LA-UR-04-6515

Approved for public release;
distribution is unlimited.

DOE/NV/11718--996

Title: Low-Temperature Measurements on Shock Loaded Tin

Author(s): A. Seifter, M. Grover, D.B. Holtkamp, J.R. Payton,
P. Rodriguez, D. Turley and A.W. Obst

Submitted to: SPIE Hi-Speed Photonics Conference
Alexandria, Virginia Sept 19-24, 2004

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Form 836 (8/00)

Low-Temperature Measurements on Shock Loaded Tin

A. Seifter^a, M. Grover^b, D.B. Holtkamp^a, J.R. Payton^a,
P. Rodriguez^a, D. Turley^b and A.W. Obst^{a,*}

^aPhysics Division, Los Alamos National Laboratory, Los Alamos, NM 87545

^bBechtel Nevada/Special Technologies Laboratory, Santa Barbara, CA 93111

ABSTRACT

In an effort to understand the influence of different surface finishes and the effect of ejecta mass on free surface temperature measurements, we performed a series of high-explosively (HE) shocked tin experiments. In this series of experiments the surface finish (i.e. specular, shallow grooves (16 μ inch), deep grooves (200 μ inch) and "ball-rolled" surfaces) and the ambient atmosphere (from 1.2 torr, to atmospheric air, as well as 1 atm helium) were varied. With a $\sim$ 180 kbar shock pressure the temperature results agreed for all but the very deep groove (>200 μ inch) surfaces investigated.

Keywords: shock physics, pyrometry, temperature measurements, high explosives, ejecta

1. INTRODUCTION

High-speed, low-temperature measurements of HE shocked free surfaces present a technical challenge. We have investigated the suitability of various tin surface finishes to such measurements, using near-infrared (NIR) and visible multiwavelength optical pyrometry. The relatively low-pressure ($\sim$ 180 kbar) HE facility at the Bechtel Nevada Special Technology Laboratory (BN/STL) in Santa Barbara, CA was chosen for these experiments. At this pressure Sesame tables, using Mie-Grunheisen theory [1], predict a tin free-surface temperature of $\sim$ 430 K, somewhat below the 505 K melting point. At these low temperatures great care must be taken to shield the small blackbody signals from potentially large background light from HE burn products. Also, rough surface finishes can produce undesirable hot ejecta emission, to which visible wavelength channels are much more sensitive than NIR channels, thus producing a misleading substrate temperature. Conversely, extraction of a true temperature from a radiance temperature is much more sensitive to the dynamic emissivity at long wavelengths than at short wavelengths. The surfaces tested ranged from specular (diamond-turned), to shallow- (16 μ inch) and deep-grooved (200 μ inch) machine finishes, to so-called "ball-rolled" surfaces (machined surfaces processed with a technique described below). The experiments were performed in a rough vacuum (1.2 torr), air and helium. The detector wavelength range of the five channels used varied from one visible 5 ns risetime photomultiplier (300 to 800 nm) to four 17 ns risetime NIR InSb's (centered at 1.8, 2.3, 3.5 and 4.8 microns).

2. THE EXPERIMENT

Two grams of detasheet¹ were attached directly to a tin sample and detonated inside a firing chamber ("boom box"), resulting in a shock wave with a peak pressure of about 179 kbar near the free surface of the 2mm thick tin sample (as inferred from earlier VISAR free surface velocity measurements with a similar experimental geometry). This shock raises both the volume and surface temperatures, and we measured the latter with a time-resolved optical pyrometer. The sample thermal radiance is collected by means of off-axis-parabolic (OAP) mirror optics and relayed through the chamber window to collecting optics outside the boom box. The different components are described in the following subsections.

¹ Detasheet (DuPont) is a flexible high explosive developed by DuPont. Sheet explosives have both military and commercial applications. It is composed of an integral mixture of PETN and a binder. This explosive is flexible over a wide range of temperatures. It is waterproof and available in a variety of extruded shapes and in sheets and cords. For more details on detasheet see Ref. 2.

2.1 The Boom Box

The boom box at BN/STL is an explosive test chamber purchased from Reynolds Industries, Inc (RISI). It is designed and used to perform small scale shock physics experiments in a laboratory environment. This welded steel tank is fitted with an entry door the diameter of the tank, two viewing ports, and an exhaust port. For more details on the boom box see Ref. 3 and Figures 1 and 3.

Fig 1. Schematic of the RISI boom box used at BN/STL.

2.2 The HE package

A schematic of the HE package can be seen in Figure 2. The tin target was 40 mm in diameter and 2 mm thick. Two grams of detasheet, 0.5" in diameter, were press fit directly to the sample. A stainless steel ring (R) held down the target coupon (T), as seen in Figure 2, in order to prevent hot background-producing gases from entering the pyrometry field-of-view (FOV). The housing itself was made from black polycarbonate, 45 mm in diameter. This was slightly larger than necessary in order to reduce edge effects.

Fig 2. The HE package: target (T); stainless steel ring (R); high explosives (HE); detonator (D); black polycarbonate housing (H).

2.3 The Pyrometer Setup

Five pyrometer channels were used in this series of experiments. The four NIR channel wavelengths were centered at 1.8, 2.3, 3.5 and 4.8 μm . These four channels are combined in a single instrument, consisting of three components: the front end optics, the connecting fiber and the detector unit. The single visible channel is an open (no filter, sensitive in the 300 to 800 nm spectral region) photo-multiplier-tube (PMT). A schematic of the optics setup is shown in Figure 3. The target-sample thermal radiance is collected with a 1"-diameter, 2"-focal-length (FL) OAP mirror made of protected aluminum. This mirror is mounted with three plastic posts and screws to the solid-steel experimental stand. The collimated light is baffled by black-painted plastic tubes in order to shield from background HE light. The chamber window consisted of a $\text{CaF}_2/\text{Al}_2\text{O}_3$ sandwich. Here the dispensable thinner CaF_2 window protected the thicker sapphire window from experimental debris. Outside the boom box the collimated beam is split with a dichroic filter, reflecting over 80% of the light above 1600 nm and transmitting over 80% of the light below 1600 nm.

Both beams are then each focused by another OAP mirror (1" FL for the NIR pyrometer, 2" FL for the visible channel) onto their respective fibers. A 1 mm core C2 chalcogenide fiber [4] delivered the NIR light to the NIR pyrometer. The pyrometer consisted of four LN_2 -cooled InSb detectors (rise time < 20 ns),

matching transimpedance preamplifiers and line drivers, rechargeable-battery power supplies, dichroic beamsplitters, filters, and broadband anti-reflectance coated ZnSe lenses [5, 6]. The visible light was transported with a 1 mm core low-OH fused silica fiber to the PMT. Only the solid-steel stand inside the boom box survived each shot. The OAP mirror, baffling, HE package, and CaF_2 protective window were replaced each time. The vacuum shots had an additional small enclosure around the HE package with a CaF_2 window in order to limit the pumping volume.

Fig 3. Schematic of the experiment setup and the pyrometer optics: high explosives package (HE); sending OAP mirror (OAP1); baffling (B); $\text{CaF}_2/\text{Al}_2\text{O}_3$ window sandwich (W); boom box (BB); dichroic beam splitter (DBS); receiving OAP mirror for the NIR pyrometer (OAP2); infrared fiber (IRF); receiving OAP mirror for the visible channel (OAP3); visible fiber (VF).

2.4 The Tin Samples

The tin samples had a diameter of 40 mm and a thickness of 2 mm. The purity was 99.9%² with a variety of different surface preparations, as follows:

- diamond-turned specular finish.
- 16 μinch RMS roughness fly-cut machine finish.
- ~200 μinch RMS roughness fly-cut machine finish.
- ball rolled, starting with both 16 and 200 μinch fly-cut machine finishes. Ball rolling is an emerging technology in industry which restores the fatigue strength and toughens the surface by applying residual stress and work hardening. In industry this process is automated [7, 8], in our case ball rolling was done manually [9].

A profilometer surface scan on a typical 16 μinch finish can be seen in Figure 4.

² Electronic Space Products International (ESPI), stock number Knc8773, purity 3N+, lot number 05473, tel. 800-638-2581.

Fig 4. Surface scan and results of a roughness measurement on a typical 16 μinch machine finish sample. Ra is the arithmetic mean deviation from the mean line; Rq is the corresponding RMS value; Rt is the maximum peak-to-valley height.

3. RESULTS

The integrating sphere reflectometry (ISR) technique provided initial normal static emissivities (ϵ) of each tin coupon at a wavelength of 1.55 μm , using a 70 mm diameter gold coated sphere. The results of these measurements are shown in Table 1 [10]. Since pyrometry alone can only yield radiance temperatures³ ($\epsilon=1$), additional assumptions about the normal spectral emissivity at the pyrometer wavelengths have to be made. The basis for our assumptions include the 1.55 μm room temperature measurements, data on polished tin [12], melting temperature emissivity values at the wavelengths of the NIR instrument [13], and spectral emissivity data on 16 μinch machine-finish tin [14].

First, the offset of the measured values at 1.55 μm from the value of a polished surface at the same wavelength has been scaled to the NIR pyrometer wavelengths, using the values in Refs. 12 and 14. This scaled offset is then added to the emissivity values of a polished surface at the wavelengths of interest, providing an ambient static value for the rough surface. Finally, the rise in emissivity from ambient to melt temperature (obtained by subtracting the values from Refs. 12 and 13) is assumed to be linear with temperature for all wavelengths. Therefore the rise in emissivity from ambient to 430 K (assumed sample shock temperature, predicted by calculations [1, 17]) was interpolated and added to the ambient value, leading to the assumed normal spectral emissivity used in the true temperature calculations.

Table 1. Results of the static normal spectral emissivity measurements at 1.55 μm .

Surface	Emissivity, %
Diamond turned	16.0
16 μinch ball rolled	18.2
200 μinch ball rolled	18.1
16 μinch machined	21.3
200 μinch machined	24.7

As these assumptions are based on another set of assumptions, a careful error analysis was performed by comparing this interpolation method with the so-called "high-low" method [15, 5]. The interpolation temperatures were found to be within the temperature interval that would have been obtained using the "high-low" method. The "high-low" uncertainties were adopted, which are on the order of 30 K. A listing of the 18 experiments producing data is given in Table 2.

³ The radiance temperature is the temperature of a blackbody generating the same amount of thermal radiance at the wavelength of interest as the sample. It is always lower than the true temperature unless the normal spectral emittance of the surface is 1 [11].

Table 2. Listing of the shot numbers yielding data.

Surface	Helium	1atm Air	1.2Torr Air
Diamond turned	# 3 & 17	# 12	# 22
16 μ inch machined	# 6 & 18	# 8 & 10	# 21
16 μ inch ball rolled	# 5 & 19	# 11	
200 μ inch machined	# 7, 13, 16 & 20		
200 μ inch ball rolled	# 14		# 23

Much has been written on tin [16], with few Hugoniot published. In the Mabire and Hereil work [17] one Hugoniot pressure identical to ours, 179 kbars, was identified, and therefore we have chosen to show this calculation in Fig 5. Here the discontinuity due to the heat of transition is shown in both the Hugoniot and isentropic release curves, each displaced by hysteresis from equilibrium. The Hugoniot or bulk temperature predicted here is seen to be 545 K. If the Hugoniot and release curves are both correct, then a free-surface temperature of ~ 430 K is predicted, to be compared with inferred values ranging between 450 and 480 K in the present experiment.

Fig 5. Calculated Hugoniot (black) and release isentrope (red) for an internal pressure of 179 kbar on tin [17].

3.1 Temperature Results

Figures 6 thru 8 show the inferred true temperatures and also the signal levels of the visible channel, under different atmospheric conditions. Pyrometer calibration and data analysis procedures are detailed in Refs. 5 and 6. Since the visible channel has a threshold radiance temperature of 900 K, which is much higher than the expected temperature, it serves as an excellent background detector. In the absence of any background this channel would be expected to have no signal. The presence of any signal is therefore attributable entirely to background events. At shock breakout time ($\sim 8 \mu$ s) a small transient temperature rise is visible on the specular and machine finishes in the NIR data. The temperatures, for 2-3 microseconds, range between 450 and 480 K for all but the roughest surface, which shows a temperature of ~ 700 K.

Fig 6. True temperatures inferred from the four NIR channels (top) and signals from the visible channel signal (bottom) for five different surface preparations for the experiments performed in a helium atmosphere.

In the visible channel only the deep groove ($> 200 \mu\text{inch}$) surfaces exhibit a shock breakout spike in the helium experiments. The other surfaces exhibit non-zero signals at 50-55 μsec , consistent with target debris arriving at the first OAP mirror in Fig 3. Earlier spikes are consistent with ejecta impacting this mirror. This ejecta cloud appears to dominate the visible signal from the 600 μinch surface beyond 30 μsec .

Fig 7. True temperatures inferred from the four NIR channels (top) and signals from the visible channel signal (bottom) for three different surface preparations for the experiments performed in an ambient air atmosphere.

The experiments performed in ambient air exhibit a distinctly different behavior, as seen in Fig 7. The true temperatures inferred from the four NIR channels show marked disagreement. The values increase with decreasing wavelength and are also not constant with time. This suggests the presence of a second light source, as discussed below. Here the visible channel shows a non-zero signal for all of the surfaces

investigated, clearly indicating that ambient air is a poor choice for free-surface optical temperature measurements. The late-time features are similar to those in helium, with increased dispersion due the larger drag force in air separating the ejecta particles by size.

Fig 8. True temperatures inferred from the four NIR channels (top) and signals from the visible channel signal (bottom) for three different surface preparations for the experiments performed in a low pressure (1.2 Torr) air atmosphere.

The low-pressure air results, shown in Fig 8, are very similar to the ambient air shots. Here again, in the visible channel, the ball-rolled surface shows the least amount of signal over the time range of interest. The earlier rise in signal, shown here beyond 20 μsec , is due to the CaF_2 window in the additional vacuum enclosure. Some of these anomalous wavelength-dependent results may be due to the high shock-heating of both helium (~ 700 K) and air (~ 1500 K) at these pressures [1]. Even though the emissivities of these gases are very low, they might sustain a hot ejecta glow especially from rough surfaces.

An unforeseen lack of adjustment flexibility precluded simultaneous measurements of VISAR [18] with pyrometry. Therefore a pressure value of 179 kbar was adopted. This assumption seems to be justified by the high reproducibility of several VISAR measurements on similar HE packages in this boom box configuration [19]. Future experiments should permit simultaneous VISAR and pyrometry measurements.

3.2 Data Interpretation

Figure 9 shows the temperature peak at shock breakout for an experiment performed on a 600 μm machine-finish surface of tin in a helium atmosphere. Three different explanations for this spike are suggested:

- hot ejecta emitted, then cooled by radiation,
- hot ejecta emitted, then cooled by convection, and
- a hot surface layer, cooled by conduction back into the bulk material.

The first two possibilities can be excluded by the following arguments. The cooling rate for hot ejecta, assuming a diameter of 1 μm , would be on the order of several Kelvin per microsecond for radiative cooling and on the order of several tens of Kelvin per microsecond in the case of convective cooling (assuming perfect heat transfer). Neither rate can explain the very rapid cooling of almost 500 K in a fraction of a microsecond. Also, if this spike were ejecta-related, the pyrometer would see only a small fraction of the 2 mm spot area as ejecta. Most of the FOV would consist of the 430 K surface. In that case, the apparent temperature from different wavelengths would increase with decreasing wavelength, as will be discussed later. Now assume a thin layer of hot material with an initial peak temperature at shock breakout T_p and this layer is cooled by conduction back into the cooler bulk material at T_b . This leads to the following equation for temperature versus time (assuming the layer is very thin compared to the bulk thickness):

$$T(t) = T_b + (T_p - T_b) \cdot e^{-\frac{2\lambda}{s^2 \cdot \rho \cdot c_p} \cdot t} \quad (1)$$

Here T_b is the bulk temperature, T_p is the peak temperature, λ is the thermal conductivity, s is the thickness of the hot layer, ρ is the density, and c_p is the specific heat.

Using values of 66.6 W/m.K for thermal conductivity, 7280 kg/m³ for the density and 227 J/kg.K for the specific heat yields the purple (2 μm layer thickness) and the red (3 μm layer thickness) curves in Figure 9. The similarity between the calculated and measured cooling curves leads to the suggestion that in rough surfaces a thin, hot surface layer is created, which conductively cools back into the bulk material. With this surface finish the late-time temperature is observed to be higher than the calculated bulk temperature in Fig 5 and measured on diamond turned and ball rolled surfaces. One possible explanation for the higher late-time temperature may be found from the observation that a ~ 140 μm thick spallation layer is launched after shock breakout, as indicated by VISAR traces observed on similar HE-packages [18]. In that case the final temperature would be the mixing temperature of the hot surface layer (up to 1600 K as indicated by the visible pyrometer channel in Fig 10) and the 430 K spallation layer temperature. If the hot surface layer is thick enough the equilibrium temperature would be higher than 430 K, with no initial hot surface layer present.

Fig 9. Shock breakout peak from a 600 μinch machine-finish surface of tin in helium.

Fig 10. Comparison of typical VISAR spallation time with temperature slope change in the visible PMT channel. This PMT data is from the same shot as the NIR data shown in Fig 9, while the VISAR data is from a similar shot.

The peak temperature observed in Fig 10, as compared to Fig 9, is likely due to the higher bandwidth of the PMT detector, which is more capable of tracking rapid temperature changes. The uncertainty on the temperature shown in Fig 10 is approximately ± 80 degrees K. An abrupt change in the cooling rate of the free surface can in fact be seen in Fig 10, but only in the visible channel (due to a slightly better signal-to-noise ratio in the PMT detector). This abrupt change occurs about 75 ns after shock breakout and at the same time the free surface VISAR indicates spallation. This change in cooling rate was observed reproducibly in several shot records. The period of the ringing in the VISAR velocity record corresponds to a spall layer thickness of 144 ± 9 μm.

In almost all of the experiments performed in air (both ambient and low-pressure) the true temperatures inferred in all four NIR channels do not agree with each other (except the 200 μm ball rolled sample in 1.2 Torr air). The values increase with decreasing wavelength, which is always the case when a small portion (area fraction α) of the surface is at an elevated temperature T_a . The sample thermal radiance at a wavelength λ is then:

$$L = (1 - \alpha) \cdot \frac{c_2}{\lambda^5 \left(e^{\frac{c_2}{\lambda T}} - 1 \right)} + \alpha \cdot \frac{c_2}{\lambda^5 \left(e^{\frac{c_2}{\lambda T_a}} - 1 \right)} = \frac{c_2}{\lambda^5 \left(e^{\frac{c_2}{\lambda T'}} - 1 \right)} \quad (2)$$

Here c_2 is Planck's second radiation constant, α is the area fraction, T_a is the temperature of the hot spots, λ is the wavelength, and T' is the apparent inferred temperature. If the apparent inferred temperature is calculated from this superposition of two temperature sources, the following expression is obtained:

$$T' = \frac{c_2}{\lambda \cdot \ln \left[\frac{1}{\frac{1 - \alpha}{\left(e^{\frac{c_2}{\lambda T}} - 1 \right)} + \frac{\alpha}{\left(e^{\frac{c_2}{\lambda T_a}} - 1 \right)}} + 1 \right]} \quad (3)$$

The spectral and hot-spot temperature dependence of the apparent inferred temperature can best be seen graphically, as shown in Figure 11. Here a hot-spot area fraction α of 1% was arbitrarily chosen.

Fig 11. Apparent inferred temperature for a hot spot fractional area fraction of 1%, calculated for the wavelengths of the pyrometer channels used in this study.

As can be seen in Figure 11, the shorter wavelengths are much more sensitive to background light than the longer wavelengths. For example, NIR channel 4, centered at 4.8 μm , misreads T' by 9.5 K at a T_a of 1500

K, channel 3 at 3.5 μm misreads by 104 K, channel 2 at 2.3 μm misreads by 235 K, channel 1 at 1.8 μm misreads by 325 K, and the visible channel, assumed centered at 0.5 μm , misreads by 729 K. This behavior is observed for the experiments performed on the deep-groove as well as specular surfaces but not for the 200 μm ball rolled sample in air at low pressure and to a limited extent for the 16 μm ball rolled sample in ambient air. Furthermore, since the amount of ejecta produced by different surface finishes should not depend on the surrounding atmosphere, the presence of such wavelength dependence in air suggests nitrogen luminescence induced by hot ejecta. We also observed inconsistent radiances in the ball rolled and specular samples shocked in ambient air (and 1.2 Torr air) so it is likely that there is also wavelength dependent background light generated by the shocked air as well.

4. CONCLUSIONS

Surface temperature measurements using a variety of surface finishes agreed reasonably well with the predicted value of 430 K using a helium atmosphere. In both ambient and low pressure air atmospheres a wavelength dependent temperature in all five channels was observed for all surface finishes and the temperature results are suspect for experiments in air. This wavelength dependence was minimal for the ball rolled surfaces, suggesting that this surface is best suited for pyrometric free-surface temperature measurements. The diffusivity of the ball rolled surface also makes it ideal for VISAR measurements.

The temperature spike at shock breakout is believed to be due to a thin layer of hot material which is cooled by conduction back into the bulk material. The rough surfaces often have a higher late-time temperature than the expected bulk temperature. One explanation is that the equilibrium mixing temperature is higher when the hot surface layer mixes with an $\sim 140\text{ }\mu\text{m}$ thick spallation layer at 430 K. The spike at the time of shock breakout is observed in almost every experiment with rough surfaces but neither with ball rolled nor specular finishes. We plan to obtain more NIR imaging data in order to better understand the effects of grain size, material purity, and surface finish on hot-spot distribution and shock breakout temperatures. More information on hot spot distributions can be found in Ref 20. A more extensive characterization and quantification of ejecta production as a function of surface finish using piezo-pins, x-ray techniques and shadowgraphy is required to validate extend our inferences on the effects of ejecta. Also, experiments at higher shock pressures using, for example, PBX 9501 instead of detasheet, where tin melts on release, would lead to a deeper insight into the phenomena observed in this study.

ACKNOWLEDGMENT

The authors thank Ted Strand from the Lawrence Livermore National Laboratory and Pat Reardon from LANL (MST-7) for providing their knowledge and help in ball rolling. We also wish to thank J.D. Johnson from LANL (T-1) for calculations and many hours of insightful discussions.

REFERENCES

1. J.D. Johnson, private communication.
2. <http://heritage.dupont.com>
3. <http://www.risi-usa.com/0products/4acc/page55.html>
4. Amorphous Materials, Inc., 3130 Benton, Garland, Texas 75042 USA, www.amorphousmaterials.com
5. Boboridis K. and Obst A.W., "A High-Speed Four-Channel Infrared Pyrometer", in *Temperature: Its Measurement and Control in Science and Industry*, 7, Part 2, edited by D.C. Ripple, (AIP, New York, 2003), p. 759.
6. Seifter A., Boboridis K. Payton J.R. and Obst A.W., "A High-Speed, Four-Wavelength Infrared Pyrometer for Low Temperature Shock Physics Experiments", to be published in the *Proceedings of High Speed Photography and Photonics 2004*.
7. Prevey P. and Mahoney, M., "Improved fatigue performance of friction stir welds with low plasticity burnishing: residual stress design and fatigue performance assessment", *Materials Science Forum*; 2003; vol. 426-432, pt. 4, p. 2933-40.

8. Migala T.S., Jacobs T.L., "Low Plasticity Burnishing: An affordable, effective means of surface enhancement", SURFACE ENGINEERING: COATING AND HEAT TREATMENTS, PROCEEDINGS; 2003; p. 151-159.
9. Strand, O.T., "Handbook for the Manybeam Velocimeter", UCRL-JD-147167, March 8, 2002.
10. Achim Seifter, Konstantinos Boboridis, Andrew W. Obst, "Comparison of emissivity measurements using an integrating sphere reflectometer and a laser polarimeter on surfaces with various degrees of roughness", *Proceedings of XVII IMEKO World Congress*, 2003.
11. DeWitt D.P., Nutter G.D. *Theory and Practice of Radiation Thermometry*, John Wiley & Sons, New York, 1988.
12. Palik E.D., "Handbook of Optical Constants of Solids", *Academic Press*, San Diego, CA, 1998.
13. K. Boboridis, A. Seifter, A.W. Obst, and D. Basak, "Radiance Temperatures and Spectral Emittances (in the Wavelength Range of 1500-5000 nm) of Tin, Zinc, Aluminum and Silver at their Melting Points by a Pulse-Heating Technique", *Int. J. Thermophys.*, Vol. 25, No. 4, p 1187-1202, 2004
14. L.M. Hanssen and S.G. Kaplan, private communication.
15. Partouche-Sebban D., Holtkamp D.B., Lelissier J.L., Taboury J. and Rouyer A., "An Investigation of Shock Induced Temperature Rise and Melting of Bismuth using High-Speed Optical Pyrometry," *Shock Waves*, V. 11, pp 385-392, 2002.
16. Jean-Paul Davis and Dennis B. Hayes, "Isentropic compression experiments on dynamic solidification in tin", in *Shock Compression of Condensed Matter*, 2003 (M.D. Furnish et al., eds), pp. 164-166.
17. Catherine Mabire and Pierre L. Hereil, "Shock induced polymorphic transition and melting of tin," in *Shock Compression of Condensed Matter*, 1999 (M.D. Furnish et al., eds.), pp. 93-96.
18. Barker L.M., Hollenbach R.E., "Laser interferometer for measuring high velocities of any reflecting surface", *J. Appl. Phys.*, **43**, No. 11, pp. 4669-4675, 1972.
19. W.D. Turley, private communication
20. Craig W. McCluskey, Mark D. Wilke, William D. Turley, Gerald D. Stevens, Lynn R. Veaser, and Michael Grover, "Infrared Images of Shock-Heated Tin", this volume.

*obst@lanl.gov, phone: 1.505.667.1330, fax: 1.505.665.4121