Risk-Based Explosion Assessment
Internal Explosion of Exploration Upper Stage in Vehicle Assembly Building

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ABSTRACT

This paper presents risk-based explosion analyses used to determine if an explosion of NASA's Space Launch System (SLS) Exploration Upper Stage (EUS) during fueling in Vehicle Assembly Building (VAB) High Bay 4 can hazard the Space Launch System (SLS) being processed in Bay 3. This paper focuses on blast fragmentation as it was the controlling hazard. An estimate of the amount of Net Explosion Weight (NEW) was used to develop a fragment list (mass, shape, takeoff velocity/angle) given an explosion occurs at ground level in Bay 4. Intervening superstructure that exists between Bay 4 and Bay 3 (that could potentially block EUS fragments) was modeled based on detailed visual images (VISSIM) and AUTOCAD/structural drawings. The fragment list was input to a 3D trajectory application that performs multiple random explosion simulations; each simulation varying fragment ballistic coefficient and takeoff angle/velocity. Individual fragments are tracked until stopped by the intervening superstructure or reach Bay 3, potentially impacting the SLS. The probability of impacting the SLS is then determined from the random simulations; the results are used to help decision-makers determine the efficacy of co-processing within the VAB and decide what mitigations may be appropriate.

INTRODUCTION

ACTA was asked to evaluate hazards that could result if a hydrazine explosion occurred during processing of an Exploration Upper Stage (EUS) in VAB High Bay 4 while the SLS is being processed in Bay 3.[1] Figure 1 shows the Vehicle Assembly Building and a plan view of VAB Bays 3/4 with the EUS processing location in Bay 4 and the SLS in Bay 3.

Figure 1. Plan View of VAB High Bays 3 and 4.

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[1] Complete documentation is available in Reference [1].

While the SLS is being processed in Bay 3 (only the Center Core Stage and the two SRMs), NASA wants to perform concurrent EUS processing in Bay 4 (including the fueling of four hydrazine tanks). If an EUS "explosion" occurs during processing, it will generate a blast wave as well as fragments that could hazard the SLS in Bay 3. As Figure 2 shows, to reach the SLS, the blast wave and EUS fragmentation must pass through/over two "box-truss" wall systems that bound the Transfer Aisle and miss several SLS work platforms, the mobile launch platform and other intervening structure.

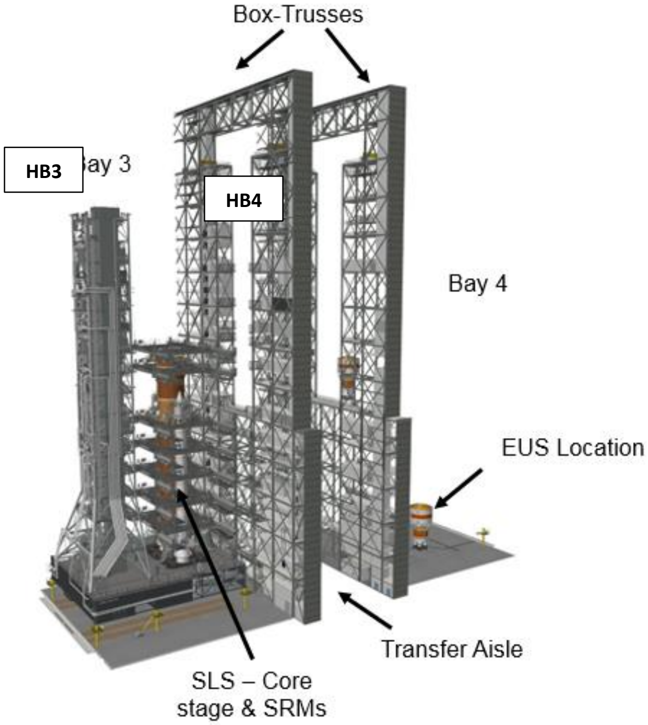

Figure 2. Concurrent Processing of SLS and EUS.

EUS EXPLOSION ACCIDENT

Figure 3 shows that the EUS when integrated with the SLS sits above the Interstage Adapter. The EUS uses four small hydrazine tanks to feed a thrust system; totaling XXXX lb of hydrazine. Used as a mono-propellant, it decomposes when contacting a catalyst producing impulsive forces. It is highly toxic and corrosive but unlikely to explode when used as a mono-propellant. The most likely failure mode is an over-pressurization of the tanks during fueling caused by an XDT (Unknown Delayed Detonation Transition) and sudden release of stored energy.

EUS Explosion Yield

In order to perform a site-specific "explosion" siting analysis, the Net Explosive Weight (NEW), lbs-TNT needs to be determined[2] The NASA QD Standard [2] does not define a Yield Factor for hydrazine. One reason for this is that an accident involving a mono-propellant fuel (such as hydrazine) is unlikely to result in a true TNT explosion (or mass detonation). The most likely accident scenario is one that leads to over-pressurization of the fuel lines and/or tank (e.g., a fire that heats the tanks/lines, a run-away chemical reaction of the hydrazine and catalytic surfaces or, an XDT resulting from contaminants or liquid/vapor phase changes caused by erratic flow patterns).

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[2] NEW is the equivalent amount of TNT that would participate in an explosion: NEW = Yield Factor x Total Weight

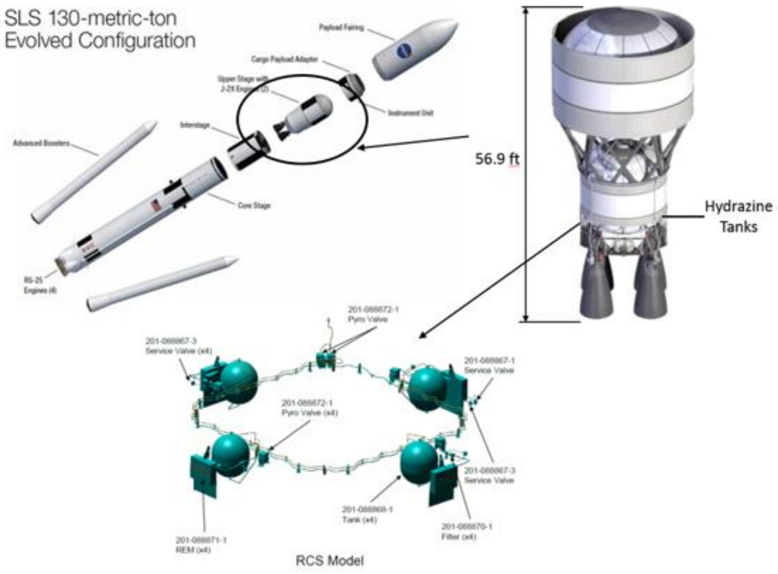


Figure 3. EUS Location in SLS Stack.

If a simple over-pressurization of the small hydrazine tanks were to occur, the sudden release of the stored energy can be converted into an equivalent amount of TNT. Assuming an isentropic energy release process, the equation for the stored energy is:

$$E = \frac{PV}{\gamma - 1}\left[1 - \left(\frac{P_a}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

where: E = energy (ft-lb); P = burst pressure (psfa); V= volume (cu. ft.); P_a = atmospheric pressure (psfa); γ = specific heat ratio of the gas (1.4 is used). TNT conversion: $1.545 \text{x} 10^6$ ft-lb per lb-TNT.

Each of the four small hydrazine tanks has a volume of approximately 7 cu. ft. with a nominal storage pressure of around 50 psi. The tanks have an maximum operating pressure (MOP) of 1200 psi. Assuming the tank failure pressure will be three times the MOP (to acount for a design safety factor), the equivalent amount of TNT (NEW) from a sudden tank burst is 4.7 lbs. If all four tanks fail the NEW is 18.8 lbs, TNT; this corresponds to a Yield Factor of 18.8/1200 = 1.6%

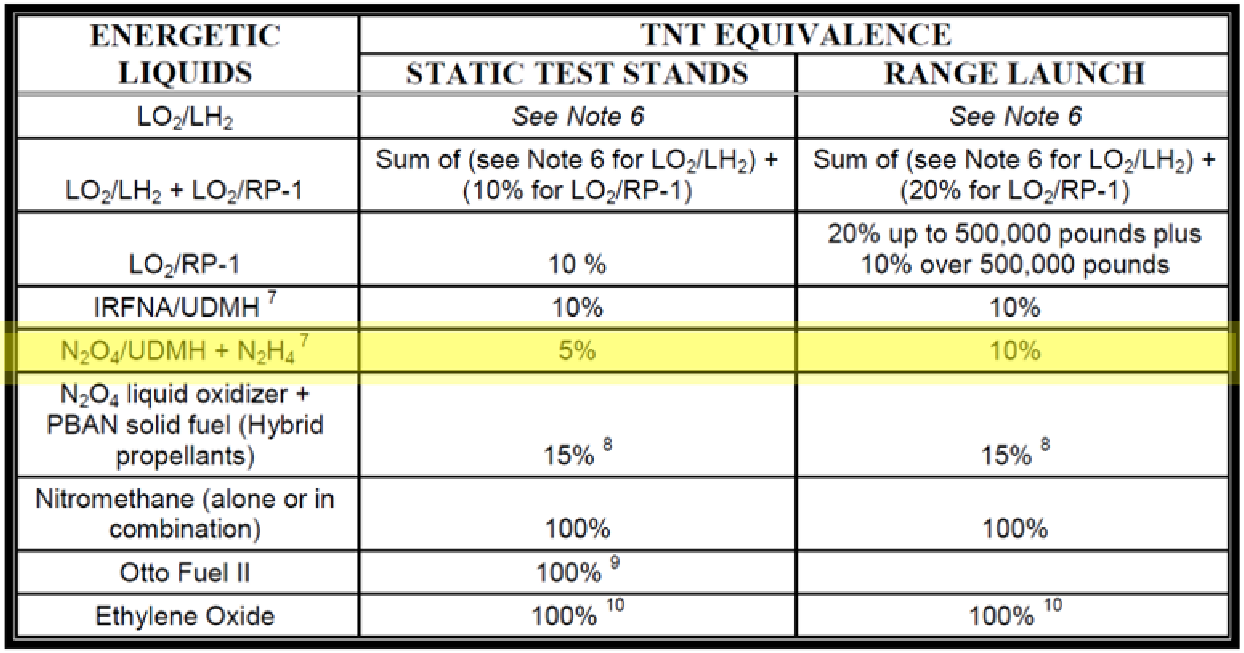
To gain insight into a possible upper bound Yield Factor, Table 1 shows an excerpt from the NASA Explosives Standard. For the energetic liquid highlighted in "yellow" (Dinitrogen tetroxide and Unsymmetrical dimethylhydrazine), two yield factors are provided: "Static Test Stand (5%)" and "Range Launch (10%)", the latter being higher due to the "dynamic" type of operations being performed at a launch pad. These yield factors should be considered as conservative upper bounds for EUS processing in VAB Bay 4 since they represent the potential for direct "mixing" of a fuel and oxidizer residing in close proximity. During EUS hydrazine processing there will be no oxdizer present, making these volatile scenarios "worst" case. For this ground safety study, it was decided to first consider a yield factor of 10% [NEW = 0.1(XXX) lbs, TNT] to account for the potential of an XDT (unknown delayed detonation transition) accident scenario.

EUS Explosion Fragmentation

To determine the hazards posed by explosion generated debris, a fragment list must be developed consistent with the EUS structural configuration/components, the location of the explosion within the EUS, the distance from the explosion to EUS components and the NEW (lb, TNT). ACTA obtained multiple data sources from NASA including a mass property spreadsheet and dimensions/locations of EUS subsystems and components (Figure 4 shows a sample).

The final EUS fragment list consists of a set of fragment groups defined by their average attributes [weight, shape, ballistic coefficient (drag coefficient/mass*area), and takeoff X, Y, Z location, angle, velocity]. Figure 5 shows a summary of the number of EUS fragments thrown as a function of their weight.

Table 1. NASA Explosives Standard Yield Factors for Fuel/Oxidizers.



ENERGETIC LIQUIDS	TNT EQUIVALENCE	
	STATIC TEST STANDS	RANGE LAUNCH
LO_2/LH_2	*See Note 6*	*See Note 6*
LO_2/LH_2 + LO_2/RP-1	Sum of (see Note 6 for LO_2/LH_2) + (10% for LO_2/RP-1)	Sum of (see Note 6 for LO_2/LH_2) + (20% for LO_2/RP-1)
LO_2/RP-1	10 %	20% up to 500,000 pounds plus 10% over 500,000 pounds
IRFNA/UDMH [7]	10%	10%
N_2O_4/UDMH + N_2H_4 [7]	5%	10%
N_2O_4 liquid oxidizer + PBAN solid fuel (Hybrid propellants)	15% [8]	15% [8]
Nitromethane (alone or in combination)	100%	100%
Otto Fuel II	100% [9]	
Ethylene Oxide	100% [10]	100% [10]

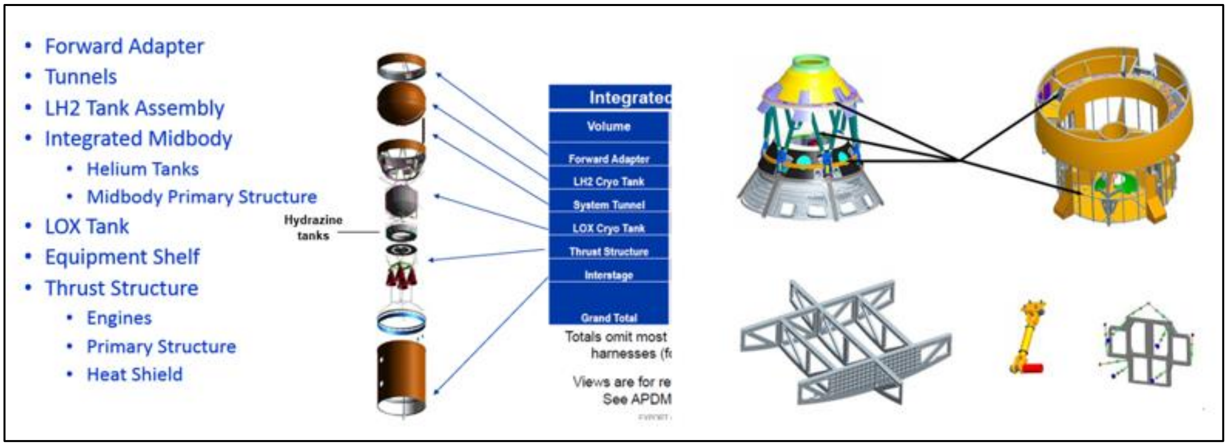


Figure 4. Sample of Subsystem and Component Data/Images.

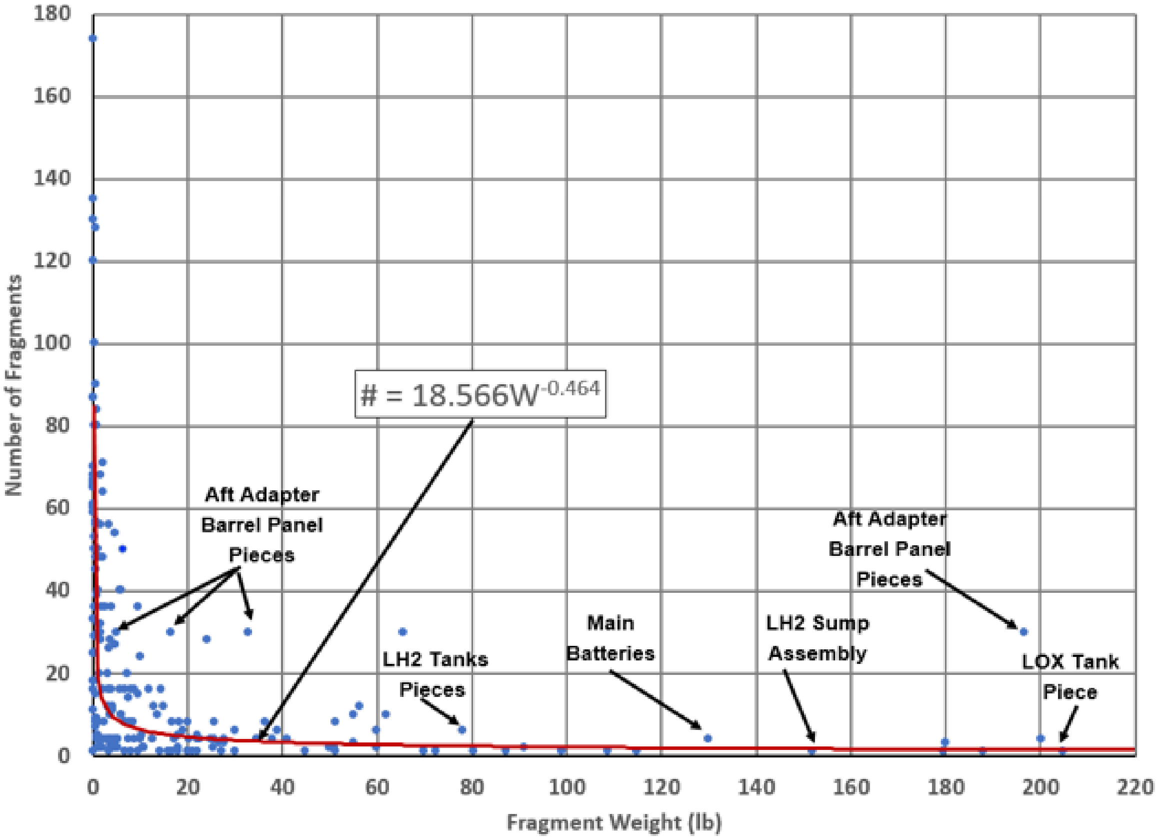


Figure 5. EUS Fragment Weight vs. Number of Fragments Thrown.

The "mean" takeoff velocity of each fragment group is calculated based on a "Modified" Gurney equation [3], [4]; the velocity is a function of the fragment mass and area exposed to the explosion center (but not the radial distance from the explosion source as in other impulse-momentum methods). The "Modified" Gurney (MG) equation is:

$$\frac{U}{\sqrt{2E_g}} = \left[\frac{m}{c} + \frac{n}{n+2}\right]^{-\frac{1}{2}}$$

$$\sqrt{2E_g} = 0.887\varphi^{0.5}{\rho_o}^{0.4} = Gurney\,Velocity$$

$$\varphi = N\sqrt{MQ} \qquad \rho_o = \frac{c}{V}$$

- U = mean fragment velocity
- M = total mass of fragments
- C = mass of hydrazine
- n = shape factor integer (cylinder =2, sphere = 3)
- N = moles of gaseous products per gram hydrazine
- M = molecular weight of gases
- Q = Heat of hydrazine detonation
- V = volume within which hydrazine release explodes

The standard Gurney equation was developed for “cased” weapons where solid propellant fills in the volume of a heavy-walled shell casing. The standard Gurney method produces very high fragment velocities and is overly conservative for spacecraft breakup where liquid propellant tanks are used and there can be significant unconfined volumes within the spacecraft compartment. The ME equation computes an effective propellant density, ρ_o = (mass of hydrazine)/(volume within which the hydrazine explodes), to account for the lack of confinement.

The MG equation provides an average fragment velocity assuming all fragments within a group are identical. In practice, “real” fragments will have a wide range of masses and surface to weight ratios; light-weight pieces with large surface area will tend to be accelerated more than small dense pieces. To account for this, the MG velocity is first applied to the total fragment weight to compute the overall kinetic energy. The total “face” area of all fragments is then computed along with the fraction of the total area represented by each fragment’s “face” area. The fraction of total face area allocated to each fragment is then used to assign a portion of the total KE to each fragment. Finally, the fragment velocity is calculated using $KE_{frag} = 1/2 * M_{frag} * (V_{frag})^2$. Figure 6 shows the relationship between EUS fragment velocity and ballistic coefficient (drag coefficient/mass*area). The drag coefficients (Cd’s) are based on the fragment’s shape and velocity.

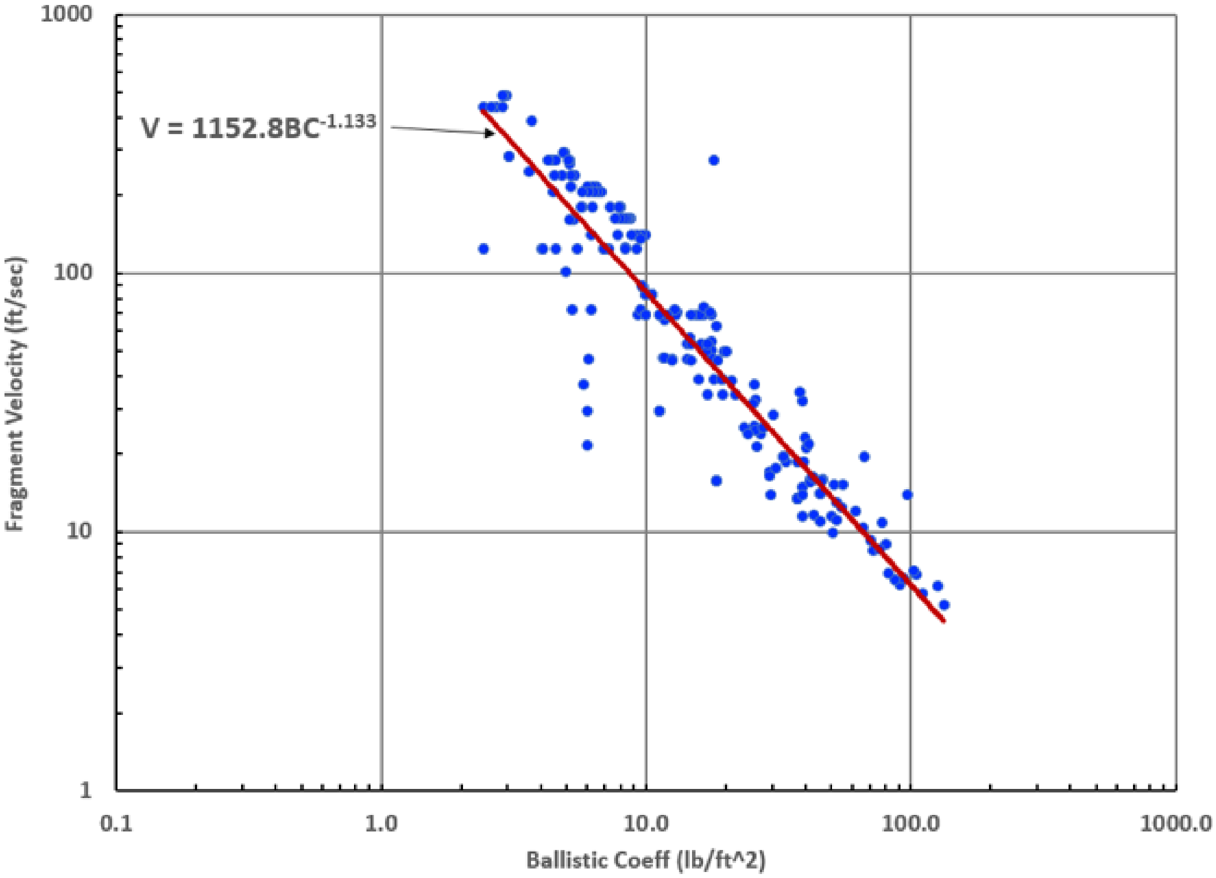


Figure 6. EUS Ballistic Coefficient (W/C_dA) vs. Fragment Takeoff Velocity.

EUS Fragmentation Analysis

The EUS fragment list was input to ACTA’s FRAG3D application to assess the probability of impacting the SLS in Bay 3 with fragments thrown from the EUS location in Bay 4. FRAG3D performs multiple random simulations of the EUS explosion accident; during each simulation the fragment’s weight, ballistic coefficient, and takeoff location, angle and velocity are sampled. Figure 7 shows a schematic of how the fragments are thrown based on their location relative to the hydrazine tanks. During each random accident simulation, fragments above the explosion center are thrown with an upward hemispherical distribution (U), fragments below the explosion center are thrown with a downward hemispherical distribution (D), while fragments adjacent to the explosion are thrown with a radial normal distribution (R) with a mean takeoff of zero degrees (horizontal) and a 6-degree standard deviation. During this study, FRAG3D did not include bounce or ricochet; therefore, fragments that impact the ground or intervening superstructure were assumed to stop (subsequent analyses are including bounce/ricochet).

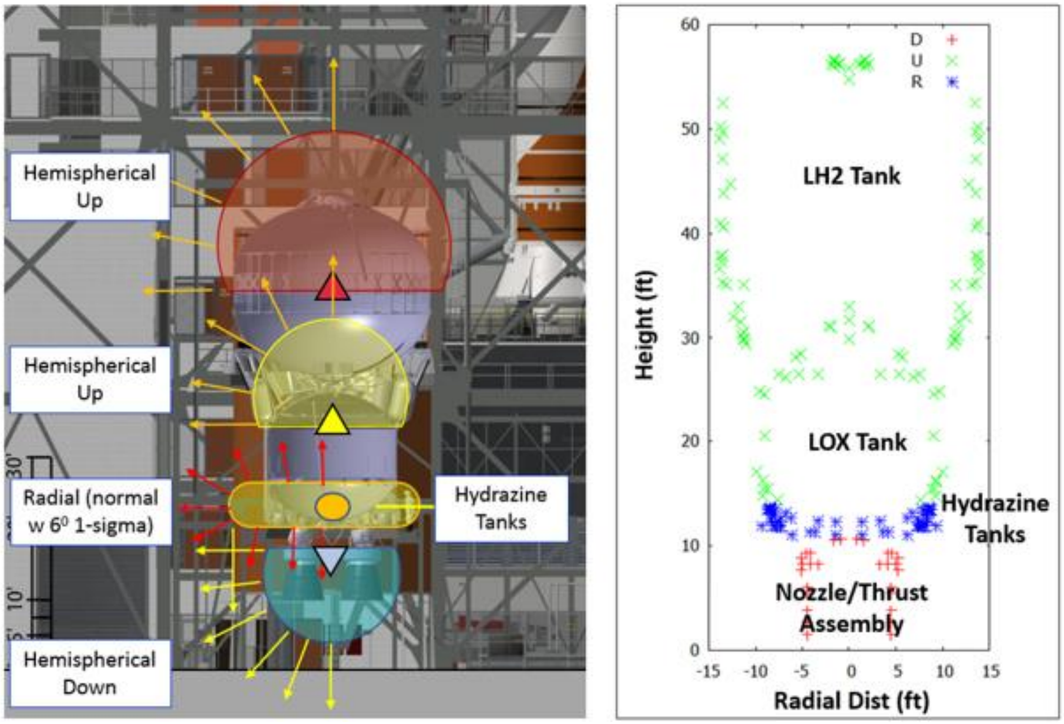


Figure 7. Fragmentation Takeoff Locations and Angle Distributions.

Figures 8 shows one random simulation of fragments thrown from the EUS Bay 4 ground processing location and Figure 9 shows the probability of impacting the SLS/SRMs in Bay 3 with hazardous fragments based on 500 accident simulations.[3]

Given the accident occurs, the impact probabilities range from 0.05/0.1% for the two SRMs to 0.2% for the Core (or, 1 explosive accidents out of 1,000 similar accidents would result in SRM impact and 2 out of 1,000 would impact the Core).

EUS Mitigation Analysis

The previous section showed that although the hazards to the SLS in Bay 3 due to an EUS explosion in Bay 4 are small given an accident occurs, the decision-makers must decide if they can accept <u>any</u> probability of fragments impacting the SLS. One method of eliminating the fragmentation hazards is to position an impact resistant draping (e.g., Kevlar, wire mesh) so that fragments are prevented from propagating towards the SLS (Figure 10). If a local fragment protective draping is applied on the EUS facing and above the SLS, the distance from the explosive source to the draping will be approximately 25-30 feet.

Of concern, however, is that the explosion will generate high blast loads that could destroy/remove the draping before the fragments arrive. To evaluate this, the arrival of the blast wave was determined and compared to the estimated fragment velocities.

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[3] A hazardous fragment is defined as having a KE ≥ 10 ft-lb; therefore, virtually all fragment impacts are counted.

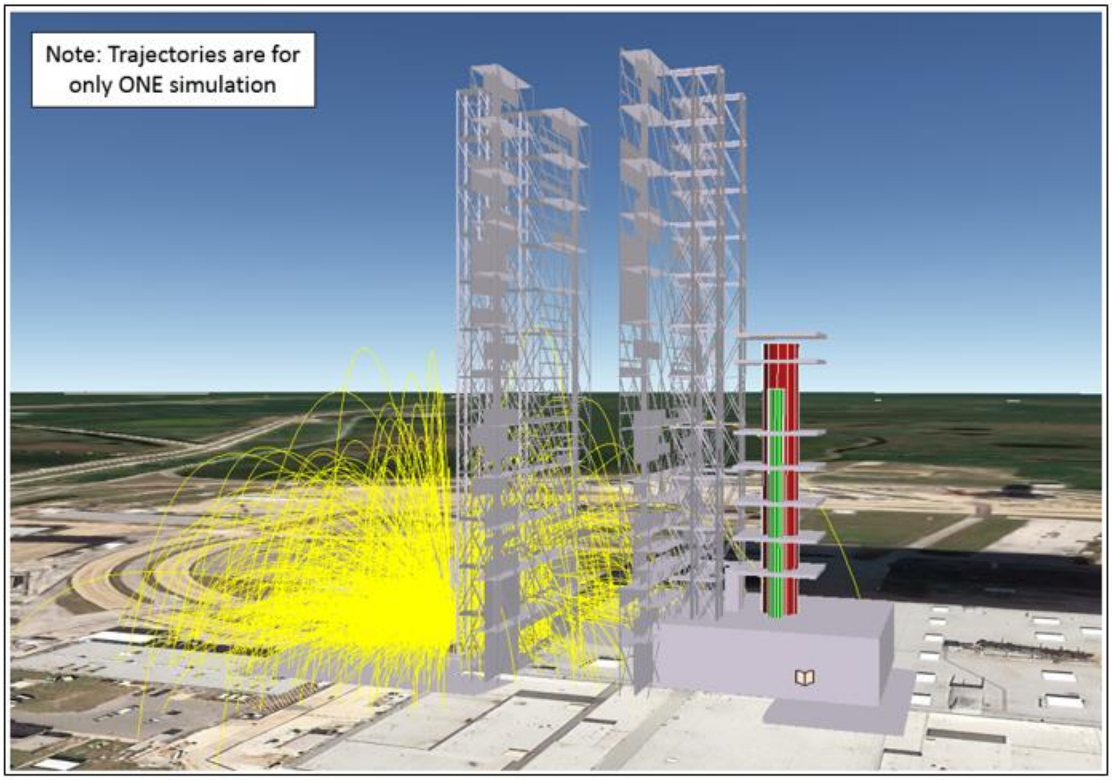

Figure 8. One Random Trajectory Simulation.

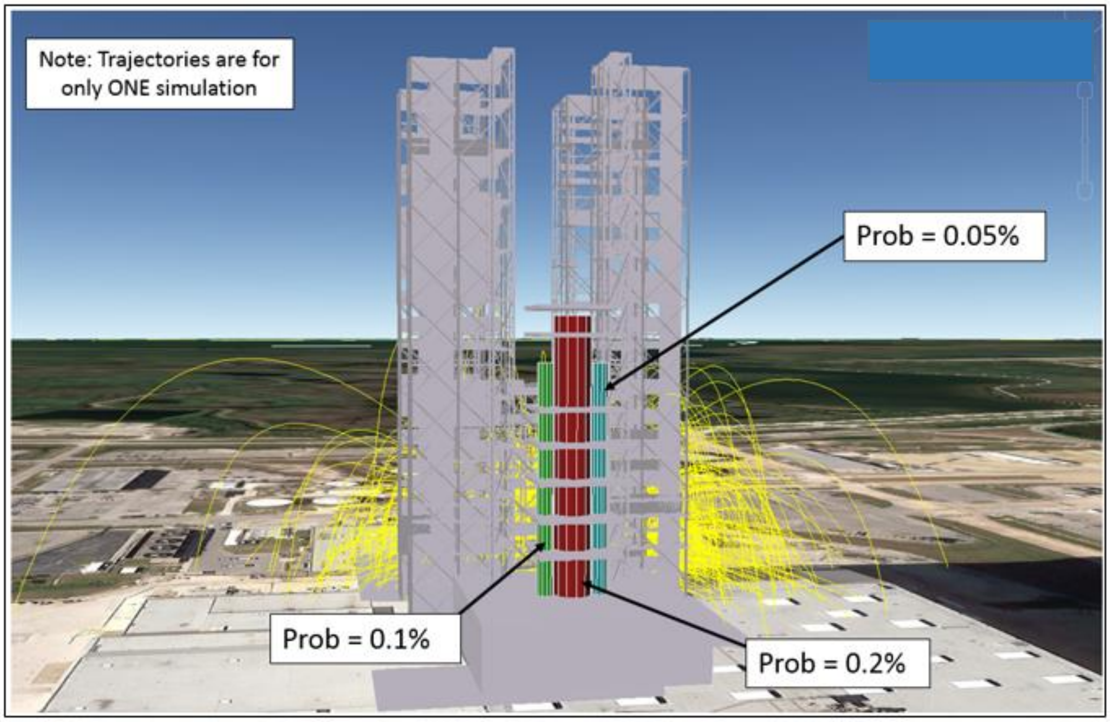

Figure 9. Probability of Fragment Impacts (KE>10 ft-lb).

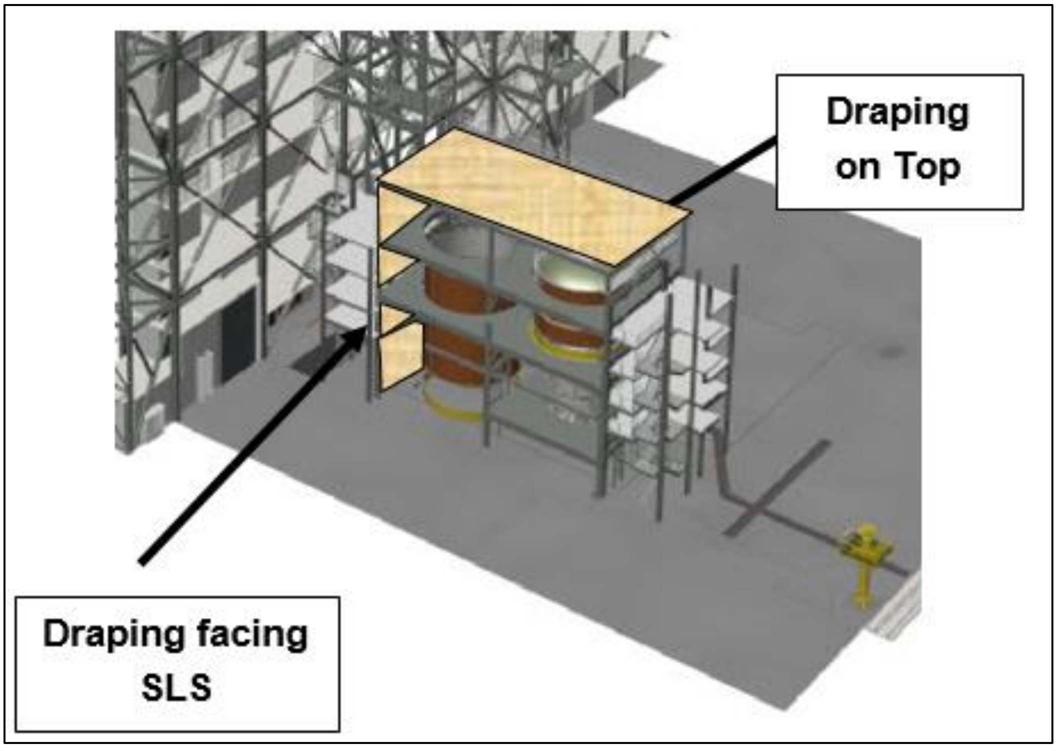

Figure 10. View of EUS Location in Bay 4.

The ideal shock wave velocity (Reference [5]) is given as:

$$U = c[(1+6P_{inc}/7P_o)]^{1/2}$$

where: c = speed of sound (ft/sec) = 1125.3, P_{inc} = incident blast overpressure (psi), P_o = ambient pressure (psi) = 14.7. Figure 11 shows the ideal blast front velocity as a function of distance.

Given that the EUS fragment velocities are on the order of 100-500 feet/sec, they are generally moving an order of magnitude slower than the blast front which is supersonic (>1,000 ft/sec). This implies that a solid, rigidly connected drape could be blown away by the time the first fragments arrive. If protective draping is used, it should be designed to: a) stop the fragment(s) that have the highest Kinetic_Energy/Impact_Area, KEA, b) allow passage of the blast wave without damage to the draping, and c) resist damage from a fireball that may occur first. The first requirement will define the type/thickness of the draping material. An evaluation of the EUS fragment list shows that the highest nominal KEA is 8,000 ft-lb/ft^2; the draping material should therefore be designed to conservatively block fragments up to 10,000 ft-lb/ft^2. The second requirement implies that the draping should be some type of open mesh (Figure 12) with loose connection to the EUS work platforms to allow the blast wave to pass through while still able to block hazardous fragments. The third requirement will insure that the mesh can withstand high thermal loads long enough to allow the mesh to block fragments.

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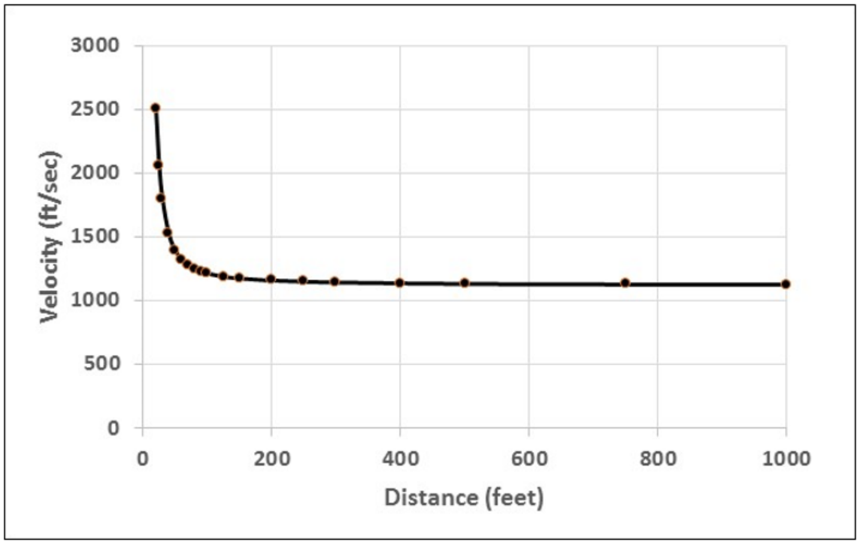

Figure 11. Blast Front Velocity vs. Distance.

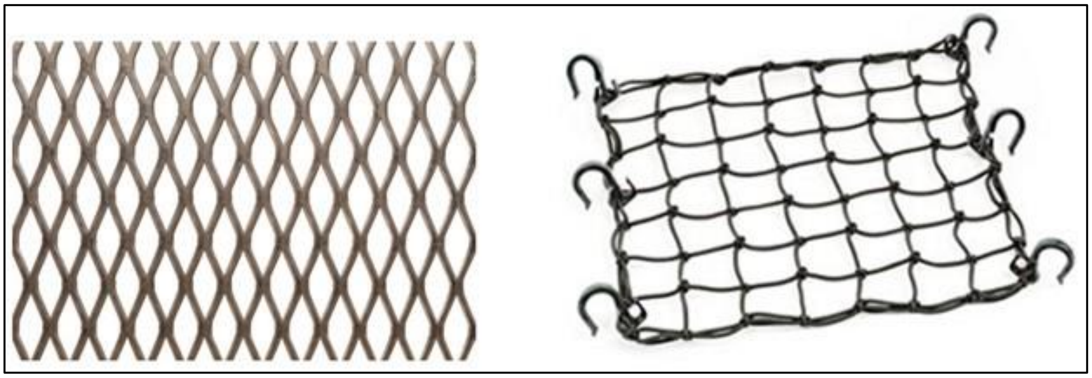

Figure 12. Sample Mesh Configurations.

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