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A Video Thermography Technique for Temperature Measurements of Pulse-Heated Metallic Rods

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Abstract

A video thermography technique for measuring the surface temperature of metallic rods is described in this report. The technique employs a video camera with charge-coupled devices as the detection elements; it is applicable to materials that can be preheated to form an oxide layer with a stable emissivity. The procedure is illustrated by the measurement of the surface temperature of molybdenum rods that have been rapidly heated to about 800 K by an electrical discharge. The thermal emission profile of the sample is observed with the video camera, and the final surface temperature is inferred from previously obtained calibration data. The time-dependent current through the rod is also measured and used as input in theoretical calculations that describe the coupled transport of electromagnetic fields and heat through the sample. The temperatures predicted by the model calculations are in excellent agreement with the values inferred from the experiments.

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A VIDEO THERMOGRAPHY TECHNIQUE FOR TEMPERATURE MEASUREMENTS OF PULSE-HEATED METALLIC RODS

1. Introduction

Much of the database pertaining to the thermophysical properties of metals have been accumulated in static, direct current (DC) conditions or dynamic conditions at heating times in the millisecond range. Although a number of very accurate measurements of thermophysical properties have been made for heating times in the microsecond and even the sub-microsecond range, the samples employed typically are very small diameter wires or thin foils. The goal in many of these experiments was to obtain data at very high temperatures. The procedure followed generally uses a current pulse whose time dependence, in conjunction with the small physical dimensions of the sample, is such that both skin depth effects and heat transport within the sample may be neglected.

Some Army applications of pulsed power and electromagnetic technology involve heating times in the microsecond range. In these applications, the conductors are too large to ignore diffusion processes and size-related effects. For this reason, an exploratory effort to study the behavior of particular metals and alloys that are heated electrically in times on the order of 100 microseconds is under way at the U.S. Army Research Laboratory (ARL). In these experiments, a capacitor bank supplies electrical currents that reverse direction in a few tens of microseconds. The purpose of this work is twofold. First, data are not available for some materials of special interest to the Army, and it is desired to provide these data. Second, there is a requirement to provide data to validate numerical computer codes developed to support Army applications.

The period of heating in these experiments is so short that thermal conduction in the sample does not play a significant role. Sample geometry, specific heat, and resistivity largely determine both the sample temperature and the voltage produced across the sample. Thus, measurement of the voltage across a portion of the sample and the current through it provides information about the validity of these parameters. Theoretical calculations that couple the diffusion of current with heat transport in the sample [1] are then required in order to properly interpret the measured voltage. In some recent ARL experiments with substances whose properties are well known, excellent agreement between theory and experiment was obtained for the time-dependent voltage drop across the heated rod. Known values [2] for the relevant thermophysical properties were employed in the theoretical calculations. This agreement has lent credence to our use of similar techniques to determine properties of relevant materials that are not well characterized.

In order to complete the validation of our codes, it is also desirable to measure the temperature of the samples subjected to pulsed heating. Since the current pulse in our experiment has the functional form of a damped sine wave that persists for about 200 microseconds, a continuous measurement of the temperature during this period would be difficult and would require specialized instrumentation. However, the final temperature of a heated rod, with appropriate precautions and sample preparation, can be measured by a thermography technique that employs standard video cameras. In this report, we describe a technique for surface temperature measurement that relies on the response of an electronically shuttered camera that is sensitive to visible and near infrared (IR) radiation. The radiation is detected in an array of charge-coupled devices (CCDs).

The method is applied to the measurement of the final temperature of the surface of a molybdenum rod heated to approximately 800 K, and the results are compared with the value predicted by theoretical calculation. Although measurements were performed on a variety of materials, molybdenum was chosen as an element to illustrate the technique because it has been studied intensively by the National Institute of Standards and Technology (NIST) [3]. Its thermophysical properties, resistivity, and specific heat are known to approximately 3% accuracy for the temperature range of interest to us. In our experiments, an oscillatory current was used which produced peak heating rates greater than 10 million degrees Kelvin per second (K/s).

The voltage measurements discussed previously will be presented in another report. Our purpose here is to describe the technique for measuring the final surface temperature of a heated rod.

2. Temperature Measurement Technique

Several proven thermography techniques exist, which are based on the measurement of spectral radiance over a narrow spectral band, at two or more narrow spectral bands, over a broad spectral band, or integrated over all wavelengths [4]. In this work, measurements were made over a broad spectral band extending to wavelengths below the shortest wavelength emitted by the heated sample. Video thermography, wherein a thermal emission image of the source is acquired and the video levels are calibrated to provide a direct reading of temperature, is the technique used in our measurements. Stumpfel [5] discussed some of the underlying theory that relates thermal emissions from an emitting metallic surface to the response of a detector.

The response characteristics of systems that are particularly sensitive to the shorter wavelength portion of a given emission spectrum can be illustrated by simple application of Planck's distribution law for blackbody emission. This distribution shows that for wavelengths much shorter than the value at which peak spectral radiance occurs, there is an extremely strong dependence of spectral radiance on temperature. For example, for temperatures around 800 K, the peak spectral radiance occurs at 3622 nm. For this same temperature, the spectral radiance at 1000 nm increases with temperature as T^{18} . Thus, a temperature increase from 800 K to 900 K would increase the spectral radiance at 1000 nm by a factor of about eight.

Any system that responds across this short wavelength band (as our system does) will therefore exhibit extremely strong temperature dependence. This sensitivity to temperature change increases the accuracy of temperature measurements, but the saturation level of the CCDs limits the temperature range observed with a given setup of the camera. For example, with the lens aperture and exposure time used in the present measurement at 800 K, the range of observable temperatures was only about 100 K.

A major difficulty in making temperature measurements in the present experiment is the high level of light produced at early times by the electrical arcs that normally accompany current initiation when high voltages and large currents are involved. These arcs can complicate the measurement by producing (a) extraneous light that is reflected from the sample, (b) saturation in the detectors, or (c) both. These problems suggest that a detector with some form of electronic shuttering is desirable. The availability of a silicon CCD-video camera, the "Flashcam",¹ which has a fast electronic shutter and external triggering capability, appears to offer a good choice for the present experiment. A preliminary study of heated rods with the Flashcam camera indicated that this system has adequate sensitivity to observe blackbody radiators at temperatures above ~670 K.

2.1 The Camera

The Flashcam is a programmable, fast shutter, multiple exposure camera that responds to radiant flux in the wavelength range from 350 to 1040 nm. The camera can be operated with the following properties: (a) 1 to 10 exposures per frame; (b) exposure times of 1 to 1000 μ s; and (c) time between exposures is selectable from 1 to 1000 μ s. In the triggered mode, an external pulse triggers the camera, which begins an exposure sequence after a pre-set delay. The Flashcam can be triggered at any time or with repeated triggers, and imaging frequencies as fast as 60 frames per second are attainable.

¹The Cooke Corporation, Flashcam serial no. 335NG0041.

The camera can be operated in one of two output modes, capturing a single digital image or recording images continuously on videotape. The analog output from the CCD array is digitized by an 8-bit analog-to-digital converter, stored as a digital image, and made available for transfer to a personal computer via a standard printer cable. In the triggered mode, a single digital image that may contain the summation of as many as 10 exposures is retained in a buffer. In addition, an 8-bit digital-to-analog converter transforms the digitized image to a standard RS-170 video signal that is provided at a video output jack. When operated in a free-run mode (no trigger), the camera resembles a normal video camera except that the video signal is obtained by re-conversion from the digital signal. In this mode, the re-converted signal is normally stored continuously on videotape. In the course of our calibrations and experiments, we have used the camera in both triggered and free-run modes.

2.2 Sample Preparation and Emissivity Considerations

Before any temperature measurements can be attempted, it is necessary to prepare samples with stable thermal emission characteristics. In general, metal surfaces oxidize when heated in air. The oxidization rates accelerate rapidly for most metals as the temperature rises above 600 K. For a given metal and temperature, the resultant layer of oxidized metal may tend to flake off or remain on the surface. For some metals (e.g., copper and iron) at higher temperatures (e.g., above 1000 K), a very porous oxide layer forms and continually scales off, revealing new metal. In this case, the bulk metal may be completely oxidized and may crumble in a short time. Such metals are not good candidates for these experiments. Fortunately, there are elements whose surfaces at certain temperatures will form a dense oxide layer that prevents additional oxygen atoms from reaching the underlying metal atoms. These metals can often maintain a quasi-stable surface over a considerable range of high temperatures. Metals that oxidize in this manner are the best candidates for these experiments; molybdenum is such a metal.

All molybdenum samples were 99.97% pure and in the form of cylindrical rods, 150 mm in length by 5 mm in diameter. The samples were received from the supplier with freshly machined surfaces. In pulsed heating experiments with freshly machined molybdenum, the un-oxidized surface of the rod begins to oxidize at a high rate when the rod is rapidly heated in air to temperatures around 800 K. Because the current pulse in our experiments is so brief, most of the oxidization will occur after the pulse ends, i.e., as the sample cools over a period of many seconds. To minimize changes in the surface during the experiment and also during repeated heating for calibration, it is necessary to work with samples that have been oxidized previously in a controlled manner. Several factors must be considered to achieve the proper preparation.

The emissivity, ϵ , of the sample is an important quantity for the temperature measurement as the observed radiation is directly proportional to its value.

Because a freshly machined metallic surface originally has a very low emissivity, estimated to be less than $\epsilon \sim 0.1$, the emissivity will begin to increase in an unknown manner as soon as the rod is heated by the current pulse. For some metals, the emissivity continues to rise as the thickness of the oxide layer increases until a quasi-equilibrium value is reached. Emissivity is determined by the composition and morphology of both the oxide layer and the underlying oxide-to-metal interface. Because a thin oxide layer may partially transmit IR radiation, the composition and morphology of the underlying oxide-to-metal interface may have a significant effect on the overall emissivity. There are examples of materials, which on the basis of the high transmittance of the oxide layer and the high reflectance of the metal, might be expected to have low emissivities; however, those materials actually have quite high emissivity values². Such high values may result from an irregular morphology in the interface region, particularly at the interface between the metal oxide layer and the metal.

The general description of oxide layer formation just given would probably apply to the oxide layers formed on molybdenum rods heated in these experiments. Oxide layers 0.2 μm thick on molybdenum are observed to transmit visible and near IR [6]. Knowledge of the details of the surface and its emissivity is not critical to the temperature measurement technique described herein, but any variations in emissivity (e.g., between calibration and the experimental measurement) will increase uncertainty in the temperature measurements. Appendix A of this report shows that even a fairly large uncertainty in the value of emissivity leads to only a small uncertainty in the measured temperature for these experiments. Therefore, reasonable care in stabilizing the emissivity results in only small uncertainties in temperature measurements.

2.3 Procedure for Preparing the Sample Surface

When a freshly machined molybdenum rod with low emissivity is heated, it will oxidize, and its emissivity will increase considerably. To avoid this large emissivity increase, an approach of pre-oxidizing the surfaces to form a stable oxide layer was used. This approach minimizes the uncertainty in the temperature measurement attributable to uncertainty in the sample emissivity. The sample was pre-heated in air to form a stable black oxide layer with emissivity much increased over that of the freshly machined surface. The treatment for molybdenum consisted of placing the sample, initially at room temperature, in an oven at 770 K for 10 minutes. The appearance of the surface changed from specularly reflective to diffusely black as a result of this treatment.

In addition to the initial surface oxidization treatment (heating at 770 K for 10 minutes), one sample was also repeatedly heated to selected temperatures in order to calibrate the Flashcam camera. This procedure consists of heating the

²A well-known example is transmissive sapphire, Al_2O_3 , "hard-coated" onto reflective aluminum.

sample for a few minutes to achieve thermal equilibrium and then quickly removing it and viewing it with the camera. This process was repeated for a series of temperatures from 750 to 850 K. After these additional heating cycles, the sample was observed to lose its small remaining specular reflectance and appear more diffusely black. This change in appearance probably was accompanied by a slight increase in the emissivity, estimated to be within the range between 0.8 and 0.9. In future tests, the oven oxidization treatment for molybdenum could be performed at a temperature higher than 770 K or extended to times longer than 10 minutes in order to further stabilize the emissivity of the sample. Considerable uncertainties in the emissivity are shown in Appendix A to cause only small uncertainties in the temperature measurement for these experiments. The authors estimated the emissivity of the sample after treatment by comparing it to that of a blackbody by the procedure described in the next section.

The thicknesses of the oxide layers for the pre-oxidized molybdenum samples are not well known at present. It is estimated from prior experience and existing literature, however, that the thicknesses of these layers probably lie in the 5- to 50- μm range. After the samples are removed from the oven and allowed to cool, the oxide layers at both ends of the rods are removed, and the resistances of the oxidized molybdenum rods are re-measured. No change in resistance from the original room temperature value (410 $\mu\Omega$) could be detected to within the 10- $\mu\Omega$ accuracy of our resistance bridge for any of the samples.

2.4 Calibration Procedures

In the following discussion, calibration procedure refers to the process of establishing the relationship between rod temperature and Flashcam signal level. Although a blackbody simulator (BBS) was used to assist in choosing the proper settings for the camera and to verify some assumptions about sample emissivity, it was not an integral part of the calibration procedure. Because several steps are involved in both calibration of the camera and the assignment of a temperature to an experimental result, the procedure is summarized in Appendix B. A more detailed description is presented in the remainder of this section of the report.

After the desired oxide layer was achieved, the sample was assumed to have a stable average spectral emissivity, estimated to be about 0.9 in the band detected by the Flashcam camera (350 to 1040 nm). To check this assumption, the sample was compared to a BBS by heating it to the same temperature as the BBS and then viewing the sample in front of or alongside the BBS. The Flashcam signals for the sample and BBS were compared and showed only small differences, thus indicating that the sample had very high emissivity in the response band of the Flashcam. The small difference in signal could be attributed both to the slightly lower emissivity of the sample and to experimental uncertainties associated with knowing the true temperature of the BBS and the true temperature of the sample

after its removal from the oven. For this comparison, the uncertainties in the true temperatures are estimated to be ± 10 K for the BBS and ± 20 K for the molybdenum sample.

Because the sample cools during transfer from the oven to the viewing position, it was heated to a somewhat higher temperature than the desired calibration value. An example of the comparisons is given in Figure 1, which shows the Flashcam images of a heated molybdenum sample and the BBS. In this case, the sample was heated initially to a temperature of 779 K, removed from the oven, and placed in "vee-block" supports just in front of the BBS, held at a temperature of 773 K. A computer program was written to tabulate the CCD detector values along a row selected by positioning a cursor in the Flashcam image. Figure 2 shows the results of horizontal scans taken across the diameter of the BBS and along the sample. The camera was triggered manually just after placement of the rod in the blocks, and therefore, a delay of about 2 seconds occurs in obtaining the first image. Some cooling occurs during the transfer of the rod from the oven to the vee-blocks. The reduced amplitudes of video signals near the ends of the rod relative to the center are a result of subsequent cooling attributable to conduction through the supports.



Figure 1. Flashcam Image of Heated Rod and Blackbody Simulator.

In order to characterize the Flashcam's response to blackbody radiation over a range of temperatures, calibration data were acquired for various camera apertures and exposure integration times. Typical response curves are shown in Figure 3.

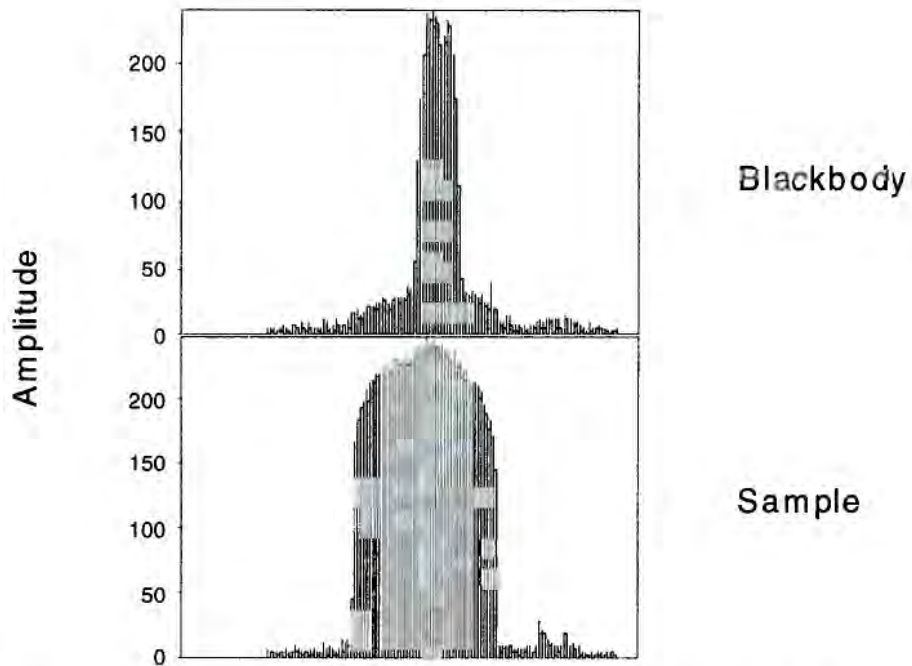


Figure 2. Digitized Scans of Images of Heated Rod and Blackbody Simulator.

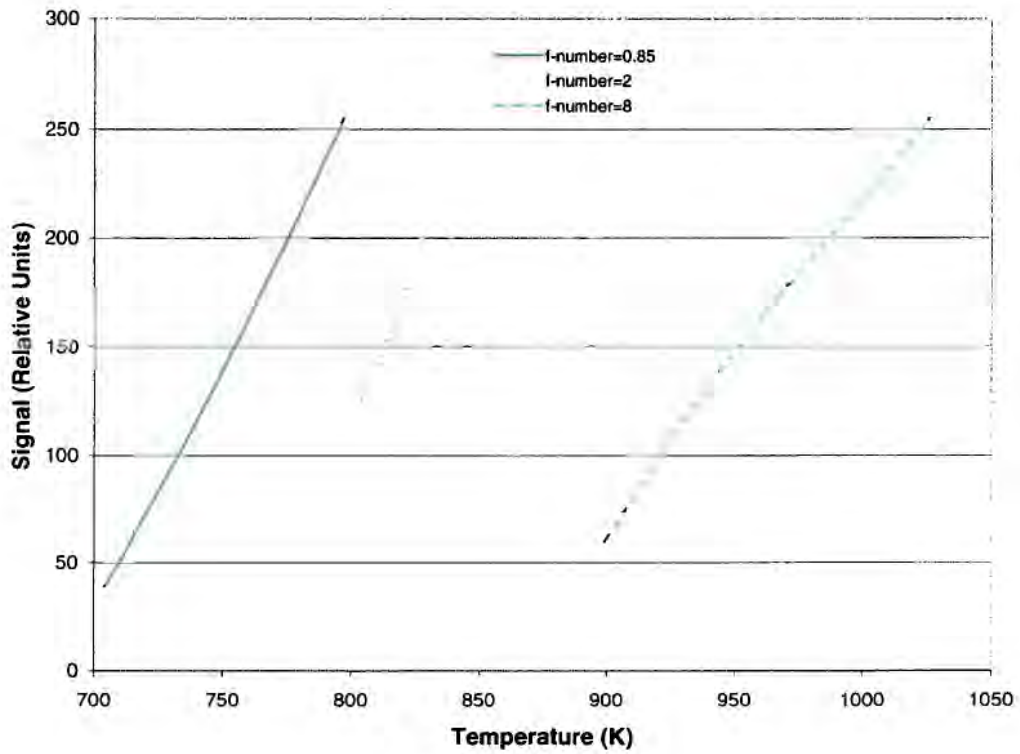


Figure 3. Flashcam Response to Simulated Blackbody Radiation.

The rate at which the heated rod cools may possibly affect the accuracy of the temperature measurement and must be considered during the calibrations and for the experiment. The rod cools by three mechanisms: (a) radiation, (b) convection to air, and (c) by conduction to the rod supports or electrical clamps. During calibration, cooling is readily observed by recording the Flashcam images at a standard video rate of 30 frames per second. Over many separate runs, the center of the rod sample was observed to cool at a rate of about 10 K/s from initial temperatures of around 800 K.

The distance between the support points for the rod was the same for both the experiment and the calibration. Not surprisingly, the cooling rates observed during the experiment (discussed in Section 3 of this report) were about the same as those recorded during the calibration runs. Because of the short delay, 50 ms, between heating and image capture in the experiment, no corrections for sample cooling were necessary.

3. Experimental Arrangement and Procedures

3.1 Electrical Setup

The heating source is a 1600- μ F capacitor bank consisting of eight 200- μ F capacitors. A 40-m Ω resistor attached directly to the terminal of each capacitor limits the output current of the capacitor. Two RG-217 coaxial cables carry the current from each capacitor to the input terminals of a triggered vacuum flash-over switch [7]. The output of the switch is coupled through 16 coaxial cables to the electrode plates shown in Figure 4. This arrangement produces a nearly axisymmetrical current into the conducting wire or rod. The outer copper braids of the coaxial cables are clamped to brass fittings threaded into the ground plate. The *copper center conductor, surrounded by a polyethylene core*, is carried through the gap to the second plate where the conductor makes electrical contact with the second or "hot" plate. The electrode assembly and capacitors are housed in a limited access range, whereas the charging unit and recording instruments are situated in a remote control room. The vacuum flash-over switch is triggered remotely after the capacitor bank is charged to the desired voltage.

Both current and voltage measurements are required in order to compare theory and experiment in the work described in the introduction. To avoid errors associated with either the differentiation or integration of recorded signals, the current and the derivative of the current are measured separately. Four Pearson coils are used to measure the total current from the capacitor bank. The center conductors of the two cables attached to each capacitor are routed through the center of a Pearson coil. The connections become coaxial again at the periphery

of the capacitor container where the center conductors are routed through the outer braids of the cables. A Rogowski belt embedded in the ground plate (see Figure 4) measures the derivative of the current.

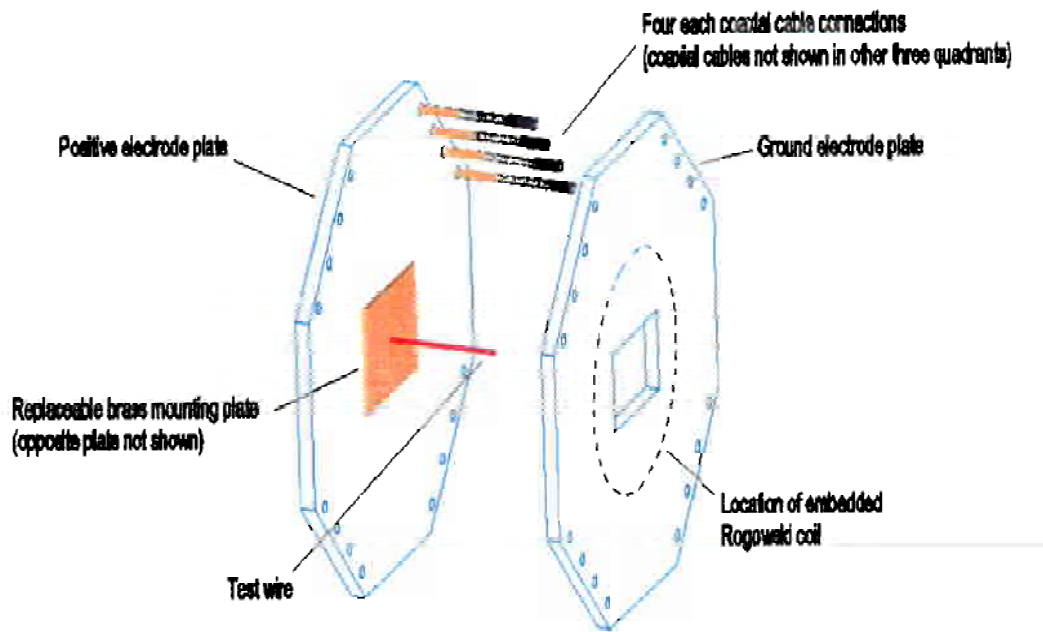


Figure 4. Experimental Arrangement.

3.2 Temperature Measurement Procedure

The electrode plates are spaced 76 mm apart, and the voltage probes are attached across the central 50 mm of the rod. Initiation of current flow in the sample is accompanied by the production of electrical arcs between the plates, particularly at contact points. Copious quantities of visible light, to which the Flashcam is particularly sensitive, are produced. This light is troublesome for two reasons. First, arc emissions may reflect directly from the sample surface or indirectly from the surfaces of the aluminum electrodes. Such reflections, if added to the thermal emissions of the rod, will produce significant errors in the temperature measurement. Second, detectors in the CCD array may be saturated by arc emissions, a situation that could produce errors because of uncertainties in the recovery time of the detectors. Thus, it is necessary to avoid data accumulation until the initial illumination has decayed and the detectors have recovered. By observing a series of images of decaying arcs and molybdenum rods heated electrically, the authors determined that a 50-ms delay was more than adequate to ensure that the arc light did not affect the images of the thermal emission from the rod. For all the experiments involving the capture of a single image, the camera was triggered 50 ms after the pulse and the integration time was 10 ms (ten 1-ms exposures). The measured cooling rate of 10 K/s implies that sample temperature drops only 0.5 K during the 50-ms delay. Thus, no correction for cooling is necessary.

The limited range of temperatures that can be measured with the Flashcam (about 100 K) makes it necessary to have a good estimate of the final temperature before measurement in order to properly set the f-stop and exposure time for the camera. To this end, a series of computer calculations [1], based on a model described in Section 5, was undertaken to estimate the final temperature of the rod as a function of capacitor-bank charge voltage. The time-dependent current used in the calculations was taken from a circuit theory model via the parameters (i.e., resistance, inductance, and capacitance) known from experience to represent average values for the experiment. The computations were continued until the charge voltage required (about 7.5 kV) to produce an approximate final temperature of 800 K was identified.

For all temperature measurements with the capacitor bank, the camera was positioned with a lens-to-sample distance of 65 cm, the same distance employed for the calibration runs. Temperature measurements were made by both recording methods discussed previously.

4. Theoretical Analysis

Calculations of the temperature and electromagnetic fields as a function of both space and time within the sample are undertaken with a simplified version of a model previously developed. The model calculations serve two purposes: first, as previously discussed, they predict the approximate charging voltage needed to produce a given temperature at the surface of the sample. Second, they also provide detailed results that can be compared to the experimental data, e.g., the final temperature of the sample surface. The data that are required as input into the model consist of the total current as a function of time as well the thermophysical properties of the sample undergoing study.

The simplified model is one-dimensional in the radial direction. This approximation should be valid, provided the current input is nearly axisymmetrical and provided the region of interest is not too close to the electrode plates. The pertinent equations to be solved consist of the coupled heat transport and Maxwell equations. These equations have been derived, presented, and discussed for a reasonably general two-dimensional case [1]. For the one-dimensional limit and for a situation in which the sample is motionless and melting is ignored, the simplified equations reduce to

$$\mu\sigma \frac{\partial B}{\partial t} = \frac{\partial^2 B}{\partial r^2} - \frac{B}{r^2} + \frac{1}{r} \frac{\partial B}{\partial r} - \frac{1}{\sigma} \frac{\partial \sigma}{\partial r} \frac{\partial B}{\partial r} - \frac{B}{\sigma} \frac{\partial \sigma}{\partial r} \quad (1)$$

and

$$\rho C \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial r^2} + \frac{\kappa}{r} \frac{\partial T}{\partial r} + \frac{\partial \kappa}{\partial r} \frac{\partial T}{\partial r} + \frac{1}{\mu^2 \sigma} \left(\frac{\partial B}{\partial r} + \frac{B}{r} \right)^2. \quad (2)$$

In these equations, B represents the magnetic induction field, T represents the temperature, and μ represents the magnetic permeability. The variables σ , ρ , C, and κ represent the electrical conductivity, the density, the specific heat, and the thermal conductivity of the sample, respectively. The last three of these properties and the resistivity η ($=1/\sigma$) are obtained from curve fits to data in references 2 and 3 and approximated as a power series in T. For any such property F,

$$F = \sum_j a(j) T^j. \quad (3)$$

The coefficients for any particular property, in appropriate SI units, are listed in Table 1 for molybdenum.

Table 1. Coefficients for Thermophysical Properties of Molybdenum

Coefficient	C (J/kgK)	η (Ω -m)	κ (W/mK)	ρ (kg/m ³)
a(-3)	0	0	3.16906×10^9	0
a(-2)	0	0	-2.67950×10^7	0
a(-1)	0	0	7.85718×10^4	0
a(0)	2.22624×10^2	-1.95022×10^{-8}	5.564×10^1	1.023×10^4
a(1)	1.12844×10^{-1}	2.41338×10^{-10}	0	0
a(2)	-5.87392×10^{-5}	1.89567×10^{-14}	0	0
a(3)	2.08333×10^{-8}	1.54632×10^{-18}	0	0
a(4)	0	-5.0×10^{-22}	0	0

Equation (1) describes the transport of the magnetic induction field within the sample, and Equation (2) describes both the transportation and generation of heat. Ordinary heat conduction is accounted for, although it is usually negligible on the time scales of interest. The last two terms on the right-hand side of Equation (2) can be recognized as the energy dissipated per unit volume and time by ohmic heating. No other source terms or transportation mechanisms are considered. Clearly, the two equations are coupled since the electrical conductivity depends upon temperature, and the source term in the energy equation depends on the magnetic induction.

Equations (1) and (2) must be solved, subject to the boundary conditions that the temperature gradient be zero both at $r = 0$ and at $r = r_0$, where r_0 is the radius of the sample. From Ampere's law, it also follows that $B(r = 0) = 0$ and

$$B(r = r_0) = \frac{\mu i}{2\pi r_0} \quad (4)$$

where i is the total pulsed current at time t . The value of i as a function of time is input directly from the experimental data or from the circuit fits described earlier. The equations are then represented in standard finite difference form and solved numerically by an iterative procedure as described in reference 1.

5. Results

Three runs were made with pre-oxidized samples at a charge voltage of approximately 7.5 kV. A plot of the circuit current used to heat the sample in Shot S2 is shown in Figure 5. The calculated surface temperature of the sample as a function of time for this shot is shown in Figure 6.

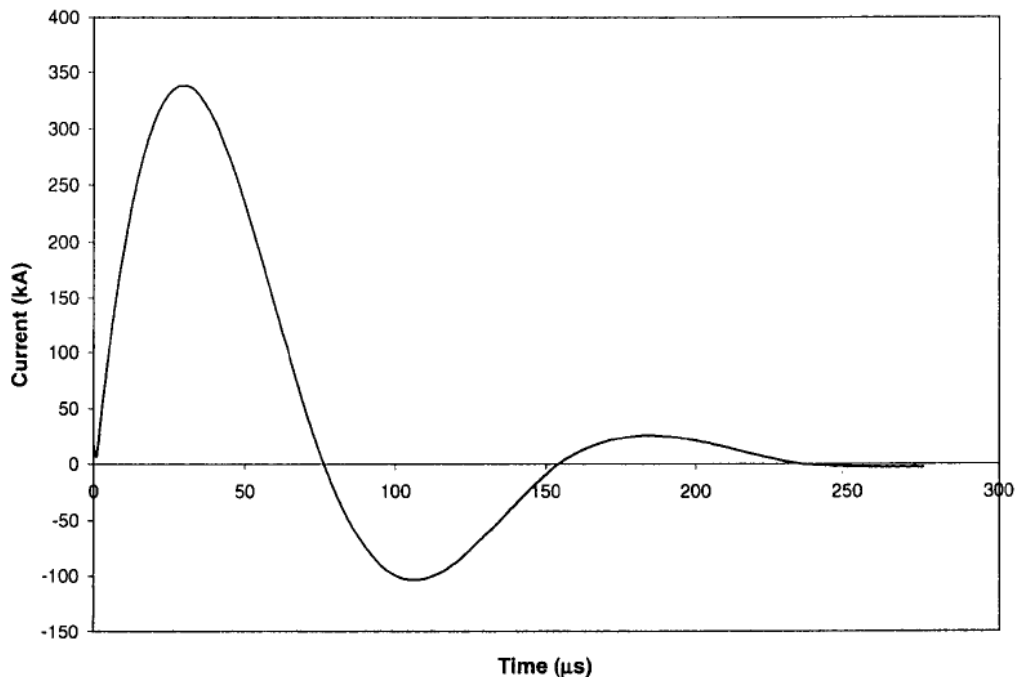


Figure 5. Current Trace for Shot S2: Charge Voltage = 7.51 kV.

As noted previously, the camera was calibrated in both the triggered and free-run mode of operation, and both were used in the experiments. The Flashcam image of a molybdenum rod heated to approximately 800 K is shown in Figure 7; the digitized Flashcam output for all three shots is shown in Figure 8. Also shown in Figure 8 are three calibration curves that indicate the temperature to be associated with a given signal amplitude. The horizontal position of the calibration curves in this graph has been arbitrarily shifted for clarity of presentation. All data, both calibration and experiment, were obtained for the following conditions: (a) f-number of 0.85, (b) 10 successive 1-ms exposures, and (c) a lens-to-sample distance of 65 cm.

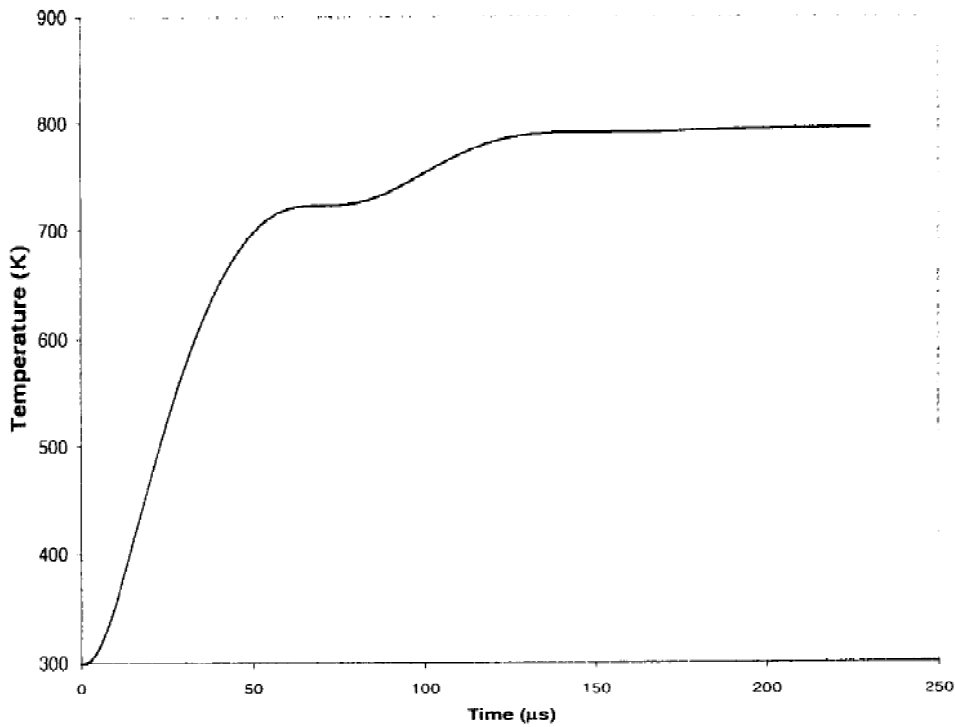


Figure 6. Predicted Surface Temperature Versus Time for Shot S2.

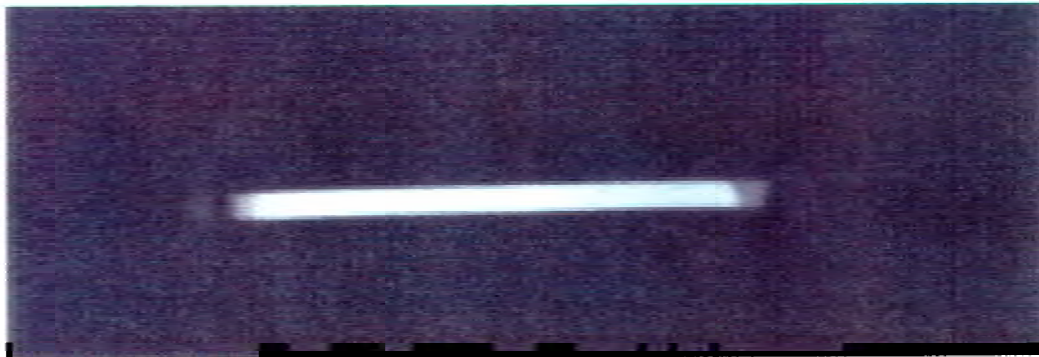


Figure 7. Flashcam Image of Molybdenum Rod.

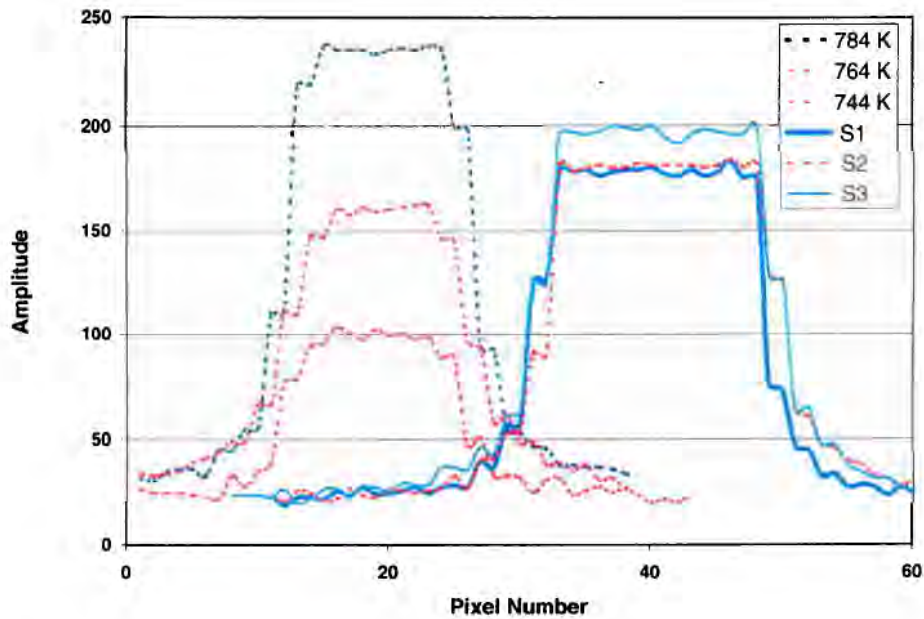


Figure 8. Profiles of Surface Temperature of Heated Rods Versus Calibration Curves.

The three separate temperature measurements and corresponding theoretical predictions are compared in Table 2. The predictions were obtained with the model discussed previously and with the experimentally measured current used as input. The differences between the theoretical and experimental results are well within the experimental uncertainty, but they do not reflect the normal spread of differences because the number of experiments was limited.

Table 2. Comparison of Theoretically Calculated and Experimentally Measured Temperatures (all results are in K.)

	Theory	Experiment	Difference
S1	774	770	- 4
S2	776	772	- 4
S3	777	774	- 3

This result provides an important and necessary confirmation of our approach. It also provides the impetus to continue efforts to develop a procedure for the

evaluation of some of the thermophysical properties for new alloys and materials in electrical heating experiments with a capacitor bank.

6. Discussion and Future Work

In recent years, data pertaining to the thermophysical properties of several elements and alloys, which are important for various Army applications of pulsed power, have been accumulated in ARL experiments. Emphasis has centered on three elements, molybdenum, tantalum, and tungsten, because the thermophysical properties of all three materials are known to very high accuracy—an essential requirement for validating the experiments. In this report, we have shown that the temperature predicted by the preferred thermophysical parameters for molybdenum is in agreement with the experimentally measured temperature at 800 K.

For future work, the experimental uncertainties in the temperature measurement by our video thermography technique could be reduced. The largest uncertainty is associated with establishing a value for the temperatures of the rods during calibration. This uncertainty consists of two components: ascertaining the true temperature of the rod within the oven and knowing how much the rod cools during removal from the oven and positioning for calibration. A more direct, automated way of transfer of the heated rod from the oven to a position near the BBS could be devised. The present manual procedure used to remove the sample from the oven and position it for calibration requires that a correction for cooling be applied. This correction was estimated to be -15 K. The overall uncertainty associated with our temperature measurement is estimated to be ± 20 K.

Many options and alternate techniques, not exercised in the present experiment, could be used to extend the range of temperature measurements with video thermography. Broad band spectral techniques, such as those used in the present experiment, will always offer more potential for high speed imaging than will narrow band techniques because more photons are collected. However, the use of narrow spectral band filters, possible at the radiances associated with higher temperatures, could also be a useful tool in some situations, e.g., as a means of reducing extraneous arc light or to improve accuracy. A two-color thermometry technique, based on the ratio of spectral radiance in two bands [8], may offer advantages for very high temperature measurements.

Moreover, the spatial resolution capability of the camera was hardly exploited in the present experiment because, at the time of measurement, the entire rod was at the same temperature. It could be useful in future studies employing high

speed imaging techniques to observe the changing temperature distributions on rapidly heated rods.

Finally, the earliest time when measurement of the surface temperature occurs could be reduced by the redesigning of the fixtures used to mount the sample. These fixtures were not designed with temperature measurements in mind. Redesign could significantly reduce the arc light output during heating.

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APPENDIX A

CALCULATION OF UNCERTAINTY IN TEMPERATURE
MEASUREMENT ATTRIBUTABLE TO UNCERTAINTY IN EMISSIVITY

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CALCULATION OF UNCERTAINTY IN TEMPERATURE MEASUREMENT ATTRIBUTABLE TO UNCERTAINTY IN EMISSIVITY

In this appendix, we evaluate the uncertainty in temperature measurement attributable to uncertainty in emissivity of the sample. The area of concern involves possible differences between the emissivity during calibration and the emissivity during the experiment. For example, if the calibration were performed with a rod having an emissivity of 0.8 but the experiment were performed with a rod having 0.6, what error would be introduced in the temperature measurement? A more complete analysis of these kinds of uncertainties is given by Stumpfel [5].

The contribution to the signal generated by the Flashcam system at any wavelength is proportional to the spectral emissivity; the total signal produced results from integration over a range of wavelengths. To calculate the signal expected for a given temperature and emissivity, the following procedure was used.

For each of several selected spectral emissivities, the spectral radiance was calculated from Planck's Distribution Law. This calculation consisted of an integration of the distribution function over wavelength with the limits determined by the "cut-off" wavelengths of the Flashcam, 350 and 1040 nm, respectively. Finally, the response of the Flashcam to various wavelengths, i.e., data supplied by the manufacturer, was folded into the results of the integration. As an example of these calculations, the relative response curves versus temperature over a temperature range of 780 to 820 K and for an emissivity of 1.0 and graybody³ emissivities of 0.6 and 0.8 are plotted in Figure A-1.

The effect of uncertainty in the emissivity on the temperature measurements can be quickly evaluated for a range of emissivities via this computational procedure. The values in Table A-1 were obtained from plots of signal versus temperature such as those of Figure A-1.

Let T_m represent the measured temperature and T_t the true temperature. Then, the difference or error, ΔT , is defined as

$$\Delta T = T_m - T_t.$$

³A graybody is defined as an emitter with spectral emissivity that is less than one and independent of wavelength.

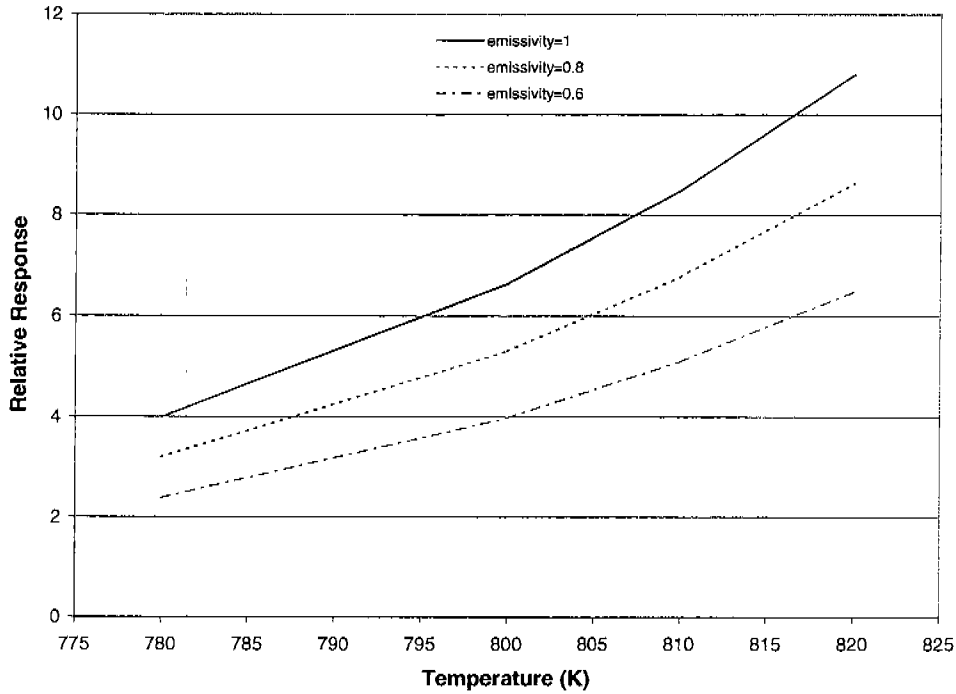


Figure A-1. Relative Response of Camera for Selected Emissivities.

At measured temperature, T_m , around 800 K, the following temperature errors, ΔT , result when the emissivities for the calibration and experiment are as indicated in Table A-1.

Table A-1. Temperature Error, ΔT (K), at 800 K Resulting From Different Emissivities, ϵ , During Calibration and During the Experiment

ϵ , Calibration	ϵ , Experiment			
	0.4	0.6	0.8	1.0
0.4	0	+14	+28	+38
0.6	-16	0	+10	+20
0.8	-30	-12	0	+10
1.0	-40	-22	-8	0

With the particular surface preparation of the rod used in the experiment, we estimate that the probable emissivity for both calibration and experiment is around 0.8. Let us assume that the emissivity uncertainty is ± 0.2 . Then from the table, if the emissivity during the calibration were 0.8 and the emissivity during

the experiment were 0.6, then the error, ΔT , would be -12 K with the measured temperature lower than the true temperature. Likewise, for an emissivity of 1.0 during the experiment, the error would be +10 K with the measured temperature higher than the true temperature. The errors in this example are about 1.5% of the absolute temperature of 800 K. However, when the pre-oxidization surface technique is used (including the blackbody comparison), we believe the emissivity variations are much less than ± 0.2 . We conclude that the uncertainties in our measured temperatures attributable to uncertainties in the emissivity of the samples are small. This insensitivity is a general characteristic of systems that sense the shortest effective wavelengths emitted by a thermal source. A discussion of this principle is given by DeWitt [4].

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APPENDIX B

SUMMARY OF PROCEDURES FOR CALIBRATION OF FLASHCAM
SYSTEM AND TEMPERATURE MEASUREMENT

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SUMMARY OF PROCEDURES FOR CALIBRATION OF FLASHCAM SYSTEM AND TEMPERATURE MEASUREMENT

Calibration:

1. Pre-oxidize molybdenum sample using oven treatment so that surface is stable and has a high emissivity.
2. Place molybdenum sample in pre-heated oven and heat to desired calibration temperature.
3. Remove sample rapidly from oven and record digital image or series of images on videotape.
4. Repeat Steps 2 and 3 using temperature steps appropriate for complete coverage of the desired temperature range.
5. Measure output video signal levels versus temperature and save in appropriate form for later comparison to corresponding data from experiment.

Experiment:

1. Pre-oxidize molybdenum sample using oven treatment so that the surface has a stable, high emissivity similar to that used in the calibration. The same rod used for calibration may also be used in the measurement.
2. Place rod between electrode plates and discharge current through rod.
3. Record, with selected delay time, either a single digitized image or a series of images on videotape.
4. Use signal level versus temperature results from the calibration to assign temperatures based on the signal levels recorded in the experiment.

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