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Citation: Journal of Applied Physics 35, 3055 (1964); doi: 10.1063/1.1713166
View online: http://dx.doi.org/10.1063/1.1713166
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temperature jump was caused by the irreversible heating produced by bombardment heating, since the onset of the two types of radiation occur at quite different current levels [for example, compare points (A) and (B) of Fig. 1].

The authors wish to express their thanks to Dr. F. M. Charbonnier and E. C. Cooper for helpful discussions.

* This work is supported by National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio.

Response of a Thermocouple Junction to Shock Waves in Copper*

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(Received 27 April 1964)

In the course of experiments to measure temperatures in the vicinity of craters produced by high-velocity impact, thermocouples were attached to the surfaces of metal targets and embedded in them. In many cases, a small jump in output voltage was observed to occur at the time of impact. This was followed by a slower rise in temperature as heat was conducted from the crater to the region of the thermocouple. It was suspected that the initial temperature jump was caused by the irreversible heating produced by passage of a strong wave.

These thermocouple voltage measurements were made with a microvolt meter having a response time of about 1 sec, so no detailed observations of the initial voltage rise could be made. The small voltages obtained (20 µV) precluded the use of a fast-response amplifier and oscilloscope to observe the thermocouple output.

To produce waves strong enough to be easily measured, a thin copper target was used with a constantan wire silver-soldered to the rear surface to form a thermocouple. A 4.76-mm-diam copper ball impacted at velocities ranging from 0.5 to 2.1 km/sec. With this system, thermocouple voltages up to 60 mV were observed using a Tektronix type 533 oscilloscope with a type E preamplifier. Noise in the system required the use of the differential amplifier, although its frequency response was inadequate for the fast transient present. These preliminary experiments clearly demonstrated the feasibility of using a thermocouple junction to measure wave strength. However, a definite relationship between voltage output and wave parameters could not be determined because of the difficulty of hitting directly over the thermocouple, thus making it impossible to calculate the actual wave strength at the junction.

To produce plane waves, the system shown in Fig. 1 was devised. A Tektronix type B preamplifier was used with a type 533 oscilloscope. The transient response of this system was adequate to observe details in the voltage rise and decay in the junction. A typical voltage waveform is also shown in Fig. 1. The voltage rises rapidly (within 2 µsec), levels off, and then may swing widely in either polarity. The waveform after the initial rise and leveling varies from shot to shot and depends on the mode of disintegration of target and junction. Various interesting oscillations related to wave transit times in wire and target are observed in the voltage output, but only the magnitude of the first step is considered in the data reported here. We interpret the initial voltage step as being due to the establishment and decay of a brief "stationary" flow condition between the rear face of the target and the thermocouple wire.

The results of a series of shots on 1.68-mm-thick copper plates, 24 AWG constantan wires, and copper and 24 T4 aluminum projectiles are shown in Fig. 2. A straight line is drawn through the copper data for reference. The indicated error comes from uncertainty in reading the oscilloscope trace due to noise with the signal or to the occurrence of more than one step in the voltage trace during the first 4 µsec. The theoretical curve for the alumi-

FIG. I. Fowler–Nordheim plot of current–voltage data from clean tungsten electrodes. (A) represents point where the transition radiation was first detected on the anode. At (B) the radiation has increased in intensity, while the anode has reached a temperature of −700°C. At (C) the radiation is still visible against an incandescent background (1350°C).

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FIG. 1. Gun, projectile, and thin-plate target used to measure response of a thermocouple junction to a shock wave. A typical waveform of thermocouple output voltage is also shown.
The above analysis neglects the fact that the Fowler–Nordheim equation is applicable only at high voltages. At low voltages, the tunneling current, like all other currents, must obey the Ohmic relation $I = AV$. That the tunneling current does this is well documented.\footnote{A Fowler–Nordheim graph of the Ohmic region is described by the equation $I = AV^2 \exp(-B/V)$, where $A$ and $B$ are constants determined by the material and geometry of the system.}