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ELECTRON BEAM PRODUCED LICHTENBERG FIGURES

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High energy electron beams when absorbed by certain dielectrics may produce decorative and unusual patterns called trees or Lichtenberg Figures (1)(2)(3). The position, size, and density of branching of the trees as well as the coloration of the dielectric, are all variable and may be controlled to some extent. Thus it is possible to create three dimensional figures of esthetic and educational interest in lucite with high energy electrons from medical therapy machines. This contrasts with the long known two dimensional Lichtenberg Figures observed on dielectric surfaces when in contact with a charged conductor.

TECHNIQUE

The electron beam of a Varian Associates 6 Mev Clinac (clinical linear accelerator) is used to irradiate blocks of one half to one inch thick lucite (plexiglass, perspex, or poly methyl methacrylate). Blocks of thicknesses greater than the electron range are prepared by milling the edges smooth then fire-polishing with an oxygen-acetylene torch. Blocks rough-sawed from a sheet will do but are not esthetically appealing, nor can a lateral view be observed through the rough edge. Furthermore, polishing the blocks prevents spurious discharge to a random crack on the rough edge during irradiation.

A dose of approximately 0.1 megarads or greater delivered within a few minutes will produce trees similar to those in Figs. 1, 2, and 3. The blocks may be placed on any convenient support and irradiated at room temperature. Absorbers of thin masonite, lucite, or similar material, may be interposed in the electron beam and will bring the region of the tree formation nearer the entry surface due to a lowering of the energy and consequent shortening of the electron range. The point of origin of the discharge may be controlled by tapping the side of the otherwise smooth block with a sharp instrument.

Fig. 1. A few minutes after receiving 0.2 megarads 6 Mev electron dose this block was lightly tapped with a sharp point producing this self-illuminated photograph.

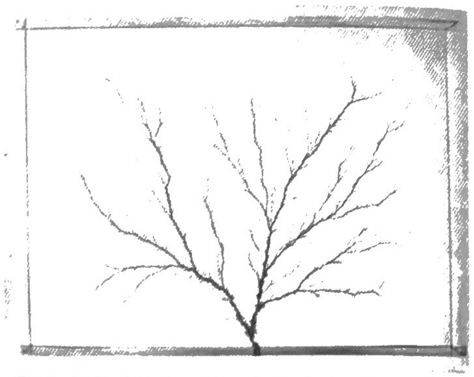

Fig. 2. Lucite block viewed from the irradiated surface. Same block as in Fig. 1 but photographed by reflected light.

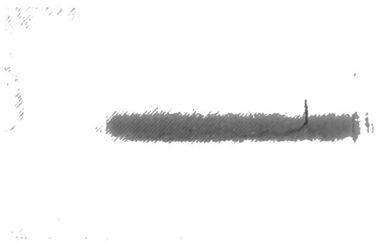

Fig. 3. Edge view of irradiated block. The electrons entered at the surface near the top of this photograph. Notice the position of the colored region and the tree.

RESULTS

During irradiation the block emits a white fluorescent glow whose intensity is directly related to the dose rate. This is easily observed if the room is darkened. There is no afterglow persisting when the irradiation is terminated (4).

Coloration of the blocks precedes tree formation and increases with dose (5). Initially a greenish hue is imparted to the region of the block which receives the maximum absorbed dose. Within one hour after irradiation, the color changes to red-brown and remains thus for many weeks, gradually diminishing in intensity. The color disappears if the block is placed in water at 100° C for several hours.

The tree-like discharge pattern is formed during irradiation if a scratch or crack is present on the block or if a sharp instrument has been used to form a small surface fracture. Lightning-like flashes occurring at discharge are observed superimposed on the fluorescent glow. Blocks irradiated first and then tapped exhibit a visible and audible spark discharge coincident with tree formation and lasting with decreasing intensity between 20 and 30 seconds. Fig. 1 is a photograph made by the light of the block's discharge.

The location of the semi-planar tree is the rear interface of the colored zone and the clear lucite which indicates the region of maximum electron entrapment. The tree location, like the thickness of the colored region, depends on the incident electron energy. The lateral boundaries of the tree do not extend to the edges of the block but conform to its contour. Even with irregularly shaped blocks this conformity is observed and suggests that electrons leak out or diffuse rather quickly to the surfaces. A time delay of one hour between irradiation and tapping results in a wider clear zone around the edge and a less dense tree. A delay of a day results in no tree formation at all. The boundaries of the tree and colored region may be shaped by excluding the electron beam from portions of the lucite with lead absorbers. In this way almost any desired outline such as a circle, cross, or initial can be achieved (Fig. 4).

Fig. 4. Shaped discharge pattern. Lead blocks were placed on the lucite and excluded the electrons' entry except where the tree appears.

Placing the lucite under mechanical stress during irradiation results in coloration but no tree, even for doses up to 0.6 megarads. After removal of the stress and upon re-irradiation, normal tree formation occurs. Exposing a one inch thick lucite block to 6 Mevp x-rays at an average rate of 4000 rads/min. to a total dose of 0.6 megarads produces coloration but no tree.

DISCUSSION

The existence of a white fluorescent glow coincident with the irradiation is directly analogous to the production of x-rays in a high Z target when bombarded by electrons. Lucite has a low Z number, and consequently the characteristic radiation is in the visible range. Rudolph describes a technique for suppressing this glow by cooling during irradiation. Upon warming, "frozen" electrons are released from excited states producing thermoluminescence (6).

Initially the colored region extends to neither surface although for a thick block (Fig. 3) it lies closer to the electron entry surface. A clear indication of the build-up of absorbed dose and rapid fall off is thereby demonstrated. Bolt, Schneider, and Day have used electron spin resonance techniques and detected the presence of free radicals which they attribute to radiation-induced rupture of the polymer molecules (5)(7)(8). These free radicals along with some trapped electrons, like F-centers in ionic crystals, would be expected to cause coloration. According to this scheme the rapid change from green to red-brown and the gradual disappearance of all color would represent either a rapid diffusion of trapped electrons out of the block followed by a slower decay of free radicals to less excited levels or the converse. Since lucite mainly undergoes scission rather than further polymerizations when irradiated, there should be many free radicals formed (9). In contrast, irradiation of polystyrene with electrons to high doses produces slight yellowing with no rapid color change and no tree formation. The difference in observed effects is evidently due to the predominance of cross-linking in this plastic versus main chain scission in lucite.

Formation of the tree-like discharge pattern is due to dielectric breakdown caused by the large localized space charge of electrons and the high electric field intensity surrounding the sharp point which initiates a spark discharge (10)(11). The strong positive field extends into the dielectric as electrons leave the space charge layer forming a carbonized channel along the line of rupture. Finally this layer itself becomes the area of high field intensity until all the trapped electrons escape and the structure of a positive Lichtenberg Figure remains. If lucite is irradiated to a dose in excess of 0.5 megarads, large cracks appear in the main discharge channel. Measurement of the distribution of charge with depth in lucite for 3 Mev electrons by Gross and Wright confirms the existence of a layer of arrested electrons at a depth corresponding to the position of the discharge figure (12). According to Gross the stored charge is several microcoulombs, somewhat less than the total charge delivered by the electron beam (3). Measurements by Hardtke and Ferguson indicate an initial pulse length of a few microseconds; hence the current is approximately one ampere (13). Similar discoloration and Lichtenberg Figure formation are observed as a result of electron and gamma irradiation of high density glasses (6)(13)(14)(15). These phenomena cause some difficulties in hot cell shielding windows and in insulators exposed to large amounts of radiation. The effect is less marked at higher temperatures.

Failure of tree formation while the block is under mechanical stress may be due to a lowered resistance to electron flow along strain lines in the block and consequent charge leakage. The lack of tree formation when lucite is exposed to x-rays may be due to two factors. First, the exposure rate for x-rays is approximately 100 times lower than for electrons allowing more charge leakage during irradiation. Second, no narrow region of Compton interaction exists which would deposit electrons in a compact space.

Many investigators suggest using the color change as a measure of absorbed dose (16). Application of the Lichtenberg Figures to dosimetry is unlikely. Except for their high density, glasses might provide, after irradiation, a source of electrical power for satellite instrumentation where a single large pulse is required. In borosilicate glass the stored charge persists for more than a month with little leakage (15). The dielectric coloration and tree formation also serve as teaching aids for demonstrating the electron depth dose and range in materials of different density and composition.

Finally, mention should again be made of the purely esthetic value of these Lichtenberg Figures. To call them art may be an overstatement since little control is exerted by the "artist", but to classify them as science alone is unnecessarily restrictive. Above all, the patterns are beautiful and delicate, and like snowflakes each is unique.

SUMMARY

Lucite blocks, when irradiated with the electron beam of a 6 MeV medical linear accelerator, yield beautiful permanent discharge patterns, called trees or Lichtenberg Figures. Intense coloration also occurs. The theory of tree formation and coloration is discussed. Variations in patterns can be produced. Analogous effects of gamma irradiation in high density glass are listed. Possible applications mentioned are: radiation dosimetry, pulsed power sources for satellite equipment, a demonstration of electron depth dosage, and a new art form.

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grant of $11,790 was given to Dr. Ernest Furchtgott, professor of psychology, for continuation of his research entitled "Genetic Effects of Radiation: Mammalian Behavior." AEC also granted $24,000 to provide for a traineeship program for graduate students in nuclear engineering for the 1965-66 academic year. This program is under the direction of Dr. P. F. Pasqua, professor and head of the UT Department of Nuclear Engineering. Dr. K. J. Monty, professor and head of the Department of Biochemistry, was awarded a $33,121 grant for an extension on research entitled "Studies of the Metabolism of Inorganic Ions." The UT Department of Physics received a $16,090 grant from AEC to purchase equipment in radioisotope technology education. Under the direction of assistant professors, R. W. Lide and H. F. Bowsher, the greater part of these funds will be used to purchase a multichannel analyser.

Arthur S. Gloster II has been appointed head of a new Data Processing Center at the Oak Ridge Institute of Nuclear Studies. Mr. Gloster will be responsible for the general direction of processing programs for divisions, offices and departments within the Institute.

Charles H. Weaver, a former University of Tennessee engineering professor who later moved to the Auburn University faculty, returns to UT this fall as dean of the College of Engineering. Dr. Weaver will succeed Prof. Armour T. Granger, dean of the college since 1956. Dean Granger requested to be relieved of his administrative duties in order to devote full time to teaching.