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MEASUREMENTS IN SOLID PROPELLANT PLUMES AT AMBIENT CONDITIONS

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ABSTRACT
The study of aluminum particle ignition in an open atmosphere propellant burn is of particular interest when considering accident scenarios for rockets carrying high-value payloads. This study observes the temperatures of an open atmosphere Atlas V solid propellant burn as a function of height from the burning surface. Two instruments were used to infer this temperature: two-color pyrometer and a UV spectrometer; the spectra was fitted to a model of energy states for aluminum monoxide and the temperature which provided the best match between the model and data was taken as the reaction temperature. Emissions above 30 inches from the surface of the propellant were not sufficiently strong for data reduction; perhaps obscured by the alumina smoke cloud. The temperature distribution in the plume increased slightly with distance from the burning surface, presumably indicating the delay in ignition and heat release from the larger aluminum particles in the propellant. The pyrometer and spectrometer results were found to be in excellent agreement indicating plume temperatures in the range of 2300K to 3000K.

INTRODUCTION
The primary objective of this experiment was to support development of a model of the environment that a rocket payload could be subjected to in an accident scenario, for instance, a space probe launch abort involving high-value payloads. Specifically, this experiment will focus on the behaviors surrounding aluminum while other experiments involving solid propellant burning in open atmosphere situations have provided the temperature, radiative properties and heat flux estimates for solid propellant plumes [1]. Propellants are designed to burn in a rocket motor at high pressure where aluminum, in the form of microscale particles, combusts in the chamber adding considerable energy to the flow. In an off-design accident configuration with open burning at atmospheric conditions, the role of aluminum is less clear.

In an example of aluminum particles impacting a surface, if the particles were to simply melt in the hot combustion gases and not oxidize, then solidification on an impacted surface can initially add heat of fusion to that surface. If the aluminum were to partially react and develop an oxide coating, this could build a porous layer on the surface and develop insulating properties and provide some partial protection from convective and radiative flux originating from the burning propellant. But if the aluminum were to ignite, then considerable increase in plume temperature is expected. An alumina coating may eventually provide some unquantified thermal protection. This is one of the reasons for the interest in the aluminum reaction process discussed in this paper.

Previous experiments in which data were compared to a model based simply on thermochemical properties of the propellant have indicated that the role of aluminum needs to be understood in order to improve such comparisons [2]. In an effort to better understand this role, studies have been made on the particle size and corresponding burn times of aluminum [3], the ignition conditions for aluminum [4], the combustion process of an aluminum droplet in open atmosphere conditions [5], and the effect of gas concentrations and aluminum particle sizes on heat flux and combustion efficiencies of solid propellants [6].

In the current experiment, aluminized ammonium perchlorate (Atlas V) propellant burning at atmospheric pressure was studied. The top surface of the propellant was ignited and

Spectroscopy and two-color pyrometry were used to determine temperatures in the rising plume as a function of height above the burning surface. While these two instruments were each sensitive to different plume components, some level of agreement was expected due to mixing and small particle sizes. For example, the pyrometer detects solid surface radiation which may be molten aluminum droplets, aluminum droplets with an oxide coating, or alumina smoke. The spectrometer detects the molecular emission spectra of AlO in the wavelength region of 420 nm to 550 nm. Aluminum monoxide is an intermediate species in the combustion of aluminum and is taken as evidence of aluminum combustion. Relative emission intensities of the rotational-vibrational progressions and sequences were used to infer temperature. The spectroscopic temperatures were compared with those obtained from the pyrometer measurements.

METHOD

The tests were conducted in a 20 by 20 foot square environment isolated from disturbances due to ambient air currents and wind. Fans brought outside air into the bottom of the chamber at a rate of 8500 cfm to purge smoke with the intention of: ensuring video recording was possible, and creating an environment in which modelers know the ambient boundary condition. The plume was allowed to escape the chamber through a chimney at the top. The propellant was placed on a stand above the floor and previous modeling of the flow field has indicated that the flow field is similar to that which would be obtained in an open air burn. A schematic of the test building with propellant and track is shown in Figure 1.

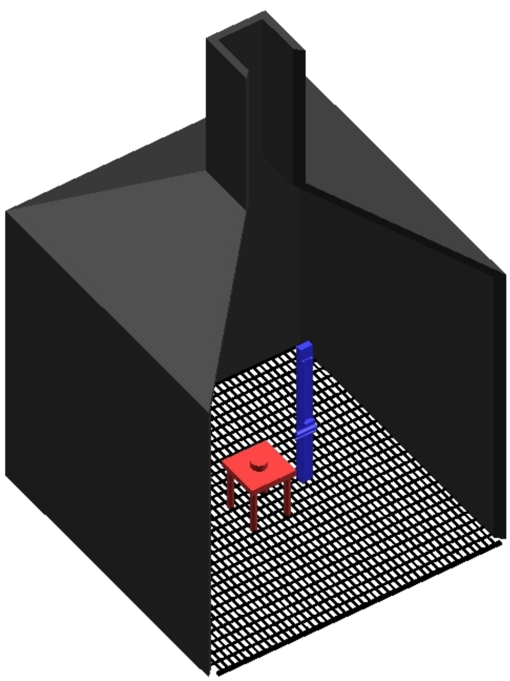

Figure 1: Schematic of test building with propellant on table next to track. Grated floor allows for ventilation and purge of smoke.

The propellant testing included a vertical scan of the rising propellant plume. The scan took pyrometer and spectrometer samples at specified time intervals. An eight-foot vertical track equipped with stepper motor was placed 4 feet away from each of the propellant tests. This stepper motor was oriented so that the optics faced the center of the plume and lasers were used to align the optics and ensure they were oriented along a horizontal plane. This experimental setup is shown in Figure 2.

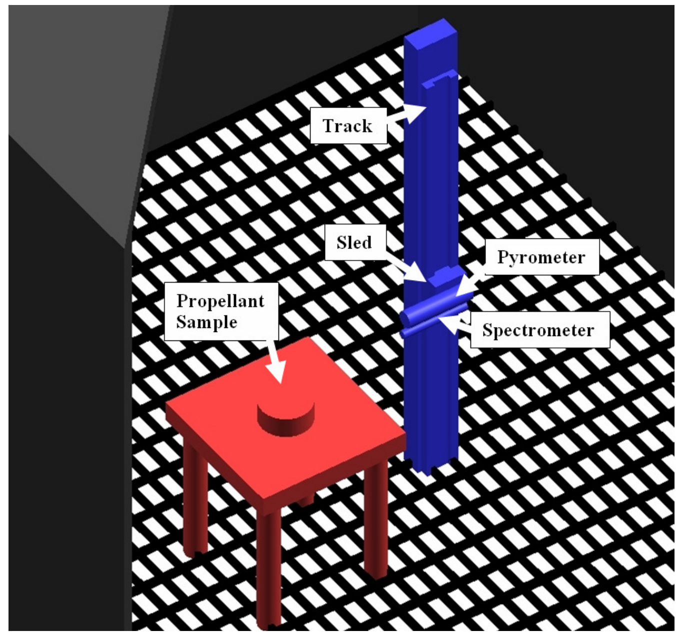

Figure 2: Closeup of test setup

The pyrometer uses the relative intensities at two wavelengths to infer the temperature of the particulates in the plume by comparing the surface radiation intensities to Plank's blackbody radiation curve. The Ocean-Optics UV spectrometer used dedicated software to measure the intensity of various wavelengths over a given integration time. For each measurement made, the spectrum of wavelengths inside of the operating interval of the spectrometer was recorded.

The stepper motor was set to travel at 0.56 inches/second, and took a single reading once per second as the sled traveled up the track. Once at the top, the sled traveled down the track and continued to take readings. This provided redundant data for some of the longer burns. To further correct for the position of each measurement, the burn height for each propellant was noted before each test. Assuming a constant burn rate, the height of the burning surface could be calculated at any point in the test knowing the test interval and initial height.

RESULTS

Table 1 is a summary of the tests conducted during this series of tests. The letters A and B indicated a misfire in which the igniter failed to ignite the propellant (see Figure 3). For each of these tests, the experiment was retried until a successful ignition was achieved, even if the test was already deemed a misfire. The letter R indicates a scheduled rerun to provide redundant data.

Table 1: Summary of Tests conducted for this Series

Test #	Date	Thick.	Dia.	Scan Height	Weight (gm)
17A	6/22/2010	5.625"	5"	42"	3658.89
17B	6/22/2010	5.75"	5"	42"	3658.89
17	6/23/2010	5.75"	5"	42"	3658.89
17R	6/23/2010	5.5"	5"	42"	3499.81
18A	6/23/2010	5.25"	5"	32"	3499.81
18	6/23/2010	5.5"	5"	32"	3340.72
18R	6/24/2010	1.8125"	5"	32"	1058.00
19	6/24/2010	4.75"	12"	42"	13608.33
20	6/24/2010	3.875"	18"	23"	27215.54

Figure 3: Igniter and Propellant Sample on Test Bed

The temperatures recorded by the spectrometer were the result of an AlO model applied to the spectrum collected [7]. A sample curve is seen in Figure 4.

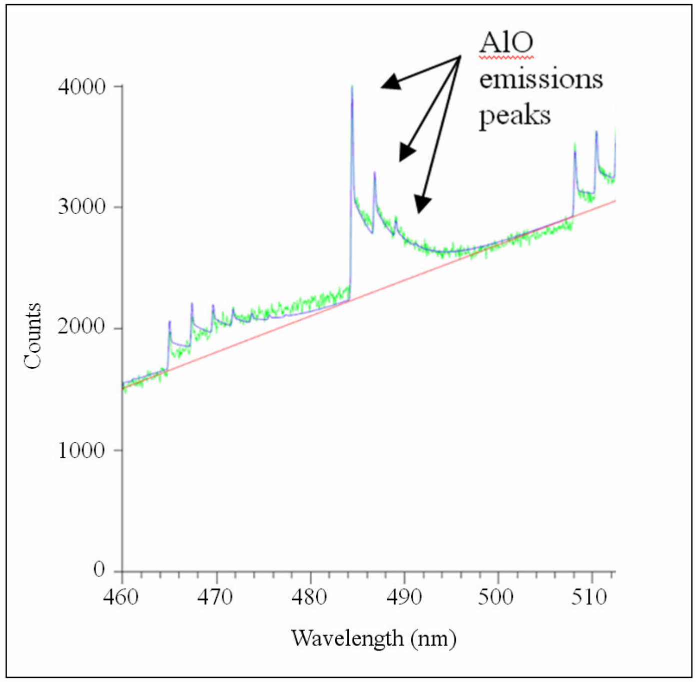

Figure 4: Sample Spectra from a Single Reading

For the plot seen in Figure 4, the x-axis is the spectrometer wavelength range (in nanometers) and the y-axis is the number of 'counts' observed by the spectrometer over the 2 millisecond time interval.

For each data sample, these AlO emissions peaks were fitted to a model of relative peak intensities versus temperature of the combustion [8]. Using this method, temperatures of the combusting aluminum could be determined as a function of height from the propellant surface. It is also important to note that these temperatures are not related to a blackbody curve used for the pyrometer.

The temperature outputs for the pyrometer and spectrometer as a function of height are compared for each of the tests in Figures 5-12 below. The spectrometer readings saturated the collector for tests 17A, 17B, and 17. The pyrometer reached its maximum temperature and reported erroneous readings for tests 18R-20.

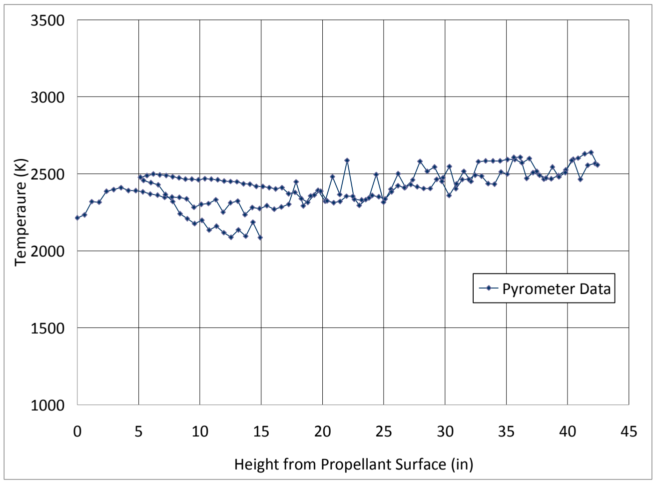

Figure 5: Temperature Output from Pyrometer for Burn 17A

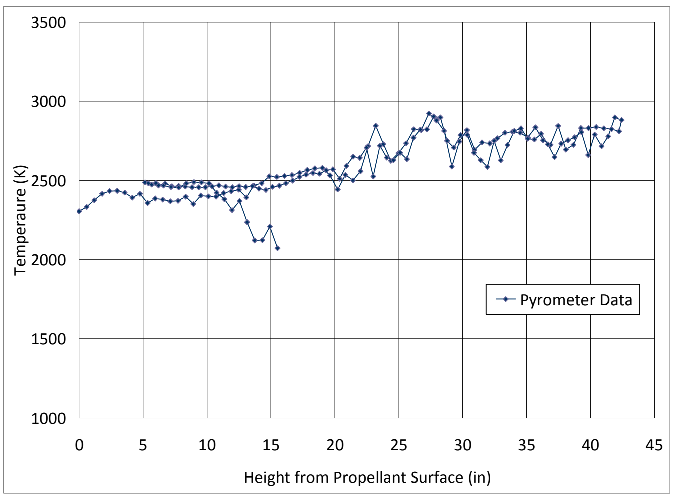

Figure 6: Temperature Output from Pyrometer for Burn 17B

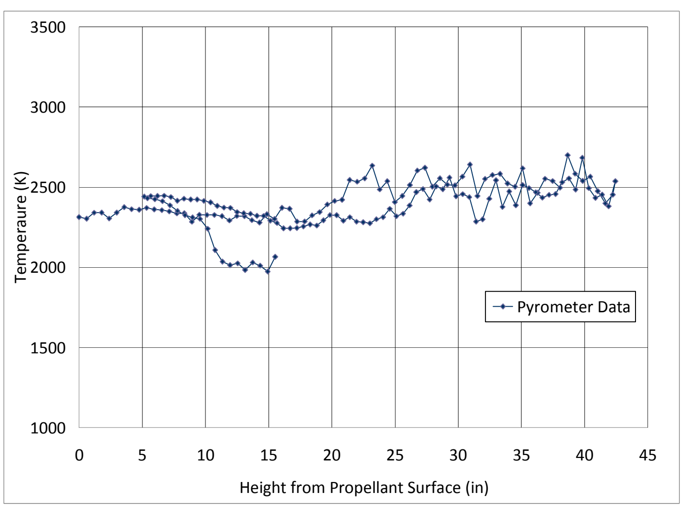

Figure 7: Temperature Output from Pyrometer for Burn 17

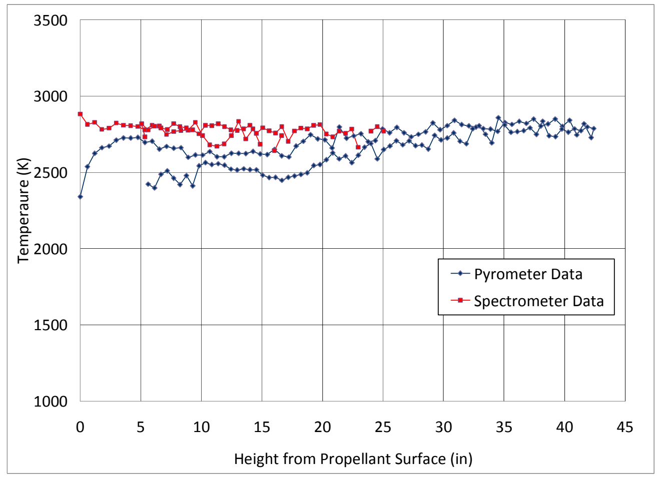

Figure 8: Temperature Outputs from Spectrometer and Pyrometer for Burn 17R

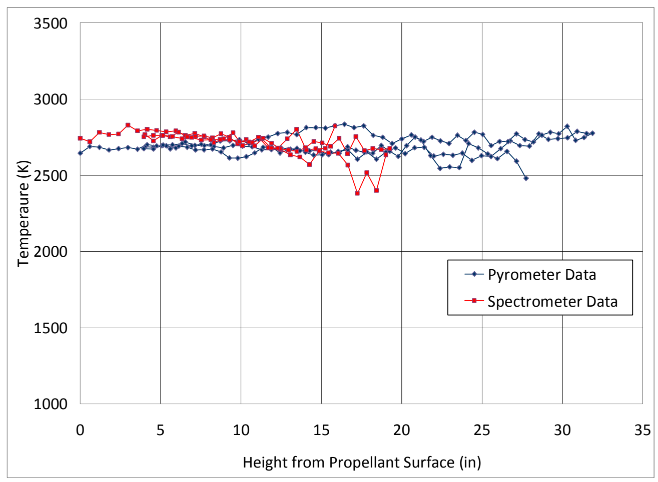

Figure 9: Temperature Outputs from Spectrometer and Pyrometer for Burn 18

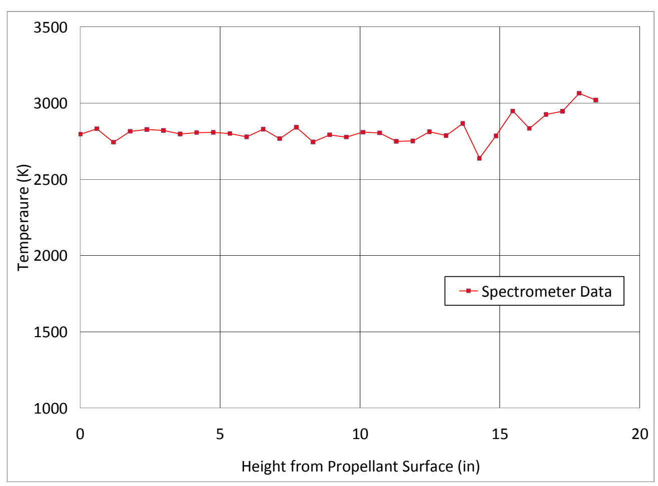

Figure 10: Temperature Output from Spectrometer for Burn 18R

All of the above test results are relatively comparable due to the constant diameter of the propellant sample. Spectrometer data were available for the entire scan of the plume; however, emissions detected by the spectrometer diminished as the stepper motor traveled up the propellant plume. The data for this section are not graphed visually because the peaks detected by the spectrometer were not intense enough to distinguish from the background noise and a temperature measurement with acceptable uncertainty could not be obtained. Once the stepper motor returned closer to the source of the plume, readings usually began to be distinguishable again and temperature measurements were made.

The following test results were made with the spectrometer only because the temperature for these tests exceeded the maximum temperature the pyrometer could read, i.e., 3000K. Figures 11-12 were larger diameter propellant samples than in the previous tests. Figure 11 includes data from a 12" diameter sample, and Figure 12 includes data from a 18" diameter sample.

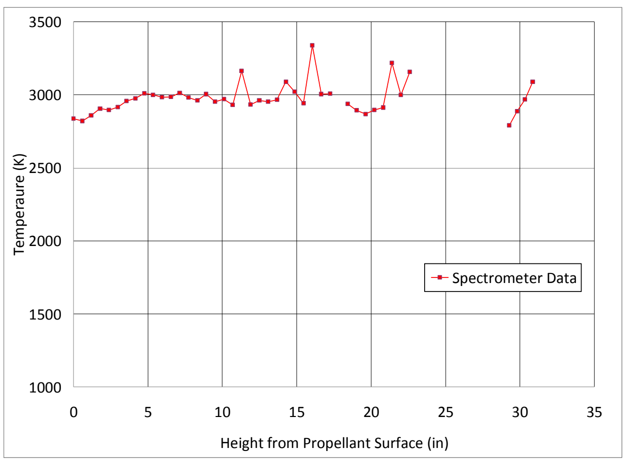

Figure 11: Temperature Output from Spectrometer for Burn 19

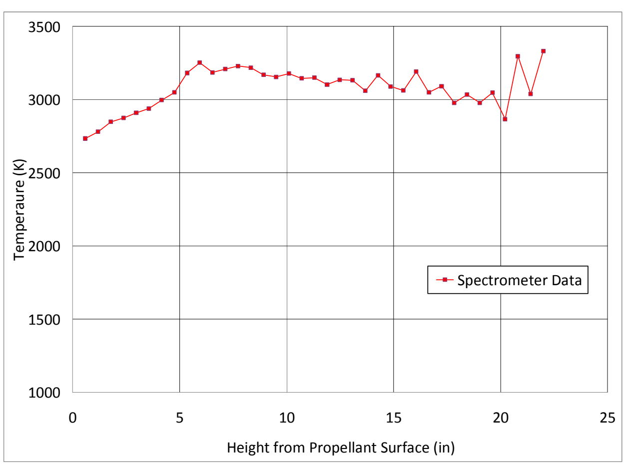

Figure 12: Temperature Output from Spectrometer for Burn 20

Both the pyrometer readings and the spectrometer emissions fit agree closely between samples for the same diameter propellant. However, it is difficult to determine that the pyrometer and spectrometer were reading emissions from the same particles in the flame (in fact, it is likely they are not). The observation that the noted temperatures were quite close can be taken as an indication that there exists local thermal equilibrium as a function of height.

One way of understanding these data is by observing the heights at which the spectrometer readings could be obtained. Since the spectrometer data come from a fit to an AlO emissions model, and accurate temperature measurements are only available for data nearer to the propellant surface, it is reasonable to conclude that the emissions seen by the aluminum reaction were either obscured or virtually non-existent near the top of the propellant plume.

The temperatures interpreted from the spectrometer were higher for the larger diameter burns. However, the pyrometer did record temperatures with a range as large as 200 K within the same five inch sample when all tests were compared against one another. Figure 13 shows the uncertainties associated with the measurements made at a given location for the combined pyrometer data of the five inch diameter samples. In this plot, the average for a given height range is plotted. The light error bars indicate the minimum and maximum data point seen in the range, and the dark error bars indicate the upper and lower quartiles of the data.

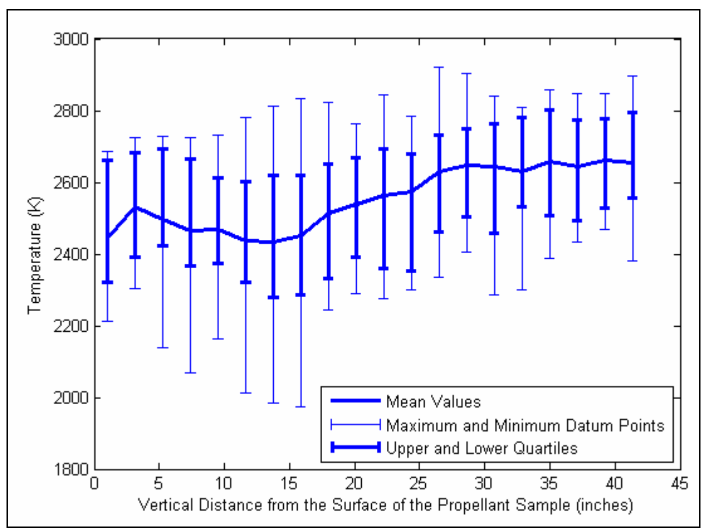

Figure 13: Combined Pyrometer Temperature Data for 5" Diameter Propellant Burns (Tests 17-18R)

The temperature observed in the propellant plume increases with increasing height from the surface of the burning sample. This result is an indication of the continuing heat release from combustion of aluminum and the time required to consume the particle.

CONCLUSION

In conclusion, the spectrometer results indicate that the presence of an aluminum reaction beyond 25 inches is not clear for any of the diameter samples. This could be due to the aluminum oxide cloud obscuring the emissions, or because all the aluminum in the propellant plume has either been converted to aluminum oxide, or has been expelled from the plume.

When comparing the pyrometer and spectrometer readings, there is an initial "spike" in the pyrometer data in the first three inches of the plume that is not seen in any of the spectrometer readings. This spike is also very apparent in the combined pyrometer temperature readings seen in figure 13. This is most likely due to the heat capacity of the aluminum droplets in the plume. Since the pyrometer observes radiation emitted by solid particles in the plume, and the spectrometer observes radiation emitted by reactions (gasses) in the plume, it is evident that a heat balance between the gasses and solid particles is occurring in the first few inches of the plume. This spike seen in the data is the result of the relatively cool aluminum droplets being heated by the ongoing reactions inside of the plume as these particles rise away from the burning surface.

The temperatures recorded were well above the melting point of alumina corresponding to the an ignition requirement as described by Yuasa (3) for particles with a heavy oxide coating. This allowed the oxide layer to melt and release aluminum vapor for reaction with oxidizer.

ACKNOWLEDGMENTS

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REFERENCES

[1] Hunter, L. W., et al., 2007, "The Environment Created by an Open-Air Solid Rocket Propellant Fire". Combustion Science and Technology, 179, pp. 1003-1027.

[2] Lee, D. O., Hardee, H. C., and Donaldson, A. B., 1975, "Thermal Model for Solid Propellant Fires", Sandia National Laboratories, SAND75-0051.

[3] Gill R. J., et al., 2009, "Sizing and Burn Time Measurements of Micron-Sized Metal Powders". Review of Scientific Instruments, 80, 064101.

[4] Yuasa, S., et al., 1997, "Ignition and Combustion of Aluminum in Oxygen/Nitrogen Mixture Streams". Combustion and Flame, 108: pp 387-396.

[5] Parr, T. P., et al., 1996, "Flame Structure Measurment of Single, Isolated Aluminum Particles Burning in Air". The Combustion Institute, Symposium (International) on Combustion, 26(2), pp. 1899-1908.

[6] Price, E. W., et al., 1982, "Behavior of Aluminum in Solid Propellant Combustion". Atlanta : Air Force Office of Scientific Research, DTIC ADA118128.

[7] Dors, I. G., et al., 1998, "Spectroscopic Temperature Determination of Aluminum Monoxide in Laser Ablation with 266-nm Radiation", Optics Letters, 23(22).

[8] Parigger, C. G., et al., 2011, "Computation of AlO $B^2\Sigma^+ \rightarrow X^2\Sigma^+$ Emission Spectra", Preprint: Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy.

