of this will be a reduction in the vaporization, because the decrease in size could result in a portion or all of the RPS fuel being to the side of the propellant rather than underneath or on top. If it is to the side, it will see a much smaller heat flux and have less vaporization as a result.

If an aeroshell is used, there is a possibility of having liquid propellants within the SV. If the blast from the rupture of the liquid propellant tanks on impact is large enough, there is potential that it could alter the burn geometry. Calculations performed up to this point indicate that the impulses induced by these blasts are not high enough to move an appreciable amount of debris. It is also unclear as to whether the RPS and/or the solid propellant would also be moved in such an event. If the SV blast environment has a much higher energy in future missions, this would warrant consideration on whether or not it should be incorporated into the model.

Model Implementation

A simple approximation for the melting of the LV and SV debris is that once enough energy is deposited into the aluminum to cause complete melting (about 9.9E5 J/kg), it offers no further protection from the solid propellant fire. Equation 1 governs this process.

$$qAt = mh_f + mC_p\Delta T \qquad (1)$$

Where q is the heat flux from the solid propellant fire [W/m^2], A is the area of the exposed aluminum directly below the propellant (same cylindrical radius) [m^2], t is time [s], m is the mass of aluminum [kg], h_f is the heat of fusion [J/kg], C_p is the specific heat capacity [J/kg-K], and ΔT is the difference between ambient temperature and the melting temperature of aluminum [K].

The exposure time of the RPS fuel is equal to the total burn time of the fragment minus the time it takes to melt the aluminum debris.

RESULTS

Results of model implementation will vary depending on the mission being evaluated, but are driven by the launch vehicle (number of SRBs). The launch vehicle used in the following scenarios was the Atlas 541, which utilizes four solid rocket boosters. The mass of debris is approximated from an average Atlas 541 payload, and does not reflect any particular RPS launch.

The accident being evaluated is an early launch accident. The area of dispersal for the SRB fragments will be smaller with this lower altitude event, giving a higher likelihood that an SRB fragment will threaten the RPS. The source term reduction will be less for the high altitude accidents; however, because of their high likelihood of solid propellant fires the low altitude events make the greatest contribution to risk.

The heat flux emitted by the solid propellant is dependent on burn geometry and varies throughout the duration of the burn. Results calculated using average heat fluxes of 0.5 MW/m^2 and 1 MW/m^2 will both be presented here.

The values of interest related to the source term are the mean total fuel (Pu-238) mass released as well as the mean effective fuel mass released. The effective mass is simply the mass with particle sizes less than 10 microns, which are more respirable and therefore have higher consequence. Table I gives the average change in these values for the two heat flux scenarios as compared with no debris shielding.

Table I. Solid Propellant Fire Debris Shielding Model Results for 0.5 MW/m^2 and 1 MW/m^2 Heat Fluxes

Solid Propellant Heat Flux (MW/m^2)	Change in Mean Total Fuel Mass Released (%)	Change in Mean Effective Fuel Mass Released (%)
0.5	-20.5	-48.2
1	-14.0	-38.5

To determine the change in risk for these scenarios, the source term would need to go through atmospheric transport with consequence modeling codes. Past calculations have shown that the change in risk is comparable to the change in mean effective fuel mass released. So an average reduction of approximately 40% would be expected in the risk based on these results.

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REFERENCES

1. A. C. MARSHALL, *Space Nuclear Safety*, Krieger Publ. Co., Malabar, FL, 2008.

2. T. RADEL, D. ROBINSON, “Launch Safety Analysis Code for Radioisotope Power Systems,” Proc. PSA 2008, Knoxville, Tennessee, Sept. 7-11, 2008, American Nuclear Society (2008) (CD-ROM).