Nov. 15, 1955 A. J. GALE 2,724,059

METHOD OF AND APPARATUS FOR INCREASING UNIFORMITY OF IONIZATION IN MATERIAL IRRADIATED BY CATHODE RAYS

Filed Aug. 21, 1952 5 Sheets-Sheet 1

FIG. 1

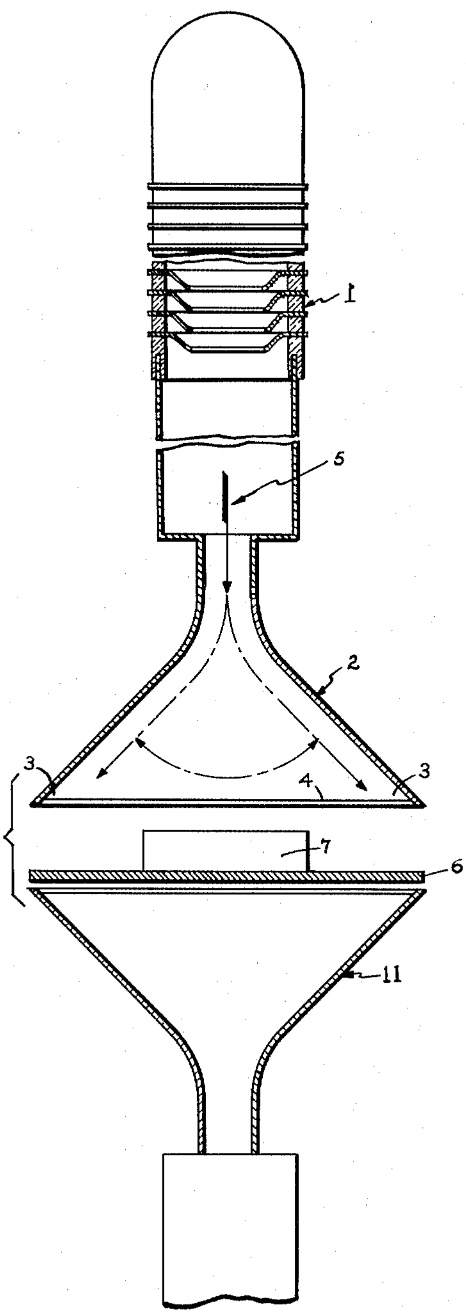

FIG. 2

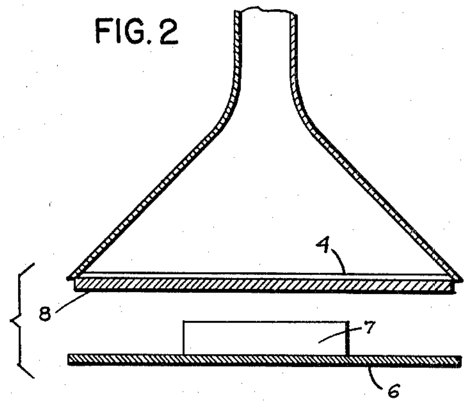

FIG. 3

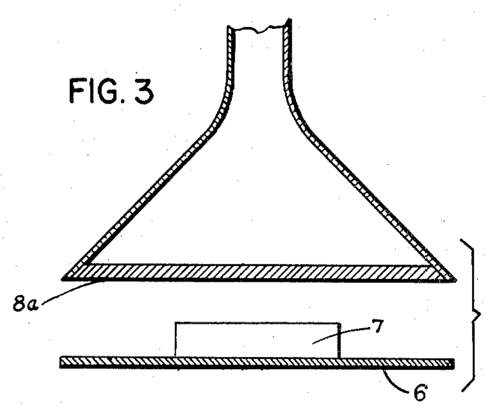

FIG. 3 A

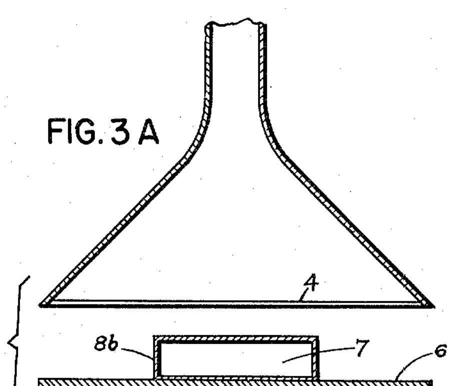

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FIG. 4

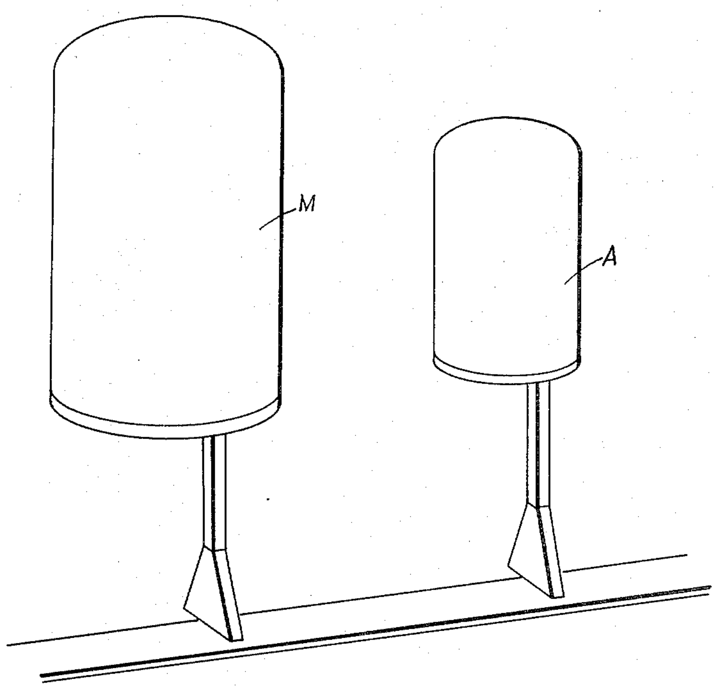

FIG. 5

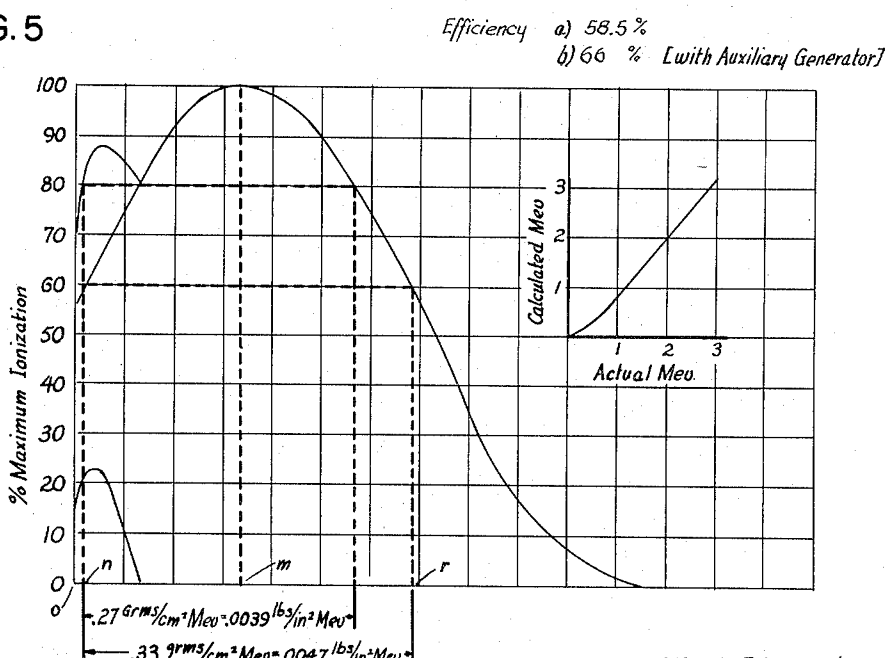

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FIG. 6

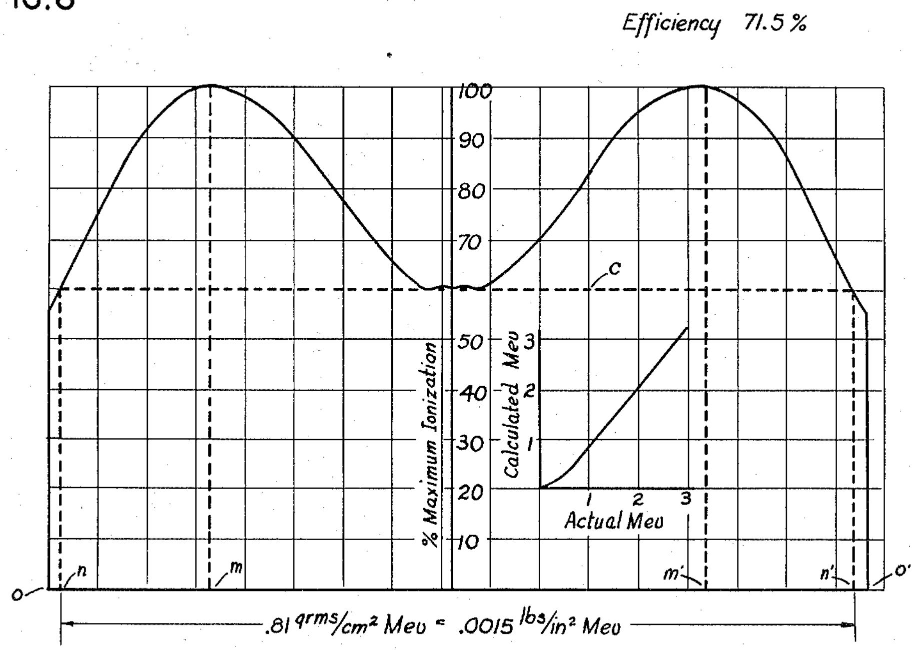

FIG. 7

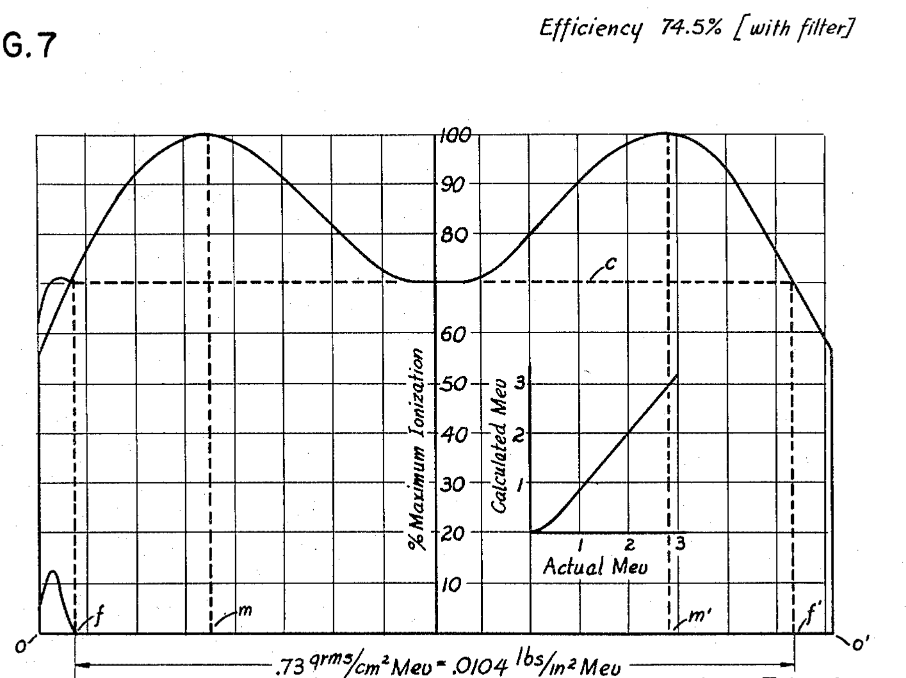

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FIG. 8

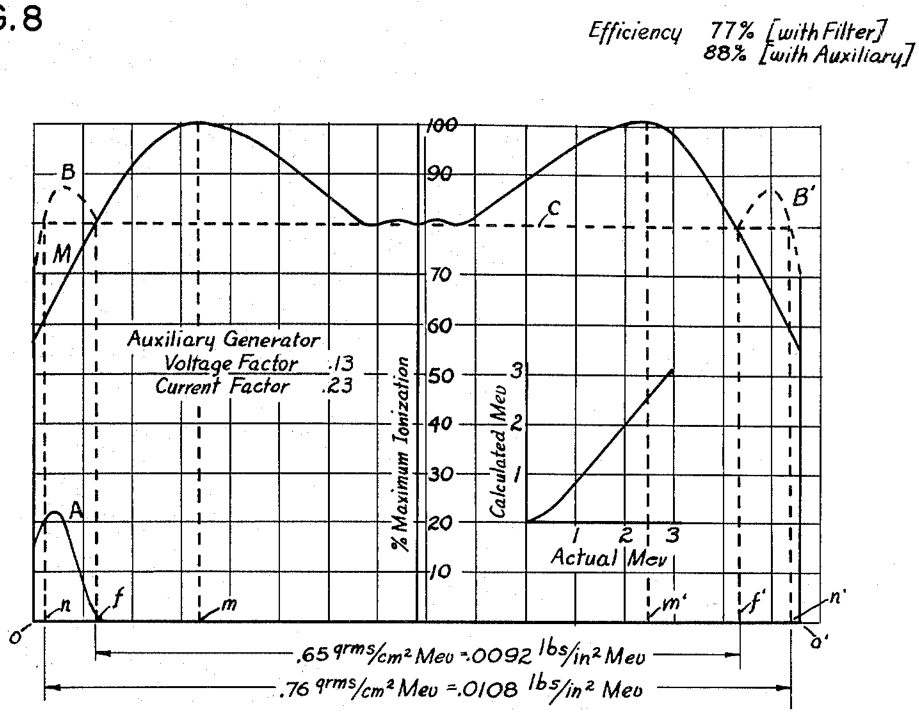

FIG. 9

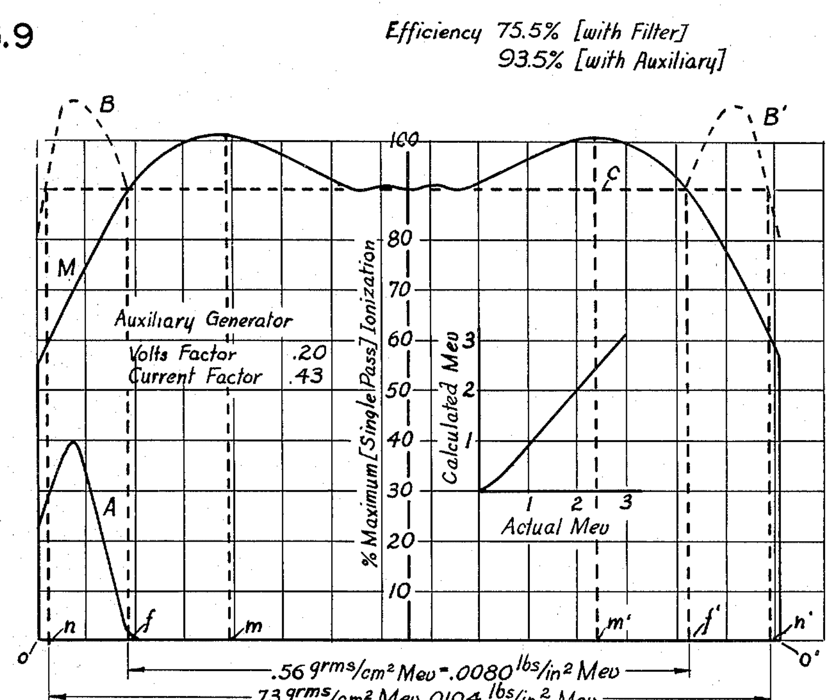

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FIG. 10

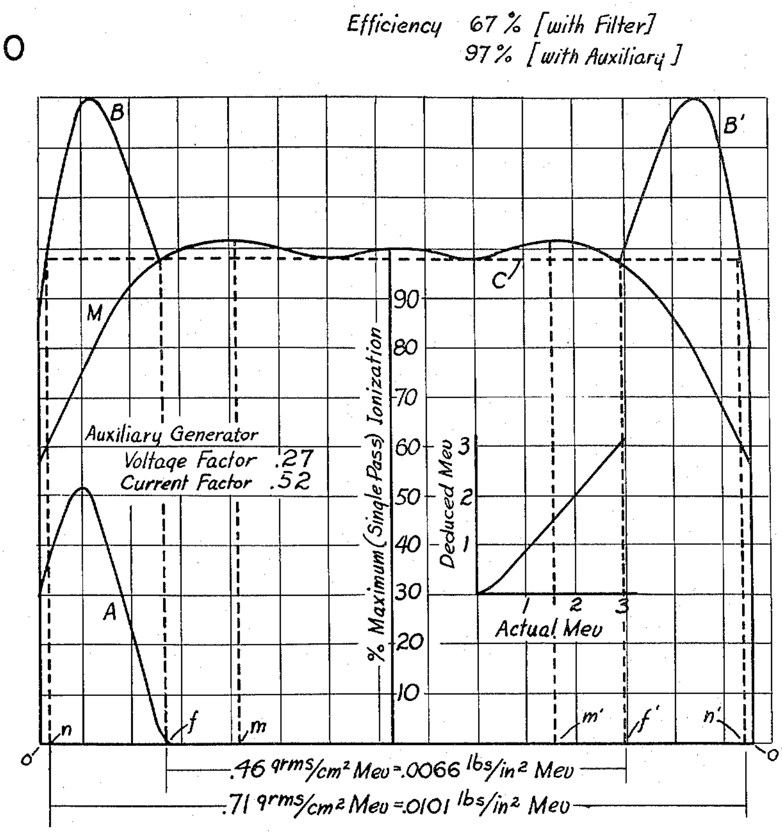
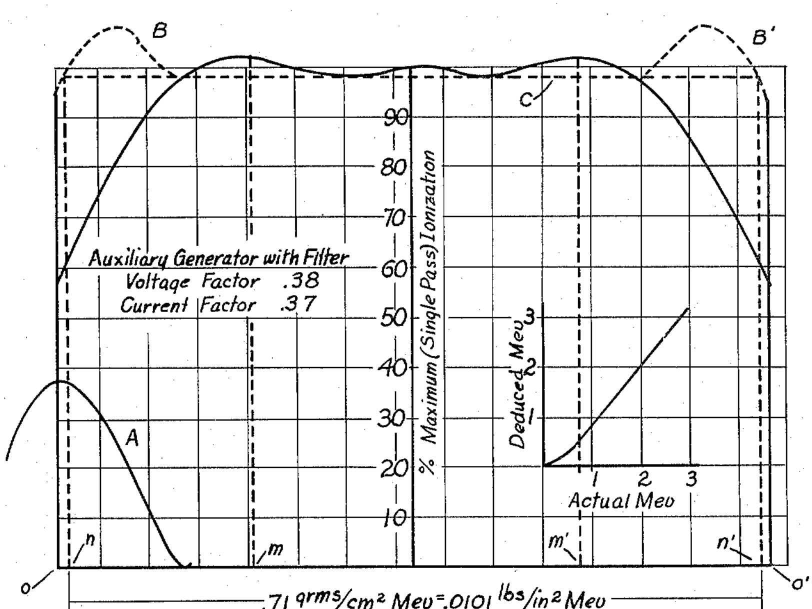


FIG. 10 A



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METHOD OF AND APPARATUS FOR INCREASING UNIFORMITY OF IONIZATION IN MATERIAL IRRADIATED BY CATHODE RAYS

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Application August 21, 1952, Serial No. 305,633

8 Claims. (Cl. 250—49.5)

This invention relates broadly to the ionization of material by cathode radiation, and more particularly to a method of and apparatus for increasing the uniformity of ionization produced in material by irradiation with high-energy electrons, thereby increasing efficiency of operation. Still more particularly and specifically stated, the invention relates to the irradiation of a substance, either packaged or non-packaged, with at least one main flux of electrons having a relatively high velocity component in a direction normal to the surface of said substance, whereby a maximum ionization level is effected in said substance a certain distance below said surface, and also irradiating said substance with at least one auxiliary flux of electrons having a relatively low velocity component in a direction normal to said surface, and if desired, with more than one auxiliary flux, so as to increase the ionization level at said surface in relation to said maximum ionization level.

The main flux of electrons may be provided in the practice of my invention by any cathode-ray generator capable of delivering high-energy electrons in the energy range between .1 and 20 m. e. v., and the invention is used with advantage whenever the ionization level produced by said main flux at the surface of the material irradiated is less than the maximum ionization level.

In one embodiment of means for practicing my invention, the auxiliary flux of electrons is provided by an auxiliary generator of lower voltage and current than those of the main installation. The use of auxiliary generators is of particular importance in multiple generator installations where spares may be used as auxiliaries without impairing their readiness to take over the full duty. Alternatively, a main generator operating below performance may continue as an auxiliary until maintenance is convenient. The use of auxiliary generators in accordance with my invention is quite different from ordinary double bombardment techniques, for both the voltage and the current of the auxiliary generator are preferably markedly less than the voltage and the current, respectively, of the main generator.

In an alternative embodiment of the apparatus of my invention, the auxiliary flux of electrons is effected or provided by decreasing the normal component of the velocity of some of the electrons in the main flux. For example, I may place an absorber or filter between the cathode ray window and the product, or I may simply increase the thickness of the window. For some products the outer layers of packaging material may provide some or all the absorber thickness required.

Efficiency may be raised either by using optimum thickness filters or auxiliary generators. Furthermore, the use of filters or auxiliary generators may give greater uniformity of ionization throughout the product and, accordingly, minimize unwanted side effects.

One object of my invention is to increase the efficiency of operation in the ionization of material in either a packaged or a non-packaged condition by cathode radiation.

Another object of my invention is to increase the uniformity of ionization produced in such material by cathode radiation.

Another object of my invention is to provide means for filtering cathode rays which are used to ionize such material, so as to increase the ionization produced by said cathode rays in the surface layers of the material irradiated, whereby either efficiency of operation or uniformity of ionization or both may be increased.

Still another object of my invention is to increase the ionization in the surface layers of material which has been irradiated by a main cathode ray installation, by irradiating such material with cathode rays from at least one auxiliary generator operating at lower voltage and current than those of the main installation, whereby either efficiency of operation or uniformity of ionization or both may be increased.

It is clearly to be understood that more than one auxiliary generator may be employed in the practice of my invention, and in carrying out the method thereof.

In order that the principle of the invention may be more readily understood, these and other objects of the invention will be best understood by reference to the following description when taken in connection with the accompanying drawings disclosing different apparatus by which the method may be practiced, while its scope will be more particularly pointed out in the appended claims.

In the drawings:

Fig. 1 is a view partly in side elevation and partly in vertical central section of one form of acceleration tube for the creation of high-energy electrons, together with a similar view of the lower end of a second acceleration tube shown merely for the purpose of illustrating ordinary double bombardment technique;

Fig. 2 is a side elevation, but partly in vertical section, of the lower end of the form of acceleration tube shown in Fig. 1, and illustrates the use of one form of absorber or filter;

Fig. 3 is a view similar to that of Fig. 2, and illustrates the use of a thick cathode-ray window;

Fig. 3A is a view similar to that of Fig. 2 and illustrates the use of the outer layers of packaging material in order to provide the absorber thickness required;

Fig. 4 is a diagram illustrating one arrangement of an auxiliary generator in conjunction with a main generator;

Fig. 5 is a graph illustrating the ionization/depth relationship for single-pass irradiation;

Fig. 6 is a graph illustrating the ionization/depth relationship for double bombardment with cathode rays of equal energy and current, with a central ionization level of 60%;

Fig. 7 is a graph illustrating the ionization/depth relationship for double bombardment with cathode rays of equal energy and current, with a central ionization level of 70%;

Fig. 8 is a graph illustrating the ionization/depth relationship for double bombardment with cathode rays of equal energy and current, with a central ionization level of 80%;

Fig. 9 is a graph illustrating the ionization/depth relationship for double bombardment with cathode rays of equal energy and current, with a central ionization level of 90%;

Fig. 10 is a graph illustrating the ionization/depth relationship for double bombardment with cathode rays of equal energy and current, with a central ionization level of 97½%; and

Fig. 10A is a graph similar to that of Fig. 10 and illustrates the ionization/depth relationship where a filter is used on the auxiliary generator.

The principal effect upon material irradiated thereby, of cathode rays in the energy range between .1 and 20

m. e. v., is ionization. This ionization may produce various useful results, including sterilization and deinfestation of foods and drugs, acceleration of chemical reactions, coloration of glass, and treatment of skin diseases. Whatever the ultimate object to be achieved, the immediate effect of the cathode rays is ionization of the material irradiated thereby, and the dose received at any point in the material irradiated is proportional to the ionization at that point.

The dose required should be and is herein referred to in terms of the minimum dose which must be received at all points within the material. The minimum dose produced by the high-energy electrons must therefore be equal to the minimum dose required. If the ionization produced by the high-energy electrons is not uniform, it will be necessary that some portions of the material receive a dose greater than the minimum dose required. More energy is thus expended than is necessary, and inefficiency of operation results. Furthermore, unwanted side effects may be produced in those portions of the material which receive more than the minimum dose required.

Although my invention may be used in connection with and may be practiced with the use of various types of cathode ray generators, I prefer to use a generator of the type shown in the U. S. patent to Robinson, No. 2,602,751, dated July 8, 1952, Serial No. 179,910, and assigned to the same assignee as the assignee of the present invention. With such a generator, the product may be irradiated by scanning an electron beam of homogeneous energy across the width of the product, while the product moves at constant speed in a direction perpendicular to the direction of scan. In this way the entire surface of the product may be substantially uniformly irradiated, so that the ionization produced at any depth in the product may be substantially uniform throughout the product at that depth.

However, the ionization is not uniform in depth. The electron beam is unable to penetrate beyond a certain depth, and so no ionization is produced below this point. For example, 2 m. e. v. electrons have a maximum penetration of about 1 cm. in water. Maximum ionization is produced at a depth of about ⅓ the maximum penetration, while the ionization produced at the surface of the product is about 60% of maximum ionization.

Greater economy is obtained when double bombardment techniques are adopted, wherein the product is irradiated from opposite sides by cathode rays of equal energy and current. Substantial uniformity of ionization in the central part of the product may also be obtained through the use of double bombardment. However, the ionization produced at the surface of the product is still only 60% of maximum ionization, and this relatively low ionization in the surface layers limits the uniformity and efficiency obtainable.

Referring to the drawings, and first to Fig. 1 thereof, therein is shown such parts of a cathode-ray generator as are necessary to an understanding of this invention. The said generator is of the type shown in the patent to Denis M. Robinson, No. 2,602,751, dated July 8, 1952, Serial No. 179,910. The invention herein claimed may be practiced by the said type of cathode-ray generator but my invention is not limited to being practiced by or with such type of generator.

In said Fig. 1, a small portion, broken away, of one form or type of the acceleration tube of a Van deGraaff electrostatic generator, but to the use of which my invention is not limited, is indicated at **1**. The said generator is capable of producing a narrow beam of high speed electrons, the energy whereof is or may be on the order of several million volts and as much as five million or more volts, and is manufactured by High Voltage Engineering Corporation of Cambridge, Massachusetts. The lower end **2** of said acceleration tube **1** is shown as markedly outwardly flared or flaring at **3** to left and to right (that is, in two opposite directions) so as in one direction to be in cross section of greatly elongated length as indicated, but the width of such flaring portion is about the same as the normal diameter of said acceleration tube above the flaring portion, or it may be less. The said flaring portion **3** terminates at its extreme lower end in a window **4**, which is a long narrow slot and is covered by a thin aluminum foil. Such window must support atmospheric pressure on the outside with vacuum on the inside. The narrowness of the slot and the support given by the closely spaced long sides of the frame insure this.

The length of the said window **4** is preferably such that I may impart to the electron beam within the said flaring portion **3** a scanning or sweeping motion extending through fifty degrees or more, and if desired as much as ninety degrees. For that purpose I employ magnetic coils, or I may employ parallel conducting plates, or other suitably shaped electrodes (not shown), and I preferably make said magnetic coils or conducting plates small enough to position them suitably within the flaring portion **3**. This gives close coupling with the electron beam and accordingly reduces the scanning power required. Also the material of the vacuum wall thus serves as a shield against stray external fields.

The high speed electron beam emanating from the cathode of the acceleration tube **1** is indicated at **5**. The electrons of the beam **5** are accelerated through the vacuum region of the acceleration tube **1** in a manner not necessary to explain herein in detail, and they travel in a straight line or path until they reach the flared portion **3**, at which point the scanning or sweeping motion referred to above is imparted to the electron beam.

A conveyor belt **6**, or other suitable conveyor, which supports the product to be irradiated, indicated diagrammatically at **7**, is positioned close below the window **4**, which is at the extreme lower edge of the said flaring portion **3**. Said belt **6** is driven at constant speed in a direction preferably perpendicular to the plane of the drawing, and hence preferably perpendicular to the direction of scan.

Improved operation may be obtained if the product **7** is simultaneously irradiated from the opposite side by a second cathode-ray generator, the lower end of which is indicated at **11**, and which generator is desirably substantially identical with the first generator **1**. If the product **7** is in solid mass form, the same effect may be achieved by sequentially irradiating the product from opposite sides by the same generator. Such type of treatment, either simultaneous or sequential, I call "double bombardment," as opposed to "single-pass irradiation" wherein or whereby the product is irradiated from one side only.

The apparatus embodying or for practicing the method of my invention will now be described in terms of its application to the first generator **1**. If double bombardment is used, it will be understood that the same apparatus is to be applied to the second generator **11**.

In one embodiment of the apparatus of and for practicing the method of my invention, I place an absorber or filter **8** immediately below the window **4**, as shown in Fig. 2. Said absorber or filter **8** comprises a thin sheet of material which may be attached to the lower extremity of the flared portion **3** in any convenient manner; for example, it may be cemented thereto. Said sheet **8** may be of any material but is preferably a metal of low atomic number, in order to minimize back-scatter whereby electrons are reflected back towards the acceleration tube. In particular, I prefer to use an aluminum absorber, because in addition to having a low atomic number, aluminum has a high thermal conductivity, so that heat generated in the filter by the high-energy electrons is quickly dissipated. Furthermore, aluminum filters are readily formed by rolling and machining. The sheet **8** extends beyond the edges of the window **4**, so as to cover the window **4** completely and thus intercept an electron beam 5 at all times. The thickness of sheet 8 is determined in a manner to be set forth hereinafter, but in general the thickness will be on the order of 1 mm. for an aluminum sheet.

Instead of attaching a thin sheet of aluminum 8 to the lower extremity of the flared portion 3, I may increase the thickness of the said aluminum sheet or foil which covers the window 4. The additional thickness is computed in the same manner as is computed the thickness of the thin sheet 8 shown in Fig. 2. Fig. 3 illustrates the use of a thickened window 8*a* instead of a separate filter. Alternatively, the outer layers of packaging material surrounding the product 7 may provide the required filter thickness 8*b*, as shown in Fig. 3A. The thickness of the packaging material must be such that the required amount of absorption is provided. The proper thickness is computed in the same manner as that employed in computing the thickness of the thin sheet 8 illustrated in Fig. 2.

In the second embodiment of the apparatus of my invention, for the practice of the method thereof, I use an auxiliary generator in combination with each main generator. One possible arrangement is shown diagrammatically in Fig. 4. The auxiliary generator A operates at lower voltage and current than those of the main generator M.

Referring now to the diagram, Fig. 5, therein is illustrated the variation of ionization with depth for single pass irradiation by a single cathode-ray generator without filter. Ionization is expressed as a percentage of maximum ionization. Depth is expressed as a g./cm.^{2}-m. e. v. or, alternatively as lb./in.^{2}-m. e. v. When these units are used, the curve is substantially independent of the material irradiated and approximately independent of the energy of the bombarding electrons. The curve is plotted for 2 m. e. v. electrons, and the inset curve gives the correction for electron energies other than 2 m. e. v. To avoid ambiguity, the terms "normalized depth" and "normalized thickness" will be used to indicate measurements in g./cm.^{2}- m. e. v., while the terms "linear depth" and "linear thickness" will refer to measurements in cm. Normalized depth is calculated by multiplying the linear depth by the density of the material irradiated and dividing the product by the energy of the bombarding electrons.

Since the acceleration tube by which the method of my invention is practiced is highly evacuated, practically no ionization takes place within the tube, so that normalized depth=0 is taken as the inner surface of the cathode-ray window. The diagram, Fig. 5, shows that the ionization at this point is about 55%. If the aluminum-foil cathode-ray window has a linear thickness of .0074 cm., the normalized thickness of the window is

$$\frac{.0074 \text{ cm.} \times 2.7 \text{ g./cm.}^3}{2 \text{ m. e. v.}} = .01 \text{ g./cm.}^2\text{-m. e. v.}$$

where the density of aluminum is taken as 2.7 g./cm.^{3} and where the energy of the electrons is taken as 2 m. e. v. Since the product is positioned very close to the window the normalized thickness of the intervening air is negligible. Consequently, that part of the surface of the product where the electrons enter the product corresponds to a normalized depth of 0.1 g./cm.^{2}-m. e. v. This part of the surface I call the "near surface," shown at *n* in the diagram Fig. 5, and the corresponding "near surface ionization level" is shown by the diagram Fig. 5 to be about 60%.

Ionization increases with increasing depth up to a maximum ionization level of 100% at depth *m*. Beyond this depth *m*, ionization decreases with increasing depth. The part of the surface of the product where the electrons emerge from the product I call the "remote surface," shown at *r* in Fig. 5, and it is apparent from the diagram Fig. 5 that the corresponding "remote surface ionization level" depends upon the normalized thickness of the product.

As hereinbefore stated, one object of this invention is to increase uniformity of ionization, and another object is to increase efficiency of operation. Uniformity of ionization is defined as the quotient of the minimum ionization level in the product divided by the maximum ionization level therein. If at least a certain minimum ionization must be effected at all depths in the product, but if greater ionization than this minimum is not required, then efficiency of operation may be defined as follows:

$$\text{Efficiency} = \frac{\text{minimum ionization level} \times \text{normalized product thickness}}{I}$$

where I is the total ionization which depends only upon the current and voltage of the generator.

For singles-pass irradiation, illustrated in the diagram, Fig. 5, the maximum ionization level is always 100% by definition. Consequently, uniformity is always equal to the minimum ionization level. It is apparent from the shape of the curve in the diagram, Fig. 5, that uniformity is always equal to either the near surface ionization level or the remote surface ionization level, whichever is lower. The remote surface ionization level may be increased by decreasing the normalized thickness of the product (i. e. by decreasing the linear thickness of the product or by increasing the generator voltage). However, the near surface ionization level limits the uniformtiy obtainable to 60%.

For a minimum ionization level of 60%, the maximum normalized product thickness obtainable is that which corresponds to a remote surface ionization level of 60%, and is indicated in the diagram, Fig. 5, by the normalized thickness of *n*—*r*. Said normalized thickness *n*—*r* is seen from the diagram Fig. 5 to be .33 g./cm.^{2}-m. e. v. If water is being irradiated with 2 m. e. v. electrons, the corresponding linear product thickness is

$$\frac{.33 \text{ g./cm.}^2\text{—m. e. v.} \times 2 \text{ m. e. v.}}{1 \text{ g./cm.}^3} = .66 \text{ cm.}$$

Therefore, the maximum efficiency obtainable with the maximum uniformity of 60% is

$$\frac{60\% \times .33 \text{ g./cm.}^2\text{—m. e. v.}}{I}$$

This may be calculated to be 58.5%. Minimum ionization levels of less than 60% result in decreased efficiency, so that the maximum efficiency obtainable with single-pass irradiation is 58.5%.

If the product is irradiated by ordinary double bombardment, the ionization/depth curve is obtained by superimposing upon the curve in the diagram Fig. 5 the mirror image thereof in such a manner that the total normalized depth is equal to the total normalized thickness. Thus the diagram Fig. 6 illustrates the irradiation of a product having a normalized thickness of .81 g./cm.^{2}-m. e. v. by double bombardment with cathode rays which pass through an aluminum foil window having a normalized thickness of .01 g./cm.^{2}-m. e. v. Hence the total normalized depth is

$$.01 + .81 + 0.1 = .83 \text{ g./cm.}^2\text{-m. e. v.}$$

The diagram Fig. 7 illustrates the irradiation of a product having a normalized thickness of .73 g./cm.^{2}-m. e. v. by double bombardment with cathode rays which pass through a total normalized absorber thickness of .035 g./cm.^{2}-m. e. v. Hence the total normalized depth is

$$.035 + .73 + .035 = .80 \text{ g./cm.}^2\text{-m. e. v.}$$

The diagram Fig. 8 illustrates two cases: (*a*) the irradiation of a product having a normalized thickness of .76 g./cm.^{2}-m. e. v., by double bombardment with cathode rays which pass through an ordinary aluminum foil window, and (*b*) the irradiation of a product having a normalized thickness of .65 g./cm.^{2}-m. e. v., by double bombardment with cathode rays which pass through an increased absorber thickness. Both cases result in the same total normalized depth:

(*a*) .01+.76+.01=.78 g./cm.²-m. e. v.
(*b*) .065+.65+.065=78 g./cm.²-m. e. v.

Similarly the diagram Fig. 9 illustrates a total normalized depth of .75 g./cm.²-m. e. v., and Fig. 10, the diagram, a total normalized depth of .73 g./cm.²-m. e. v.

For double bombardment without filter and without auxiliary generator the two near-surface ionization levels *n* and *n'* are always 60%, as shown in the diagrams Figs. 6, 8–10. Since there is no "remote surface" in double bombardment, the near surface ionization level may be referred to simply as the "surface ionization level." The maximum ionization levels, corresponding to depths *m* and *m'*, are always at least 100%, although they may exceed 100% (as shown, for example, in the diagram Fig. 10), since ionization is expressed as a percentage of the maximum single-pass ionization level.

It is apparent from the shape of the curves in the diagrams Figs. 6–10 that the minimum ionization level will be equal to either the surface ionization level or the central ionization level *c*, whichever is the lesser, where the term "central ionization level" is defined as the lowest ionization level between depths *m* and *m'*. The central ionization level *c* may be increased by decreasing normalized product thickness. Thus, the central ionization level *c* in the diagram Fig. 6 is 60% with a normalized product thickness of .81 g./cm.²-m. e. v., whereas the central ionization level *c* in the diagram Fig. 10 is 97½% with a normalized product thickness of .71 g./cm.²-m. e. v. However, uniformity is limited by the surface ionization levels *n* and *n'* to a maximum of 60%.

Since two identical electron beams are employed in double bombardment, the total ionization is 2(I) and efficiency is equal to

$$\frac{\text{(minimum ionization level)} \times \text{(normalized product thickness)}}{2I} = \frac{\text{(minimum ionization level)} \times \frac{1}{2}\text{(normalized product thickness)}}{I}$$

For a minimum ionization level of 60%, the maximum normalized product thickness obtainable shown at *n*—*n'* in the diagram Fig. 6 is .81 g./cm.²—m. e. v., so that the maximum efficiency obtainable with the maximum uniformity of 60% is

$$\frac{60\% \times .405 \text{ g./cm.}^2\text{—m. e. v.}}{I}$$

This is greater than the maximum efficiency of

$$\frac{60\% \times .33 \text{ g./cm.}^2\text{—m. e. v.}}{I}$$

obtainable with single pass irradiation, and may be calculated to be 71.5%. Minimum ionization levels of less than 60% result in decreased efficiency, so that the maximum efficiency obtainable with ordinary double bombardment is 71.5%.

To summarize, the maximum uniformity obtainable with ordinary single-pass irradiation or with ordinary double bombardment is 60%. The maximum efficiency obtainable with ordinary single-pass irradiation is 58.5%, and the maximum efficiency obtainable with ordinary double bombardment is 71.5%. Both uniformity and efficiency are limited by the ionization level near the surface of the product.

As stated, in one embodiment of apparatus for practicing the method of my invention I raise the ionization level near the surface of the product by providing a filter, as shown in Fig. 2. The effect of such a filter is to increase the normalized depth corresponding to the surface of the product. Thus, if an ordinary aluminum foil window is used, the surface of the product corresponds to a normalized depth *n*=.01 g./cm.²—m. e. v., as shown in the diagram Fig. 6. By using an aluminum foil window of increased thickness, the surface of the product may be caused to correspond to a normalized depth *f*=.035 g./cm²—m. e. v., as shown in the diagram Fig. 7. The same effect is achieved by placing an absorber of normalized thickness .025 g./cm.²—m e. v. between an ordinary thin window of normalized thickness .01 g./cm.²—m e. v. and the product. The diagram, Fig. 7, shows that if the total normalized absorber thickness is .035 g./cm.²—m. e. v., the ionization level at the surface *f* is 70%. With 2 m. e. v. electrons the required total normalized absorber thickness may be achieved by using an aluminum window of linear thickness

$$\frac{.035 \text{ g./cm.}^2\text{—m. e. v.} \times 2 \text{ m. e. v.}}{2.7 \text{ g./cm.}^3} = .026 \text{ cm.}$$

or by using an absorber of linear thickness

$$\frac{.25 \text{ g./cm.}^2\text{—m. e. v.} \times 2 \text{ m. e. v.}}{2.7 \text{ g./cm.}^3} = 0.19 \text{ cm.}$$

in conjunction with the ordinary thin aluminum foil window of linear thickness

$$\frac{.01 \text{ g./cm.}^2\text{—m. e. v.} \times 2 \text{ m. e. v.}}{2.7 \text{ g./cm.}^3} = .0074 \text{ cm.}$$

By making the normalized product thickness *n*—*n'* equal to .73 g./cm.²—m. e. v., so that the central ionization level *c* is also 70%, a uniformity of 70% and an efficiency of

$$\frac{70\% \times .365 \text{ g./cm.}^2\text{—m. e. v.}}{I} = 74.5\%$$

may be obtained.

The surface ionization level may be further raised simply by increasing the total normalized absorber thickness, which is equivalent to increasing the normalized depth *f* of the surface of the product. The diagram Fig. 8 shows that with a total normalized absorber thickness of .065 g./cm.²—m. e. v. the surface corresponds to a normalized depth *f* of .065 g./cm.²—m. e. v., and the surface ionization level is 80%. Similarly, when the surface corresponds to a normalized depth *f* of .095 g./cm.²—m. e. v., the surface ionization level is 90%, as shown in the diagram Fig. 9; and when the surface corresponds to a normalized depth of *f* .13 g./cm.²—m. e. v., the surface ionization level is 97½%, as shown in the diagram Fig. 10.

Since the central ionization level may also be increased simply by decreasing the normalized product thickness *n*—*n'*, it is possible to increase uniformity up to almost 100% through the use of filters. Although the use of very thick filters will decrease efficiency of operation, owing to the energy used up by absorption outside the product, the use of a filter of moderate thickness actually results in greater efficiency than that obtainable with an ordinary thin window. The following table shows that a total normalized absorber thickness of .065 g./cm.²—m. e. v. results in maximum efficiency with double bombardment.

Total absorber thickness in g./cm.²—m. e. v. (ordinary double bombardment)	Uniformity, percent	Efficiency, percent
.01	60	71.5
.035	70	74.5
.065	80	77
.095	90	75.5
.13	95	67

The use of filters with single-pass irradiation does not increase efficiency, although, as has been seen in the case of double bombardment, increasing the total normalized absorber thickness may increase uniformity.

In the second embodiment of apparatus for practicing the method of my invention, I raise the ionization level near the surface of the product by using an auxiliary generator in conjunction with each main generator, as shown in Fig. 4. The effect of the auxiliary generator upon the ionization level near the surface of the product is shown for double bombarment in the diagrams Figs. 8–10.

Referring more particularly to the diagram Fig. 8, it will be recalled that a uniformity of 80% and an efficiency of 77% were obtained by irradiating a product of normalized thickness $f-f'=.65$ *g./cm.*^{2}—m. e. v., with cathode rays passing through a total normalized absorber thickness f of .065 g./cm.^{2}—m. e. v. If an ordinary aluminum foil window without filter be employed, the total normalized absorber thickness is reduced to $n=.01$ g./cm.^{2}—m. e. v., and the normalized product thickness is increased to

$$n-n'=.76 \text{ g./cm}^2\text{—m. e. v.}$$

Uniformity is then reduced to 60%, owing to the ionization level at the surfaces n and n'. However, if the product is also irradiated by an auxiliary generator of lower voltage and current than those of the main generator, the additional ionization produced in the surface layers $n-f$ and $n'-f'$ may raise the uniformity to 80%.

The ionization/depth curve for the auxiliary generator is shown at A in the diagram Fig. 8. This curve A is obtained by transferring the ionization/depth curve of the diagram Fig. 5 onto the graphs of Fig. 8 with appropriate adjustments for the difference in units. Thus the diagram Fig. 5 shows the ionization/depth curve for the auxiliary generator, where ionization is expressed as a percentage of the maximum ionization level produced by the auxiliary generator; but in the diagram Fig. 8 ionization is expressed as a percentage of the maximum ionization level produced by the main generator. If the auxiliary generator current factor is .23, which means that the current of the auxiliary generator is 23% of the main generator current, the maximum ionization level of the auxiliary generator will be 23% of the maximum ionization level of the main generator, as shown by curve A on the graph of Fig. 8.

Similarly the diagram Fig. 5 shows the ionization/depth curve for the auxiliary generator, where depth is expressed as

$$\text{Depth (Fig. 5)}=\frac{\text{(Linear depth)}\times\text{(Density)}}{\text{Auxiliary generator voltage}}$$

but in the diagram Fig. 8 depth is expressed as

$$\text{Depth (Fig. 8)}=\frac{\text{(Linear depth)}\times\text{(Density)}}{\text{Main generator voltage}}$$

$$=\frac{\text{Auxiliary generator voltage}}{\text{Main generator voltage}}\times\text{(Depth (Fig. 5))}$$

$$=\text{(Auxiliary generator voltage factor)}\times\text{(Depth (Fig. 5))}$$

Thus, for example, the maximum penetration of the auxiliary generator is shown by the diagram Fig. 5 to be .565 g./cm.^{2}—m. e. v. If the auxiliary generator has a voltage factor of .13, the maximum penetration on the graph of Fig. 8 will correspond to a normalized depth of

$$.13\times.565 \text{ g./cm.}^2\text{—m. e. v.}=.073 \text{ g./cm.}^2\text{—m. e. v.}$$

as shown by curve A in the diagram Fig. 8.

When the ionization level produced by the auxiliary generator, shown by curve A, is added to the ionization level produced by the main generator, shown by curve M, the ionization level produced by the two generators together is shown by curve B. The diagram Fig. 8 shows that with an auxiliary generator voltage factor of .13 and an auxiliary generator current factor of .23, the ionization level throughout the surface layers $n-f$ and $n'-f'$ is raised to at least 80%. Uniformity is thus 80%, and the efficiency of the main generators is

$$\frac{80\%\times\frac{1}{2}(n-n')}{I}=\frac{80\%\times.38 \text{ g./cm.}^2\text{—m. e. v.}}{I}$$

which may be calculated to be 88%.

The diagram Fig. 9 is similar to that of Fig. 8, and shows that an auxiliary generator voltage factor of .20 and an auxiliary generator current factor of .43 will raise the ionization level throughout the surface layers $n-f$ and $n'-f'$ to at least 90%. By reducing the normalized product thickness $n-n'$ to .73 g./cm.^{2}—m. e. v., the central ionization level c may also be raised to 90%. The maximum ionization level is raised by the ionization level in the surface layers, so that uniformity is only

$$\frac{90\%}{108\%}=83.3\%$$

However, the efficiency of the main generators is

$$\frac{90\%\times\frac{1}{2}(n-n')}{I}=\frac{90\%\times.365 \text{ g./cm.}^2\text{—m. e. v.}}{I}$$

which may be calculated to be 93.5%.

Similarly the diagram Fig. 10 shows that an auxiliary generator voltage factor of .27 and an auxiliary generator current factor of .52 will raise the ionization level throughout the surface layers $n-f$ and $n'-f'$ to at least 97½%. The central ionization level c is also raised 97½% by reducing the normalized product thickness $n-n'$ to .71 g./cm.^{2}—m. e. v. The high ionization level in the surface layers $n-f$ *and* $n'-f'$ limits the uniformity to

$$\frac{97\tfrac{1}{2}\%}{129\%}=75.6\%$$

However, the efficiency of the main generators is

$$\frac{97\tfrac{1}{2}\%\times\frac{1}{2}(n-n')}{I}=\frac{97\tfrac{1}{2}\%\times.355 \text{ g./cm.}^2\text{—m. e. v.}}{I}$$

which may be calculated to be 97%.

The efficiency of the main generators may be increased still further by increasing the voltage and current of the auxiliary generator. However, the increased voltage and current required of the auxiliary generator would become rapidly uneconomical, and the overall efficiency would be reduced. Furthermore, the resultant increased ionization level in the surface layers would cause a marked decrease in uniformity.

The following table illustrates the variation of uniformity and main-generator efficiency with auxiliary generator voltage and current.

Auxiliary generator		Uniformity, percent	Main generator efficiency, percent
voltage factor	current factor		
(ordinary double bombardment)			
0	0	60	71.5
.13	.23	80	88
.20	.43	83	93.5
.27	.52	76	97

An auxiliary generator may also be used to raise the efficiency of single-pass irradiation. The remote surface ionization level may be raised by decreasing normalized product thickness, and the near-surface ionization level may be raised by using an auxiliary generator. The diagram Fig. 5 shows that for a normalized product thickness of .27 g./cm.^{2}—m. e. v. the remote surface ionization level will be 80%. It has been hereinbefore stated that in the case of double bombardment, an auxiliary generator of voltage factor .13 and current factor .23 will raise the surface ionization level to 80%, as shown in the diagram, Fig. 8. Similarly, the near-surface ionization level in the case of single-pass irradiation may be raised to 80% by the use of such an auxiliary generator, as shown in the diagram Fig. 5. Uniformity will then be 80%, and efficiency will be

$$\frac{80\% \times .27\ \text{g./cm.}^2-\text{m. e. v.}}{I}$$

which may be calculated to be 66%.

Referring again to double bombardment and in particular to the diagram Fig. 10, therein it is shown that by using an auxiliary generator it is possible to increase the main generator efficiency to 97%. However, this increased efficiency is accompanied by two disadvantages. First, the high ionization level in the surface layers $n-f$ and $n'-f'$ tends to limit uniformity. Second, the current required of the auxiliary generator is more than half that of the main generator. High current may be more difficult to obtain than high voltage, especially if a generator of the type shown in the aforementioned patent to Robinson is employed.

In the diagram Fig. 10, curve A shows the ionization/depth relationship for an auxiliary generator voltage factor of .27 and an auxiliary current factor of .52.

By using a filter on the auxiliary generator, I am able to increase uniformity in the surface layers $n-f$ and $n'-f'$. As hereinbefore set forth, the effect of a filter is to increase the normalized depth corresponding to the surface of the product. If the total normalized absorber thickness on the auxiliary generator is such that the maximum ionization level produced by the auxiliary generator occurs at the surface n of the product, the auxiliary generator ionization/depth curve will appear as shown at A in the diagram Fig. 10*a*, and the ionization level produced by the two generators together is shown at B. With such a filter, the auxiliary generator voltage factor required is .38, and the auxiliary generator current factor required is .37. It is apparent from a comparison of the diagrams Figs. 10 and 10*a* that although the addition of the filter increases the voltage factor from .27 to .38 the current factor is reduced from .52 to .37.

Having thus described several embodiments of apparatus for practicing the method of my invention, it is to be understood that although specific terms are employed, they are used in a generic and descriptive sense and not for purposes of limitation, the scope of the invention being set forth in the following claims.

I claim:

1. Apparatus for irradiating substances with high energy electrons, comprising in combination, a main cathode-ray generator, including means for creating a main beam of high velocity electrons and also including means for directing said main beam from one aspect onto the surface of the susbtance to be irradiated, and an auxiliary cathode-ray generator of lower voltage and current than those of said main cathode-ray generator, said cathode-ray generator of lower voltage and current including means for creating an auxiliary beam of electrons having a voltage less than one-half the voltage of the electrons in said main beam, the current in said auxiliary beam being less than three-fifths the current in said main beam, and also including means for directing said auxiliary beam from the same aspect onto the surface of such substance.

2. Apparatus for increasing the uniformity of ionization produced in a substance by the passage of high energy electrons therethrough, comprising a source of high energy electrons, means for directing said high energy electrons onto the substance to be irradiated, and an absorber positioned between said source and said substance, said absorber having a total normalized thickness of more than .01 g./cm.^{2}—m. e. v. and less than .16 g./cm.^{2}—m. e. v.

3. Apparatus for increasing the efficiency of operation in the irradiation of substances by double bombardment with high energy electrons, comprising at least one source of high energy electrons, means for directing said high energy electrons onto the substance to be irradiated, and an absorber positioned between each of such source and said substance, each absorber having a total normalized thickness of approximately .065 g./cm.^{2}—m. e. v., and said substance having a total normalized thickness of approximately .65 g./cm.^{2}—m. e. v.

4. That method of making more nearly uniform throughout all the volume of a substance, the degree of ionization therein that is effected by irradiation with high-energy electrons, which method comprises irradiating said substance with at least two essentially opposed main fluxes of electrons, said main fluxes having respective currents such that the maximum ionization produced thereby in said substance is not more than the maximum ionization desired therein, said main fluxes having respective voltages such that the ionization produced in said substance is less than the minimum ionization desired therein at the surface layers only of said substance, and also irradiating said substance with at least two essentially opposed auxiliary fluxes of electrons, said auxiliary fluxes having respective currents less than three-fifths the respective currents in said main fluxes, said auxiliary fluxes having respective voltages less than one-half the respective voltages of said main fluxes.

5. That method of making more nearly uniform throughout all the volume of a substance, the degree of ionization therein that is effected by irradiation with high-energy electrons, which method comprises irradiating said substance with at least one flux of electrons having a relatively high velocity component in a direction substantially normal to the surface of said substance, whereby a maximum ionization level is effected in said substance; and decreasing the component normal to said surface, of the velocity of some of the electrons in said flux by directing said flux through matter having a total normalized thickness of not less than .01 g./cm.^{2}—m. e. v. and not more than .16 g./cm.^{2}—m. e. v. before said electrons impinge on said surface, so as to increase the ionization level at said surface in relation to said maximum ionization level.

6. Apparatus for increasing the uniformity of ionization produced in a substance by the passage of high energy electrons therethrough, comprising in combination means for creating and directing a beam of high energy electrons, said means including an evacuated acceleration tube having an electron source at one extremity thereof and an electron window at the opposite extremity thereof; and filter means supported to extend across the path of the electrons issuing from said electron window, the total normalized thickness of said electron window and said filter means being not less than .01 g./cm.^{2}—m. e. v. and not more than .16 g./cm.^{2}—m. e. v.

7. Apparatus in accordance with claim 1, wherein said auxiliary cathode-ray generator includes an evacuated acceleration tube having an electron source at one extremity thereof and an electron window at the opposite extremity thereof, said electron window having a normalized thickness of not less than .01 g./cm.^{2}—m. e. v. and not more than .16 g./cm.^{2}—m. e. v., said normalized thickness being measured with respect to the voltage of said auxiliary cathode-ray generator.

8. Apparatus for irradiating substances with high energy electrons, comprising in combination: a main cathode-ray generator, including means for creating a main beam of high velocity electrons and also including means for directing said main beam from one aspect onto the surface of the substance to be irradiated; an auxiliary cathode-ray generator of lower voltage and current than those of said main cathode-ray generator, said cathode-ray generator of lower voltage and current including means for creating an auxiliary beam of electrons having a voltage less than one-half the voltage of the electrons in said main

beam, the current in said auxiliary beam being less than three-fifths the current in said main beam, and also including means for directing said auxiliary beam from the same aspect onto the surface of such substance; and filter means supported to extend across the path of the electrons issuing from said auxiliary cathode-ray generator.

References Cited in the file of this patent

UNITED STATES PATENTS

1,907,507	Coolidge	May 9, 1933
2,429,217	Brasch	Oct. 21, 1947
2,602,751	Robinson	July 8, 1952