ANALYSIS OF ALUMINUM DROP COMBUSTION IN THE GAP REGION BELOW A BURNING PROPELLANT. F. Gelbard, Sandia National Laboratories*, Mail Stop 0747, PO Box 5800, Albuquerque, New Mexico 87185, fgelbar@sandia.gov. *(Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This work is supported by the DOE Office of Space and Defense Power Systems.)

Introduction: The temperature below a burning propellant during a hypothetical accident is of interest for determining possible vaporization of hazardous fuels. In a test with a downward-facing burning solid propellant, the temperature in the gap region above a ground surface of sand and below the propellant was approximately 3000 ± 100 K [1]. A schematic diagram of the gas flow and geometry is given in Fig. 1.

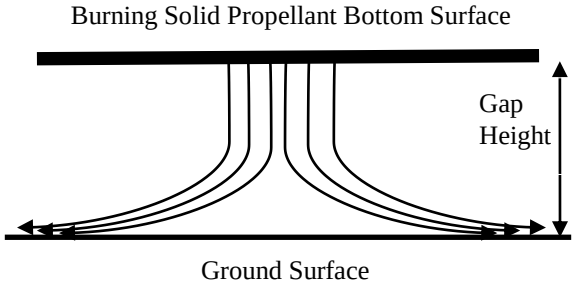

Fig. 1. Schematic of gas flow and geometry.

In this test nearly all the released aluminum drops from the propellant oxidized to alumina. Without aluminum oxidation, the adiabatic combustion temperature would be below 2600 K [2], which is below the melting point of the fuel which is 2763 K. Because aluminum oxidation resulted in a much higher temperature, and vaporization of the hazardous fuel is significantly enhanced at higher temperatures, the conditions for aluminum drop oxidation in the gap are explored in this work.

Aluminum Drop Oxidation: Aluminum particles embedded in propellants are on the order of 30 μm in diameter. These particles agglomerate on the burning surface, and when entrained in the gas flow form drops ranging in diameter from about 30 to 400 μm [2]. For 20 m/s gas velocities out of the propellant and gap heights of centimeters, the characteristic residence time of drops in the gap is on the order of a few milliseconds. For the assumed drop size distribution, much of the aluminum will be swept from the gap before having the opportunity to completely oxidize. Because essentially complete aluminum oxidation was observed in the test, in the model for the test, the drops splash upon impacting the ground and subsequently oxidize with CO_2 and H_2O in the gap. Splashing is needed so that the resulting smaller secondary drops have a much larger surface area to mass ratio which enhances oxidation, and therefore releases heat before the drops are swept out of the gap region by gas flow. This work assesses the extent of drop splashing needed to oxidize completely the secondary drops.

For a gap region confined between two flat parallel surfaces, in which the gap height is much smaller than the extent of the surfaces, we model the gas flow as steady, axisymmetric, incompressible, isothermal, and with a uniform velocity emanating from the upper surface. With these assumptions, a solution to the Navier-Stokes Equations is available for the gas velocity that includes a boundary layer above the bottom surface. For nominal conditions in the gap, the flow is very close to the inviscid potential flow solution, except for the boundary layer in which the radial velocity departs from the inviscid solution and goes to zero at the bottom surface. After release from the propellant, aluminum drops are subjected to gas flow drag, gravity, and size reduction by oxidation. In this model the drops oxidize at a rate determined from the Beckstead correlation for the time to burn an aluminum drop as a function of initial drop diameter [3]. The Beckstead correlation and gas flow model are combined with a drop momentum balance to establish a burn fraction distribution and impact velocity, both as a function of initial drop diameter and release location from the propellant surface. The fraction of aluminum burned prior to impact with the ground surface is determined by combining the burn fraction distribution with the drop size density function. As given below in Fig. 2, for a propellant gas velocity of 20 m/s, the normal component of the drop impact velocity is less than 9 m/s for gap heights of 4.3 and 8.6 cm. Also shown in the Figure is the impact diameter after the drop has traversed the gap and partially oxidized. Drops smaller than about 70 μm completely oxidize before impacting the ground surface, but much of the aluminum mass is unoxidized before impact.

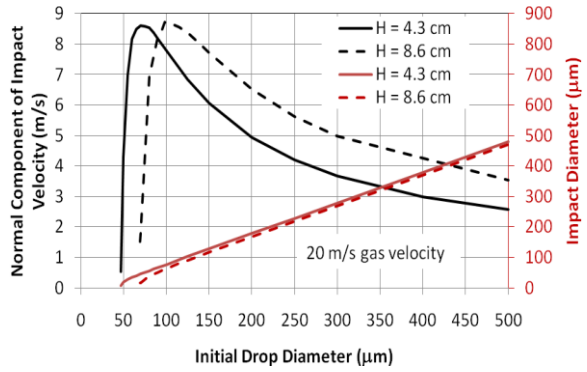

Fig. 2. Aluminum drop velocity and impact diameter as a function of initial diameter and gap height.

The number of secondary drops that can be formed upon impact is bound by the kinetic energy of the impacting drop that is available to form new surface area. From Fig. 2, a 280 μm aluminum drop released from the propellant will impact the ground at 5 m/s with a diameter of about 250 μm. The ratio of the impact diameter to the secondary drop diameter is given in Fig. 3 as a function of the impact velocity and the fraction of primary drop kinetic energy available for secondary drop formation, ε. These curves were determined by assuming that ε times the impact kinetic energy was used to create the surface area of the secondary drops. The maximum theoretical value of ε is 1.0, with more realistic values on the order of 0.3 – 0.1. As can be seen from Fig. 3, for ε = 0.3, the ratio of drop diameters is ~2.8, for an impact velocity of 5 m/s. Thus a 250 μm diameter drop would shatter to 90 μm diameter secondary drops. Based on the Beckstead correlation, these secondary drops would require more than 10 ms to oxidize, and therefore be swept out of the gap before oxidizing and releasing the heat of reaction within the gap.

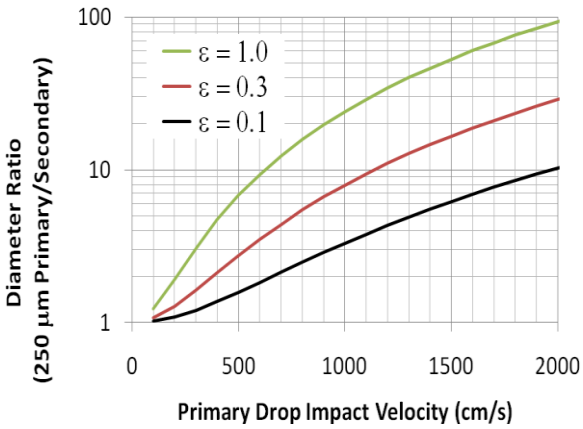

Figure 3. Ratio of primary to secondary drop diameters for a 250 μm primary drop as a function of the primary drop impact velocity and ε, the fraction of primary drop kinetic energy available for secondary drop formation.

Therefore, other processes are proposed that may contribute significantly to aluminum oxidation and high gap temperatures. These processes are, (1) the drop size distribution emanating from the propellant is shifted towards the smaller embedded aluminum particle size, and therefore more readily oxidized within the gap, (2) irregularities of the ground surface provide flow obstacles, and primary drops shatter on these irregularities, (3) variations in the burn-time correlation and/or drag coefficient results in drops oxidizing faster prior to impact, and (4) the deposited liquid aluminum completes oxidation while on the ground surface and deposits the heat of reaction to the gases in the gap. These processes are explored and evaluated in this work as additional mechanisms for the observed high temperatures in the gap. The range in parameter space over which these processes can result in essentially complete aluminum oxidation on the time scale of interest is presented.

References: [1] Hunter, L. W. et al. (2007) *Combustion Science and Technology*, **179**, 1003-1027. [2] Price, E. W., et al. (1979) Air Force Weapons Laboratory, AFWL-TR-78-34, 1979. [3] Beckstead, M. W. (2002) Proceedings of JANNAF 37th Combustion Meeting, pp. 485-594.