LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-CONF-222292

Combustion of Shock-Dispersed Flake Aluminum - High-Speed Visualization

P. Neuwald, H. Reichenbach, A. Kuhl

June 21, 2006

37th International Conference of ICT
Karlsruhe, Germany
June 27, 2006 through June 30, 2006

37th International Annual Conference of ICT
Energetic Materials
Insensitivity, Ageing, Monitoring

COMBUSTION OF SHOCK-DISPERSED FLAKE ALUMINUM – HIGH-SPEED VISUALIZATION

Peter Neuwald and Heinz Reichenbach
Fraunhofer-Institut für Kurzzeitdynamik – Ernst-Mach-Institut –
Eckerstr. 4, 79104 Freiburg i. Br., Germany

Allen L. Kuhl
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA, USA, 94551-0808

ABSTRACT

Charges of 0.5 g PETN were used to disperse 1 g of flake aluminum in a rectangular test chamber of 4 liter inner volume and inner dimensions of approximately 10 cm x 10 cm x 40 cm. The subsequent combustion of the flake aluminum with the ambient air in the chamber gave rise to a highly luminous flame. The evolution of the luminous region was studied by means of high-speed cinematography. The high-speed camera is responsive to a broad spectral range in the visible and near infra-red. For a number of tests this response range was narrowed down by means of a band-pass filter with a center wavelength of 488 nm and a half-width of 23 nm. The corresponding images were expected to have a stronger temperature dependence than images obtained without the filter, thus providing better capability to highlight hot-spots.

Emission in the range of the pass-band of the filter can be due to continuous thermal radiation from hot Al and Al_2O_3 particles or to molecular band emission from gaseous AlO. A time-resolving spectrometer was improvised to inspect this topic. The results suggest that AlO emission occurs, but that the continuous spectrum is the dominating effect in our experiments.

Correspondence to
Dr. Peter Neuwald, – Ernst-Mach-Institut – Fraunhofer-Institut für Kurzzeitdynamik,
Eckerstr. 4, 79104 Freiburg i. Br., Germany
Tel. +49 (0) 761/2714-324, Fax +49 (0) 761/2714-316, e-mail : neuwald@emi.fraunhofer.de

INTRODUCTION

Over the years considerable efforts have been made to develop reliable and efficient numerical methods for the prediction of combustion-related energy release in detonations (e.g., after-burning of TNT detonation products). In unbalanced, non-ideal explosives the after-burning energy can easily be in excess of the heat of detonation. Thus a number of concepts have been developed to increase the performance of explosives by the addition of excess fuel like aluminum. However, in such cases the performance of a charge relies on the rapidity of combustion, which again depends on various factors. These have to be taken into account in the numerical models. In support of such modeling efforts, the Experimental Fluid Dynamics Group of the Ernst-Mach-Institute has carried out a variety of experiments at laboratory scale to gather some phenomenological insight into specific aspects of the problem and to provide a database for code validation.

At the 36th ICT Conference [1], we presented the results of these experiments, which based upon studies of the pressure evolution in closed explosion vessels due to the detonation of miniature SDF (shock-dispersed-fuel) charges. These consist of a spherical booster charge of 0.5-g PETN, which is surrounded by powdered fuel compositions contained in a paper cylinder of ~ 2.2-cm^3. The study covered five geometries of different volumes and aspect ratios with a special focus on flake aluminum as the dispersed fuel.

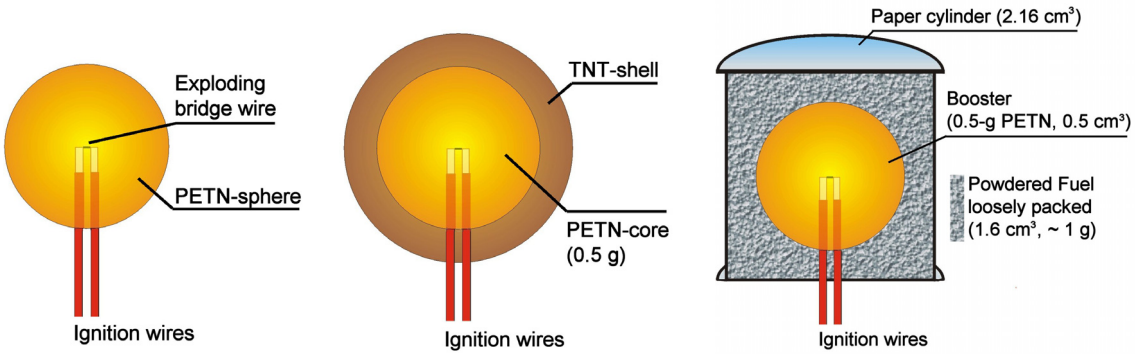

Figure 1 Schematic sketch of a spherical PETN charge, a composite PETN-TNT charge and an SDF charge.

Since then the studies have been continued in further geometries; among these a rectangular chamber of 4 liter volume and a length-to-diameter ratio of 3.8. This chamber has the benefit that it can easily be equipped with transparent polycarbonate windows. Thus we could supplement the measurement of the pressure evolution with optical observations of the explosively driven combustion inside the chamber.

Experimental Set-Up

The test chamber shown in Figure 2 is made from 20 mm steel plates and has inner dimensions of 101.5 mm x 101.5 mm x 386 mm. Either transparent polycarbonate or steel plates can be bolted to the front and back-side. The model can be instrumented with up to 11 piezo-electric or piezo-resistive pressure gages.

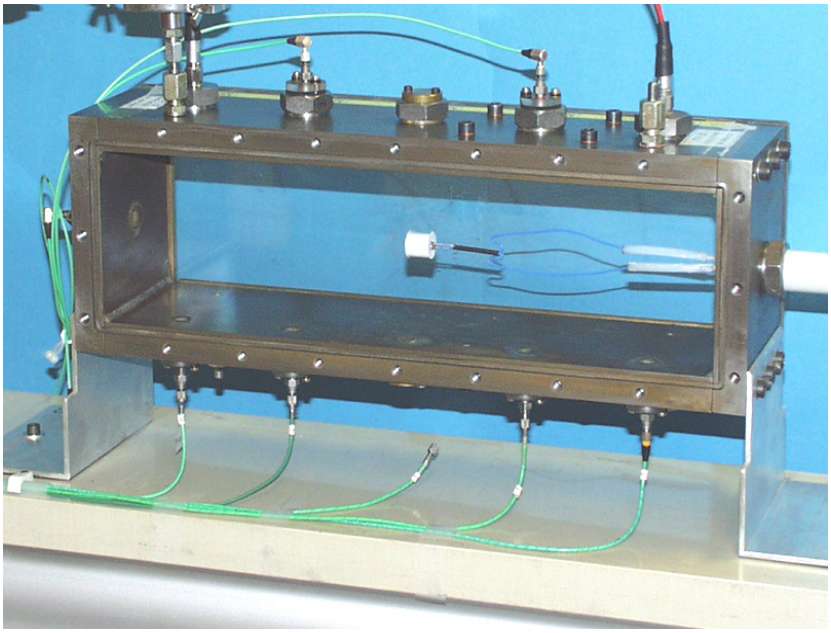

Figure 2 Photograph of the rectangular 4-l chamber with mounted SDF charge (polycarbonate window removed).

When the SDF charge is detonated, a highly luminous flame develops rapidly, especially in the case of dispersed flake aluminum. This luminous flame was filmed by means of a digital high-speed camera positioned at a distance of approximately 2.5 m in front of test set-up.

The camera we used is the Photron Fastcam Ultima SE (also marketed under the name Kodak HS4540) originally developed in 1991 by T. G. Etoh. It features an NMOS based sensor with 256 x 256 pixels, an 8-bit gray value range and recording rates ranging from 30 frames per second (fps) to 4500 fps in full frame mode and up to 40500 fps in partial frame mode. The light sensitivity is stated to be equivalent to ISO 3000 when the higher of the two possible gain settings is used. The product specifications give no details on the spectral response, however, we expect responsivity for wavelengths in the range from 400 nm to about 1100 nm.

The visualization experiments were typically done with the lower gain setting (factor 0.5 in the light sensitivity) and at a recording rate of 9000 fps, which allows for an image size of 256 x 128 pixels. The camera is not shuttered, thus the exposure time is the inverse of the recording rate (in our case 111 µs). The imaging optics were a Canon zoom lens V6x16 with a focal length ranging from 16 to 100 mm and a nominal relative aperture of 1:1.9.

When used without filters in the set-up the luminous flame severely overexposed the camera. Thus we had to attenuate the irradiance by means of neutral density filters, which we put in front of the imaging optics. The necessary attenuation was about 72 to 75 dB for an SDF charge with flake aluminum in air, about 62 dB for an SDF charge with flake aluminum in nitrogen or helium and 53 dB for a composite PETN-TNT charge in air. This indicates an increase of the irradiance by a factor of about 100 when the dispersed fuel is flake aluminum instead of TNT detonation products.

Since we had to attenuate the irradiance strongly we also used a band-pass filter instead of the neutral density filters, thus narrowing down the spectral response of the camera. The filter was a four-cavity interference filter with a center-wavelength of 488 nm and a half-width of 23 nm. This filter in the blue-green was selected for two reasons:

- In the case of a continuous thermal spectrum (e.g., from solid Al and Al_2O_3) an increase of the temperature will shift the spectrum to shorter wavelengths. Images filtered in the blue-green are thus emphasizing the regions of high temperatures when compared to images obtained at the full spectral bandwidth of the camera.
- It is generally accepted that gaseous AlO is a common short-lived by-product of aluminum combustion. The spectrum of AlO [2, 3, 4] is characterized by emission/absorption bands between 450 nm and 530 nm, from which the filter selects the peak region of the main band. If this were a dominating effect in the emission spectra from our experiments with shock-dispersed aluminum, then the band-pass-filtered images would be a direct indicator of AlO concentration and thus combustion activity.

Examples From the High-Speed Visualization

Figure 4 shows a few sample images from two high-speed movies. In both tests an SDF charge with a 0.5-g PETN-booster and a fill of 1 g flake aluminum was detonated at the center of the test chamber. The original gray-value images were converted to a pseudo-color version to make their visual appearance less dependent on the characteristics of the output medium. The conversion scheme is shown in Figure 3.

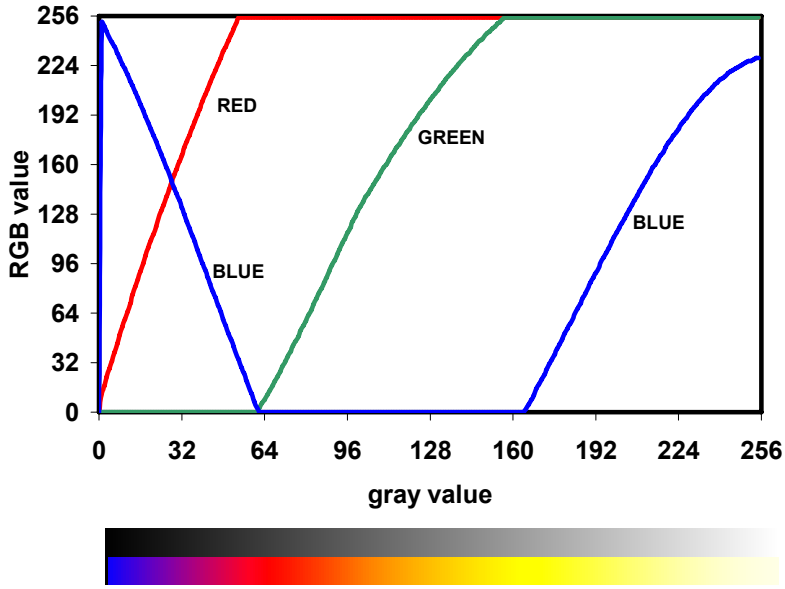

Figure 3 Conversion of gray values to pseudo RGB-color. Top: characteristic curves, bottom: 256-step gray wedge and its pseudo-color representation.

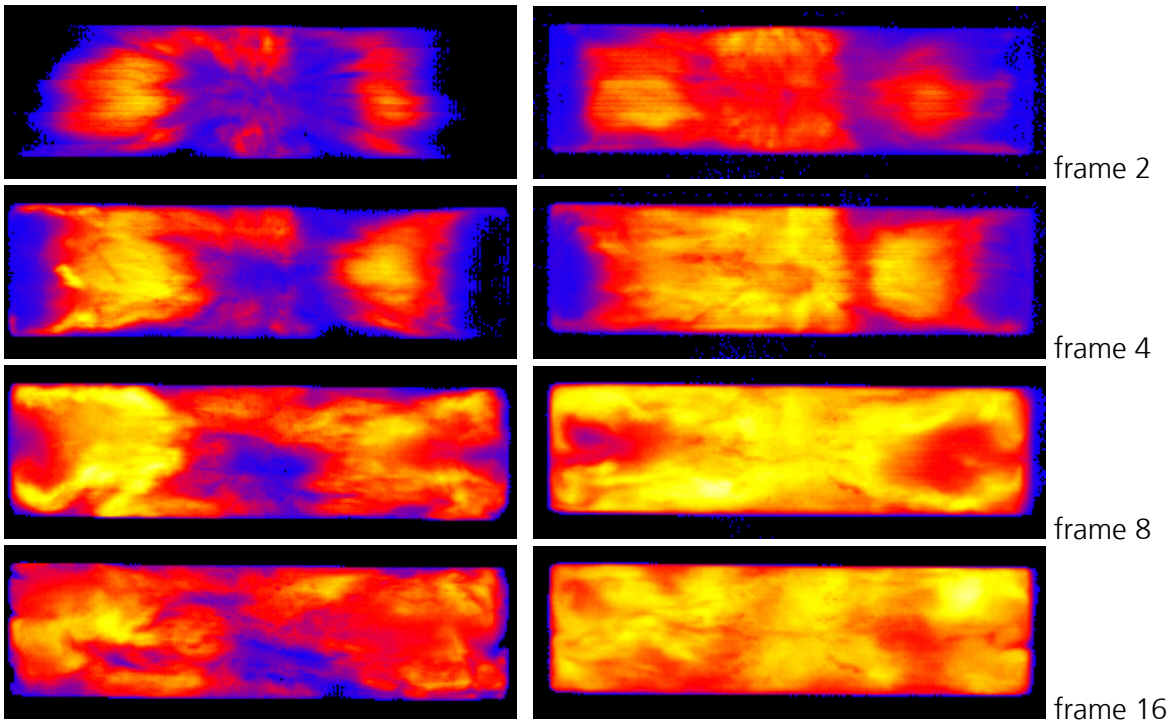

Figure 4 Sample frames from two high-speed movies on the combustion of shock-dispersed flake aluminum. Gray values converted to pseudo-color. Left column: the spectral range narrowed down to a 23 –nm band-centered at 488 nm, attenuation in pass-band -42 dB. Right column: broad spectral range (VIS/NIR), attenuation -75 dB.

Even with the interference filter we still had to attenuate the irradiance by means of additional neutral density filters. The optimum attenuation was about 42 dB. Thus the total irradiance weighted with the spectral response of the camera is about 30 dB or a factor 1000 stronger than the irradiance in the narrow spectral band of the interference filter.

As expected, we find some differences between the broad-band movies and those obtained with the band-pass filter. Bright regions in the band-pass filtered images are typically smaller and more structured than the bright areas in the broad-band movies. They also occur at different positions: while in broad-band images the center of the test chamber is often bright, the band-pass filtered images have bright patches mainly away from the center. However, it is difficult to discuss the differences in detail because there are considerable test-to-test variations in the structures, even though the general appearance is fairly reproducible.

Thermal Continuum or Molecular Band Emission?

Even with the observed differences between the filtered and unfiltered images it remains open whether the radiation is due to a thermal continuum spectrum or to the molecular emission bands of AlO or to a combination of both. In [2] the AlO band emission was clearly dominating the spectrum, in [4] it was a detectable, but minor effect overlaying a continuous spectrum and in [3] the relative intensities of the continuum and the band emission depended on the measurement location. Neither of the three studies is directly comparable to our experiments. Thus we decided to improvise a time-resolved spectroscopy set-up to investigate the problem.

Since our workgroup has no dedicated spectroscopy equipment at its disposal, we diverted an available monochromator from its intended use and combined it with the high-speed camera. A schematic sketch of the set-up is shown in Figure 5. The central element is the monochromator, a modified Ebert type with a focal length of 120 mm and a single diffraction grating with 1200 lines/mm that can be rotated mechanically. Lens L1 with a focal length of 150 mm and an aperture of f/5 images a small portion of the test chamber onto the entrance slit of the monochromator. The exit slit was removed, yielding a circular exit aperture of 22 mm. A second lens L2 with a focal length of 120 mm and an aperture of f/2.4 images the exit plane onto the camera sensor. To diminish the influence of stray light we shielded the complete optical path by means of telescopic cardboard tubes.

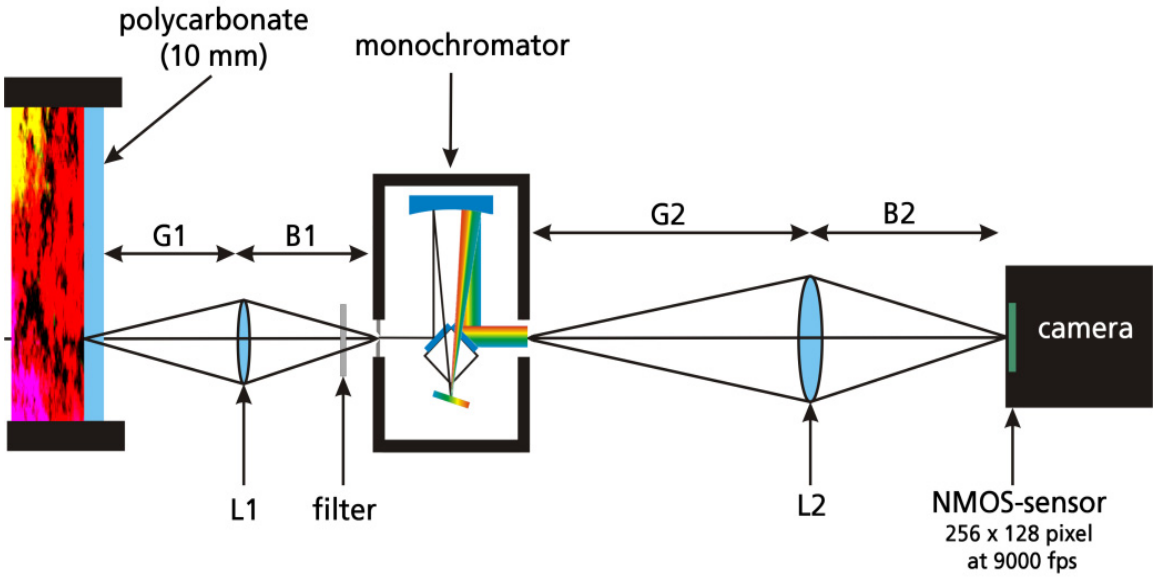

Figure 5 Improvised set-up for time-resolved spectroscopy of the combustion of shock-dispersed flake aluminum.

The object and image distances of lens L2 were chosen such that the (de-)magnification was 2/3. The center wavelength of the monochromator was set to 500 nm. With these settings the resultant inverse linear dispersion was approximately 0.41 nm/pixel (according to a simple wavelength calibration). The width of the entrance slit was set to 50 µm. Since the camera pixels are 40 µm x 40 µm, the image of the slit is slightly less than one pixel wide. Thus two spectral lines should nominally be resolved if their images on the camera sensor are separated by at least one pixel. This yields a nominal resolution of approximately 1.23 nm. This estimate does not take into account the possibility of pixel cross-talk. In addition, we used a 20 pixel high horizontal pixel band for the evaluation of the spectral data. With the help of a standard image processing software we performed a simplified form of vertical binning. Imperfections of this process might further degrade the actual resolution of the set-up.

In terms of intensity we calibrated the set-up by means of a tungsten-halogen-bulb operated at 12 V and 4.8 A. We assumed a color temperature of 3000 K for this bulb. The intensity calibration was especially necessary since we found the spectral response of the camera sensor to be sinusoidally modulated by a thin-layer-interference (optical pathlength about 5.45 µm, reflection factor in terms of amplitude about 0.2).

Previous to the actual experiments on the combustion of shock-dispersed aluminum we tested the set-up with a Xenon-flash and light from a laser-diode. These tests showed that the line-structure of both sources could be detected at reasonable resolution.

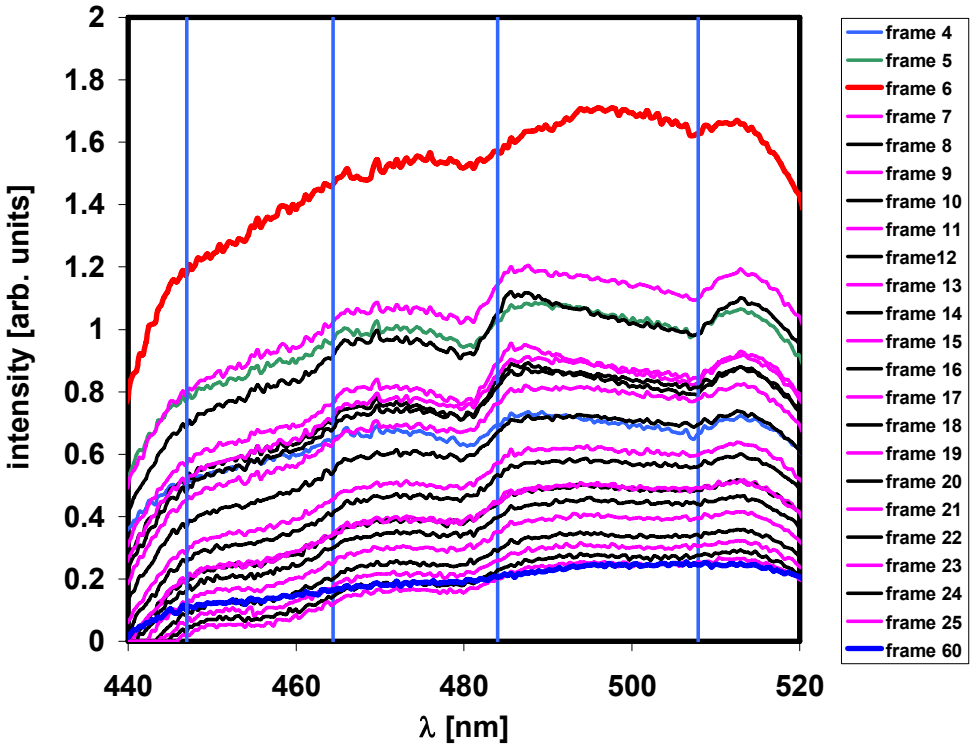

Figure 6 Spectral distribution as derived from the high-speed images obtained with the set-up in Figure 5. Vertically lines indicate the wavelengths where the band-heads of the AlO emission are expected.

The result of the final test on shock-dispersed aluminum is shown in Figure 6. The investigated flame area was a rectangle of 42 µm width and 1 mm height in the test chamber close to the vertical center and horizontally about a quarter of the model length from the left side. Figure 6 shows that the spectral distribution deviates from a smooth curve for most of the initial frames of the high-speed movie. The vertical straight lines in Figure 6 indicate the wavelengths that characterize the start of the four AlO emission bands with $\Delta\nu$=2, 1, 0 and -1. The observed modulation in the spectral distribution seems to support the idea of AlO emission contributing to the radiation from the combustion chamber. However, the modulation is only about 16% of the underlying continuous spectrum. Thus AlO emission appears not to be the dominant contribution in the investigated spectral range.

Figure 7 shows the same spectra as Figure 6, but in form of a 3-D graph to give more information on the time evolution. Under the assumption that the observed modulation of the spectra is due to AlO emission we made a rough estimate on the peak intensity for the emission bands with $\Delta\nu$=0 and -1. For the band with $\Delta\nu$=0 we estimated the peak by the difference of the intensities at 487 nm and 482 nm, for the band with $\Delta\nu$=-1 we chose the difference of the intensities at 508 nm and 513 nm.

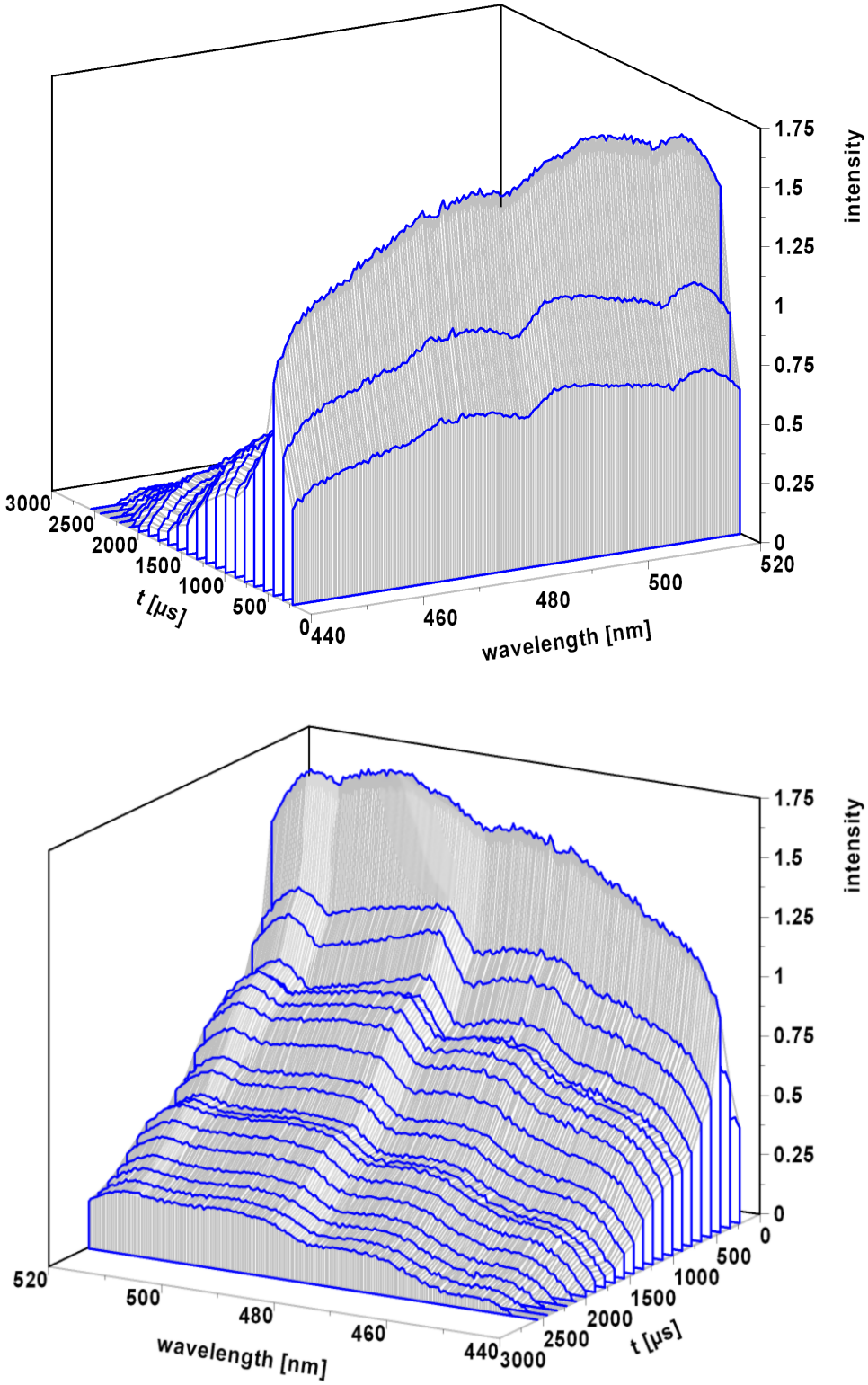

Figure 7 Time evolution of the spectral distribution observed in an experiment with shock-dispersed flake aluminum in the 4-l chamber.

Figure 8 displays the evolution of these estimated peak intensities for both bands. As a means of comparison Figure 9 shows the evolution of the average intensity per wavelength interval, as derived from the data for the spectral range from 440 nm to 520 nm.

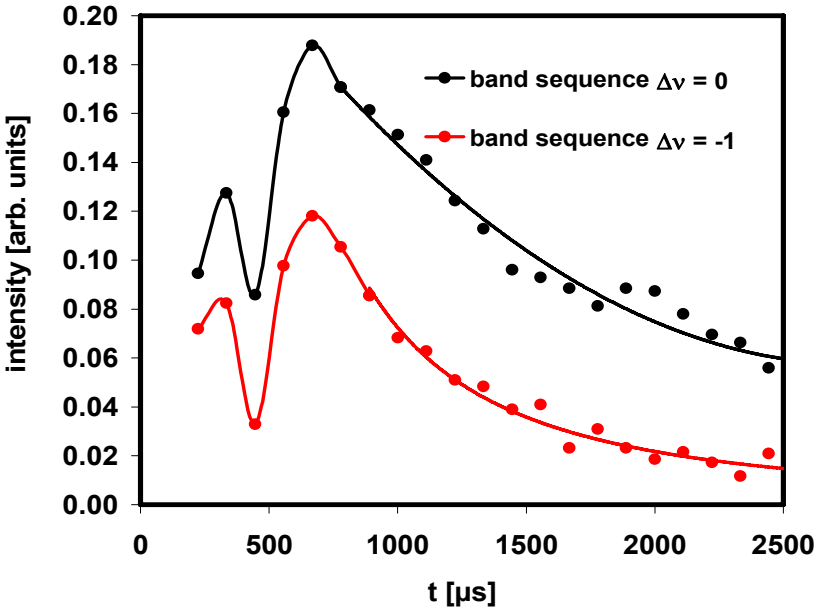

Figure 8 Time evolution of the estimated peak intensities for two bands of the presumed AlO emission.

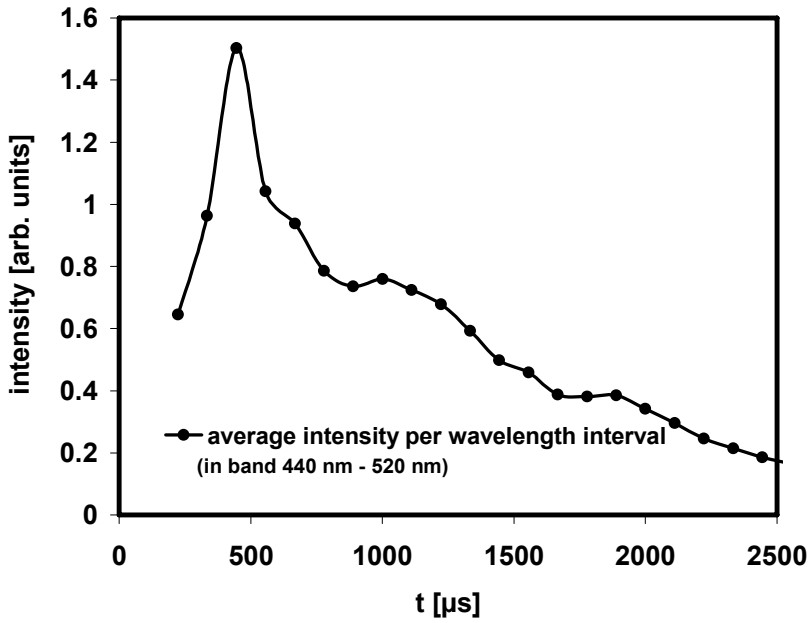

Figure 9 Time evolution of the average intensity per wavelength interval. The average is formed with regard to the wavelength range from 440 nm to 520 nm.

The average intensity at our measurement location rapidly increases and peaks at an early time of about 450 µs. The peak is followed by an initially rapid decay followed by an approximately exponential decay with a characteristic decay time of about 1.1 ms. The estimated band intensities peak somewhat later at about 670 µs. The characteristic decay times are about 1.6 ms for the band $\Delta\nu=0$ and 0.95 ms for the band $\Delta\nu=-1$. Least indication of the emission bands is found when the average intensity peaks.

SUMMARY AND DISCUSSION

Typically it is fairly straightforward to infer information about non-luminous phenomena from images (e.g., shock positions from schlieren- or shadow photographs, our traditional visualization tool). Photography of self-luminous phenomena is more difficult to interpret, especially in the case of extended, optically thick (in terms of absorption) luminous regions. The visual appearance of the images depends to a large extent on the temporal, spatial and spectral characteristics of the luminous source ***as well as*** on the characteristics of the image-forming receiver. Often the knowledge about the spectral response of the receiver is only perfunctory, as it is in the case of our high-speed camera. Narrowing down the spectral range by filtering is thus a means to achieve a better definition of the image content. However, this does not necessarily clear the true nature of the observed luminosity. Time-resolved spectroscopy can supply valuable additional information, even when done only in a few measurement locations.

The spectroscopy experiment discussed in this paper was done as a feasibility study. Its results suggest the benefits of a more stern study. Inspection of a broader spectral range could reveal more about the continuous spectrum and the associated temperatures. Keeping the observed spectral range constant at increased resolution might yield more information about the AlO emission. However, due to the limitations of the monochromator and the high-speed camera these are no options for the current feasibility set-up. Nevertheless this set-up gave strong evidence that it is rather the continuous spectrum that dominates the band-pass filtered images rather the AlO emission.

This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. w-7405-Eng-48.

REFERENCES

[1] Neuwald, P., Reichenbach, H., and Kuhl, A. L., Shock-Dispersed Flake Aluminum – Performance in Environments of Different Geometries*, Proc. 36th International Annual Conference of ICT, Energetic Materials*, Fraunhofer-Institut für Chemische Technologie, Pfinztal, 2005, ISSN 0722-4087

[2] Glumac, N.; Krier, H.; Bazyn, T.; Eyer, R., Temperature Measurements of Aluminum Particles Burning in Carbon Dioxide, Combust. Sci. and Tech., 177: 485 – 511, 2005

[3] Mamen, J.; Goroshin, S.; and Higgins; A.; Spectral Structure of the Aluminum Dust Flame, *Proc. 20th Int. Colloquium on the Dynamics of Explosions and Reactive System*, Montreal, July 31 to August 05, 2005

[4] Yuasa, S.; Sogo, S.; and Isoda, H.; Ignition and Combustion of Aluminum in Carbon Dioxide Streams, Proc. 24th Int. Symp. On Combustion, Comb. Inst., 1992, pp. 1817-1825