

Dec. 1, 1959

E. LEMMERS
TUBULAR ELECTRIC LAMP

2,915,664

Filed April 9, 1956

3 Sheets-Sheet 1

FIG. 1.

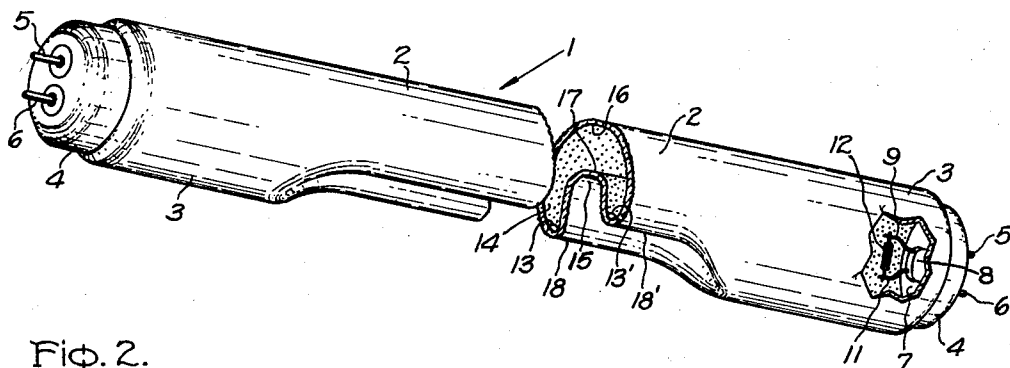
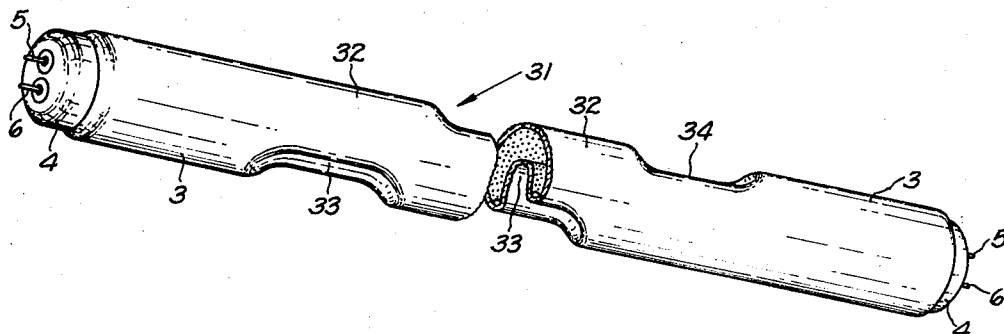
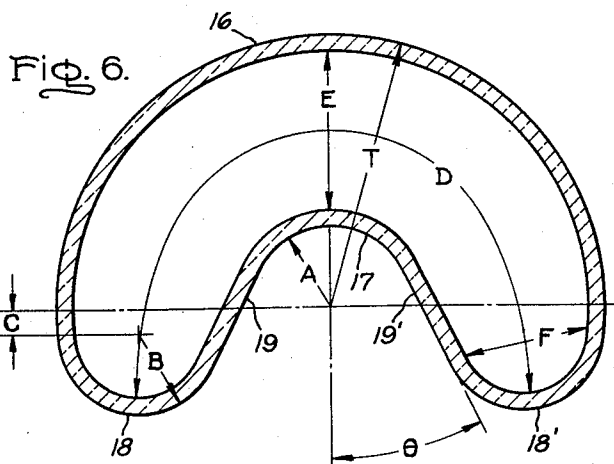


FIG. 2.



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FIG. 3.

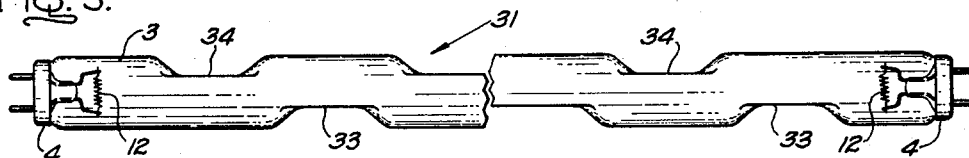


FIG. 4.

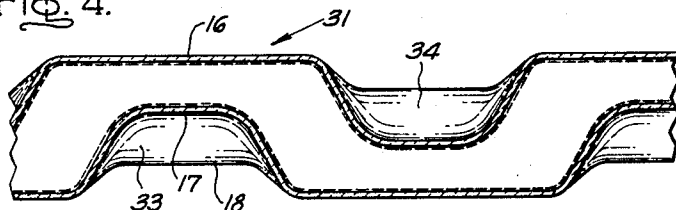


FIG. 5.

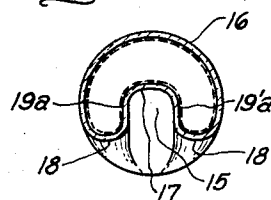
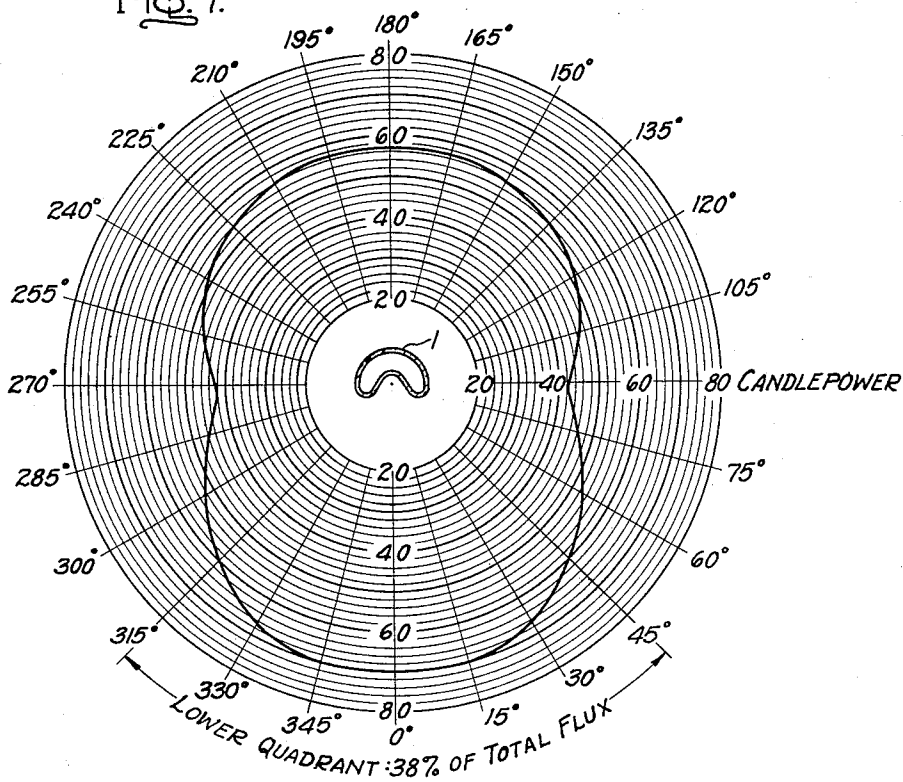


FIG. 7.



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FIG. 8.

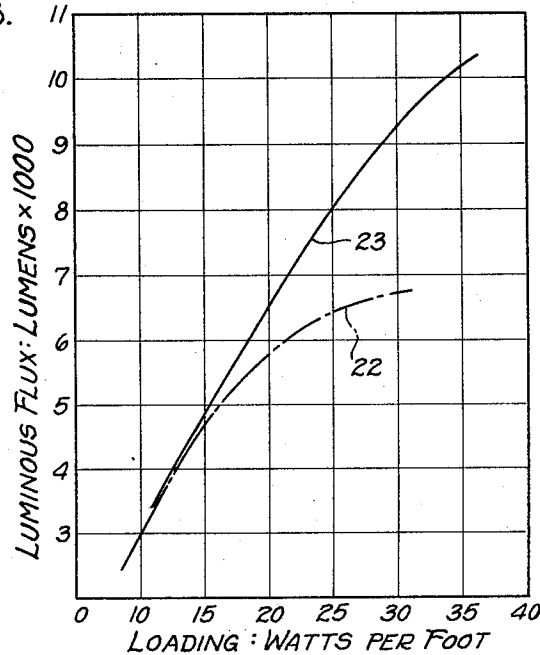


FIG. 9.

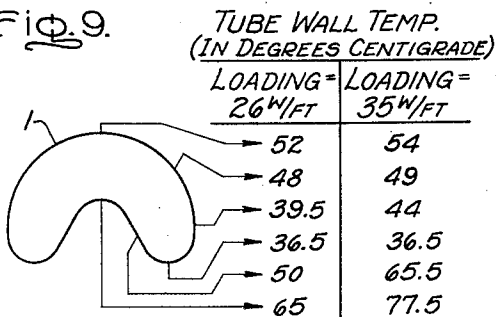
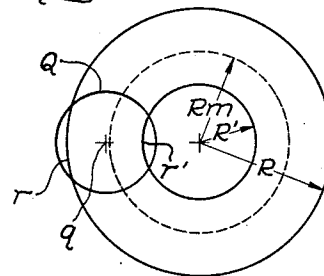


FIG. 10.



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2,915,664

TUBULAR ELECTRIC LAMP

Eugene Lemmers, Cleveland Heights, Ohio, assignor to General Electric Company, a corporation of New York

Application April 9, 1956, Serial No. 577,017

25 Claims. (Cl. 313—109)

This invention relates to electric lamps and similar devices having elongated tubular envelopes. The instant application is a continuation-in-part of my copending application, Serial No. 475,036, filed December 14, 1954, entitled "Imposition Resistant Lamp Envelopes," assigned to the same assignee as the instant application, now abandoned.

Certain aspects of the invention relating to structural features of vitreous envelopes are particularly useful in connection with low pressure discharge lamps but may be used generally with electric devices comprising a sealed elongated vitreous envelope. Other aspects of the invention relate specifically to low pressure resonance radiation discharge lamps wherein the radiation is emitted from the discharge medium by diffusion, and make possible in such lamps higher loading or higher efficiency simultaneously with highly advantageous directional effects in the radiant output.

In the case of fluorescent lamps of the usual low pressure positive column type in which phosphors are excited by the resonance radiation of mercury, as well as in other resonance radiation lamps (such as germicidal mercury lamps, and sodium lamps), it is possible, as pointed out in my Patent No. 2,482,421—Flat-Tube Electrical Device, to improve the radiation efficiency at a given loading by increasing the ratio of perimeter to area of the cross section (henceforth abbreviated p./a.). Thus, increasing the p./a. ratio permits either improved efficiency at a given wattage per unit length of lamp, or higher wattage loading per unit length for the same efficiency. For a given perimeter, a tube of circular section has the lowest p./a. ratio. The ratio may be increased by departing from a circular section, for instance, by flattening the tube or otherwise deforming it out of round.

The manner in which increasing the p./a. ratio improves the radiation efficiency is not perfectly understood. According to one theory, the ionizable medium including the mercury vapor, in reabsorbing resonance radiation, reduces the proportion which reaches the phosphor at the envelope wall, thereby reducing the radiation efficiency. The degree of reabsorption will vary with the distance which the mean unit of radiation or quantum must travel before reaching the envelope wall; evidently, this effect will be less pronounced when the p./a. ratio is increased by deforming a round tube inasmuch as the envelope perimeter is greater for a given cross sectional area of discharge, and, correspondingly, the mean distance to the envelope wall is thereby reduced. Another theory is that the electron temperature in the ionizable medium is determined in part by ion losses to the envelope walls. A greater envelope surface then produces a higher wall loss and the electron velocity increases to maintain the discharge, with a resulting increase in efficiency of generation of resonance radiation. Probably the mechanisms proposed by both theories play a part in the increase in efficiency with increase of the p./a. ratio.

Notwithstanding the advantages of flat tubes over round tubes for discharge lamps, flat tubes have presented

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a very serious drawback which has prevented their use to any great extent: namely, weakness against implosion or inward collapse by external atmospheric pressure when they are evacuated. The gaseous filling of low pressure discharge lamps, such as fluorescent lamps, is at such a low pressure relative to the atmosphere that, for the present purpose, the envelopes may be considered evacuated. In my Patent 2,482,421—Flat-Tube Electrical Device, there is disclosed a way of improving the resistance to collapse of flat-tube lamps which consists in prestressing the narrow longitudinal edges of the flat tube to a state of permanent precompression strain. This may be effected by heating the tube above the strain point of the vitreous material and then cooling the narrow edges of the tube before its wide approximately flat longitudinal walls cool below this temperature. Whereas such treatment does provide a definite improvement in implosion resistance, it does not lend itself to providing the configuration and form which characterizes my present invention.

It will be appreciated that present day fluorescent lamps are a compromise between radiation efficiency which is increased by making the tube smaller and lowering the current density, and quantity of radiation or light produced which increases with the cross sectional area of the tube and the current density. Since a commercially acceptable lamp must produce a reasonable quantity of light, there are obviously practical limits to increasing the efficiency by reducing the size of the tube; conversely, the requirement for efficiency has imposed limits on the maximum size of tube.

Accordingly, an object of the invention is to provide an elongated vitreous tube of unique form or configuration having a perimeter-to-area ratio greater than round tubes of like cross sectional area and having greater strength and higher resistance to implosion than simple flattened tubes.

A specific object is to provide an elongated low pressure discharge lamp of unique form having a ratio of perimeter to area such as to permit a substantial increase in loading without reduction in efficiency by comparison with conventional round tube lamps, and which has sufficient resistance to implosion by external atmospheric pressure as to make a practicable lamp without requiring excessive thickness of the envelope walls.

Another object of the invention is to provide an elongated low pressure resonance radiation discharge lamp having a discharge space cross section of improved form making the lamp capable of a higher loading for a given efficiency than heretofore possible and causing it to emit a higher proportion of its radiation in a given sector of its cross section.

A further more specific object of the invention is to provide an improved low pressure fluorescent discharge lamp utilizing resonance radiation of mercury vapor and permitting a higher loading and lumen output per unit axial length at a given efficiency than heretofore possible and at the same time providing a preferential light output in a given sector of its cross section.

According to one aspect of the invention, a resonance radiation lamp of greatly increased loading capacity at a given efficiency and having the desired radiation pattern simultaneously with improved implosion resistance, comprises an elongated tube of light-transmitting material formed with a longitudinally extending transversely reentrant portion or groove. The cross section of such a tube appears kidney-shaped, as seen in the drawings, and may be generally described as a flattened tube transversely rolled up into an inverted U-shape. The cross section of the discharge space is in general a sector of an annulus defined by generally concentric walls and bounded by rounded convex edge walls.

In a preferred embodiment of the invention which is

particularly advantageous with respect to structural qualities of the vitreous tube, that is, resistance to implosion, the cross section of the tube, while retaining the general shape of a sector of an annulus, is modified somewhat to provide a re-entrant portion or groove having divergent inner side walls. The side walls merge inwardly of the tube into the curvature of the inner concave wall of the groove and outwardly of the tube into the curvature of the outer edge walls which in turn join to the convex outer concentric wall of minimum curvature (maximum radius).

In another embodiment of the invention, the longitudinally extending groove is provided in portions which are relatively short and spaced apart and alternate on opposite sides of the tube, giving a dimpled or crenelated appearance. With this configuration, all re-entrant portions of the envelope wall have a double curvature, that is, a curvature transverse to the axis of the tube and a curvature along the axis of the tube, thereby providing additional increase in strength and resistance to implosion. This particular configuration consisting of short groove sections alternating on opposite sides has been found particularly advantageous in providing suitable implosion resistance to thin wall tubing of large size.

According to another aspect of the invention, I have found that the provision of a re-entrant portion in the envelope wall of a discharge device wherein the useful radiation is emitted from the discharge medium by the process known as "resonance radiation diffusion," produces totally unexpected effects in connection with higher efficiency and concentration of light or radiation in the re-entrant portion. This aspect of the invention appears limited to discharge devices or lamps operating with a plasma, that is, a region having substantially equal concentrations of electrons and positive ions, wherein atoms are excited to the resonant state and produce photons which reach the surface by the diffusion process. In this process, a photon or quantum of radiation which originates through the fall of an atom from an excited level to its ground level, is reabsorbed and re-emitted many times before it reaches the surface of the discharge medium and finally escapes. This recurrent absorption is sometimes referred to as imprisonment of resonance radiation. At each re-absorption, the photon raises an atom to the excited level. The excited atom has a random movement in the plasma and shortly falls back to the ground level whereupon a photon of light is again emitted. This is the process of generation of the mercury resonance radiation 2537 A. (ultraviolet) in the ordinary fluorescent lamp. It is likewise the process which occurs in the sodium lamp producing 5890-5896 A. (visible yellow) radiation.

In such lamps, that is, resonance radiation lamps, a totally unforeseen result of the instant cross section is that the plasma appears to conform itself more closely to the re-entrant portion, or stated otherwise, the plasma hugs the groove, and the groove or re-entrant portion receives resonance radiation per unit area at a rate much greater than the mean of the envelope per unit area. The resonance radiation is converted by the phosphor which coats the envelope walls into visible radiation or light. The net result is that light is emitted from the region of the groove at a high efficiency and the groove has a much higher brightness than the lamp as a whole. Actual measurements have shown the groove to be as much as 40% brighter than the envelope wall on the opposite side. This increased brightness of the groove may be used to achieve directional effects which are highly advantageous in lighting applications. The remarkable and totally unexpected brightness of the groove is an outstanding feature of the invention.

For a more detailed description of the invention, attention is now directed to the following description and accompanying drawings. The features of the invention:

believed to be novel will be more particularly pointed out in the appended claims.

In the drawings:

Fig. 1 is a pictorial view of a discharge lamp embodying the invention with a continuous transversely re-entrant portion or groove extending longitudinally along its underside, portions of the envelope wall being broken out to shorten the figure.

Fig. 2 is a similar view of another lamp embodying the invention with short lengths of groove or indentations alternating on opposite sides.

Figs. 3, 4, and 5 are side elevation, longitudinal section and cross section views, respectively, of the lamp of Fig. 2. In the case of Fig. 5, the view represents also a cross section of the lamp of Fig. 1;

Fig. 6 is an enlarged cross-sectional view of an improved re-entrant groove configuration which has been found particularly advantageous in respect of structural qualities, that is increased implosion resistance.

Fig. 7 is a polar diagram of the light distribution achieved with a re-entrant groove lamp in accordance with the invention such as illustrated generally in Fig. 1.

Fig. 8 is a graph affording a comparison of the loading capacity of re-entrant groove lamps with prior lamps.

Fig. 9 is a diagram illustrating the temperature distribution about the cross section of re-entrant groove lamps at different loadings.

Fig. 10 is a diagram illustrating the effect of the boundaries upon the radiation diffusion process.

In order to facilitate the detailed description of the invention, it will be presented under the following headings:

- (1) The Grooved Lamp
- (2) Improved Grooved Lamp Cross Section
- (3) Grooved Lamp Design Considerations
- (4) Light Distribution
- (5) Factors of Efficiency
- (6) Theoretical Considerations
- (7) Reduction in Elastic Losses
- (8) Temperature Distribution
- (9) Vapor Pressure Regulating Property
- (10) Phosphor Lumen Maintenance
- (11) Physical Basis of Groove Brightness
- (12) Crenelated Grooved Lamp
- (13) Implosion Resistance
- (14) Manufacture

(1) The grooved lamp

Referring to Fig. 1, there is shown a fluorescent lamp 1 of the low pressure, positive column type embodying the invention. The lamp comprises an elongated envelope 2 having circular or round tube ends 3, 3 which are annularly reduced or shouldered at their extremities for securing thereto bases 4, 4, each provided with a pair of insulated contact terminals or pins 5, 5 and 6, 6. As shown at one end of the lamp, the electrode mount or stem flare 7 is sealed peripherally into the circular tube end and includes a press 8 through which are sealed current inlead wires 9, 11. The inward projections of the lead wires support the filamentary cathode 12, whereas the outward projections are connected to the terminal pins 5, 6. Cathode 12 may consist of a coiled-coil of tungsten wire provided with an over-wind and coated with an activated mixture of alkaline-earth oxides, such as the usual mixture comprising barium and strontium oxides. The other end of the lamp is provided with a similar cathode and one of the stem flares is provided with an exhaust tube which is sealed or tipped off in the usual fashion. The cathodes may be of the low resistance and low thermal capacity rapid start type disclosed in my copending application Serial No. 250,106, filed October 6, 1951, now Patent No. 2,774,918, "Electric Discharge Device," and assigned to the same assignee as the present invention.

The lamp contains an ionizable atmosphere including a starting gas or mixture of one or more of the inert rare

gases of group 0 of the periodic table at a low pressure, for instance argon at a pressure of 0.5 to 5 millimeters of mercury, and mercury vapor. The droplets of mercury indicated at 13 and 13' exceed in amount the quantity vaporized during the operation of the lamp wherein the mercury vapor exerts a partial pressure in the range of 1 to 20 microns for optimum generation of mercury resonance radiation at 2537 Å. The exact value of partial pressure of mercury vapor for optimum generation of 2537 Å., that is for maximum lumens, may vary with the kind of starting gas, that is, whether argon, krypton or xenon, with the pressure of the starting gas, and with the current density. Where the starting gas is argon at approximately 3 millimeters pressure, the optimum pressure of mercury vapor is usually from 5 to 8 microns.

The phosphor coating indicated at 14 on the inside of the envelope converts the 2537 Å. resonance radiation into visible light. It may be a halophosphate phosphor activated with antimony and manganese as per U.S. Patent 2,488,733, McKeag et al. of the assignee as the present invention, and producing a cool white light. The envelope may be coated externally with a water-repellent or hydrophobic coating to facilitate starting under high humidity or adverse atmospheric conditions. A suitable coating is a hydrolized organo-silicon halide as described in U.S. Patent 2,408,822, Tanis of the assignee as the present invention. It may be produced by exposing the lamp for a few minutes to the vapor of methylchlorosilane for instance, in a suitable enclosure maintained at 50% relative humidity.

In accordance with my invention, vitreous envelope 2 is provided with a transversely re-entrant portion or groove 15 extending longitudinally substantially throughout its length between the round ends 3, 3. The envelope, as shown in Fig. 5, may be generally described as a flattened tube which has been rolled up transversely into an inverted U-shape. More exactly, the cross section of the discharge space may be regarded as a sector of an annulus defined by generally concentric walls 16 and 17 and bounded by rounded convex edge walls 18, 18'. Convex outer wall 16 has the minimum curvature, its radius being that of the original round tube from which the instant grooved tube was formed. Concave inner wall 17 has a greater average curvature than outer wall 16, its radius of curvature being approximately one-third that of outer wall 16. The convex joining or edge walls 18, 18' would in theory, assuming perfectly concentric inner and outer walls and a mean radius of curvature for inner wall 17 exactly one-third that of the outer wall 16, have exactly the mean radius of curvature of concave inner wall 17. In practice, however, convex edge walls 18, 18' are provided with a slightly greater mean curvature than concave inner wall 17. This is done because whereas it is desirable to have the wall-to-wall spacing substantially constant, it is essential to avoid a constriction at the center. If such a constriction were permitted, the discharge would not fill the discharge space uniformly and would tend to occupy the space to one side or the other of the constriction. Since the molding of glass cannot in any event be performed with perfect accuracy, a practical solution resides in making the radius of curvature of the convex edge walls somewhat less than that of concave inner wall 17, or somewhat less than one-half the wall-to-wall spacing of the concentric inner and outer walls 17, 16.

A number of lamps like that illustrated in Figs. 1 and 5 have been made by suitably reshaping the envelopes or tubes used for the 100-watt, 60-inch long fluorescent lamps commonly designated F100T17. These tubes are approximately $2\frac{1}{4}$ inches in outer diameter (17 units of $\frac{1}{8}$ inch) and consist of lime glass with a nominal wall thickness of .050 inch. Such a tube can be flattened to a cross section of approximately 1 by 3 inches in dimension. Thus flattened, the tube can hardly withstand 1 atmosphere, that is, a pressure of 15 pounds per square inch,

without imploding. However, when the tube is formed to an inverted U-shaped section as illustrated in Fig. 1, it can withstand about 2 atmospheres before implosion. Thus, the longitudinally extending re-entrant groove configuration in accordance with the invention has at least doubled the implosion resistance over that of a flattened tube of equivalent cross section.

Experience has taught that for safety in handling and long-term usage, lamp envelopes should have an implosion resistance of five atmospheres or more, round tubes being in this range. In order to increase the implosion resistance of the lamp illustrated in Fig. 1 to 5 atmospheres when made with T17 tubing, the tube wall must be made thicker, as hereinafter disclosed by way of example and discussed under the next heading. Alternatively, with the same wall thickness previously mentioned, namely .050 inch, the desired degree of implosion resistance could be achieved by reducing the cross-sectional dimensions of the tube.

(2) Improved grooved lamp cross section

A preferred embodiment of the form of my invention illustrated in Fig. 1 having a continuous groove on the underside of the tube has the cross section illustrated in Fig. 6. This cross section has been found particularly advantageous with respect to resistance to implosion.

Referring to Fig. 6, the cross section retains the general shape of a sector of an annulus with an outer convex wall 16 of minimum curvature and concentric concave inner wall 17 of greater curvature. The convex joining or edge walls 18, 18' have a curvature slightly greater than that of concave inner wall 17. The curvatures discussed herein are those of the inside surface of the glass which bounds the discharge space. However, the present cross section is modified from that disclosed in my prior co-pending application No. 475,036 "Implosion Resistant Lamp Envelopes" and illustrated in Fig. 5 of this application, in that the groove is provided with more or less straight slanting sections 19, 19' interposed between the curvatures of the top of the groove and of the edge walls. The side walls of the groove are thus outwardly divergent, that is, slanted downwardly and outwardly. Stated otherwise, the side walls of the groove are slanted like an inverted V rather than an inverted U and vertical side wall sections, such as appear in Fig. 5 at 19a, 19'a with reversals of curvature on each side, are avoided.

Grooved test lamps made with the cross section illustrated in Fig. 6 have shown an increase in implosion resistance of as much as 30 percent over that of similar test lamps made with the cross section shown in Fig. 5. Analysis of these test results indicates desirable dimensions in lamps made with T17 size tubing of nominal outer diameter $2\frac{1}{4}$ inches with a wall thickness of approximately .075 inch to be as follows. The radius of curvature T of outer wall 16 is 1.0625 inches measured to the outer surface. The radius of curvature A at 17 in the top of the groove is 0.3125 inch measured to the outer surface of the glass. The radius of curvature B of the edge walls 18, 18' is 0.3125 inch measured again to the outer surface of the glass. The center of the radii of curvature of the edge walls is located a distance C equal to 0.0938 inch below the center of the radius of curvature of the concave inner wall of the groove. The slanting side walls of the groove slope outwardly at an angle θ to the vertical which should be at least 15° in order to realize substantial benefits: in the illustrated cross section, θ is 27° .

It will be appreciated that whereas the radii A and B of the groove and of the edge walls are equal as measured, when viewed from the inside of the envelope the radius of the edge wall is actually less than that of the groove by twice the thickness of the glass. In other words, taking .3125 inch as the measured radius to the external glass surface in each case, and taking .075 inch as the thickness of the glass, the effective radius of curva-

ture of the groove as defining the discharge space is .3875 inch and that of the edge walls is .2375 inch. The radius of curvature of the edge walls as seen from the discharge space is thus less by approximately 39% than that of the groove, likewise as seen from the discharge space. These lamps show an implosion resistance of approximately 90 lbs. per square inch when tested under compressed air. The illustrated cross section thus is eminently satisfactory from the point of view of implosion resistance and in fact surpasses the implosion resistance safety requirement of 5 atmospheres. The foregoing specific lamp dimensions have been given by way of example only, and obviously the principles involved can be applied to other lamp sizes.

(3) Grooved lamp design considerations

In designing a re-entrant groove lamp, several factors must be taken into account in determining the envelope geometry or cross section. The following mathematical expressions state approximately the changing characteristics of the discharge in terms of its geometry:

$$Vg = k_1 \cdot k_2 \cdot \frac{p}{a}$$

where

Vg is the voltage gradient,
 k_1 is a constant for the vapor used,
 k_2 is a constant for a given current density,
 p is the perimeter, and
 a is the cross sectional area.

For constant efficiency in fluorescent lamps, that is, for a constant ratio of lumens per watt, the following expression holds:

$$W = \frac{p^2}{a^{3/4}}$$

where

p and a have the same significance as above, and
 W is the wattage consumption per unit length.
 The value

$$\frac{p^2}{a^{3/4}}$$

may be referred to as the figure of merit for loading. In general, the watts per foot to which a fluorescent lamp may be loaded without dropping below a given efficiency in lumens per watt will vary proportionally with the figure of merit. As a round tube is deformed out of round, as by forming a re-entrant groove, the figure of merit initially increases very slowly, but then more and more rapidly as the depth of groove increases. For the purposes of this discussion, it is convenient to refer to the degree of equivalent flattening by analogy to the simple flattened tube discussed in my Patent 2,482,421. The degree of equivalent flattening may be taken as the ratio of curved annular breadth of the discharge space, given by D in Fig. 6, to the maximum wall-to-wall spacing opposite the groove and given by E .

Equivalent flattening in a ratio of 2:1 is about the least to offer any real advantage. Any lesser degree of equivalent flattening has such slight effect on the figure of merit

$$\frac{p^2}{a^{3/4}}$$

as not to be worthwhile. Higher degrees of equivalent flattening, for instance 3:1 and up, are very decidedly advantageous.

The upper limit to the degree of equivalent flattening may be set by the characteristics of the discharge or by the structural limitations of the vitreous envelope and the necessity for avoiding sharp bends where excessive strain may develop in the glass.

The pertinent electrical characteristic of the discharge is the tendency to constrict, that is, the tendency of the diffuse positive column to draw away from the narrow

edge walls and assume a more generally cylindrical cross section. This tendency appears to be connected with the phenomenon of two stage ionization which is notably present in a discharge medium consisting of mercury vapor and an inert starting gas. The tendency to constrict may be reduced by reducing the inert gas pressure, for instance to less than 1 millimeter. With a starting gas consisting of argon at 0.5 millimeter pressure, equivalent flattening in a ratio of 6:1 is possible without excessive constriction of the plasma. Thus the cross section illustrated in Fig. 6 applied to T17 tubing gives D equal to 2.972 inches and E equal to 0.600 inch and provides an equivalent flattening of approximately 5:1; such lamps operate with the plasma substantially filling the cross section. Increase in the degree of equivalent flattening beyond 6:1 results in greater constriction of the discharge and a limit is reached, for instance at approximately 10:1 beyond which further equivalent flattening is ineffective, because the plasma will not spread out to the edges of the discharge chamber.

Closely related to the degree of equivalent flattening is the degree of taper of the wall-to-wall spacing toward the edge walls 18, 18', that is, towards the ends of the depending leg portions. As has previously been mentioned, the discharge space cross section theoretically should be a sector of an annulus. However, in practice, some taper is preferable in order to counter manufacturing variables and assure stability of the discharge. In the cross section illustrated in Fig. 6, the maximum wall-to-wall spacing over the groove is given by E equal to 0.600 inch and the minimum wall-to-wall spacing at the beginning of the edge wall curvature is given by F equal approximately to 0.475 inch. Thus, the taper is approximately

$$\frac{0.125}{0.600}$$

or 21% and this degree of taper assures stability simultaneously with substantial filling of the cross section by the plasma. With high degrees of taper, for instance, degrees of taper exceeding 50%, constrictive effects become pronounced and the plasma will not penetrate into the leg portions to the edge walls. Of course, very highly tapered cross sections, such as a lune or crescent are decidedly to be avoided because the plasma will not spread into the sharp recesses.

It is to be noted that the degree of equivalent flattening in a discharge cross section in the shape of a sector of an annulus having an open groove is immediately related to the breadth of the re-entrant groove 17 and to the depth to which the groove re-enters the circular outer wall 16. Thus, when the degree of equivalent flattening is specified, the cross section is generally determined; other characteristics, such as the degree of taper across the annular breadth of the discharge cross section and the angle of divergence of the side walls of the groove may then be determined according to the considerations which have been discussed above.

In resonance radiation lamps where secondary ionization effects are less pronounced or possibly substantially absent, as in sodium vapor lamps, theoretical considerations indicate that the tendency of the plasma to constrict should be much less. Accordingly in such lamps, the limits as to the permissible degree of equivalent flattening may exceed considerably those which have been given above for mercury resonance radiation lamps.

(4) Light distribution

The most striking feature of a resonance radiation lamp with a longitudinally extending re-entrant portion or groove is the remarkable brightness of the groove. This result is totally unexpected and none of the prior work done with flattened tubing or other non-circular shapes gave any indication of the possibility of the instant development. The high brightness in the groove produces an asymmetrical distribution of light, which, in

lighting applications, can result in an increase of as much as 50 percent in light on the working surface. The increase considered here is due entirely to the asymmetrical distribution and is in addition to the other properties of higher efficiency or loading capacity of the re-entrant groove lamp.

Referring to Fig. 7, there is shown a polar diagram of the light distribution achieved with a re-entrant groove lamp in accordance with the invention. The cross section of lamp 1 is reproduced at the center of the polar diagram and the radial distance from the center to any point on curve 21 indicates the candlepower in the direction which the point makes with the origin. Integration of the candlepower curve over a given sector gives the total luminous output or flux of the lamp in that sector. When this is done, it is found that the lamp delivers 58.6% of its flux below the horizontal and 41.4% above. Furthermore, the lamp delivers 38% of its flux in the 90° sector or quadrant which includes the groove, that is the quadrant including 45° on each side of a vertical line down from the center of the groove. It will be appreciated that with a round lamp having a symmetrical light distribution, the light flux in any quadrant is 25% of the total, so that the instant re-entrant groove configuration provides an increase of approximately 50% in light output in the lowermost quadrant.

The flux distribution pattern illustrated is highly advantageous for general illumination applications wherein it is usually desirable to increase the downward light component. With ordinary round tube lamps having a circular flux distribution, this must be achieved by the reflecting surfaces of the fixture. The fixture will introduce losses which are aggravated by dust and dirt on the fixture itself and on the upper surface of the lamp where dust readily collects. It is also frequently desirable to reduce the light component at low angles relative to the horizontal in order to cut down glare. Fixtures will ordinarily do this by means of translucent side panels which become additional sources of losses. The re-entrant groove flux distribution thus approaches of itself the ideal for many lighting applications, inasmuch as it has a reinforced downward component and reduced lateral component without any of the losses which would be incurred in achieving such redistribution by means of the fixture.

(5) Factors of efficiency

The longitudinally extending re-entrant groove configuration in a resonance radiation discharge lamp provides a considerable increase in efficiency at a given loading. Even more remarkable, however, is the fact that it provides a tremendous increase in loading capacity for a given efficiency.

Referring to Fig. 8, curves 22 and 23 illustrate respectively the luminous output of round and re-entrant groove lamps under similar conditions. Both were of 5 feet nominal length with equal perimeters, having been formed from T17 tubing. It will be observed that curve 22 for the round lamp rapidly flattens out when the loading is increased beyond the conventional 20 watts per foot, whereas curve 23 for the re-entrant groove lamp shows that the loading may be increased up to 35 watts per foot before encountering a similar degree of flattening.

Comparative tests of re-entrant groove and conventional round tube fluorescent lamps in the T17 size have shown that at loadings of 20 watts per foot, their efficiencies are approximately 59 and 48 lumens per watt, respectively, the re-entrant groove lamp being approximately 23% more efficient. Even more remarkable, however, is the fact that the re-entrant groove lamp can be loaded up to 36 watts per foot before its efficiency drops to the level of the standard T17 round lamp at its conventional 20 watt per foot loading, that is, 48 lumens per watt; thus, for the same efficiency in lumens per watt, the re-entrant groove configuration permits an increase of approximately 80% in loading.

The luminous efficiency figures considered above were determined using a halophosphate phosphor producing a standard cool white (4500° K) color with which the light conversion efficiency is nearly equal to that obtained with a standard warm white (3500° K) color, being but a few percent (2% to 4%) lower. As is well known, in the case of the standard warm white (3500° K) color, the average luminosity is approximately 47% of the luminosity of the 5540 Å. yellow-green line to which the eye is most sensitive, and the conversion by the phosphor from the 2537 Å. ultraviolet line proceeds according to a quantum ratio of approximately 44% at a utilization efficiency of approximately 86%.

Further useful increase in the loading capacity of re-entrant groove fluorescent lamps may be achieved by lowering the starting gas pressure into the range of 0.1 to 1.0 millimeters of mercury as taught in my copending application No. 475,035, filed December 14, 1954, now abandoned, entitled "Low Pressure Discharge Lamps," and assigned to the same assignee as the present invention. For instance, by using for the starting gas argon at 0.5 millimeter pressure, it is possible to achieve loadings in excess of 40 watts per foot at an efficiency at 48 lumens per watt, thus more than doubling the loading capacity over the round tube lamp at the same efficiency.

The re-entrant groove cross section has changed the entire pattern of design limits for fluorescent lamps. The minimum efficiency for a commercially acceptable fluorescent lamp intended for general illumination and producing a warm white color (3500° K) is approximately 50 lumens per watt; for a cool white color (4500° K), the efficiency may be a few percent lower. The wall loading in prior art lamps having acceptable efficiencies was generally under 0.043 watt per cm.² (0.28 watt per in.²), a much used figure being 0.02 watt per cm.² (0.13 watts per in.²); maximum linear loading was approximately 20 watts per foot, the most generally used figure being 10 watts per foot. (See for instance I.E.S. Lighting Handbook, copyright 1947 by the Illuminating Engineering Society, pages 6-40, Figs. 6-36.) The re-entrant groove cross section makes practical wall loadings up to approximately 0.08 watt per cm.², the most useful range being approximately 0.05 to 0.08 watts per cm.² (0.32 to 0.52 watts per in.²), and linear loadings up to approximately 40 watts per foot. Thus, for instance a T17 re-entrant groove lamp having a perimeter of 16.9 cm. (6.66 in.) and a cross sectional area of 12.1 cm.² (1.88 in.²) operating at 2.5 amperes arc current with a voltage drop of approximately 84 volts in a 5 foot length, consumes approximately 175 watts for a light output of 10,000 lumens at an efficiency of 57 lumens per watt, a wall loading of 0.07 watt per cm.², a linear loading of 35 watts per foot and a current density of 0.2 ampere per cm.² In practical layman's language, the foregoing example demonstrates that the invention permits the same physical size of lamp to produce twice as much light without any loss in efficiency, in fact with some gain.

It will be appreciated that the above ranges of parameters represent a radical departure from prior limits and constitute an outstanding step forward in the art.

(6) Theoretical considerations

Several factors are believed to contribute to the high efficiency and extraordinary high loading capacity in the re-entrant groove lamp.

As to why the efficiency of a lamp increases with increase of the p./a. ratio, that is as the perimeter is increased for a given area of cross section, two answers have been proposed to this question. One answer is that the smaller average distance from an excited atom in the plasma to the envelope wall allows the 2537 Å. radiation to diffuse out more quickly, so that it suffers a smaller chance of destruction by a dissipative collision. The second answer is based on the theory that the elec-

tron temperature or velocity in the ionizable medium is determined by losses to the envelope walls. An increase in the wall perimeter without a commensurate increase in the discharge cross section then produces a higher wall loss, so that the electron velocity increases to maintain the discharge, thereby enabling more effective production of 2537 Å. resonance radiation.

(7) Reduction in elastic losses

While the above explanations are believed valid, they do not show where the actual saving in wasted energy is made. It is further believed that the saving occurs in the much smaller elastic losses suffered in the tube of greater perimeter by virtue of the reduction in the electron population in the plasma.

It is estimated that in a round tube, 40-watt T12 fluorescent lamp, the elastic losses are approximately 20% of the total wattage consumption. When an electron strikes an atom and bounces off elastically, that is without excitation or ionization of the atom, a small average fraction f of its energy is imparted to the atom, given by:

$$f = \frac{m}{2M}$$

where m is the mass of the electron and M that of the atom. While this fraction is exceedingly small, the rate of collisions with gas atoms in fluorescent lamps is so large that a considerable heating of the gas results. Now the energy of the electron being proportional to electron temperature T_e , and the speed of the electron to $\sqrt{T_e}$, the energy R_L lost in this way per second per electron will be given by:

$$R_L \propto \frac{m}{2M} \cdot T_e^{3/2}$$

Theoretical considerations show that the number of electrons varies approximately inversely as the perimeter for a given cross sectional area of discharge. On the other hand, the electron temperature increases but at a much slower rate than according to the ratio of perimeters. Therefore, whereas an increase in perimeter for a given cross section will result in an increase in the total elastic loss per electron collision with an atom, this will be more than offset by the proportionally greater reduction in the total number of such collisions. The final result is a net reduction in elastic losses in the tube.

(8) Temperature distribution

Another feature of the re-entrant groove configuration, and which is believed to be an important factor in the remarkable increase in loading capacity without commensurate reduction in efficiency of the lamp, is the distribution of temperature about the cross section of the lamp when it is operated with the groove lowermost. This is the usual mode of operation inasmuch as the asymmetrical light distribution providing a greater intensity in the groove quadrant is normally utilized with that quadrant facing downward.

Actual measurements of surface temperature of T17 re-entrant groove lamps operated at 26 and 35 watts per foot in an ambient temperature of 24° C. have shown the temperature distribution given by the two columns of tabulated figures in Fig. 9. Referring to the left-hand column, it is seen that the hottest point in the cross section is the top of the groove which attains a temperature of 65° C. at a lamp loading of 26 watts per foot, while the coolest point is the bottom of the legs or joining edge walls at a temperature of 36.5° C. Referring now to the right-hand column, it is seen that increasing the wattage to 35 watts per foot raises the temperature at the top of the groove to 77.5° C., but hardly affects the temperature at the bottom of the legs or edge walls which remain at 36.5° C. All other points show an intermediate rise in temperature.

While the foregoing temperature measurements are fairly accurate relative to one another, they are only approximate as to absolute values since they were obtained through thermocouple readings. Moreover exact values in any given case will vary of course with the ambient temperature, air movement, and location of the lamp relative to other surfaces. In the same vein, a somewhat higher temperature is to be expected with the lamp mounted in a fixture, and such factors must be taken into account in designing the lamp for optimum vapor pressure in its normal environment.

Some effects of the temperature distribution described above will be discussed hereafter under the next two headings to follow.

(9) Vapor pressure regulating property

The foregoing temperature distribution demonstrates several factors which are pertinent to efficiency and to lumen maintenance. Firstly, the joining edge walls or legs are the coolest part of the lamp and their temperature hardly changes with increase in loading. This effect is believed due to increase in convection air current with increase in wattage dissipation, simultaneously with some constriction of the plasma within the lamp as the loading is increased. The constriction of the plasma or discharge causes it to draw away from the edge walls or legs of the cross section with consequent reduction in heating effect in those regions. The two factors operating together tend to maintain the temperature of the edge walls substantially constant despite increase in loading, and indicate that ambient air movement will have less effect on vapor pressure than with round tube lamps. Since the mercury vapor pressure is determined by the coolest part of the lamp (36.5° C.), it is apparent that the mercury vapor pressure will remain substantially constant at the design optimum despite the increase in loading. The optimum mercury vapor pressure may vary, of course, with different lamps, depending on factors such as the kind of starting gas, its pressure, and the current density.

Thus another unexpected and highly desirable property of the instant re-entrant groove configuration is the inherent or built-in mercury vapor pressure regulating property. It is well known, of course, that departure of mercury vapor pressure from the optimum entails a reduction in efficiency. Thus the factor of variability of mercury vapor pressure, which factor is degenerative of efficiency, is substantially reduced or avoided with the re-entrant groove cross section, and this may serve to explain in part the tremendous loading capacity of re-entrant groove lamps.

(10) Phosphor lumen maintenance

The temperature distribution achieved with the re-entrant groove cross section is believed to be moreover conducive to superior lumen maintenance. One factor of depreciation of fluorescent lamps during life is connected with condensation of mercury vapor on the phosphor coating with resulting decrease in efficiency of conversion of 2537 Å. radiation into visible light. The mercury vapor evidently will condense in the coolest part of the cross section of the tube. In the instant case, it is observed that the coolest part of the cross section is the depending legs or edge walls and the mercury vapor will naturally condense in those sections. Concurrently, the minimum condensation of mercury vapor is to be expected at the hottest part of the lamp, which is the top of the groove. As has already been pointed out, the top of the groove is the portion of the lamp that runs the brightest and which is the most effective in producing light. The bottoms of the legs or edge walls are the least effective parts of the lamp in producing light and may have a comparative brightness 30% of that of the top of the groove. Obviously, since condensation of mercury must occur somewhere in the lamp, such con-

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densation will be the least damaging in respect of reduction of efficiency if it occurs at the bottoms of the legs or joining edges, as indicated by the observed temperature distribution. Thus another unexpected benefit of the re-entrant groove configuration is the present factor of superior lumen maintenance.

(11) Physical basis of groove brightness

The brightness of the groove in the re-entrant groove configuration is one of the most striking features of the invention. This feature is believed to result from the fact that the radiation produced in the plasma is emitted by the process of diffusion. It is only with resonance radiation lamps that this process occurs to any substantial extent.

The resonance radiation of an atom is the spectral line or lines produced by the fall of the atom from the first excited state or level to the ground level. Lines of this kind are called resonance lines, and since they are the most easily produced they represent the greatest proportion of all the transitions taking place at any one instant and are the most intense of the spectral lines. In mercury, the resonance radiation line is 2537 Å. and represents the drop in potential of the mercury atom from the first excited level at 4.86 electron volts. In sodium, on the other hand, the first two excited levels are at 2.09 and 2.1 electron volts and the falls from these levels to the ground level produce 5896 and 5890 Å. visible yellow radiation. Since the final level of the transition in the case of resonance radiation is the normal state of the atom, the reverse process, namely the excitation of a normal atom by absorption of quanta of resonance radiation, is not only possible, but in view of the high population of atoms in the plasma, is highly likely. It has been estimated that the number of re-absorptions of a quantum of radiation or photon produced in a low pressure fluorescent lamp in a T12 envelope (1½ inches in diameter) is in the range of 100. In this respect, the emission of radiation from a resonance radiation lamp is totally different from the emission in the case of a nonresonance radiation lamp, such as a neon tube. In neon, for instance, 6,402 Å. visible red radiation is produced by the transition of the atom from the 18.5 to the 16.6 electron volt level. In this case, of course, re-absorption of the quantum by raising an atom at the 16.6 electron volt level to the 18.5 electron volt level is possible, but is highly improbable in view of the relatively very small population of atoms at the 16.6 level. The result is that in the neon lamp, the photon of light is emitted from the plasma directly and substantially without any reabsorption.

The diffusion of the photon in the case of resonance radiation proceeds according to the principle of the random walk. According to this principle, N advances or steps in perfectly random directions will on the average result in a progression to a point $\sqrt{N}$ steps away from the starting point. Considering the diffusion process taking place in a discharge space bounded by two cylinders of radii R and R', as shown in Fig. 10, it is possible to arrive at certain conclusions with regard to the ion or electron density in the plasma within such a discharge space. From elementary principles, the ion density n must be zero at both surfaces. There will be maximum ion density n at some radial distance R_m , as represented by the dotted circle. Inside R_m , ions will diffuse to the inner cylinder and outside R_m , they will diffuse to the outer cylinder.

Considering the principle of the random walk and the fact that ions are rushing about in all directions, it is reasonable to expect that ions will tend to congregate most densely in the region where on the whole they are farthest away from the surfaces which bring about their destruction. Referring to Fig. 10 and considering circle Q therein, this circle has its center q midway between the two boundary cylinders. Let this circle be deemed

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to represent the distance of random diffusion of ions from its center after a given time if there were no boundaries. Now it is clear upon inspection that the outer concentric cylinder R has a greater surface area (chord r) within circle Q than does the inner concentric cylinder R' (chord r'). Since the areas of the cylinders which encroach upon the circle are to some extent indicative of the ion destructive effect of the boundaries, it follows that the outer cylinder is more effective in absorbing ions originating from the center of the circle than is the inner cylinder. Accordingly, it is to be expected that R_m will be nearer to the inner cylinder than to the outer, that is:

$$R_m < \frac{R+R'}{2}$$

According to the above picturization, it is to be expected that the plasma will hug the groove and laboratory observations have shown this to be the case. The rate of generation of quanta will, in general, be proportional everywhere to the concentration of electrons (and ions). Since all are moving by diffusion, the flux of resonance quanta to the boundaries will follow the same pattern as the flux of electrons and ions. Therefore, quanta or photons generated on the inner side of circle R_m will diffuse to the inner cylinder R', whereas those generated outside R_m will diffuse to the outer cylinder R. Theoretical considerations indicate that the generation of quanta on either side of R_m is such, relative to the area of the inner and outer cylinders, that the inner cylinder R' will receive radiation at a substantially greater rate per unit area than the outer cylinder R. Inasmuch as the re-entrant groove cross section is a sector of an annulus, the same general conclusions will apply and are confirmed by the laboratory determination that the brightness of the groove is 40% brighter than the envelope wall on the opposite side. Taking into account the internal transmission of light (visible radiation, not 2537 Å. resonance radiation) from the inside surface of the groove to the envelope wall on the opposite side and which operates to reduce somewhat the relative brightness of the groove, the above 40% figure is in substantial agreement with that predicted by more rigorous mathematical treatment of the problem.

In order additionally to confirm the foregoing theory, a re-entrant groove lamp envelope with the cross section shown in Fig. 6 was filled with neon at a few millimeters pressure (about 3) instead of mercury and a starting gas. As previously mentioned, the visible radiation from neon is non-resonance radiation so that there is substantially no diffusion of this radiation caused by multiple absorption and re-emission, such radiation being emitted directly. Except at low current densities, there is very pronounced constriction; for instance, at 1.5 amperes, a comparatively low figure for a re-entrant groove lamp according to the invention, the arc constricts markedly to the center and will not spread into the dependent portions or legs bounded by the edge walls. At low currents, for instance under 100 milliamperes, the discharge begins to spread; nevertheless, the groove becomes no brighter. Except for slight lens effects, the radiation pattern, as determined by photocell measurements, is circular and substantially uniform in all directions at right angles to the longitudinal axis of the lamp, thus providing striking confirmation of the fact that the benefits of the present aspects of the invention can only be had with resonance radiation lamps.

Further confirmation of the foregoing theory is provided by the fact that the visible mercury lines (non-resonance) in a re-entrant groove lamp show no appreciable concentration in the groove. Thus if the phosphor coating is omitted from the lamp of Fig. 1 so that only the pale blue light from the visible mercury lines are seen, that light is emitted substantially uniformly in all

directions at right angles to the axis of the lamp and

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the groove appears no brighter. On the other hand if the lamp envelope is made of an ultra-violet transmitting glass as for a germicidal lamp and the 2537 A. resonance radiation pattern is measured with a suitable instrument, the concentration of 2537 A. radiation in the groove sector is again noted.

Whereas it would appear that a perfectly annular discharge space defined by concentric tubes would offer the advantage of high brightness of the phosphor surface of the inner tube, it does not realize the desired polar distribution including a reinforced downward light component, nor does it offer any solution to the problem of efficiently utilizing the light generated at the inner tube. Also a longitudinally fluted tube, that is a tube with several grooves extending longitudinally of the axis, fails to realize the advantage of the re-entrant groove cross section inasmuch as the plasma will spread only if the grooves are shallow; if they are deep, the plasma will constrict into the center in either case, the advantages of high brightness of the groove and inherent vapor pressure regulation will be substantially reduced or lost, and of course the desired polar light distribution could not in any event be achieved.

(12) Crenelated grooved lamp

Figs. 2 and 3 to 5 illustrate another lamp 31 embodying the invention and having yet greater resistance to implosion than equivalent uniformly grooved lamps. Here the envelope 32 is provided with spaced indentation or re-entrant portions 33, 34 on diametrically opposite sides giving a dimpled or crenelated appearance. The indentations 33, 34 may be considered to be short sections of a longitudinal groove alternating on opposite sides of the envelope. A cross section of the envelope through one of the indentations is similar to that of lamp 1 and is illustrated in Fig. 5. It comprises a convex outer wall 16, a concave inner wall 17, and convex edges 18, 18'. The groove sections or indentations 33, 34 are relatively short. For maximum strength of the envelope, the groove sections are preferably of a length not in excess of three tube diameters, that is, not in excess of three times the diameter of convex outer wall 16: for instance, in a T17 envelope of 2 1/4 inch diameter, the indentations may be 3-4 inches long. The groove sections may of course be made longer, but at the expense of some reduction in implosion resistance. Lamp 31 is provided, as is lamp 1, with circular tube ends 3, 3 to which are attached the usual bases 4, 4. In all other respects, lamp 31 may be similar to lamp 1 and including similar electrodes and filling within the envelope.

A number of lamps 31 made from T17 tubing of .040 to .050 inch wall thickness have passed 70 pounds per square inch pressure tests, and have since been standing at atmospheric pressure without implosion for a period of time well in excess of two years as of the filing date of this application. Thus, the interrupted groove or crenelated configuration of envelope 32 provides a discharge lamp having an implosion resistance well within the requirement for a practical lamp. Such a configuration entails an increase of approximately 50 percent in ratio of circumference or perimeter to area when averaged over the entire length of the envelope including the re-entrant portions and the intervening gaps, and is equivalent to flattening in a ratio of approximately 3 to 1. Lamps so constructed have been operated and found to yield approximately 20 percent more light than equivalent conventional round lamps under the same operating conditions. When the dimpled lamps were operated at a wattage to yield the same efficiency as the conventional round tube lamps of the same perimeter, the lumen output of the dimpled lamps was approximately 60 percent higher.

Crenelated grooved lamp 31 shows in general operating characteristics similar to those of continuously

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grooved lamp 1, but modified in accordance with the alternation of the groove sections on opposite sides. Both the upward and downward facing groove sections operate with enhanced brightness, so that the polar diagram of the luminous output shows reinforced upward and downward components while the lateral components are reduced. If the groove sections are of equal length on both sides of the tube as shown in Fig. 3, the upward and downward components of the luminous output will be equally reinforced: by making the groove sections unequal in length, for instance by making the groove sections in the underside longer than in the top side, the downward light component may be reinforced more than the upward component.

(13) Implosion resistance

The vastly improved implosion resistance of vitreous tubes or envelopes, in accordance with my invention, is explainable by two principles which may be applied either singly or jointly. The first principle is that the distribution of stress resulting from increasing the area of an envelope by means of a re-entrant portion makes better use of the physical characteristics of thin-walled envelopes made of vitreous materials, such as glass, which have low resistance to bending moments. This principle explains the increase in implosion resistance afforded by the transversely re-entrant longitudinal groove configurations of the envelope in Fig. 1. The second principle is that the provision of double curvature, that is curvature in two intersecting planes, in a vitreous body provides a definite increase in strength inasmuch as it effects a conversion of bending moments into compressive stresses by providing compressive or tensile support around the entire periphery of doubly curved areas, and is applicable, along with the first principle, to the interrupted groove configuration of the envelope of Fig. 2.

On the basis of the first principle, the improved implosion resistance of the envelope with a longitudinally extending transversely re-entrant portion illustrated in Figs. 1 and 2 may be explained by analogy to a flat tube which has been bent into an inverted U-shape. By bending into a U-shape, the strain in the convex outer wall 16 and in the concave inner wall 17 reduces the strain in the convex joining edges 18, 18' (Figs. 5 and 6). Thus the stresses and the resulting strains are distributed over four radii instead of over the two radii of the narrow edges in the plain flattened tube. Accordingly, the strains developed are less and, for a given thickness of envelope wall, the strength is greater than in the case of the flat tube.

The second principle involved is that of double curvature and it applies to the crenelated grooved lamp of Fig. 2. The situation may be analogized to the conversion of radial forces due to the atmosphere acting on an evacuated sphere, into compressive stress in the walls of the sphere. Another way of viewing the matter is that a glass area of double curvature may be considered to be supported in tension or compression on all four sides instead of on two sides only as in the case of a glass area of single curvature. According to formulae well known in the art of Strength of Materials, the stress developed in a thin sheet by the application of a force at the center thereof varies inversely as the square of the thickness when the sheet is supported on two opposite sides only, and inversely as the cube of the thickness of the sheet when it is supported on all four sides. Thus, referring to the envelope illustrated in Fig. 2, it can be seen that as the indentations are made short enough, they approach the condition of being supported all around instead of axially along the edges only. Thus, the condition of a thin sheet supported on all four sides is approximated and the stress in the envelope walls is reduced accordingly.

(14) Manufacture

Several methods may be used to form the various enve-

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lopes shapes of Figs. 1 and 2. For small production, the most economical is heating a suitable round envelope or tube, either before or after internal coating with the phosphor, to a plastic temperature, positioning the envelope into a suitable heated mold, and then clamping the mold about the tube and allowing the whole to cool slowly below the strain point of the glass. Where the curves are relatively sharp, as in the envelope of Fig. 2, a puff of a suitable gas may be blown into the tube to force the walls of the tube to conform closely throughout to the walls of the mold. Where the envelope has been coated with phosphor prior to the molding operation, the gas blown into the tube should be of a non-oxidizing kind in order to avoid spoiling the phosphor. For higher production rates the tubing may be shaped as it is drawn from the glass furnace by using molds in the form of rotating wheels with grooved and suitably shaped circumferences to form the tubing to the desired shape. For the envelope of Fig. 2 two such wheels with grooves of generally circular cross section but having therein up-standing bosses alternately spaced in each wheel, may be placed at a point in the line of draw of the tubing where the glass is still plastic enough to form the depressions or indentations.

While certain specific embodiments of the invention have been illustrated and described in detail, various modifications will readily occur to those skilled in the art. It will be appreciated that whereas these embodiments have been described with envelopes of glass, the features of the invention relating to the inherent operating characteristics of the re-entrant groove discharge device or lamp, such as higher efficiency, increased loading capacity, temperature regulation, spreading or non-construction of the plasma and enhanced transmission to the groove walls, are not necessarily or inherently dependent upon use of glass or vitreous envelopes. In the case of a lamp of course, a radiation transmitting material must be used, however it need only be pervious to the radiation desired to be emitted. For a fluorescent lamp where the internal phosphor coating converts the 2537 Å. radiation to visible light, a material pervious to visible light suffices; for a germicidal lamp on the other hand, a material pervious to ultraviolet (2537 Å.) is required; for a so-called black light lamp, it may be desirable to use material opaque to the visible spectrum but pervious to the desired ultraviolet; or again, as in sun-tanning lamps, it may be desired to use an envelope material pervious to the desired erythral radiations along with a phosphor to effect conversion of the resonance radiation to the erythral (long-wave ultraviolet). The appended claims are intended to cover any such modifications coming within the true spirit and scope of the invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. An electric discharge device comprising an elongated generally tubular envelope of vitreous material, a pair of electrodes sealed into opposite ends thereof, and an ionizable medium within said envelope comprising an inert starting gas at a low pressure and a small quantity of mercury, said envelope having transversely re-entrant portions extending longitudinally substantially the length thereof, said re-entrant portions providing a generally kidney-shaped cross section and being proportioned in depth and curvature to afford an average ratio of circumference to area of cross section for said envelope equivalent to that of a cylindrical envelope flattened in a ratio in excess of two to one.

2. An electric discharge device comprising an elongated generally cylindrical thin-walled envelope of vitreous material, a pair of electrodes sealed into opposite ends thereof, and an ionizable medium within said envelope comprising an inert starting gas at a low pressure and a small quantity of mercury, said envelope having a transversely re-entrant groove extending continuously substantially the length thereof to provide a generally

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kidney-shaped cross section affording a ratio of circumference to area equivalent to that of a cylindrical envelope flattened in a ratio in excess of 2 to 1 but having an implosion resistance substantially greater than that of said equivalent flattened envelope.

3. An electric discharge device comprising an elongated generally cylindrical envelope of vitreous material, a pair of electrodes sealed into opposite ends thereof, and an ionizable medium within said envelope comprising an inert starting gas at a low pressure and a small quantity of mercury, said envelope having longitudinally extending transversely re-entrant spaced portions of length comparable to the maximum diameter of said envelope and providing a generally kidney-shaped cross section.

4. A low-pressure positive column discharge lamp comprising an elongated tubular thin-walled vitreous envelope, a pair of electrodes sealed into opposite ends thereof, and an ionizable medium within said envelope comprising an inert starting gas at a low pressure and a small quantity of mercury, said envelope having transversely re-entrant portions extending longitudinally substantially the length thereof, said re-entrant portions providing a generally kidney-shaped cross section and being proportioned in depth and curvature to afford an average ratio of circumference to area of cross section for said envelope equivalent to that of a cylindrical envelope flattened in a ratio in excess of two to one.

5. A low-pressure positive column discharge lamp comprising an elongated tubular thin-walled vitreous envelope, a pair of electrodes sealed into opposite ends thereof, and an ionizable medium within said envelope comprising an inert starting gas at a low pressure and a small quantity of mercury, said envelope having longitudinally extending transversely re-entrant portions of length comparable to the maximum diameter of said envelope and alternating on opposite sides thereof and providing a generally kidney-shaped cross section.

6. A low pressure electric discharge device comprising an elongated envelope having electrodes sealed into opposite ends and containing an ionizable medium wherein an electric discharge maintains a plasma containing atoms at an excited level which emit quanta of resonance radiation as a result of transitions back to the normal ground level which quanta eventually reach the plasma boundary by the process of resonance radiation diffusion, said envelope defining a discharge space having the general cross section of a sector of an annulus to allow substantial diffusion of the plasma therethrough.

7. A low pressure electric discharge lamp comprising an elongated radiation pervious envelope having electrodes sealed into opposite ends and containing an ionizable medium wherein an electric discharge maintains a plasma containing atoms at an excited level which emit quanta of resonance radiation as a result of transitions back to the normal ground level which quanta eventually reach the plasma boundary by the process of resonance radiation diffusion, said envelope defining a discharge space having the general cross section of a sector of an annulus wherein the rate of transmission of resonance radiation to the inner annular wall portion per unit area substantially exceeds that to the outer annular wall portion.

8. A low pressure electric discharge lamp comprising an elongated radiation pervious envelope having electrodes sealed into opposite ends and containing an ionizable medium wherein an electric discharge maintains a plasma containing atoms at an excited level which emit quanta of resonance radiation as a result of transitions back to the normal ground level which quanta eventually reach the plasma boundary by the process of resonance radiation diffusion, said envelope having an outer wall of generally circular section and a longitudinally extending groove forming a re-entrant wall portion defining with the circular wall portion a discharge space

having the general cross section of a sector of an annulus wherein the re-entrant wall portion receives resonance radiation from the plasma per unit area at a rate substantially in excess of that of the mean unit area of the envelope.

9. A lamp according to claim 8 having a vitreous envelope and wherein the cross section of the discharge space has a ratio of annular breadth to maximum annular wall-to-wall spacing in excess of 2:1 whereby to provide a substantial increase in the ratio of perimeter to area over a circular sectioned envelope of the same perimeter in a lamp having substantially greater implosion resistance than an equivalently flattened envelope and simultaneously realizing thereby a higher rate of transmission of resonance quanta per unit area of the re-entrant groove wall portion than through the mean unit area of the envelope.

10. A low pressure positive column fluorescent lamp comprising an elongated vitreous envelope having electrodes sealed into opposite ends and containing an ionizable medium including an inert starting gas and mercury vapor wherein an electric discharge maintains a plasma containing mercury atoms at an excited level which emit quanta of resonance radiation as a result of transitions back to the normal ground level which quanta eventually reach the plasma boundary by the process of resonance radiation diffusion, said envelope having an outer wall of generally circular section and a longitudinally extending groove forming a re-entrant wall portion defining with the circular wall portion a discharge space having the general cross section of a sector of an annulus and wherein the re-entrant wall portion receives resonance radiation from the plasma per unit area at a rate substantially in excess of that of the mean unit area of the envelope, and a phosphor coating on the internal surface of said envelope responsive to said resonance radiation and achieving in said re-entrant wall portion a substantially higher brightness than over the remainder of the envelope.

11. A low pressure positive column lamp comprising an elongated vitreous envelope having electrodes sealed into opposite ends and containing an ionizable medium including an inert starting gas and mercury vapor wherein an electric discharge maintains a plasma containing mercury atoms at an excited level which emit quanta of 2537 A. resonance radiation as a result of transitions back to the normal ground level which quanta eventually reach the plasma boundary by the process of resonance radiation diffusion, said envelope having an outer wall of generally circular section and a longitudinally extending groove forming a re-entrant wall portion defining with the circular wall portion a discharge space having the general cross section of a sector of an annulus and wherein the re-entrant wall portion receives resonance radiation from the plasma per unit area at a rate substantially in excess of that of the mean unit area of the envelope, the degree of equivalent flattening of said envelope as determined by the ratio of annular breadth to maximum annular wall-to-wall spacing in the discharge space being between the limits of 2:1 and 10:1, and the degree of taper in the wall-to-wall spacing in said annular discharge space being less than 50% from the center to the edges.

12. A fluorescent lamp according to claim 11 which includes a phosphor coating on the internal surface of the envelope responsive to 2537 A. radiation and achieving in said re-entrant wall portion a substantially higher brightness than over the remainder of the envelope.

13. A low pressure positive column resonance radiation lamp comprising an elongated vitreous envelope having electrodes sealed into opposite ends and containing an ionizable medium including an inert starting gas at a low pressure and mercury vapor wherein an electric discharge maintains a plasma containing mercury atoms at an excited level which emit quanta of 2537 A. resonance

radiation as a result of transitions back to the normal ground level which quanta eventually reach the plasma boundary by the process of resonance radiation diffusion, said envelope defining a discharge space having the general cross section of a sector of an annulus wherein the inner annular wall portion receives resonance radiation from the plasma per unit area at a rate substantially in excess of that of the mean unit area of the envelope and wherein wall loadings in the range of 0.05 to 0.08 watt per cm.² result in optimum mercury vapor pressure for generation of 2537 A. radiation.

14. A low pressure positive column resonance radiation lamp comprising an elongated vitreous envelope having electrodes sealed into opposite ends and containing an ionizable medium including an inert starting gas at a low pressure and mercury vapor wherein an electric discharge maintains a plasma containing mercury atoms at an excited level which emit quanta of 2537 A. resonance radiation as a result of transitions back to the normal ground level which quanta eventually reach the plasma boundary by the process of resonance radiation diffusion, said envelope having an outer wall of generally circular section and a longitudinally extending groove forming a re-entrant wall portion defining with the circular wall portion a discharge space having the general cross section of a sector of an annulus and wherein the re-entrant wall portion receives resonance radiation from the plasma per unit area at a rate substantially in excess of that of the mean unit area of the envelope, said lamp having a degree of equivalent flattening as determined by the ratio of annular breadth to maximum annular wall-to-wall spacing in the discharge space in the range of 2:1 to 10:1 and being operable with wall loadings in the range of 0.05 to 0.08 watt per cm.² for optimum mercury vapor pressure for generation of 2537 A. radiation.

15. A lamp according to claim 14 supporting linear loadings from 20 to 40 watts per linear foot to effect optimum mercury vapor pressure for generation of 2537 A. radiation.

16. A low pressure positive column fluorescent lamp comprising an elongated vitreous envelope having electrodes sealed into opposite ends and containing an ionizable medium including an inert starting gas at a low pressure and a small quantity of mercury wherein an electric discharge maintains a plasma containing atoms at an excited level which emit quanta of 2537 A. resonance radiation as a result of transitions back to the normal ground level which quanta eventually reach the plasma boundary by the process of resonance radiation diffusion, said envelope having an outer wall of generally circular section and a longitudinally extending groove forming a re-entrant wall portion in its underside which defines with the circular wall portion an inverted U-shaped discharge space having the general cross section of a sector of an annulus and wherein the groove portion receives resonance radiation from the plasma per unit area at a rate substantially in excess of that of the mean unit area coating on the internal surface of said envelope responsive to said resonance radiation and achieving in the groove a substantially higher brightness than over the remainder of the envelope resulting in a polar light distribution pattern providing an increase of approximately 50% in light output in the quadrant of the cross section which includes the groove.

17. A fluorescent lamp according to claim 16 having a degree of equivalent flattening as determined by the ratio of annular breadth to maximum annular wall-to-wall spacing in the discharge space in the range of 2:1 to 10:1 and being operable with wall loadings in the range of 0.05 to 0.08 watt per cm.² and linear loadings from 20 to 40 watts per foot to effect optimum mercury vapor pressure for generation of 2537 A. radiation in the range of 1 to 20 microns as determined by the temperature at the lower ends of the legs of the inverted U-

shaped cross section, and a light generation efficiency not substantially less than 50 lumens per watt.

18. A fluorescent lamp according to claim 16 having a degree of equivalent flattening as determined by the ratio of annular breadth to maximum annular wall-to-wall spacing in the discharge space of approximately 5:1, and supporting a wall loading of approximately 0.07 watt per cm.², a linear loading of approximately 35 watts per foot, with an average current density of approximately 0.2 ampere per cm.² throughout the cross section of the discharge space to effect generation of 2537 A. radiation at approximately optimum mercury vapor pressure in the range of 1 to 20 microns as determined by the temperature at the lower ends of the legs of the inverted U-shaped cross section, and a light generation efficiency not substantially less than 50 lumens per watt.

19. An evacuated electric device comprising an elongated vitreous envelope of generally tubular form having a longitudinally extending transversely re-entrant groove portion defining a cross section of the general shape of a sector of an annulus bounded by a convex outer wall of minimum curvature, a concave inner wall of greater curvature, convex edge walls of maximum curvature having a radius of curvature less than that of the concave inner wall to an extent not exceeding 50%, said convex edge walls being joined to the convex outer wall, and outwardly diverging substantially straight wall sections inclined at an angle of at least 15° to the medial plane of the groove joining the concave inner wall to the convex edge walls, whereby to realize a substantial increase in the ratio of perimeter to area along with maximum implosion resistance of the envelope.

20. A device according to claim 19 wherein said concave inner wall has a radius of curvature approximately one-third that of the convex outer wall.

21. A device according to claim 19 wherein said concave inner wall has a radius of curvature approximately one-third that of the convex outer wall and wherein the inclination of the outwardly diverging wall sections to the medial plane of the groove is approximately 27°.

22. A low pressure positive column fluorescent lamp comprising an elongated vitreous envelope of generally tubular form having electrodes sealed into opposite ends and containing an ionizable medium including an inert starting gas at a low pressure and a small quantity of mercury wherein an electric discharge maintains a plasma containing atoms at an excited level which emit quanta of 2537 A. resonance radiation as a result of transitions back to the normal ground level which quanta eventually reach the plasma boundary by the process of resonance radiation diffusion, said envelope having a longitudinally extending transversely re-entrant groove portion defining a cross section of the general shape of a sector of

an annulus bounded by a convex outer wall of minimum curvature, a concave inner wall of greater curvature, convex edge walls of maximum curvature having a radius of curvature less than that of the concave inner wall to an extent not exceeding 50%, said convex edge walls being joined to the convex outer wall, and outwardly diverging substantially straight wall sections inclined at an angle of at least 15° to the medial plane of the groove joining the concave inner wall to the convex edge walls, and a phosphor coating responsive to said 2537 A. radiation on the internal surface of said envelope.

23. A resonance radiation lamp comprising an elongated vitreous envelope having electrodes sealed into opposite ends and containing an ionizable medium wherein an electric discharge maintains a plasma containing atoms at an excited level which emit quanta of resonance radiation as a result of transitions back to the normal ground level which quanta eventually reach the plasma boundary by the process of resonance radiation diffusion, said envelope having an outer wall of generally circular section and a plurality of longitudinally extending groove portions alternating on opposite sides of the envelope and forming re-entrant wall portions defining with the circular wall section a discharge space having the general cross section of a sector of an annulus and wherein the re-entrant wall portions receive resonance radiation from the plasma per unit area at a rate substantially in excess of that of the mean unit area of the envelope.

24. A lamp according to claim 23 wherein the length of the re-entrant wall portions is not in excess of approximately 3 times the maximum diameter of said envelope.

25. A lamp according to claim 23 wherein the ionizable medium includes an inert starting gas and mercury vapor producing 2537 A. resonance radiation, and wherein the degree of equivalent flattening of the envelope as determined by the ratio of annular breadth to maximum annular wall-to-wall spacing opposite the re-entrant wall portions lies in the range of 2:1 to 10:1.

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