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CHARACTERISTICS OF COMPOSITE CARBON RESISTORS USED FOR MEASURING ACCELERATOR TERMINAL VOLTAGES

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Lewis Research Center
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ABSTRACT

A voltage-divider board, composed of 1152 22-MΩ composite carbon resistors used to measure the terminal voltage of a 3-MeV Dynamitron, was investigated. The board was calibrated in place by using the Be^9 and D photoneutron threshold reactions and a magnetic analyzer. The present calibration of the divider board, made after more than 5 years of extensive accelerator usage agreed within 2 percent with the original factory calibration. The temperature and voltage coefficients of resistance were also measured. Results showed that composite carbon resistors and the techniques described can be applied with confidence to the measurement of high voltage.

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SUMMARY

A voltage-divider board, composed of 1152 22-megohm composite carbon resistors used to measure the terminal voltage of a 3-MeV Dynamitron was investigated. The board was calibrated in place by using the beryllium-9 (Be^9) and deuterium (D) photoneutron threshold reactions and a magnetic analyzer. The present calibration of the divider board, made after more than 5 years of extensive accelerator usage, agreed within 2 percent with the original factory calibration. The measured linear temperature coefficient of resistance was + $(0.85 \pm 0.10) \times 10^{-3}$ per $^{\circ}C$ in the range 25° to 35° C. The divider board resistance decreased linearly with voltage (-1.1×10^{-5} percent/V) up to 2 MeV, which corresponds to 1750 volts on each resistor. The results showed that composite carbon resistors and the techniques described can be applied with confidence to the measurement of high-voltage.

INTRODUCTION

A voltage divider network composed of composite carbon resistors used for the measurement of the terminal voltage of a 3-MeV Dynamitron (ref. 1) electron accelerator was investigated. In operation, the energy of the accelerated beam of electrons is determined by a measurement of the current passing from the high-voltage terminal to ground through the resistor network mounted on a board adjacent to the beam tube. Using composite carbon resistors for measuring high voltages is much less expensive than using a comparable wire-wound resistor divider network and offers the same advantages of simple, rapid, and precise energy measurement and ready adaptability to automatic electronic control of the accelerator operation. The suitability of composite carbon resistors for this application has been questioned in the literature (ref. 2) because of anticipated problems with long-term stability and nonlinearity of the voltage-current characteristics. However, the authors do not know of any prior reported detailed investigation of the behavior of composite carbon resistors in measuring the terminal voltage of an accelerator.

The need for a convenient and accurate means of measuring accelerator energy in many different experiments has led to a proliferation of devices and instruments for this purpose. Some of the instruments reported in the literature are the generating voltmeter (ref. 3), the adiabatic calorimeter (ref. 4), the capacitive voltage divider (ref. 2), the polyvinyl chloride (PVC) range energy detector (ref. 5), the partial energy absorption detector (ref. 6), the lithium-drifted silicon charge detector (ref. 7), and the sodium iodide scintillation detector (ref. 8). The absolute voltage scale in the low MeV range is based on measurements made with electrostatic and magnetic analyzers (refs. 9 to 11) that have an accuracy of 0.1 percent or better. The measurements of suitable nuclear threshold and resonance reactions with these analyzers at different laboratories have been used to arrive at a set of recommended energy values (ref. 10) with which other absolute and relative instruments can be calibrated.

The primary objective of the present investigation was to recalibrate the NASA Lewis Research Center Dynamitron resistor divider network board, which has been subjected to over 6000 hours of accelerator operation since installation in November 1962, and to compare it with the factory calibration that was done prior to installation. Also reported along with these long-term stability data are measurements of the voltage and temperature coefficients that were made during the calibration.

EXPERIMENTAL PROCEDURE

A schematic diagram of the experimental apparatus is shown in figure 1. The accelerator is a vertically mounted 3-MeV Dynamitron. The resistors comprising the voltage-divider network are mounted in a zig-zag configuration on a 2.7-meter-long polystyrene board located adjacent to the beam tube. The resistors are electrostatically shielded by a grid of wires to prevent the occurrence of corona and accidental-spark breakdown damage. The energy of the accelerator during operation is determined by the current through the resistor network, which can be obtained precisely from a potentiometric measurement of the voltage drop across a series-connected 1000-ohm wire-wound standard resistor (as done in the present calibration) or more conveniently by a microammeter located on the control console (as done in a usual experimental run). Also shown in figure 1 are the water-cooled heat exchanger with blowers for circulating the gas, the toroid coil from the oscillator resonant circuit where most of the internal heat is generated, and several of the important internal accelerator components. The accelerator vessel is pressurized with a minimum of 6 atmospheres of sulfur hexafluoride gas, which serves the dual purpose of a heat-exchange medium and a high-voltage insulator.

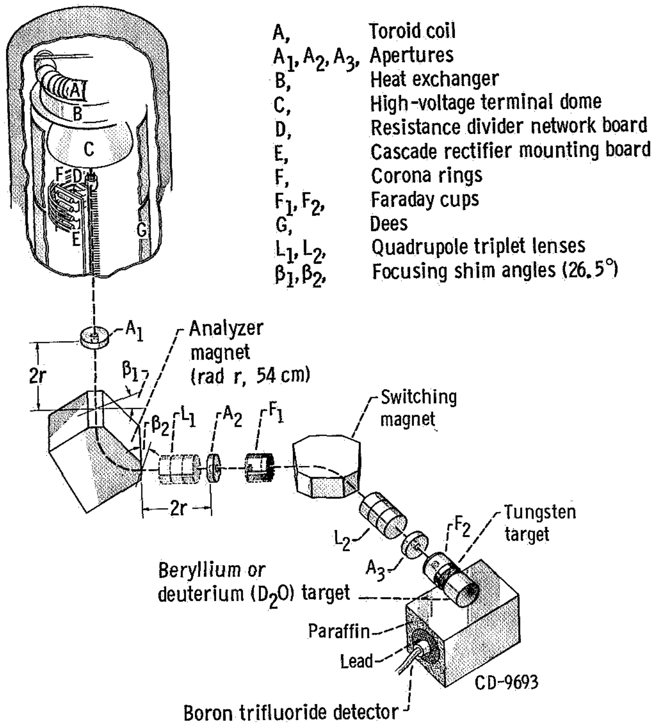

Figure 1. - Schematic diagram of accelerator and experimental apparatus.

On the resistor board are 192 strings of resistors mounted serially, each string consisting of six Allen-Bradley-type HB, 2-watt, 22-megohm composite carbon resistors of 20 percent tolerance. Thus, the total resistance of the board is nominally 25.3 kilomegohms. When the accelerator is operating at its maximum voltage, each resistor dissipates less than 0.4 watt but sustains a potential of 2600 volts, which is considerably in excess of the resistor manufacturer's 750-volt rating. Bench tests established that the self-heating of the resistors to be expected during accelerator operation was negligible. In these tests, the temperature of similar individual resistors increased linearly with wattage dissipation. At 0.4 watt, the measured rise above ambient temperature was 10° C under conditions of free convection and was 4° with moderate circulation from a small blower. Camilli, Gordon, and Plump (ref. 12) reported that the free-convection heat-transfer coefficient of sulfur hexafluoride at 2 atmospheres is 2.5 times that of air at atmospheric pressure. Taking into account that the present experiments were performed with a minimum of 6 atmospheres of sulfur hexafluoride under conditions of forced convection and that all the data were taken below 2.6 MeV, the self-heating, in the resistors was estimated to be less than 1° C in the worst case. Also established from measurements in the accelerator vessel was that the temperature gradient was negligible, except in the immediate vicinity of the toroid coil. Therefore, the temperature of the insulation gas, measured near the base of the accelerator vessel, is reported herein as the temperature of the resistors.

In one part of the investigation, the electron beam from the accelerator was magnetically analyzed to provide an energy calibration and to measure the voltage coefficient of the resistor board. The geometry of the analyzer and the path of the central trajectory are shown in figure 1. The electron beam emerges from the accelerator, passes through the analyzing magnet, and impinges on the Faraday cup F_1. The magnetic analyzer, consists of a 90° double-focusing magnet with a radius of curvature r of approximately 54 centimeters, and object and image apertures A_1 and A_2 (1.27-cm diam) located at 2r upstream and downstream, respectively, from the magnet. The focusing shim angles β_1 and β_2 were set for 26.5°. When the magnet is operated as an analyzer, the quadrupole triplet lens L_1, which is part of the normal beam transport system, is removed. The energy resolution of this system was analyzed by using the first-order matrix theory developed by Penner (ref. 13), and others. For the aforementioned conditions, an object-image relation existed between A_1 and A_2 with a magnification of 1, and the energy resolution of the analyzer was about 0.2 percent. The predicted energy resolution was in agreement with experimental observation.

When it was necessary to measure nuclear threshold energies, the Faraday cup F_1 was removed and the lens L_1 restored. The electron beam then passed through aperture A_3 (1.27-cm diam) and was brought to focus on Faraday cup F_2, which has a thick water-cooled tungsten end cap for producing X-rays. Neutrons from the (γ, n) threshold reactions in 5-centimeter cylindrical targets of beryllium and deuterium (in the form of D_2O) which occur at 1.662±0.003 and 2.227±0.003 MeV, respectively (ref. 9), were detected by a 25-centimeter-long enriched boron trifluoride detector (2.54-cm o.d.) located directly below the photodisintegration target. The detector was effectively shielded from gamma pile-up by a 5-centimeter annular ring of lead. The neutrons were moderated for increased detection efficiency by a minimum of 5 centimeters of paraffin.

RESULTS AND DISCUSSION

The results of the (γ, n) threshold experiments are presented first. A typical neutron-yield curve near the threshold energy for the beryllium target is shown in figure 2. Since a 1-microampere increment in board current corresponds to approximately 17 keV at this energy, it can be seen that the data were obtained for energies no greater than 30 keV above the threshold. Extrapolation of these data to zero yield gives the resistor divider board current at the known threshold energy from which the resistance of the board can be computed to an accuracy of about 0.2 percent. Similar results

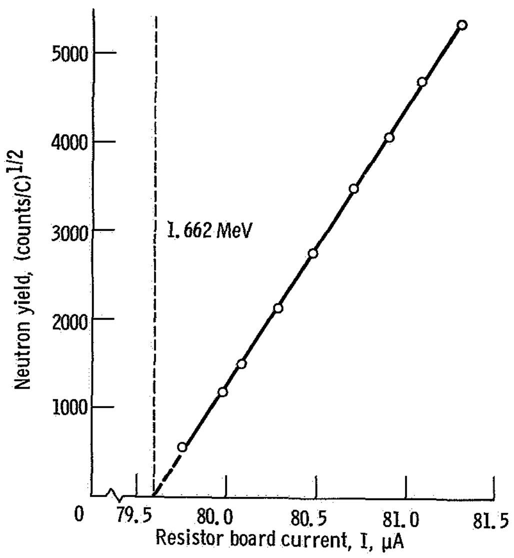

Figure 2. - Typical photoneutron-yield curve for beryllium.

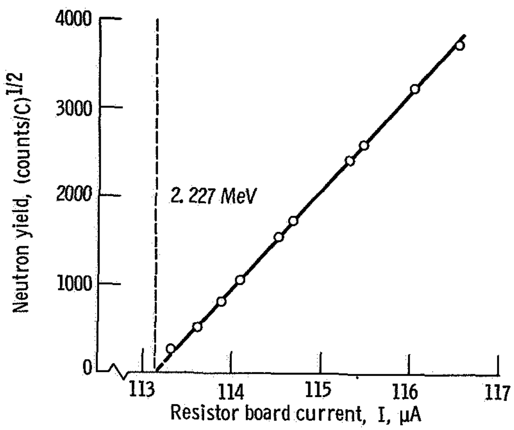

Figure 3. - Typical photoneutron-yield curve for deuterium.

for a deuterium target are shown in figure 3. Data for a complete-yield curve were taken only after the accelerator insulation gas temperature had stabilized to $\pm 0.1^{\circ}$ C. The results of a large number of photodisintegration threshold determinations for both targets are shown in figure 4, where the resistance of the divider board is plotted as a function of gas temperature with typical error bars indicated. The gas temperature was varied by adjusting the gas density and the water flow to the heat exchanger and also by taking advantage of seasonal variations in water supply temperature. Note that

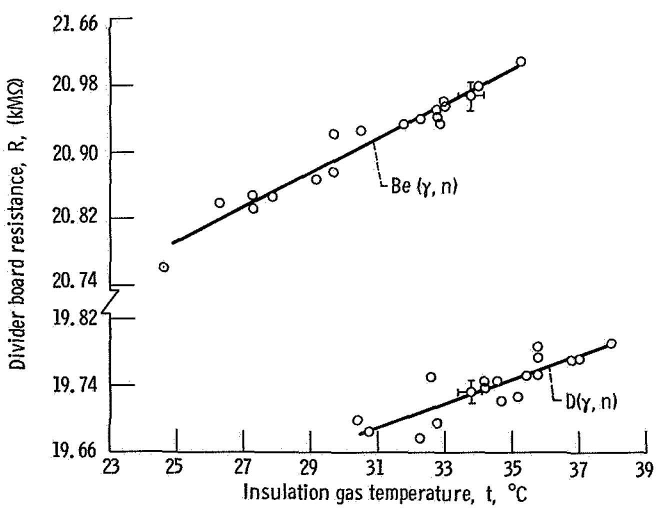

Figure 4. - High-voltage divider board resistance as function of insulation gas temperature. The straight lines represent least-square data fits.

the temperature coefficient of resistance is positive over the observed range. Tada (ref. 14) examined the internal construction of a group of commercial composite carbon resistors and suggested that since the structural properties are not uniform, the conductivity of the carbon resistance material would also be nonuniform. Thus, when a potential is applied, the field is distorted and local heating occurs. Changes in the local resistivity due to this heating could oppose the negative thermal coefficient of carbon resistivity and thereby explain the observed positive temperature coefficient. The displacement between the two least-square lines in figure 4 is caused by the voltage dependence of the composite resistors which is discussed with the magnetic analyzer results. The difference in slope between the two lines results from a combination of experimental error, voltage-dependent resistance, and the limited temperature range over which resistance data could be obtained. An average linear temperature coefficient of resistance $(1/R'_0(dR/dt)$, where R'_0 is the resistance at 25° C for each voltage) was computed from the least-square lines in figure 4 to be $(0.85 \pm 0.10) \times 10^{-3}$ per $^\circ$C.

The magnetic analyzer described previously was used to extend the voltage calibration of the resistor board at the threshold energies from 0.3 to 2.6 MeV. The motion of a relativistic electron in a magnetic field is given by (ref. 15)

$$r = \frac{\left[T(T + 2W_0)\right]^{1/2}}{3\times10^{-4}\ B} \tag{1}$$

where

r orbital radius, cm

T electron kinetic energy, MeV

W_0 electronic rest energy, 0.511 MeV

B magnetic field, G; 10^{-4} Wb/m^2

The relation given in equation (1) is utilized in the magnetic analyzer to determine one parameter (usually T) from a measurement of the two other variables. In the present situation, first r was determined experimentally (to take into account small fringe field effects in the calibration of the analyzer) by measuring the magnetic field for the two previously determined photoneutron threshold energies and then computing the radius from equation (1). The average value of the radius was 54.1 centimeter ±1.5 percent. The mean deviation of the two independent radius determinations was 0.4 percent.

The final energy calibration of the resistor board obtained with the magnetic analyzer is shown in figure 5, where the current through the resistor network board is plotted as a function of energy. The circles represent data obtained with the magnetic analyzer, where the resistor board temperature was normalized to 25° C by use of the

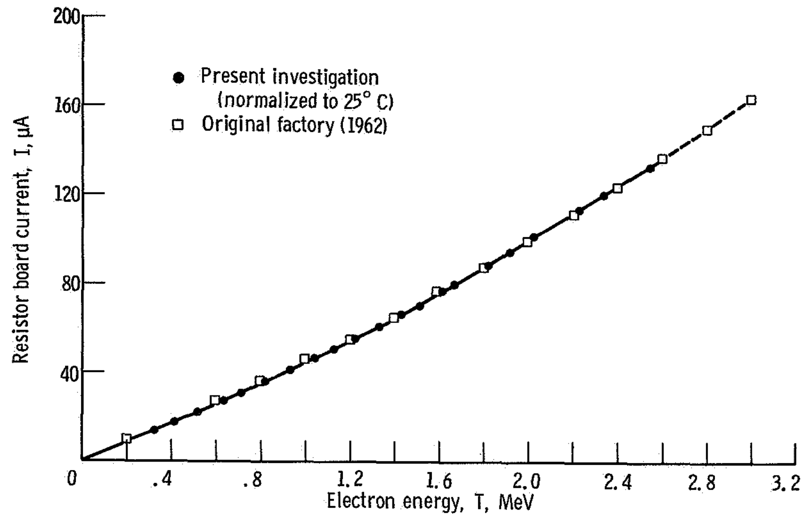

Figure 5. - Final calibration showing divider board current as function of electron energy.

temperature-coefficient data from the results just discussed. The squares represent the original factory calibration done early in 1962 by using Ohm's law and taking into account the voltage dependence of the resistors. This calibration consisted of measuring the voltage drop across a string of six resistors as a function of several standard input currents. The individual potential drops were summed to obtain the terminal potential corresponding to a given resistor board current. Then a smooth curve was passed through the data points for interpolation. The accuracy of the original calibration, made on the bench under conditions of free convection at room temperature (which was not recorded), was estimated to be ±2 percent. As shown in figure 5, close agreement exists between the two calibrations. Above 1 MeV, the agreement is better than 1 percent. This agreement must be considered somewhat fortuitous since the factory calibration did not take into account the small but significant effects due to temperature. As a result of the rise in temperature of the local water supply during the summer months (when most of these data were taken), it was not possible to extend the calibration up to the maximum 3-MeV rating because of the excessive internal temperature in the accelerator vessel. This condition is presently being corrected by the installation of a closed-loop refrigerated-water cooling system. Also noteworthy is that the curvature in figure 5 results from the voltage dependence of the resistor board and indicates that the resistance is decreasing with voltage.

The data in figure 5 were used to calculate the resistance of the divider board as a function of voltage, and the results are shown in figure 6. The data up to 2 megavolts can be fitted within experimental error by a straight line that extrapolates to 25.3 kilomegohms at zero voltage and is in good agreement with the nominal resistance

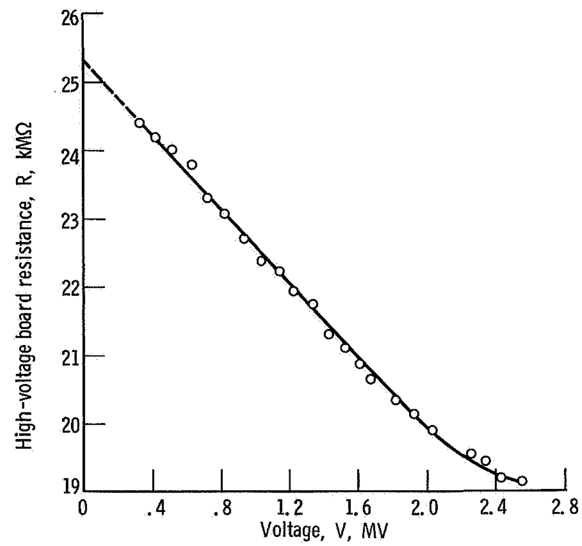

Figure 6. - Resistance of high-voltage-divider board network as function of terminal voltage (normalized to 25° C).

of the board. From this line, a voltage coefficient of resistance for the divider board (defined as $1/R_0$ (dR/dV), where R = 25.3 kMΩ and dR/dV, the slope of the line in fig. 6) is computed to be -1.1×10^{-5} percent per volt. This coefficient is independent of voltage up to 2 megavolts or 1750 volts per individual resistance. The data above 2 megavolts are inconclusive but indicate that the resistance becomes less voltage dependent.

The linear voltage coefficient of resistance of a resistor can be shown to be n times the voltage coefficient of a resistor composed of n resistors of the same type connected serially. Thus, the computed individual average voltage coefficient of resistance of the 22-megohm composite carbon resistors comprising the high-voltage resistance divider board was -0.012 percent per volt. This value is within the manufacturer's maximum specification of -0.02 percent per volt (ref. 16). Although an explanation of the voltage-dependent resistance of composite resistors, given on speculation of detailed mechanisms involved, would be unjustified at this time, a few empirical observations on their variation with resistance value and the consequences of this variation are appropriate. The beam tube of the dynamitron is provided with a divider board, the purpose of which is to apply the accelerating potential in increments to the beam tube dynodes. This beam tube divider board is comparable to the high-voltage divider board discussed herein in every respect except that it is composed of 10- rather than 22-megohm composite carbon resistors. Thus, it has a total resistance about one-half that of the high-voltage board. From Radiation Dynamics calibration of this board (which used the previously mentioned Ohm's law method), a linear voltage coefficient was computed to be one-half the value found for the high-voltage board. With this coefficient, the data were fitted up to 3 megavolts. This fit not only indicated that the voltage coefficient decreased with resistance value but also that the behavior was linear over a wider voltage range than that for the 22-megohm resistors. This wider range has practical importance, in that a voltage divider board with a linear, and therefore readily predictable, voltage dependence can be constructed to cover the entire voltage range of the accelerator. In such a board, the current I is related to the terminal voltage V by

$$I = \frac{V}{R_o(1 + \alpha_V V)} \tag{2}$$

where R_o is the resistance of the board at zero voltage, and α_V is the linear voltage coefficient. Provided that $\alpha_V V$ is small with respect to 1 (as is the case with the present resistor boards), equation (2) can be expanded with no significant loss in accuracy in a power series in which only the first two terms are retained to give an expression of the form

$$I = aV + bV^2 \tag{3}$$

where a and b are considered as constants to be determined by the calibration, although they are also defined in terms of α_V and R_o. The two independent constants in equation (3) can be readily evaluated in place for a board composed of appropriately chosen resistors with the beryllium and deuterium photoneutron threshold reactions. The resulting calibration over the entire accelerator energy range is rapid and accurate and can be conveniently rechecked when necessary.

Lewis Research Center,
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Cleveland, Ohio, September 20, 1968,
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