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Emission Spectroscopy of Hypervelocity Impacts on Aluminum, Organic and High-Explosive Targets

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Abstract

Laboratory experiments of hypervelocity impacts on aluminum, nylon and high-explosive targets are presented. Spectral measurements of the impact flash are recorded, together with radiometric measurements to derive the temperature of the flash. Such experiments aim at demonstrating that the impact flash produced by a ballistic missile interception contains the spectral information required to identify the content of the intercepted missile. It is shown that the elements that are part of the aluminum projectile and/or aluminum target are successfully identified from the obtained spectra. For the case of a nylon/aluminum target organic molecular emission lines characteristic of CN and C₂ are also identified. The CN molecular band is also observed for the case of a high-explosive target, although the detection of organic elements from such targets is more difficult than for nylon targets. In most cases, the temperature of the impact flash measured using the radiometer is in the range 2500 – 4000 K, whereas a comparison between simulated and experimental spectra shows temperatures up to 9000 K. Hence a conclusive impact flash temperature could not be obtained.

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1. Introduction

The assessment of a successful missile intercept requires insight in a number of events. For instance: has the threat been hit by the interceptor, has the threat been (partially) damaged, and is the payload still harmful after impact? Answers to these questions (obtained as quickly as possible) would largely benefit to a complete kill assessment. One possible way to support the intercept assessment is to perform spectral measurements on the impact flash resulting from a successful intercept. The aim is to identify the excited species that are characteristic to the payload content. In this way the content of the threat would be readily identified and proper measures could be taken on the ground such as evacuation and shelter. In order to demonstrate the feasibility of a post-intercept spectral analysis, laboratory experiments are conducted where spectral measurements of hypervelocity impact flashes are recorded. In realistic scenarios, potential threats are high-explosives (HE), chemical, biological, radiological and nuclear payloads. This investigation aims at the detection of HE targets as well as aluminum targets since it can be part of the missile skin.

The development of a kill assessment technique that relies on spectral measurement of the impact flash has been the scope of a number of investigations. In particular, experiments were performed at Sandia National Laboratories where

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aluminum targets were impacted at 6, 10 and 25 km/s by aluminum and titanium flyers [1] using light-gas launchers and the Z-machine. Spectral measurement of the impact flash revealed aluminum and titanium emission lines. Mihaly *et al.* [2] performed similar experiments where a nylon projectile accelerated at ~6 km/s impacted an aluminum target. Several emission lines characteristic to aluminum and organic elements were observed in the spectrum. However, the spectral resolution in these two studies was relatively low (on the order of one nanometer) which increased the difficulty to make conclusive assessments of the observed emission lines. In addition, they did not attempt to identify organic elements from HE target material.

Detection of organic elements from HE samples has previously been demonstrated using two techniques. Lucena *et al.* [3] used Laser-Induced Breakdown Spectroscopy (LIBS) on different types of explosive (they considered MNT, DNT, TNT, RDX, ANTHRA, DAT, MNA and PENT). They used a laser to generate plasma from the sample and spectral emissions could be measured. They were able to identify the organic elements that composed the studied explosives, such as carbon, hydrogen, oxygen, nitrogen, as well as the CN and C₂ molecules. Another technique consists of detonating HE charges and observing the emission spectra immediately after breakout. Glumac [4] performed time-resolved spectroscopy of a PBX-9407 charge where organic molecular emission lines can be observed within 8 μs after breakout, such as OH and CN.

In this investigation high-resolution (0.1 – 0.3 nm) spectrometers are used to better distinguish the different peaks and therefore increase conclusiveness of the recorded spectra. Furthermore, a radiometer was employed in order to monitor the radiant intensity and to obtain the temperature of the impact flash. This measurement gives an indication of whether the impact cloud temperature is sufficiently high for atomic excitation.

2. Experimental apparatus

The experimental setup consists of the launchers, the test section, the selected targets, two spectrometers and a radiometer. A brief description of these components is included in the following sections, as well as the test conditions.

2.1. Launchers and projectiles

Implosion-driven hypervelocity launchers developed at McGill University [5, 6] were used to accelerate projectiles up to 7 km/s. A schematic of its operation is presented in Fig. 1. The two main parts of the launcher are the gas tube and the launch tube. During normal operation, the self-sealing projectile is inserted in the launch tube and a lip at the back of the projectile prevents it from slipping inside the launch tube due to the increasing pressure in the gas tube. However, the lip ruptures at the desired pressure threshold and the projectile starts to accelerate. Primasheet 1000 (a PETN-based HE) is wrapped around the gas tube. The launcher is fired by initiating the Primasheet 1000 from the back. Due to a thick tamper covering the Primasheet 1000, the explosive energy is mainly directed inward to implode the gas tube and to pressurize the helium towards the projectile. The velocity at which the gas tube is imploded (from the back towards the projectile) is dictated by the detonation velocity of the Primasheet 1000. When the implosion arrives near the back of the projectile, the lip of the self-sealing projectile ruptures and the projectile accelerates in the barrel. The projectile diameter fits the bore diameter and sabots are not used.

2.2. Test section, targets and trigger

The test section is presented in Fig. 2. Windows are located on both sides of the test section for visual access to the impact flash. A 50-mm diameter circular quartz window is placed on the back side (as shown in Fig. 2), whereas a long rectangular (75 x 400 mm) Lexan window is located on the front side. The quartz window allows wavelength transmittance down to 270 nm which was required for the spectral measurements. This was however not required for the other instrumentation (the radiometer and the high-speed camera for velocity measurement). The Lexan windows were used for these purposes since they can resist a much higher internal pressure compared to quartz.

An optical trigger was used to trigger the recording of the spectrometer. A Photo-Diode Array (PDA) as shown in Fig. 2 monitored the impact flash and a trigger was sent to the spectrometer whenever the signal reached a specified intensity. The radiometer recorded the event in continuous mode.

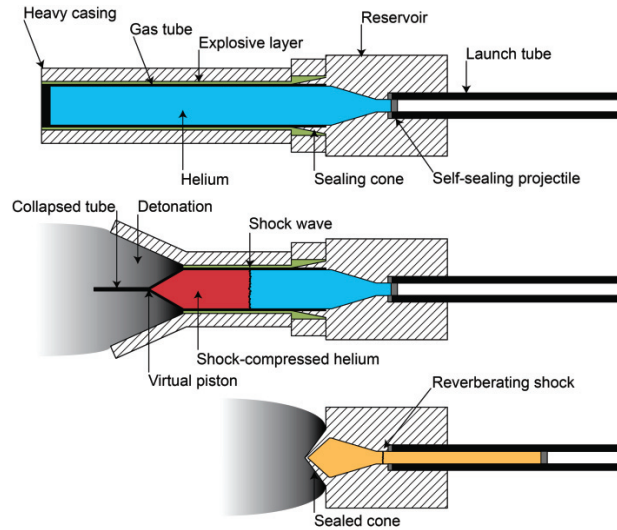


Fig. 1. Schematic of the operation of a linear implosion driven hypervelocity launcher.

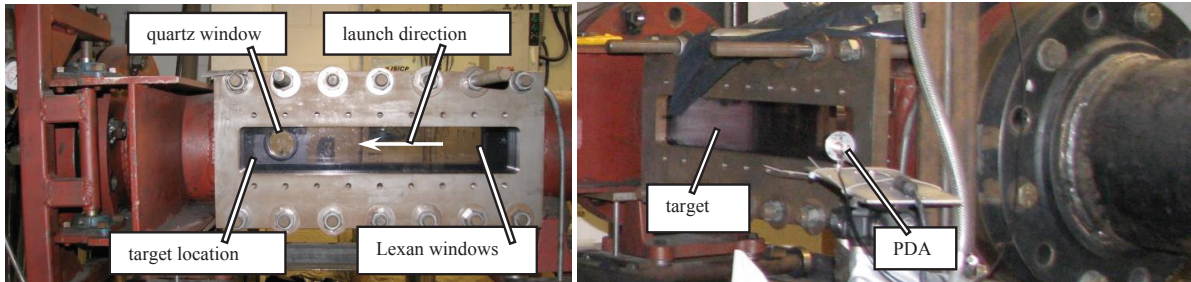


Fig. 2. Assembly of the test section.

The target material selection (used individually or combined) is:

- Aluminum 6061 T6
- Nylon (non-reactive organic compound)
- Primasheet 1000 (a PETN-based sheet explosive fabricated by Ensign-Bickford)

The alloy composition of aluminum 6061 T6 (target material) and aluminum 7075 (projectile material) is provided in Table 1. The target material and thickness for each experiment is provided in Section 2.5.

2.3. Spectrometers

Two spectrometers were used during the experiments: the Aryelle 200 fabricated by Lasertechnik Berlin and Andor's Mechelle ME5000 spectrometers. Both instruments are shown in Fig. 3 and their fibre optics were mounted on a tripod in front of the quartz window. The Aryelle spectrometer is $f/10$ and employs a $40\text{-}\mu\text{m}$ entrance pinhole. The Mechelle is $f/7$ and employs a $250\times 50\text{-}\mu\text{m}$ entrance slit. Both spectrometers use similar iCCD cameras (Andor iStar 334 and Andor iStar DH734, respectively) with the same intensifier. The Aryelle spectrometer allows a higher spectral resolution ($0.1 - 0.3\text{ nm}$) whereas the Mechelle spectrometer allows a higher sensitivity ($\sim 1.5\times$ improvement in the SNR). The spectral range of both spectrometers is similar from approximately 250 to 800 nm. Three types of fiber optics were used in the experiments and their specifications are provided in Table 2. The fiber type used in each experiment is specified in the caption of all figures presenting a spectrum. Both spectrometers provided time-integrated spectra. The exposure time is reported for each experiment and it varies between 7 and 70 μs , which is specified in Section 2.5.

Table 1. Alloy composition of Al 6061 T6 and Al 7075.

Element	Weight %	
	Al 6061 T6 (targets)	Al 7075 (projectiles)
Silicon	0.4 – 0.8	0 – 0.4
Iron	0 – 0.7	0 – 0.5
Copper	0.15 – 0.4	1.2 – 2
Manganese	0 – 0.15	0 – 0.3
Magnesium	0.8 – 1.2	2.1 – 2.9
Chromium	0.04 – 0.35	0 – 0.28
Zinc	0 – 0.25	5.1 – 6.1
Titanium	0 – 0.15	0 – 0.2
Aluminium	95.85 – 98.56	87.1 – 91.4

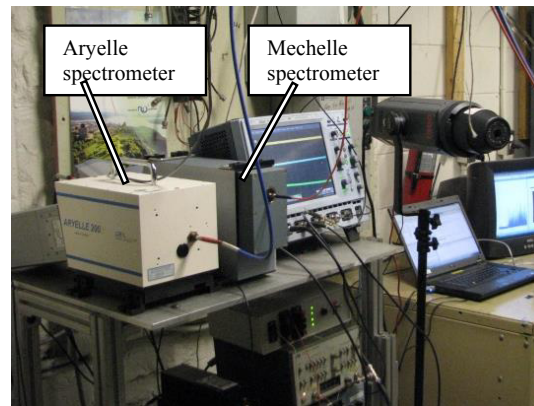


Fig. 3. Aryelle and Mechelle spectrometers.

Table 2. Transmittance of the fiber optics used with the spectrometers.

Diameter (μm)	Transmittance (nm)
400	180 – 1150
600	400 – 2200
600	180 – 1150

2.4. Radiometer

The ColoRad C6 is a radiometer fabricated by IARD Sensing Solutions Ltd. and is suited for field tests where it measures detonation flashes from long distances (a few kilometers). This instrument was adapted to laboratory experiments and it uses three channels equipped with 5 m optical fibers that have fiber collimators placed in front of the aperture for each channel. The extremity of each fiber was placed on a holding plate (approximately 40 mm apart from each other) with a small diode laser used for alignment. The holding plate was located approximately 2 m in front of the Lexan window of the test section. The three channels measured simultaneously at three different wavelengths determined by the filters used. In this case, the filters were situated at 0.8 μm (Ch#1), 1.0 μm (Ch#2) and 1.6 μm (Ch#3). The temperature of the impact flash was calculated from the radiometric data using the method of "two-colour" radiometry applied on two pairs of the channels: Ch#1/Ch#3 and Ch#2/Ch#3. This method assumes that the emissivity in all channels is treated as that of a "grey body". Consequently, whenever emission lines appear within the spectral bands of the different filters the calculated temperature is altered and the two temperature calculations may differ from each other.

2.5. Test conditions

Spectra obtained from three experiments are presented in the next section. The experimental conditions for these three tests are provided in Table 3. The impact velocity was measured in Case 2 using high-speed videos of the projectile passing through the test section before impacting the target. For Case 1, an estimated velocity (2 – 4 km/s) was based on other similar launches where the velocity was accurately measured. For Case 3 the projectile fragmented before the impact and the velocity of the fragment that initiated the HE target could not be measured. The target for Case 1 consisted of a 3.2-mm thick aluminum plate. Two-layer targets were used for Cases 2 and 3 where a 19-mm thick aluminum plate was used for the back layer whereas Nylon and HE were used for the front layer, respectively. The test section was evacuated down to 0.8 – 4.0 kPa. The exposure time of the spectrometer was set at 70 μ s for Cases 1 and 2 and at 7 μ s for Case 3.

Table 3. Test conditions.

Case	1	2	3
Projectile diameter (mm)	10	5	10
Projectile mass (g)	1.14	0.14	1.14
Projectile velocity (km/s)	not measured (estimated in the range 2 – 4)	6.8	N/A
Intact projectile ?	yes	yes	no
Back target material	Al	Al	Al
Thickness (mm)	3.2	19	19
Front target material	none	Nylon	HE
Thickness (mm)	N/A	3.2	1
Test section pressure (kPa)	4.0	1.7	0.83
Spectrometer exposure time (μ s)	70	70	7

3. Experimental results

The results of the three cases outlined in Table 3 are presented here. For each case, the temperature and the emissive area of the impact flash derived from the radiometric measurements are provided, as well as the spectral measurements.

3.1. Case 1: Aluminum target

Case 1 consisted of an impact on an aluminum target at a velocity between 2 and 4 km/s. The target after impact is shown in Fig. 4(a). Two profiles of the flash temperature derived from the radiometer's measurements are displayed in Fig. 4(b). This figure also shows the recording window of the spectrometers which corresponds to when the cloud temperature varies from 2000 K to 4000 K according to the radiometric measurements. The resulting spectrum recorded by the Aryelle spectrometer is presented in Fig. 5. Many emission lines can be recognized from this spectrum. For better clarity, this spectrum is divided into five spectra shown in Fig. 6 to Fig. 8.

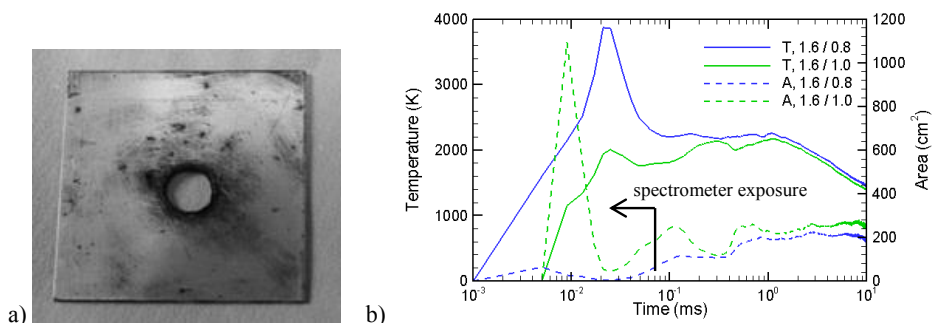


Fig. 4. (a) Aluminum target after impact for Case 1. (b) Temperature and emissive area of the impact flash for Case 1.

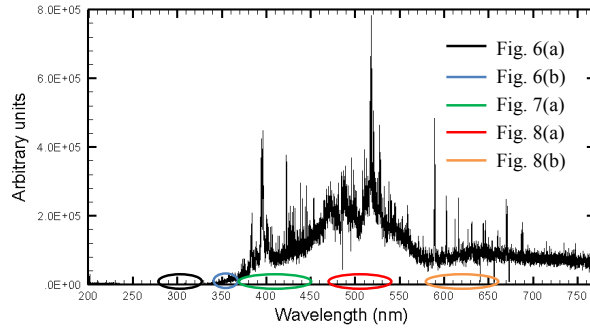


Fig. 5. Spectrum (Aryelle spectrometer, 600 μm , 400 – 2200 nm fiber) for Case 1 (aluminum target).

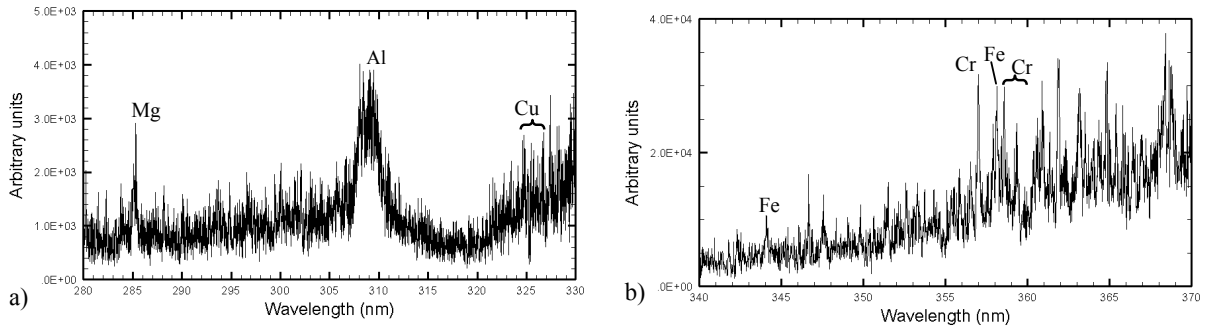


Fig. 6. Spectra (Aryelle spectrometer, 600 μm , 400 – 2200 nm fiber) for Case 1 in the range (a) 280 – 330 nm and (b) 340 – 370 nm.

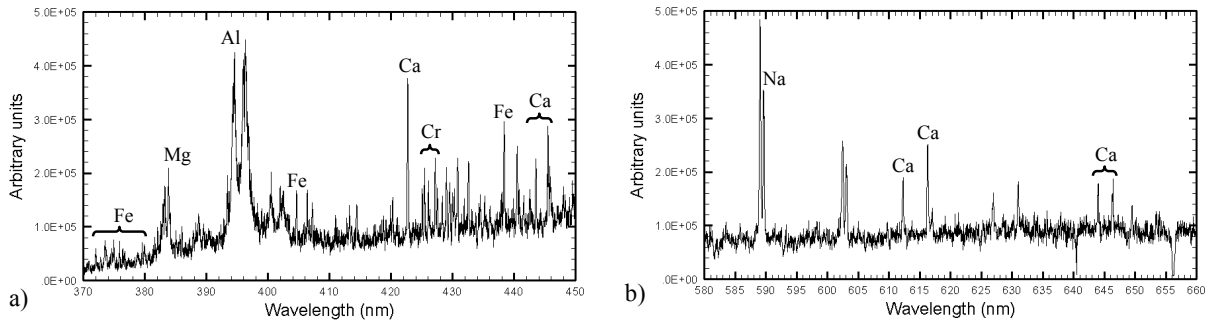


Fig. 7. Spectra (Aryelle spectrometer, 600 μm , 400 – 2200 nm fiber) for Case 1 in the range (a) 370 – 450 nm and (b) 580 – 660 nm.

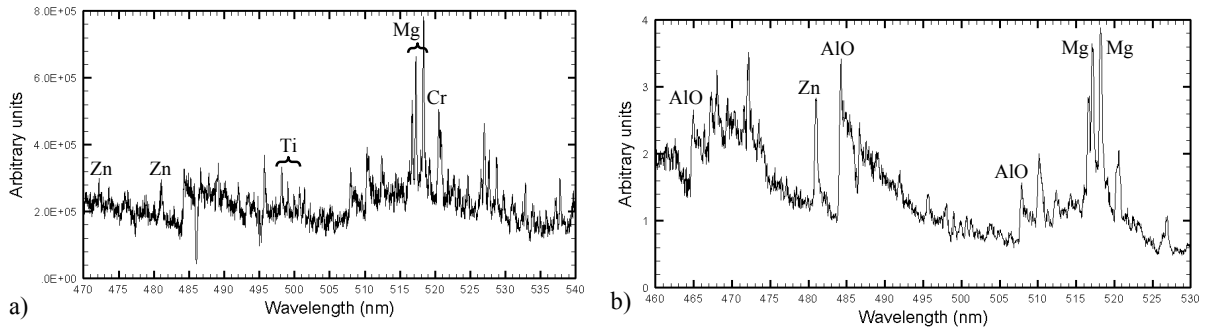


Fig. 8. (a) Spectrum (Aryelle spectrometer, 600 μm , 400 – 2200 nm fiber) for Case 1 in the range 470 – 540 nm. (b) Spectrum (Mechelle spectrometer, 600 μm , 400 – 2200 nm fiber) for Case 1 in the range 460 – 530 nm.

The identified elements are summarized in Table 4. Apart from the elements originating from the surroundings (sodium and calcium), all identified species (magnesium, aluminium, copper, iron, chromium, zinc and titanium) are part of the alloy composition of both the projectile and target (see Table 1). Furthermore, the molecular emission lines of aluminium oxide (AlO) are also present at 484 and 508 nm. Therefore, aluminium is successfully identified from the impact flash produced by a hypervelocity impact when this material is used for both the projectile and the target.

Table 4. Identified elements for the detection of aluminum alloys in different spectral ranges.

Figure	Spectral range (nm)	Element identified
6(a)	280 – 330	magnesium, aluminium, copper
6(b)	340 – 370	iron, chromium
7(a)	370 – 450	iron, magnesium, aluminium, chromium
8	470 – 540	zinc, titanium, magnesium, chromium, aluminium oxide
7(b)	580 – 660	sodium, calcium

3.2. Case 2: Nylon / aluminum target

For Case 2 a 5-mm projectile with a velocity of 6.8 km/s was used against a nylon & aluminum target as shown in Fig. 9(a) and Fig. 9(b). The temperature of the impact flash measured with the radiometer is presented in Fig. 9(c). During the spectrometer exposure time window, the cloud temperature according to the radiometric measurements was on the order of 2500 K. The sudden temperature decrease between 0.2 and 0.9 ms is an experimental artefact and has no physical basis that occurred during the analysis of the measured radiant intensity. During each experiment, a strobe flash was used for back illumination necessary to monitor the projectile velocity from the high-speed videos. Since the trailing edge of the strobe signal overlapped with the leading edge of the flash signal, it was necessary to subtract the strobe signal (measured before each experiment) from the flash signal. It should be noted that the strobe signal was not a reproducible one and it created certain bias in the flash signal such as negative values. In this case, a negative radiant intensity was obtained due to the presence of the particles ejected from the impact.

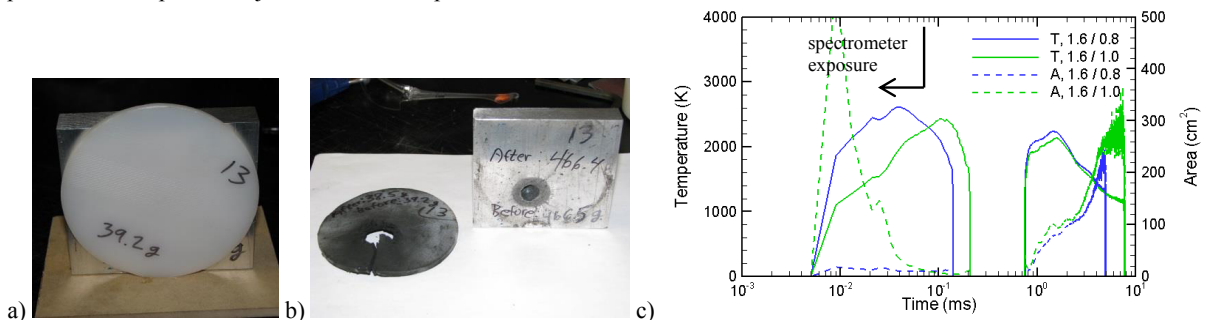


Fig. 9. Nylon / aluminum target (a) before and (b) after impact for Case 2. (c) Temperature and emissive area of the impact flash for Case 2.

A high-speed photograph of the impact flash during the spectrometer's exposure time is presented in Fig. 10. The target location is shown with the dashed lines. Due to the relatively thick aluminum (19 mm) target the projectile did not perforate the aluminum plate and the impact flash remained in front of the target. The nylon in front of the aluminum allowed organic elements to be excited in the hot cloud produced by the impact.



Fig. 10. High-speed camera image of the impact flash during the spectrometer's exposure for Case 2.

The spectrum acquired with the Aryelle spectrometer is displayed in Fig. 11(a). This spectrum is divided into three spectra in the ranges 250 – 320 nm, 350 – 430 nm and 460 – 570 nm shown in Fig. 11(a) and Fig. 12. From these spectra, organic molecular emission lines characteristic of CN and C₂ are identified. Molecular emission spectra are more complex (and provide more information) than atomic emission spectra due to the presence of vibrational and rotational transitions in addition to the electronic transitions. For example, the $\Delta v=0$, $\Delta v=-1$ and $\Delta v=+1$ progressions for CN are visible with bandheads at 359.4 nm, 388.3 nm, and 421.5 nm. Due to the high temperature, higher vibrational energy levels are also populated and hence transitions from these levels are also apparent in the progression. Since the test section was evacuated to a pressure of 1.7 kPa, the observed nitrogen most likely originates from the target, although the influence of the surrounding air cannot be ruled out. From this experiment, it was thus possible to identify organic elements from a hypervelocity impact on a nylon target.

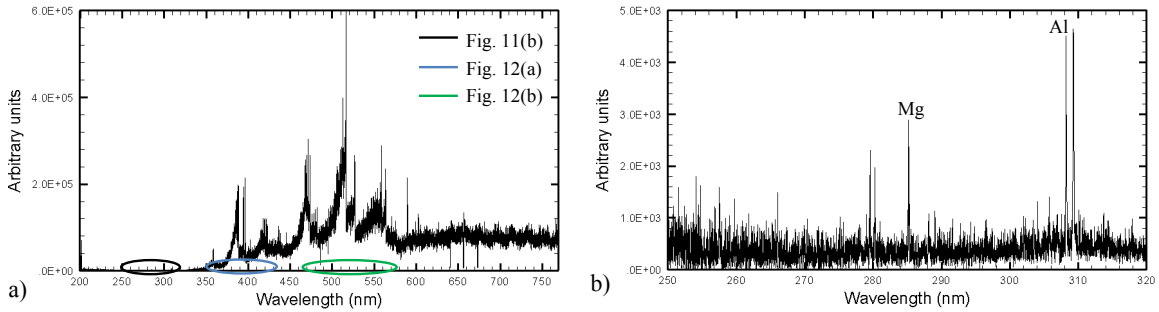


Fig. 11. Spectrum (Aryelle spectrometer, 400 μ m, 180 – 1150 nm fiber) for Case 2 in the range (a) 200 – 750 nm and (b) 250 – 320 nm.

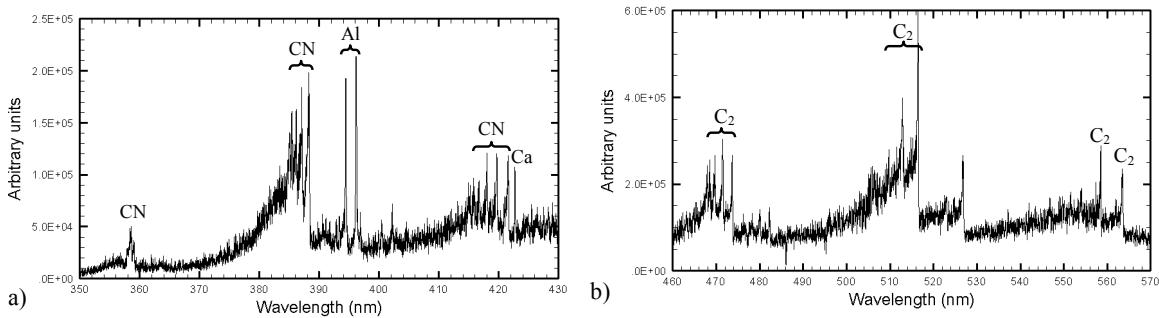


Fig. 12. Spectrum (Aryelle spectrometer, 400 μ m, 180 – 1150 nm fiber) for Case 2 in the range (a) 350 – 430 nm and (b) 460 – 570 nm.

In Fig. 13, the spectrum obtained with the Mechelle spectrometer from Case 2 is compared with simulated spectra of the CN radical at different temperatures. Increasing the temperature increases the population in higher vibrational energy levels, thereby increasing the intensity of the peaks at shorter wavelengths with respect to the (0 \leftarrow 0) band at 388.3 nm. The quality of the current spectra is not sufficient to determine the temperature accurately by this method, but it is striking that the temperature determined by molecular emission is considerably higher (>7000K) than that determined by radiometric measurements. It is possible that the post-processing of the radiometric measurements (subtraction of the strobe back illumination from the measurements) results in calculated temperatures that are underestimated due to the presence of the ejected particles present in the cloud. Therefore, the temperature of the impact flash can only be estimated to be in the range 3000 – 9000 K.

3.3. Case 3: Primasheet 1000 / aluminum target

In the previous sections, it is shown that aluminum and organic elements can be identified from spectral measurements of the impact flash. The next step is to pursue the identification of organic elements from a HE target.

The target before impact is displayed in Fig. 14(a) where a 1-mm thick Primasheet 1000 is placed in front of a 19-mm thick aluminum plate. The radiant intensity and the temperature of the impact flash measured with the radiometer are

presented in Fig. 14(b). For this experiment, the duration of the spectrometer exposure time window was reduced to 7.7 μs to capture the light from the impact flash while avoiding possible light contamination from the fireball. During this time, the apparent temperature of the cloud according to the radiometric measurements is below 2000 K.

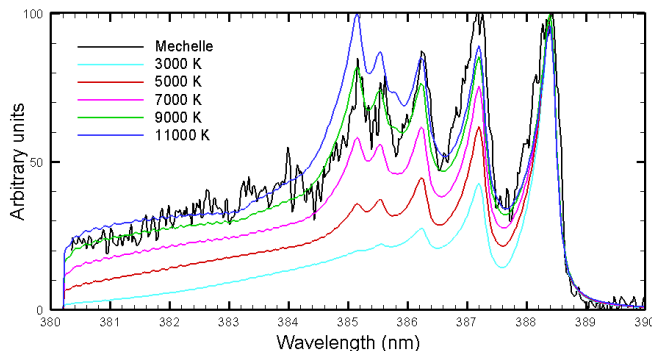


Fig. 13. Comparison between the measured spectrum for Case 2 (nylon/aluminum target) and simulated spectra at various temperatures.

Unfortunately, the launcher did not operate normally for this experiment. The Primasheet 1000 was initiated by a high-velocity small fragment that could not be discerned in the high-speed video (hence the impact velocity could not be measured) and the main projectile arrived in the test section after the Primasheet 1000 detonated. Nevertheless, the photodiode detected the initiation of the Primasheet 1000 and triggered the spectrometers shortly after breakout. Figure 15 shows the fireball during the spectrometer exposure time.

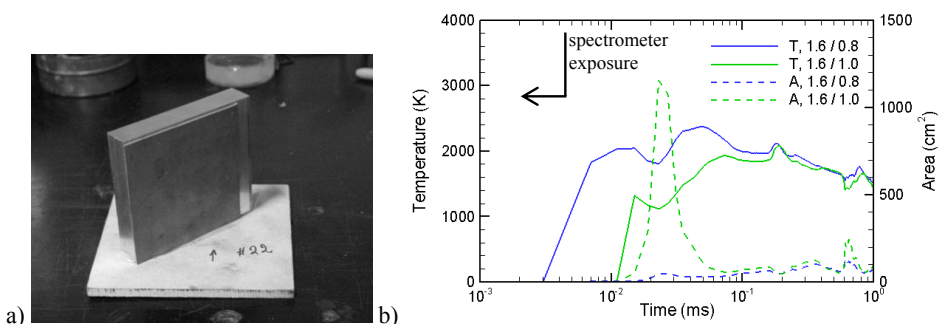


Fig. 14. (a) Primasheet 1000 / aluminum target before impact for Case 3. (b) Temperature and emissive area of the impact flash for Case 3.



Fig. 15. High-speed camera image of the impact flash during the spectrometer's exposure for Case 3.

The corresponding spectrum acquired by the Mechelle spectrometer is shown in Fig. 16. The CN molecular emission lines are identified in the spectral range 350 – 400 nm. The relative intensity of the CN spikes compared with the continuum is weaker than for the nylon target (Fig. 12(b)). This is due to the lower cloud temperature and the shorter exposure time. Nevertheless this experiment successfully revealed organic elements from the acquired spectra.

Based on the experimental results, it proved to be more difficult to identify organic elements from HE targets compared to nylon targets. This might be due to a number of phenomena. Firstly, it is important for the cloud temperature to be sufficiently high to excite the organic molecules. The detonation temperature is between 2500 and 3000 K. Case 2 suggests that a temperature of 2500 K is sufficient, although this temperature might be underestimated (see Fig. 13). Secondly, soot

is formed as a detonation product which reduces optical access through the cloud and possibly blocks the photons emitted by the excited molecules of interest. Thirdly, time-resolved spectroscopy would be useful to determine whether the elements of interest are excited soon after the onset of the detonation. Therefore, identification of organic elements in a detonation event might be more easily achieved with some modifications to the measurement technique employed in this investigation. Nevertheless, the present results indicate that it is feasible to identify organic emission from a detonation event.

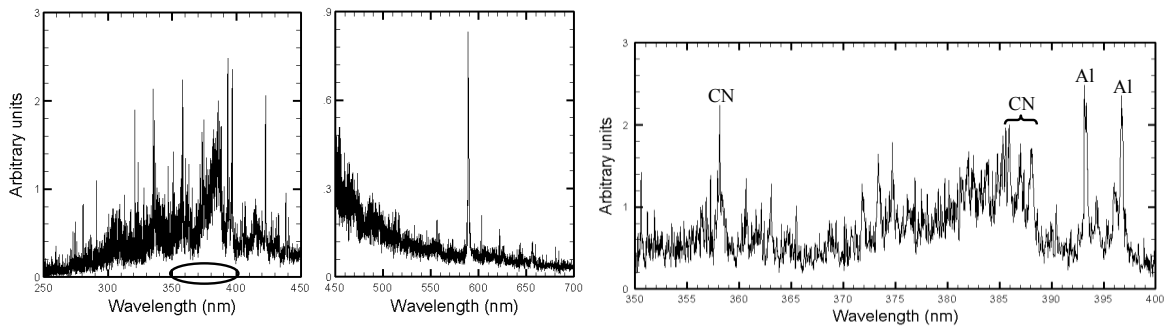


Fig. 16. Spectrum (Mechelle spectrometer, 600 μm , 180 – 1150 nm fiber) for Case 3 in the range (a) 250 – 700 nm and (b) 350 – 400 nm.

4. Conclusions

Hypervelocity impacts of 5- to 10-mm aluminum projectiles at 3 – 7 km/s against aluminum, non-reactive organic and HE targets were conducted in a laboratory environment. The purpose was to perform spectroscopic measurement on the impact flash in order to identify the composition of the target materials. This method represented a first step towards demonstrating the feasibility for remote detection of a payload containing HE due to an intercept event. This experimental campaign showed that this technique has the potential to achieve this goal since the composition of different targets could be observed from the measured spectra. The identified elements from the different target materials are the following:

- Aluminum target: atomic emission lines of aluminum and its alloy composition (magnesium, copper, iron, chromium, zinc and titanium) were all identified in the acquired spectrum, as well as the molecular emission line AlO.
- Nylon target: organic molecular emission lines were identified, such as CN and C₂, in the acquired spectrum from a combined nylon and aluminum target.
- Primasheet 1000 target: organic molecular emission lines from the CN molecule were identified for a combined Primasheet 1000 / aluminum target.

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