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Link et al.

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[54] **METHOD AND APPARATUS FOR IRRADIATION TREATMENT OF ELONGATE MATERIALS**

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[73] Assignee: **Applied Radiation Corporation,** Walnut Creek, Calif.

[22] Filed: **Feb. 24, 1969**

[21] Appl. No.: **824,016**

[52] **U.S. Cl.**..........**250/49.5 TE,** 219/121 EB, 250/52
[51] **Int. Cl.**..**H01j 37/00**
[58] **Field of Search**.......204/159.2; 264/26; 219/121 EB; 250/49.5

[56] **References Cited**

UNITED STATES PATENTS

2,897,365 7/1959 Dewey et al..........................250/49.5
2,994,801 8/1961 Hanks.............................219/121 EB

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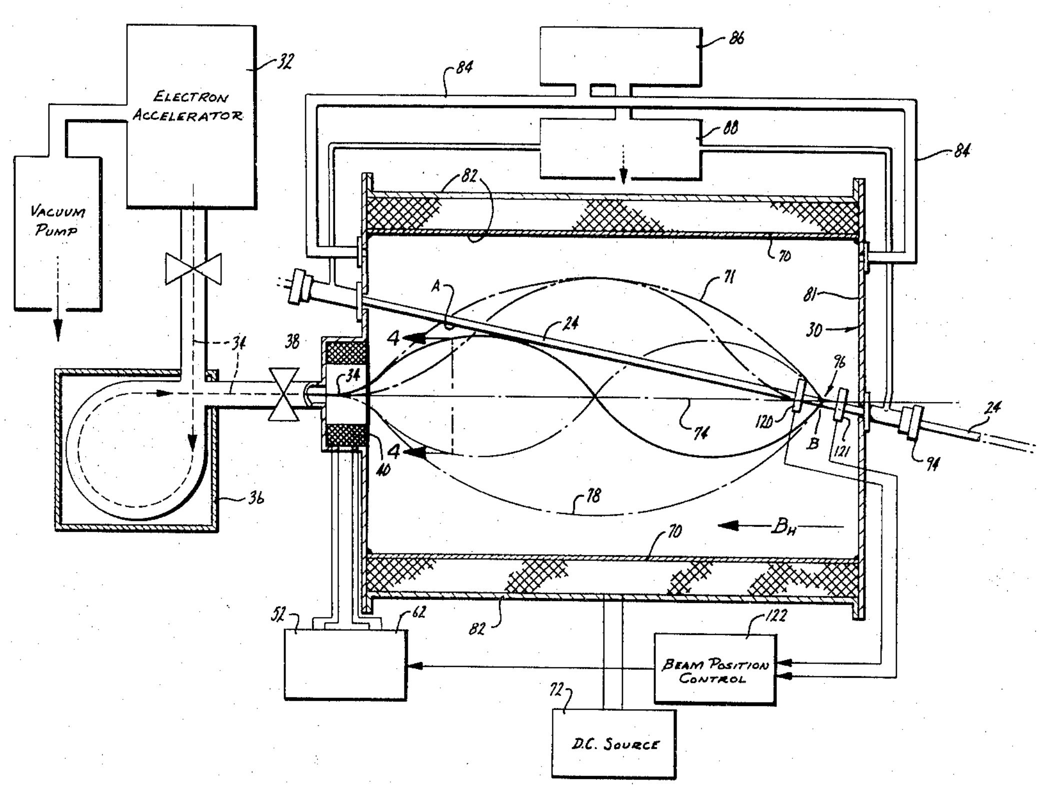
This Application Filed Under Rule 47b

[57] **ABSTRACT**

An irradiation method and apparatus in which an electron beam is diverted along a path which is caused to rotate about the beam axis and to intersect and sweep about a cone directed through the target to be irradiated and to thereby enter the target at an oblique angle. Apparatus is disclosed for causing the beam to take a rotating helical path and for passing the target through the imaginary apex of the cone shaped irradiation pattern of said rotating beam. Other apparatus is disclosed for coaxial irradiation from within hollow tubular targets and is particularly adapted for the irradiation of plastic tubing at the time of extrusion.

6 Claims, 13 Drawing Figures



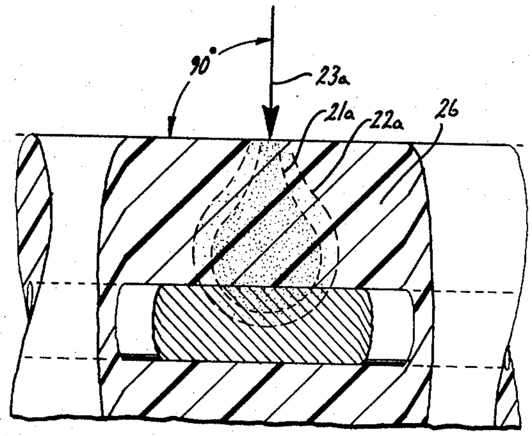


Fig. 1A

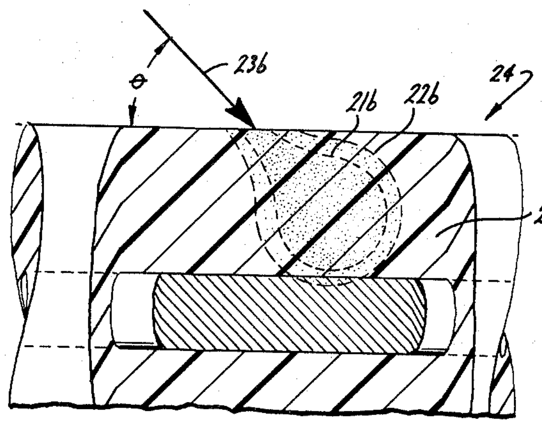


Fig. 1B

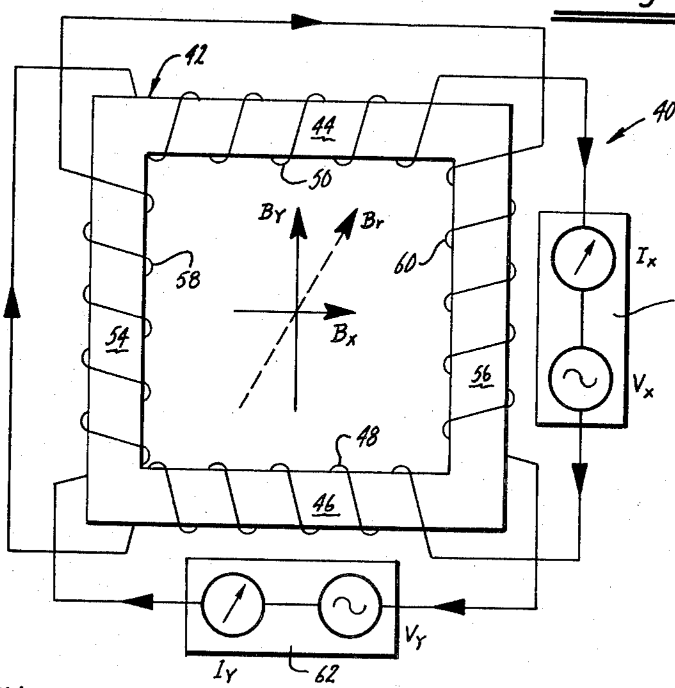


Fig. 4

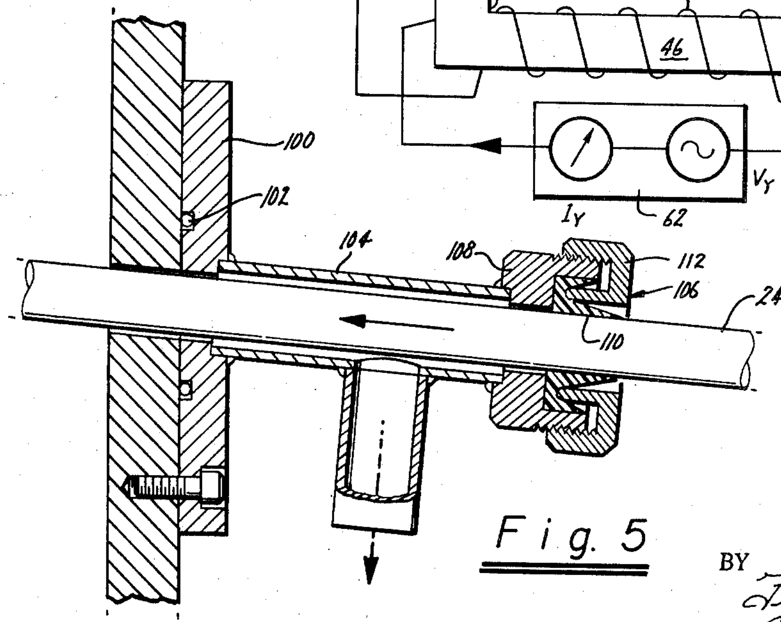


Fig. 5

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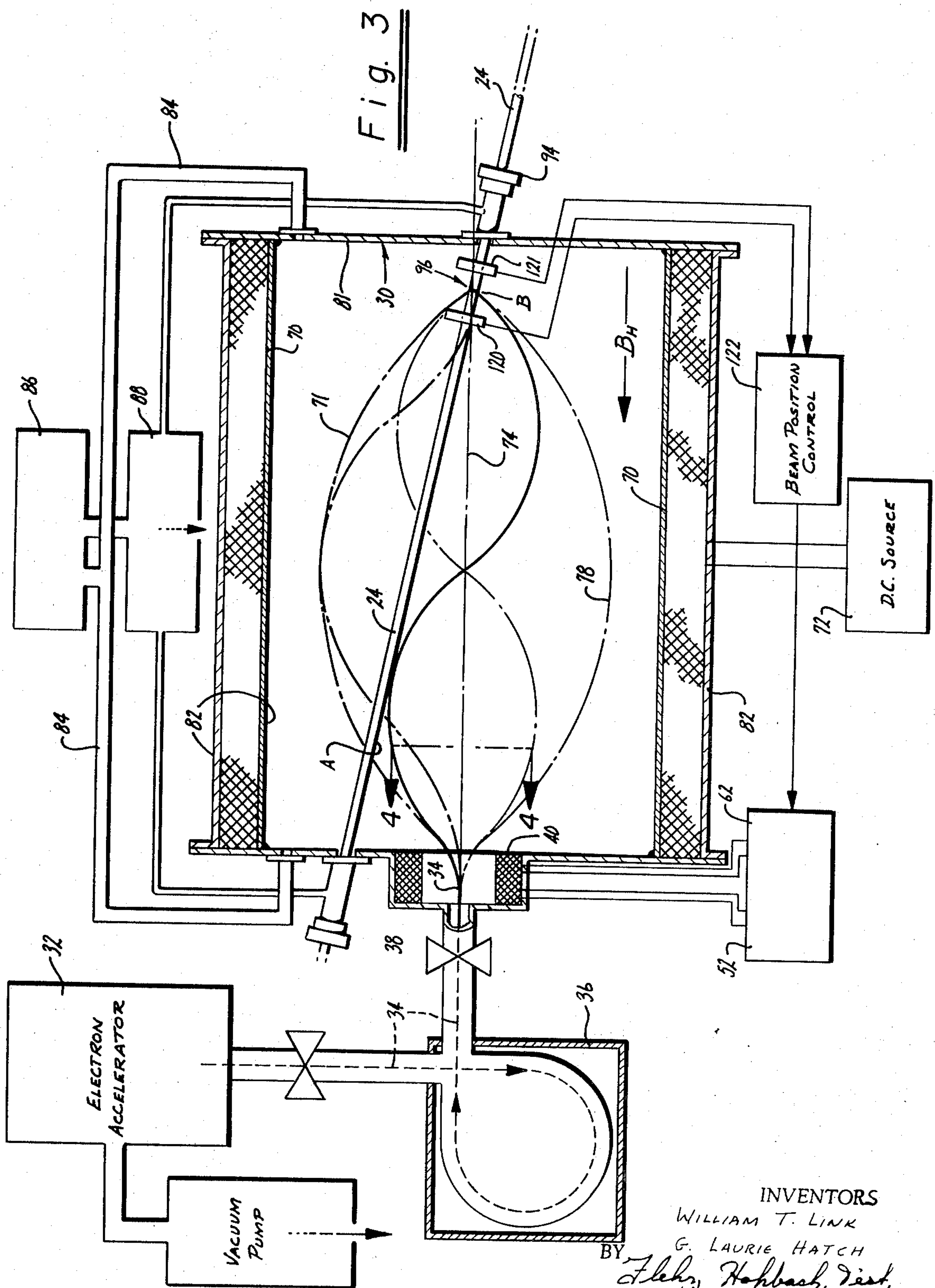

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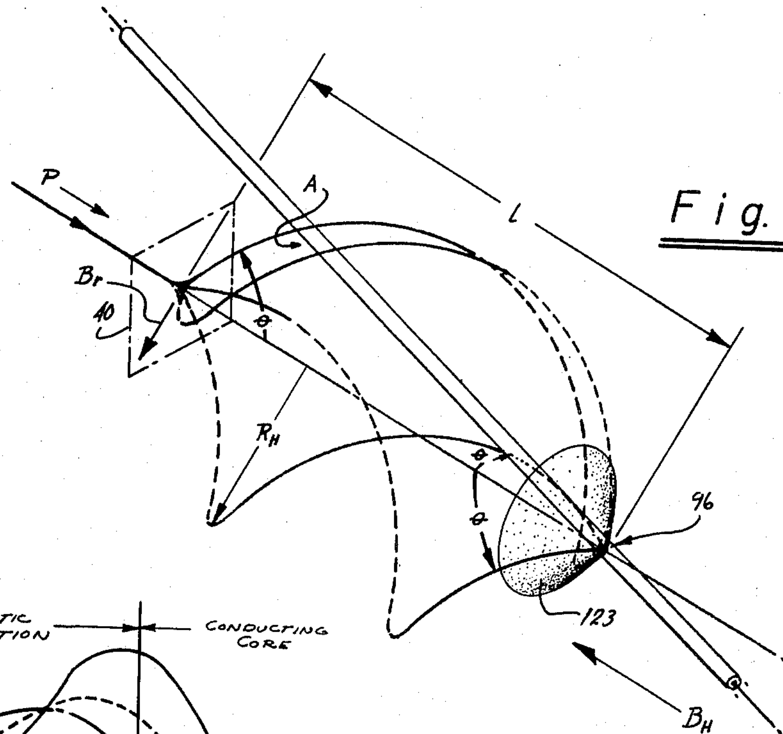

Fig. 6

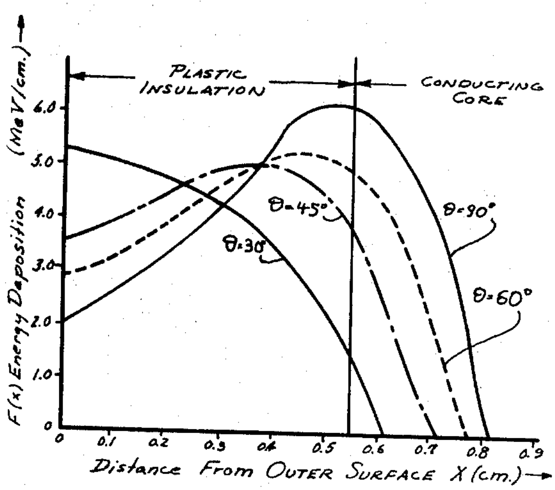

Fig. 2

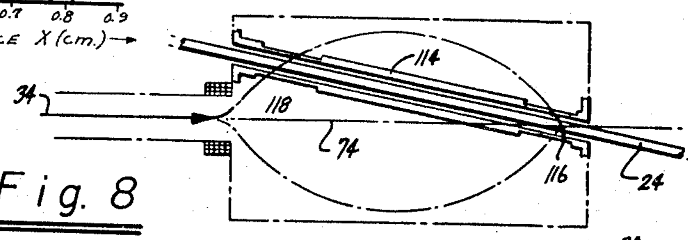

Fig. 8

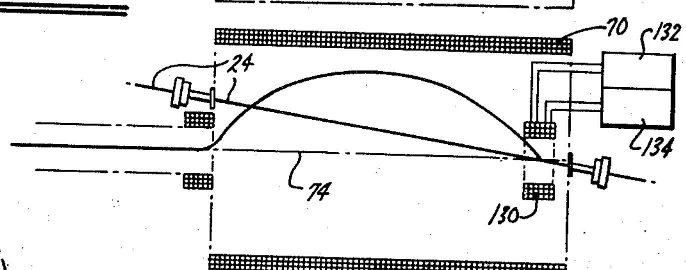

Fig. 11

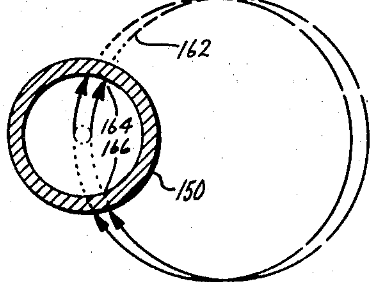

Fig. 7

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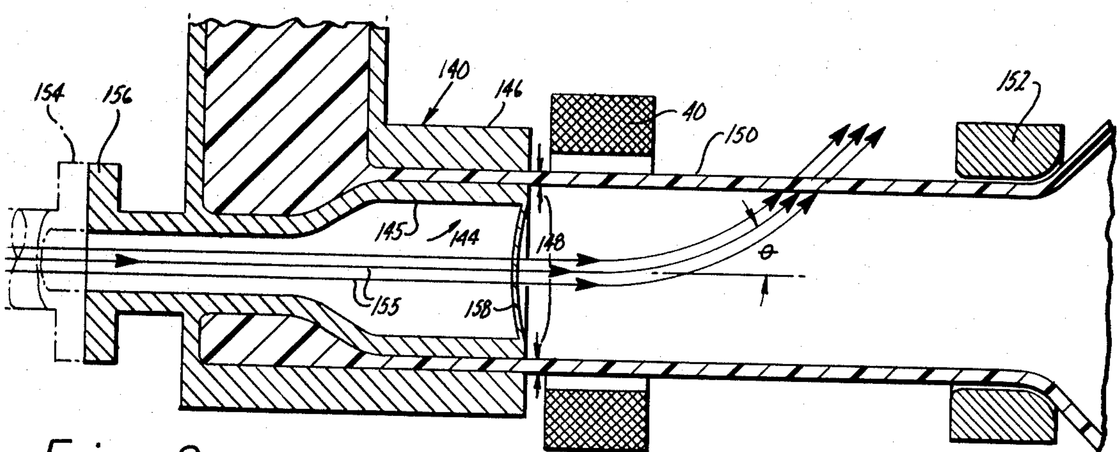

Fig. 9

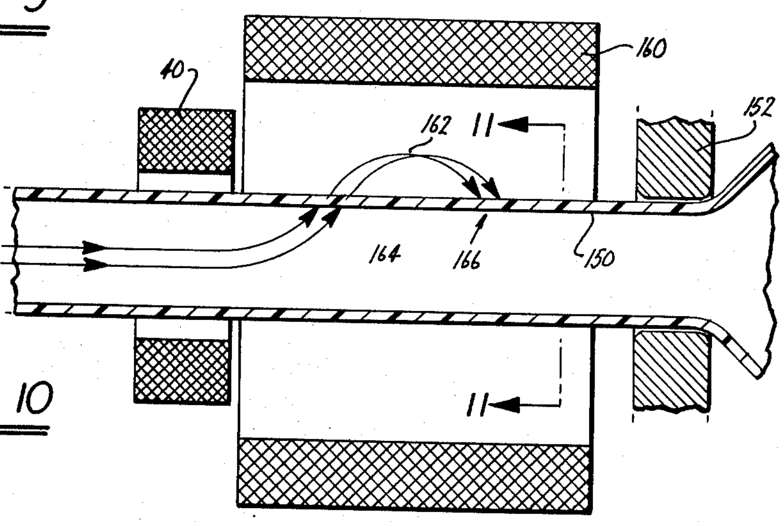

Fig. 10

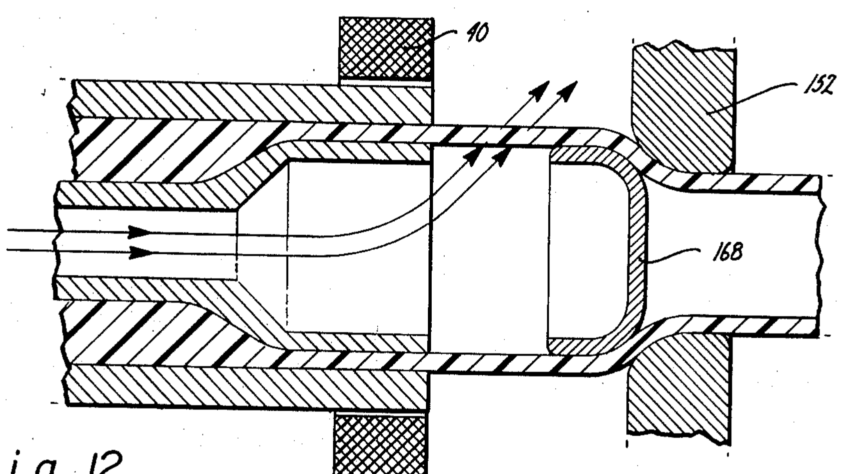

Fig. 12

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METHOD AND APPARATUS FOR IRRADIATION TREATMENT OF ELONGATE MATERIALS

BACKGROUND OF THE INVENTION

This invention relates to the irradiation treatment of materials and as in the cross-linking of plastics and more particularly to methods and apparatus for uniformly irradiating such materials as plastic coated wire and plastic coated cable, plastic tubing, and the like with an electron stream.

In the cross polymerization of plastic products, such as plastic coated wire and cable or tubing, it is desired to obtain uniformly cross-linked product with a minimum of wasted irradiation in energy. Heretofore, a number of irradiation methods have been proposed generally involving manipulation of an electron beam of suitable energy so that it impinges upon the target material in a plane normal to its surface and to movement of the material. Examples of such methods include those disclosed in the patents to D. R. Dewey et al, U.S. Pat. No. 2,897,365, entitled "Irradiation Method and Apparatus," issued July 28, 1959; H. R. Smith, Jr., U.S. Pat. No. 3,104,321, entitled "Apparatus for Irradiating Plastic Tubular Members with Electrons Deflected by a Non-Uniform Magnetic Field," issued Sept. 17, 1963; and to S. F. Skala, U.S. Pat. No. 3,246,147, entitled "Magnetic Methods and Apparatus for Manipulating a Beam of Charged Particles," issued Apr. 12, 1966. Generally, the irradiating techniques disclosed in these patents are subject to a number of problems such as critical dependence upon constant energy beam for uniform energy deposition in the target, blank irradiation spots occurring in the target due to shielding effects that cannot be eliminated, and beam control problems from increased instability as focusing is increased.

Additionally, the standard beam irradiation angle is normal to the surface of the target. Normal irradiation is found to produce low dose levels immediately below the surface of the material and much larger doses deeper within the material, resulting in undesirable non-uniformities in the dose.

There is, therefore, a need for a new and improved method and apparatus for the irradiation treatment of materials.

SUMMARY OF THE INVENTION AND OBJECTS

In general, it is an object of the present invention to provide a new and improved method and apparatus for irradiation of material which will overcome the above disadvantages and limitations. The invention is particularly applicable to the cross-linking of elongate continuous tubing or insulation and capsulated wire cable.

Another object of the present invention is to provide a method and apparatus of the above character by which the effect of the irradiation treatment shall be of significantly more uniform effect throughout the body of material to be treated so that economy of operation can be achieved while providing a high grade irradiation product.

A further object of the invention is to provide a method and apparatus of the above character which is relatively insensitive to energy dispersion error of the input electron beam or of aiming errors, which is substantially free of blind spot effects, and which does not require a highly stable input beam.

In general, the above objects are achieved with a system employing a scanning motion of the electron beam in a conical pattern having the target at its apex so that the target is irradiated obliquely to its surface or axis. It is found that irradiation normal to the surface, as heretofore used, produces maximum effects deep within the target material. That is to say, when investigated with three-dimensional model, the energy deposition contours (as a function of the depth of penetration) cause the principal energy of the beam to be deposited away from the point of entry and deeper within the material. It is believed that this results from significant electron penetration before scattering, after which the electron energy is deposited in an enlarged ball of randomly directed electrons. A measure of the size of this enlarged ball can be obtained by looking at the shape of the energy deposition profile at the deepest point of penetration where a little memory of the original beam direction exists. This analysis is strictly valid at low energy where scattering phenomena dominate the beam stopping process. However, it is believed that it can be supported in its general features up to the energies of use in irradiation processes. This type of scattering is illustrated in FIG. **1**A of the accompanying drawings, which shows contours **21***a*, **22***a* of constant energy deposition obtained by semi-analytical methods for the case of a pencil beam **23***a* of electrons incident normally on wire **24** jacketed in plastic insulation **26**. Analysis of the curves shows that most of the energy is dissipated in a spherical ball defined by contours **21***a*, **22***a* and that this nature of these three-dimensional deposition contours support the ball model previously discussed. Obviously, depositing the energy of the electron beam too deep within the wire or tubing, so that the wire itself or the void space within the tubing become heavily irradiated, is wasteful and ineffective.

The present invention follows from the realization that the drop or ball-like profile of energy deposition can be repositioned to advantage in order to produce a more uniformly irradiated target by aiming the beam into the target obliquely to its surface in such a manner that the symmetry of the energy profile within the target is shifted so that the enlarged portion of the profile is brought up to the surface of the target at a point remote from the entry of the beam. By utilizing oblique entry, the portions of material at and immediately below the surface are given substantially the same dosage of radiation as the deeper portions resulting in a much more uniform dose. This is illustrated in FIG. **1B** wherein the energy deposition profile contours **12***b*, **22***b* are distributed much more uniformly throughout a complete thickness of the cylindrical shell of insulation. For applications involving insulated wire and cable, or tubing, the energies and the deposition profile can be selected to selectively irradiate the shell and to eliminate wasted energy deposition within the core itself. For materials having essentially no core, the energies and angle of oblique entry can be adjusted to irradiate substantially the entire body of material, including the core.

FIG. **2** is a series of graphs relating to the quantity of energy deposited with depth of material from cylindrical cable geometry, such as shown in FIG. **1**A. As the oblique angle θ is varied, the family of curves is generated, those for 30°, 45°, 60° and 90° being shown. It is seen that the dose deposited near the surface increases by about a factor of two and that the dose deposited in the core is reduced as the angle θ is changed from 90° to lower than 45° and that the uniformity of dose is improved markedly. By controlling the angle θ of incidence, the energy deposition profile is also controlled to give an additional control parameter over the irradiation process.

It is a further object of the present invention to provide a method and apparatus which utilizes the oblique entry of the bombarding electron beam to obtain uniform energy deposition profile of portions of the target at or near its surface as well as deeper portions.

A further object is to provide a method and apparatus of the above character in which the beam is scanned about an elongate target by rotating the beam so that it traces a converging conical path having an apex centered within the target and an axis generally aligned along the elongate dimension of the target, the speed of rotation or precession of the beam and of movement of the target through the beam being adjusted so that the target is helically swept by the beam and uniformly irradiated along its length.

Another object of the invention is to provide a method and apparatus of the above character which is less sensitive to various aiming and energy errors of the beam than previous systems.

In general, the above procedure is achieved by an electron beam sweeping apparatus which induces the electron beam to follow a generally helical path which intersects the object to be irradiated at the end of **360** helical degrees. The orientation of the helical path is caused to rotate or precess about an axis coincident with the initial beam axis so that, initially, the helical path diverges from the beam axis and, then, converges towards the beam axis to describe a cone which passes through the axis obliquely. For objects smaller than the beam helical path, the target object is passed through the apex of the converging cone (**360** helical degrees removed). For targets having no core, such as tubing, and a dimension of the same order of magnitude as the helical path of the beam, an arrangement is provided for passing the beam coaxially of the target so as to obliquely pass through it as the helix expands and obliquely return through it at a remote point (360 helical degrees removed).

These and other objects and features of the invention will become apparent from the following description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** illustrates the energy deposition profile for an electron beam impinging upon a target at a normal angle of incidence.

FIG. **1**A shows an energy deposition profile for an electron beam impinging upon a target at an oblique angle of incidence.

FIG. **2** are graphs of energy deposition versus depth for various angles of oblique bombardment of a cylindrical insulated cable with 1.8 MeV electrons.

FIG. **3** is a schematic diagram of a wire and cable irradiation apparatus constructed in accordance with the present invention and using oblique irradiation.

FIG. **4** is a view taken along the lines **4—4** of FIG. **3**.

FIG. **5** is a cross sectional view of the cable seal arrangement of the apparatus of FIG. **3**.

FIG. **6** is an isometric view taken from above the input beam and facing generally toward it, this view illustrating the relationship between the rotating helical paths of the beam and the cable being irradiated.

FIG. **7** is a modified form of irradiation apparatus similar to that of FIG. **3** and utilizing additional means for controlling the oblique entry angle.

FIG. **8** is a cross sectional view of a modified irradiation apparatus constructed in accordance with the invention and utilizing a reentrant cable transport.

FIG. **9** is a cross sectional view of apparatus suitable for coaxial internal irradiation of hollow tubular members in connection with a plastic extrusion apparatus.

FIG. **10** is a cross sectional view similar to FIG. **9** and showing a modified form thereof.

FIG. **11** is a cross sectional view taken along the lines **11—11** of FIG. **10**.

FIG. **12** is a cross sectional view of another modified form of irradiation apparatus similar to that of FIG. **9**.

Referring to FIGS. **3** and **4**, there is shown apparatus for the irradiation treatment of plastic incapsulated wire and cable and includes a suitable means for delivering a pencil-like beam of electrons to an irradiation chamber **30**. Such means can consist of electron accelerator **32** which delivers an electron beam **34** to beam shaping and bending device **36** for forming the beam and focusing it into the input **38** of the irradiation chamber **30**. Many types of electron accelerators and focusing devices are suitable for use with the present invention, it only being required that output beam be reasonably collimated and of the desired energy range.

Means is provided for diverting the electron beam as it enters the irradiation chamber **30** and for causing the diverted beam to rotate or precess about the axis of the undiverted beam to thereby describe a cone. Such means is illustrated in FIG. **4** which shows a magnetic structure **40** known as a magnetic box. This structure generally consists of a magnetically permeable ring **42** having a square conformation in which the upper and lower legs **44, 46** are provided with windings **48, 50** in series with each other and a suitable power supply **52** as for developing a magnetic field B_x having a direction aligned with the legs. The magnetic circuit between the upper and lower legs is closed by side legs **54, 56** which are also provided with windings **58, 60** in series with each other and a suitable power supply **62** to develop a magnetic field B_y aligned with the side legs and directed at right angles to the field B_x. Let magnetic fields B_x and B_y be defined in accordance with the drawing and connected to respective power supplies V_x and V_y. The box structure has the feature that the fields B_x and B_y are remarkably constant up to the edges of the box. If power supplies V_x and V_y supply alternating current in time quadrature (90° phase shift with respect to each other), the resultant magnetic field within the box rotates according to the following equations.

$$B_x = B \cos \omega t,$$

$$B_y = B \cos(\omega t - 90°) = B \sin \omega t,$$

$$B_r^2 = B_x^2 + B_y^2 = B^2,$$

$$B_r = B, \text{ a constant.}$$

Thus, although B_x and B_y individually oscillate in magnitude, their resultant total field is constant in magnitude and rotates with angular frequency ω. Accordingly, as the electron beam passes through the box normally, as shown, it will be diverted from its path by interaction with the rotating magnetic field and successive portions of the beam will trace a diverging cone much as the spinning top precesses along a conical path.

The beam diversion structure could also be achieved by utilizing a magnetic dipole positioned with its field transverse to the beam and mechanically rotated at the desired frequency. Such a modification would eliminate the necessity for cooling the electromagnetic structures, such as that of FIG. **4**, but would possess other disadvantages.

Irradiation chamber **30** is surrounded by a solenoid **70** connected to a suitable source **72** of direct current for establishing a uniform magnetic field B_H in alignment with the undeflected axis **74** of the beam.

As will be explained in greater detail, the field B_H interacts with the induced velocity component in the beam which is directed at an angle to the field and causes the beam to take a helical path which is rotated about the axis **74**, the envelope of possible paths being indicated by the curves **76, 78**.

The irradiation chamber **30** includes vacuum tight walls **80, 81, 82** and is connected by piping **84** to series connected vacuum pumps **86, 88**. Pump **86** is capable of lowering the pressure in the chamber to below about 0.1 Torr and aided by starting at the reduced pressure delivered by pump **88**. Pump **88** also maintains a partial vacuum through piping **90** on cable feed seals **92, 94** mounted in the end walls **80, 81** so that a cable to be irradiated can be pulled through the chamber and intersect the axis **74** at the same position as the end **96** of the one helical beam cycle.

One of the seal assemblies **92, 94** is shown in detail in FIG. **5** and includes a mounting flange **100** secured to the chamber with a suitable O-ring seal **102**. The flange supports a neck **104** aligned with the direction of motion of the cable and terminating its outer end in a suitable vacuum seal **106** which also permits linear motion of the cable through the chamber. The neck of the seal assembly is connected to pump **88** for partially evacuating a seal to aid and maintain the vacuum within the irradiation chamber. Seal **106** includes a body **108** having a recess therein for receiving an annular packing **110** retained by a gland **112**.

Other means for delivering the cable and passing the same through the irradiation chamber can be utilized. One such means is illustrated in FIG. **8** and can consist of an elongate tube **114** sealed at each end to walls **80, 81** of the chamber so as to completely isolate the cable from the vacuum interior. The tube is purposely designed to be thin to the passage of electron radiation at such points **116, 118** where the radiation is designed to strike the cable within the tube.

In either arrangement the cable is fed through the irradiation apparatus at a slight angle to the initial axis of the electron beam before diversion and intersects this axis at a remote point which is spaced a helical 360° away from the beam input. This distance also establishes the overall size of the chamber which is large enough to accommodate the helical distance, both along the axis **74** and transverse of it, to the extreme outer limit of the helix.

Position sensing detectors **120, 121**, such as current collecting plates, surround the cable on each side of its intersection **96** with the beam. When the beam shifts away from intersection **96**, it causes an unbalance in the plates which is sensed by position control circuitry **122** and used to vary the energy applied to the magnetic beam diverter **40** to thereby restore the beam to an equilibrium position at the intersection **96**.

Reference is made to FIG. **6** wherein the relationship between the cable passing through the irradiation chamber and the electron beam helical orbit is amplified. The trajectory of the electron in the helical orbit begins at the diverting magnetic box **40** and terminates on the cable **34**. The axis of motion to which the following discussion refers is to that **74** of the initial electron beam and not to that of the helix itself. In fact, in the present discussion, the axis of the helix is moving about the cable and is inconvenient to use. In being injected through the bending field B_r of magnetic box **40**, the electron beam is deflected through an angle θ from the axis of its incident direction. The beam continues to move in a axial direction with a velocity V_z while executing thereafter a circular orbit with radius R_H in the plane perpendicular to the magnetic field B_H due to the solenoid **70**. After traversing 360° of the helical path, the beam returns again to its initial axis at the angle θ. As shown, the cable makes a slight angle (approximately 10°) with the initial beam axis **74**. This is necessitated by the practical consideration requiring introduction of the cable at a point spaced from the introduction of the beam itself. As the sweeping field B_r rotates the beam about axis **74**, the path of incidence of the beam into the cable will trace a cone and will make an angle to the cable which varies from $\theta - \phi$ to $\theta + \phi$ where ϕ is the angle between the cable and the axis **74**. Let the following parameters be defined:

- L — is the axial distance the beam travels in the Helicon from the center of the sweep magnet **40** to the position **96** of cable irradiation
- R_S — is the radius of curvature for electron momentum P at the sweep magnet
- θ — is the angle of bend of electrons in the sweep magnet
- ϕ — is the angle between the axis **74** and cable
- R_H — is the radius of curvature for momentum $P_r = P \sin \theta$ in the field B_H
- V_z — is the axial component of electron velocity
- V_r — is the radial component of electron velocity
- T — is the period of revolution for an electron with momentum P_r perpendicular to a magnetic field B_H.

The distance L travelled by the helical path of the beam to the point of cable irradiation is given from the following calculations:

$$L = V_z Y$$

Since $Y = (2\pi R_H)/V_r$, $R_H = P_r/(eB_H)$, and $V_z/V_r = 1/\tan\theta$,

then $L = (2\pi P_r)/eB_H \; 1/\tan\theta$

and finally $L = ((2\pi P)/(eB_H)) \cos\theta$

In the sweeping field $\sin\theta = Z/R_S = (ZeB_r)/P$
Combining,

$$L = 2\pi/(eB_H) \sqrt{P^2 - (ZeB_r)^2}$$

If the magnetic fields are well regulated then the main error in L will come from changes in P

$$dL/L = (dP/P)(1/\cos^2\theta).$$

By way of example, maximum deposition efficiency occurs for $\theta \cong 53°$ for electron energies around 1.8 MeV and $dL/L = 2.8$ **dP/P** for $\theta = 53°$. Thus, the positional error dL/L will be about thrice the error in momentum. This leads to the desirability of employing the detectors **120, 121** and associated circuitry **122** to determine the position of the beam and to change the strength of the diverting magnet field B_r to stabilize the position L at a fixed value.

Continuing to refer to FIG. **6**, there are shown several helical orbits of the electron beam which intersect at the target position **96**. As the beam spirals down the chamber and about the target, it traces a helical spiral, the pitch of which is determined by its axial velocity component V_z. The axial component V_z of the beam velocity is unaffected by the constant magnetic field of solenoid **70** for they are parallel. But the radial (or transverse) component of the velocity V_r generated by the sweep magnet **40** causes the diverted beam to trace circular orbits when viewed on end so that the combined linear and circular motions form a helix. Since the beam is being diverted azimuthally about a conical surface at the input, the helix is transported about axis **74** to describe a generally conical surface **123** which converges at **96**. Each portion of the beam is directed through the axis at **96** at an oblique angle determined by the pitch of the helix. This angle is a parameter which can be adjustable to suit the circumstances such as the thickness of material being irradiated, the density of the material and the energy of the electrons. It will be noted that the system also is a chromatic in the sense that any energy electron emitted from the SOURCE will spiral back to axis **74**. The point at which electrons intersect the axis will be further away for the higher energy electrons and closer for the lower energy electrons.

Where the accelerator has a pulsed output, the sweeping frequency ω of the sweep field is adjusted to provide many revolutions of the beam for each output pulse of the accelerator. The cable speed itself is set by the overall efficiency of the system. For example, the beam pulse for a resonant transformer beam source might be about 1.4 milliseconds so that a 10 kHz sweeping frequency would rotate the beam fourteen times per pulse burst. Under these circumstances, there would be no beam for 42 revolutions and fourteen revolutions during which the beam is on. At 30 cm per second cable feed, a one cm wide beam would advance 0.4 cm while there is beam and .12 cm while there is

not any beam; thus, the irradiation would be quite uniform along the cable. Other pulsed beam systems will require adjustment of the values of efficiency, sweeping speed and feed speed to obtain a satisfactory relationship between them.

It will be noted that the helical path of the beam intercepts the cable at the point A once in every cycle of rotation of the beam. It can be shown that the point A of interception of the cable for the linear feed through is on the same side of the cable as is being irradiated at B. Since portions of the cable passing A proceed to pass B, these losses are self-compensating. Thus, even the small amount of potential azmuthal nonuniformity due to interception of the target at A is utilized to irradiate the target at the same point irradiated at its subsequent intercept B, and, charge not delivered to that side of the cable at B because of interception of A is nevertheless delivered at A itself. Furthermore, the actual unirradiated section is minimized because of the actual divergence of a practical helical beam at A and the convergence of the beam at B so that the diverging beam is not blocked as much as would be expected with a perfectly collimated thin beam.

FIG. 7 shows a sketch of a modified form of apparatus, such as shown in FIG. 3, and including an additional, second sweeping magnet **130** normal to and surrounding axis **74** at the position **96** of the target. Sweeping magnet **130** is of the same construction as magnet **40** and has windings (not shown) connected to suitable power supplies **132, 134**. These supplies are phase locked to supplies **52, 62** but are independently adjustable as to amplitude of applied signal. By varying the amplitude and sign of the currents flowing in the second sweep magnet **130**, control of beam convergence and the value θ of oblique entry is facilitated.

Another application of the present invention relates to the irradiation of extruded tubing. Referring to FIG. **9**, there is shown an arrangement incorporating the present invention for use with a cross-head extruder **140**. The extruder supplies softened plastic **142** to an extruding nozzle **144**, including an inner hollow member **145**, which is coaxially arranged and mounted in an extruding head **146** to form an annular gap **148** through which the tubular extrusion **150** is passed. The resulting tube is brought out into air and passed through snubber **152** at a location spaced away from the extruding head **144**. Means **154** for forming an electron beam **155** is coaxially mounted to a flange **156** at the rear of the extruding head and directs beam **155** coaxially through the head of the extruder which is sealed with a suitable vacuum window **158**.

A beam sweeping magnet **40** encircles the beam as it passes coaxially out of the extruding nozzle and causes beam **155** to be diverted into a conical path which intersects the extruded plastic tubing **150**. Sweeping magnet **40** is of the same construction and function as that shown in FIG. **4** and need not be reexplained. It serves to rotate the beam at a suitable frequency for scanning about a cone which diverges through the wall of tubing at an oblique angle θ.

If desired, a solenoid **160** can be provided as shown in FIGS. **10** and **11** to surround the extruded tubing following the sweep magnet **40** and establish a constant magnetic field over a length of the extruded plastic so that the diverted beam is directed into helical paths

162. The strength of the solenoidal field, the energy of the beam, and the amount of diversion of the scanning magnet 40 are adjusted so that the beam follows a helical path 162 which traverses the tubing at 164 as the helix expands away from the electron beam axis and again converges through the tubing at a remote location 166. This result follows for helical path diameters greater than the radius of the tubing. As the beam helical path rotates about the beam axis, two zones of irradiation are swept out on the tubing, the first being as the beam diverges from its axis and the second as it converges from its axis. While scattering at 164 reduces the effectiveness of the beam thereafter, a portion of the residual energy is still usefully recovered in the second pass at 166.

FIG. 12 shows a modification of the apparatus in which vacuum window is replaced by a floating plug 168 to form a vacuum seal. Plug 168 is prevented for following the tubing by providing snubber 152 with a constriction smaller than the plug.

Many modifications and adaptations of the invention will occur to those skilled in the art to which this invention pertains without departing from the spirit and scope of the invention. It should be understood, therefore, that the disclosure and description of apparatus herein are illustrative of the invention and are not to be taken as a limitation thereon.

We claim:

1. In the method for irradiating an elongate cylindrical target with a linear beam source of electrons comprising the steps of inducing said electron beam to divert from its path at a predetermined point thereon, establishing a constant magnetic field aligned with the initial path of said electron beam in the region into which said diverted electron beam is diverted so that said electrons follow helical paths converging at a point on said initial electron beam path 360 helical degrees away from the point of diversion, passing said elongate target through said point of conversion at a small angle to the initial axis of said linear electron beam whereby said electrons impinge into said target at an oblique angle corresponding substantially to the pitch angle of said helix, said electron beam thereby entering the surface of said elongate target material at an oblique angle, and causing the direction of diversion of said electron beam to rotate about said axis.

2. In a method for irradiating a cylindrical object through a surface thereof within an electron beam, the steps of bending said electron beam along a helical path having a length of 360 helical degrees, said path beginning and ending on the initial axis defined by said electron beam, rotating the helically bent beam about the initial axis to thereby intersect said axis at an oblique angle and sweep a cone-shaped path thereabout having an apex at a point on said axis and making an angle thereto lying in the range from about 10 to 80°, delivering an object to be irradiated through said cone-shaped path at said apex so that said beam intersects that object at an oblique angle determined substantially by the pitch of said helix and at said oblique angle, said beam being effective thereby to irradiate portions of said object at or near the surface thereof and in a region immediately adjacent to the position of entry of said beam into said object together with deeper portions of said object which are spaced from said surface.

3. In apparatus for irradiating an elongate object with an electron beam, means forming a linear stream of electrons travelling along a predetermined axis, an irradiation chamber having an input for receiving said electron stream, means for maintaining a reduced pressure within said chamber, means located at said input for diverting said electron stream from said axis, said means including a magnetic ring for generating a magnetic field directed transversely to said stream and rotating about said stream at a uniform speed, means associated with said chamber for feeding said elongate object therethrough while permitting said partial pressure to be maintained in said chamber, a solenoid magnet surrounding said chamber to establish a uniform magnetic field within said chamber and oriented in alignment with the direction of said electron beam axis for causing said diverted electron stream to follow a helical path having a focal point 360 helical degrees along the axis, said means for feeding said elongate object being arranged to cause said object to intersect said focal point at less than a small angle to said axis.

4. Apparatus for irradiating an elongate cylindrical target with a linear beam source of electrons comprising means for inducing said electrons to divert from the path of said beam from a predetermined point thereon, magnetic means for establishing a constant magnetic field aligned with the initial electron path in the region into which said diverted electron beams are directed so that said electrons follow helical paths therein converging at a point on said path 360 helical degrees away from said point of diversion, means for passing said elongate target through said point of convergence at a small angle to the initial axis of said electron beam whereby said electrons impinge into said target at an oblique angle corresponding generally to the pitch angle of said helix, said electron beam thereby entering the surface of said elongate target material at an oblique angle, and means for causing the direction of diversion of said beam to rotate about said axis.

5. Apparatus as in claim 4 further including beam position detectors located on each side of the target position, means for sensing the output of said detectors and for using the same to control the means for diverting said beam so that change of position of said convergence point causes corresponding change in the strength of said diverting field to thereby stabilize the position of said beam on said target.

6. Apparatus as in claim 4 in which said means for diverting said electron beam comprises a magnetic box serving to develop a magnetic field of constant strength directed normally to the beam axis and which rotates about the beam axis at a uniform angular velocity.

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