PRELIMINARY TEMPERATURE MEASUREMENTS BEHIND STRONG SHOCK WAVES IN ARGON

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SUMMARY

The need for temperature measurement in strong shock waves is discussed briefly and requirements for a suitable experimental method are established. Spectrometric methods are shown to be appropriate and the radiative line intensity technique is discussed. Experiments using photography for both time-integrated and time-resolved exploration of the argon emission spectrum in a $M_s = 11.3$, $p_1 = 3$ torr shock are described. The results were used in the main series of experiments, which gave time-resolved records from photo-multipliers monitoring the intensities of selected neutral argon lines. These records are analyzed, including self-absorption correction, to a time-resolved excitation temperature profile for the neutral argon atoms. The probable uncertainty in these measurements is computed and the shape of the temperature profile is discussed. The conclusions are that the atom excitation temperature rises to an approximately constant value of about 11,500$^\circ$K behind the shock front, which is in fair agreement with the calculated equilibrium value of 11,300$^\circ$K, but that uncertainties were too great to allow, for example, cooling calculations based on the shape of the temperature profile. Experimental improvements are suggested to reduce uncertainties and allow detailed analyses in future work.
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1. INTRODUCTION

The purpose of this work is to undertake a preliminary experimental investigation of the temperature distribution behind an ionising shock wave propagating in argon in the UTIAS 4 in. x 7 in. shock tube. Establishing a method for this measurement will lead to the detailed study of the several zones in such shock waves, i.e., the precursor regime in front of the shock wave; the relaxation region immediately behind the shock front; the equilibrium zone, and finally, the region where radiative cooling is important.

Interest in such studies arises on three counts: a) the need for better fundamental understanding of the particle interactions and energy-sharing mechanisms for extremely rapid energy transfer rates, for which the shock wave is an excellent laboratory model; b) a more practical necessity for knowledge about the energy dissipation and transfer properties of strong shock waves with a view to the design of satellites and space-vehicles for entry or re-entry to planetary atmospheres; c) the immediate need to understand better the behaviour and properties of the shock waves generated in the UTIAS 4 in. x 7 in. facility.

From initiation, this project was undertaken as a short term study to establish a method, which precluded detailed investigation of any one of the topics outlined above. Establishment of a method was necessary as it was already clear that different investigators in this field have reported dissimilar results, let alone any differences in conclusions. For example (figure 1) Coates and Gaydon (Ref. 1) obtained time-resolved radiation records, from a shock wave of $M_\infty = 11.3$ into argon at 3 torr, which peaked very rapidly just behind the shock and then decayed slowly until arrival of the contact surface, when the signal fell to zero. But Harwell and Taylor (Ref. 2), studying radiation from shocks of $M_\infty = 8.4$ into argon at 2 torr, found an initial small peak followed by a strong rise to a second peak, of five times the first signal, at the contact surface. While some understanding of such contradictions may be gained from close study of the literature, the variety of experimental conditions and complexity of equipment details prevent the emergence of a clear picture.

In the absence, therefore, of any accepted system which could be immediately applied to work at UTIAS it was necessary to perform preliminary experimental studies in situ. Although a considerable body of work has already been completed (Refs. 3, 4, 5, and 7) using the UTIAS 4 in. x 7 in. facility no study has been directly concerned with the measurement of temperature as a sensitive parameter of the atomic or molecular energy states. This report deals with the first step towards a quantitative study of the temperature distribution behind strong shock waves in the UTIAS 4 in. x 7 in. facility.
2. METHOD

Devices and techniques for temperature measurement are undoubtedly more numerous than for any other physical measurement. However, the severity of requirements for shock wave studies eliminate all but a very few of these methods. The basic requirements are:

a) measurements in the range 8,000° to 20,000°K, say;

b) non-interference with shock propagation;

c) good temporal resolution - say 1 µs;

d) good spatial resolution - say 1 cm.

Surveys of possible methods have been made by Glass and Hall (Ref. 8), Ladenburg et al (Ref. 9), Gaydon and Hurle (Ref. 10) and many other workers. Another such review will not be attempted here. With the possible exception of electron-beam absorption probing (finally discounted owing to the desire not to seed the shock with electrons) optical techniques alone seem useful. Even then optical density (refractive index) methods were discarded owing to their insensitivity at high temperatures. The conclusion was that radiative methods were most appropriate and that emission spectroscopy promised greatest convenience if the available emitted intensity were adequate.

The advantages of emission spectroscopic techniques for temperature measurement are many: in view of the aims of the present work the greatest strength of the method is the exact correspondence of the emitted radiation with the energy states of the radiating species and there is no question of uncertainty about dependent properties (as, for example, refractive index methods perhaps may be queried as to the invariance of the Gladstone-Dale constants at very high temperatures). The first two requirements listed above for measurement in shock waves are plainly satisfied while fulfillment of the last two conditions is purely at the option of the experimenter in selecting and arranging his apparatus (though it is necessary to restrict the radiations studied to those with brief radiative life-times, i.e. the infra-red region must be used with circumspection as life-times of excited states before emission can be of the order of 1 to 100ms (Ref. 11).

Both continuum and line radiations are emitted from shock waves. The continuum emission is due to free-bound electron transitions (as in ionisation re-combination) and to free-free electron transitions (bremsstrahlung, considered negligible in the present work (Ref. 1)). The line radiations are due to bound-bound electron transitions in the various species present. The intensity of emission from any of these causes is always a function of temperature so that, in theory, any of these radiations can be used to measure temperature. A useful account of possible methods is given by Griem (Ref. 12). Selection of the most suitable approach will depend upon the experimental environment (for example, it is futile to attempt measurements based on radiation from a doubly-ionised species if the plasma temperature is too low to give an adequate population of such a species) and also, to be practical, on the availability of basic data which is necessary to interpret the results (for example, the transition probability for a line radiation).
Preliminary tests of the useful emission showed that the shock studied \( (M_s = 13.3 \text{ into argon at } 3 \text{ torr}) \) gave a good set of excited neutral atom lines with some background continuum. No lines from argon ions were found, except for a faint trace of AlII at 5772 Å and 6644 Å. From this information it is clear that the method to be adopted must rely on line emission from excited neutral atoms of argon or the ionisation re-combination continuum. (Use of radiation from added impurities was ruled out firstly on the ground on non-interference with the shock and secondly in that measurements would no longer derive directly from the energy states of the argon species.) To decide which approach is preferable the temperature sensitivity of the continuum and line emissions may be compared. For the visible wavelength region above 4000 Å, to which this work was anyway restricted by apparatus limitations, the emission coefficient \( \epsilon_\nu \) for the re-combination continuum at frequency \( \nu \), from McChesney (Ref. 16), may be expressed as:

\[
\epsilon_\nu = \xi(\nu) \frac{32\pi^2 e^6 N_i N_e}{3\sqrt{3} c^6 (2\pi m_e)^{3/2}} \frac{1}{\sqrt{kT}}
\]

where \( \xi(\nu) \) is the Biberman-Norman factor allowing for the field due to surrounding ions and which here can be taken as a constant of about 1.2; \( e \) is the electronic charge in e.s.u.; \( N_i \) and \( N_e \) are the total ion and electron number densities respectively; \( c \) is the velocity of light; \( m_e \) is the electron rest mass; \( k \) is Boltzmann's constant and \( T \) here is the "electron temperature". It is clear, therefore, that the continuum emission is inversely proportional to the square root of temperature and hence not a very temperature-sensitive parameter.

On the other hand, the intensity of the spectral line emitted as an electron falls from energy level \( E_n \) to level \( E_m \) can be stated, e.g. Gaydon, (Ref. 1), as:

\[
I_{nm} = \frac{h\nu}{4\pi} g_n A_{nm} \frac{N_0}{\phi_0} \exp\left(\frac{-E_n}{kT}\right)
\]

where \( h \) is Planck's constant; \( \nu \) the line frequency; \( g_n \) the statistical weight of the upper energy level; \( A_{nm} \) is the probability for the particular transition; \( N_0 \) and \( \phi_0 \) are, respectively, the number density and partition function for the emitting species; \( E_n \) is the energy of the upper level; \( k \) is again Boltzmann's constant and \( T \) is the "excitation temperature" of the emitting species. In contrast with the result for the continuum, here we see that the intensity of the line emission is proportional to the exponential of temperature and is therefore a highly temperature-sensitive parameter.

The conclusion here is that line emission from excited neutral atoms offers the most sensitive - and hence potentially most accurate - parameter for temperature measurement. This method has been adopted for the present work (further formulation of the theory will be given below) and it is seen that the parameter which will be the outcome of the experimental measurements will be the excitation temperature.

It is convenient at this point to interject a brief comment on the significance of "temperature" in the environment of the phenomenon studied in the present work, i.e. the shock wave. Now that a specific experimental method has been selected the discussion of this aspect can take a concrete form and centre around the parameters which concern the present work. The main
point presented here is that whatever means are used to measure the parameter "temperature" the result will directly reflect the method of measurement, even if the method is of the non-interfering description.

Without a complete review of accepted principles of the concept of temperature, it may be stated that considering any one degree of freedom for an assembly of particles, say, there will be some constituents with one (elemental) range of energy and other constituents with other energy values: i.e. there will be a distribution of energies among the component particles within a particular degree of freedom. The form of the energy distribution curve will be a function of the particular mechanisms for energy transfer and also will depend on whether steady-state or transient conditions apply. For equilibrium (this condition is quite specific, e.g. Clarke and McChesney (Ref.14)) the energy distribution has a particular form precisely described by the Boltzmann equation: i.e. the number of particles \( n_E \) with an energy \( E \) divided by \( n \) the total number of particles is related to the energy \( E \) by:

\[
\frac{n_E}{n} = \frac{g_E \exp(-E/kT)}{Z}
\]

where \( g_E \) is the degeneracy (or statistical weight) of the energy level \( E \); \( Z \) is the partition function (sum over all energy states, \( Z = \sum g_i \exp(-E_i/kT) \)) and \( k \) is Boltzmann's constant. \( T \) is a parameter which can be kept constant while the entire distribution curve is drawn. If \( T \) is then given a new value, the corresponding distribution will be found to differ from the first. So a family of curves may be drawn, each curve characterised by one value of the parameter \( T \). Also, the higher the value of \( T \) the greater will be the total energy summed over all states, while if \( T \) falls the particular degree of freedom contains less energy. The parameter \( T \) is, of course, commonly called the temperature but even in this brief account it is plain that the term temperature applies only to one degree of freedom and only if the energy distribution follows the Boltzmann form. If we now consider a system where there are \( n \) degrees of freedom each separately in equilibrium and each obeying a Boltzmann distribution law then, in general, there will be \( n \) different temperatures. However, if these different degrees of freedom are allowed to interact and exchange energies until, at overall equilibrium, the energy contained in each degree of freedom is the same (equi-partition of energy) then the \( n \) temperatures characterising the \( n \) degrees of freedom will all be equal. Only under these circumstances can the energy of the entire system be characterised by the single value of \( T \), which is then the true temperature for the system.

Generally, methods of temperature measurement rely on sampling the energy in one or more energy modes. For example, a thermocouple samples principally translational energy, but may need correction for chemical energy (catalytic) perturbations; refractive index methods also rely on the translational mode but other optical methods may rely on very different bases. As seen above, continuum monitoring in the shock wave studied here yields the electron temperature, i.e. the parameter \( T \) which will allow the Boltzmann law to describe the free electron energy distribution, while neutral atom lines gives the excitation temperature, another such parameter which describes the energy distribution in the excited atom states. Hence, even for non-interfering methods the temperature derived will reflect the method of measurement.

Expansion of this account to consider the relation between different modal temperature in the present work will be reserved for discussion
following presentation of the experimental results. For now, having defined the
terms used and shown the nature of the temperature yielded by the methods here
adopted, we may return to conclude this section by a brief outline of the manner
in which the excitation temperature is derived from intensity measurements of
the line emission from the shock wave.

In the absence of self-absorption the intensity of line emission
is given by:

\[
I_{nm} = \frac{h \nu}{4\pi} g_n A_{nm} \frac{N_O}{\phi_0} \exp \left( \frac{-E_n}{kT} \right)
\]  

(2)

using the same terminology as before. This intensity is measured experimentally
by a photo-multiplier monitoring the luminous intensity at the exit slit of a
monochromator or spectrometer which serves to isolate a small wavelength range
d\lambda at wavelength \lambda. The output of the photo-multiplier, however, is a function
not only of the shock emission at \lambda (considering line emission only, the
continuum background is separately corrected for) but also of the photo-multiplier
sensitivity at this wavelength and also of the losses in the spectrometer and
associated optical train, all of which may be a function of wavelength. The
output current of the photo-multiplier, \text{A}_{\lambda}, at wavelength \lambda as a function of
the input luminous intensity \text{I}_{\lambda} can be represented as:

\[
A_{\lambda} = s_{\lambda} K_{\lambda} M_{s\lambda} \theta K_{w\lambda} I_{\lambda}
\]

(4)

where \text{s}_{\lambda} is the photo-multiplier sensitivity at wavelength \lambda; \text{K}_{\lambda} is the trans-
mittance of the spectrometer and optical train; \text{M}_{s\lambda} is the reflectance of the
mirror used to direct light from the shock tube into the spectrometer; \text{K}_{w\lambda} is
the transmission of the shock tube window, all at wavelength \lambda, while \theta is the
geometrical factor, i.e. the solid angle of the window into the shock tube seen
from the spectrometer slit.

A calibration procedure is necessary at each wavelength studied
to eliminate the unknown factors. Details of this procedure are described in
the Appendix, but here we may say that the photo-multiplier current \text{A}'_{\lambda}
for standarisation at wavelength \lambda due to light from a standard lamp of intensity
\text{I}'_{\lambda} incident on the spectrometer is given by:

\[
A'_{\lambda} = s_{\lambda} K_{\lambda} M_{L\lambda} \theta' K_{L\lambda} I'_{\lambda}
\]

(5)

The factors \text{s}_{\lambda} and \text{K}_{\lambda} are as before, while \text{M}_{L\lambda} is the reflectance of the mirror
used to direct light from the standard lamp into the spectrometer (this is, in
fact, equal to \text{M}_{s\lambda} as the two mirrors used were a matched pair), \theta' the geo-
metrical factor for the lamp and \text{K}_{L\lambda} is the transmission of the lens used to
image the lamp filament onto the spectrometer slit. From these two relations-
ships we obtain, as \text{M}_{s\lambda} = \text{M}_{L\lambda}:

\[
I_{\lambda} = \frac{\theta' K_{L\lambda} A_{\lambda}}{\theta K_{w\lambda} A'_{\lambda}} \cdot I'_{\lambda}
\]

(6)

The colour temperature of the standard lamp is known as a function of the heat-
ing current in the filament, which can be measured accurately (see Appendix).
Hence \text{I}'_{\lambda} is calculated while \text{A}'_{\lambda} and \text{A}_{\lambda} are measured at any one wavelength.
From this point exact evaluation of \theta, \theta', \text{K}_{L\lambda} and \text{K}_{w\lambda} will give the absolute
line intensity $I_{\lambda}$, but then equally exact knowledge of number density and partition function would be necessary to obtain the temperature. To minimise errors this work used a relative intensity technique and compared the intensity of lines at different wavelengths. The only requirement for this method is that $\theta'/\theta$ and $K_{\lambda}/K_{\lambda'}$ are not significant functions of wavelength in the range of interest. This is plainly true for the ratio of geometric factors and is also adequately approximated for the ratio of lens to window transmission. Writing the product of the two ratios as $B$, say, we obtain:

$$I_{\lambda} = B \frac{A_{\lambda}}{A_{\lambda'}} I'_{\lambda}$$

(7)

Hence, putting $\nu = \frac{C}{\lambda}$ in equation (2):

$$\frac{A_{\lambda} \cdot I'_{\lambda} \cdot \lambda}{A_{\lambda'} \cdot g_n \cdot A_{nm}} = \frac{h c N_0}{4 \pi B \phi_o} \exp \left( - \frac{E_n}{kT} \right)$$

(8)

As all lines used arise from excited neutral states of argon only, both $N_0$ and $\phi_o$ are the same for all line intensities measured. This equation can therefore be stated in the form:

$$\ln \frac{A_{\lambda} \cdot I'_{\lambda} \cdot \lambda}{A_{\lambda'} \cdot g_n \cdot A_{nm}} = \frac{-E_n}{kT} + \text{constant}$$

(9)

Quantities $A_{\lambda}$, $A_{\lambda'}$, $I_{\lambda}$ are measured or calculated. Having identified the spectrum, the wavelength $\lambda$ is known while appropriate values for $E_n$ and the statistical weights and the transition probabilities can be found in the literature. For each line monitored, therefore, a point is obtained in a graph of the left-hand-side of equation (9) against $E_n$. The slope of the straight-line graph is measured and so $T$ obtained from placing:

$$\text{slope} = \frac{1}{kT}$$

(10)

3. **EXPERIMENT**

The Hypersonic Shock Tube. The stainless-steel shock tube used in this work has been fully described by Boyer (Ref. 3). For convenience a brief summary is given here. The internal cross-section of the channel (driven section) is 7 in. high and 4 in. wide. The driver section is 14 ft. long, when used to generate strong shocks, and the driven section 48 ft. long, though the test station for the present work was only 24 ft. from the diaphragm. To produce a shock wave into argon at 3 torr with $M_s = 13.3$ at the test station, a combustion driver was used consisting of 16.6% hydrogen; 8.3% oxygen; 11.2% argon and 63.8% helium by volume at a total cold pressure of 180 psia. Use of a mixture of inert gases as diluent was found necessary to give the required shock conditions. The driven section was prepared by pumping down to $5 \times 10^{-3}$ torr and then admitting argon to 3 torr. External impurities were therefore 0.17%. Mass spectrometric analyses of the argon for $14 < M/e < 44$ showed no detectable impurities with the exception of a possible trace of water to less than 0.1%. The driver was fired by the discharge of a condenser through a tungsten wire. The diaphragm was of stainless-steel, 1/16" thick and pre-scribed to give a bursting pressure of 1475 psia.
Shock speed was measured by pressure transducers, mounted flush with the inner surface of the driven section, triggering digital chronographs. Three or four such detectors were used for each run, giving two or three transit times in the region of the test station as a constant guard against equipment malfunction. In addition, this distribution of detectors allowed a check of the shock attenuation: the shock speed was found to vary by ±1.5% over the 8 ft. length in which the test station was centrally located. The reproducibility of shock speed from run to run was ± 0.75% and the error in speed measurement was ± 0.2%.

Spectrometric Studies. The window into the shock tube, used for all spectrometric work, was a 1/8 in. by 1/4 in. slit set across the tube axis in the top wall and covered internally by a 1/4 in. thick fused quartz window set flush with inner surface of the tube (figure 2). Light passing through the window came from the depth of the tube, i.e. the emission was derived from a plasma 7 in. thick. Above the window a surface-silvered mirror directed the light into the spectrometer slit, which was 35 cm from the window along a ray path. This means that the spectrometer "saw" a length of 0.4 cm at the tube axis, giving, at $M_S = 13.3$ where the shock speed is 0.43 cm/µs, a time resolution of about 1 µs. The spectrometer was a 1.5 m Jarrell-Ash instrument (model 78-090) using a reflection grating in a Wadsworth mounting. The reciprocal dispersion in the first order (used for the red lines) was 10.91 Å/mm and in the second order (used for the blue lines) 5.46 Å/mm. The two orders were segregated partly by the use of filters and partly by the cut-off in sensitivity for both photographic and photo-multiplier detection.

a) Time-Integrated Photographic Spectrum Mapping. The initial experiments were to determine the nature of the argon emission in the shock wave studied. Most convenient mapping of a whole spectrum is by photographic recording. In the present case the exposure is controlled by the very rapid passage of the shock wave, hence the exposure is very short and the amount of light falling on the film is very small. This posed severe sensitivity requirements for the emulsion. Fortunately Kodak Recording Film 2475, a recently perfected film of very high speed even under reciprocity-failure conditions, proved adequate to the task, though a very wide entrance slit (300 µm) was necessary to give a good record with only one run. The spectrometer was calibrated, initially, with 20 lines of the helium spectrum and then with a full argon spectrum obtained from a Geissler tube. This allowed the small deviation from dispersion linearity to be found (roughly sinusoidal in shape, the correction varied from +7Å to -7Å over the range 9000Å to 4000Å in the first order) and so the identity of the shock spectrum could be found by measurement and comparison of the film under a travelling microscope. Some 29 Al and one AII multiplet lines were identified. In addition 46 Al and one AII lines were recognised but not identified as multiplet constituents. A number of other lines were found, including strong Hα and Hβ, but most of these wavelengths were not identified at all (see section "Results" below).

b) Time-Resolved Photographic Method. To get some idea of the spectrum emitted as a function of time, an attempt was made to produce a time-resolved spectrum on film. The method evolved was very simple and cheap, but the shock speed of 4 mm/µs made severe demands on film sensitivity and only partial success was obtained. The arrangement (figure 3) consisted of a radially slotted slit, driven by a small electric motor, set in front of the spectrometer slit. For a given motor speed of $R$ rpm the speed of vertical traverse of the intersection of a disk slot with the spectrometer slit is approximately $\pi r R/30 \sin \alpha$ mm/s where $r$ is the length and $\alpha$ the angle to the vertical of the line joining
the disk axis to the centre of the spectrometer slit. Although this speed, apparently, could be increased infinitely by reducing the angle $\alpha$ in fact the finite width of the disk slots soon sets a limit, after which the entire spectrometer slit is given an approximately simultaneous exposure as the slot passes. The minimum speed of the vertical traverse is plainly the position where $\alpha = \pi/2$, i.e., the disk axis is level with the centre of the spectrometer slit. First trials soon showed the futility of attempting the highest traverse speeds as the photographic exposure proved barely sufficient to give a record with the arrangement such that $\alpha = \pi/2$. In the final set up the disk, of radius 55 mm, rotated at 3,000 rpm with $\alpha = \pi/2$. There were 20 equally spaced slots, each about 0.5 mm wide, so that as one slot rose above the top of the spectrometer slit the next slot began its vertical traverse from the bottom. In the focal plane of the spectrometer, therefore, the entire spectrum would appear as a 0.5 mm high band right across the exit plane and sweep downwards, due to image reversal. As the spectrum vanished at the base of the exit plane so another such spectrum would appear at the top and repeat the action. In this fashion the complete width of the spectrum is swept repeatedly and no synchronization of shutter and shock is required. To avoid multiple exposures the "time-base" of the system i.e. the time taken for one complete sweep, must be longer than the duration of the luminous phenomenon. In the manner used here, the time-base was about 1 ms for the 15 mm high spectrometer slit. It was intended to reduce this considerably after the first trials but the problem of sufficient photographic exposure prevented any such increase in speed. The rotation rate of the disk was monitored simultaneously with the passage of the shock wave and at the same time the position of the disk slot over the spectrometer slit was identified in relation to the position of the shock wave. This was done by positioning a small battery-powered flashlight bulb to shine onto a photo-diode through the disk slots (figure 4). Display of the diode output on an oscilloscope screen together with the output of shock detectors (figure 5) in the shock tube allowed relative positions to be found following an initial "calibration" adjustment of the bulb/diode assembly so that a $\pm$ slot signal appeared as another slot began to traverse the spectrometer slit. Further development of this method was abandoned owing to the limitations set by film speed. However, the method did establish the approximate duration of emission and showed that all wavelengths radiated at the same time. It will be seen that this method is potentially superior to that of Bartky and Bass (Ref. 15) where only a single time sample is obtained and which cannot be triggered from an external source. However, photographic techniques are anyway unsatisfactory for intensity measurements owing to the need for photographic density measurements and full knowledge of the sensitometric properties of the emulsion.

c) Time-Resolved Photo-Multiplier Method. For quantitative results a photomultiplier method is preferable owing to the straight line response of a photomultiplier over light intensity ranges of $1:10^6$ or even $1:10^8$ (Ref. 17). The other two advantages of a photomultiplier relevant here are firstly the very high sensitivity to weak light compared with any photographic material and secondly the extremely rapid response time (the very ordinary photomultiplier tubes used in this work - 1P28 - have a pulse rise time of $10^{-9}$ s and the actual speed of the tube will be limited by the accompanying electronic circuitry rather than the tube itself (Ref. 18)). The electrical nature of the device is also a great convenience in that electronic amplifiers may be used to magnify the signal and fast-writing oscilloscopes to record the result on any desired time-base. The principal disadvantage of a photomultiplier in spectroscopic work is that each tube can be used to monitor only one region of the spectrum. However, in the present case the entire emission had already been mapped by photographic methods so that a few lines could be selected for detailed
study. As with photographic emulsions, photo-multipliers require calibration at each wavelength monitored (see last part of section 2 above and the Appendix below).

For the present work, lines were selected from the mapped argon spectrum according to suggestions by Gaydon (Ref. 1). This resulted in the use of the blue lines at 4266 and 4300\textAA and the red lines 7147 and 7273\textAA. Equipment limitations prevented the monitoring of more than two wavelength regions for any one run. The procedure adopted was to align photo-multiplier A on, say, 4266\textAA (in the second order) and photo-multiplier B on, say, the red continuum at 7179\textAA for one run. The next run left A in the same position to check repeatability and set B to a new wavelength. The third run would use A at a new wavelength while leaving B at its previous adjustment. The whole apparatus was quite crude, the photo-multiplier glass envelope being cemented to a brass carrier (figure 6) which slid in a curved frame fixed to the focal plane of the spectrometer (figure 7). Setting to any particular wavelength was by inserting a Geissler argon source before the spectrometer slit and, having identified the spectrum from experience, adjusting a photo-multiplier until the output signal reached a maximum. Setting for a continuum wavelength was by linear interpolation between the known positions of lines at the spectrometer focal plane. Experience showed that an entrance slit setting of 60 \mu m gave sufficient intensity but the exit slits were made considerably wider to ensure collection of the whole line intensity even under the broadening and shifting conditions which can apply in the shock (see broadening calculation in section 4e). (It should be pointed out that the photographic mapping showed no detectable shift for the lines studied here, though the entrance slit of 300 \mu m used for the photograph would hide shifts of less than about 1\textAA.)

The exit slits were formed by two razor-blade edges mounted over the brass carrier (figure 6) at the required separation. The photomultiplier envelope was covered with aluminum tape to eliminate stray light and give a grounded electrical shield. Owing to the low intensity of the light levels which the photo-multipliers were to measure, there was some concern over the amount of stray light which would affect results. A test of this was made by running a shock under normal conditions except that a matt black mask was placed over the diffraction grating. Although the photo-multiplier output was amplified to a degree greater than used for any measurements, no output whatever was detected. It was concluded that all signals obtained normally therefore derive only via the grating and hence there were no perceptible stray light effects.

The electrical circuit for the photo-multiplier is shown in figure 8. For adjustment of the photo-multiplier in the Geissler illumination anode loads of 1M\Omega were used to give maximum voltage output for the oscilloscope as the illumination level was very low indeed. These anode loads were used also for the calibration procedure when the anode currents were measured by a D.C. digital voltmeter across a standardized 1M\Omega resistor (the illumination from the standard lamp was, of course, of a D.C. nature rather than the alternating illumination given by the Geissler lamp operated through a high voltage transformer from the 60 Hz supply. For shock wave records the leads from the photo-multipliers were terminated at the oscilloscope by 50 \Omega pads, which therefore acted as the anode loads. First trials on shock waves used oscilloscope preamplifiers with rise times no greater than 0.01\mu s, but a very high photon noise level made the oscilloscope records useless (figure 9). Attempts to match the output into the appropriate RC values for damping were hopeless as 50 \Omega pads were essential for proper termination of the leads. A
satisfactory solution was found in the use of oscilloscope pre-amplifiers with the slow rise time of 0.17 μs. These gave results as in figure 13 while still retaining a time resolution considerably better than 1 μs limit set by the shock tube/spectrometer optical geometry.

The voltage amplification of the oscilloscope pre-amplifiers was found to be significantly different from the engraved values. A simple calibration procedure was undertaken to ensure that the actual amplification, in terms of volts per centimeter, was known for each voltage range used. The accuracy of this calibration was as high as the reading error of oscilloscope traces permit, i.e. approximately 2%.

The photo-multiplier calibration procedure is described separately (Appendix below) but it is convenient to state here that the tungsten strip standard lamp was mounted near the front of the spectrometer. An enlarged image of the filament was thrown onto the spectrometer slit by a well-corrected enlarging lens via a front-silvered mirror. The mirror was removably mounted in guide rails and so easily positioned for calibration before every experiment. (figure 10.) The reason for calibration before every run was to ensure a value of A'λ for each wavelength, not to safeguard against variations in the photo-multiplier H.T. supply. A side experiment was conducted on the effects of H.T. variation. The normal value of anode-cathode voltage used was 1,250V and with care this was always set within ± 5V, i.e. to ± 0.4%. The variation in anode currents for photo-multipliers set one in the red and the other in the blue while the H.T. was varied from 1,250 to 1,000V was measured. This showed that the ratio of the photo-multiplier outputs varied by only 15% for the H.T. range of 20%. Hence, for a latitude of ± 0.4% in H.T. supply the possible error in output ratio measurement was only ± 0.3% and so quite negligible for the present work.

RESULTS

The Shock Wave. The initial conditions for the shock wave were

\[ P_1 = 3.00 \pm 0.05 \text{ torr}, \quad P_2 = 1475 \pm 25 \text{ psia with } T_1 = 298^\circ \text{K.} \]

The Mach number of the shock measured at the test station, was 13.3 measured to better than 0.5% but some shocks differed slightly so that a figure of 13.3 ± 0.1 is best taken. From these figures calculations were made by Osborne (Ref. 24) as described by Arave and Brown (Ref. 19) to find the predicted temperature, degree of ionization and specie number densities at equilibrium. The relaxation time for this case has been predicted by Petchek and Byron (Ref. 20) as 9 μs; Wong and Bershader (Ref. 21) found a value of 20 μs while a recent experimental check on light emission by Drewry (Ref. 22) suggests 30 μs. However, a recent publication by Jones and McChesney (Ref. 23) developed a new calculation which was in excellent agreement with experimental results and gives a relaxation time of 8 μs for the shock wave studied here. Calculations for the flow time, i.e. the time interval at the test station between passage of the shock front and arrival of the contact surface, were made after Boyer (Ref. 3) and corrected for real conditions (i.e. diaphragm-opening time, shock interaction, etc.) by an arbitrary factor of 0.5. Finally, an estimate was made of the time required for the contact surface to reach the test station, i.e. the "age" of the last shocked gas to pass the test station just before arrival of the contact surface. All these quantities are listed in Table I for shock Mach numbers of 13.2, 13.3 and 13.4.
Spectrometric Studies

a) Time-Integrated Spectrum Mapping. The film used was Kodak Recording Film type 2475 which has a long wavelength cut-off at about 7200Å while filters over the spectrometer slit (Kodak glass U.V. filter plus a gelatine 2B haze filter) eliminated wavelengths below 3600Å. Within the range 3600 to 7200Å over a hundred lines from the argon shock were found. These varied from very bright to very weak while at even lower intensities yet more lines could be detected. A study of the complete spectrum was not performed but a record of the hundred stronger lines may be useful in further work. A picture of the film record is shown in figure 11, though few of the weaker lines will be detectable in the reproduction. Of the 100 lines whose wavelengths were measured from the spectrogram, 75 were identified as AI and 2 as AII, using the lists in the Handbook of Chemistry and Physics (Ref. 25). Some of the other 25 lines have been identified, e.g. there is no doubt for the bright Hα and Hβ lines but the clear, if faint, HeI lines at 6678.2 and 7065.7Å are rather puzzling though trace impurities in the argon may be responsible. The attribution of some of these lines is doubtful, for example a sharp and quite strong line at 3969Å may well be CaII at 3968.5Å but its occurrence in the shock was not expected. Table 2 gives these non-argon lines with guesses at the possible sources but some lines are quite clear, e.g. 5590Å, and not easily attributable.

However, our main concern here is with the argon emission. Both the AII lines, at 5772.1Å and 6643.8Å were quite faint and certainly a poor basis for accurate intensity measurements. It should be noted, though, that such conclusions should not be drawn too hastily where a potentially useful line would occur near the wavelength sensitivity limit of the film used. For example, both the AI 7147Å and 7273Å lines later used in this work were not noticed in these first mapping experiments as, due to sensitivity cut off at 7200Å, the recorded density was considered too low. Of the 75 AI lines identified, only 25 could be found in the multiple table by Moore (Ref. 26) presumably because the remaining 50 lines were not considered adequately relevant to astrophysical work to warrant their inclusion. All the argon lines noticed in the photographic mapping of the spectrum are shown in Table 3. Where relevant the multiplet number as listed by Moore is given and the configurations of both upper and lower energy levels can be found by consulting the appropriate entry.

For the purposes of the present work detailed knowledge of the exact energy state jumps is as yet rather irrelevant. Interest in a line, if temperature measurements are the real objective, must depend simply on whether a reliable value for the transition probability is or is not available.

b) Time-Resolved Photographic Method. As stated above, the emission even from the argon shock wave (very bright compared with, say, oxygen) was insufficient to give good records even on the very rapid 2475 emulsion. This was due, in great part, to the very large dispersions of the spectrometer and were, say, the Hilger medium quartz instrument to be used far better results would be expected. With a time base of 1 μs, i.e. the sweep-time over the 15 mm high, spectrometer slit was 1 μs, and a slit width of 15 μm (this could well have been increased considerably) a very faint trace could be detected on the film. As far as could be adjudged from visual inspection, the spectrum was identical with the time-integrated result and all emissions appeared to begin and end at the same times. An estimate of the spectrum height, about 1 mm, suggested the duration of strong emission from the shock wave was of the order 70 to 100 μs (later photo-multiplier results confirmed that this was a fair first estimate) while the position of the trace showed that onset of emission coincided closely with the shock front.
c) Photo-Multiplier Studies. The lines selected for monitoring by photo-multiplier were 4266.3Å and 4300.1Å in the blue and 7147.0Å and 7272.9Å in the red. Normally more lines would be used to obtain more points on the graph of equation (9), and the scatter of results found in the present work make this most desirable in the future. There are three reasons why so few lines were monitored. Firstly, the number of argon lines for which transition probabilities are reliably known is distressingly small: for example two very recent publications (Refs. 1, 27) have more than doubled the amount of reliable information available. Secondly, only in the red and blue regions were lines of known $A_{nm}$ found that rose sufficiently above the continuum to promise reasonable accuracy. Thirdly, apparatus limitations were such that only one photo-multiplier could be used in each wavelength range. It will be seen that this situation allowed a maximum of two photo-multipliers and, as the continuum had also to be monitored, more than 4 lines would have required more shock runs than was possible in this short-term study. Subject to apparatus limitations and $A_{nm}$ availability, the need to use the greatest possible range of $E_n$ governed selection of the four lines used, together with the desire for lines which are reasonably intense compared with the continuum. Selection in the blue, where self-absorption is negligible, was straightforward, but in the red the strong lines suffer greatly from this effect. For this reason the two red lines are not the most intense in that region but were selected under advice by Gaydon (Ref. 1) to diminish the self-absorption correction.

A total of 8 runs were used to obtain records for interpretation into a temperature/time profile for the total duration of observed emission. The oscilloscope time-base for these experiments was 20 μs/cm. Another 3 runs were carried out for the express purpose of studying the shock front, for which a time-base of 5 μs/cm was used. Three samples of the first series are shown in figure 12. The selection of these three was based only on the convenience of exhibiting a complete set of all wavelength intensities monitored at the same voltage scales, i.e. 0.385 V/cm for the blue trace (upper) and 0.045 V/cm for the red trace (lower). All oscillograms for the second series are shown in figure 13. Owing to lack of time and present uncertainty in the validity of interpreting these latter traces into meaningful temperatures in the relaxation zone no analysis has yet been undertaken on these results.

d) Analysis of Photo-Multiplier Results. The first step in use of the oscilloscope traces was to enlarge them by transmission printing onto bromide paper in a normal enlarger (the highlight transparency of Polaroid paper prints is quite adequate for this). The enlarged record was then marked by vertical lines at 8 μs intervals, the zero for each trace arbitrarily being placed 16 μs in front of the trace peak. The best curve was drawn through each trace and the vertical deflection from the trace base read off at each 8 μs intersection. This gave about 20 readings for each trace as a function of time. Comparisons between traces for the same wavelength showed no significant differences, after allowance for varying oscilloscope range settings, so all such results were averaged at each value of time. Tables 4 to 9 list the 120 final average deflection values in terms of centimetres on the oscilloscope screen as a function of time for the lines 4266, 4300, 7147 and 7273Å and for the continuum at 4276 and 7179Å.

Correction of the line values for the included continuum background was not carried out until after conversion to relative intensities, in order that variations in photo-multiplier sensitivity over the frequency range concerned (the intervals vary from 11 to 94 Å) should cause no error. However,
it was assumed that the continuum level was constant (within ± 3%, the accuracy of oscilloscope trace reading) over these intervals. Deflection values were converted to relative intensities by first calculating the photo-multiplier current (from the deflection, the amplification in volts/cm and the photo-multiplier anode resistance) and then applying the factor $I'_{\lambda}/A_{\lambda}$ from the standardization experiment. The amplifications were found by a simple calibration of the oscilloscope pre-amplifiers and the anode load resistances measured in a Wheatstone Bridge. The values of these quantities are noted in the relevant tables (Tables 4 - 9) where the relative intensities are listed as functions of time. The continuum intensities were then subtracted to determine the line intensities and the value of $I_{\text{nm}} \lambda/g_n A_{\text{nm}}$ calculated. Figures for $g_n$ and $A_{\text{nm}}$ were as recommended by Gaydon (Ref. 1). They may be compared with some values by Malone and Corcoran (Ref. 27) which were received too late for consideration here:

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>Gaydon and Coates</th>
<th>Malone &amp; Corcoran</th>
</tr>
</thead>
<tbody>
<tr>
<td>4266</td>
<td>$g_n$ 5</td>
<td>$g_n$ 5</td>
</tr>
<tr>
<td>4300</td>
<td>$A_{\text{nm}}$ 253,000</td>
<td>$A_{\text{nm}}$ 265,000</td>
</tr>
<tr>
<td>7147</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>7273</td>
<td>3</td>
<td>-</td>
</tr>
</tbody>
</table>

e) Correction for Self-Absorption. The thickness of the emitting plasma is 7 in. and at the pressures involved correction is needed for self-absorption in the red lines, the blue emission being negligibly affected. The method of correction was patterned after the "curves of growth" given by Penner (Ref. 28) and in a more convenient form by Gaydon (Ref. 1). In the latter presentation a graph is offered for $I_t/I_m$ as a function of $S(\ln 2)^{\frac{1}{2}}/b_D$, where $I_t$ is the true emitted intensity and $I_m$ is the measured intensity with losses due to self-absorption. $X$ is the plasma thickness, $b_D$ the Doppler half-width of the line considered and $S$ is given by

$$S = \frac{C}{4 \pi \nu^2} \frac{N_0}{\nu} \exp \left( \frac{-E_m}{kT} \right) \frac{g_n}{g_m} A_{\text{nm}} \left( 1 - \exp \frac{-h\nu}{kT} \right)$$

The curves on the graph are each valid for one value of the line shape parameter $a$ where

$$a = \frac{b_N + b_C}{b_D} (\ln 2)^{\frac{1}{2}}$$

where $b_N$, $b_C$ and $b_D$ are, respectively, the natural, collision (Stark Effect) and Doppler half-widths. The first step therefore is evaluation of $S$ and $a$.

For calculation of $S$ the predicted equilibrium temperature for the shock was used. Ideally, as the temperature is measured as a profile through the shock a guess at the temperature followed by a self-absorption correction and an evaluation of the measured temperature should be followed by a re-iteration until the value is stable for each point. However, the accuracy of the final result in the present work would not warrant such elaboration and only one correction was made, using an assumed temperature of 11,500°K, and applied to all points in the temperature profile. For each of the lines 7147Å and 7273Å the
appropriate values of $v, E_m, g_n, g_m$ and $A_{nm}$ were used while $N_0$ was taken from the equilibrium calculation for neutral atoms. Accepted values were used for the universal constants.

For $a$ it was necessary to evaluate $b_N, b_C$ and $b_D$. The natural half-width, of course, is quite negligible compared with the collision half-width of about 0.2 Å for the red lines. The collision broadening is due to perturbation of the electron orbits by the Stark effect during "collisions", which really amount to near-approaches, with the electrons and ions surrounding the emitting species. The method for calculation is described by Griem (Refs. 12 and 29) and is summed up in the expression for $w_t$ the total half-width due to the electron and ion broadening as:

$$w_t = [1 + 1.75 \alpha (1-0.75 R)] w$$

for $\alpha < 0.5$ and $R < 0.8$ where $\alpha$ is the ion broadening parameter (which contributes very little) and $R$ is the ratio of the mean collision separation and the Debye radius. Values for $w$ and $\alpha$ are tabulated by Griem (Ref. 12) and are simply corrected to 11,500°K and the electron density of the shock (a graphical method was used here but the accuracy was undoubtedly excessive for the present purpose). The procedure for 7147 Å is very straightforward but an additional operation is needed for 7273 Å as the values are given only for the first member of the spectral series containing this line and a further correction has to be made (Ref. 12). Evaluation of $R$ was from

$$R = \left(\frac{N_0}{2}\right)^{1/2} \left(\frac{15}{17}\right)^{1/3} e^2 (kT)^{-1/2}$$

where $e$ is in e.s.u., and it was found that $R = 0.50$. The final results were that for 7147 Å $b_C = 0.20\AA$ and for 7273 Å $b_C = 0.21\AA$.

The Doppler half-width $b_D$ was evaluated from the relation (Ref. 31)

$$b_D = \frac{2kT \ln 2}{mc^2}$$

where $v$ is the central frequency of the line and $m$ is the mass of the radiating species. The half-widths found were 0.043 Å at 7147 Å and 0.042 Å at 7273 Å, in very good agreement with a suggested value from Gaydon (Ref. 30) of 0.08 cm⁻¹ (≈ 0.04 Å).

To summarise, using a plasma thickness of 17.78 cm, it was found that at 11,500°K, for an electron and ion number density of $4.3 \times 10^{16}$ cm⁻³:

<table>
<thead>
<tr>
<th>$\lambda$ Å</th>
<th>$b_N$ Å</th>
<th>$b_C$ Å</th>
<th>$b_D$ Å</th>
<th>$a$</th>
<th>$S$</th>
<th>$SN(\ln 2)^{1/2}$</th>
<th>$b_D$ Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>7147</td>
<td>0</td>
<td>0.20</td>
<td>0.043</td>
<td>3.84</td>
<td>0.0114</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>7273</td>
<td>0</td>
<td>0.21</td>
<td>0.042</td>
<td>4.17</td>
<td>0.0517</td>
<td>18.2</td>
<td></td>
</tr>
</tbody>
</table>

Now it was plain that the graph to evaluate $I_t/I_m$ given by Gaydon (Ref. 1) could not be used directly as no curve is given for $a = 4$. However, as the ordinate varies as $\sqrt{a}$ for a constant abscissa (Ref. 28) a series of straight line plots were made on a basis of Gaydon's curves for $a = 1.0, 1.5$.
and 2.0, the values determined for $a = 4.0$ and re-plotted (figure 14). Small corrections\footnote{gave curves for $a = 3.87$ and $a = 4.17$ and allowed the self-absorption factor to be read off.} gave curves for $a = 3.87$ and $a = 4.17$ and allowed the self-absorption factor to be read off. The values finally used (shown in the tables 6 and 7) were $x 1.15$ for $7147\AA$ and $x 1.52$ for $7273\AA$.

5. DISCUSSION

The aim of the present work is towards establishing a method for temperature measurement rather than any detailed study of the shock wave. However, two perplexing features of the final results do require some attention: firstly, the apparent continued rise of temperature behind the shock front and secondly, the rapid fall in emitted light intensities (especially in view of the apparent rising temperature). Before commenting on these results it is necessary to have some test of their significance through an estimate of the effects of experimental and data errors on the results.

To see how errors affect the temperatures finally deduced let us consider an idealised two-line method of temperature measurement, ignoring corrections for background continuum and self-absorption. Using the nomenclature and conditions of equation (2) and putting $\nu = c/\lambda$ we may write

$$\exp \left( -\frac{E_n}{kT} \right) = \left( \frac{I_{nm,\lambda}}{g_n A_{nm}} \right) \frac{4 \pi \phi \lambda}{hc N_0}$$

Applying this to two spectral lines at $\lambda_1$ and $\lambda_2$ which are emitted from the same species (in our case the neutral argon atom) so that the only parameters which differ between the two lines are $E_n$, $I_{nm,\lambda}$, $g_n$ and $A_{nm}$. Replacing all suffixes by 1 and 2 to identify the two lines, we may write, comparing the intensities as a ratio:

$$\exp \left( -\frac{E_1 - E_2}{kT} \right) = \frac{I_1 A_2}{I_2 A_1} \frac{g_2 \lambda_1}{g_1 \lambda_2}$$

putting

$$E = \frac{E_1 - E_2}{k} \ , \ r = \frac{I_1}{I_2} \ , \ a = \frac{A_1}{A_2} \ , \ G = \frac{g_2 \lambda_1}{g_1 \lambda_2}$$

this can be expressed as

$$T = \frac{E}{\ln a - \ln r - \ln G}$$
Knowledge of the energy levels, Boltzmann's constant, the statistical weights and the wavelengths is very well established and errors in these quantities, and hence in $E$ and $G$, may be neglected compared with probable errors in intensity and uncertainty in transition probabilities. The error in $T$ due to errors in $a$ and $r$ can be deduced by simple calculus from equation (18), giving the result for the fractional temperature error:

$$\frac{dT}{T} = \frac{T}{E} \left( \frac{da}{a} - \frac{dr}{r} \right)$$  \hspace{1cm} \text{(19)}$$

But in fact this derivation assumes that $dT$, $da$ and $dr$ are very small quantities compared with $T$, $a$ and $r$ (implicit assumption in the infinitesimal calculus) and this assumption may well be unjustified here. It is necessary, therefore, to consider the case where significant errors $\Delta a$ and $\Delta r$ in $a$ and $r$ produce a significant error $\Delta T$ in $T$. From equation (18):

$$T + \Delta T = \frac{E}{\ln(a+\Delta a) - \ln(r+\Delta r) - \ln G}$$  \hspace{1cm} \text{(20)}$$

Therefore by subtraction with equation (18) and rearrangement:

$$\Delta T = E \frac{\ln a - \ln r - \ln G - \ln(a+\Delta a) + \ln(r+\Delta r) + \ln G}{(\ln(a+\Delta a) - \ln(r+\Delta r) - \ln G)(\ln a - \ln r - \ln G)}$$  \hspace{1cm} \text{(21)}$$

or

$$\Delta T = \frac{T(T+T)}{E} [\ln(r+\Delta r) - \ln r - \ln(a+\Delta a) + \ln a]$$  \hspace{1cm} \text{(22)}$$

so

$$T \frac{1 - \frac{E}{E} \ln \frac{r-r}{r} - \ln \frac{a+a}{a}} = T^2 \frac{\ln r+\frac{r}{r} - \ln \frac{a+a}{a}}{E}$$  \hspace{1cm} \text{(23)}$$

Therefore

$$\frac{\Delta T}{T} = \frac{\ln \frac{1+\frac{\Delta r}{r}}{1+\frac{\Delta a}{a}}}{E \frac{1+\frac{\Delta r}{r}}{1+\frac{\Delta a}{a}}}$$  \hspace{1cm} \text{(24)}$$

which is identical to the result by Chuang (Ref. 32). It can be seen immediately that the selection of lines must be such that $(E_1 - E_2)$ is as great as possible, else $E/T$ will be comparable with the second term in the denominator and result in errors of very large magnitudes (to quote Chuang "beyond hope and reason"). It must be realised that the magnitude of such errors amount to values rarely encountered in scientific work, of the order of several hundred per cent and up! However, in the present work the greatest possible range of upper energy levels for work at visible wavelengths has been invoked and it remains to find figures for $\Delta r$ and $\Delta a$ to assess the success of the method without extension to the U.V. or I.R. regions.

The uncertainty in the transition probabilities is easily found. Although until recently experimental values for $A_{nm}$ were rarely available while
computed values were dubious (to the extent of at least $\pm 50\%$) except for the very simplest hydrogenic systems, two very useful publications specific to argon atoms appeared in 1966. The first, by Coates and Gaydon (Ref. 1), gives $A_{\text{nm}}$ for all lines used in this work and claims an accuracy for these values of $\pm 5\%$. The second publication, by Malone and Corcoran (Ref. 27) gives $A_{\text{nm}}$ only for the blue lines but is nevertheless encouraging as the values given, to a claimed accuracy of $1.7\%$ and $1.3\%$ respectively for 4266Å and 4300Å do lie within $5\%$ of Gaydon’s values. If only two lines were used, as assumed in the ideal two line method then the value of $\Delta a/a$ would be found from a figure $\pm 5\%$ for error in $A_{\text{nm}}$. However, the present work used two lines in the blue and two lines in the red and the best straight line on the graph (figure 15) uses the average position of each pair of points. The errors associated with each point, being random, may therefore be combined to find the most probable error for the average position of the two points in the red and in the blue. The average position can then be considered an imaginary line and the two-line method applied to these two imaginary lines in the red and the blue respectively.

Firstly, the probable error for each imaginary point is not due to an arithmetic mean for the transition probability so the fractional error is best used. If the individual fractional error is $\pm 5\%$ then the most probable error for the mean of two points is $\pm 5\% \sqrt{2}$, i.e. $\pm 3.5\%$. Secondly, $a$ is the ratio of two transition probabilities, in this case two imaginary values each with a probable error of $\pm 3.5\%$. The probable fractional error in $a$ is therefore $\pm 3.5 + 3.5 \sqrt{2} \%$. The equation (24) may be immediately simplified to:

$$\frac{\Delta T}{T} = \frac{1 + \frac{\Delta r}{r}}{\ln \frac{1.05}{1 + \frac{\Delta r}{r}}}$$

Considerably more study is needed to evaluate $\Delta r/r$ owing to the number of steps in the derivation of $r$ from the original measurements. However, the error in measuring the intensity by means of an oscilloscope is the overwhelming error component. This is convenient for this calculation but very unfortunate for the experiment as a whole in that regardless of efforts to achieve precise photo-multiplier calibration, steady H.T. voltages, etc. the hope of decent accuracy will always founder on the rock of the oscilloscope reading problem, and a solution of this is difficult to envisage. Values are as follows:

1) Oscilloscope reading accuracy for line and continuum is $\pm 0.3$ mm.

2) Conversion to a relative intensity figure is by equation (6) where the only significant error lies in $I'_\lambda$ basically due to uncertainty in lamp filament temperature, and amounts to less than 1%.

3) Correction of line intensity for continuum intensity combines two oscilloscope reading errors of $\pm 0.3$ mm and also reduces the signal value.

4) Correction for self-absorption is hard to assess for error as the basic uncertainty lies in the data and theory rather than the experimental measurements. However, a fractional maximum error of
$\pm 3\%$ is realistic giving a probable error of $\pm 2\%$. Note that this would apply only to the red lines anyway, self-absorption is negligible in the blue.

Summing these errors we see that all measurements of relative intensity are liable to a fixed fractional error totalling $\pm 4\%$ plus a probable total reading error of $\pm 0.4$ mm. The luminous intensity for the line alone varies from a peak equivalent to some 10 mm just behind the shock front to a value of 3 mm at 84 $\mu$s behind this peak, while in the last stages for which measurements were made—say 120 $\mu$s behind the peak—the equivalent signal strength of a line is as low as 1 mm. The probable fractional errors corresponding to the fixed reading error are therefore $\pm 4\%$ at best (at the luminous peak), $\pm 3\%$ at 84 $\mu$s behind the peak and $\pm 40\%$ at 120 $\mu$s behind the peak. The total probable errors may be summed as $\pm 6\%$ at the luminous peak, $\pm 15\%$ at 84 $\mu$s later and $\pm 42\%$ near the tail of the emission.

Reverting now to the calculation for $\Delta r/r$, invoking the earlier argument that each pair of experimental points is averaged to give the so-called imaginary point for the two-line ratio method, the averaging reduces the probable fractional error in the intensity to the values $\pm 4\%$, $\pm 11\%$ and $\pm 30\%$ at the luminous peak, 84 $\mu$s later and 120 $\mu$s later respectively. For these three times we can compute the probable fractional error in the intensity ratio as $\pm 6\%$; $\pm 15\%$ and $\pm 42\%$ respectively.

For substitution in equation (24) we require $(1 + \Delta r/r)/(1 + \Delta a/a)$ and this is tabulated here for the three times considered. The errors can be either of same or opposite signs, but the opposite sign has been assumed.

<table>
<thead>
<tr>
<th>$t$ (ms)</th>
<th>$\Delta a/a$</th>
<th>$\Delta r/r$</th>
<th>$1 + \Delta r/r$</th>
<th>$1 + \Delta a/a$</th>
<th>$\ln(1 + \Delta r/r)/(1 + \Delta a/a)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>at the peak</td>
<td>16</td>
<td>$\pm 5%$</td>
<td>$\pm 6%$</td>
<td>1.116</td>
<td>0.11</td>
</tr>
<tr>
<td>84 $\mu$s behind the peak</td>
<td>100</td>
<td>$\pm 5%$</td>
<td>$\pm 15%$</td>
<td>1.211</td>
<td>0.19</td>
</tr>
<tr>
<td>120 $\mu$s behind the peak</td>
<td>136</td>
<td>$\pm 5%$</td>
<td>$\pm 42%$</td>
<td>1.495</td>
<td>0.40</td>
</tr>
</tbody>
</table>

For final evaluation of $\Delta T/T$ we need to substitute figures for $E/T$ and for this $E_1$ has been taken as 117, 100 cm$^{-1}$ in the blue and $E_2$ as 107,300 cm$^{-1}$ in the red.

Using the calculated equilibrium temperature of $T = 11,300^\circ$K we obtain $E/T = 1.25$. So for the temperature error:

<table>
<thead>
<tr>
<th>$t$ (ms)</th>
<th>$\Delta T/T$</th>
<th>$T$ at $11,300^\circ$K</th>
</tr>
</thead>
<tbody>
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<td>at the luminous peak</td>
<td>16</td>
<td>$\pm 9.6%$</td>
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<td>84 $\mu$s behind the peak</td>
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<td>$\pm 17.9%$</td>
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<td>120 $\mu$s behind the peak</td>
<td>136</td>
<td>$\pm 47.1%$</td>
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These error limits are shown alongside the temperature-time distribution in figure 16. The error summing procedure used here in deriving the total error can be queried as to the significance of (a) finding the error of an average of n values by taking the average error and multiplying by $1/\sqrt{n}$ when n is only 2; (b) finding the total error in a quotient by summing the error and again applying the factor $1/\sqrt{2}$. The justification for doing this cannot be on statistical grounds owing to the very small sample size, but it can still be argued that when two values are combined, each having its own maximum error, the total probable error to be expected is greater than either individual error but less than the arithmetic sum, which represents the maximum possible excursion of the data. To adopt the factor of $1/\sqrt{2}$ is admittedly intuitive but it is intended only to give a "half-width" or probability value as opposed to the maximum range. It cannot be argued that use of the maximum error limits would carry any more significance and it is considered that the "probable" error used here gives a realistic picture of the uncertainty.

From figure 16 it is now seen, taking account of the area of uncertainty calculated, that the phenomenon of a continually rising temperature behind the shock front may be apparent rather than real. In fact, the margin for error is such that the temperature profile could peak at, say, 32 µs and then fall steadily, which would be expected from consideration of radiative cooling effects. The fall with time in luminous intensity of both line and continuum would then fit into the picture and require no specific explanation.

The area of uncertainty seems large and the room for doubt of the actual behaviour of the plasma behind the shock will appear excessive. Although disappointing it must be realised that it was exactly to assess such problems that this project, a pilot for later investigations, was undertaken. Furthermore, this work has been by no means unusual in finding such uncertainty. For example, Thornton and Cambel (Ref. 33) found very similar fast decays of luminous intensities (and offered no special explanation) which gave rise to very large uncertainties in, for example, electron densities at later times. For this reason some of their derived profiles are intuitively interpreted rather than calculated from the oscilloscope trace (e.g. their figure 7, quote: "portion of curve sketched from oscillograms"). There is no reason why this method should not be used here to "sketch" the temperature, as the only variable which could give rise to fall-off in both line and continuum intensity is the fall in temperature: after relaxation it is impossible to conceive of a fall in the number density of the neutral atoms, while absorption in a growing boundary layer can hardly affect all monitored wavelengths (including the continuum) in exactly the same fashion.

The use of the spectroscopic method investigated here is plainly hampered by drastic reduction in experimental accuracy due directly to the problem of reading the oscilloscope trace. The method otherwise seems quite successful and is not too cumbersome in application to the 4 in. x 7 in. UTIAS hypersonic shock tube, even with the rather inadequate and inappropriate spectroscopic equipment already available. Introduction of, say, a 6-channel photo-multiplier attachment for the Jarrell-Ash would speed up experimental work enormously and also give more reliable results as only one shock would be needed to give a full set of data. However, the problem of oscilloscope reading still remains. It should be possible here to improve on present-day techniques in quite a simple fashion: instead of relying on only one oscilloscope trace for the entire profile there is no reason why each photo-multiplier output should not be recorded
by, say, three oscilloscopes or three channels on one oscilloscope with different sensitivity settings for each channel. As a working example, take a case where the peak signal, just behind the shock front, reaches a value of 1 volt and at the limit of interest, say 120 μs later, falls to 0.05 volts (this is quite typical of results in the present work for the blue line at 4300 Å). If the maximum usable beam deflection is, say, 3 cm then one channel can be set to 0.5 V/cm, the second to 0.1 V/cm and the third to 0.05 V/cm, the time-bases all being identical in scale and carefully synchronised in position. The photomultiplier output will then be recorded as three traces: the first on channel 1 will look quite like figure 12 in this report; channel 2 will lose the first part of the trace and begin recording when the signal falls to 0.3 volts; the third trace would come in at a signal strength of 0.15 volts. By combining interpretation of all three traces it should be possible to reduce reading errors to less than a maximum of ± 5% at all parts of the trace. At present this is barely possible at the peak of the signal. It will be necessary to ensure a trace which is smoothed by rise-time selection and yet of adequate temporal resolution - there seems to be little difficulty here as the rise-time of 0.17 μs used in the present work gave quite a good result (compare with Thornton and Cambel (Ref. 33) figure 5) and could well have been further increased within the desired temporal resolution of ± 1 μs. The figure of ± 5% for reading accuracy quoted above is based on a reading error of ± 0.5 mm. This is not set by the problem of locating the trace for measurement (this is done quite accurately by the technique of making enlarged copies and then using a pair of dividers) but rather by uncertainty in the true value of the signal due to noise levels and in part to doubt of the linearity of the oscilloscope amplifiers (± 3% is guaranteed for Tektronix instruments). Improved smoothing up to the limit of required temporal resolution and precise calibration of the oscilloscope amplifiers linearity could give improvement up to the point where reading errors are reduced to the level of errors from other sources, which is the optimization ideally sought for.

This discussion can be usefully concluded by a prediction of the total probable error level attainable if the improved techniques suggested are put into practice. If the reading error can be reduced to ± 3% everywhere on the profile (and the improvements suggested should provide this) then using summing and averaging techniques to produce probable errors as before we find a probable error of ± 5% for Δr/r. Retaining the probable error of ± 5% for Δa/a and 1.25 for E/T we find that, from equation (24) assuming that excursions for Δr and Δa are in opposite directions (the worst case), ΔT/T = 8.7%. This error is only marginally smaller than the error of 9.6% found for the luminous peak in the present work, but it would be valid over the entire profile as opposed to present errors of 18% and even 47%.

6. CONCLUSIONS

The purpose of this work was to measure the temperature profile behind a strong shock wave in argon and this has been achieved. The accuracy obtained, with available equipment, is comparable with other studies but is considered inadequate for detailed investigations of the whole profile. It is suggested that minor revamping of the equipment can give the precision required for detailed analyses.
Experimental results specific to the shock wave studied were self-consistent within the error margins of the work. Without more exact results detailed conclusions would be speculative, but a rapid fall-off in emitted intensity for both line and continuum radiations suggest a rapidly cooling plasma behind the shock. Hope that the measured temperature profile would allow correlation with cooling calculations was dashed, again by experimental uncertainties, but the profile obtained did contradict any suggestion of cooling unless the total area within error margins was taken into account.

The principle conclusion must be that further work along these lines is highly desirable and should be most fruitful, especially in view of the discovery that the equipment already available will allow useful work to be done.
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**TABLE 1**

Calculated Parameters for Shock Wave into Argon at 3 torr Which has $M_s = 13.3$ at 24' from Diaphragm

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<th>Ms</th>
<th>equilibrium temperature $^\circ $K $\pm 50^\circ $K</th>
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<th>neutral atom density $N = N_e$ $\text{cm}^{-3}$</th>
<th>relaxation time $\mu s$</th>
<th>flow time $\mu s$</th>
<th>approx. flow Mach No.</th>
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### TABLE 2

**Found Lines which are Not Argon**

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TABLE 3

Identified Neutral Atom Lines

(Identified from reference 25; multiplet classification by Moore 26)

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TABLE 4
Relative Line Intensity Calculations for Al 4266Å

Oscilloscope range: 0.385 V/cm
P.M. anode load: 51.0 Ω

\[ \frac{\lambda}{g_n A_{nm}} = 3.37 \times 10^{-11} \]

\[ \frac{W_A \cdot d_A}{A_{\lambda}} = 4.21 \times 10^8 \text{ erg.cm}^{-2}\text{s.amp}^{-1} \]

\[ E_n = 117200 \text{ cm}^{-1} \]

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<tr>
<th>time (μs)</th>
<th>total oscilloscope deflection (cm)</th>
<th>relative total intensity x 10^{-6}</th>
<th>relative line intensity x10^{-6}</th>
<th>relative ( I_{\lambda,\lambda} ) x 10^{5}</th>
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<th>total intensity x10^-6</th>
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</table>
### TABLE 6

**Relative Line Intensity Calculations for Al 7147Å**

Oscilloscope range: 0.045 V/cm  
P.M. anode load: 66Ω  

\[ \frac{w \cdot d\lambda}{A_{\lambda}} = 249 \times 10^8 \text{erg.cm}^{-2} \text{sr}^{-1} \text{amp}^{-1} \]

\[ \frac{\lambda}{g_n A_{nm}} = 3.36 \times 10^{-11} \]

\[ E_n = 107,100 \text{ cm}^{-1} \]

Self absorption correction factor = 1.15

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<th>Total oscilloscope deflection (cm)</th>
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<th>relative total intensity x 10^-6</th>
<th>relative line intensity x 10^-6</th>
<th>[ \frac{I_{\lambda,\lambda}}{g_n A_{nm}} ] (x10^5)</th>
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TABLE 7
Relative Line Intensity Calculations for Al 7273Å

Oscilloscope Range: 0045
P.M. anode load: 66Ω

\[
\frac{w_\lambda d}{A^f_\lambda} = 356 \times 10^8 \text{erg.cm}^{-2}\text{cm}^{-1}\text{amp}^{-1}
\]

\[
\frac{\lambda}{g_n A_{nm}} = 1.19 \times 10^{-11}
\]

\[
E_n = 107,500 \text{cm}^{-1}
\]

self-absorption correction factor = 1.52

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</table>
Relative Continuum Intensity Calculations

**TABLE 8**
Blue continuum at 4276Å

Oscilloscope range: 0.385 V/cm  
P.M. anode load: 51.0 Ω

\[
\frac{w_\lambda \cdot d_\lambda}{A'_\lambda} = 4.26 \times 10^8 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ amp}^{-1}
\]

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**TABLE 9**
Red continuum at 7179Å

Oscilloscope range: 0.045 V/cm  
P.M. anode load: 66 Ω

\[
\frac{w_\lambda \cdot d_\lambda}{A'_\lambda} = 259 \times 10^8 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ amp}^{-1}
\]

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FIG. 1
COMPARISON OF PHOTO-MULTIPLIER RECORDS

SHOCK

CONTACT FRONT

100 μsec.

P.M. OUTPUT OF
HARWELL AND
TAYLOR

100 μsec.

SHOCK FRONT

6965 Å

P.M. OUTPUT OF
GAYDON AND
COATES

CONT.
FIG. 2
SHOCK TUBE WINDOW

TO SPECTROMETER

QUARTZ WINDOW

7"
4"
FIG. 3
ROTATING DISK SHUTTER

R rpm.

Disk Slots

Spectrometer Slit
Figure 4: Rotating Disk Shutter and Shock Tube Window
Figure 5: Oscilloscope Traces from Run Number 204

Upper Two Traces: Ionization Gauge and Photo-Diode Output at 200 ms. per cm.
Lower Trace: Photo-Diode Output at 1 ms. per cm.
FIG. 8
PHOTOMULTIPLIER CIRCUIT

H.T. + (1250 V.)

ALL CONDENSERS: 0.15 μF, 300V.
ALL RESISTORS: 100 KΩ
PHOTOMULTIPLIER: I P 28
POWER SUPPLY: HANMER N. 401

H.T.-

11 CATHODE

1
2
3
4
5
6
7
8
9
10 ANODE

pin

DYNODES
Figure 9: Oscilloscope Trace (Run #238) Showing High Noise
Figure 11  ARGON SPECTRUM
Figure 12: Oscilloscope Traces of Runs #259, 262, 253.
Time Base: 20 ms. per cm.
Figure 13: Oscilloscope Traces of Runs #265, 266, 267.
Time Base: 5 ms. per cm.
FIG. 14 CURVES OF GROWTH

GAYDON’S ORIGINAL GRAPH, SQUARED UP AND ADDED TO.

\[ \frac{I_t}{I_m} \]

\[ SX \left( \log_2 \frac{1}{b_D} \right) \]

\[ a = 1.0 \]

\[ a = 1.5 \]

\[ a = 2.0 \]

\[ a = 3.87 (7147 \text{ Å}) \]

\[ a = 4.0 \]

\[ a = 4.17 (7273 \text{ Å}) \]
FIG. 15
PLOTS OF INTENSITY
vs. $E_n$

$$\ln \left[ \frac{I_{nm} \lambda}{g_n A_{nm}} k_{self} \right] / E_n$$

$E_n$ (cm$^{-1}) \times 10^{-5}$

$7147 \text{ Å}$

$7273 \text{ Å}$

$1.06$ $1.08$ $1.10$ $1.12$ $1.14$ $1.16$ $1.18$
FIG. 16
PROFILE OF TEMPERATURE vs. TIME

K x 10^3

TIME IN μs. (SHOCK TUBE)
FIG. 17
OPTICAL PATHS

A. FOR SHOCK MONITORING

MIRROR

WINDOW

SHOCK TUBE

FILTERS AND SPECTROMETER

PHOTO-MULTIPLIER

B. FOR PHOTO-MULTIPLIER STANDARDISATION

MIRROR

ENLARGING LENS

STANDARD LAMP

FILTERS AND SPECTROMETER

PHOTO-MULTIPLIER
FIG. 18
STANDARD LAMP POWER SUPPLY

D.C. SUPPLY
+1
-2

Q01 Ω
+3
POT
-4
+5

BATTERY
-6

CENTRE
+7
LAMP
8

RIM

10 Ω 200 W. DIVIDOHMS
#1357

2.5 Ω

10 Ω

INC

D.C. SUPPLY

DEC

TO 5

TO 6

TO 7

TO 8

TO 3

TO 4

BATTERY SWITCH

BATTERY CURRENT METER

LAMP CURRENT CONTROL

1 Ω 200 W. DIVIDOHM

1 Ω 225 W.

TO PRODUCE 14 AMP. D.C.
Figure 19: Arrangement for Standardisation Procedure.
Figure 20: The 4 in. by 7 in. Shock Tube from the Driver End.
Figure 21: The Channel Section of the 4 in. by 7 in. Shock Tube
Figure 22: Instrumentation of the 4 in. by 7 in. Shock Tube
APPENDIX A

Standardisation of Photo-Multipliers

For relative measurements of line intensities there is no need for absolute calibration of whatever photo-sensitive device is used to monitor the spectrum lines. If the energy sensitivity of the device were independent of the wavelength and if the rest of the optical train (windows, spectrometer, etc.) were equally non-discriminating then no calibration at all would be required. However, all photo-sensitive devices, whether photo-electric or photographic, are strongly wavelength-dependent while the optical train will also have some wavelength dependence, certainly if a dispersive element such as a spectrometer is involved. In addition, for photo-multipliers, the output is sensitive to variations in the applied high tension voltage and some internal standardisation is anyway desirable for consistent results.

The output signal of the photo-multiplier is a current, $A$, which is not affected by the magnitude of the external resistive load. As voltage measurements are easily made with high precision it is common practice to insert a resistive load of an appropriate value and measure the potential difference across it due to the passage of the current $A$. It should be noted here that during a shock tube experiment, when the luminous intensity was very high, the resistive load used was a simple 50 ohm terminator at the oscilloscope input. This gave transient potential difference signals of the order of 1 volt. During standardisation, however, the luminous intensity of the standard lamp was far lower and the output current of the photo-multiplier decreased accordingly (to the level of microamps). For standardisation, therefore, a resistive load of $10^6$ ohms was used to return the potential difference to the level of about 1 volt. This procedure uses two properties of photo-multipliers (Ref. 17): a) the current output is independent of the load; b) the luminous energy input/electrical energy output characteristics are linear over a very wide range.

Theoretical Basis

The arrangement of the apparatus is shown schematically in figure 17a for recording the shock luminosity and in figure 17b for standardisation. Using the nomenclature adopted in Section 2 above, for a photo-multiplier of sensitivity $s_\lambda$ (i.e. the output current of the photo-multiplier is $s_\lambda$ amps for unit luminous energy received at wavelength $\lambda$) the output current $A_\lambda$ due to a source of luminous intensity $I_\lambda$ in the shock tube is given by:

$$A_\lambda = s_\lambda K_\lambda M_\lambda \theta K_{\text{w} \lambda} I_\lambda$$  (4)

where $K_\lambda$, $M_\lambda$, and $K_{\text{w} \lambda}$ are absorption factors lying between zero and unity to describe the losses at wavelength $\lambda$ in, respectively, the spectrometer/filter train, the mirror and the shock tube window. $\theta$ is the solid angle of the spectrometer slit seen from the shock front.

For the standardisation arrangement, the output current $A'_\lambda$ for a lamp of luminous intensity $I'_\lambda$ at the same wavelength $\lambda$ is given by:

$$A'_\lambda = s_\lambda K_\lambda M_{\text{L} \lambda} \theta' K_{\text{L} \lambda} I'_\lambda$$  (A.1)
where $M_{\lambda}$ and $K_{\lambda}$ are the absorption factors for the mirror and lens, respectively, used to image the lamp filament on the spectrometer slit and $\theta'$ is the corresponding geometrical factor.

The luminous intensity of the shocked gas at wavelength $\lambda$ may then be expressed as:

$$I_\lambda = \frac{M_{\lambda} K_{\lambda} \theta'}{M_{s\lambda} K_{w\lambda} \theta} \cdot \frac{A_\lambda}{A'_{\lambda}} \cdot I'_\lambda$$  \hfill (A.2)

However, the two mirrors are a matched pair of front-silvered reflectors and so $M_{\lambda} = M_{s\lambda}$. The geometrical factors are not functions of wavelength and therefore are in constant ratio. The absorption constants for the shock tube window and the lens used to image the lamp filament are not significant functions of wavelength over the range used (Ref. 30) and so their ratio also is a constant. Let the product of these two ratios be $B$.

For the relative intensity method we now apply relationship A.2 at a second wavelength $\lambda_2$ and obtain:

$$I_\lambda = B \cdot \frac{A_{\lambda_2}}{A'_{\lambda_2}} \cdot I'_\lambda$$  \hfill (A.3)

so that together with equation A.2 we obtain the ratio of the luminous intensities of the shocked gas at wavelengths $\lambda$ and $\lambda_2$:

$$\frac{I_\lambda}{I_{\lambda_2}} = \left( \frac{A'_{\lambda}}{A_{\lambda_2}} \cdot \frac{I'_\lambda}{I'_\lambda_{2}} \right) \frac{A_{\lambda}}{A_{\lambda_2}}$$  \hfill (A.4)

where the quantities in parentheses are all standardisation data and the currents $A_{\lambda}$ and $A_{\lambda_2}$ are the measurements to be made on shocks.

**Experimental Method**

**Summary** The problem now is simply to obtain the values of the standardisation data in equation A.4 taking account of the following conditions:

(i) standardisation measurements to be made at exactly the same wavelength as shock measurements;

(ii) the geometrical factors $\theta$ and $\theta'$ must not vary from experiment to experiment;

(iii) variations in the high tension supplies to the photo-multipliers must not cause significant variation of the photo-multiplier sensitivity;

(iv) the quality of the light from the standard lamp falling on the photo-multiplier cathode must be known accurately. This requires that the luminous flux entering the spectrometer slit must
be from a portion of the standard lamp filament which is at a
uniform temperature while the filament current must be measured
accurately so that this temperature may be found from the lamp
calibration table. In addition the wavelength range \( \Delta \lambda \)
selected by the spectrometer exist slits must be known for the
calculation of \( I_\lambda \);

(v) the anode current of the photo-multipliers must be measured sim-
ultaneously with measurement of the standard lamp conditions;

(vi) voltage measuring devices (i.e. the oscilloscope amplifier ranges
and the digital voltmeter) must be calibrated and the resistances
of the various photo-multiplier anode loads found so that the
anode currents can be determined accurately. (This procedure
has been reported in the main body of this note.)

(i) Wavelength Correspondence. The sensitivity of photo-multiplier tubes is a
strong function of wavelength (Ref. 17). This introduces the requirement that
if equations 4 and A.1 are to be combined to eliminate \( s_\lambda \) and \( K_\lambda \) the wave-
lengths for the two equations must be identical. In practice this need was
easily met: after alignment of the photo-multipliers (using the argon Geissler
tube as source to aid wavelength location) at the particular wavelengths to be
monitored in the next shock run, the standardisation procedure was carried out.
The photo-multipliers were not then moved until the run was completed. (In fact
another standardisation was always conducted immediately after a run to check
consistency: this was always satisfactory.)

(ii) Invariance of the Geometrical Factors. If the ratio of the geometrical
factors \( \theta \) and \( \theta' \) is to be eliminated in the relative intensity procedure then
it is essential that these factors be kept accurately constant for the shock
experiments and for standardisations respectively. This condition was satisfied
by the simple experimental arrangement shown in the photograph (figure 10). The
mirror reflecting light from the shock tube into the spectrometer was fixed in
position, so giving a constant value for \( \theta \). To direct light from the standard
lamp into the spectrometer a second (matched) mirror was inserted between a set
of plastic-covered steel guide posts. This ensured high reproducibility in the
angle of the mirror, which always gathered the whole light cone.

(iii) Effect of High Tension Variations. The \( 1P28 \) photo-multipliers were
supplied at the maximum recommended high tension of 1250 V to obtain the high-
est sensitivity compatible with reasonable life. The power supply (Hammer Type
N.401) was well stabilised and provided with a voltmeter and a fine control.
The meter could be read to \( \pm 5 \) V. The voltage of 1250 V could therefore be
applied to the photo-multipliers within an error margin of \( \pm 5 \) V, any transient
variation being eliminated by the stabilising effect of the supply unit while
slow variations were manually corrected. The effect of this \( \pm 0.4\% \) uncertainty
is reported in the main body of this note, i.e. the ratio of photo-multiplier
outputs varied by only \( \pm 0.3\% \).

(iv) The Standardisation Illumination. The standard lamp (E.21) used in this
work was supplied by Phillips of Eindhoven together with a calibration table
giving the filament current/filament temperature relation when the lamp is
operated in the recommended fashion. The various details of experiment and
calculation are described below.
1. The calibration table refers only to the temperature of a portion of the lamp filament near an index mark. It is therefore essential that the light entering the spectrometer be derived solely from this area of the source. The problem of filling the 15 mm height of the spectrometer slit with the 5 mm (approx.) height of the region of uniform temperature on the filament was solved by using a lens to throw an enlarged (inverted) image of the filament via a mirror onto the spectrometer slit. The conditions to be satisfied were, first, to provide sufficient magnification; second, to ensure complete "filling" of the spectrometer cone (f/24); third, to have the lens at least 50 mm from the filament as the lamp window prevented smaller separations. Simple lens calculations showed these conditions could be satisfied by a lens of 50 mm focus and at least f/6 aperture positioned 59.3 mm from the filament, which was to be at a total optical distance (via the mirror) of 237.1 mm from the spectrometer slit. The lens must be well corrected for colour aberrations. The lens used for the present work was a Ross Resolux 50 mm f/3.5 enlarging lens stopped down to f/4.5 to ensure high resolution together with over-fill of the spectrometer light cone. It may be noted that enlarging lenses are particularly suitable for such application as they are computed especially to give good performance at small object-image separations.

2. The recommended operating conditions for the lamp required that DC current be used. It was found that a filament current of between 9 and 10 amps was required to give adequate intensity for standardisation at both red and blue ends of the wavelength range used. A control unit was built to provide a steady current of up to 14 amps (figure 18). In supplying this current a high degree of stability was essential and the necessity to use DC was an unwelcome restriction. The principle adopted was to power the lamp from a 12 V tractor battery, which was simultaneously trickle-charged from the laboratory DC supply to maintain the battery state. (Alternatively, the method could be said to power the lamp from the DC supply with a 12 V battery acting as stabiliser.) The method was quite successful and the current through the lamp could be kept at, say, 9 amps for more than 8 minutes with a maximum deviation of ± 0.4 milliamps, i.e. the unsteadiness of the filament current was within ± 0.04%. For accurate measurement, the current was passed through a standard 4-terminal 0.01 ohm resistor in series with the lamp filament. The consequent potential difference across the voltage terminals of the resistance was measured on a Pye Universal Precision Potentiometer, with the null-point shown by a lamp-and-scale-galvanometer (figure 19). Including uncertainties in the EMF of the standard cell and in the calibration of the 0.01 ohm resistor the total error in measuring lamp current was found to be less than ± 0.01% and so negligible compared to the current unsteadiness of ± 0.04%.

The standardisation procedure for the relative intensity method requires knowledge of the distribution of luminous energy over the wavelength range rather than the absolute value of the total energy flux. For calculation of \(I'\lambda\), therefore, the colour temperature of the filament is required (Ref. 34). The lamp calibration table provides these values as a function of the filament current. The other quantity required is the wavelength elementary range \(d\lambda\) and this is found by measuring the widths of the spectrometer exit slits with a travelling microscope and multiplying by the spectrometer dispersion. For calculation of \(I'\lambda\) Wien's Law may be used, as for the wavelength range 4000 Å to 7000 Å the laws of Wien and Planck differ by less than 0.001%. 
Hence

\[ I' \lambda \propto \frac{c_1}{\lambda^5 \exp \left( \frac{c_2}{\sqrt{\lambda T}} \right)} \quad \text{(A.5)} \]

The proportionality is due to solid angle selection, spectrometer losses, etc. and vanishes, together with \( c_1 \), as soon as ratios are taken for the relative intensity technique. \( c_2 \) is a universal constant (1.4384 cm.deg), \( T \) is the colour temperature in deg K while \( \lambda \) and \( d\lambda \) are the wavelength and wavelength range in centimeters.

**Errors.** The error in measuring the lamp filament current has been shown to be determined by the \( \pm 0.04\% \) unsteadiness of the DC supply rather than the method of measurement. Inspection of the calibration table of the standard lamp shows that for colour temperature \( T \) in deg K and current \( A \) in amps:

\[ T = 144A + 850 \quad \text{(A.6)} \]

(but this approximate equation was not used to find \( T \) for a measured value of \( A \)). The error \( \Delta T \) in \( T \) corresponding to an error \( \Delta A \) in \( A \) is therefore \( 144 \Delta A \).

Thus for an uncertainty of \( \pm 0.04\% \) in \( A \) the error in \( T \) is \( \pm 0.5 \) degK, as \( A \) and \( T \) are respectively about 9 amps and 2150 degK. However, the calibration table supplied with the lamp already has a stated error of \( \pm 5 \) degK, showing that accuracy in finding \( T \) is limited by the lamp calibration and not by local experimentation, which has 10 times the precision of the provided calibration. The conclusion here must be that the expected error in \( T \) at 2150 degK is \( \pm 5 \) degK or \( \pm 0.23\% \). Remembering that the final aim of the standardisation procedure is the evaluation (equation A.4) of the ratio of the standardising intensities at two different wavelengths, i.e. \( R = \frac{I'_1}{I'_2} : \frac{I'_2}{I'_1} \), it is easily shown from equation A.5 that:

\[ \frac{\Delta R}{R} = 5.5 \frac{\Delta T}{T} \quad \text{(A.7)} \]

so that the error in the ratio measurement amounts to \( 5.5 \times 0.23\% \), i.e. the final error in the standardising intensity ratio is \( \pm 1.3\% \).

(v) Measurement of Photo-Multiplier Current. This was a relatively simple procedure. For the standardisation experiments the photo-multiplier output (figure 8) was connected across a \( 10^6 \) ohm resistance (the precise value of which was separately found) and the consequent potential difference across the resistor displayed on a digital voltmeter (figure 19). This method of current measurement greatly facilitated simultaneous measurement of photo-multiplier current and standard lamp current. Having set the lamp current near the desired value, a few moments were allowed to elapse for the steady state to be reached. The potentiometer reading the lamp current was then balanced and the slide-wire contact left closed. The lamp-and-scale galvanometer then showed, by small excursions from the null-point, any deviations of the lamp current from the set value while the digital voltmeter displayed continuously the potential difference due to the photo-multiplier current. It was found simple to observe both displays at once (figure 19) and to note the digital voltmeter indication when the galvanometer had remained steadily at the null-point for a while.

**Errors.** The digital voltmeter gave a measurement, typically 1.043 V, which had an uncertainty of \( \pm 0.1\% \). The errors in calibrating the voltmeter and the
$10^6$ ohm anode load were negligible in comparison. The unsteadiness of $\pm 0.04\%$ in the lamp current was not relevant here as measurements of the photo-multiplier currents were made only when the galvanometer showed no deviation from the set value of the lamp current. Each photo-multiplier current measurement had to be corrected by subtracting the dark current value (obtained by closing the spectrometer shutter) so that the total error for each value of $A'_\lambda$ was $\pm 0.2\%$. As the final figure required here (equation A.4) is the ratio of photo-multiplier currents at wavelengths $\lambda$ and $\lambda_2$, the final error in determining $A'_\lambda : A'_\lambda$ is $\pm 0.4\%$.

Conclusions

The method for standardisation of the photo-multipliers has been described. The purpose has been to find values for the ratio $I'_\lambda : I'_\lambda$ in equation A.4 together with the corresponding ratio for $A'_\lambda : A'_\lambda$. Section (iv) showed how to derive the intensity ratio from the measured lamp currents and section (v) showed the method of finding the photo-multiplier current ratio. The error in the first operation has been found to be $\pm 1.3\%$ and for the second measurement $\pm 0.4\%$. The overall error is therefore $\pm 1.7\%$, which is seen to be small compared with errors in the principal measurements.
The need for temperature measurement in strong shock waves is discussed briefly and requirements for a suitable experimental method are established. Spectrometric methods are shown to be appropriate and the radiative line intensity technique is discussed. Experiments using photography for both time-integrated and time-resolved exploration of the argon emission spectrum in a $M_s = 11.3$, $P_1 = 3$ torr shock are described. The results were used in the main series of experiments, which gave time-resolved records from photo-multipliers monitoring the intensities of selected neutral argon lines. These records are analyzed, including self-absorption correction, to a time-resolved excitation temperature profile for the neutral argon atoms. The probable uncertainty in these measurements is computed and the shape of the temperature profile is discussed. The conclusions are that the atom excitation temperature rises to an approximately constant value of about $11,500^\circ K$ behind the shock front, which is in fair agreement with the calculated equilibrium value, but that uncertainties were too great to allow, for example, cooling calculations based on the shape of the temperature profile. Experimental improvements are suggested to reduce uncertainties and allow detailed analyses in future work.
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