Assessment of Launch Vehicle Debris Risk During Ascent Aborts

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SUMMARY & CONCLUSIONS

In the event of a space launch vehicle explosion during ascent, the debris field generated by the explosion poses a risk to the crew. To evaluate this risk, a model of the debris environment was created and used to determine the probability of a debris strike on the crew module. The model uses experimental data to determine the initial debris field due to a launch vehicle explosion and computes the trajectory of each piece of debris. The trajectory of the crew module after the abort is also computed. The relative position of the debris field and the crew module is determined as a function of time after abort and explosion. A debris flux about the crew module is computed based on this information. The debris flux is used to compute the probability of a debris strike on the crew module using the Poisson distribution. The effect of system and model parameters—such as warning time, the number of debris pieces and abort system thrust—on the debris strike probability is assessed.

I DEBRIS STRIKE MODEL

A current design of a space launch system is shown in Figure 1. The design utilizes a solid rocket motor first stage and a liquid-fueled second stage to put a crew exploration vehicle (CEV) into low Earth orbit. The design has a launch abort system (LAS) intended to quickly separate the crew capsule from the launch vehicle in the event of a failure during ascent. One such failure possibility is the loss of structural integrity due to rapid pressurization of the first stage or explosion of the second stage. Such a failure exposes the crew to an overpressure and debris field, both of which can lead to a loss of crew. Models have been created to address the risk to the crew due to blast overpressure and impulse [1]. The current work focuses on the risk posed by the debris field.

Figure 1 – Launch Vehicle Design

To assess the debris field risk to the crew, a physics-based model was created to evaluate the probability of a debris strike on the crew capsule. The model starts by assuming an initial debris field based on a probabilistic model developed by Baker et al. [2]. The probabilistic model, in turn, was based on experimental data obtained from Project PYRO drop tests of a LH2/LOX rocket stage [3]. The initial debris field is defined by the total number of pieces of debris and the mass, surface area, velocity, flight path angle, heading and drag coefficient of each individual piece. The Baker model provided log-normal distributions for the debris area and velocity. Roughly 300 pieces of debris were recovered in the experiment. The debris mass was related to the debris area using a relationship developed from bomb studies, as recommended by Baker [3].

It was assumed that all the debris emanates from a point corresponding to the center of mass of the vehicle segment. The debris velocity vector was assumed to be normal to the axial direction of the vehicle. The resultant debris velocity vector was the vector sum of the initial debris velocity and the vehicle velocity at the time of the explosion.

The trajectory of each piece of debris is then computed using a three-degree-of-freedom trajectory tool [4]. A constant value of drag coefficient was used and was randomly generated for each piece of debris within a range of values that included drag coefficients corresponding to spheres, blocks and flat plates. The lift coefficient was set to zero.

The post-abort trajectory of the crew capsule is also computed using the same trajectory tool. The abort trajectories for the crew capsule were modeled after those used in the Apollo program [5]. Mode I aborts used the LAS to pull the crew capsule away from the remainder of the vehicle stack. Mode II aborts were used if an abort occurred after the LAS was jettisoned shortly after first stage separation. In a Mode II abort, the reaction control system was used to separate the crew capsule from the launch vehicle. For aborts due to an imminent explosion of the launch vehicle, the service propulsion system (SPS) was used to increase the separation distance between the crew capsule and the launch vehicle. In the current model, the SPS is used to provide thrust during Mode II aborts. An analysis of the risks involved with the abort trajectories is presented in Ref. 6.

The relative position of the crew capsule and the debris field are tracked as a function of time after the abort. The distance between the crew capsule and each piece of debris is used to compute the debris flux about the capsule. At each time interval after the explosion, the debris pieces that traveled the same distance as the crew capsule from the explosion point are counted. The distance between each of these debris pieces
and the crew capsule is computed. The debris flux is computed from the number of debris pieces and the surface area of a spherical cap large enough to contain half the counted debris pieces. The probability of a debris strike is computed from the debris flux using the Poisson distribution.

The model is used to compute the strike probability for aborts occurring at any time during ascent. Additional system parameters included in the model include the warning time available, the abort system thrust available and the number of debris pieces assumed. The effect of each parameter on the strike probability is assessed.

2 RESULTS

The trajectories of the launch vehicle, crew module and debris field due to an explosion of the upper stage at various explosion times is shown in Figure 2. For an explosion early in the ascent (Figure 2a), the LAS is active and separates the crew module from the launch vehicle. The higher aerodynamic forces on the debris due to the dense, lower atmosphere serve to rapidly slow down the debris field, allowing the crew module to clear the debris field. For an explosion at about the midpoint of the ascent (Figure 2b), the LAS has been jettisoned. Therefore, the debris field and the crew module travel at about the same rate and distance, increasing the exposure of the crew module to a debris strike.

For an explosion at the end of the trajectory (Figure 2c), the debris field is scattered over a large area.

The computed debris flux about the crew capsule for an explosion at a mission elapse time (MET) of 200 sec is shown in Figure 3. The model indicates that the highest risk of a debris strike occurs immediately after the explosion and drops off with time. The warning time is defined as the time between the abort and the explosion. As the warning time increased, the debris flux decreased since the crew capsule has time to move away from the launch vehicle before the explosion.

The probability of a debris strike on the crew capsule as a function of mission elapse time (MET) is shown in Figure 4. The strike probability was computed based on the following set of assumptions: 1) an explosion of the upper stage; 2) one second of warning time; 3) 15g of thrust from the launch abort motor; 4) after LAS jettison, the service propulsion system with an estimated thrust level is used to separate the crew capsule from the launch vehicle; and, 5) three hundred pieces of debris. The strike probability was evaluated at METs of 10 sec, 20 sec, 50 sec and then at 50-sec intervals along the
ascent. The launch abort system is active for aborts occurring on or before 150 sec MET. The model shows an increase in debris strike probability after the LAS is jettisoned due to the reduction in separation distance between the crew module and the launch vehicle at the time of the explosion. The SPS thrust is much lower than the LAS thrust, resulting in the reduction in separation distance.

The effect of the number of debris pieces on the strike probability is shown in Figure 6. In Figure 6, the solid lines are the strike probabilities assuming 300 pieces of debris while the dashed lines are the strike probabilities assuming 766 pieces of debris. The strike probability increases with an increase in the number of debris pieces in the field.

The experimental data used by Baker et al. to develop their model indicated that the explosion generated a total of about 300 pieces of debris. The debris catalog developed by Hinckley et al. [7] for the space shuttle listed 766 pieces of debris for the external tank. To investigate the effect of number of debris pieces on the strike probability, the Baker model was used to generate an initial debris field consisting of 766 pieces of debris.

The effect of warning time is shown in Figure 5. The strike probability is reduced with an increase in warning time. With the LAS active, one second of warning time is sufficient to reduce the debris strike probability to near zero. Using the SPS, two seconds of warning time reduces the strike probability two orders of magnitude.

The effect of LAS thrust on the debris strike probability is shown in Figure 7. The LAS is active for aborts occurring before 150 sec MET. The model indicates that the strike probability increases with decreasing thrust level as the distance between the crew capsule and vehicle stack is reduced with reduced thrust level. However, the effect of LAS thrust level is much smaller than the effect of warning time and number of debris pieces.

The debris strike model shows that warning time and the number of debris pieces have a large effect on the strike probability. The amount of warning time available is dependent upon the health monitoring systems and sensors available on the launch vehicle. The debris strike model can be used to provide guidelines as to the amount of warning time available.
required to lower the debris strike risk to an acceptable level. It can also be used to assess the risk associated with an existing or proposed vehicle sensor package. The dependence of the strike probability on the number of debris pieces points to the need for an accurate assessment of the debris catalog resulting from an explosion of the launch vehicle.

The debris strike probability model presented in this paper provides an assessment of the debris strike risk to the crew after an abort and explosion of the launch vehicle. The model is capable of assessing the effects of system and model parameters on the strike probability. The effects of warning time, LAS thrust level and number of debris pieces were discussed. The information generated by the model can be used in a probabilistic risk assessment of the launch abort system.

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