United States Patent [19]

Austin et al.

[11] **3,925,671**

[45] **Dec. 9, 1975**

[54] **IRRADIATING STRAND MATERIAL**

[75] Inventors: **James Raymond Austin,** Williamsville, N.Y.; **Martin John Brown,** Lambertville; **Leonard Donald Loan,** New Providence, both of N.J.

[73] Assignees: **Bell Telephone Laboratories; Western Electric Company, Inc.,** both of New York, N.Y.

[22] Filed: **Sept. 19, 1974**

[21] Appl. No.: **507,500**

Related U.S. Application Data

[63] Continuation of Ser. No. 304,458, Nov. 7, 1972, abandoned.

[52] **U.S. Cl.** .... **250/400;** 204/159.2; 250/492 R

[51] **Int. Cl.**^{2}.. **A61N 5/00;** A61K 27/02; C08F 2/46

[58] **Field of Search** 250/396, 398, 400, 492; 204/159.2

[56] **References Cited**

UNITED STATES PATENTS

3,144,552 8/1964 Schonberg et al. 250/400

FOREIGN PATENTS OR APPLICATIONS

817,033 7/1959 United Kingdom 250/400

OTHER PUBLICATIONS

"Facilities for Wire Irradiation with an Electron Beam Generator", by R. P. Skundberg from Wire and Wire Products, Oct. 1959, pp. 1328, 1329, 1330, 1366 and 1367, 250–400.

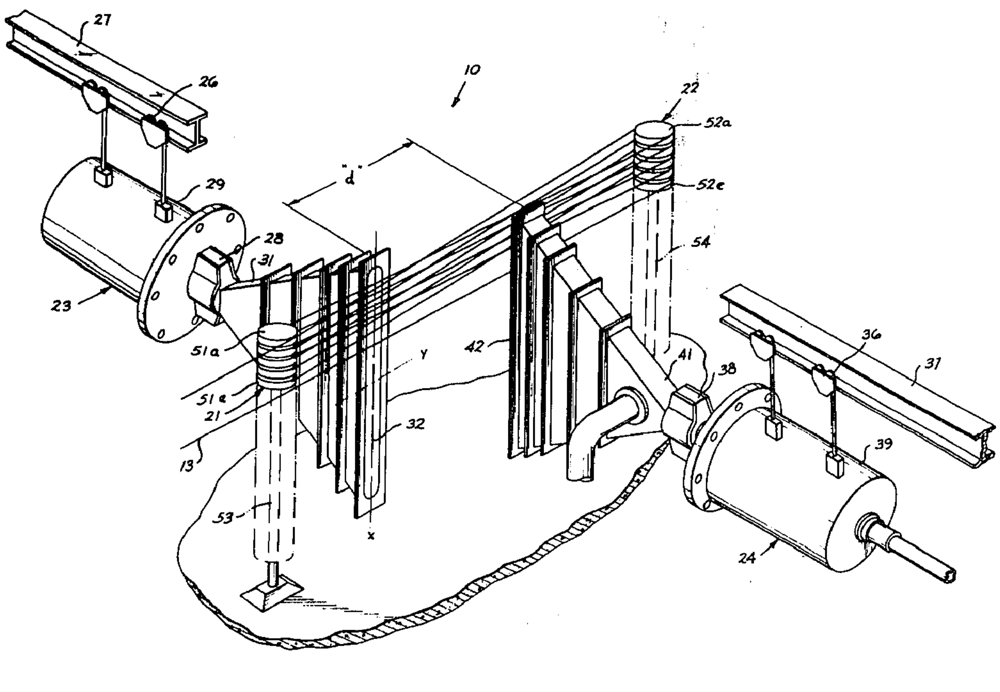
Primary Examiner—James W. Lawrence
Assistant Examiner—T. N. Grigsby
Attorney, Agent, or Firm—E. W. Somers

[57] **ABSTRACT**

Conductors covered with insulation which is to be irradiated are passed between two groups of coaxial sheaves mounted rotatably individually. Successive sections of the conductors are advanced past the window of one accelerator head, around the associated sheave or sheaves, and then past the window of another accelerator head. The accelerators face in substantially opposite directions and are staggered along the paths of the conductors to avoid any substantial overlap of the electron beams associated therewith. The windows extend vertically to encompass all the generally horizontal passes of the conductors as between the two groups of sheaves. Preferably, conductors are strung-up between the sheaves in a modified figure eight pattern. The pattern is a figure eight modified to intermittently include a pass between the sheaves which is parallel to a line joining the axes of the two groups of sheaves. This reverses the direction of travel of the conductors and optimizes the uniformity of exposure of the cross sectional area of the insulation of the conductors to irradiation.

The use of a figure eight path for the conductors causes the successive sections of the conductor to turn about the longitudinal axes thereof as they are advanced around the sheaves. In this way the insulation is more uniformly irradiated. In a preferred embodiment, twisted conductor pairs may be irradiated. The twist accentuates the longitudinal turning of the conductor pair. The irradiation of twisted pairs achieves obvious manufacturing economies while avoiding the necessity of having to twist irradiation cross-linked conductors.

8 Claims, 14 Drawing Figures



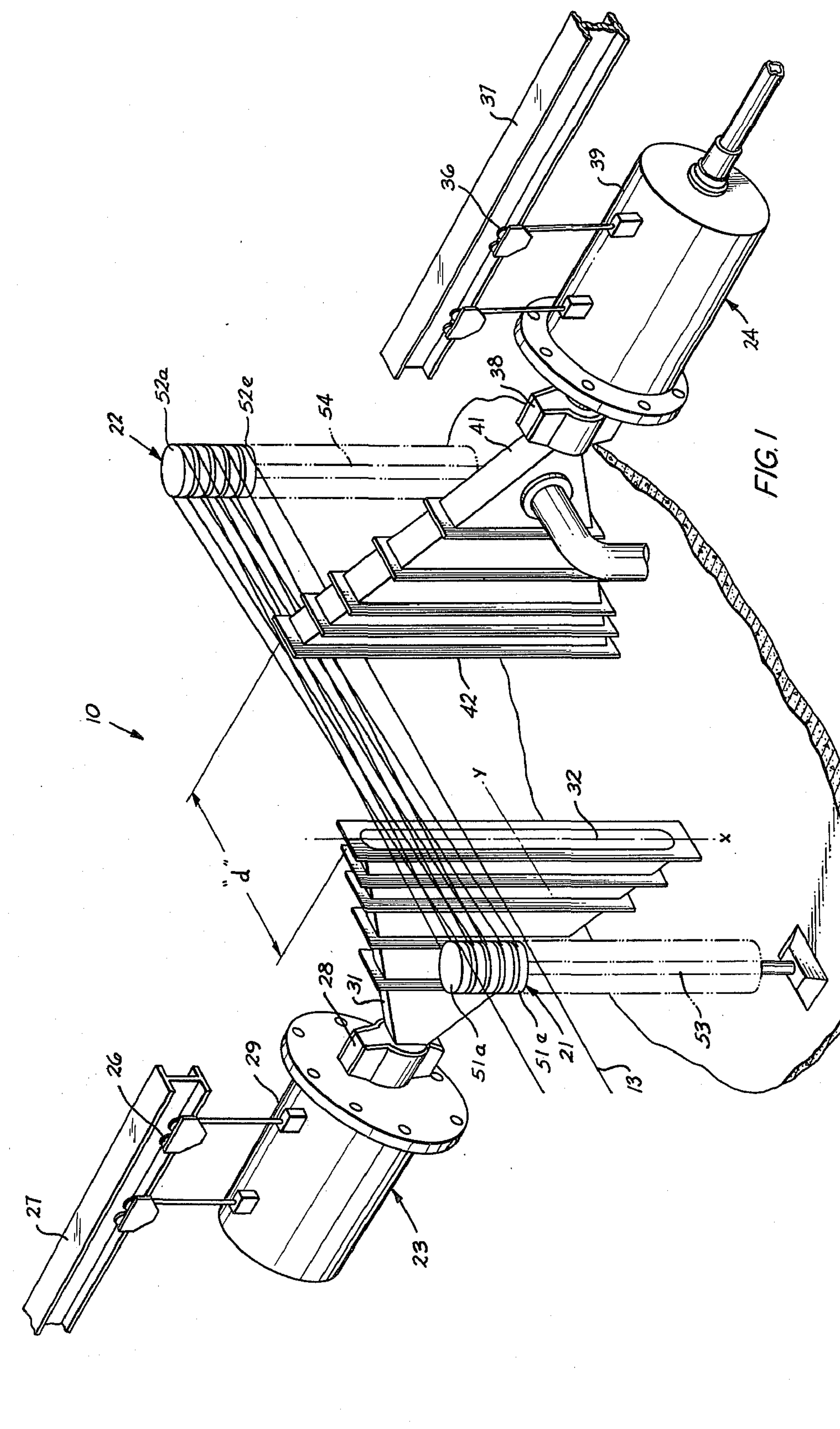

10
22
52a
52e
54
41
38
36
31
39
24
42
32
y
x
"d"
28
31
51a
51a
21
13
53
26
29
27
23

FIG. 1

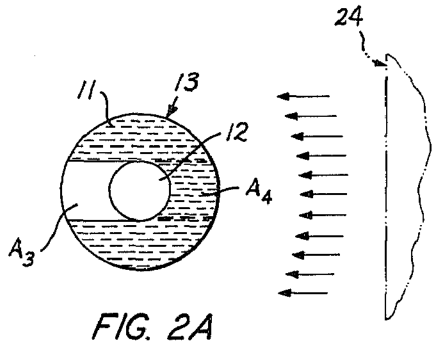


FIG. 2A

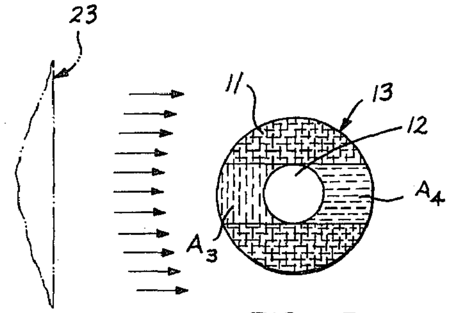


FIG. 2B

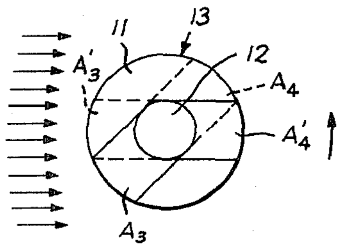


FIG. 2C

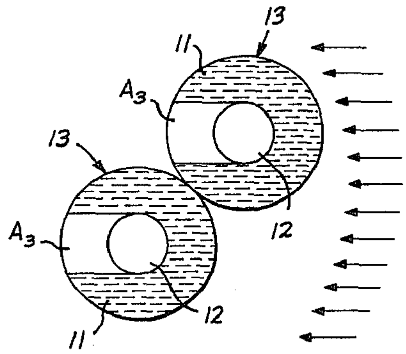


FIG. 2D

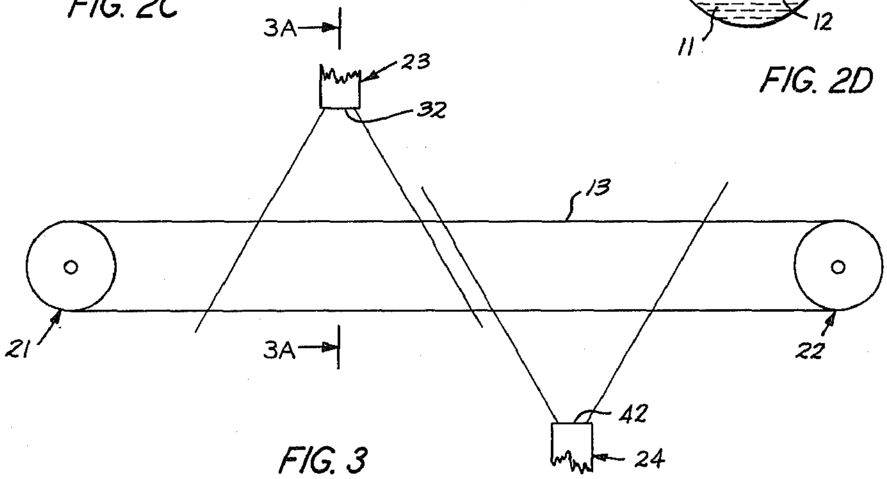


FIG. 3

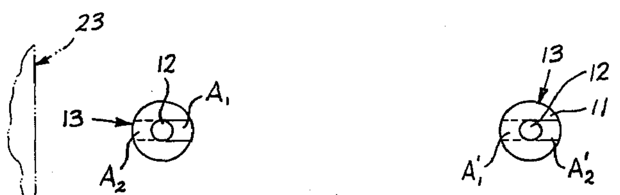


FIG. 3A

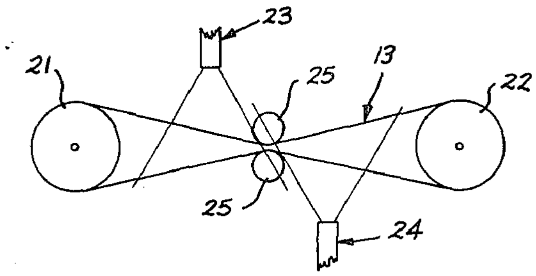


FIG. 3B

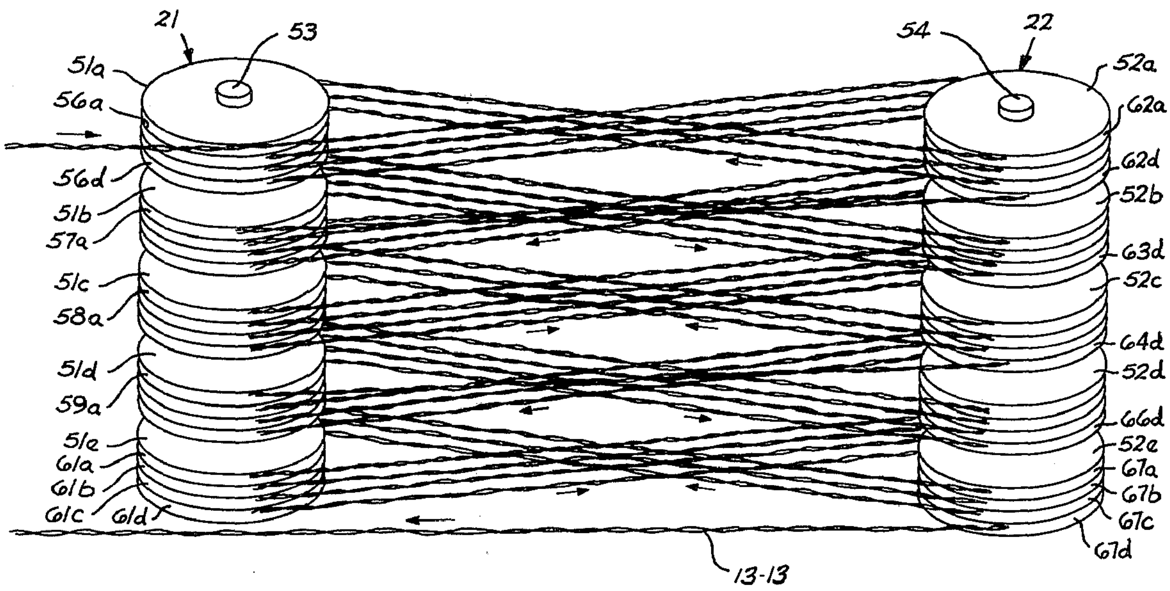

21
53
54
22
51a
56a
56d
51b
57a
51c
58a
51d
59a
51e
61a
61b
61c
61d
52a
62a
62d
52b
63d
52c
64d
52d
66d
52e
67a
67b
67c
67d
13-13

FIG. 4

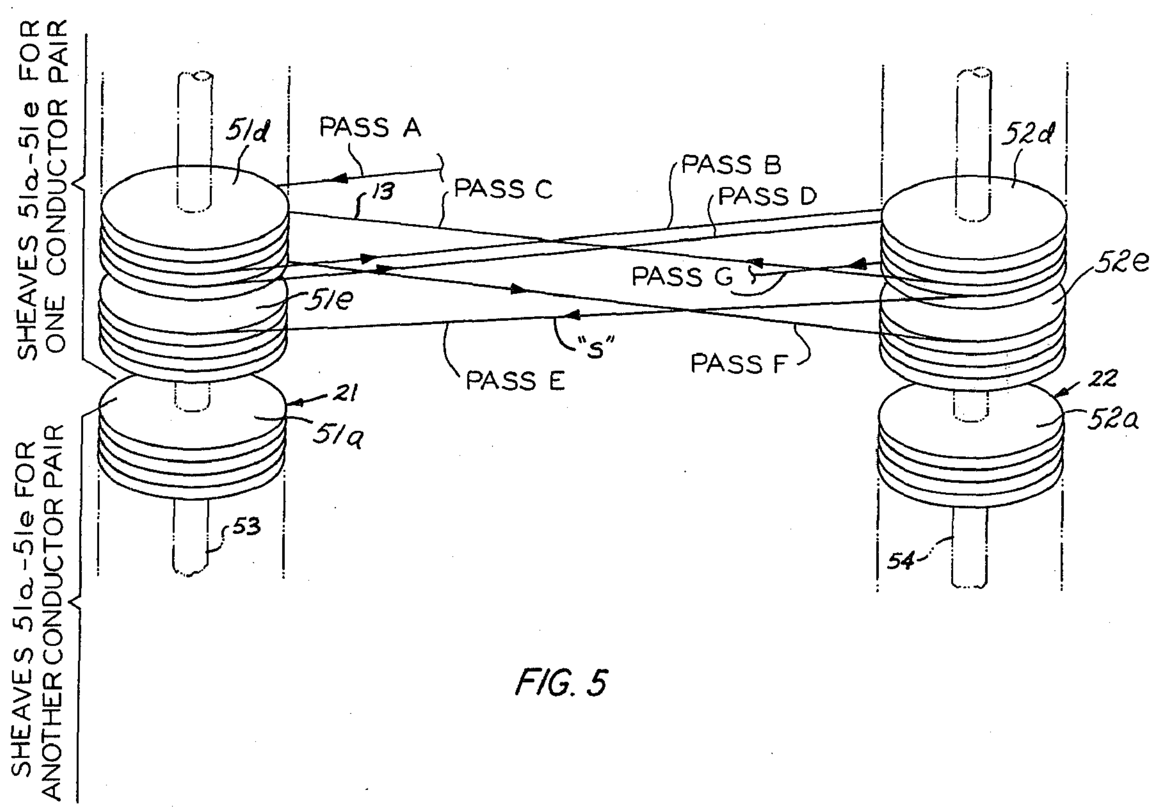

SHEAVES 51a-51e FOR ONE CONDUCTOR PAIR
SHEAVES 51a-51e FOR ANOTHER CONDUCTOR PAIR
51d
PASS A
PASS C
13
PASS B
PASS D
52d
52e
PASS G
51e
"S"
PASS E
PASS F
21
51a
22
52a
53
54

FIG. 5

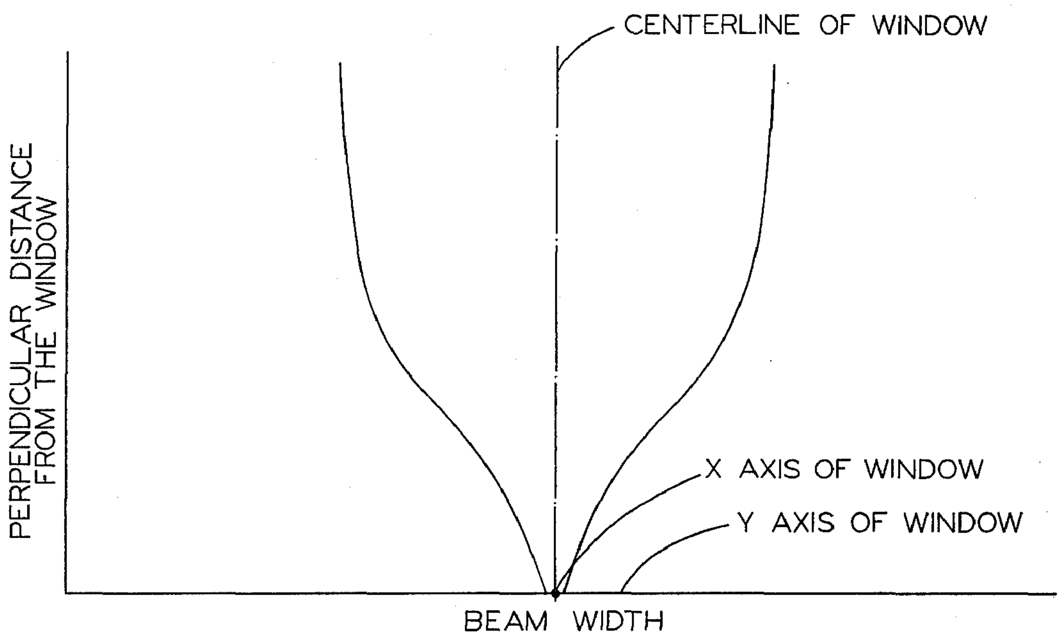

CENTERLINE OF WINDOW
PERPENDICULAR DISTANCE FROM THE WINDOW
X AXIS OF WINDOW
Y AXIS OF WINDOW
BEAM WIDTH

FIG. 6

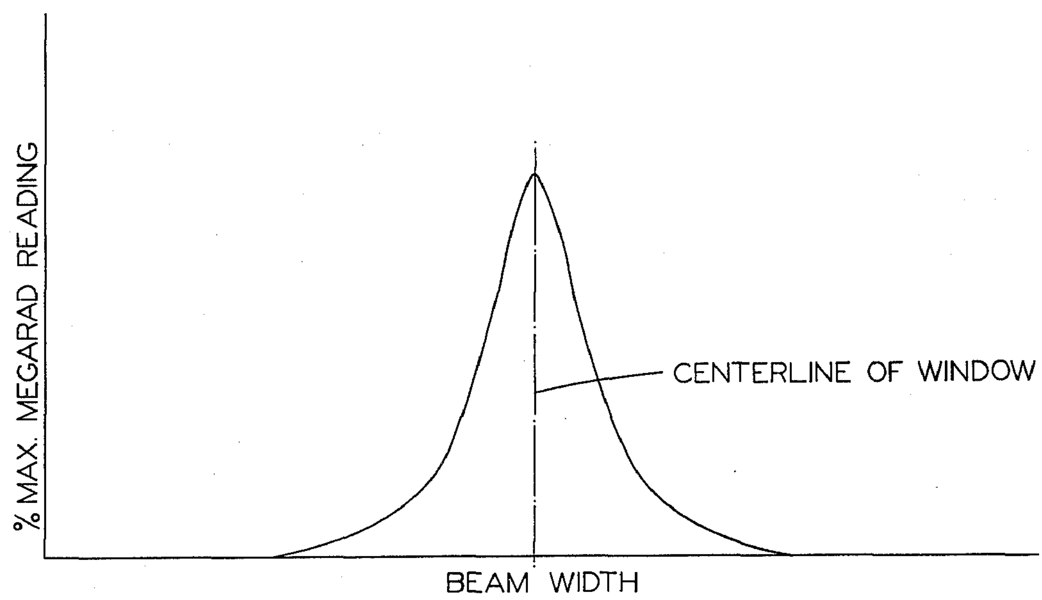

% MAX. MEGARAD READING
CENTERLINE OF WINDOW
BEAM WIDTH

FIG. 7

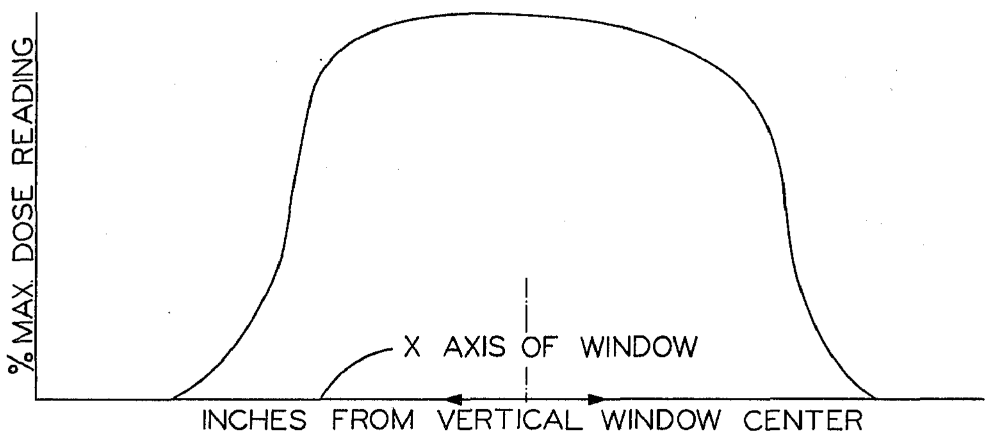

% MAX. DOSE READING
X AXIS OF WINDOW
INCHES FROM VERTICAL WINDOW CENTER

FIG. 8

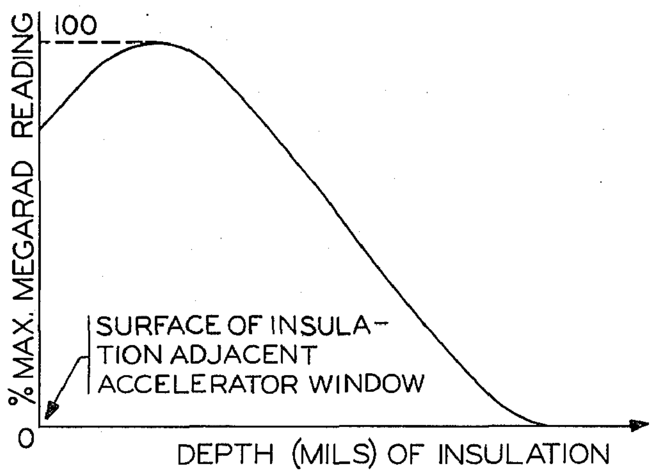

100
% MAX. MEGARAD READING
SURFACE OF INSULATION ADJACENT ACCELERATOR WINDOW
0
DEPTH (MILS) OF INSULATION

FIG. 9

IRRADIATING STRAND MATERIAL

This is a continuation of application Ser. No. 304,458 filed Nov. 7, 1972 and now abandoned.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to irradiating strand material, and more particularly, to methods of and apparatus for the radiation of insulated conductors to uniformly dose the insulation and cross-link the insulation to produce a covering which possesses unusually desirable mechanical and electrical properties while optimizing the use of the source of radiation.

2. Technical Considerations and Description of the Prior Art

In the telephone communications industry, the changing of a telephone number requires that a craftsman rearrange a connection in a central office. Whenever possible, unused conductors are removed by merely pulling them out from one end thereof through a supporting trough and guides and around corners. The conductor must possess adequate tensile strength and also be capable of withstanding abrasion during the pulling thereof through troughs in engagement with adjacent conductors and mechanical or structural members. Also, the conductor insulation must resist fire damage as well as soldering heat during the reconnection process of the wire or adjacent wires.

The conductor presently used for central office wiring is a three-layer structure including an extruded polyvinyl chloride primary insulation, textile layer, and a fire retardant lacquer. A conductor covered with a single layer of irradiation cross-linked insulating material to replace the three layer structure is shown in U.S. Pat. No. 3,623,940 issued on Nov. 30, 1971 in the names of Harold M. Gladstone and Leonard D. Loan and in an article authorized by L. Donald Loan and Warren A. Salmon appearing in the Sept. 1972 issue of The Bell Laboratories Record starting at page 239. An improved irradiation cross-linked insulating composition is disclosed in an application Ser. No. 292,469 filed Sept. 26, 1972 in the names of J. R. Austin, L. D. Loan, N. W. Murray, Jr., W. A. Salmon and T. J. Szymczak and now abandoned.

The rigidity, toughness and resistance of the irradiated material are functions of the amount of cross-linking. The amount of cross-linking is related to the amount of radiation which the material receives. The term irradiation as used herein is interpreted as high energy electron radiation of at least approximately 100,000 electron volts.

The irradiation of polyethylene as an insulation material is known in the wire and cable industry. For example, see "The Use of Irradiated Polyethylene in Wire and Cable" authored by Allen B. Towne and published in Wire and Wire Products, Oct. 1959 at page 1923. A typical irradiation facility including an electron beam generator positioned in an appropriately shielded enclosure is disclosed in an article "Facilities for Wire Irradiation with an Electron Beam Generator" authored by R. P. Skundberg and published at page 1328 of the Oct. 1959 issue of Wire and Wire Products.

The total radiation energy absorbed by a conductor is determined by the control of the electron beam generator's output, the speed at which the successive sections of the conductor are passed through the beam exposure area as well as the distance from the window to the conductor. In one commercially utilized layout, successive sections of a conductor are advanced over a sheave, past the accelerator, and around a second sheave in a figure-eight pattern past the accelerator and then out of the exposure area for further processing. The same conductor may be strung up for multiple passes in front of the accelerator or a plurality of the conductors may be strung up for advancement past the window of the accelerator head. In this layout, the window of the accelerator spans the crossover points of the multiple passes of the one conductor or of the several passes of each of the conductors.

Irradiation techniques are used for curing paint on automobile parts to impart outstanding abrasion resistance thereto. Two accelerators are arranged, one above the other, to provide complementary beams which overlap. After one side of the parts is exposed to a beam, the parts are turned through 180° and passed again in front of the accelerator windows to cure and cross-link the paint on the other side of the part.

Multi-accelerator heads have been used to irradiate a coating on parts having a complex configuration, e.g., automobile dashboards. In those applications, the part is conveyed along a path with accelerator heads being at different angles to irradiate differing portions of the part.

In the foregoing described prior art arrangement, if one or more of the accelerators become inoperable or is shut down for repairs, the process become inoperative. This, of course, is a serious drawback where one irradiation facility is used to process conductors from several insulating lines. Since each accelerator is designed to irradiate a specific portion of the part, the demise of that accelerator precludes irradiation of the associated portion of the part.

Still other techniques involve the use of two accelerators arranged in alignment to oppose one another to irradiate a coated sheet (see U.S. Pat. No. 3,501,390). This may suffice where the coated sheet proximates the size of the window. However, in the irradiation of conductors or other strand material, this arrangement of accelerators would tend to overheat the opposing windows which are made of a very thin material.

The prior art also includes irradiating conductors in which the string-up pattern is run lengthwise of the longest dimension of the accelerator window. This causes the entire pattern to be constantly exposed to the window of the accelerator, but may cause some problems in process control.

The prior art includes arrangements for irradiating an elongated material run transversely of the accelerator window. For example, as disclosed in U.S. Pat. No. 3,330,748, polyethylene plies are repeatedly passed through a beam of high energy radiation. Each successive pass of a given section is subjected to a different intensity of irradiation than in the immediately previous pass through the same beam. By the time a given section of the material finally leaves the irradiation zone, it will have an accumulated dose equal to the sum of the movements it has been received in each ply depth. Also, as shown in U.S. Pat. No. 3,676,249, a composite sheet is advanced in loops such that the one loop is adjacent an accelerator window with each successive loop being spaced further from the window. The lineal paths of the sheet between the rolls are either transverse of the window or parallel thereto.

Summary of the Invention

It is an object of this invention to provide methods of and apparatus for irradiating strand material.

It is still another object of this invention to provide methods of and apparatus for moving strand material relative to multiple facilities for electron beam radiation to uniformly dose the insulation of the strand material while optimizing the use of the beams thereof.

With these and other objects in mind, the present invention contemplates the stringing-up of a strand material in a path, directing a first electron radiation beam toward the path and into engagement with the strand material, while directing a second beam toward the path and into engagement with the strand material without overlapping the first beam, and advancing the strand material along the path to expose the insulation to the first and then to the second beams to substantially uniformly dose the insulation. The advancing is accomplished to periodically reverse the direction of travel and to rotate the strand material about the longitudinal axis thereof as it is being advanced.

More particularly, at least first and second accelerators suitable for irradiation cross-linking conductor insulation are arranged to have the windows thereof facing each other but staggered from each other so as not to overlap each other and with the axes of the windows being parallel. A plurality of twisted conductors are strung up to form a plurality of superimposed modified figure eight paths with corresponding portions of the paths being adjacent the first accelerator and with other corresponding portions of the paths being adjacent the second accelerator. Each of the twisted conductor pairs are advanced transversely of the windows to expose the conductors alternately to the two beams. The twist of each conductor pair causes the pair to be rotated about the longitudinal axis of the twisted pair as the conductors are advanced in engagement with the stringing-up facilities to equalize circumferentially the exposure of the insulation to the accelerators and obtain a substantially uniformly dosed pair.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects and features of the present invention will be more readily understood from the following detailed description of specific embodiments thereof when read in conjunction with the accompanying drawings, in which;

FIG. **1** is an overall view in perspective and showing an apparatus for carrying out the principles of the invention to irradiation cross-link the insulation of successive sections of insulated conductors;

FIGS. **2A** and **2B** are enlarged cross-sectional views of an insulated conductor in relation to a high energy electron beam from one of the accelerators and then a beam from the other one of the accelerators, respectively, and showing those portions of the insulation which are radiation-dosed by each of the beams;

FIG. **2C** is an enlarged cross-sectional view of an insulated conductor having been exposed to one source of irradiation as in FIG. **2A** and then to the other source of irradiation after and during the turning the conductor about its longitudinal axis as it is advanced;

FIG. **2D** is an enlarged cross-sectional view of a twisted pair of conductors being subjected to irradiation;

FIG. **3** is a plan view showing two electron beam accelerators staggered from each other with the conductor strung up in a simple loop therebetween and showing the associated divergent beams with no overlap of the beams;

FIG. **3A** is a view in elevation partially in section of one of the accelerators in FIG. **3** taken along lines **3A—3A** thereof and showing the conductor in the portion of the path adjacent the accelerator window and that portion of the path removed from the accelerator window by approximately the diameter of a sheave about which the conductor is passed and blocked from the accelerator by the sections of the conductor in the pass adjacent the window;

FIG. **3B** is a plan view of a modified simple loop string up of the conductor;

FIG. **4** is an enlarged view in perspective showing two spaced banks of quadra-sheaves and illustrating the string-up of a twisted conductor pair in a modified figure eight pattern between the sheaves;

FIG. **5** is an enlarged view in perspective showing portions of the two spaced banks of sheaves and illustrating in simplified form the string-up of several loops of a strand material in a figure eight pattern modified to facilitate the periodic reversing of the direction of travel of the strand material;

FIG. **6** is a graph which shows the width of the electron beam of one of the accelerators illustrated in FIG. **1** plotted against the perpendicular distance from the accelerator window;

FIG. **7** is a normalized curve showing the beam width taken at a predetermined distance from the accelerator window plotted against the percent maximum megarad reading;

FIG. **8** is a graph showing the dosage as a percent maximum dose reading plotted as ordinates against the distance along the elongated dimension of the window; and

FIG. **9** is a depth-dose curve in which the ordinates represent the percent maximum megarad reading plotted against depth of penetration of the insulation of successive sections of a conductor being passed a specific distance from the accelerator window.

DETAILED DESCRIPTION OF THE INVENTION

Overall Radiation Facilities

Referring now to FIG. **1**, there is shown an apparatus, designated generally by the numeral **10**, which embodies the principles of this invention, for irradiating the insulation **11** covering (see FIG. **2A**) a conductive element **12** of successive sections of an insulated conductor **13**. The apparatus **10** generally includes facilities for moving successive sections of the conductor **13** in a path adjacent irradiation facilities and for impinging high energy electron beams on successive sections of the conductor.

Each of a plurality of conductors **13—13** (only one being shown in FIG. **1** for purposes of simplicity) is strung up in superimposed modified figure eight paths between sheave banks, designated generally by the numerals **21** and **22**. Dual accelerators, designated generally by the numerals **23** and **24**, which are positioned between the sheave banks **21** and **22**, are used to irradiation cross-link the insulation of the successive sections of the strand material. The accelerators **23** and **24** face in opposite directions with the accelerators being staggered from each other so that the beams thereof do not overlap.

The conductor **13** is advanced in from the left, as viewed in FIG. **1**, into engagement with the sheave bank **21**, then around the sheave bank **22** in the plurality of groups of superimposed figure eight paths. As the conductor **13** is moved from one group of figure eight paths to another, the direction of travel in the figure eight path is reversed. The use of a figure eight path engenders a progressive screwing effect to cause the sections of the conductor **13** to turn about the longitudinal axes thereof to obtain a more uniform dosing of the insulation **11.** In a preferred embodiment, twisted pairs of the conductors **13—13** are irradiation cross-linked. The progressive screwing effect is even more pronounced when using twisted pairs.

Description of Radiation Equipment

Referring now to FIG. **1**, there is shown the electron accelerator **23.** The accelerator **23** is suspended from rollers **26—26** which are supported from which may be moved along the flange of a beam **27.** This facilitates the positioning of the accelerator **23** appropriately with respect to the conductor **13** for a required radiation dosage.

Also, the accelerator **23** includes a scan magnet **28** interposed between an accelerator head **29** and a scan horn **31.** The scan horn **31** is tapered with the largest dimension being removed from the scan magnet **28.** A forward end of the scan horn **31** is covered with a metallic screen **32,** commonly referred to as a window. The window **32** is capable of maintaining a vacuum within the accelerator, yet is thin enough, e.g., 1 mil, to permit electrons to pass therethrough without a great loss of energy.

As can best be seen in FIG. **1**, the window **32** is oriented so that the longitudinal dimension thereof, which is referred to herein as the window length, is substantially vertical. Of course, the orientation of the window **32** in and of itself is not critical. What is important is the position of the window **32** relative to the path of the conductor **13.**

The accelerator **23** is a 400 Kev rated electron beam accelerator having a maximum beam current of fifty milliamperes. A frequency of one hundred cycles per second is used to scan the beam over the window length which is approximately 48 inches. The electron beam is generated in a vacuum and then passed through the 1 mil thick titanium window **32** to impinge on the successive sections of the conductor **13,** the insulation of which is irradiated in an air medium. Such an accelerator is a Dynacote Accelerator Model No. 400–50, available commercially from the Radiation Dynamics Company.

The use of a 400 Kev capacity accelerator **23** represents a departure from those prior art radiation facilities having at least 1,000,000 electron volts capacity. Of course, the use of an accelerator of that capacity generally obviates any concern over the relative positioning of the product and the accelerator within a wide latitude.

Several characteristics were considered in determining the type of accelerator to be used. The voltage required is a function of the product of the density of the insulation **11** being irradiation cross-linked and the thickness thereof. The voltage required is also a function of the thickness of the conductor **13,** the tolerances allowed in dosage variations throughout the insulation **11,** and the distance that the conductor is run from the accelerator window **32.** As the voltage is decreased, a higher percentage of the radiation energy is absorbed by the window rather than being transmitted therethrough. This causes the window **32** to overheat.

Another characteristic considered in determining the source of radiation to be used in the scan length. The scan length is the usable portion of the window **32** over which the radiation is essentially uniformly distributed.

The scan length of the accelerator **23** is dependent upon the number of individual conductors **13—13** that are to be irradiated, the conductor speed through the accelerator, beam rating of the unit, scan frequency of the unit, and the number of conductor passes required in front of the beam.

While the electron beam can be scanned in both the x direction (along the length or elongated axis of the window **32**) and the y direction (along the width or narrow dimension of the window), it is believed that the beam need only be scanned in the x direction. If accelerators of greater capacity are used, it may be necessary to use an x—y scan in order to prevent overheating of the window **32.** The accelerator **23** was chosen to have a window length of approximately 54 inches and a scan length of approximately 48 inches.

By increasing the scan frequency of the accelerator **23,** the number of scan beam hits that a point on the conductor **13** receives per unit time is increased. However, this does not influence the dosing of the insulation **11** at a point since the duration of the beam engagement at that point per beam traverse is decreased. Nevertheless, the faster the rate of scan for a moving product, the more uniform is the dose rate. This occurs because the dose is smeared out. It is desirable that the scan frequency be greater than a certain critical value determined by the speed at which the conductor **13** is moved.

The maximum current allowed in the accelerator **23** is dependent upon the scan length and energy of the electrons due to the physical and electrical properties of the material used for the accelerator window **32.**

The heating of the window **32** limits the maximum beam current. The amount of window heating is determined by the window material, beam voltage (the higher the voltage, the higher the apparent transparency of the window), and the beam current per unit area of window. For example, a current density of 1.2 milliamperes per square inch is the maximum rating for 400 Kev electrons on a 1 mil thick titanium window. The actual beam current needed is determined by the conductor speed, the scan frequency, the required dosage of radiation, the volume of the product, and the required number of passes of the conductor **13.**

It should be noted that in this invention the accelerator **23** is positioned in a shielded enclosure into which the conductor **13** is advanced and then irradiated and then advanced out of the enclosure. It is also within the scope of this invention to use an in-line accelerator in a manufacturing area by utilizing localized shielding.

Radiation Beam and Dosage Considerations

The apparatus **10** is designed to dose uniformly the insulation **11** of the conductor **13** while optimizing use of the accelerator beam. Uniformity in dosing is interpreted to mean a dose between predetermined minimum and maximum values. These values are chosen so that insulation **11** dosed within that range will meet the required physical test requirements, e.g. percent elongation.

Of course, the cross-linking of the monomer with the polyvinyl chloride is a function of the insulation wall thickness and of the composition of the insulation **11.** The accelerator rating and the spacing of the source of radiation from the conductor **13** are also important factors determinative of the total amount of energy absorbed during the exposure time. The exposure time is a function of the line speed.

The conductor speed is a major factor in determining the ultimate capacity of the process. It must not be assumed that the greater the conductor speed the better the process.

The number of conductor breaks may be decreased by using a lower line speed. A reduction in speed results in fewer conductor passes for the same beam current thereby permitting a greater number of conductors to be run past the window **32.** This increases the number of conductor handling systems, but the loss of a string-up would result in a smaller percentage of the total capacity being lost. It can be very costly if the entire operation has to be shut down because a single string-up is such a high percentage of the total capacity. With slower speeds and a greater number of conductors **13—13** being irradiated simultaneously, a conductor break in one of the string-ups would not require shutting down the entire process.

The conductor handling equipment could be simplified for lower speeds. This more than offsets the cost of the extra pay-offs and take-ups. Also, the simplification of the conductor handling equipment allows a reduction in the required floor space. Similarly, the design of all interfacing equipment could be simplified at lower speeds.

Considerations such as these indicate that the irradiation cross-linking of the insulation **11** on the moving conductor **13** is a complex matter. The nature of the product as well as the motion involved require a unique arrangement to successfully irradiate.

Effective beam utilization requires matching the beam to the geometry of the product. This is a controlling factor in determining the manner in which the beam is brough to bear on the product, which in preferred embodiments are an insulated conductor **13** on a twisted pair of conductors. There must be sufficient beam energy to not only penetrate the insulation **11** of the conductor **13** but also to insure a minimum variation of dose with depth.

In order to accomplish this, preliminary investigations, including depth-dose studies, were conducted. The profile of the depth-dose curve varies with the design of the accelerator **23** and depends on such factors as window thickness, window material and the nature of the high voltage supply.

The dosimetry required to plot the depth-dose curves may be accomplished by the quantitative bleaching of blue cellophane as determined by a spectrophotometer standardized against an adibatic water calorimeter. Experiments have been conducted in which pieces of blue cellophane positioned at various points in a grid in front of the window of the accelerator **23** were subjected to radiation. First, the cellophane is positioned at a plurality of points along a line transverse of the window **32** and spaced a predetermined distance therefrom. Then, the procedure is repeated at each of a plurality of lines parallel to the first but spaced at increasingly greater distances from the window **32.** Photometer readings are taken before and after radiation. The reading after radiation is higher because the bleached cellophane is not as opaque, thereby transmitting more light.

The electron beam diverges along both the x and the y coordinate axes, the y axis being that which is transverse the window **32** (see FIGS. **1, 6** and **8**). However, the scattering of the beam in the y direction is negligible near the window **32** but becomes more significant as the distance from the window increases. There are approximately 48 inches of uniform beam intensity at the prescribed distance of the conductor **13** from the window **32.** As the distance from the window **32** increases, the length of beam uniformity increases, but the total dosage decreases.

A depth dose curve (see FIG. **9**) may be constructed at a particular distance from a window surface. On this curve, the abscissa represents the depth of penetration of the insulation **11** in mils. The ordinate represents a relative dose reading with respect to the maximum dose received by the conductor **13** at some specific depth and expressed in terms of percent maximum dose. Of course, the point of maximum beam intensity occurs at the vertical and horizontal center of the window **32** (see FIG. **7**).

The point (or depth) of the highest energy absorption within the insulation **11** can be linearly approximated for different distances from the window surface of the accelerator **23.** The depth of this maximum point of energy absorption decreases with increasing distances from the window **32.** This is an indication that as the electrons travel through the air, the velocity thereof decreases, causing the incident energy to be lower. Also because of this, as the distance from the accelerator window **32** increases to a determinate value, the surface dosage increases with respect to the maximum dose reading within the insulation **11.**

There is a relationship between surface dosage and the perpendicular distance from the vertical and horizontal center of the window **32** for constant beam current and exposure time. For a constant beam current and exposure time, there is a significant change in the energy absorbed within say an insulation having a thickness of say 8 mils. Of course, as the distance from the window **32** increases, the total energy absorbed decreases (see FIG. **9**).

The constancy of the max-to-min dose ratio throughout the thickness of the insulation **11** is an indicator of the uniformity of the irradiation process.

In this discussion, it is assumed that the beam makes a 90° angle with the conductor **13.** However, the accelerator **23** generates a narrow beam of electrons which are scanned electromagnetically over the surface of the window **32.** The scanning distributes the energy to limit the window and conductor heating and to provide a better match to the conductor geometry.

It should also be noted that there is a back reflection of electrons from the copper conductor element **12** perhaps as much as 10% of the incident electrons.

Although the concentration of energy is much greater at distances closer to the window **32,** the beam width adjacent the window is less than that at some distance from the window (see FIG. **6**) "Beam width" connotes beam width taken in a direction of the window width along the y direction. The surface dose per conductor pass decreases for distances greater than approximately ten inches from the window **32.** Presumably, this is due to the energy loss of the electrons in air becoming significant with respect to the total energy of the incident electrons at these distances.

Another factor which could affect the determination of the surface dose per conductor pass is the scattering of the beam in the vertical direction along the length of the window **32.** This could cause a change in dosage depending upon the position of the conductor pass with respect to its position along the length of the window **32.** Since the scanning of the beam is accomplished in the vertical direction, no significant variation in dosage will be noticed unless a conductor pass is outside of the scanning length which is the area of constant dosage in the vertical direction.

In order to determine the energy absorbed within a given thickness of insulation **11** on the moving conductor **13,** the actual exposure time of a point on the insulation must be calculated. Knowing the exposure time and the average surface dose per unit time for a particular conductor speed and distance from the accelerator window **32,** the actual surface dose per pass can be determined.

If equal surface or entrance dose readings are taken for different distances from the window **32,** the curves can be interpreted to determine total energy absorbed by a material. Knowing the surface dose and the energy absorbed at one specific distance from the window **32,** the surface dosage required to equal the total energy absorbed at a different distance from the window may be determined. It must be realized that average distances are being used, and that the distance through which the electrons travel to reach the conductor **13** will vary over the width of the beam. By computing the surface dosage and total energy absorbed, an optimum distance of the conductor **13** from the accelerator window **32** can be determined.

The total energy absorbed by the insulation **11** is proportional to that area under the depth-dose curve (see FIG. **9**). The larger the area under the depth-dose curve the less will be the dose variation and the higher the efficiency of the process. The efficiency is formed by taking the product of the total beam energy absorbed and the minimum relative dose anywhere within the insulation. The degree of beam utilization is the percent of the total beam energy absorbed, and graphically is equal to the area subtended by the product under the depth-dose curve.

Arrangement of Radiation Source and Conductor

Another consideration in attempting to maximize the production capabilities of an irradiation facility is to determine whether the conductor **13** should be passed transversely across the width of the accelerator window **32** (see FIG. **1**) or along the length thereof. The main advantage in running the passes along the length of the window **32** is that the beam exposure time per pass is increased thereby allowing the number of conductor passes per string-up to the reduced. Notwithstanding this, it has been determined that the conductor passes should be run across the width of the window **32.**

The amount of energy that the conductor **13** is subjected to as successive sections are passed across the width of the window **32** is constant over approximately the entire scan length. Therefore, each individual conductor **13** being irradiated can have the same number of passes in front of the accelerator window **32.** The energy distribution transversely across the width of the window **32** varies (see FIG. **7**) drastically. Therefore, for vertical passes, each of the conductors **13—13** being irradiated would have a different number of passes in front of the accelerator, depending on its location with respect to the longitudinal axis of the window **32.**

A change in the electron filament or scanning magnet could shift the point of maximum radiation intensity along the width of the window **32.** This would require changes to be made in the number of passes required per individual conductor if vertical passes along the width of the window **32** were used. Such a change does not affect a string-up using passes across the width of the window **32** since there, the passes are run perpendicular to the direction of the scan.

In addition, difficult alignment problems would be experienced in typing to align conductor passes along the width of the window **32.** In the event of a conductor break, there is a greater probability of the conductor **13** hitting the surface of the window if the passes are along one length. Finally, there is less heating of the insulation **11** for passes transverse of the width of the window **32** since the dosage per pass is less. This will allow more cooling time in the air between consecutive beam exposures.

After it has been decided that the conductor **13** should be passed transversely of the window **32,** the positioning of the source of radiation must be considered in relation to the conductor. The string up pattern of the conductors **13—13** is critical. A single source of radiation could be used with the conductor **13** passed transversely therepast on a one-time basis. The conductor **13** could simply be run as many passes as desired in a simple loop (see FIG. **3**) past the single accelerator **23.**

However, this arrangement would not result in the insulation being uniformly dosed. As can best be seen in FIG. **3A,** the conductive element **12** of the section of the conductor **13** adjacent the window **32** substantially precludes the irradiation cross-linking of the portion A_1 of the insulation directly therebehind. Also, although the portion A_1' is exposed to the accelerator **23** on the return pass of the conductor **13,** it is removed from the window **32** by the diameter of the engagement surface of the sheave bank **21.**

Of course, a modified simple loop arrangement shown in FIG. **3B** could be used to irradiate some portions of A_1 and A_1'. This may be done by passing the conductor **13** over opposed sheaves **25—25** positioned between the sheave banks **21** and **22.** In this way, portions of the loop are converging so that the accelerator **23,** for example, may more effectively irradiate all of the insulation except portion A_1 on the near pass and then most all of the insulation, with a lower dose rate, except the portion A_2, on the far pass.

The figure eight pattern of the process described under the prior art hereinbefore could be used but only if the single accelerator **23** were placed adjacent the crossover points. As can be seen from FIG. **4** in tracing the path of the conductor **13,** if the single accelerator **23** were placed elsewhere with respect to a figure eight path, then portions of the insulation would not be uniformly irradiation cross-linked.

It is possible to use a single source of radiation to irradiate the conductor **13** as strung up in a pattern which contains a combination of the simple loop of FIG. **3** and the figure eight pattern. In this arrangement, a plurality of superimposed single loops such as that in FIG. **3** are run transversely of the window **32.** Then, at approximately the midpoint of the length of the accelerator window **32,** the conductor **13** is advanced through a single figure eight path and then back into a plurality of simple loops in the remainder of the window length. This causes the direction of travel of the conductor 13 in the latter plurality of loops to be in a reverse direction from those associated with the other half of the window **32.**

Dual accelerators could be used in an attempt to more uniformly dose the insulation **11.** Even then, if the conductor 13 was simply looped in an elongated closed loop about the sheave banks 21 and 22 (see FIG. 3), only the outwardly facing portions of the successive sections of the conductor 13 would be dosed by the dual accelerators. The inwardly facing portions of the insulation 11 would go undosed.

This occurs since the same portion of the insulation 11 of the conductor **13,** with respect to a vertical plane parallel to and through the longitudinal axes of the successive sections of the conductor would be adjacent the window 32 and then adjacent the window. This problem is not present in the curing of paint on components or the irradiation of webs of material where there is no metallic element which effectively acts as a shield to block the irradiation of material therebehind.

Although the conductor insulation 11 is sufficiently thin to permit single sided irradiation, the shadow cast by the opaque copper conductor 12 necessitates the passing of the conductor repeatedly under a beam as in a figure eight path in such a way that both sides of the conductor are exposed to the beam. This can be done using the two accelerators 23 and 24 with a modified figure eight string-up (see FIGS. 1 and 4).

Dual accelerators are used in order to avoid shutting down the line in the event of malfunction of an accelerator and in order to achieve a uniformly dosed insulation. By using two staggered accelerators, the accelerator 23 and the other accelerator **24,** which is identical to the one accelerator, the reliability within the system is enhanced. In the event mechanical problems are experienced with one of the accelerators 23 and **24,** the other one of the accelerators may be used with a higher beam current or the conductor 13 advanced at a slower speed to maintain the same energy absorption level. It should be observed from FIG. 1 that the designation of the elements of the accelerator 24 is that of the corresponding element of the accelerator 23 advanced by ten.

If the properties of the resultant insulated conductor 13 are dose-related, then every lineal inch and every degree of circumferential surface of the successive sections of the conductor must receive at least a minimum dose of radiation. This is accomplished by the method of advancing the successive sections of the conductor 13 with respect to the stationary accelerators 23 and **24.** Or in the alternative, relative motion must be caused to occur between the accelerators 23 and 24 and the conductor 13 in such a way that each portion of the conductor insulation 11 is exposed to at least a minimum amount of radiation.

The two accelerators 23 and 24 are also positioned in order to avoid damaging each other. The window 32 is comprised of a thin material capable of being transparent to electrons. During the acceleration process, the temperature of the window rises due to the friction of the electrons in engagement with the material of the window. Care must be taken to avoid putting in more heat to the window than is taken out. A window **32-to-**window 42 confrontation must be avoided to avoid overheating of the windows. This is accomplished by staggering the accelerators 23 and 24 as along a path

between the two sheave banks 21 and 22 (see FIG. 1) with the conductor 13 being passed between the sheave banks.

The positioning of the accelerators 23 and 24 with respect to each other and with respect to the path of the conductor 13 is of utmost importance. Path in this invention is defined as the continuous course travelled by successive sections of the conductor 13 and which may include a plurality of superimposed loops. It may be observed from FIG. 1 that the accelerator 23 is displaced or staggered a predetermined distance *d* from the accelerator 24 with the windows 32 and 42 thereof facing in opposite directions.

Thought must also be given to the amount of the lateral offset of the two accelerators 23 and **24.** As has been mentioned hereinbefore, the bean of high energy electrons emitted from the accelerator window diverges. The accelerators 23 and 24 are positioned with respect to each other such that the divergent beams do not overlap (see FIG. 3). Desirably, the positioning is such that the adjacent boundaries of the two beams are substantially coincident.

Overlap is defined to mean where two sources of radiation may be stacked one above the other or side by side and that a portion of the space adjacent the sources is dosed by overlapping portions of both beams. Overlap is also intended to define the situation in which opposing beams impinge on one another.

Experiments have also been conducted to determine the optimum spacing of that portion of the conductor path adjacent each of the accelerators from the windows thereof. Then, the lateral offset of the accelerators 23 and 24 and the diameter of the sheave engagement surfaces are determined so as to avoid any overlap of the radiation beams.

Increasing the exposure time per pass will increase the efficiency of the dosage per pass for the accelerators 23 and **24.** This can be accomplished by moving the conductor passes across the width of the windows 32 and 42 at an angle to the beam pattern. Of course, if the accelerators 23 and 24 are positioned adjacent one of the loops of the figure eight pattern, then at least a portion of the path of the conductor 13 is at an angle to the window **32.**

In the preferred embodiment, a plurality of conductors 13-13 may be simultaneously passed between the staggered accelerators 23 and 24 and strung between the sheave banks 21 and **22.** Of course, the line speed and the proximity of the accelerators 23 and 24 to the plane of the sheave banks 21 and 22 must be adjusted to compensate for that exposure achieved by using the multiple pass pattern.

Consideration must be given to the string up details between the sheave banks 21 and **22.** The objective is to overcome certain problems and obtain a uniform dosing of the insulation 11 while irradiating a plurality of the conductors 13—**13.** For example, it would appear that each of the accelerators irradiates at least a partially different portion of the insulation **11.** As the conductor 13 is advanced past the accelerator **24,** all of the insulation 11 except an area designated A_3 (see FIG. 2A) is irradiated. The area A_3 is the portion of the insulation essentially shielded by the conductive element **12.** Then, as the conductor 13 is advanced past the accelerator 23 (see FIG. 2B), the area A_3 is irradiated but an area A_4, now shielded from the accelerator **23,** is not irradiated. This would appear to cause portions of the insulation 11 to be dosed by both of the accelerators **23** and **24** while other portions thereof are dosed only by one of the accelerators.

There are other problems peculiar to irradiation cross-linking the insulation **11** of the conductor **13** having a circular cross-section. The insulation thickness varies along chordal lines with respect to the direction of the incident electrons. Also, the conductive element **12** causes some back scattering of electrons and creation of X-rays which could change the characteristics of the depth-dose curves.

STRING-UP OF STRAND MATERIAL

The string-up of the strand material with respect to the accelerators **23** and **24** will now be described. Strand material is intended to define an elongated material may, for example, include one or more insulated conductors **13—13**.

In order to maximize the efficiency of the insulation irradiation process, the arrangement of the conductor **13** must be coordinated with the accelerators **23** and **24**. The use of the beam energy is maximized not only by the foregoing arrangements but also by spacing the figure eight patterns in front of the windows **32** and **42** as close as possible to each other. This is of help in minimizing the amount of beam energy impinging on space unoccupied by the conductors **13—13**. The precise spacing is, of course, a function of the diameter of the insulated conductor **13** and the physical dimensions of the sheave banks **21** and **22**. However, the dimensions of the sheave banks **21** and **22** can be controlled by grooving portions thereof instead of using individual sheaves for each conductor turn.

By coordinating the available beam current and the physical size of the sheave banks, the maximum number of conductors **13—13** that can be physically placed along the scan length of the accelerator window **32** can be determined. There are a number of combinations, within the limits of the beam rating of the accelerators **23** and **24**, in which the conductor speed and the number of conductor passes in front of the accelerators can be varied to obtain the required dosage on the conductors **13—13**. The only criteria on conductor passes is that a minimum number must be allowed to guarantee against dose variation within the insulation **11**. Even this requirement is not a critical one since most of the physical property requirements of the insulation of the conductor **13**, e.g., solder heat resistance, abrasion resistance, adhesion and plastic elongation, are permissive of some variations within the insulation thereof.

A delicate balancing must be achieved between the properties desired in the final product and the number of sheaves over which the conductor **13** is passed. From one standpoint, it is desirable to pass the conductor **13** over as many sheaves as possible in order to be able to more uniformly dose the conductor. Also, by making multiple passes throughout the height of the windows **32** and **42**, it is possible to use a higher line speed. On the other hand, the more sheaves over which the conductor **13** is passed, the greater the degree of work hardening of the conductive portion **12** which had priorly been annealed. This consideration then would tend to cause a reduction in the number of sheaves.

The remainder of the apparatus **10** is concerned with the facilities for guiding successive sections of the conductor **13** along a predetermined path relative to the windows **32** and **42** of the accelerators **23** and **24**, respectively. These facilities include the bank **21** of sheaves **51***a*–**51***e* and the bank **22** of sheaves **52***a*–**52***e*

mounted rotatably individually on spindles **53** and **54**, respectively (see FIG. **4**).

Each of the sheaves **51** and **52** are quadra sheaves each having four grooves formed therein. The quadra sheaves may be replaced with four thin pulleys (not shown). It should also be noted that the sheaves **51** and **52** are not driven, but rather are turned by the successive sections of the conductor **13** being pulled thereover.

Referring now to FIG. **4**, it can be seen that the quadra sheave **51***a* has four grooves, **56***a*, **56***b*, **56***c* and **56***d*, formed therein. The quadra sheaves **51***b*–**51***e* each have four grooves **57***a*–**57***d*, **58***a*–**58***d*, **59***a*–**59***d* and **61***a*–**61***d* formed therein, respectively. On the other bank **22**, the quadra sheaves **52***a*–**52***e* have grooves **62***a*–**62***d*, **63***a*–**63***d*, **64***a*–**64***d*, **66***a*–**66***d* and **67***a*–**67***d* formed therein, respectively.

Each group of the quadra sheaves associated with one of the conductors **13—13** could be mounted independently of the quadra sheaves associated with other ones of the conductors. In this way, conductors **13—13** having varying insulation, both as to diameter and composition, may be passed through the beams at differing speeds.

Only a portion of each window **32** and **42** need be allocated to one of the conductors **13—13**. Sufficient passes of one of the conductors **13—13** may be made past that portion of the window **32** and **42** to satisfy the dosage requirement. This, of course, permits the use of the remaining portions of the windows **32** and **42** for the radiation of plural passes of additional conductors **13—13** and optimizes beam utilization.

Eight conductors **13—13** are simultaneously moved back and forth past the windows **32** and **42**. The effective window length, as measured along the elongated dimension thereof is approximately four feet. Approximately 6 inches of each window **32** and **42** are allocated to each of the conductors **13—13**. Each 6 inches is distributed among five of the quadra sheaves **51***a*–**51***e* and associated sheaves **52***a*–**52***e* (see FIG. **4**). Each set of five quadra sheaves **51***a*–**51***e* and **52***a*–**52***e* are associated with one of the conductors **13—13** and provide forty passes of each conductor past each accelerator.

The conductors **13—13** are strung up about the sheave banks **21** and **22** (see FIG. **1**). The sheave banks **21** and **22** which are mounted on the spindles **53** and **54**, respectively, are spaced apart a distance greater than that by which the scan horns **31** and **41** are staggered. In this way, successive sections of the conductors **13—13** are advanced in a path transversely of the window **32** and of the window **42**.

In one string-up pattern, each of a plurality of conductors **13—13** are advanced in toward the first sheave bank **21**, over a top most sheave **51***a* (see FIGS. **1** and **4**), then in the figure eight path transversely of the windows **32** and **42** and in a groove **62***a* the associated sheave **52***a* in the sheave bank **22**. Then the conductor **13** is advanced back past the windows **42** and **32**, around the groove **56***b* in the sheave **51***a* and continuously in a figure-eight pattern until the conductor is advanced out of engagement with the groove **67***d* of the bottom most sheave **52***e*.

As can be seen in FIG. **5**, the conventional figure eight pattern is modified such that as the successive sections of the conductor **13** are removed from one level or one of the quadra sheaves to the next one of the quadra sheaves, there is a straight (designated *s*), as opposed to a diagonal path, between the spaced sheave banks **21** and **22.** In other words, the pass *s* is parallel to a line intersecting the axes of the spindles **53** and **54** and normal thereto.

This causes the successive sections of the conductor **13** to be moved in a figure eight pattern in that next level to be in a reverse direction as that in the preceding level. As a result, the irradiation of the insulation **11** of the successive sections of the conductor **13** tends to become more uniform. Since the paths of the wires in alternate figure eight patterns are in opposite directions, alternate ones of the sheave sets are turned rotatably in opposite directions.

In the above arrangement, some portions of the insulation **11** appear to be dosed by both accelerators **23** and **24** while other portions are dosed effectively by only one accelerator. Referring now to FIG. **2A,** it can be seen that as successive sections of the conductor **13** are advanced past the accelerator **23,** all of the insulation except that portion, designated A_3, is exposed to irradiation. Of course, the exposure of that portion of the insulation **11** closest to the associated accelerator **24** is subjected to the greatest dosage.

Then, when the successive sections of the conductor **13** are advanced around the associated one of the sheaves **52—52,** the insulation, including portion A_3 (see FIG. **2B**), is exposed to the window **32** of the accelerator **23.** However, during this part of the process, there is a portion, designated A_4 horizontally behind the conductive element **12,** which although irradiated by the accelerator **24** is not exposed to the accelerator **23.** This assumes that the conductor cross section is oriented rotationally the same with respect to the accelerator **24.** If this were true, then the portions A_3 and A_4 of the insulation **11** would have not received the same double dosage of irradiation which the other portions of the insulation have received.

It should be appreciated that even under this apparent explanation of the dosing of the irradiation, after the conductor **13** has been passed around the sheave bank **22,** the portion A_3 may be exposed to some radiation since it now is on the near side with respect to the accelerator **24.** This also occurs in the portion A_4 of the conductor with respect to the accelerator **23** after the conductor has been passed around the sheave bank **21.** Nevertheless, the dosage so received by A_3 and A_4 on the return passes is generally negligible and would not result in equalizing the dosage.

The problem of uniformly dosing a strand material having a metallic element centrally disposed therein is not one encountered in the prior art radiation of components. The conductive element **12** is opaque to the radiation beam but the insulation **11** is translucent thereto. Only x-rays pass through the conductive element **12** and these are ineffective to cross-link the insulation **11** therebehind. The exposure of the insulation **11** to dual sources of radiation causes a summing effect to occur.

It should be realized that while the principal embodiment therein is concerned with uniformly dosing the insulation **11** throughout the cross-section thereof, that this invention is not so limited. The use of two or more accelerators together with the string-up and handling of the conductor **13** may be used to uniformly dose the surface of the conductor.

To substantially eliminate the dose variation, the insulated conductor **13** must be turned about the longitudinal axis thereof as it is passed adjacent the accelerator windows **32** and **42.** This may be accomplished by canting alternate ones of the sheaves **51—51** and associated ones of the sheaves **52—52.** For example, the sheaves **51a** and **52a** are canted in one direction and the sheaves **51b** and **52b** in another direction. The choice of cant angles determines the amount of turning of the conductor **13.** Then, as the conductor **13** advances around the sheaves **51—51** and **52—52,** it is turned about the longitudinal axis thereof.

This causes sequentially different circumferential portions of the insulation to be presented to the accelerator **23** as the conductor **13** is advanced therepast and to the accelerator **24** (see FIG. **2C**). Moreover, different portions of the insulation are presented to the accelerators **23** and **24** as between successive figure eight patterns. This causes a more uniform distribution of dosage of radiation.

It will be recalled that from FIG. **2B** the portions A_3 and A_4 (diameterically opposite to one another) which effectively are dosed only by the accelerators **23** and **24,** respectively. By causing longitudinal turning of the sections of the conductor **13,** portions A_3 and A_4 are no longer necessarily diameterically opposite to one another.

This is shown in FIG. **2C** which illustrates the conductor **13** after having been irradiated by the accelerator **24** and then being irradiated by the accelerator **23.** During exposure to the accelerator **24,** the portion A_3 is not irradiated while the portion A_4 is irradiated. This is similar to the exposure pattern shown in FIG. **2A.** Without the longitudinal turning, the portion A_3 and A_4 would be oriented as shown in FIG. **2B** with respect to the accelerator **23.** However, as shown in FIG. **2C,** the turning of the conductor **13** as it is advanced from the accelerator **24** to the accelerator **23** causes the diameterically opposed portions A_3 and A_4 to assume an orientation relative to accelerator **23** which is at same angle other than 90° to the X-axis of the window **32.**

This causes different diametrically opposed portions A_3' and A_4' to be oriented normal to the x-axis of the window **32.** In this way, only a small portion of thee area A_4 may not be dosed by the conductor **23.**

This causes a greatly improved distribution of the energy absorbed and promotes uniformity of irradiation cross-linking.

Of course, the facilities are arranged such that the longitudinal turning of the conductor **13** does not successively present the conductor **13** in the same orientation to the dual accelerators **23** and **24** in the same irradiation cycle.

The canting of the sheaves **51—51** and **52—52** may only be necessary when a simple loop string-up pattern such as that shown in FIG. **3A** is used for a single conductor **13.** It has been observed that when a single conductor **13** is moved in a figure eight pattern over uncanted sheaves, a "progressive screwing" effect occurs. This is similar in effect to the canted sheave arrangement and causes successive sections of the conductor **13** to be turned about the longitudinal axes and present sequentially different portions of the insulation **11** to the window **32** as the conductor is advanced therepast and similarly to the window **42.**

Also, it should be noted that the amount of longitudinal rotation of the conductor **13** in the figure eight string-up is limited. For example, in one pass as between the sheave banks **21** and **22,** the conductor **13** may be rotated between one-quarter to one-half revolution. Nevertheless, this has been found adequate to be a factor in achieving uniform dosing of the insulation 11.

It should be realized that because of this longitudinal rotation, the areas A_3 and A_4 in FIG. 2C would not be defined as precisely as shown. Of course, if the rotation between the sheave banks 21 and 22 is limited, the rotation of the conductor 13 as it traverses the windows 32 and 42 is substantially negligible.

The longitudinal turning or progressive screwing of the conductor 13 is in one direction as the conductor is moved along the path between associated ones of the sheaves 51 and 52. Then when the conductor 13 is moved to the next associated pair of sheaves 51 and 52 to reverse the direction of movement thereof, the direction of rotation is also reversed.

The rotation of the successive sections of the conductor 13 is synchronous with the advancement of the conductor. It is possible that the use of a single accelerator with a figure eight pattern could result in the non-exposure of some portions of the insulation 11 to the radiation beams because of the scanning. Of course, the deployment of the dual accelerators 23 and 24 about the path and the use of the multiple passes of a modified figure eight string-up avoid this possible problem. The use of dual accelerators, a modified figure eight string-up and the provision for turning the sections of the conductor 13 about the longitudinal axes thereof result in cylindrical symmetry of the radiation dose.

IRRADIATING TWISTED PAIRS

In the foregoing arrangement, after the conductor 13 has been passed between the accelerators 23 and 24 to irradiation cross-link the insulation 11, pairs of the conductors must be twisted together prior to the construction of a cable or twisted pairs of distributed frame wire (not shown). Conductors 13—13 which have been subjected to radiation are somewhat more difficult to twist together than those which have not been.

It would be desirable to pass already twisted pairs of the conductors 13—13 through the radiation beams. In this way, not only is the twisting facilitated but also the capacity of the irradiation facilities is substantially doubled. Another benefit accrues in that the irradiation cross-linking of insulation 11 on twisted pairs of conductors 13—13 tends to set the twist to maintain the twist length during subsequent manufacturing operations.

Of course, this is subject to being able to uniformly dose each conductor 13 of the twisted pair. It has been found that not only is a uniform dosing accomplished, but that the uniformity is improved over that of the single conductor used in a figure eight pattern or the canted sheave arrangement. In fact, when the irradiated twisted pair of conductors 13—13 was checked for solder heat resistance, no portions of the insulation 11 were found to be substantially less resistant than others. This was true also for the portions of the insulation 11 in engagement with each other at the twist crossover (see FIG. 2D).

The uniformity apparently occurs because as the twisted pair of conductors 13 is advanced around one of the associated sheaves 51—51 and 52—52, the engagement of the twisted pair with the sheave causes the twisted pair to be turned or rolled about the longitudinal axis thereof. An accentuated progressive screwing occurs because the effect of the twisted pair of conductors 13—13 is additive to the turning caused by the figure eight path about the sheave banks 21 and 22. The forty passes of each of the twisted pairs between the accelerators 23 and 24 causes each of the twisted pairs to be constantly rotated longitudinally to sequentially expose differing or overlapping portions of each conductor 13 of each pair to the high energy radiation.

It should also be noted that there is no loss in capacity due to the irradiation of twisted pairs of the conductors 13—13. The same length windows 32 and 42 which were used to irradiate simultaneously the insulation of eight single conductors 13—13 may also be used to irradiate eight twisted pairs of conductors using repetitions of the sheave arrangement shown in FIG. 4.

The irradiation of the insulation of twisted pairs also is of help in overcoming certain manufacturing problems. For example, a twisted pair is capable of withstanding greater tension than a single conductor. Hence, there is less chance for wire breaks with accompanying down time for restringing.

It should be realized that a change in gauge size of the conductive element 12 of each conductor 13 does not generally require a change in line speed. This is true providing that the thickness of the insulation 11 does not change. If the insulation wall thickness is increased, the line speed is reduced or the beam voltage could be increased; if the thickness is decreased, the speed can be increased or the voltage decreased. Combinations of these adjustments may also be made in the event of a change in wall thickness.

In the herein-described arrangements of irradiation facilities and conductor string-up, the dosing varies with depth with respect to the insulation cross-section. This is true for each rotational orientation of the cross-sectionoof the conductor (see FIG. 9). Because of the exposure to multiple irradiation sources, the use of multiple passes and the turning about the longitudinal axes of the sections, it has been found that there is substantial uniformity in the dosing.

The uniformity is achieved longitudinally with respect to successive sections of the insulation 11 and is such that every unit of insulation volume receives a dose falling within predetermined limits required to impart required properties to the insulation. There is also circumferential uniformity of dosing about concentric circles which in a polar plot are spaced from the center of the conductor at radii corresponding to the dose. Under the conditions of FIG. 9, the circles begin with that corresponding to the surface of insulation 11, generally become larger to a circle of maximum radius corresponding to maximum dose, and then become smaller.

It is to be understood that the above-described embodiments are simply illustrative of the invention and that many other embodiments can be devised without departing from the scope and spirit of the invention.

What is claimed is:

1. A method of irradiation cross-linking the insulation of a plurality of conductors, which includes the steps of:

directing a first electron radiation beam toward and into engagement with a plurality of conductors each of which is strung up in a path between spaced conductor engagement surfaces which includes a plurality of repetitive superimposed spaced apart layers, each of the layers having a figure eight configuration, the beam being directed through a window toward a corresponding portion of one loop of each of the layers; while directing a second electron radiation beam through a window toward the path and into engagement with a corresponding portion of the other loop of each of the layers without overlapping the first beam in the vicinity of the layers, the windows being spaced from the conductors a distance substantially greater than the external diameter of the insulated conductor, the beams being oriented with respect to the superimposed adjacent layers such that each layer is exposed to substantially the same radiation dose; and

advancing the conductors along each of the layers to expose sequentially different rotational orientations of the insulation to the first and to the second electron beams thereby causing perturbation of the angle of incidence of the beams on the conductors to uniformly dose the insulation thereof substantially by exposure to direct radiation from the first and second electron radiation beams.

2. The method of claim **1**, wherein the insulation of each of the conductors is uniformly dosed throughout the cross-sectional area thereof.

3. The method of claim **1**, wherein twisted pairs of conductors are strung up in the path around spaced engagement surfaces with the radiation beams positioned therebetween, the engagement of the conductors with the engagement surfaces as the conductors are advanced being effective to cause the pair to be turned about longitudinal axes thereof to cause the insulation to be uniformly dosed and cross-linked.

4. The method of claim **1**, wherein the beams are directed in substantially opposite directions, the beams being staggered along the paths, the first one of the beams directed toward corresponding portions of one loop of each of the figure eight paths and the second beam being directed toward corresponding portions of the other loop of each of the figure eight paths.

5. An apparatus for irradiation cross-linking the insulation of each of a plurality of conductors, which includes:

means including spaced conductor engagement surfaces for stringing up each of a plurality of conductors in a path which includes a plurality of superimposed spaced layers each having a figure eight configuration, the path associated with each conductor including a pass parallel to the line joining the axes of rotation of the spaced surfaces to cause each of the conductors to be moved in opposite directions in the layers adjacent the pass parallel to the line joining the axes

means including an elongated window having a longitudinal axis for directing a first electron radiation beam toward the paths and into engagement with the portions of the conductors forming one loop of each of the figure eight layers;

means including an elongated window having a longitidinal axis for directing a second electron radiation beam toward the paths and into engagement with the conductors forming corresponding portions of the other loop of each of the figure eight layers without overlapping the first beam in the vicinity of the layers, each beam being oriented with respect to the superimposed adjacent layers such that each layer is exposed to substantially the same radiation dose, the paths of the conductors being transverse of the longitudinal axes of the windows, further the windows being spaced from the conductors a distance substantially greater than the external diameter of the insulated conductors; and

means for advancing each of the conductors along the associated path to expose sequentially different rotational orientations of the insulation to the first and to the second electron beams to uniformly dose the insulation substantially by direct radiation of the first and second electron radiation beams.

6. The apparatus of claim **5**, wherein the insulation of each of conductors is dosed uniformly throughout the cross-sectional area thereof.

7. The apparatus of claim **5**, wherein twisted pairs of conductors are advanced, the engagement of each of the twisted pairs with the associated engagement surfaces as the twisted pair is advanced being effective to cause the twisted pair to be turned about the longitudinal axes thereof.

8. The apparatus of claim **5**, wherein the surfaces include two spaced banks of sheaves with the coaxial axes of the sheaves being parallel to the longitudinal axes of the windows and radiation means are positioned between the two banks of sheaves with the beams being directed in opposite directions, the radiation means staggered to direct a first one of the beams toward corresponding portions of one loop of each of the figure eight paths and the second beam being directed toward corresponding portions of the other loop of each of the figure eight paths, the beams being oriented with respect to the superimposed adjacent layers such that each layer is exposed to substantially the same radiation dose.

* * * * *