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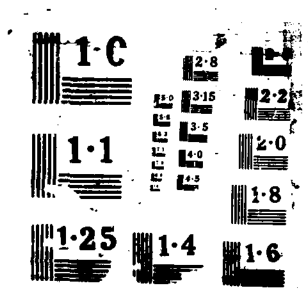
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MELBOURNE, VICTORIA

REPORT

MRL-R-1054

TEMPERATURE ESTIMATES FOR A FREE FLOWING RAILGUN PLASMA

G.A. Clark and V. Kowalenko

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REPORT

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TEMPERATURE ESTIMATES FOR A FREE FLOWING RAILGUN PLASMA

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ABSTRACT

In-bore spectroscopic observations of a free-flowing plasma for wavelengths between 3000^0A and 6250^0A were made for a series of railgun firings. In this report the experimental arrangement for the series is described dand the results are presented. Atomic species present in the plasma are identified from absorption and emission spectra. Calculations of the degree of ionisation of these species are then used to produce a temperature estimate between 11×10^3 K to 25×10^3 K for the railgun plasma. A comparison of theoretical values of the plasma electrical conductivity with values obtained from muzzle voltage records indicates that the peak plasma temperature is approximately 11×10^3 K, which is consistent with estimates obtained from the spectra.

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POSTAL ADDRESS: Director, Materials Research Laboratories
P.O. Box 50, Ascot Vale, Victoria 3032, Australia

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SYMBOLS TABLE

A	=	cross-sectional area of railgun bore, m^2
α	=	ratio of the number density of electrons to the number density of heavy particles
B	=	magnetic field, T
γ_E	=	ratio of conductivity to that in a Lorentz gas
g_{ji}	=	degeneracy factor of an ion in the i-th excited level of the j-th ionisation state
I	=	current flowing in railgun, A
I_j	=	ionisation energy needed to ionise the atom j times
J	=	current density, A/m^2
K	=	dimensionless parameter in Saha's equation
k_B	=	Boltzmann's constant, 1.3807×10^{-23} J/K
λ	=	wavelength of light, Angstroms
L'	=	inductance per unit length of railgun, H/m
m_e	=	electron mass, kg
m_o	=	atomic mass of ionised or neutral atom, kg
n_e	=	electron number density
ξ	=	dimensionless distance
P	=	plasma pressure, Pa
ρ	=	plasma mass density, kg/m^3
T	=	plasma temperature, K
U_{ji}	=	energy of the i-th electronic level of an ion in the j-th ionisation state
x_j	=	ratio of the number density of ions ionised j times to the total number density of heavy particles
Z_j	=	electronic partition function
Z	=	ionic charge

TEMPERATURE ESTIMATES FOR A FREE FLOWING RAILGUN PLASMA

INTRODUCTION

This report documents spectroscopic measurements for wavelengths between 3000°A and 6260°A of a free flowing plasma taken in a series of firings using a sma l bore (10 mm x 10 mm) railgun and reports estimates of plasma temperature derived from these observations. The observations were made along the bore of the railgun using a 0.75 m Jarrel Ash Spectrometer and recorded on photographic film. The spectrum is typically a continuum with a number of absorption lines.

The plasma armatures were created by electrically exploding a number of different metallic foils. Various ionised elements within the plasma were identified from the spectra. Calculations for the degree of ionisation for first- and second-ionised species were then used to obtain an estimate of the peak plasma temperature. These calculations are based upon certain assumptions which are discussed in this report.

This report is organised into 7 major sections. In Section 1, a brief history of the experimental and theoretical work on estimation of the temperature of railgun plasmas is presented whilst in Section 2, the experimental arrangement for the series is described. In Section 3, the theory used to obtain the temperature estimate from the spectra is presented in detail. The experimental results are presented and discussed in Section 4. The results of Section 4 are compared with the results obtained by other railgun workers in Section 5. In Section 6, the temperature is estimated from the electrical conductivity of the plasma and compared with the experimental estimates of the temperature reported in Section 4. Finally, in Section 7 we present a conclusion from the results described in this report.

1. BACKGROUND

In 1978, Rashleigh and Marshall [1] reported details of experiments with an inductively-driven railgun in which a cubic lexan projectile was accelerated to 5.9 km s^{-1}. This pioneering work has been followed by considerable railgun development and related equation of state research on plasmas. However, little experimental research into the temperature of the plasma armature within the bore of the railgun has been done.

The first attempt to measure the temperature of a railgun plasma in recent times was made by Parkes and Strachan [2]. Essentially they recorded the spectral emissions from the muzzle flash after the projectile had left the railgun. By identifying ions in the muzzle flash, an estimate of the peak temperature was made by assuming that 1/5 of the ionisation energy of an ion in a plasma represented a measure of its temperature. For their experiment, a temperature of $\gtrsim 58 \times 10^3$ K was estimated.

In 1980, McNab [3] calculated the temperature of the plasma in the Rashleigh-Marshall railgun by using a simple form of Saha's equation for the degree of ionisation. Assuming that only single ionisation occurred in the plasma, he predicted that the plasma would have a temperature of $(44 \pm 13) \times 10^3$ K and an ion density of $(8 \pm 1) \times 10^{25}$ m^{-3} for a current of 300 kA in the circuit.

Powell and Batteh [4] (hereafter referred to as PB) followed with more rigorous one-dimensional magnetohydrodynamic (MHD) calculations and a form of Saha's equation which allowed for the occurrence of double ionisation in the plasma. Some major assumptions in their model were that the plasma obeyed the ideal gas law and that the plasma was in local thermodynamic equilibrium (LTE). When applied to the Rashleigh and Marshall (hereafter referred to as RM) experiment [1], their code estimated plasma temperatures peaking at 72×10^3 K with electron densities of 2.2×10^{26} m^{-3} at peak pressures around 230 MPa and peak currents of 300 kA. This work was later developed into a two-dimensional (2-D) code by Powell [5], which made similar assumptions to those in the 1-D model. Estimates of peak temperatures in the RM experiment were revised to 47×10^3 K for electron densities of 2.5×10^{26} m^{-3}. Powell accounted for the temperature drop as being due to the greater surface area available for radiation of energy from the plasma.

In 1983, Thio [6] published details of his 1-D railgun computer simulation code in which he assumed only single ionisation. His code, PARA, used quasi-static MHD equations to model the time varying properties of the plasma whereas McNab[3] and PB [4] were essentially steady state analyses. Thio predicted temperatures of 26×10^3 K at 50 MPa for peak currents of 125 kA in a 6 x 8 mm bore railgun.

During 1983, spectroscopic observations of the plasma armature were made on a small bore railgun at MRL - the RAPID railgun. Spectroscopic observations were made by Richardson and Clark [7] of a puff of plasma ejected through a hole in the sidewall of a railgun. This work revealed that the plasma was optically dense because the spectrum contained numerous line reversals superimposed upon a continuum background. They suggested that more useful spectroscopic results would be obtained in the ultra violet (UV) spectral region where the continuum would reduce in intensity.

The above work was continued by Richardson in 1983 with spectroscopic studies of the muzzle flash of a RAPID railgun [8]. This work revealed that ablation of rail material into the plasma armature occurred. Using his spectral results, Richardson estimated that the plasma temperature was at least 30 x 10^3 K. Peak current in these railgun experiments was approximately 80 kA.

Also in 1983, Marshall [9] obtained an estimate of the plasma armature temperature of 43 x 10^3 K for a plasma current of approximately 30 kA by treating the flow of a plasma through a hole in the sidewall of a railgun as the flow of a neutral gas through a nozzle.

Gathers and Hord [10] made measurements of railgun plasma temperatures by using two-colour pyrometery and assuming black body radiation. They reported a mean peak temperature of approximately 5.7 x 10^3 K for a stationary arc in a railgun. The magnitude of the current flowing through the stationary arc was not reported.

In 1986 at the Electromagnetic Launcher Technology Conference, Marshall [11], Tidman et al [12] and Uglum [13] presented papers on railgun plasmas. Marshall [11] reported a temperature of 50 x 10^3 K in a plasma emerging from the muzzle of a railgun. The temperature was calculated from a measurement of the speed of sound in the plasma. Peak current in the railgun was approximately 100 kA.

Using a turbulent hydrodynamic approach, Tidman et al [12] calculated peak temperatures less than 25 x 10^3 K for the plasma surface. In these calculations the current and bore of the railgun were respectively 200 kA and 10 mm in diameter. According to these authors, turbulence causes a cooling of a railgun plasma with a resultant increase in its resistivity.

Finally, Uglum [13] reported spectroscopic results of a railgun muzzle flash. This work was similar to that done by Parkes et al [2]. Spectral lines belonging to CuI, CuII, AlI and SiI were identified.

As is evident from the above history, little work in the field of experimental plasma diagnostics for the temperature measurement of a railgun plasma armature within the bore of the railgun has been reported. The plasma armature is not an ideal plasma to model for it is composed of many different ionic species [8] and on some occasions its interior has density and temperature gradients [5,14]. Accordingly, numerous assumptions have to be made about the plasma so that theory can yield some insight into its properties. These are discussed later in this report.

The methods for estimating the plasma temperature presented in this report should be applicable to all the experiments discussed in this section, even though railgun currents were varied.

2. EXPERIMENTAL ARRANGEMENT

The experimental arrangement of the MRL railgun is shown in Figure 1. A 200 μF, 10 kV capacitor (Maxwell, Model 33778) was attached to a 1 turn, 1 μH inductor manufactured from 100 x 6.3 mm copper bar. The main switch was a simple copper-foil tipped-plunger which closed a gap between two copper-tungsten cylindrical electrodes. The self-activating crowbar-switch was positioned directly between the terminals of the capacitor: its mode of operation is described in Reference [15]. Each firing was carried out with the capacitor bank charged to 6 kV. The peak current was between 78.1 kA and 79.2 kA for each firing.

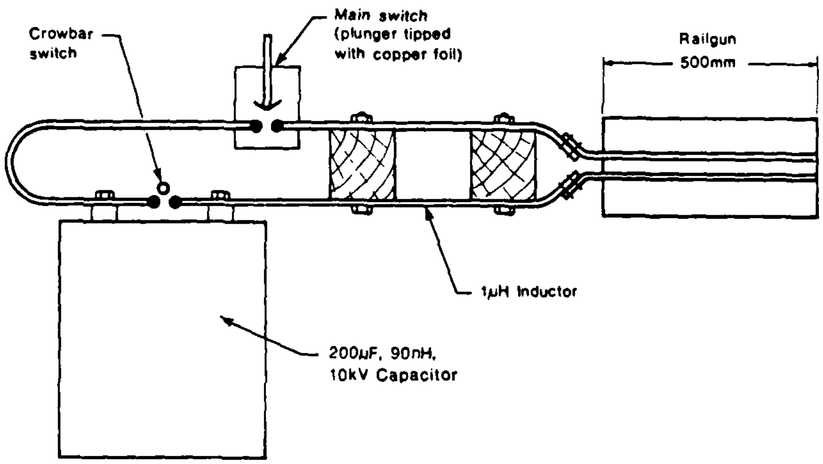

FIGURE 1 MRL railgun and energy store

The railgun (which was open to the atmosphere) was 500 mm long, manufactured from two 27 mm thick sheets of laminated polycarbonate and similar in design to the earlier RAPID railgun system [16]. The bore was 10 mm square as shown in Figure 2. Cadmium-copper rails were used because of their high conductivity and tensile strength. The cadmium content was 0.6 percent.

The initial plasma was created from the electrical explosion of a foil which shorted the rails at the breech end of the railgun. The foil was held in place by wrapping it around a polycarbonate plug which was pushed between the rails (Figure 3). A wedge behind the plug secured the plug when the foil was exploded.

Closure of the plunger-switch in the circuit (Figure 4) produced an electrical explosion of the metallic foil, which generated a plasma armature. The plasma was accelerated along the rails by the Lorentz ($\underline{J}$ x $\underline{B}$) force. It should be noted that there was no projectile ahead of the plasma in this series of firings and hence the term "free flowing" is used.

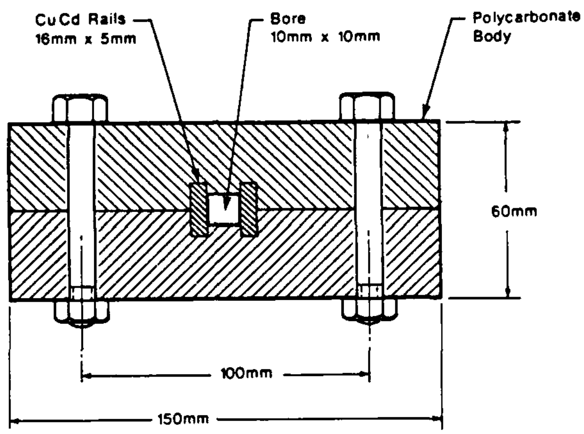

FIGURE 2 Cross-section of the railgun

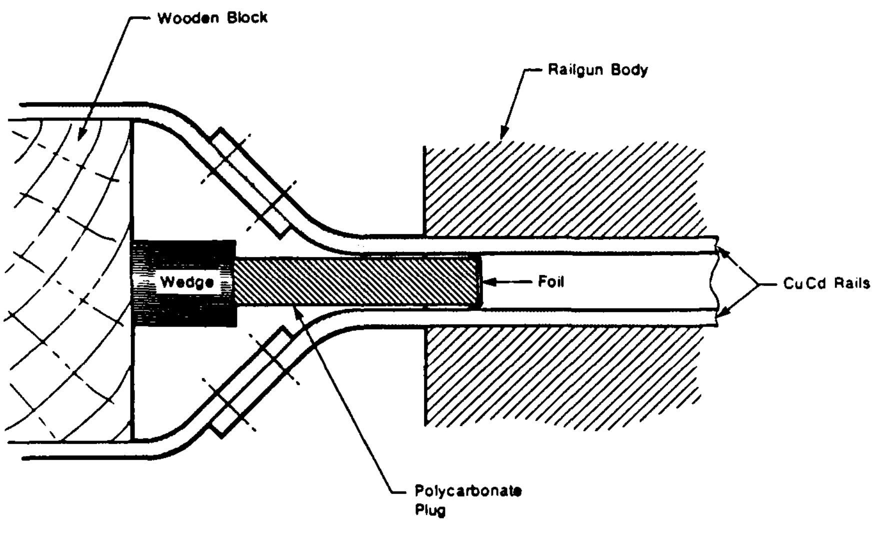

FIGURE 3 Means of holding the foil between rails

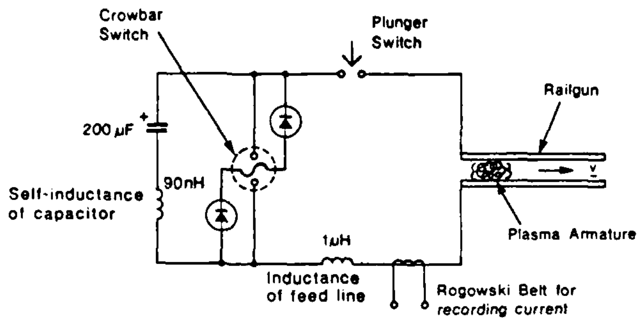

FIGURE 4 Circuit diagram of the railgun

The muzzle voltage and current were recorded by the transient recorders described in Reference [16]. After each firing the rails were cleaned by swabbing the bore with alcohol.

Creation and acceleration of the plasma armature along the railgun bore was recorded photographically through the transparent wall of the railgun by an STL image-converter camera. The camera was positioned at the side of the launcher so that it viewed the entire bore length, (Figure 5). Marker bars along the length of the gun provided position co-ordinates on the photographic record. The camera was used in a streak mode with a total streak time of 200 µs or 400 µs. Triggering of the camera was achieved by directing the light pipe from the optical trigger input at the main arc switch.

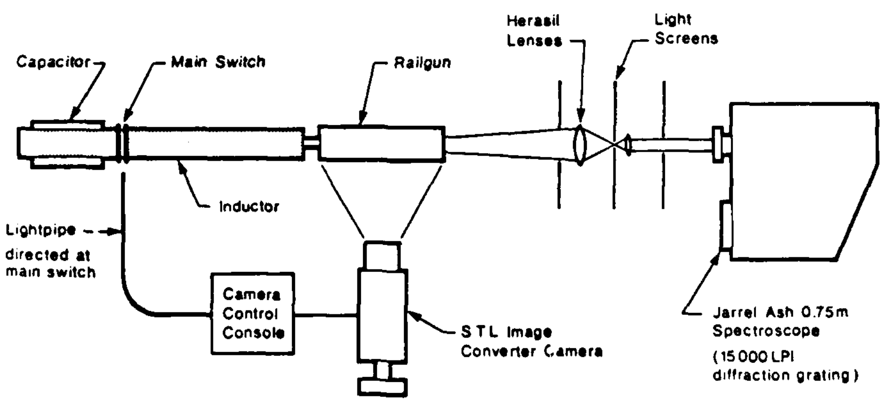

FIGURE 5 Relative positions of the image-converter camera and the Jarrell Ash Spectroscope

The Jarrel Ash spectroscope was positioned approximately 3 m away and directly in front of the railgun muzzle as shown in Figure 5. The entrance slit and optical axis of the spectroscope were aligned with the lengthwise central axis of the railgun-bore. Fused-silica (Herasil) lenses, which are transparent to ultra-violet (UV) light, provided illumination of the entrance slit of the spectroscope with light emanating from the plasma. The slit width was set at 20 μm, 5 mm high, and well-focussed lines were recorded on 150 mm x 100 mm Ilford HP5 film. Because there was low light illumination at the focal plane, the film had to be force-developed in microphen to 6400 ASA to obtain a good photograph of the spectrum.

Reference lines were obtained on the film by using an atomic absorption, hollow cathode, copper reference-lamp placed along the optical axis near the muzzle of the railgun. Adjustable optical masks at the focal plane of the spectroscope enabled the reference-spectrum to overlap the plasma-spectrum without movement of the film. Thus the spatial relationship between the reference and the plasma spectrum was direct and fixed.

The recorded spectrum was integrated over the time interval beginning with the creation of the plasma and ending when there was no current in the railgun. The spectral range was from 3000^{o}A to 6260^{o}A.

Spectral lines were resolved on the film record by using a model 24-201 Jarrel Ash microphotometer. Chart records of the copper reference-spectrum were made from each record in order to determine the dispersion factor, (wavelength/unit distance). The copper lines chosen for this determination were 3247.54^{o}A and 5218.20^{o}A. The resultant wavelength determinations were accurate to better than 0.5^{o}A on the reference films. It should be noted that a dispersion factor was required for each film because each film was slightly different. The reason for these differences is unknown but is probably due to shrinkage or expansion of the film during processing.

A different type of metallic foil was used in each firing (Table 1). The foil materials, together with the materials in the launcher and the atmosphere, provided a range of 1st and 2nd ionisation potentials from 5.21 eV to 35.12 eV, (Table 2). The choice of foils was determined by the requirement for a spread of ionisation energies as explained in the next section.

The masses of aluminium and zinc were chosen to provide (approximately) the same number of atoms of each material. This was not done for $BaCl_2$ because its powdered form required wrapping in aluminium foil when packed between the rails.

TABLE 1

Foils used in the series of firings

Shot No.	Foil Material	Mass
1	Aluminium Foil (0.050 mm thick)	9.3 mg
2	Zinc Foil (0.025 mm thick)	22.7 mg
3	$BaCl_2.2H_2O$ (wrapped in Al foil)	59 mg $BaCl_2.2H_2O$ 29 mg Al

TABLE 2

List of elements and their respective ionisation energies [17]

Neutral atom & ion	Ionisation Energy (ev)	Source
Cu	7.724	CuCd rails
Cu^+	20.29	CuCd rails
Cd	8.991	CuCd rails
Cd^+	16.904	CuCd rails
Al	5.984	Foil Al
Al^+	18.823	Foil Al
Zn	9.391	Foil Zn
Zn^+	17.96	Foil Zn
Ba	5.21	Foil ($BaCl_2.2H_2O$ salt)
Ba^+	10.001	Foil ($BaCl_2.2H_2O$ salt)
Cl	13.01	Foil ($BaCl_2.2H_2O$ salt)
Cl^+	23.8	Foil ($BaCl_2.2H_2O$ salt)
H	13.595	Foil ($BaCl_2.2H_2O$ salt) &
H^+	-	railgun body
O	13.614	Atmosphere & railgun body
O^+	35.108	Atmosphere & railgun body
C	11.26	Atmosphere & railgun body
C^+	24.376	Atmosphere & railgun body
N	14.53	Atmosphere
N^+	29.593	Atmosphere

3. THEORY

From the work of Richardson [7], it is known that the spectrum (within the visible region) produced by a railgun plasma consists of line reversals superimposed upon a continuum. Line reversals indicate that the plasma is optically thick (strongly absorbing).

Cowan and Dieke [18] have shown that line reversal occurs when the ratio of the number density of emitting atoms to the number density of absorbing atoms is not constant. This occurs when a source is not uniformly excited. For such sources, eg. metal arcs and most likely railgun plasmas, it is usual for the excitation to decrease from some inner portion of the source to the edge of the source, [18]. Furthermore, if there is only a thin, cool (absorbing) layer at the edge of the source and excitation increases rapidly towards the interior, it is highly possible that in such cases, line reversals can be used to identify the excited atoms in the interior of the plasma. In addition, according to Reference [19], line reversals will occur for ionised species. It is assumed that the above argument for excited atoms applies to ions.

The plasma temperature can be estimated by determining the various species in the railgun plasma and then using the method of PB [4] to evaluate the degree of ionisation. In their paper, and also in a later work by Powell [5], the degree of ionisation for copper is calculated as a function of temperature by using Saha's equation and assuming that only first and second ionisations occur in the plasma. Using this facet of their work, the following method was devised to estimate the plasma temperature.

If the atomic masses of the atoms in the plasma are almost the same, then momentum transfers [20] can be neglected and the partition of energy between the different elements of the plasma will depend largely on their respective concentrations assuming each of the respective concentrations of atoms or ions is at the same (average) temperature. Therefore, spectral emissions from each concentration in the plasma is representative of not only the individual species but the plasma as a whole.

Specifically, spectral emissions from each ion concentration will indicate the degree of ionisation reached by each element belonging to the plasma. For example, we know from PB's work that there is no significant 2nd ionisation below 16.3×10^3 K for a copper plasma at 10 MPa. Therefore, if we only detect single ionised species, then the peak temperature for a copper plasma is below 16.3×10^3 K at 10 MPa. Conversely, the presence of 2nd ionisation means that the peak temperature is above 16.3×10^3 K.

If the calculations are extended to include elements with different ionisation energies, then the range for the peak plasma temperature is narrowed by identifying the presence or absence of ionised species. For this reason, a number of elements were introduced into the railgun plasma. These elements and those of the rails, gun-body and the atmosphere provided a range of ionisation energies from 5.21 eV(Ba^+) to 35.108 eV(O^{++}). For each element (ten in all), the degrees of first and second ionisation were calculated at a fixed pressure using Saha's equation.

In order to apply Saha's system of equations to a railgun plasma the following assumptions are made:

(1) The magnetic field does not greatly influence the equations and the energy levels used in evaluating the partition functions.

(2) A railgun plasma is in "Local Thermodynamic Equilibrium" (LTE), which means that the densities in specific quantum states are those pertaining to a system in complete thermodynamic equilibrium with the same total mass-density, temperature and chemical composition as the actual system. LTE can be expected to hold for dense laboratory plasmas where collisional processes involving free electrons are predominant [20].

These assumptions are discussed in conjunction with the experimental results in Section 4.

Saha's system of equations [5] is:

$$\frac{x_{j+1}\alpha}{x_j(1+\alpha)} = \frac{2}{P}\frac{Z_{j+1}}{Z_j}\left(\frac{m_e}{2\pi\hbar^2}\right)^{3/2}(k_BT)^{5/2}e^{-I_j/k_BT} = K_{j+1}(T,P) \qquad (1)$$

where x_j = ratio of the number density of ions ionised j times to the total number density of heavy particles in the plasma,
m_e = electron mass,
k_B = Boltzmann's constant,
I_j = ionisation energy needed to ionise the atom j times
P = the plasma pressure,
α = ratio of number density of electrons to the number of heavy particles = $\Sigma j x_j$,
T = the absolute temperature of the plasma,
and Z_j = electronic partition-function for the ion ionised j-times (i.e. an ion in the j-th ionisation state).

The x_j's are normalised so that their sum equals unity, i.e. $\sum_j x_j = 1$. The electronic partition function is defined by:

$$Z_j = \sum_i g_{ji} e^{-U_{ji}/k_BT} \qquad (2)$$

where U_{ji} = energy of the electronic state of the i-th excited level of an ion in the j-th ionisation state
and g_{ji} is the degeneracy factor for that level.

From Equation (1) the ionisation of the j-th ion depends on the ionisation of the (j+1)-th ion. When only single and double ionisation is considered, the parameter α becomes:

$$\alpha = x_1 + 2x_2 \qquad (3)$$

So that Equations (1) become:

$$\frac{x_1(x_1 + 2x_2)}{(1-x_1-x_2)\ (1+x_1+2x_2)} = K_1(T,P) \tag{4a}$$

and

$$\frac{x_2(x_1+2x_2)}{x_1(1+x_1+2x_2)} = K_2(T,P) \tag{4b}$$

Equations (4a) and (4b) can be rewritten in the following forms as given in PB:

$$x_1 = \frac{K_1 x_2}{2\ K_2}\ [(1 + \frac{4K_2(1 - x_2)}{K_1 x_2})^{1/2} - 1] \tag{5}$$

and

$$x_2 = \frac{K_2}{K_1[(1 + \frac{4K_2(1-x_2)}{K_1 x_2})^{1/2} - 1]} \cdot \frac{(2 + 3K_1)x_2}{1+K_1}\ [\{\frac{4K_1(1+K_1)(1+x_2-2x^2)}{x_2^{\ 2}(2+3K_1)^2} + 1\}^{1/2} - 1]. \tag{6}$$

Equation (6) is solved iteratively by assuming a value for x_2 on the right hand side and then calculating a new x_2 value. The process is repeated until the old and new value agree to the desired accuracy. The degree of first ionisation x_1 follows from Equation (5).

PB used firstly 10, and then 15 terms in the partition function. They found no discernible differences in the results. However, Griem [20] states that all levels up to the reduced ionisation level have to be considered because for higher orbital momenta the statistical weights are high and their omission will lead to serious errors in the excited-state contribution to the partition function.

To avoid any potential error, three sets of calculations for copper (the computer code for which is listed in the Appendix) were carried out in which the first 15 terms were used, then all the terms up to the ionisation level and finally, all the documented terms in Moore [21]. The iteration was continued until successive values of x_2 agreed to within 1×10^{-5}, (as in PB). The results of the calculations are shown in Figure 6.

The graphs for the relative concentrations of first and second ionisation obtained by truncating the sums in the partition functions to the first 15 energy levels matched the graphs given in PB and hence provided a check on our calculations. Incorporating additional excited energy levels modified the graphs for temperatures above 13×10^3 K. The inclusion of additional energy levels up to the ionisation limit of each species lowered the concentration of singly ionised atoms and raised the temperature at which the peak in first ionisation occurred. However, the relative concentration of doubly ionised atoms for this case remained unaffected. The inclusion of all the energy levels documented in Moore to evaluate the partition functions lowered the concentration of singly ionised atoms for temperatures between

13 x 10^3 and 30 x 10^3 K. For temperatures above 30 x 10^3 K, the concentration of singly ionised atoms was above that given in PB while the concentration of doubly ionised copper at a given temperature was less.

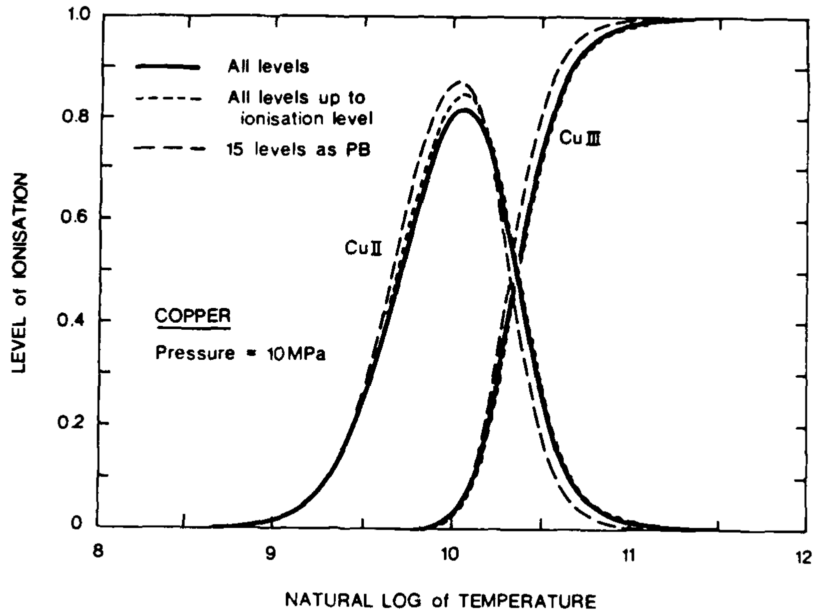

FIGURE 6 Level of ionisation of copper versus $\log_e$ (temperature) at a pressure of 10 MPa.

As a consequence of the above results, further calculations in this report include all the values documented by Moore [21] even though Griem [20] states that only levels up to the reduced ionisation energy should be considered. Griem was concerned that in summing the energy levels in the partition functions, the above procedure would result in a given state being summed twice. It was considered that as the levels documented by Moore are essentially all observed values, duplication of a given state in the summations would not occur.

4. EXPERIMENTAL RESULTS

The spectra obtained from the 3 firings are shown in Figure 7. Line reversals and the copper reference-spectrum are clearly identified.

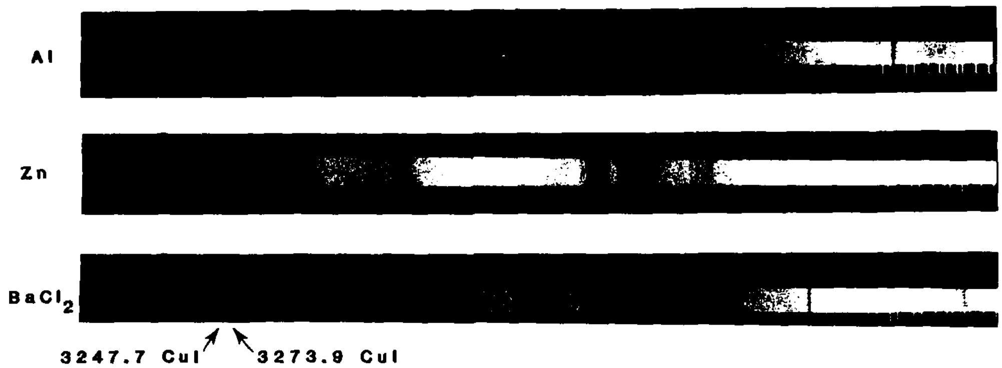

FIGURE 7 Spectra of Al, Zn and $BaCl_2$ plasmas

Microphotometer traces made from the films (Figures 8a, 8b and 8c) were read on a Farol-chart reader. Dispersion (°A/cm) of the wavelengths on the chart records was determined using the 3273.96°A and 5218.8°A lines in the copper reference spectrum. Razor scratches across the reference and plasma spectra provided the reference line from which readings were taken. Measurement accuracy was ±0.5°A. Line positions in the copper reference-spectrum were determined to the centre line at the half-height level. This method was also used for measuring the position of the line reversals. When it was not possible to determine the half height (e.g. for small line reversals), the peak position was measured. It should be noted that Figures 8a, 8b and 8c do not show the detail that the original chart-recorder records revealed.

To identify an ion, the measured wavelengths of the line reversals were compared with the most prominent wavelengths between 3000°A and 6250°A for the excited atom or ion (Table 3). These lines were determined from line intensities listed in References [17], [23] and [24]. An excited atom or ion was considered to be present if the three most prominent lines between 3000°A and 6250°A were identified. This is considered a reasonable approach since the transition probabilities [17,22] for the CuII and ZnII lines listed in Table 3 have a similar though in general slightly greater magnitude to those for CuI and ZnI respectively. Assuming that line absorption occurs for the single-ionised species, it follows that if, for example, ZnII and CuII are not detected in the plasma, then their concentration are below the concentrations of the detected neutral species. A similar argument is expected to apply to AlII although the transition probabilities for the lines considered in this case are not available.

The wavelengths measured from Firings 1, 2 and 3 are tabulated in Tables 4, 5 and 6 respectively together with the possible identification of

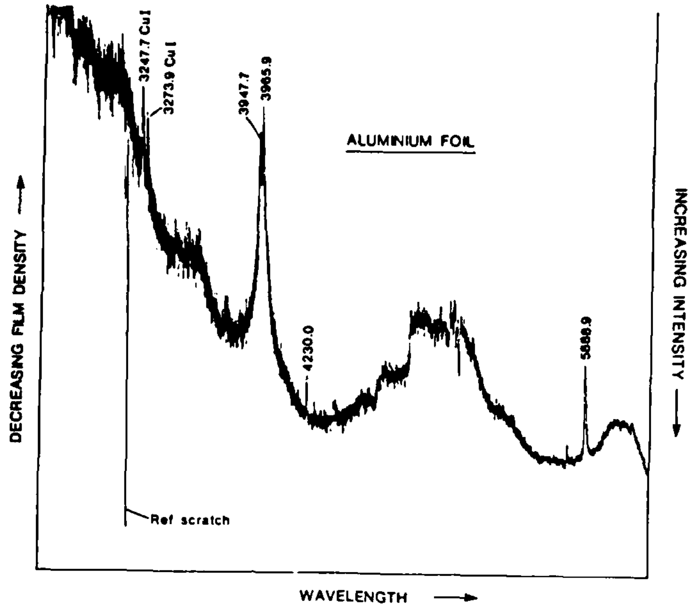

FIGURE 8a Microphotometer trace of Firing No. 1: Al foil

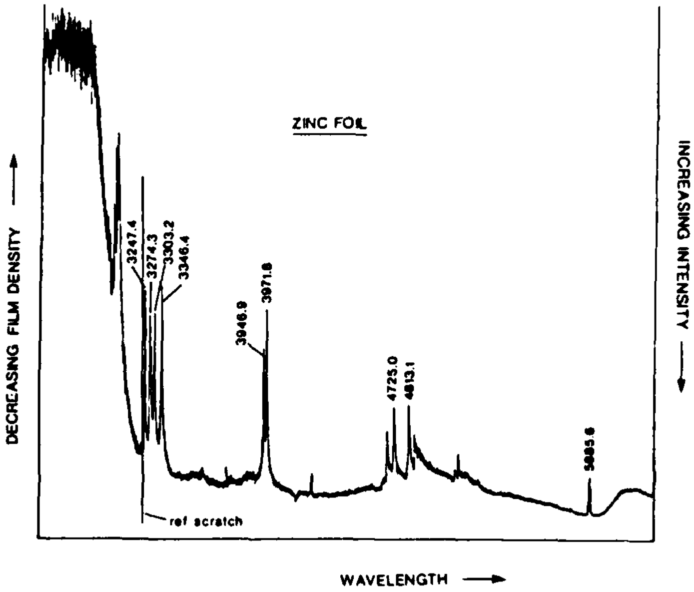

FIGURE 8b Microphotometer trace of Firing No. 2: Zn foil

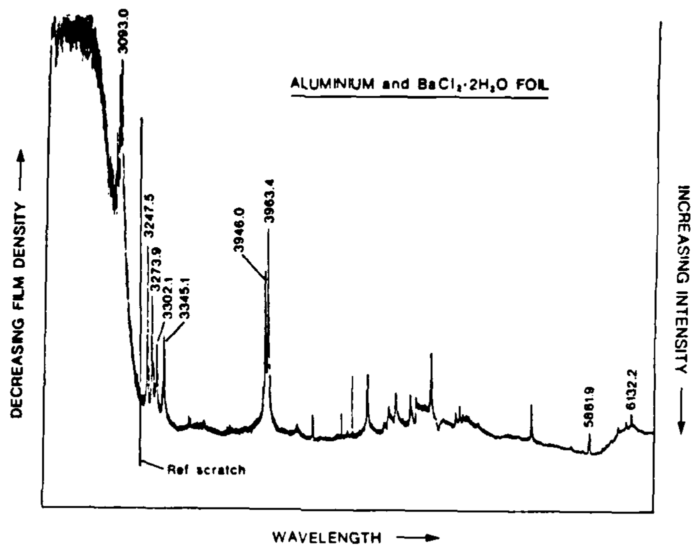

FIGURE 8c Microphotometer trace of Firing No. 3: $BaCl_2$ in Al foil

the lines. Table 7 lists the identified species as determined by the previously stated criteria.

The first notable feature of the results appearing in Table 7 is the lack of ionised species, which was unexpected. Two possible explanations for this result are:

1. The plasma was a partially ionised gas composed mainly of excited neutral atoms.

2. The absorption spectra obtained in these firings yielded the lines for the species present only in the cooler exterior regions of the plasma armature.

If the first explanation is valid, then a low temperature estimate for a railgun plasma is obtained, as shown later in this section. The second explanation questions the use of absorption spectra to determine maximum temperature estimates in an optically thick railgun plasma.

TABLE 3

Prominent lines of excited elements within the range 3000°A to 6250°A using References [17,22,23].

Excited Atom*	Wavelengths (°A) Intensity decreases from left to right
CuI	3247.540, 3273.96, 5218.20, 3036.10, 3063.41
CuII	4909.734, 3686.555, 5051.778, 4931.698
CuIII	3776.97, 4352.80, 4377.11, 3744.70
AlI	3961.527, 3092.713, 3944.032
AlII	3586.692, 3900.68, 3655.00,
AlIII	5696.60, 5722.73, 4529.19, 3601,63
ZnI	3345.020, 3302.588, 3302.94, 3282.33, 3345.57
ZnII	4911.664, 4924.03, 5894.33, 6021.18, 6111.53
ZnIII	4970.8, 5579.0, 5563.8
BaI	5535.551, 5777.65, 5519.05, 3501.11, 5424.55
BaII	4554.042, 4934.086, 5853.68, 4130.64
BaIII	3368.175, 3079.136, 3369.677, 3043.42
OI	6158.20, 6156.77, 6155.98, 5958.58
OII	4075.869, 4189.793, 4649.14, 3973.26
OIII	3265.46, 3759.87, 3260.98, 3961.59
NI	5725.50, 4963.98, 5829.54, 5764.75,
NII	3995.00, 4630.54, 5679.56, 5005.14
NIII	4379.11, 4097.31, 4103.4, 4003.58, 5320.82
HI	4101.73, 3970.074, 3889.055, 3835.397
CI	5380.34, 5052.17, 4932.05, 4771.75
CII	4267.26, 4267.00, 3920.677, 4076.00, 5145.16
CIII	4647.42, 4650.25, 5695.92, 4651.47
CdI	3610.51, 3466.20, 5085.82, 3403.65
CdII	5378.3, 5337.40, 4415.63
CdIII	3035.72
ClI	6140.25, 6114.41, 6194.757. 4526.19, 4438.49
ClII	4794.54, 5423.23, 4810.06, 4896.77, 5217.94
ClIII	3340.36, 3191.4, 3139.16, 3320.14

* Spectra of neutral, single and double ionised atoms are indicated by I, II and III respectively.

TABLE 4

Measured wavelengths of line reversals for Firing No. 1: Aluminium foil used. ([ ] means centre line at half height)

Wavelength (°A) (± 0.5°A)	Possible Identification
[3247.7]	3247.54 CuI
[3273.9]	3273.96 CuI; 3273.94 OII
[3584.9]	3584.98 CII
3603.3	-
3613.5	3613.76 CuI
3622.9	-
3634.0	-
[3737.9]	-
[3947.7]	possibly 3944.0 AlI*; 3947.3, 3947.5, 3947.6 OI
[3954.9]	possibly 3961.5 AlI*
4051.5	4050.6 CuI
[4230.0]	4230.4 CuII
4677.6	4678.156 CdI
4679.5	-
5081.8	-
5089.9	5088.26, 5088.48, 5088.98 CuII
5105.1	5105.5 CuI
5106.7	-
5109.2	5108.3 CuII
[5106.8]	-
5129.9	-
5145.0	5145.6 AlII, 5144.4, 5144.8, 5144.9 AlII; 5145.1 CII
5218.8	5218.2 CuI
5784.0	-
[5888.9]	5889.97 CII
5887.1	-
5888.4	-
5891.2	5891.65 CII

* These strong lines have possibly been shifted due to the Stark effect.

TABLE 5

Measured wavelengths of line reversals for Firing No. 2: Zinc foil used. ([ ] means centre line at half height)

Wavelength (°A) (±0.5°A)	Possible Identification
3056.8	3057.1 AlI
3063.7	3063.4 CuI; 3064.3 AlI
3080.9	-
3091.7	3093.9 CuI; 3092.713 AlI; 3092.710 AlII
3100.3	3099.9 CuI
[3247.4]	3247.54 CuI
[3274.3]	3273.96 CuI
[3281.7]	3282.3 ZnI; 3281.69 CuII; 3282.7 CuI
[3303.2]	3302.58 ZnI; 3303.516 CuI
[3346.4]	3345.5 ZnI; 3345.9 ZnI; 3345.02 ZnI
3360.0	3361.09 CII
3586.6	3585.8 CII, 3586.69 AlII
3721.7	3720.77 CuI
3724.2	-
3885.3	3883.3 ZnI; 3884.1 CuII
3937.2	3938.6 AlII
[3946.9]	3945.5 CuII; 3947.3, 3947.5, 3947.6, OI; 3944.0* AlI
[3964.8]	3965.4 ZnI; 3961.5* AlI
3971.8	-
[4230.5]	4230.4 CuII; 4231.3 CI
4641.5	4641.8 OII
4651.4	4651.1 CuI; 4650.8 OII; 4650.6 AlII
4654.5	4654.2, 4654.5 OI; 4655.05 AlII
4675.3	4674.76 CuII;
[4673.7]	-
[4725.0]	-
4737.7	-
[4813.1]	4812.9 CuII; 4812.8 CI; 4810.5 ZnI
4846.1	-
4852.7	-
4868.8	-
5080 4	-

* These strong lines have possibly been shifted due to the Stark effect.

TABLE 6

Measured wavelengths of line reversals for Firing No. 3: Aluminium wrapped around $BaCl_2.2H_2O$ used. ([ ] means centre line at half height)

Wavelength (°A) (±0.5°A)	Possible Identification
3020.4	-
3057.3	3057.154 AlI
3065.0	-
3083.0	3082.11 AlI; 3082.153 AlII
3093.0	3092.713 AlI; 3092.710 AlII
[3247.5]	3247.54 CuI
[3273.9]	3273.54 CuI
[3302.1]	3302.588; 3302.94 ZnI
[3345.14]	3345.02; 3345.57 ZnI
[3502.2]	3501.11 BaI
3571.5	-
3581.7	-
3583.4	-
3736.5	-
[3946.0]	3944.03 AlI; 3946.406* AlII; 3947.3, 3947.5, 3947.6,OI
[3963.4]	3961.5* AlI
[4230.5]	4230.4 CuII
4367.8	4366.9 OII; 4368.14 CII; 4368.3 OI
[4463.6]	-
[4557.2]	-
4686.3	4687.77 CuII
4727.0	4726.45 BaI; 4727.21 CII
4814.3	-
4846.6	-
[4935.2]	4935.03 NI, 4934.086 BaII
5082.0	-
5106.0	5105.5 CuI
5531.5	-
5881.9	-
5887.2	-
6101.5	-
6132.2	-

* These strong lines have possibly been shifted due to the Stark effect.

TABLE 7

Atomic species detected in Firings 1-3

Firing	Foil Material	Atomic Species Identified
1	Aluminium	CuI and possibly AlI
2	Zinc	CuI, ZnI and possibly AlI
3	$BaCl_2$ and Aluminium	Possibly CuI, AlI and ZnI

Another feature of the spectra is an apparent wavelength shift of the very strong transition lines, 3961.5°A and 3944.0°A of AlI. For example, in Firing No. 1, aluminium foil was used and it would be reasonable to expect that AlI and/or AlII would be present. There were two strong reversals at 3965.9°A and 3947.7°A, both slightly longer than the 3961.5°A and 3944.0°A lines. These two lines would not have been identified but for the fact that in Firing No. 2 there were also two strong reversals near the same region at 3946.9°A and 3964.8°A. In addition, when aluminium was wrapped around the $BaCl_2$ in Firing No. 3, there were 2 strong reversals at 3946.0°A and 3963.4°A. The lines in Firing No. 2 if attributed to AlI, could be due to contamination of the railgun bore. The most likely source of aluminium contamination would be aluminium alloyed or welded on the rail surfaces [21]. Such contamination would not have been removed by the simple cleaning method previously described.

The reason for any shift in these two wavelengths may be due to the Stark shift. Such shifting of the centre line frequencies is due to charged particle interaction and depends on the atom and the lines involved [26]. Because of the repeated occurrence of the two very strong line reversals, it is likely that the lines are due to AlI.

Another interesting result was that CdI was not detected. The absence of cadmium can be explained by its low concentration, as cadmium was only 0.6% of the alloyed rails. Even if rail material constituted half of the resultant plasma, there would only be 0.3% of cadmium within the plasma.

Many of the line reversals on the spectra remain unresolved because they could not be identified with any of the species expected in the plasma. These line reversals may be due to molecular transitions. Although the unknown line reversals were checked with persistent band heads for a large number of molecular species appearing in Pearce and Gaydon [27], not one was identified.

Having identified some of the species which were present within the plasmas, a value for the plasma pressure was required in order to calculate the temperature. Since no pressure measurements were made during each firing, the pressure was estimated by dividing the electromagnetic force on the plasma ($L'I^2/2$) by the bore cross-sectional area, as given in McNab [3].

Thus, $$P = (I^2L')/(2A) \qquad (7)$$

where L' = inductance per unit length of the rails (H/m),
I = current through the rails and plasma (A)
and A = cross-sectional area of the bore (m^2).

It is shown later that the predictions for the degrees of ionisation using the Saha equations are not significantly affected when the estimate for the pressure of a railgun plasma obtained from Equation (7) is increased or decreased by 50 percent.

The equation of state is given in PB by the following form:-

$$P = (1 + \alpha)\ \rho\ \frac{k_B T}{m_o} \qquad (8)$$

where m_o = atomic mass of the ion or neutral
and ρ = mass density of the arc.
and α is as defined in Equation (3).

From Equation (8), it follows that the maximum temperature occurs when the pressure is a maximum, provided $(1+\alpha)$ and ρ do not vary substantially, which is a requirement of LTE [20]. From Equation (7), the peak pressure occurs at peak current and hence the maximum temperature occurs at peak current. In Firing No. 2, the peak current was 79.2 kA as shown in Figure 9.

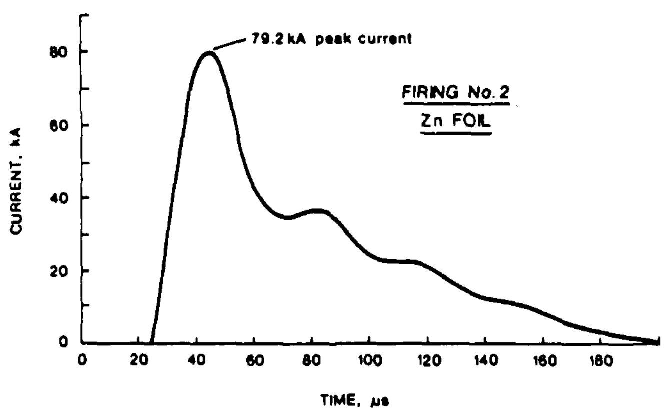

FIGURE 9 Current record for Firing No. 2

The parameter L' in Equation (7) was found following Kerrisk's method [28] and for the rails used in this series its value was found to be 0.41 μH/m. Therefore, the resultant peak pressure for Firing No. 2 was 12.8 MPa.

The levels of the degrees of first and second ionisation for copper, zinc and aluminium were calculated as functions of temperature using a plasma pressure of 12.8 MPa. The results are shown in Figures 10, 11 and 12 respectively.

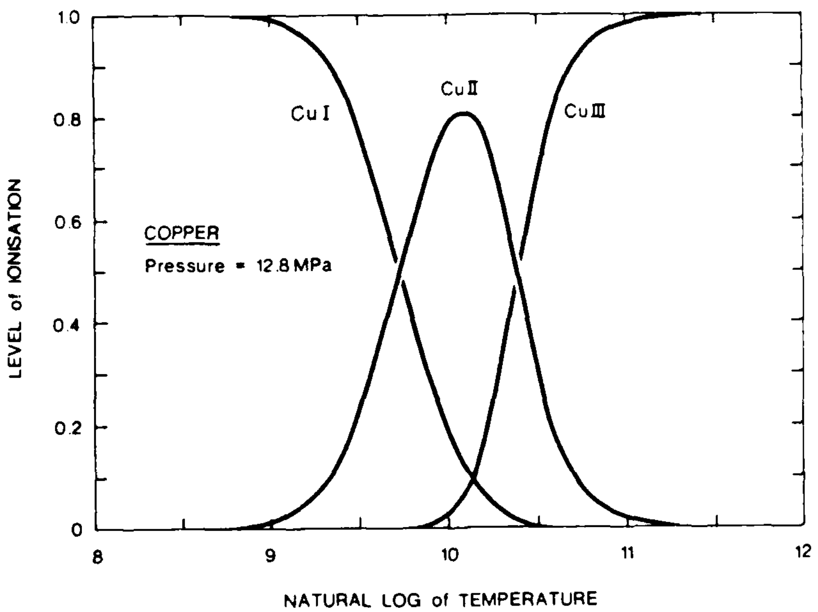

FIGURE 10 Level of ionisation for copper versus $\log_e(T)$ at a pressure of 12.8 MPa

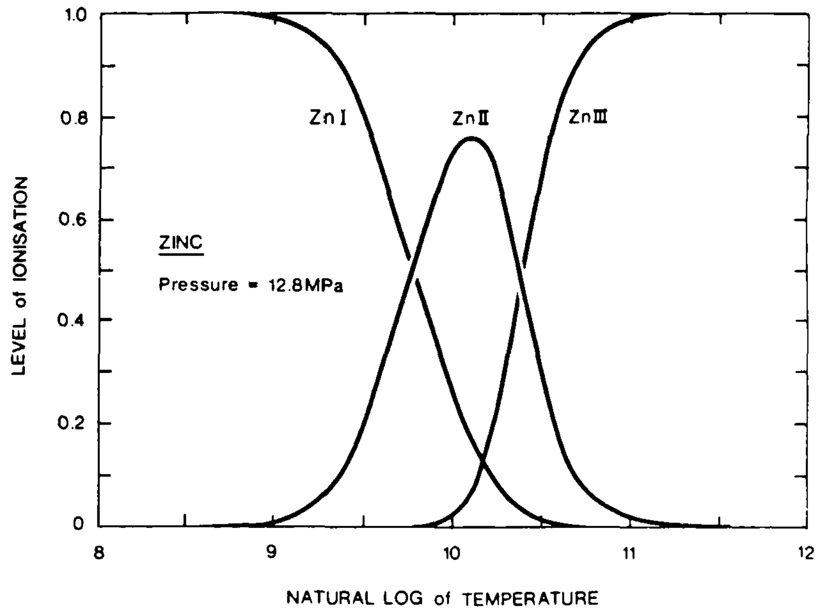

FIGURE 11 Level of ionisation for zinc versus $\log_e(T)$ at a pressure of 12.8 MPa

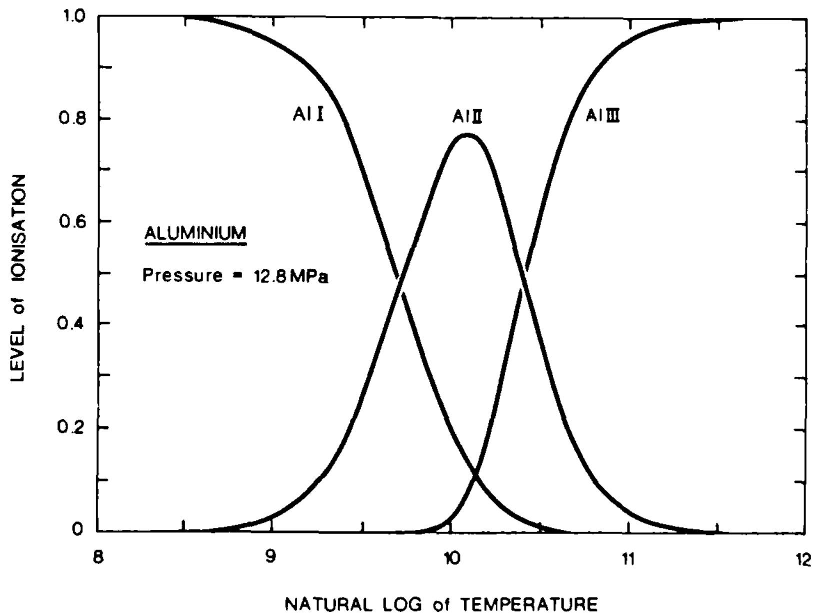

FIGURE 12 Level of ionisation for aluminium versus $\log_e(T)$ at a pressure of 12.8 MPa

Because the level of sensitivity necessary to detect the presence of a particular species could not be determined, we consider two different cases when estimating the plasma temperature. For the first case, it is assumed that lines corresponding to concentrations of species greater than 0.5% would appear on the spectra. For the second case, it is assumed that only lines corresponding to species concentrations greater than 10% will appear on the spectra.

The plasma temperature estimates for the two cases of 0.5% and 10% concentration levels are presented in Table 8. Single-ionised aluminium was not found in the plasma armature, which indicates that the peak plasma temperature was less than 6×10^3 and 11×10^3 K for the 0.5% and 10% levels respectively. Both temperature estimates are much lower than the theoretical estimates given in References [3,4,5 and 6]. These low estimates for the plasma temperature will yield low values for the conductivity of the armature which might explain why the theoretical estimates for the plasma voltage are lower than the experimentally-determined values. The discrepancy between theoretical and experimental values for the plasma armature voltage has been attributed to large voltage drops (~60 V) at each rail-plasma interface [3]. If the plasma temperature is low, then such large voltage drops may not be necessary to explain the measured muzzle voltage. According to Reference [29], the cathode and anode drops are only of the order of 10 V for copper electrodes.

TABLE 8

Temperature for the onset of first ionisation assuming detection of ionised species at the 0.5% and 10% levels of ionisation for a pressure of 12.8 MPa

Plasma Species	Temperature (K)	
	0.5% level	10% level
AlII	6000	11,000
CuII	7000	12,000
ZnII	7500	12,000

Because the railgun current varied during each firing in the series and the value of the rail inductance gradient (L') was not accurately known, the calculations of Saha's system of equations were repeated with the pressures deviating ± 10% and ± 50% (Figure 13) from the original pressure of 12.8 MPa. The results are shown in Table 9 for only the 10% levels of ionisation for CuII and CuIII because the 0.5% level showed no discernible difference in temperature.

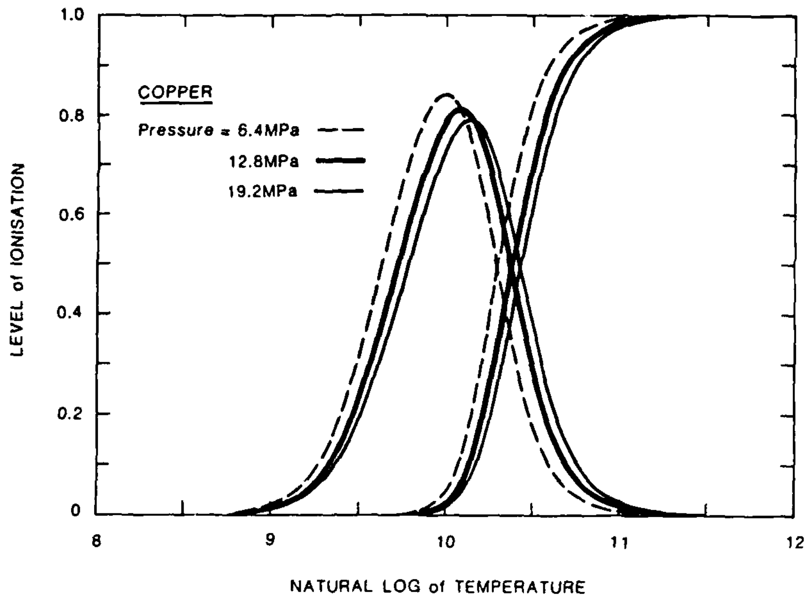

FIGURE 13 Level of ionisation for copper versus $\log_e(T)$ at a pressure of 6.4, 12.8 and 19.2 MPa

TABLE 9

Temperatures for ionisation levels of 10% in Copper

Pressure (MPa)	Temperature (K)	
	CuII	CuIII
6.4	10,570	23,700
11.5	11,170	25,060
12.8	11,270	25,310
14.1	11,360	25,590
19.2	11,730	26,450

As Table 9 reveals, a ± 50% change in the plasma pressure only produces a marginal change in the temperature for the 10% level of ionisation. Figure 13 shows that at a pressure of 6.4 MPa, the temperature ranges over which first- and second-ionised copper are expected to be present are almost identical to the temperature ranges for these species at a pressure of 12.8 MPa, even though the concentrations vary with temperature. The same behaviour is found to apply at a pressure of 19.2 MPa. Thus changing the pressure by a factor of 50% does not have a significant effect on ionised species comprising a railgun plasma. Hence, our temperature estimates are not very sensitive to the range of plasma pressures corresponding to variations in railgun current.

4.1 Discussion of Assumptions

The major assumption used in determining the temperature was that the plasma was in LTE. In order to check this assumption it was necessary to estimate the plasma particle density. Figure 14 shows the streak photograph of the plasma for Firing No. 3. In this figure the horizontal dark lines do not correspond to variations in plasma intensity but are due to position-markers placed along the gun-body. Using Figure 14, the plasma armature length was found to be 75 ± 5 mm at peak current. As unexploded foil was never recovered from any firings at MRL [8,9,16], this suggests that nearly all the foil became plasma. Even if only 10% of the foil became plasma, a number density greater than 10^{24} m^{-3} is obtained for all the firings. This density is typical for dense plasmas [31] and indicates that collisional processes involving free electrons may dominate, which is, as mentioned previously, a criterion for the validity of LTE.

FIGURE 14 400 μs streak photograph of Firing No 3. Graticule divisions are 8 μs apart.

A second assumption used in obtaining the temperature was that the effect on the spectrum of the strong magnetic field in the plasma armature was negligible. To show this, the spectral trace for Firing 3 was examined for evidence of the Zeeman effect. According to Griem [32], the Zeeman effect should produce a wavelength-shift for Gaussian profiles of:-

$$\Delta\lambda \approx 10^{-8}\ \lambda^{2}\ B$$

where λ is the wavelength (^{o}A) and B is the magnetic field (T).
The maximum magnetic field obtained by assuming a thin current sheet distribution in the rails [30] is found to be about 6.4 T. The Zeeman shift for the AlI line at 3961.4 ^{o}A is therefore:

$$\Delta\lambda \approx 1\,^{o}A$$

Since the expected Zeeman shift is very small, magnetic field effects are unlikely to interfere with the validity of Saha's equations for a railgun plasma.

It should also be mentioned that time variations and spatial inhomogeneities in the plasma may further restrict the validity of LTE. In order to investigate these, the streak film was colour-enhanced by using an image-analysis system developed at MRL [32]. The intensity contours resulting from this analysis are shown in Figure 15.

FIGURE 15 Colour-enhanced image showing intensity contours of the plasma in Firing No. 2. The intensity contours surrounding the plasma region before t=0 are believed to be due to flaring in the image intensifier tube.

As shown in Figure 15 intensity gradients appear at the rear and leading edge of the expanding plasma. These intensity gradients show the cool layers of plasma which are predicted by theory [4]. The intense central region (green) reveals a hotter region of the plasma, which is stable in intensity for approximately 30 μs around peak current or peak temperature. It is expected that any significant variation in the internal temperature and density of the plasma would be indicated by intensity gradients appearing in the central region, which did not occur. Thus photographic evidence indicates that a hot stable region exists within the plasma, thereby supporting additional criteria for the validity of LTE.

5. ANALYSIS OF PREVIOUS TEMPERATURE ESTIMATES

The temperature estimate obtained in the previous section by applying Saha's equation to the various species identified from absorption spectra is much lower than the peak temperature estimates found in previous theoretical and experimental work except for the work of Gathers and Hord [10]. Unfortunately, Gathers and Hord did not report the circuit parameters or railgun size, so it is difficult to compare their result with the results in this report.

5.1 Richardson's Emission Spectroscopy

In order to establish whether absorption spectra do provide a valid estimate for the peak temperature of a railgun plasma, our method was applied to the ions and excited neutral atoms identified from the emission spectra obtained by Richardson [8]. Richardson's railgun had a smaller bore (48 mm^2 compared with 100 mm^2) but the peak plasma current was almost identical (80 kA). Since our method for determining plasma temperature differs from Richardson's approach, it was considered of interest to see if the two different approaches yielded similar temperature estimates.

In carrying out this comparison the same rule for identifying the neutral and ionic species in the absorption spectra was applied to Richardson's results [8]. The three most prominent line-emissions of a given ionic species within the observed spectral range were sought (Table 10). It was found that CuI, AlI and OII and possibly CuII, AlII and NII were present in the muzzle flash. However, OI and NI were not found.

The approach used by Richardson to obtain a peak temperature estimate was to select the ionic species with the highest ionisation potential in the muzzle flash and then to estimate the plasma temperature by evaluating the temperature at one-fifth of the ionisation energy for that species as Parkes and Strachan [2] had done. Richardson chose OII and hence obtained a temperature greater than 30 x 10^3 K. We believe that this approach is inappropriate because it neglects the range of temperatures over which ionic species can exist in a plasma (Fig 16). In addition, Fig. 16 reveals that for a temperature of 30 x 10^3 K, at least 80 percent of the oxygen in the plasma would be doubly ionised. Lines corresponding to OIII were not found.

TABLE 10

The Most Prominent
Spectral Lines for Different Species [17]
within the spectral range (3360 to 4750°A) observed by Richardson [8]

Excited Atom	Wavelength (°A) Intensity decreases from left to right
AlI	3961.52, 3944.0, 3443.64,
AlII	3900.68, 3587.07, 3655.0
AlIII	4529.19, 3600.6, 4512.5
CuI	3530.38, 4062.64, 3599.13,
CuII	4043.48, 4073.7,4161.14
CuIII	3776.97, 4352.80, 4377.11
OI	3947.29, 3947.48, 3947.59
OII	3973.26, 4075.86, 4189.79, 3911.96
OIII	3759.89, 3961.59, 3754.65

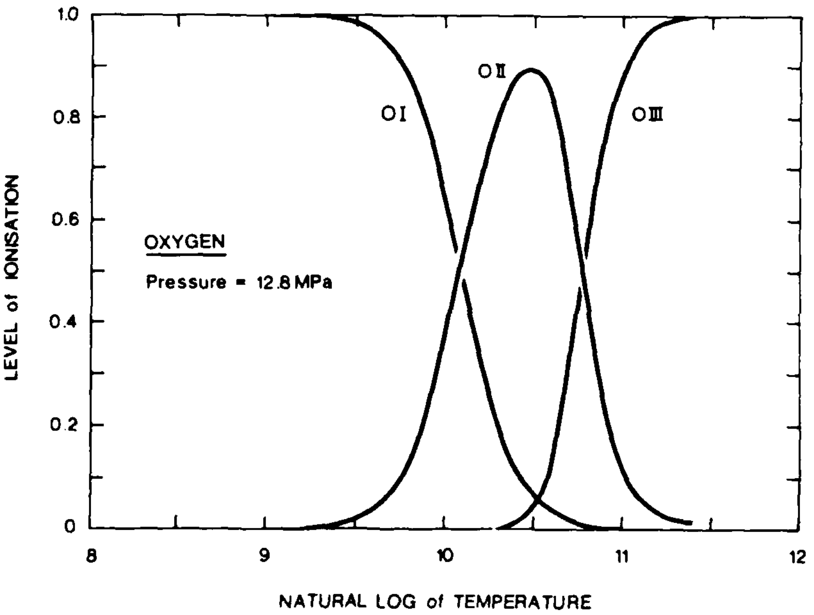

FIGURE 16 Ionisation of oxygen versus $\log_e(T)$ at a pressure of 12.8 MPa

The graphs for the first and second degrees of ionisation of oxygen using all the energy levels documented in Moore [21] appear in Figure 16. According to this figure, the degree of first ionisation peaks at about 90% when the temperature is about 36×10^3 K. At this temperature CuII, CuIII, AlII and AlIII would be expected to be present in the plasma as indicated by Figures 10 and 12. Since the relative concentrations of OI and OIII are small at 36×10^3 K, it is feasible that spectral lines corresponding to OI and OIII cannot be detected. On the other hand, according to Figure 10, the concentrations of CuII and CuIII are 35% and 65% respectively at 36×10^3 K. However, CuIII was not found even though a copper foil was used to initiate the plasma and there was doubt whether CuII was detected. These considerations suggest that the plasma could not have reached a temperature of 36×10^3 K. Hence, determining the temperature from OII alone cannot be considered reliable. These conclusions are further substantiated by the absence of AlIII and possible absence of AlII lines on the spectra* since AlII and AlIII have similar concentrations to CuII and CuIII at 36×10^3 K.

Disregarding OII yields different temperature estimates depending on whether CuII and AlII ions are present in the plasma. If these ions are not present, then the species identified in the emission spectra are consistent with those in our absorption spectra and the maximum temperature estimate of 11×10^3 K obtained in the previous section are valid for Richardson's experiments. However, if both CuII and AlII ions were in the plasma, then the temperature estimates are modified. Assuming that the concentrations of CuII and CuIII must be greater than 0.5% before being detected, the plasma temperature estimate ranges from 7×10^3 to 20×10^3 K according to Figure 10. Assuming also that the concentrations of AlII and AlIII ions must be greater than 0.5% before being detected, the temperature according to Figure 12 ranges from 6×10^3 to 19×10^3 K. Since there is some evidence that both AlII and CuII may be present, this restricts the temperature range to between 7×10^3 and 19×10^3 K. On the other hand, if the concentrations of the four species must be greater than 10% before being detected, then a different plasma temperature estimate is obtained. According to Figure 10, the temperature for CuI and CuII to be present at concentrations greater than 10% in the muzzle flash of the plasma ranges from 11×10^3 to 26×10^3 K. From Figure 12, the temperature for AlI and AlII to be present at greater than this concentration ranges from 10×10^3 to 25×10^3 K. Hence the common temperature-range is from 11×10^3 to 25×10^3 K, which is higher than the range obtained by assuming that the concentrations of the species had to be greater than 0.5%. Since emission spectroscopy is very sensitive, the concentrations of AlII and CuII are almost certainly small. Then the temperature estimate is closer to 11×10^3 K rather than 25×10^3 K. The temperature estimates presented in this paragraph are below all previous theoretical predictions and Richardson's minimum peak temperature of 30×10^3 K.

Our temperature estimates using Richardson's emission spectra were determined at the pressure of 12.8 MPa (peak current of 80 kA) whereas his

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* Aluminium species were expected in the plasma because Richardson had inserted aluminium plugs into the copper rails.

observations were at the muzzle when the pressure (current) was lower. However, it is shown in Section 3 that large pressure changes produce marginal changes at the ionisation levels considered. Furthermore, Fig. 13 shows that the temperature decreases as the pressure decreases.

5.2 Marshall's Temperature Estimate

As described briefly in Section 1, Marshall [9] has used a different approach to obtain an estimate of the plasma temperature. However, his method does not consider the following points:

(1) Plasma flow through a nozzle is affected by viscosity which is temperature dependent, varying between $T^{1/2}$ for a lightly-ionised plasma and $T^{5/2}$ for a highly-ionised plasma [33].

(2) The "degrees of freedom" associated with the change in the number of particles (dissociation, association, ionisation, chemical reactions) change dramatically for an expanding and cooling plasma [34]. This affects the ratio of specific heats, which appears in Marshall's equation.

Consequently, we believe that more investigation is required before this method can be considered as a reliable means of estimating the plasma temperature.

6. CONDUCTIVITY CALCULATIONS

From the absorption spectra, a peak plasma temperature less than 11×10^3 K (at the 10% sensitivity level) was obtained, whereas from the emission spectra a peak temperature as high as 25×10^3 K was obtained. Another method of estimating the peak temperature range is to calculate the electrical conductivity of the plasma for varying temperatures and then to compare it with conductivity-values obtained by using muzzle voltage records and image-analysis results.

The electrical conductivity of a railgun plasma was calculated by PB using a modified form of an expression of Spitzer [35]. The expression given in PB.

However, this approach was not used here for a number of reasons. Firstly, in deriving this equation it is assumed that the gas is fully ionised. In addition, Powell and Batteh have assumed that the plasma is nearly completely double-ionised and thus have set Z equal to a value of 2. This may not necessarily be the case for a railgun plasma. Also, according to Cohen et al [36], the theory used to obtain the expression used for plasma conductivity by PB breaks down completely for plasmas with high densities and low kinetic temperatures. In view of the doubtful applicability of Spitzer's expression to railgun plasmas, a computer code developed by Kovitya [37,38] was used instead. This code calculates various properties of partially and fully-ionised plasmas including the electrical conductivity and has been used by Kovitya and his co-workers in their studies of ablation-dominated arcs and sun-spot activity. They report good agreement with experiment in References [39-41].

The electrical conductivity for a copper plasma (Fig. 17) was calculated using the Kovitya code for temperatures between 8×10^3 and 26×10^3 K and for pressures between 4 and 14 MPa. Only a copper plasma was considered because the degrees of ionisation for copper, aluminium and zinc with respect to temperature are very similar (Figures 10, 11 and 12). Furthermore, in the RAPID Plasma Intensity Profiles series of railgun firings [14], it was found that the muzzle voltage records were very similar regardless of whether a copper, zinc or aluminium foil was used to generate the plasma. The pressure range included the plasma pressures previously considered in Section 5. The graph shows that for temperatures lower than 15×10^3 K, the plasma conductivities are comparable whereas for temperatures above 15×10^3 K, the plasma becomes more conductive as pressure increases.

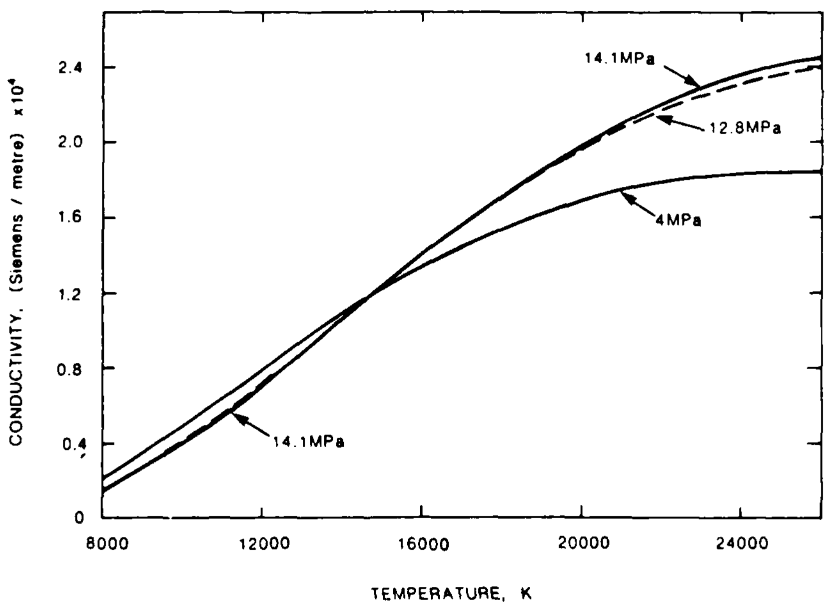

FIGURE 17 Electrical conductivity of a copper plasma vs temperature

To calculate the conductivity of the plasma from experimental results, the voltage across the plasma at peak current was obtained from the muzzle voltage record shown in Figure 18.

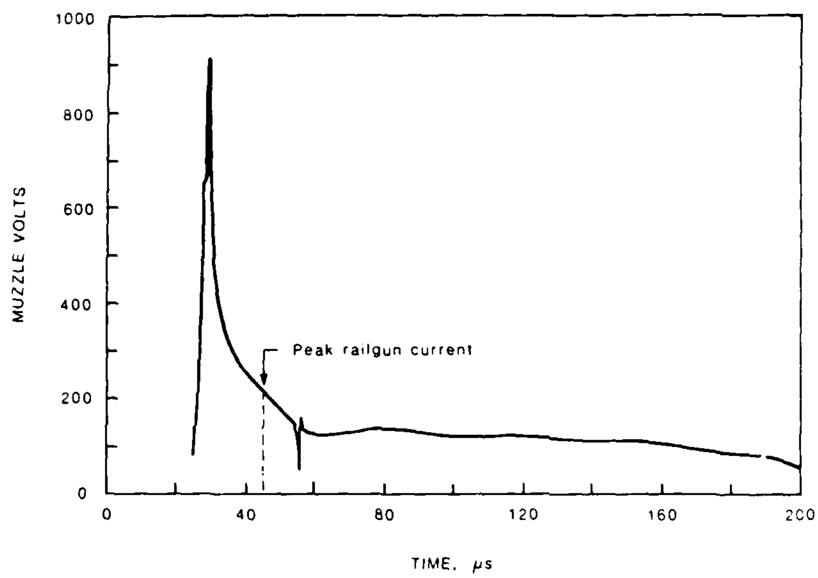

FIGURE 18 Muzzle voltage versus time (Firing No. 4)

The average muzzle voltage at peak current for a number of firings was 230 V. Allowing a total electrode voltage drop of 20 V yields a plasma voltage of 210 V, which when divided by the peak current of 79 kA produces a plasma resistance of 2.7 mΩ. Since the plasma length was found to be 75 ± 5 mm (Section 4.1) and the area of the bore is 100 mm^2, the value for the electrical conductivity of the plasma is $(5.0 \pm 0.3) \times 10^3$ S/m. From Figure 17, the corresponding peak plasma temperature for a pressure of 12.8 MPa occurs is $(10.7 \pm 0.3) \times 10^3$ K, which falls in the temperature ranges estimated from our spectroscopic observations. Even if each electrode voltage drop is assumed to be 60V, a peak temperature of only 14.7×10^3 K (at 12.8 MPa) is obtained. Thus the temperatures found by this method are closer to the temperature estimates obtained from the absorption spectra than those obtained from Richardson's observations.

It should be noted that the method employed in this section was used by Kowalenko [14] to obtain a plasma temperature of 20×10^3 K for the RM-experiment in which the current was 300 kA. This suggests that the temperature of a railgun plasma is not a strong function of the circuit current. It should also be noted that if the actual length of the plasma was only one half of the observed length, then the plasma temperature would be less than 14×10^3 K, which is a similar result to Kowalenko [14].

Furthermore, the lower temperature and subsequent higher resistivity of the plasma indicates that the assumed plasma rail interface voltages [3,4] are not necessarily so high and much lower values are possible.

7. CONCLUSION

In this report Saha's system of equations has been used to find the relative concentrations of singly and doubly ionised atoms as a function of temperature for a number of elements expected in railgun plasma armatures. When additional energy levels were used to evaluate the partition functions in Saha's system of equations, the concentrations of CuII and CuIII differed slightly from those given in PB.

The first method of determining the plasma temperature presented in this report depends on the identification of species comprising a railgun plasma appearing in absorption and/or emission spectra. This method is limited by the detection sensitivity and by the documentation of excited energy-levels for various species.

Only excited states of copper, zinc and aluminium were identified on the absorption spectra of the free-flowing railgun plasma. If the sensitivity level of the absorption spectra was such that only concentrations of each species greater than 0.5% would be detected by the spectroscope, then the temperature of the plasma armature was found to be less than 6×10^3 K. If the sensitivity level required concentrations greater than 10% (the more likely case) then the temperature was found to be less than 11×10^3 K.

Two possible explanations were given for the absence of ionised species in the plasma and hence the low temperature estimates. The first was that the plasma was only partially-ionised and thus was composed mainly of excited neutral species. The second explanation was that the absorption spectra contained the line reversals which reveal only conditions in the cooler regions of the plasma. In an attempt to determine which of the two explanations was valid, the emission spectra of the muzzle flash obtained by Richardson [8] were examined. It was shown that the method used by Richardson of estimating plasma temperatures based solely on the presence of OII in the emission spectra may not be reliable. If there were few singly-ionised species present in Richardson's plasma, then the temperature estimates obtained from the absorption spectra reported here are consistent with the estimates obtained from Richardson's emission spectra. However, some lines on the Richardson's emission spectra suggested the possibility of some singly-ionised species being present. Allowing for these, the temperature was found to range from 7×10^3 to 19×10^3 K (most probable) or from 11×10^3 to 25×10^3 K depending on the assumed detection sensitivity.

In order to narrow the temperature estimates obtained from the spectral analysis, the electrical conductivity was calculated with respect to temperature and then compared with an experimentally-determined value. The theoretical values for the electrical conductivity were obtained from

Kovitya's computer code [37,38]. This code was used because the Spitzer expression for the electrical conductivity was of doubtful applicability to railgun plasmas and because the code's results have been shown to give good agreement with experiment [39-41]. Comparison of the theoretical and experimentally-determined values for the electrical conductivity produced a peak plasma temperature of $(10.7 \pm 0.3) \times 10^3$ K, which was in agreement with the estimate obtained from the absorption spectra and within the ranges obtained from the analysis of the emission spectra. This suggests that absorption spectra can be used to obtain an estimate for the plasma temperature.

In conclusion, our examination of the spectra obtained from railgun firings and comparison of the electrical conductivity with results obtained from muzzle voltage records and image analysis indicate that the temperature of a railgun plasma is less than 11×10^3 K which is much lower than other estimates except for those given in References [10 and 14]. Substantial variation in the assumed pressure did not affect the temperature estimates greatly. The low temperature estimates obtained in this report indicate that the electrical conductivity and degree of ionisation of a railgun plasma are much lower than the values given in PB. The subsequent higher plasma resistivity also means that the assumed plasma/rail interface voltages [3,4] may not be as high as previously thought.

8. ACKNOWLEDGEMENTS

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APPENDIX A

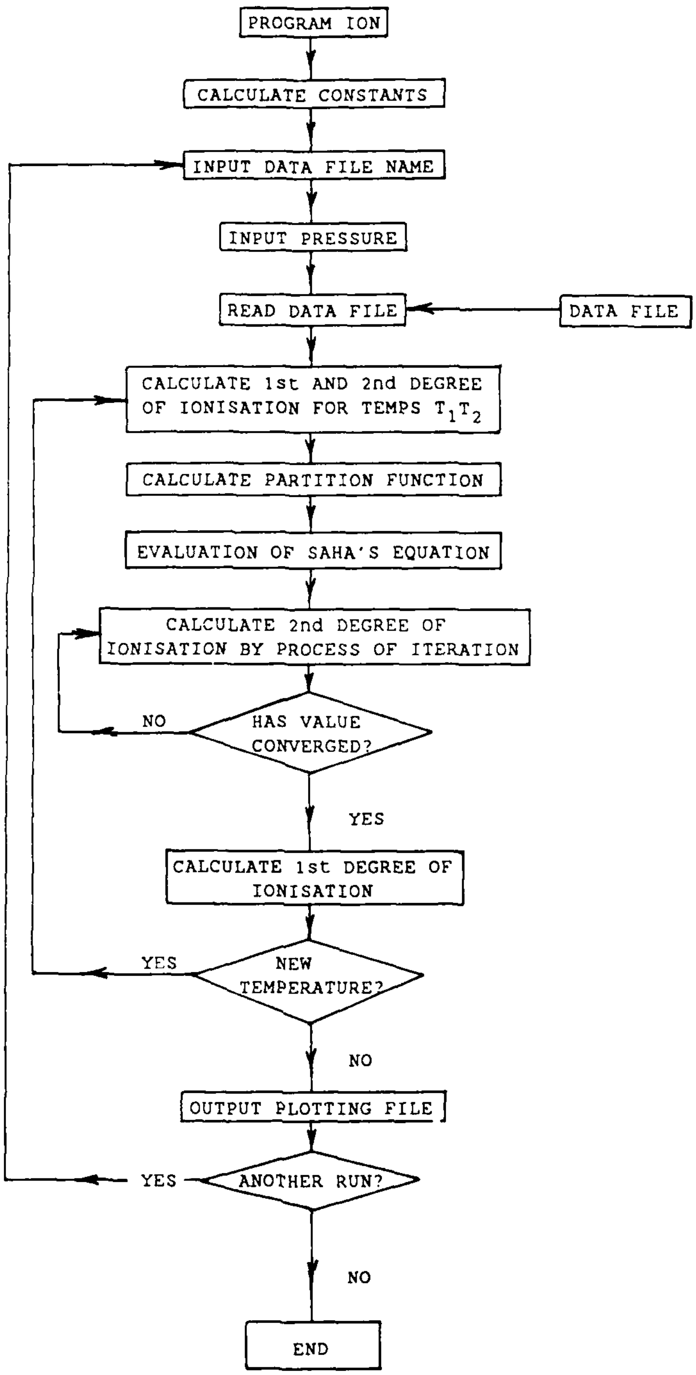
```
      PROGRAM ION
C     THIS PROGRAM CALCULATES THE LEVEL OF IONISATION IN A PLASMA.
C     THE PLASMA IS CONSIDERED TO BE IN LOCAL THERMODYNAMIC
C     EQUILIBRIUM (LTE). THE 1ST AND 2ND DEGREES OF IONISATION
C     ARE CALCULATED FROM A METHOD DETAILED IN A PAPER BY J. D. POWELL
C     AND J. H. BATTEH CALLED PLASMA DYNAMICS OF THE ARC DRIVEN
C     RAILGUN, SEPT 1980.
C
C     THIS PROGRAM READS A GIVEN DATA FILE AND OUTPUTS A FILE
C     WHICH CAN BE READ BY THE PLOTTING ROUTINE WRITTEN BY STEVEN
C     KENNETT. THE 1ST AND 2ND DEGREES OF IONISATION ARE PLOTTED
C     (FOR A CONSTANT PRESSURE) AGAINST THE NATURAL LOG OF THE
C     TEMPERATURE.
C     PROGRAM RUN ON A VAX 11/780 USING VAX FORTRAN 77.
C
C     THIS PROGRAM WAS WRITTEN BY GREGORY CLARK.
C             MATERIALS RESEARCH LABORATORIES
C                     JULY, 1985.
C     PROGRAM SWITCHES ....USE /G FLOATING SWITCH
C*******************************************************************
      REAL*8 Z(3,300),T(200),PRESS,KSAHA(2),PART(3),IP(2)
      REAL*8 U(3,300),DG(3,300),FN(6),X1(200),X2(200),CHECK
      REAL*8 CPI,C,A1,A2,A3,A4,QN,TEMP,B1,B2,B3
      REAL ATOM(6),ANS
      INTEGER NLEVEL(3)
C*******************************************************************
C     THE CONSTANTS USED IN THE PROGRAM ARE LISTED BELOW IN THE
C     FOLLOWING ORDER: CME=ELECTRON MASS (KG),CH=PLANCKS
C     CONSTANT (JOULES SEC),CKB=BOLTZMANNS CONSTANT (JOULES/KELVIN),
C     CPI=PI
C
C     REFERENCE USED....... KAYE & LABY.....14TH EDITION
C*******************************************************************
      CME=9.109534D-31
      CH=6.626176D-34
      CKB=1.380662D-23
      CPI=3.14159
C*******************************************************************
C     THE FOLLOWING CALCULATION IS A CONSTANT IN THE SAHA EQUATION.
C     IT IS CALCULATED IN THESE STEPS TO REMAIN WITHIN THE NUMBERS
C     LIMIT OF THE VAX COMPUTER......
C*******************************************************************
      C=2*CPI*(CME/CH)*(CKB/CH)
      C=C**1.5
      C=2*C*CKB
C*******************************************************************
1     TYPE *,' WHICH DATA FILE IS REQUIRED?'
      ACCEPT 2,FN
2     FORMAT(6A4)
C     INPUT PRESSURE IN PASCALS (DOUBLE PRECISION FORMAT)
      TYPE *,' WHAT PRESSURE?'
```

```
      ACCEPT *,PRESS
      OPEN(UNIT=1,NAME=FN,TYPE='OLD',READONLY)
      OPEN(UNIT=2,TYPE='NEW',NAME='ION.DAT')
C*******************************************************************
C     READ NAME OF THE ELEMENT
      READ(1,2)ATOM
C     READ IONISATION POTENTIALS (1ST. & 2ND IN eV)
      READ(1,*)IP(1),IP(2)
C     READ THE ATOMIC DATA FOR THE THREE LEVELS OF IONISATION
      DO 30 M=1,3
C     NOW READ THE VALUE OF THE QUANTUM NUMBER J AND THE ASSOCIATED
C     ENERGY LEVEL AND THEN CALCULATE THE DEGENERACY FACTOR.
      DO 20 I=1,300
      READ(1,*)QN,U(M,I)
C     DETECT END OF DATA FOR A GIVEN IONISATION LEVEL
      IF(QN.EQ.1000.)GOTO 21
C     CONVERT ENERGY VALUES (WHICH ARE DIRECT FROM C.E. MOORE)
C     INTO eV AND THEN INTO JOULES..
      U(M,I)=U(M,I)*1.2395D-4*1.60219D-19
      DG(M,I)=(2.*QN)+1.
20    CONTINUE
21    NLEVEL(M)=I-1
30    CONTINUE
C     CONVERT eV TO JOULES (IONISATION POTENTIAL)
      IP(1)=IP(1)*1.60219D-19
      IP(2)=IP(2)*1.60219D-19
C*******************************************************************
C     NOW WE CALCULATE THE 1ST AND 2ND DEGREES OF IONISATION FOR
C     A TEMPERATURE RANGE 8,000K TO (NUM*500)+7500K IN STEPS OF 500K
C*******************************************************************
      NUM=170
      DO 1000 IT=1,NUM,1
      TEMP=(DBLE(IT)*500.)+4500.
C*******************************************************************
C     NOW WE CALCULATE THE PARTIION FUNCTION FOR A GIVEN
C     TEMPERATURE.
C
C*******************************************************************
      Z(1,1)=0.0
      Z(2,1)=0.0
      Z(3,1)=0.0
      DO 100 JJ=1,3
      DO 100 I=1,NLEVEL(JJ)
      Z(JJ,I+1)=Z(JJ,I)+(DG(JJ,I)*DEXP(-U(JJ,I)/(CKB*TEMP)))
100   CONTINUE
      PART(1)=Z(1,NLEVEL(1)+1)
      PART(2)=Z(2,NLEVEL(2)+1)
      PART(3)=Z(3,NLEVEL(3)+1)
C*******************************************************************
C     CALCULATE THE VALUE OF SAHA'S EQUATION.
C*******************************************************************
      DO 150 N=1,2
      KSAHA(N)=(C/PRESS)*(PART(N+1)/PART(N))*(TEMP**2.5)
      KSAHA(N)=KSAHA(N)*DEXP(-IP(N)/(CKB*TEMP))
150   CONTINUE
C*******************************************************************
```

```
C       CALCULATE BY ITERATION THE 2ND DEGREE OF IONISATION.
C       LET THE INITIAL VALUE OF IONISATION (X2(IT) ) EQUAL 0.01.
C       400 ITERATIONS  HAVE BEEN ALLOWED FOR. THE ITERATION WILL
C       END IF SUCCESSIVE VALUES OF THE 2ND DEGREE DIFFER BY LESS
C       THAN 1 PART IN 100,000.
C
C*******************************************************************
        X2(IT)=0.01
        DO 300 L=1,400
        CHECK=X2(IT)
        A1=4.*KSAHA(2)*(1.-X2(IT))
        A1=A1/(KSAHA(1)*X2(IT))
        A1=(1.+A1)**0.5
        A1=A1-1.0
C**********************************************************
C       THE FOLLOWING "IF" STATEMENT WAS INSERTED TO
C       COVER THE INSTANT WHEN A1-1.0 GOES SMALLER THAN
C       THE 15 DIGIT LIMIT WITH THE DOUBLE PRECISION
C       /G SWITH.
C**********************************************************
        IF(A1.EQ.0.0) TYPE *,'A1 EQUALLED 0.0'
        IF(A1.EQ.0.0) A1=1.D-16
        A1=(KSAHA(1)/KSAHA(2))*A1
        A2=2.+(3.*KSAHA(1))
        A2=A2*X2(IT)/(1.+KSAHA(1))
        A3=4.*KSAHA(1)*(1.+KSAHA(1))
        A3=A3*(1.+X2(IT)-(2.*X2(IT)**2.))
        A3=A3/(X2(IT)*(2.+(3.*KSAHA(1))))**2.
        A3=(A3+1.)**0.5
        A3=A3-1.
        X2(IT)=(1./A1)*A2*A3
        IF(X2(IT).LT.1.D-5) GOTO 400
        IF(ABS(CHECK-X2(IT)).LE.1.D-5) GO TO 400
300     CONTINUE
        TYPE *,'X2 VALUE HAS NOT CONVERGED.'
C*******************************************************************
C       WE NOW CALCULATE THE 1ST. DEGREE OF IONISATION FOR
C       A GIVEN TEMPERATURE.
C*******************************************************************
400     X1(IT)=A1*X2(IT)/2.
C*******************************************************************
C       CALCULATE NATURAL LOG OF THE TEMPERATURE
C*******************************************************************
        T(IT)=LOG(SNGL(TEMP))
1000    CONTINUE
C*******************************************************************
C       OUTPUT DATA TO A FILE FOR PLOTTING PURPOSES
C       OUTPUT THE X AXIS LABEL
C*******************************************************************
        WRITE(2,600)
600     FORMAT(' NATURAL LOG OF TEMPERATURE')
C       OUTPUT A "1" FOR THE PLOT FILE FORMAT
        WRITE(2,700)
700     FORMAT(' 1')
C       OUTPUT THE Y AXIS LABEL
        WRITE(2,800)
```

```
800     FORMAT(' DEGREE OF IONISATION ')
        WRITE(2,700)
C       OUTPUT THE SUBTITLE
        WRITE(2,960)PRESS
960     FORMAT(' PRESSURE=',D10.3)
        WRITE(2,950)-NUM
        WRITE(2,900)ATOM
900     FORMAT(1X,6A4)
C       OUTPUT NEGATIVE VALUE OF THE NUMBER OF POINTS TO BE PLOTTED
950     FORMAT(1X,I4)
        DO 2000 LK=1,NUM
        WRITE(2,1050)T(LK),SNGL(X1(LK))
1050    FORMAT(1X,F6.3,',',F6.3)
2000    CONTINUE
        WRITE(2,950)-NUM
        DO 2100 LK=1,NUM
        WRITE(2,1050)T(LK),SNGL(X2(LK))
2100    CONTINUE
        CLOSE(UNIT=1)
        CLOSE(UNIT=2)
        TYPE *,'DO YOU WISH TO HAVE ANOTHER RUN? ANSWER Y/N'
        ACCEPT 2110,ANS
2110    FORMAT(A1)
        IF(ANS.EQ.'N') GOTO 3000
        GOTO 1
3000    STOP 'THATS ALL FOLKS'
        END
```

FIGURE A-1 Flow chart for program used to calculate 1st and 2nd degree ionisation.



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AUTHOR(S)	CORPORATE AUTHOR
G.A. Clark and V. Kowalenko	Materials Research Laboratories P.O. Box 50, Ascot Vale, Victoria 3032

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ABSTRACT

In-bore spectroscopic observations of a free-flowing plasma for wavelengths between 3000 Å and 6250 Å were made for a series of railgun firings. In this report the experimental arrangement for the series is described dand the results are presented. Atomic species present in the plasma are identified from absorption and emission spectra. Calculations of the degree of ionisation of these species are then used to produce a temperature estimate between 11×10^3 K to 25×10^3 K for the railgun plasma. A comparison of theoretical values of the plasma electrical conductivity with values obtained from muzzle voltage records indicates that the peak plasma temperature is approximately 11×10^3 K, which is consistent with estimates obtained from the spectra.

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