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SPECTRA AND RELATIVE INTENSITY MEASUREMENTS OF NOBLE GAS FLASH BOMB LIGHT OUTPUT

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SPECTRA AND RELATIVE INTENSITY MEASUREMENTS OF NOBLE GAS FLASH BOMB LIGHT OUTPUT

by

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February/février 1997

Approved by/approuvé par

Chief Scientist/Scientifique en chef

27 Jan '97
Date

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ABSTRACT

The light output from He, Ar or Xe filled explosive flash bombs was measured using a spectrometer system. The spectra seem to be blackbody type radiation with some characteristic spectral lines superimposed. Xenon gave the brightest and hottest flash output, helium the least.

RÉSUMÉ

La luminosité de bombes lumineuses remplies d'hélium, d'argon ou de xénon a été mesurée au moyen d'un spectromètre. Les spectres étaient du genre corps noir avec superposition de lignes spectrales caractéristiques. Le xénon a produit l'éclair le plus intense et le plus chaud, et l'hélium le mois intense et le moins chaud.

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EXECUTIVE SUMMARY

The Canadian Forces are being asked to undertake a great many peacekeeping and other operations where non-lethal weapons could be potentially useful. One such weapon would be a flash grenade that could temporarily dazzle the foe, giving a certain element of surprise.

To better understand the principles behind one possible form of flash grenade, a series of experiments was carried out to characterize the light output from a related system used at DREV for a much different purpose. A flash bomb is a noble gas filled box with a translucent exit face. An explosive is detonated on the back side of the box and the subsequent shock wave heats the gas to a very high temperature (several thousand degrees Kelvin), causing it to generate a short duration, high intensity light. These devices are commonly used for illuminating fast events. The light from several of these devices, filled with helium, argon or xenon, was examined by a spectrometer. The overall results showed that xenon gives the brightest light. The implication is that xenon is the best candidate gas for potential flash grenades which use shock heating of gases for producing light.

As a result of this work, DREV has a better quantitative understanding of the mechanisms of flash bombs and if and when the Canadian Forces expresses a desire for a flash grenade system, some preparatory will already have been done. Interest has been shown in optical munitions, which includes flash grenades, by the NATO DRG Panel 1 Specialist Team on Non-lethal Weapons.

LIST OF SYMBOLS

ϵ	greybody emissivity
λ	wavelength
c	speed of light
c_1, c_2	constants in Planck radiation formula
d	diameter of an atom
HWHM	spectral line half width at its half maximum intensity
I	intensity of light
k	Boltzmann's constant
m	mass of an atom
n	channel number
N	number density (atoms/m^3)
ND	neutral density filter attenuation
$R(\lambda)$	photodiode relative response
T	temperature (K)
γ	ratio of specific heats

1.0 INTRODUCTION

Civilian and military forces in Canada are called upon regularly to deal with situations and crises in which the use of deadly force is not widely accepted. Non-lethal options for temporarily incapacitating a belligerent could be of great use in such cases. One type of non-lethal weapons, called an optical munition, is used to dazzle (temporarily blind) an opponent. (Devices which are used with the intent of permanently blinding are banned by international treaties.) There are several ways bright light can be generated – e.g. lasers, electronic flash units or flares. Another potential way is a flash grenade based upon the explosive shock heating of a contained noble gas. This memorandum describes the light output of a related system, a flash bomb, which has been used in the detonics laboratory at DREV for many years. Surprisingly, the light output of a bomb has not been previously studied – they have been simply used as bright light sources with no regard to specifics.

This work was carried out at DREV between April and June 1996 under Project 2EC, Non-lethal Incapacitation, Thrust 2EC13, Munitions and Delivery Systems.

2.0 EXPERIMENTAL DETAILS

This section has two purposes: to describe the experiment and the equipment used and to outline how the data was reduced.

2.1 Experimental Equipment

To undertake measurements of the spectra of explosive flash lamps, two obvious things are necessary: flash bombs (or flash lamps) and a way to measure the spectra. The particular DREV system used for the present experiments will be described.

A flash bomb is particularly simple, consisting of nothing more than a moulded thin-walled plastic box with a 6" by 6" (face) by 5 1/2" deep with a translucent plastic diffusing screen on its exit face. On the back face of the box is attached a 6" by 6" by 5/8" thick slab of the plastic-bonded explosive CX-84A. This explosive is detonated by a centered RP-8 detonator, tetryl booster pellet and CX-84A booster pellet combination. The box is flushed with a noble gas for 5-10 minutes at a pressure of 2 atmospheres (absolute) and is then sealed and used immediately.

Each flash bomb was placed in the center of the firing bay and its light output was sent through an observation port in the bay's wall. A series of plane mirrors was used to direct the light in a quasi-collimated fashion to the slit of a spectrometer. No focusing optics were used. The total distance from the flash lamp to the slit was about 5.5 meters.

The instrument used was a SPEX 0.34 m spectrometer (Model 340S) outfitted with an adjustable entrance slit (250 μm was used), a 600 groove/mm line grating and a 1024 channel silicon photodiode array detector at the exit. The output was recorded by a computer. This system gives a 125 nm wide spectrum. All the experiments were performed

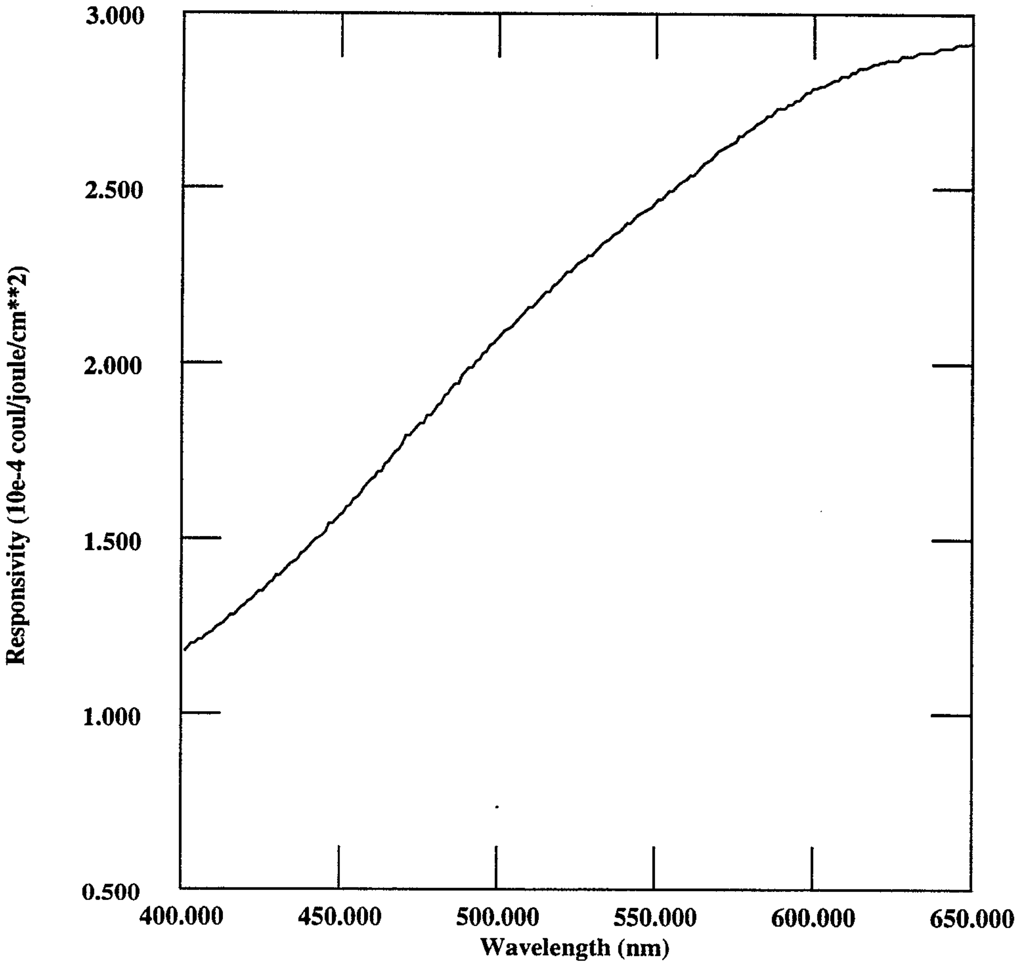

FIGURE 1 – Photodiode responsivity variation with wavelength

with a central wavelength of 540 nm which covers a wide part of the visible spectrum (485-610 nm). The response of the photodiodes to different wavelengths is not uniform. In Fig. 1, the response curve (which came with the instrument) is given for the region of interest. Neutral density filters were used in front of the entrance slit to prevent saturation of the photodiodes. For helium, a filter ND of 0.5 was used; for argon, 1.0 and for xenon, 1.3 .

Since the desired spectra had to be determined as accurately as possible over the range examined, two effects which could have changed them were considered. First, the

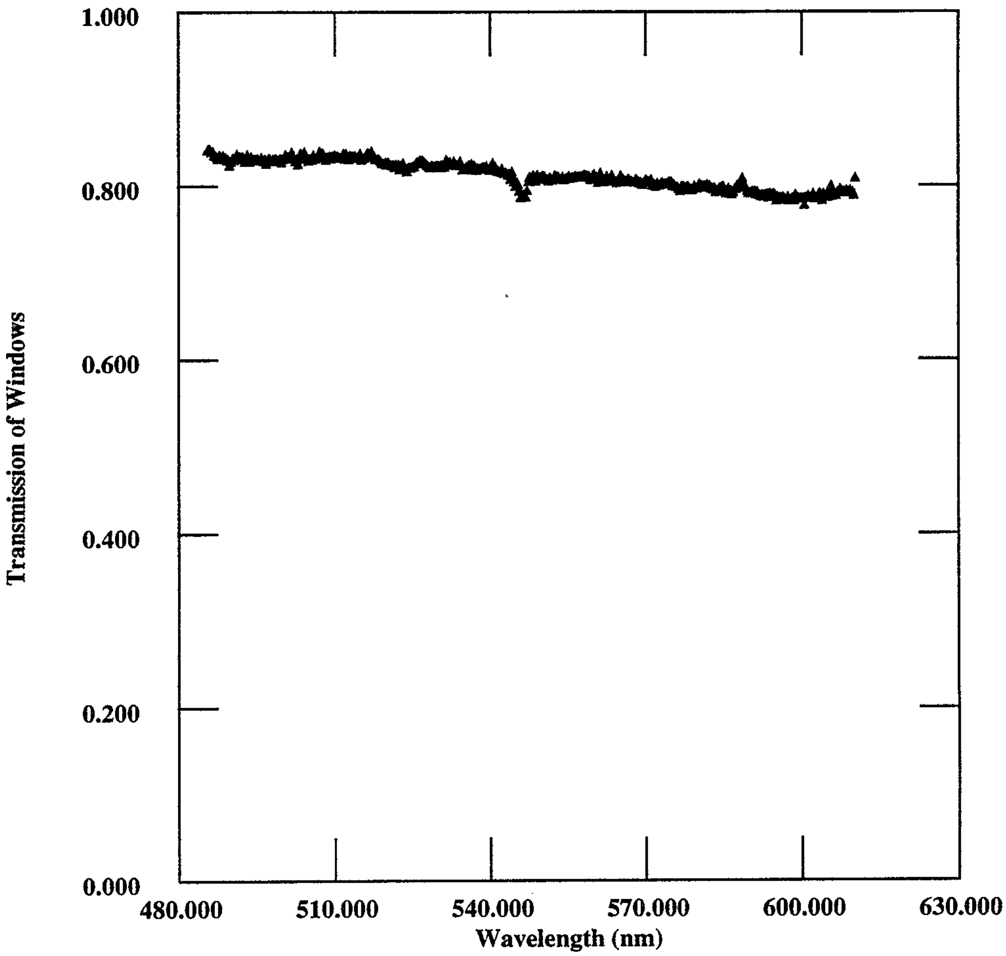

FIGURE 2 – Light transmission of firing bay window

absorption of the light by the observation port windows (1" bullet proof glass, 1/2" safety glass) was measured and found to be more or less uniform across the range (see Fig. 2). The transmitted intensity is reduced almost exclusively by Fresnel losses upon reflection at the surfaces of the windows. Second, the neutral density filters also show a flat response according to the manufacturer's reports which came with them.

Synchronization of the flash bomb and the spectrometer system is also important. The spectrometer's readout system integrates the light it receives and then takes a finite time to send the data to the computer. The short event under study must occur during the integration time of the readout system. The timing was setup as follows. An electrical pulse (5 V, 100 μs) was used to trigger the integration process of the spectrometer. According to the manufacturer, this process can start anytime between 0 and 1 ms after the trigger pulse is received. The light signal was then integrated for the next 100 ms (user specified). During this time, at 6 ms after the trigger pulse, the flash bomb was detonated. A short delay (several microseconds) occurred before light was produced. The flash bomb light output lasted about 30 μs. After the integration time elapsed, readout started and continued for 13.2 ms. The data (intensity, channel number pairs) were stored on the computer for later analysis.

2.2 Data Reduction

The raw data had to be converted to wavelength-calibrated intensity pairs. The spectra were transformed in wavelength according to

$$\lambda_{true} = \lambda_o + 0.122(n_o - n)$$

where λ_o is a known wavelength which occurs at channel n_o and λ is the wavelength at channel n. For the known wavelength, a convenient mercury line (from overhead fluorescent lights!) at 546.074 nm was used. The grating was rotated so that this line occurred near the center of the photodiode array. A calibration spectrum was taken for each day of experiment.

The spectra were corrected in intensity for photodiode response and neutral density filters according to

$$I_{true} = I_{measured} 10^{ND} / R(\lambda)$$

where I represents intensity, $R(\lambda)$ is the photodiode response curve given in Fig. 1 and ND is the amount of neutral density filtering employed. The relative intensity levels presented in the spectra are thus directly comparable.

3.0 RESULTS AND OBSERVATIONS

This section will deal with the results which were obtained. A few general comments will be made on their implications for non-lethal weapons.

3.1 Spectra and General Remarks

A series of two helium, three argon and three xenon spectra were measured and are presented below. Figures 3 and 4 show the helium spectra, Figs. 5-7, the argon spectra and Figs. 8-10, the xenon spectra. It is evident that the spectra are reproducible for a given gas and that each gas generates a characteristic spectrum. Since the effect of the neutral density filters has been accounted for in each spectrum, the intensity scales can be compared. We see immediately that helium gives the least light output, argon is next and xenon gives the strongest light output. We can also see that the underlying slope is different; in order of increasing steepness we have helium, argon and then xenon. The number of "bumps" on

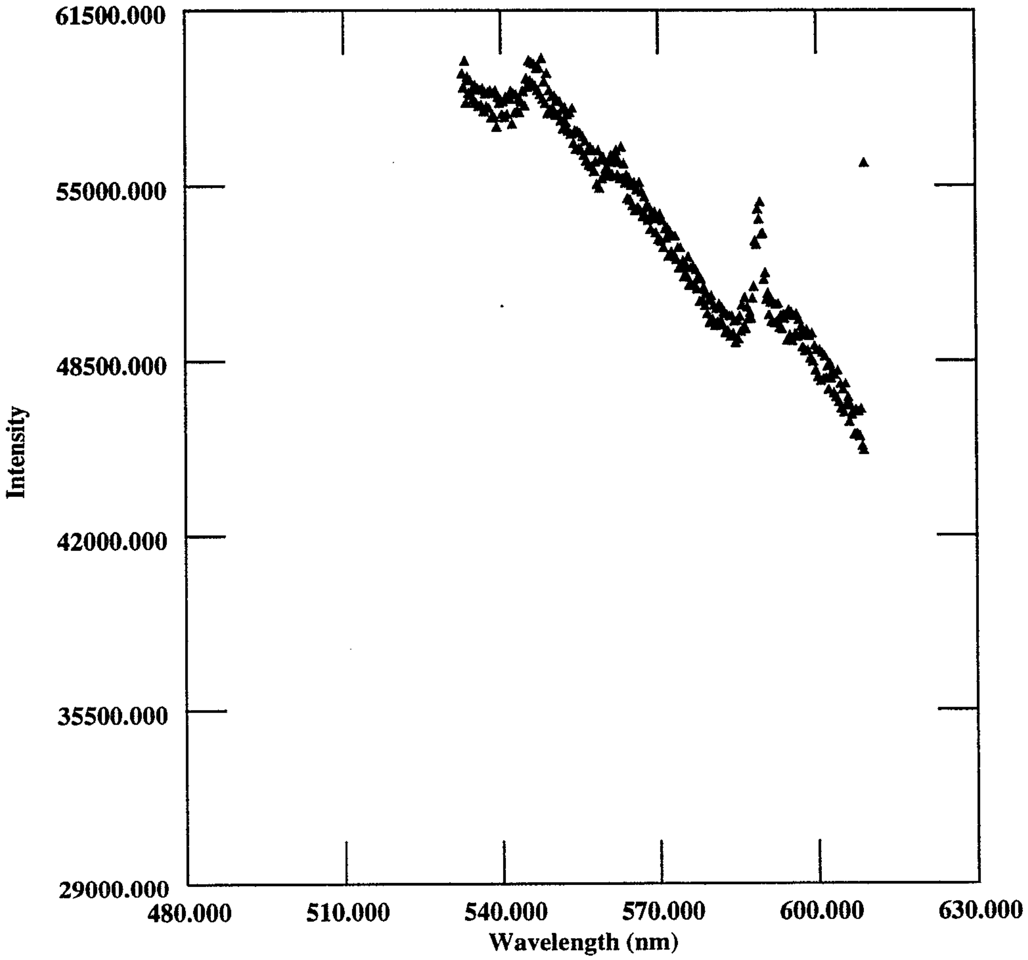

FIGURE 3 – Helium spectrum #1

each spectra also varies, helium having the fewest, argon having more and xenon having the most.

3.2 Blackbody and Spectral Line Details

As an hypothesis to explain the spectra, the following is proposed: a noble gas flash bomb spectrum is basically that of a blackbody with spectral lines characteristic of the gas

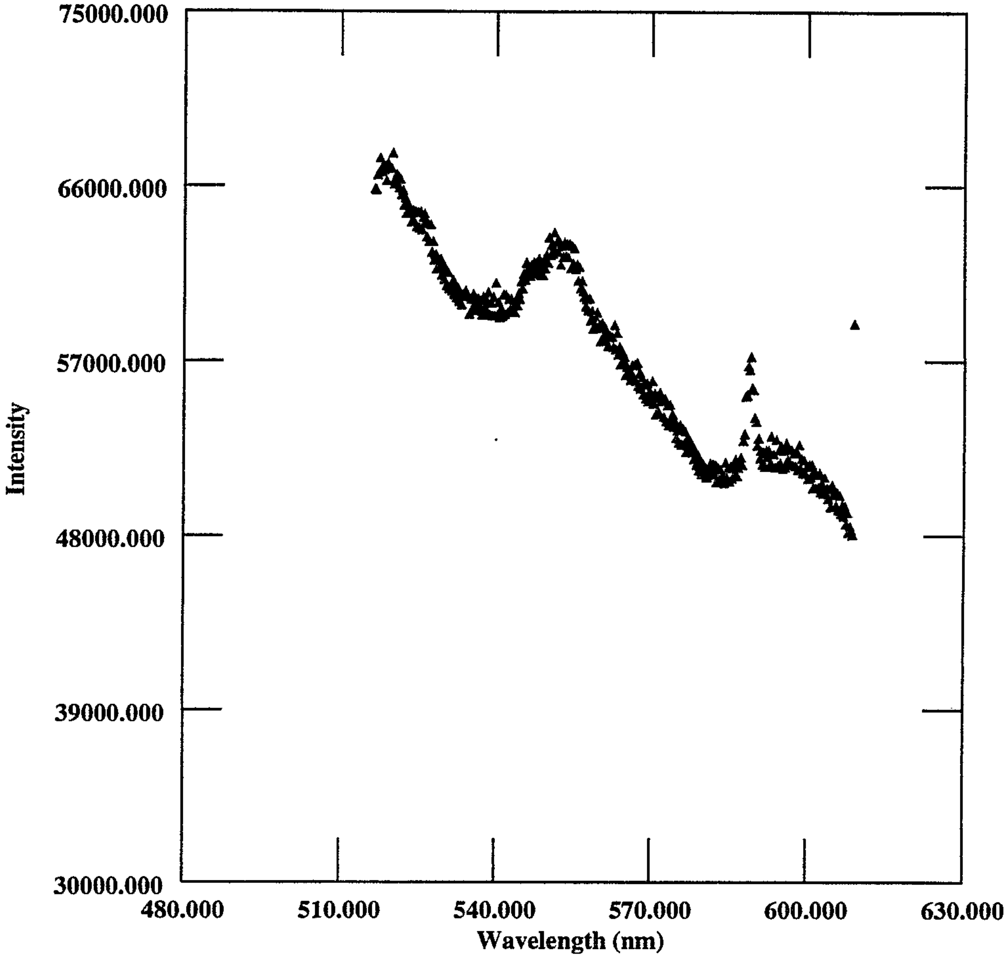

FIGURE 4 – Helium spectrum #2

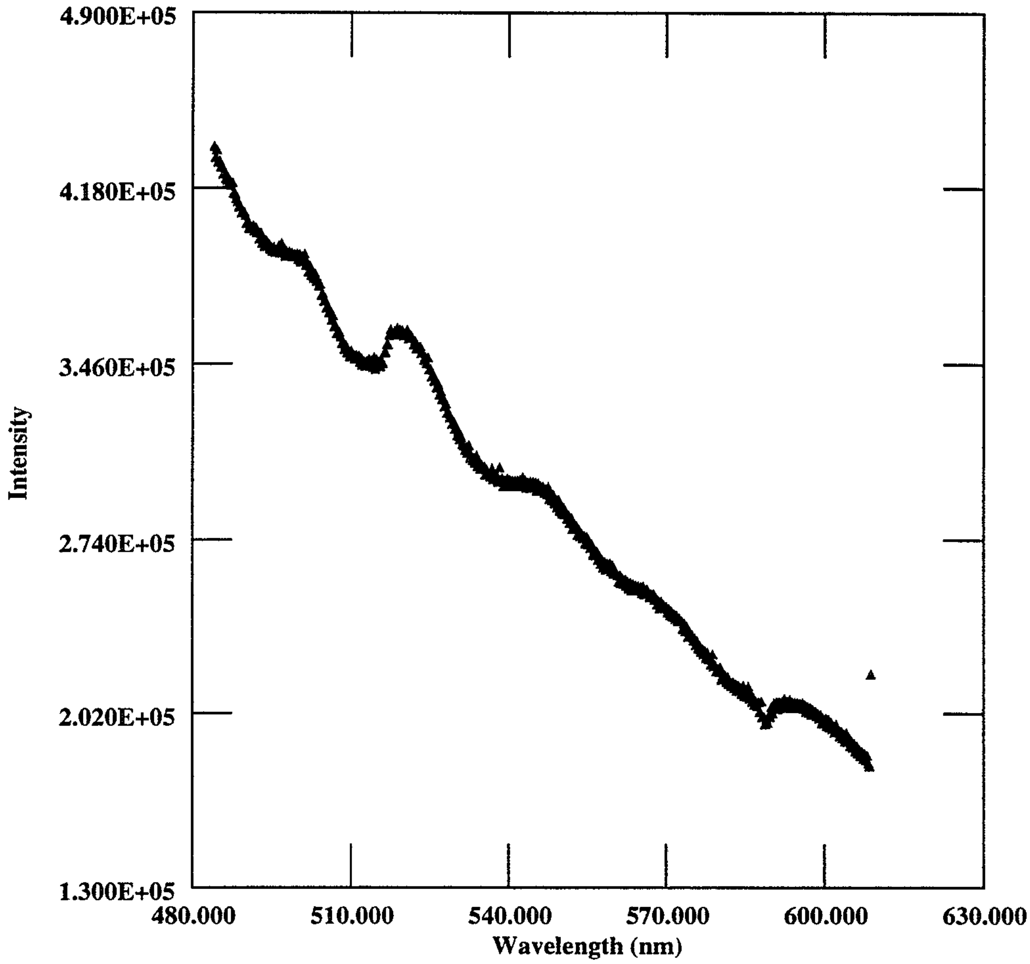

FIGURE 5 – Argon spectrum #1

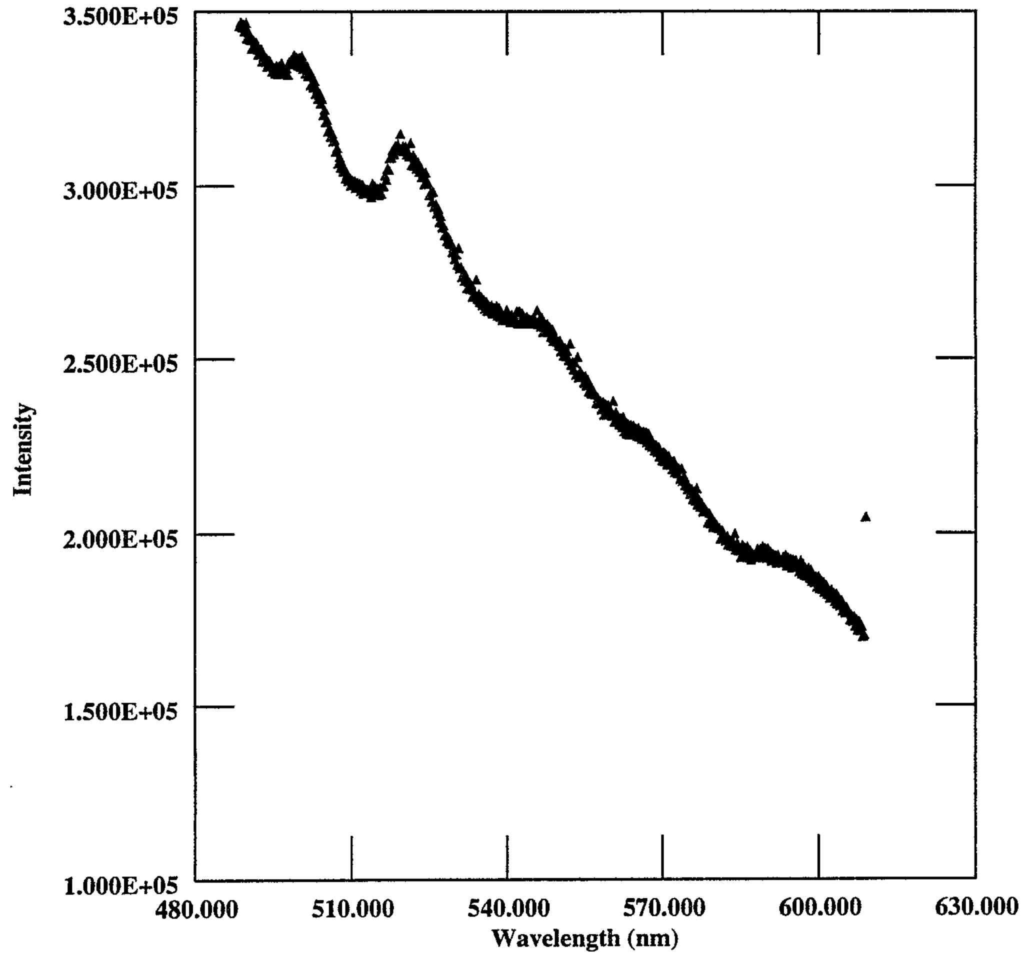

FIGURE 6 – Argon spectrum #2

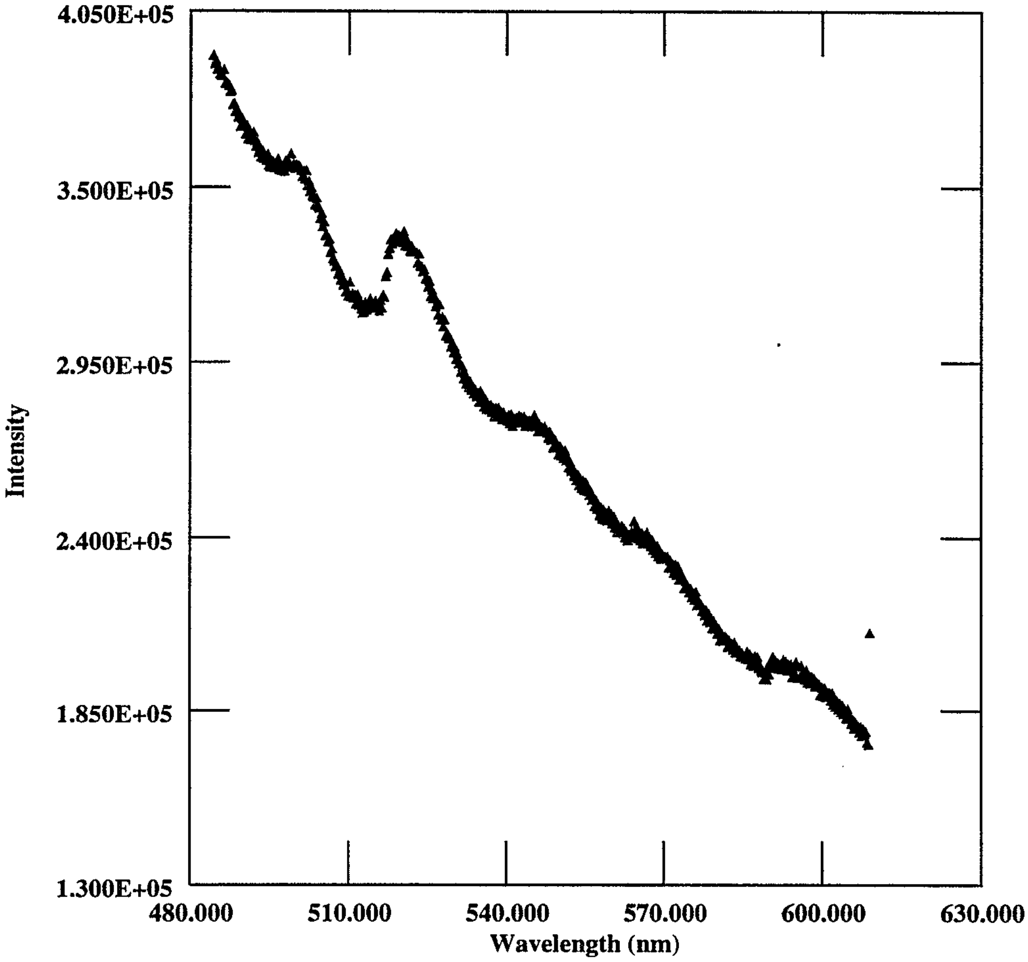

FIGURE 7 – Argon spectrum #3

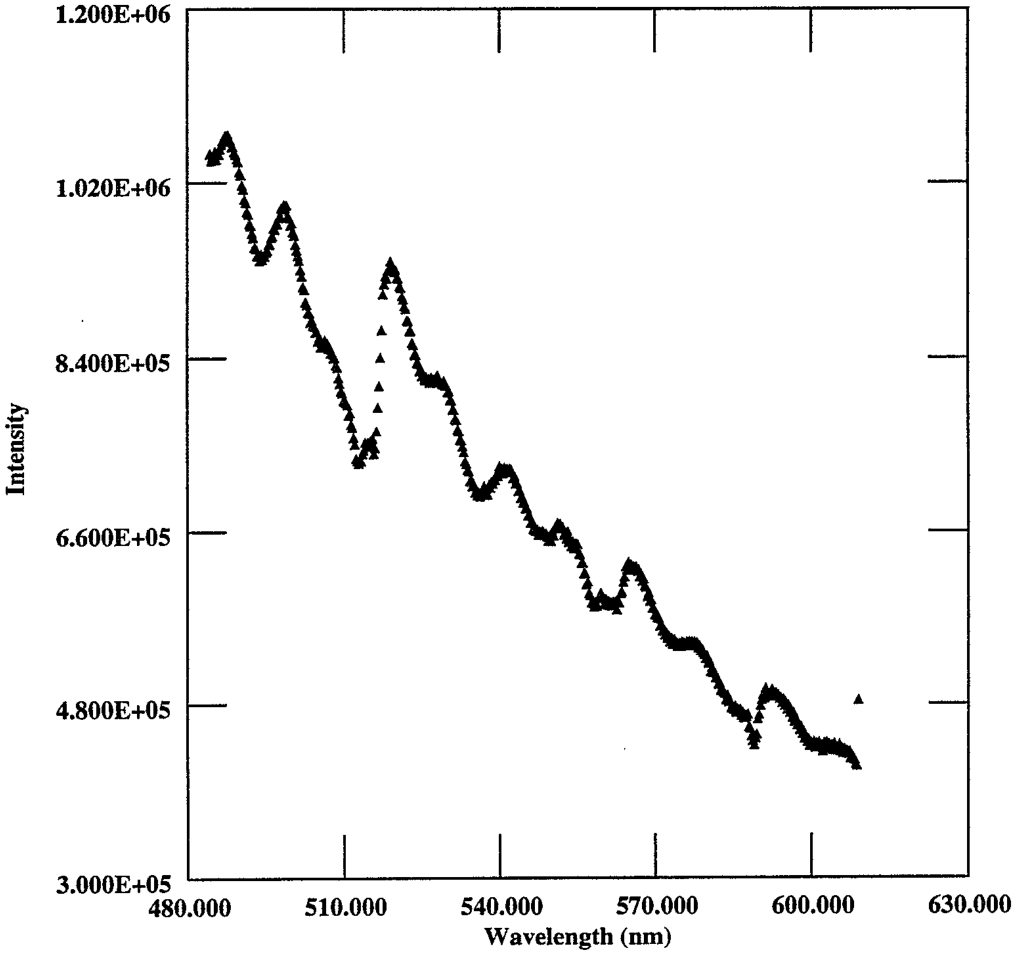

FIGURE 8 – Xenon spectrum #1

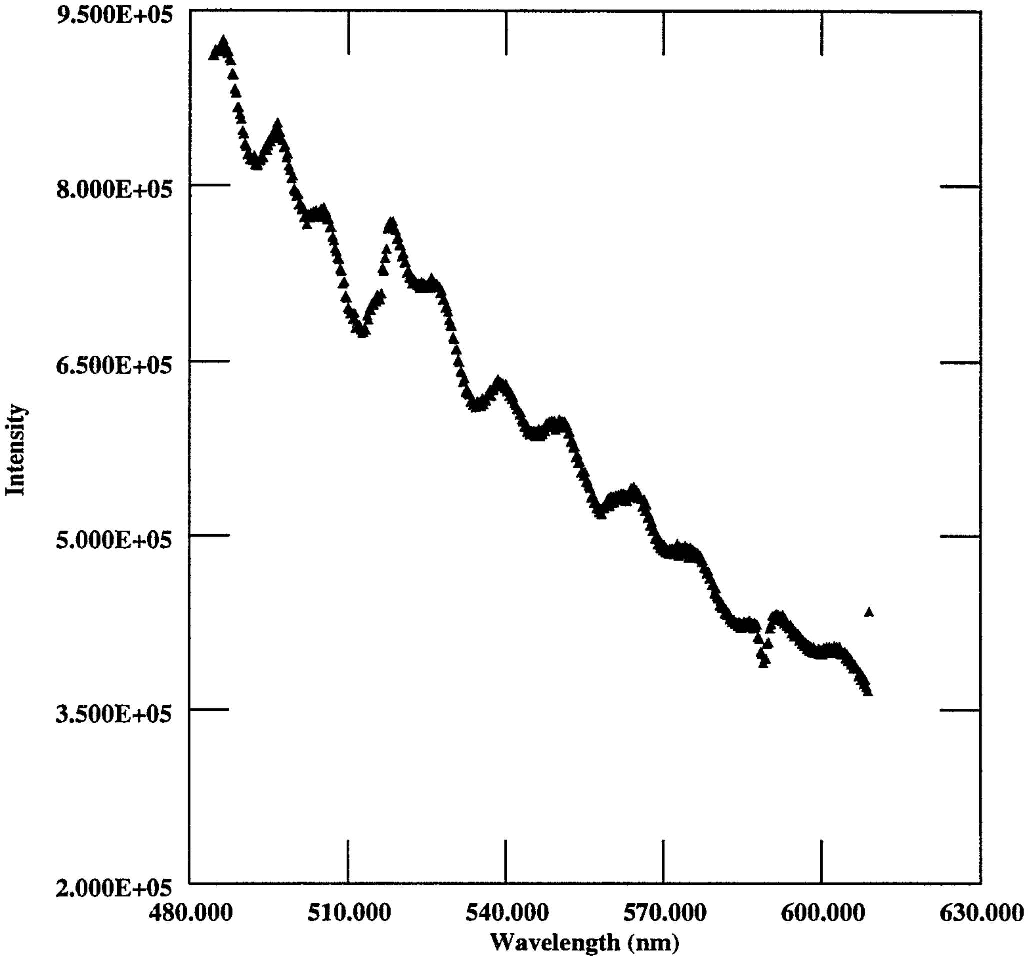

FIGURE 9 – Xenon spectrum #2

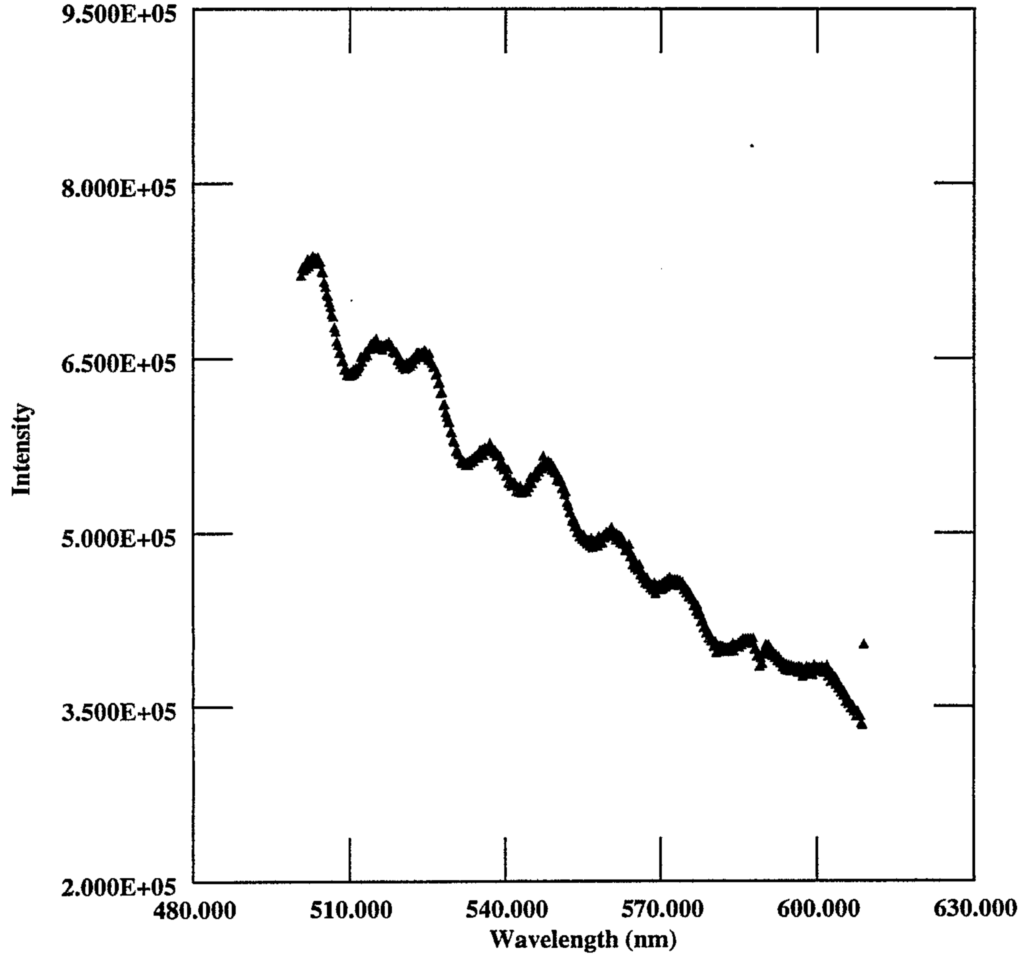

FIGURE 10 – Xenon spectrum #3

superimposed.

A blackbody spectrum is given by the Planck radiation formula (Ref.1)

$$W(\lambda) = \epsilon \frac{c_1}{\lambda^5 (e^{\frac{c_2}{\lambda T}} - 1)}$$

where c_1 and c_2 are constants and W is the power emitted into a hemisphere per unit area per wavelength interval. c_1 is 3.7405 10^4 and c_2 is 1.43879 10^4 for T in Kelvin, wavelength in microns, power in watts and area in cm^2. (The power per unit solid angle per unit area per wavelength interval, called the spectral radiance, is just W/π.) The factor ϵ is called the emissivity and is one for a perfect blackbody. If the spectrum follows the blackbody shape but the intensity is reduced, the spectrum is called a greybody for which ϵ is less than one.

To analyze the spectra, the parameters c_1 and T were optimized using the non-linear least squares fitting technique of Levenberg and Marquardt and the resulting blackbody curve was plotted against the experimental data. Since the intensities were not calibrated absolutely, varying c_1 is allowed. The parameter c_1 scales the theoretical curve up and down while changing T varies the slope (or, more precisely, the shape) of the curve in the region of interest. The fitted curves are shown in Figs. 11-13. The curves seem to indicate that the helium gas had a temperature near 8300 K, the argon 35000 K and the xenon 52000 K.

To identify the spectral lines, the wavelengths of the various peaks were determined and compared to tables of known spectral lines (Ref. 2). The lines which were tentatively identified are labeled in Figs. 11-13. There are features for all the major lines expected but

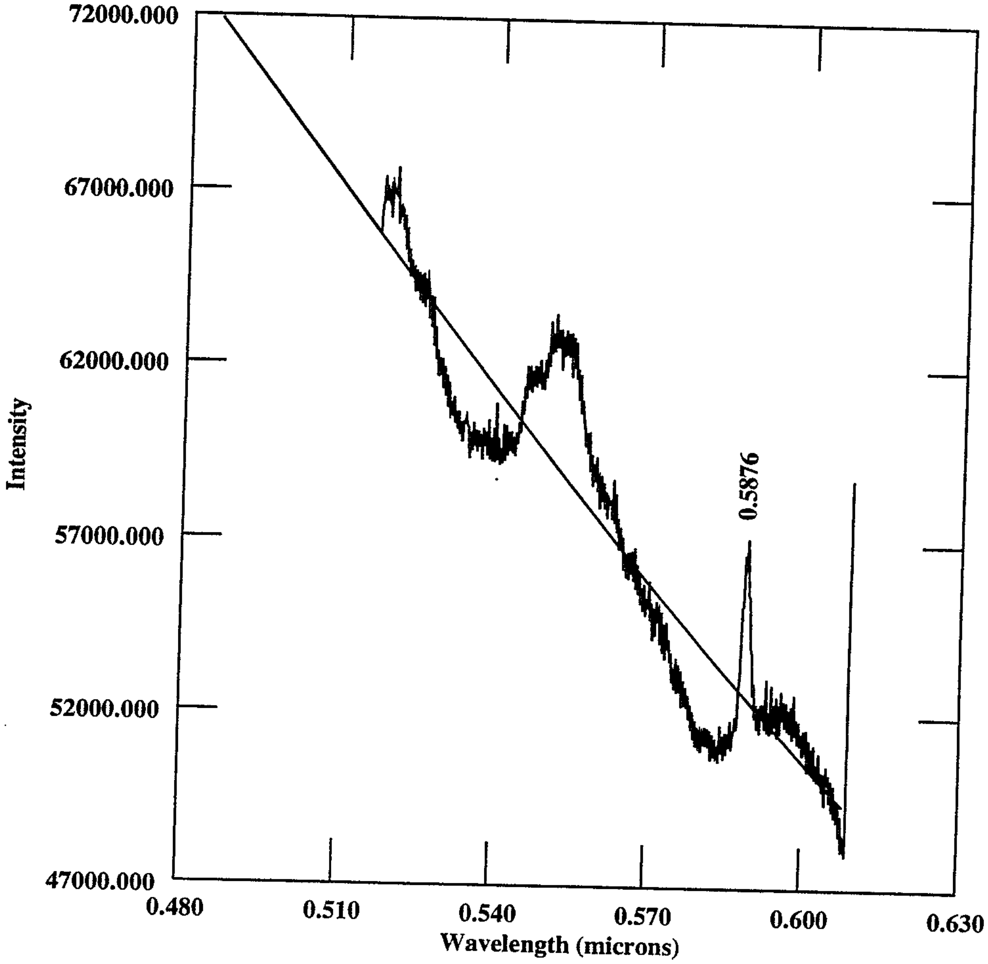

FIGURE 11 – Helium spectrum with a blackbody fit at 8297 K

in most cases, several closely spaced (less than 3 nm apart)lines are smeared together. The peaks are therefore identified by wavelength ranges corresponding to several lines. In the helium spectra, some features are not associable with any helium lines. They may be due to contamination of spectra by light from the explosive, air trapped in the bomb or some other source, but further investigation was beyond the scope of this study.

As mentioned, the spectral "lines" are very broad. To see if this could be due to pressure (collision) broadening, an estimate of the line width due to this effect was made.

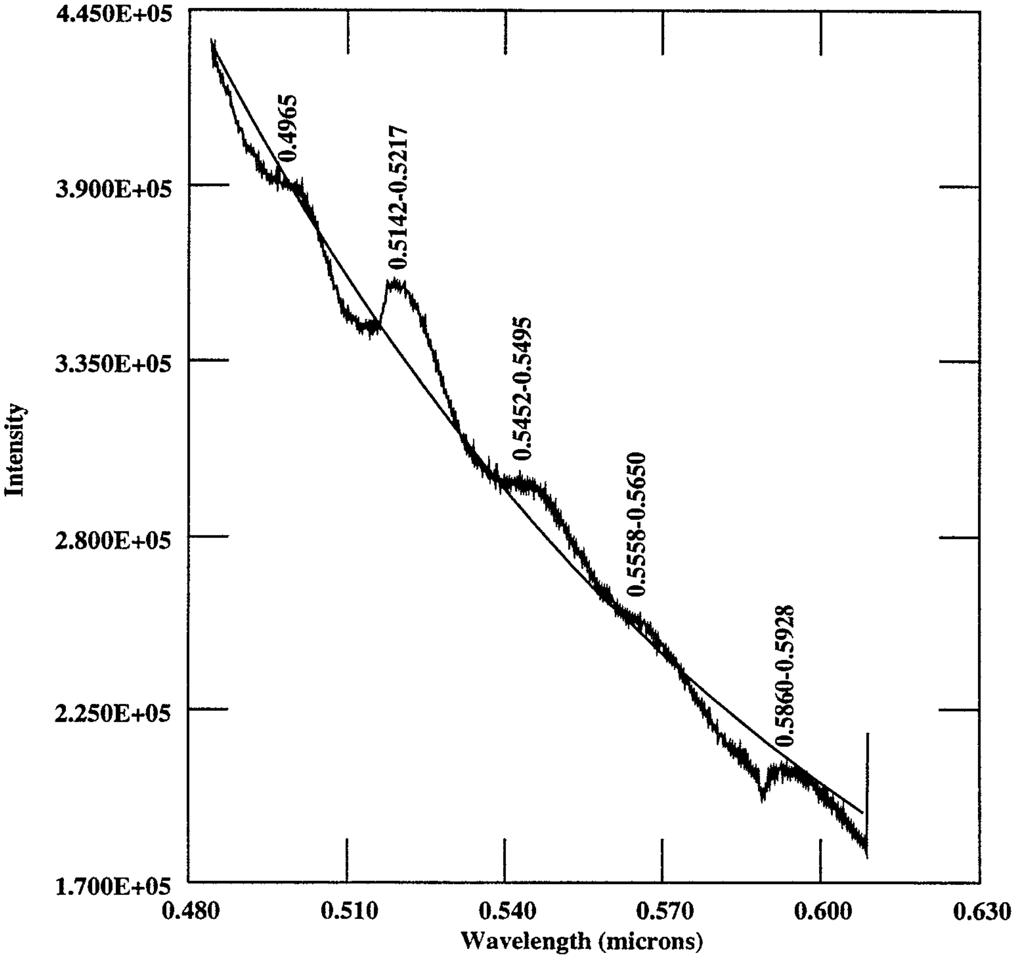

FIGURE 12 – Argon spectrum with a blackbody fit at 35236 K

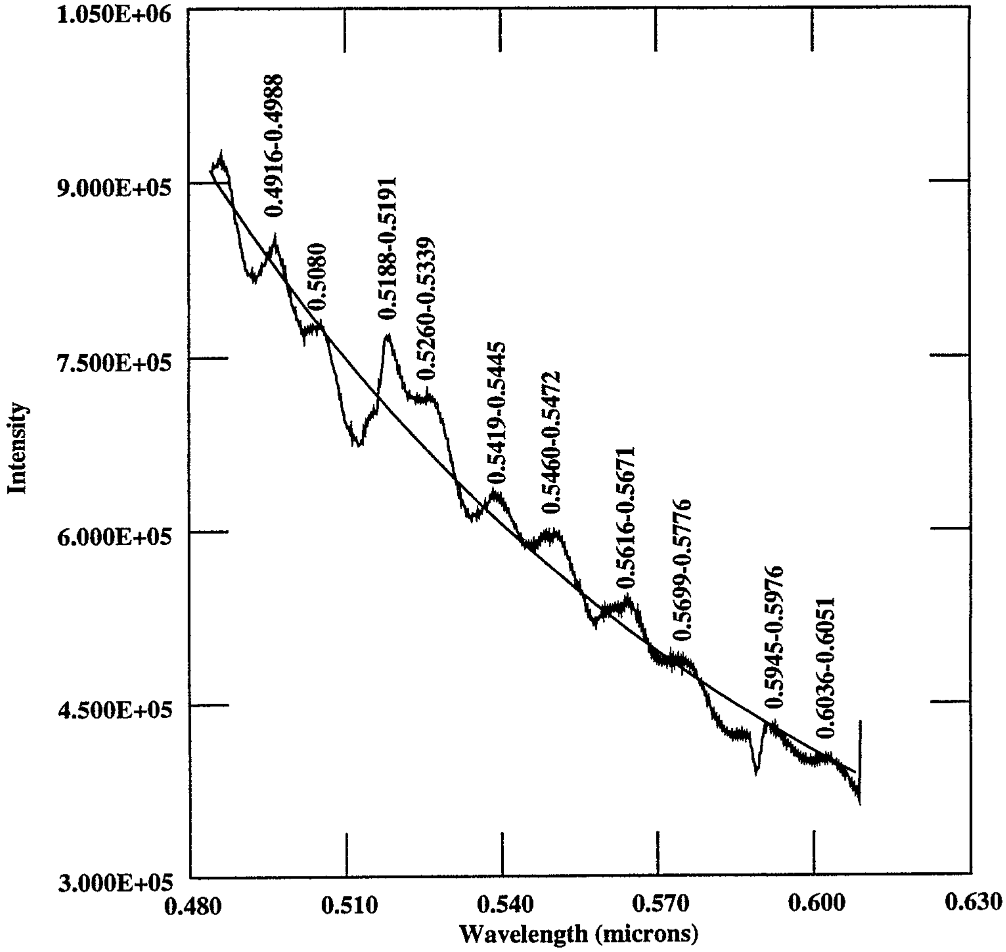

FIGURE 13 – Xenon spectrum with a blackbody fit at 52513 K

This is done using the mean collision frequency derived from elementary kinetic theory, namely, the average particle velocity divided by the mean free path. The formula for all this is

$$\frac{\Delta\lambda_{HWHM}}{\lambda} \approx [\frac{\lambda}{c}][\frac{8kT}{\pi m}]^{1/2}[\sqrt{2}N\pi d^2]$$

where c is the speed of light, k is Boltzmann's constant, m is the mass of an atom, N is the number density of atoms and d is the "diameter" of an atom. For argon gas, at 300 K and 2 atmospheres, N is about 5.4 10^{25} atoms/m^3, m is 40 times 1.66 10^{-27} kg and d is about 3.64 10^{-10} m (Ref. 3). Using a typical λ of 540 nm and a temperature of 40000 K, a linewidth of 0.15 nm results which is less than observed (on the order of 1 nm HWHM). However, since the light is coming from a shock front, the pressure and corresponding density will be higher. For an ideal gas, the maximum density in a shock wave is given by

$$\frac{\rho}{\rho_o} = \frac{\gamma + 1}{\gamma - 1}$$

where γ is 1.67 for a noble gas (Ref. 4, p.52). This yields a maximum density increase of 4 and consequently, a pressure broadening of 0.30 nm. When the effects of ionization for a non-ideal gas are included, the density ratio could be as high as 13, yielding a pressure broadening of 0.54 nm. Thus, pressure broadening could explain a large amount of the observed line widths but not all. Other line broadening mechanisms cannot be ruled out but investigation of these are beyond the scope of the present study.

3.3 Relative Light Intensities

The vast majority of the light output seems to occur as blackbody radiation. If we assume the temperatures fitted in the previous subsection, we can estimate how much the relative intensities at a given wavelength should vary from one gas to the next. At a wavelength of 608 nm, the theoretical ratio of light output at 52000 K to that at 35000 K is 1.7 . Experimentally, the xenon flash is about twice as bright as the argon flash at this wavelength. However, at a wavelength of 608 nm, the theoretical ratio of light output at 35000 K to that at 8300 K is 18.7 . Experimentally, the argon flash is about 3.6 times brighter than the helium flash at this wavelength. There is a certain amount of uncertainty in the temperatures but not enough to explain this difference. The helium would have to have a temperature around 15000 K and this is just not possible. Further investigation of this is not worthwhile as any practical device will not use helium as a fill gas.

3.4 Implications for Non-lethal Weapons Applications

Although this work is highly preliminary, some comments on the use of explosive flash grenades based upon the shock heating of noble gases can be made. The light output of a device can be estimated and compared with the light needed to temporarily dazzle an eye via flash blindness. To do so, the theoretical luminance (visual brightness), B, for a blackbody must be calculated using

$$B = \frac{683}{\pi} \int V(\lambda) W(\lambda) d\lambda$$

(Ref. 1, p. 198) where $V(\lambda)$ is the photopic response of the eye to different wavelengths (Ref. 1, p. 110) and $W(\lambda)$ is the blackbody radiation curve given earlier. The units of B are lumens per steradian per square centimeter. For a temperature of 52000 K, a luminance of 2.2 10^7 L sr^{-1} cm^{-2} is found, at 35000 K, 1.3 10^7 L sr^{-1} cm^{-2} and at 8300 K, 6.4 10^5 L sr^{-1} cm^{-2}. For determination of the effects on the eye, the flash energy received by the eye in units of troland-seconds must be calculated. (A troland is a unit of retinal illuminance which is equivalent to one lumen per steradian per square meter for a pupil area of one square millimeter.) Under the assumptions of an eye pupil diameter of 5 mm, and a flash duration of 30 μs, flash energies of 1.3 10^8 td-s at 52000 K, 7.6 10^7 td-s at 35000 K and 3.7 10^6 td-s at 8300 K are found. According to Miller (Ref. 5), after an exposure of 3 10^7 td-s, the eye requires about 110 seconds to recover. For an exposure of 2.2 10^6 td-s, a time of 28 s is needed. Thus it seems that these noble gas flash bombs do generate sufficient light to cause flash blindness for many seconds.

The light output of a flash grenade can also be compared to the light levels needed to cause permanent damage to the eyes. It is however difficult to find exact values for the damage threshold due to a broadband light source. According to Sliney et al. (Ref. 6), for a light source which has a retinal image size of 100 μm diameter, an exposure of around 100 W/cm^2 for 10 s will cause permanent retinal burns in a rabbit. Since 1 W/cm^2 corresponds to very roughly 10^9 trolands, this exposure is 10^{12} td-s. Because this is four orders of magnitude larger than the estimated exposure possible, a flash grenade should not cause permanent eye damage. This conclusion will have to be confirmed experimentally given the seriousness of the possible permanent eye damage.

Since xenon gives the best results, this is the gas which should be used in such a grenade. Although it is expensive, the cost of the quantity needed in a grenade would be only a small fraction of the overall cost. The amount of explosive needed to achieve the desired result could also be reduced, thereby reducing the risks of injuries due to the explosion and fragments inevitably produced. Obviously, more work will be needed before a practical device is available.

4.0 CONCLUSIONS

The light output from noble gas filled explosive flash bombs has been characterized. Consistent results for the observed spectra can be obtained by postulating that the gases radiate like blackbodies at a temperature which is gas dependent. Temperatures of 8300 K for helium, 35000 K for argon and 52000 K for xenon can be used. Overall, xenon gives the brightest light output but is also the most expensive to use. The light intensities generated by these flash bombs seem to be of the correct order of magnitude to cause flash blindness for many seconds. Intriguing puzzles about the helium spectra (unidentifiable lines and unexplainable low light intensity relative to argon and xenon) and the width of the spectral lines were raised but it was beyond the scope of the present work to solve these puzzles.

5.0 ACKNOWLEDGMENTS

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6.0 REFERENCES

1. Smith, Warren J., "Modern Optical Engineering", McGraw-Hill, New York, 1966
2. Weast, Robert C., Astle, Melvin J. (Eds.), "CRC Handbook of Chemistry and Physics" (62nd Edition), CRC Press, Boca Raton, Florida, 1981
3. Tipler, Paul A., "Foundations of Modern Physics" , Worth Publishers, New York, 1969
4. Zeldovich, Ya. B., Raizer, Yu. P., "Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena", Academic Press, New York, 1966
5. Miller, Norma D., J. Opt. Soc. Am. 55, 1661-1669 (December 1965)
6. Sliney, David, Wolbarsht, Myron, "Safety with Lasers and Other Optical Sources", Plenum Press, New York, 1980, pp.134-135

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