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Pulsed Electron Beam Calorimetry Utilizing Stress Wave Measurements in Solid Absorbers

R. A. Graham, R. E. Hutchison, and W. B. Benedick

Sandia Laboratory, Albuquerque, New Mexico

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INTRODUCTION

Pulsed-electron-beam machines which produce currents of thousands of amperes and current durations of the order of 10^{-8} sec are available for transient energy deposition studies. Although extremely short pulse durations are the most characteristic feature of these beams, currently available methods for calorimetry measurements on the beam are adaptations of methods previously employed for steady state sources. These methods include the passive technique of recovering blue cellophane foils[1,2] which have been exposed to the beam as well as temperature measurements on thin metallic discs.[2] It is the object of this paper to propose a new method of calorimetry based on measurements of the stress pulses which result when the beam is absorbed in thick elastic absorbers. In a recent communication we briefly described some of the properties of these thermoelastic stress pulses.[3] The stress pulses can be used to determine the intensity, end-point range, and duration of the electron beam.

Previous measurements[4-7] of stress pulses produced by radiant energy sources have been accomplished in rod-shaped absorbers with geometrically limited rise-time capabilities. The measurements by White[4,5] were obtained for conditions in which long duration electron pulses (~ 2 μsec) were absorbed on the surface of a rod.

THERMOELASTIC STRESS WAVES

To understand the operation of the calorimeter we must first consider the properties of the stress pulse which results from the absorption of the beam. The thick elastic absorber is considered to be exposed to an electron beam of uniform areal intensity such that the energy of the beam is deposited within the absorber. If the duration of the incident electron pulse is very short compared to duration of the resultant stress pulse, the absorption can be assumed to occur instantaneously. From the constant volume conditions which result from the instantaneous deposition it follows immediately that

$$\sigma_x(x) = \tau_x E(x) \quad , \tag{1}$$

where E(x) is the absorbed energy (the x-direction taken normal to the disc face), and the resulting normal stress component in the x-direction is σ_x. The thermoelastic constant, τ_x, is defined as $\tau_x \equiv \gamma_x/V \equiv (\partial\sigma_x/\partial E)_V$ where V is the specific volume and γ is the Gruneisen's ratio.[8] Thus, if the thermoelastic constant of the absorber material is known, a measurement of the stress as a function of position at deposition time provides a direct evaluation of the energy as a function of position. This energy distribution evaluation gives the maximum absorbed energy, the electron end-point range, and an absorption coefficient.

If the duration of the electron beam pulse is finite but still short compared to the duration of the stress pulse, the stresses in the immediate vicinity of the exposed surface are altered from that predicted by Eq. (1). Normally, however, the stresses at positions remote from the exposed surface are unaffected.

Once the energy is absorbed, a plane compressive stress pulse propagates along the x-direction and immediately forms a tensile stress tail to maintain zero total momentum. (The incident electrons have negligible momentum.) While progressing through the disc, the pulse lengthens in time and the peak compressive stress decreases in amplitude. If the absorber is elastic, however, these changes in pulse amplitude and duration can be analyzed as an elastic wave propagation problem. Hence, the stress pulse at some position removed from the original deposition site is directly related to the original stress distribution, and this propagated stress pulse is the basis for the proposed calorimeter.

A measurement of the stress pulse requires exceptional time resolution since significant changes in stress will occur in times of the order of 10^{-8} sec. The Sandia quartz gauge[9] produces an output current directly related to the instantaneous stress at the input electrode. The time-resolution is limited only by the planarity of the wave the rise-time of the recording equipment. With this gauge it appears feasible to obtain precise measurements of the stress pulses resulting from absorption of the electron beam. The proposed calorimeter, shown in Fig. 1, consists of this gauge and an absorber disc of large diameter-to-thickness ratio. The thickness of the absorber is chosen to be greater than the end-point range of the electrons. One plane surface of the disc is exposed to the beam and the resulting stress pulse is detected by the gauge located at the opposite surface of the disc.

EXPERIMENTAL

Experiments to study the feasibility of the proposed calorimeter have been performed utilizing 40 nsec duration electron pulses from a 2 MeV pulsed-electron-beam machine.[1] Absorber discs 25 mm in diameter and 6.35 mm thick were exposed to a 12.7 mm diameter segment of the electron beam in separate experiments in which the nominal characteristics of the beam were unchanged. The experiments were conducted with the absorber 7.6 cm from the window of the machine which was set on a charging voltage on 30 KV. The quartz gauges used were X-cut discs 12.7 mm in diameter and 6.35 mm thick. The relative stress amplitudes were measured with an accuracy of ±5%.

A typical stress pulse record obtained on an aluminum absorber is shown in Fig. 2. It is apparent from this record that the stress profile can be measured in considerable detail. The noise encountered at deposition time serves as a convenient marker for deposition time which in this case occurs 960 nsec before arrival of the peak compressive stress. The shape observed is that which would be expected for a radiation-induced thermoelastic stress pulse.

A wide variety of absorber materials were investigated; all were potentially useful calorimeter absorbers. These materials and their pertinent properties are shown in the first five columns of Table I. The materials include dielectrics, semiconductors, and metals with a range of thermoelastic constants of a factor of about six. The dilatational wave velocities, C_o, and the densities cover a range which varies about a factor of three. All materials have elastic limits high enough such that they remain elastic for the conditions of the experiment.

As previously mentioned, the 40 nsec pulse duration of the electron beam will cause peak stress amplitudes to be reduced below the values predicted by Eq. (1). The extent of this reduction for a given electron pulse duration will depend upon the stress pulse duration in the absorber. That is, very short stress pulses will be reduced in amplitude more than long duration pulses because the electron pulse deposition time is a larger fraction of the short pulse. A calculated value for the initial stress pulse duration, T_o, resulting from the energy absorption can be obtained by dividing the electron range (expressed as the depth of penetration) by the dilatational wave velocity. T_o values are calculated for 1.9 MeV electrons in the various absorbers and shown in Table I. The 40 nsec electron pulse duration should be compared to the T_o values noting that the value for sapphire is 200 nsec while this value is 590 nsec for X-cut quartz.

RESULTS

From records as shown in Fig. 2 obtained on the various absorbers the relative amplitudes of the peak compressive stresses may be compared to that calculated from Eq. (1). Both observed and calculated stress amplitudes are normalized to a value of 1.00 for X-cut quartz. This comparison is shown in the sixth and seventh columns of Table I. With the exception of the germanium and sapphire absorbers, the measurements show a ±20% spread in amplitudes between observed and calculated values (5% of the spread is due to experimental error). This indicates a shot-to-shot variation in the beam of ±15% which is consistent with other measurements. The lowered values obtained in the sapphire and germanium absorbers reflect the influence of the 40 nsec electron pulse duration on these materials with the shorter T_o values of 200 nsec and 300 nsec respectively. These measurements, as well as repeated experiments on the same absorber at various times, show that the measured stress pulses sensitively reflect the intensity of the beam.

Some difficulty might be expected for the absorption of the energy of charged particles in dielectrics compared to those absorbed in a conductor. The potential accompanying the initial electron deposition may decelerate electrons which arrive somewhat later. In the case of the quartz and sapphire absorbers, no effect was observed on the absorption compared to that in the conductors. Two other dielectrics, tourmaline and a low thermal expansion glass,[11] were observed to suffer dielectric breakdown which caused major changes in the stress wave profiles.

The indium antimonide record showed the tensile stress peak to be abnormally reduced in amplitude. Examination of the sample showed that the exposed surface had suffered a tensile stress failure which would cause the change in wave profile.

In addition to the stress amplitude data which reflects the intensity of the electron pulse, the data on the duration of the stress pulse reflects both the electron end-point range and the duration of the beam. The initial stress pulse duration is directly proportional to the electron end-point range and inversely proportional to the dilatational wave velocity. The observed stress pulse durations were used to calculate the range relative to that observed for X-cut quartz with a 1.9 MeV electrons. The results of these range measurements are shown in Table II. Experimental results are shown for X-cut quartz absorbers at various electron energies and other absorbers at an energy of 1.9 MeV. The observed range values agree with those calculated from the nominal electron energy within ±10%. With the pulses reported here it is possible to measure the pulse length within ±5%. The remainder of the variation is thought to be the shot-to-shot variation in the energy of the beam. These measurements show that the end-point range of the electrons can be measured without difficulty.

Numerical calculations show that the duration of the electron beam is explicitly shown in the measured stress pulse. The time difference between the peak compressive stress and the zero stress value immediately following the peak is equal to the beam duration. The record shown in Fig. 2 shows this time to be 35 nsec. The pulse duration measurements published by the manufacturer[1] show the main portion of the pulse to last about 40 nsec with a longer low amplitude tail lasting up to 100 nsec. Our measurements on the electron pulse do not show any indication of the long duration tail. Apparently, the long duration tail is associated with low energy electrons which are absorbed by the thin aluminum filter placed in front of the absorber.

SUMMARY AND CONCLUSIONS

These measurements show that the stress pulses resulting from the absorption of intense pulsed-electron-beams can be measured in considerable detail. The stress pulse amplitudes and durations are observed to scale quantitatively with the intensity and energy characteristics of the beams absorbed in various absorbers. In addition, the electron pulse duration is shown as a distinct feature of the stress pulse. It is concluded from this investigation that measurements of the stress pulses in thick elastic absorbers can provide a basis for calorimetry of pulsed electron beams. Presently, the measurements are limited to relative values which can be calibrated by more conventional means. Computer solutions of the complex elastic wave propagation problem will permit absolute values to be recovered from these same measured pulses.[12]

It appears that aluminum and X-cut quartz are the best absorber materials for a calorimeter. Aluminum has a much larger thermoelastic constant than quartz which gives it a superior signal-to-noise ratio. Thus, aluminum is preferable for absorbed energies less than about 8 cal/gram. However, the elastic constants of aluminum are sensitive to the temperature rise and absorbed energies greater than 8 cal/gram will cause some nonlinearities in the response of the calorimeter. The temperature independent properties of X-cut quartz absorbers make quartz a better material for higher intensity pulses.

Present measurements show that the most desirable gauge for the stress pulse measurements is a guard-ring gauge[9] 31.8 mm in diameter and 6.35 mm thick with an active center electrode diameter of 12.7 mm. In addition, improvements have led to a considerable reduction in the noise level which can be observed by comparing the record in Fig. 2 with an earlier published record.[3]

The stress pulse calorimeter is a unique and promising new device for the study of the characteristics of pulsed electron beams. In fact, the calorimeter seems far more precise and sensitive than needed for presently available sources. Since the physical basis for the operation of the calorimeter is different from that employed in other calorimeters, it is now possible to obtain independent measurements of beam properties. This capability should greatly improve our understanding of pulsed-electron-beam machines.

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Table I

Absorber Properties and Peak Stress Amplitudes

	Absorber Properties				Relative Stress Amplitudes	
Absorber	τ_x (a) bar gram/cal	Co (b) mm/μsec	ρ (c) gram/cm^3	T_o (d) nsec	Calculated	Observed (e
X-Cut Quartz	82	5.72	2.65	590	1.00	1.00
Z-Cut Quartz	66	6.36	2.65	530	0.80	0.65
Z-Cut Sapphire	237	11.1	3.99	200	2.80	1.60
[111] Silicon	42	9.36	2.33	410	0.51	0.61
[100] InSb	115	3.44	5.8	460	2.3	1.8
[111] Germanium	162	5.65	5.35	300	2.0	1.4
6061 T-6 Aluminum	236	6.32	2.70	520	2.9	3.2

(a) The component of the thermoelastic constant, τ, in the X-direction is computed using the analysis of S. W. Key.[8]

(b) C_o is the dilatational wave velocity along the axis of the disk.

(c) ρ is the density.

(d) T_o is the initial pulse length of the stress pulse calculated as the range for 2 MeV electrons[10] divided by C_o.

(e) The observed stress amplitudes are corrected for the acoustic impedance mismatch between the absorber and the gauge.

Table II

Electron Range Measurements

Absorber	Electron Energy MeV	Range, mm Measured	Range, mm Calculated (a)
X-Cut Quartz	1.9	(b)	3.36
X-Cut Quartz	1.6	2.42	2.75
X-Cut Quartz	1.3	2.18	2.19
X-Cut Quartz	0.96	1.44	1.58
Z-Cut Quartz	1.9	3.55	3.36
Z-Cut Sapphire	1.9	2.05	2.23
[111] Silicon	1.9	3.82	3.79
Aluminum Alloy	1.9	3.30	3.30

(a) These values are calculated from conventional energy vs. range relations.[10]

(b) This value is assumed to be 3.36 mm in agreement with the calculated value. Measured values for the other absorbers are computed from the measured pulse lengths relative to that assumed for X-cut quartz with 1.9 MeV electrons.

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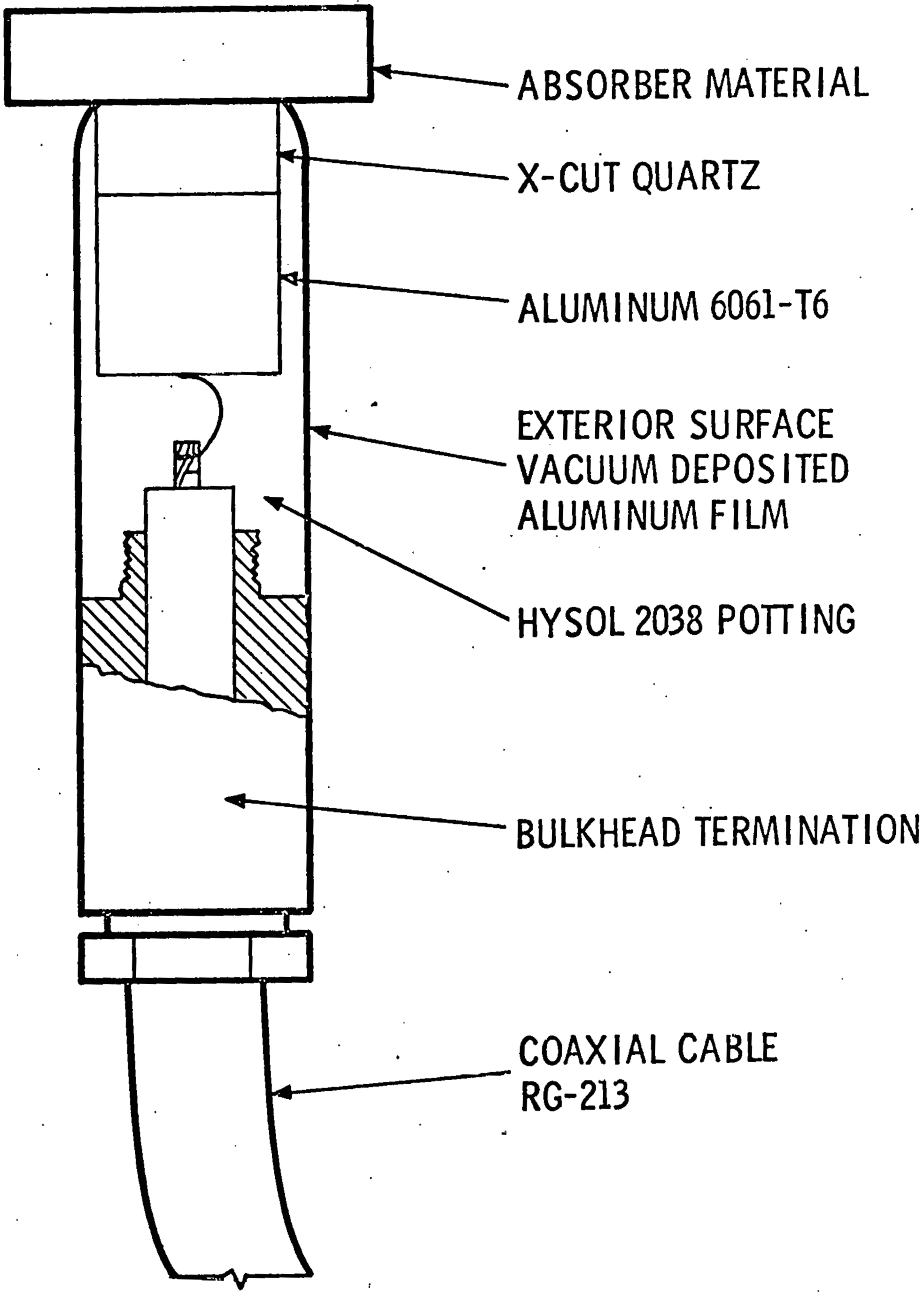
FIGURE CAPTIONS

Figure 1 Electron calorimeter consisting of a thick elastic absorber and a quartz stress gauge. The thickness of the absorber is greater than the electron end-point range. The beam is extracted in a vacuum and impinges on the upper surface of the absorber through an aluminum filter 0.33 mm thick. This calorimeter has been used to study the characteristics of a 2 MeV pulsed-electron-beam machine.

Figure 2 Stress-time profile for an aluminum absorber 6.10 mm thick. Time increases from left to right with a scale of 200 nsec per major division. The electrical noise accompanying the deposition is shown on the extreme left. The vertical scale is 0.5 volt per major division. The peak compressive stress indicated by the gauge is 0.54 kbar. Such data can be used to study the intensity, energy, and pulse duration of pulsed electron beams.


ABSORBER MATERIAL
X-CUT QUARTZ
ALUMINUM 6061-T6
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