

June 13, 1944.

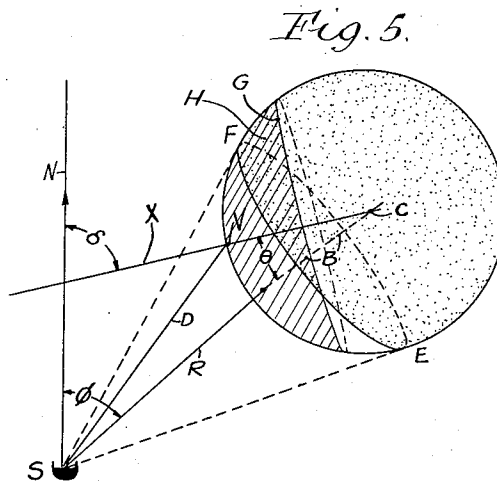
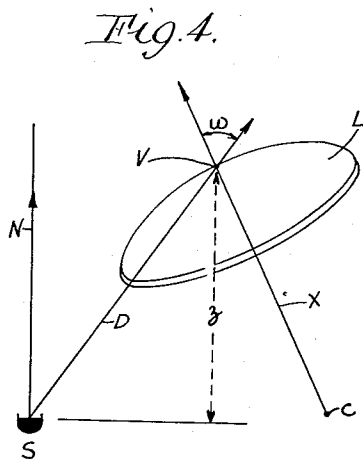
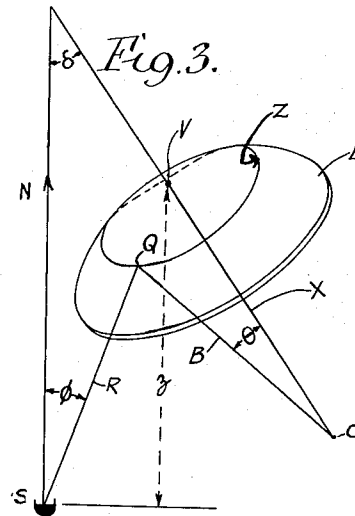
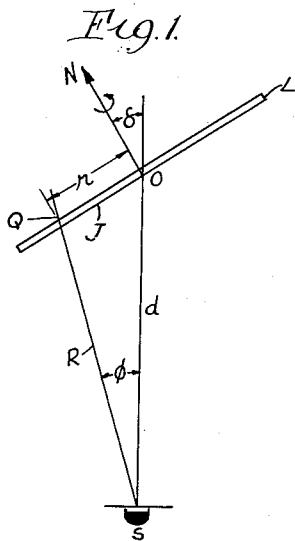
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2,351,536

METHOD OF TREATING SURFACES

Filed April 25, 1941

3 Sheets-Sheet 1



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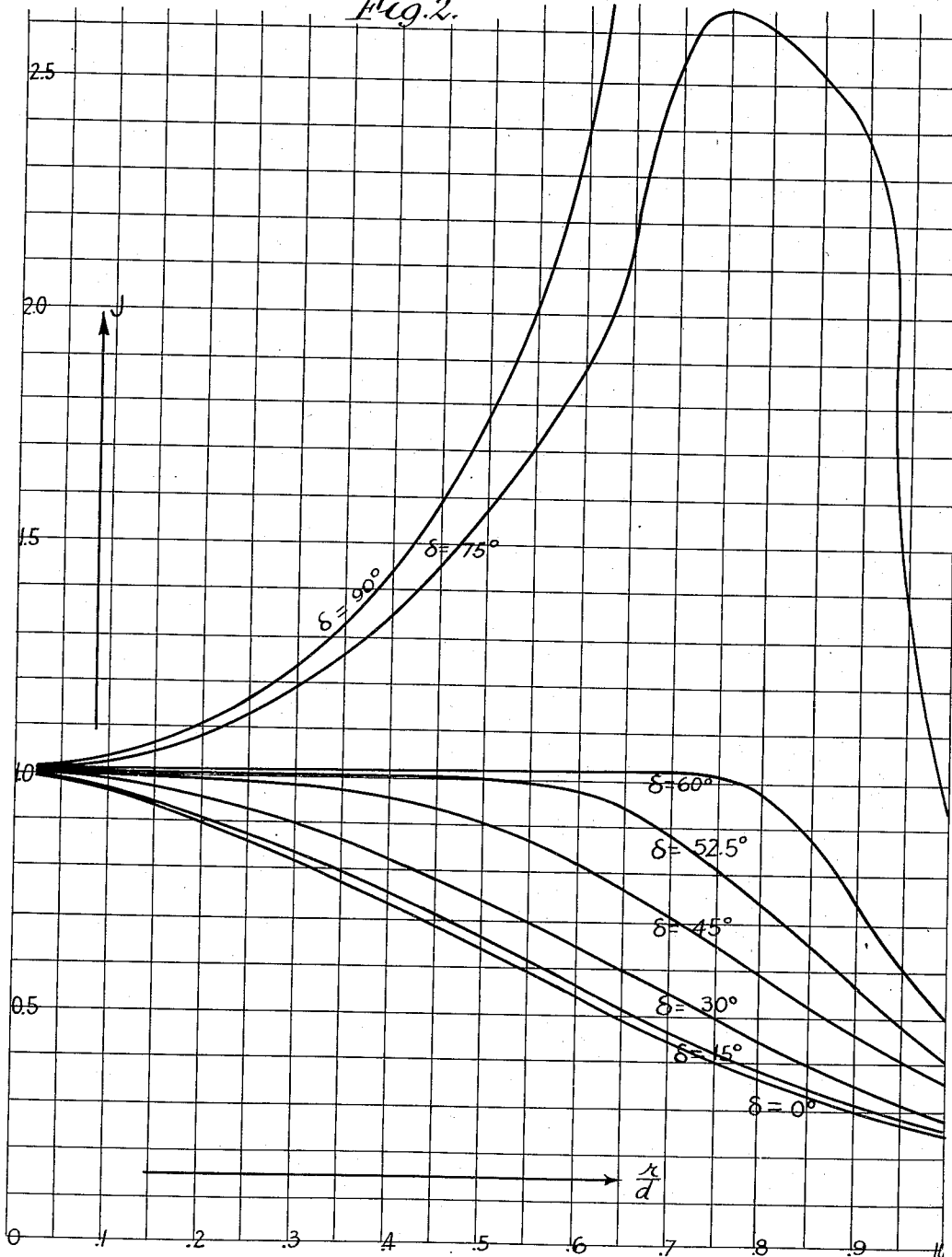
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METHOD OF TREATING SURFACES

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3 Sheets-Sheet 2

Fig. 2.



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METHOD OF TREATING SURFACES

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3 Sheets-Sheet 3

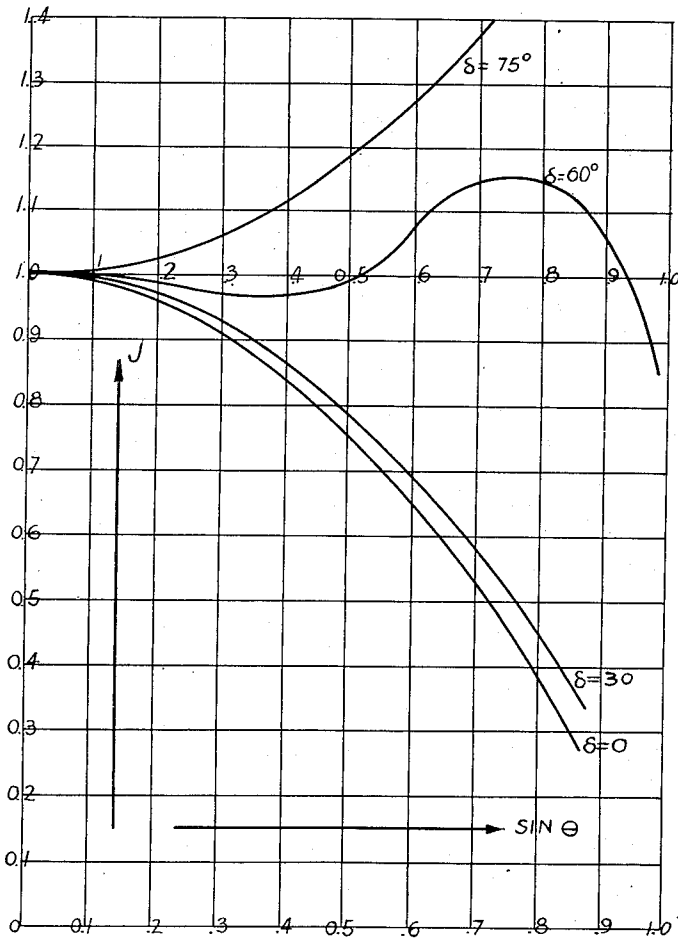
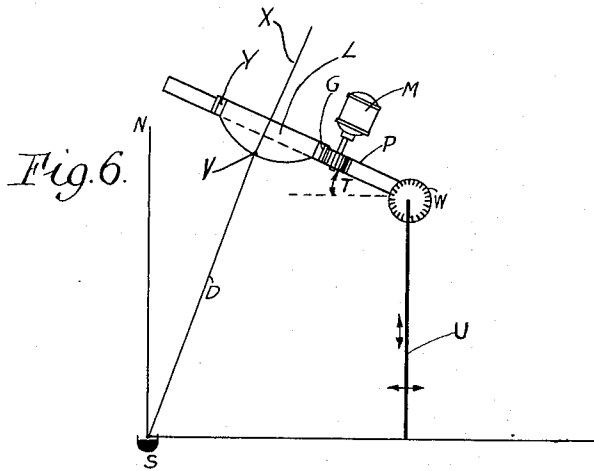


Fig. 7.

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2,351,536

METHOD OF TREATING SURFACES

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Application April 25, 1941, Serial No. 390,428

3 Claims. (Cl. 117-107)

This invention relates to a new and improved method and apparatus for treating the surfaces of articles and to articles so treated, and relates particularly to the treatment or coating of a surface of a light transmitting article to substantially eliminate the reflection of light from such surface or to change the contour of the surface and thereby alter the light transmitting and refracting properties of the article.

An object of the invention is the provision of a process and apparatus for treating or coating a surface of an article by which the amount and distribution of the coating may be definitely controlled.

Another object of the invention is to provide a new and improved method and apparatus for coating the surfaces of articles whereby the amount and distribution of the coating may be definitely controlled to provide a uniform coating over the entire surface regardless of whether the surface to be coated is flat or plano or spherical or other contour.

Another object of the invention is the provision of a process and apparatus for coating articles which allows definitely controlled variation in the thickness of the coating.

Another object of the invention is the provision of a process and apparatus for coating a surface of an article by which there may be obtained a controlled variation in thickness of the coating at will over the surface.

Another object of the invention is the provision of a process and apparatus for coating a surface of an article which allows the coating of larger surfaces than has previously been possible.

Another object of the invention is to provide a new and improved method and apparatus for coating steeply curved surfaces, particularly spherical.

Another object of the invention is the provision of an apparatus for coating the surfaces of articles, which apparatus will accommodate a great variety in the contour of the surfaces to be coated without the employment of any auxiliary apparatus.

Another object of the invention is the provision of a new and improved method and apparatus for coating a surface of an article whereby the amount and distribution of the coating may be definitely controlled and wherein the coating material is such as to alter the contour of the article to vary the light transmitting or refracting properties thereof, for ex-

ample, transforming a spherical lens surface to an aspheric surface.

Another object of the invention is to provide a new and improved method and apparatus of altering the surface of one or more lens elements of a lens system to vary the light transmitting or refracting properties of the lens system.

Another object of the invention is to provide articles having their surfaces treated or coated by the process and apparatus set forth herein.

Another object of the invention is to provide a process and apparatus of the type set forth which is simple, efficient, convenient and economical of construction and operation.

Other objects and advantages of the invention will be apparent from the following description taken in connection with the accompanying drawings and it will be understood that many changes may be made in the details of construction, arrangement of parts and steps of the process without departing from the spirit of the invention as expressed in the accompanying claims. We therefore do not wish to be limited to the exact details of construction, arrangement of parts and steps of the process shown and described as the preferred forms only have been shown by way of illustration.

Referring to the drawings:

Fig. 1 is a diagrammatic view illustrating the invention as applied to a plate having a plane surface;

Fig. 2 is a chart showing the distribution of the coating material over the surface of a plane plate when the plate is coated according to this invention;

Fig. 3 is a diagrammatic view showing the application of the invention to the coating of concave spherical surfaces;

Fig. 4 is another diagrammatic view of the invention as applied to the coating of concave spherical surfaces;

Fig. 5 is a diagrammatic view showing the invention as applied to convex spherical surfaces;

Fig. 6 is a diagrammatic view of an apparatus that may be employed for carrying out the invention; and

Fig. 7 is a chart showing the distribution of the coating material over the surface of a convex spherical surface when the surface is coated according to this invention.

The usual method of coating a surface of articles by evaporation from a source has been to place the plate or article having the surface

to be coated or treated above the source with the center of the plate on a line normal to the source and with the plane of the plate approximately perpendicular to the normal to the source. It is well known that in this case the center of the plate will receive a thicker deposit than will be received by the outer zones of the plate.

In the past attempts have been made to overcome the above nonuniformity in the deposit on the plate. One of these methods involved the use of several sources of the material to be evaporated with the sources distributed so as to give an approximately uniform deposit. One of the difficulties with this technique is that it requires many sources of the material to be evaporated and distribution of such sources must be varied from one setup to another. Another technique which has been employed has been to interpose rotating sectors between the source of the material to be evaporated and the plate to be coated in such a manner as to increase the relative deposit at the outer edges of the plate. While this gives good control for a plane plate, it does not permit the use of one sector for several set-ups, involves laborious calculations of sector dimensions, and slows down the rate of evaporation and is hardly applicable to convex spherical surfaces of small radii of curvature.

By employing the process and apparatus of this invention the amount and distribution of the coating or deposit may be definitely controlled.

The method and apparatus herein disclosed have varied uses and by employing different coating materials may be used for many purposes. One example of a use of the invention is for coating reflectors or the like with a reflective metallic coating of aluminum or other reflective metals to form a mirror, reflector or partial reflector. Another example is where the coating material is of the type set forth in Patent No. 2,207,656 to Cartwright and Turner, non-reflective coatings may be formed on the surfaces of prisms, lenses, windows, or other light transmitting articles.

Another important advantage of this method and apparatus is that it allows lenses or other light transmitting articles to have molecules deposited on the surface thereof so as to change the curvature of the surface of said lens or article. For example, by properly controlling the amount and distribution of the coating or deposit, a spherical lens surface may be transformed into an aspherical surface.

The method and apparatus of this invention also enables one to secure a substantially uniform coat over the entire surface to be coated, or a coat which is thicker at the edge than at the center, or a coat which is thinner at the edge than at the center or other controlled distribution of the coating material and permits definite control of the distribution from one extreme to the other over any part or all of the surface of the article to be coated.

In the evaporation of non-reflective films as disclosed in the Cartwright and Turner patent, the deposit at the edge of the surface should theoretically be greater or thicker than at the center of the surface, whereas with the methods previously employed such as that described in the Cartwright and Turner patent, the deposit obtained at the edge is less than that obtained at the center.

The method and apparatus of this invention also allows the coating of the surfaces of larger

articles than has been possible with prior methods.

The method and apparatus of this invention also allows of its adaptation from one set-up to another with only minor adjustments.

Because of the accuracy and definite control of the thickness and variation of thickness of the coating or film it is possible to obtain greater elimination of reflection of the surfaces of articles than was previously obtained.

The method and apparatus described herein are simple, efficient, convenient and economical of construction and operation.

The present invention may be employed for a large number of uses and with a large number of materials although we preferably use the same for coating the surfaces of such articles as lenses, prisms, reflectors, plates or the like made of glass, metal, Celluloid, quartz, transparent plastic, or resin compositions, or similar substances.

It is pointed out that while examples of the present invention particularly described herein set forth coating of surfaces by the evaporation of the coating substance in a vacuum, it may also be employed for the coating of many other substances by adapting the method and apparatus for the particular situation.

Referring more particularly to the drawings wherein similar reference characters designate corresponding parts throughout:

It is well known that in accordance with the cosine law of distribution, when molecules of the coating substance are evaporated from a source that the greatest intensity of the molecules emitted occurs along the normal to the source and falls off as a cosine of the angle of emission from said normal.

Referring to Fig. 1, it will be seen that S is the evaporating source and that S—O is the normal to said source S and that therefore according to the cosine law mentioned above the greatest intensity of the molecules emitted by said source S will be along the said normal S—O.

The source of the coating material S and plate L, the surface J of which is to be coated, are placed in a vacuum.

The plate L is pivotally mounted at its center O about its axis N. The angle or variation of the axis N of the plate L from the normal d of the source S is varied to obtain the desired control in the coating or deposit on the surface of the plate L. We have found that by properly choosing the angle δ that the coating on the surface of the plate L may be made substantially uniform or may be controlled to give a thicker coating from the edge of the center of the plate or a thinner coating from the edge to the center of the plate as desired.

In order to tilt the plate L to the necessary angle to obtain the desired coating and to compute such necessary angle, we first take a point Q which may be any arbitrary point between the center O and the outer edge of the plate L. To consider the variation of the deposit over the surface of the plate L it is convenient to refer to Fig. 1. The center O of the plate L is held at a distance d above the source S and is located on the normal to the source S. This source is assumed to obey the cosine law of emission with angle ϕ . The plate is rotated about its normal and with such angular velocity that many rotations are made during the process of evaporation. As a result of this rotation all arbitrary points Q located at a distance r from the center O can be shown to receive uniform deposit. It

is convenient to think of the locus of these points as forming a zone. Let J be defined as the ratio of thickness of deposit at the zone r to the thickness of deposit at the point O , the center of the plate L . From theoretical considerations we now find that

$$J = \frac{\left(1 + \frac{r^2}{d^2} \cos 2\delta\right)}{\left(1 + \frac{r^4}{d^4} + 2\frac{r^2}{d^2} \cos 2\delta\right)^{3/2}}$$

It will be noted that J depends on the ratio

$$\frac{r}{d}$$

and upon the angle of tilt δ . It has therefore been convenient to plot J as a function of the ratio

$$\frac{r}{d}$$

for different values of δ in Fig. 2.

The curve for $\delta=0$ gives the variation of the deposit for the prior art types of coating methods described above where the plate was held perpendicular to the normal from a single source. As the plate is tilted from this position from $\delta=0$ to $\delta \approx 60^\circ$, J becomes closely equal to unity for a long range of r , that is, the deposit becomes substantially uniform, in particular excellent uniformity is obtained or to

$$\frac{r}{d} = .8$$

This means that a plate of diameter equal to 1.6 times the distance d can be uniformly evaporated. As an example, if the point O in the plate is held 10 inches above the source S so that d is equal to 10 inches, a plate having a diameter of 16 inches can be uniformly evaporated by having the angle δ approximately 60° . We have found that when J is less than .85 so that the deposit in the corresponding zone r is 85% of the deposit at the center, the variation from uniformity was as large as can be tolerated. From Fig. 2 we note that this occurs for the value

$$\frac{r}{d} = .25$$

or for a plate whose diameter is $.5 \times d$. Note that if this plate diameter is maintained and δ made equal to 60° , very marked increase in uniformity results. This means that if increased plate diameters are not employed, corresponding increases in uniformity of deposit can be had by this method over prior art.

Further, if δ is increased above 60° , the deposit at outer zones of the plate is thicker than the deposit for the inner zones. Thus, wide variations in this deposit can be obtained by varying δ from $52\frac{1}{2}^\circ$ to 90° . It is in fact advantageous in coating lens systems with non-reflective films not to use a uniform deposit, but deposits which are thicker at the edge of the plate than at the center. This results from the fact that the angles of incidence at the outer zones in lens systems are ordinarily different from 0° , so that a larger thickness of coat is here required to produce an optical path difference of $\frac{1}{4}$ wavelength than is necessary at the center of the lens or along the axis of the lens where the incidence is more nearly normal for all bundles of rays. It will therefore be seen that great variations in the uniformity of deposit can be obtained by varying δ . If uniformity of deposit is desired, very marked increases in uniformity can be ob-

tained for a given diameter of plate. If, on the other hand, larger surfaces and increased production is desired, the maximum allowed diameter can be increased at slight sacrifices in uniformity.

It will be understood that we are not limiting ourselves to a choice of center O of the plate L located on the normal d to the source and also it is not necessary for the normal to the plate to intersect the normal of the source. We have found, however, that for most practical purposes it is most useful, convenient and effective to place the center O upon the normal d of the source. The theory of this more general case of orientation of the plane plate follows from the general theory of the sphere by letting the radius become infinity.

In Fig. 3 is shown the application of the same principle to the coating of concave spherical surfaces. In this figure are shown a concave spherical surface element L of radius X and center C , the source S with its normal N and an arbitrary point Q located in a zone Z upon said spherical surface between the edge and center thereof. As this concave surface element is rotated about its optic axis CV , the thickness of deposit upon zone Z becomes uniform. Any zone Z is distinguished by the angle θ formed by the line B connecting a point Q upon said zone Z and the center C , and the line of the optical axis CV of the concave surface element. The vertex of the surface element is located at V .

The zone Z is an infinitesimally narrow strip of area along the indicated curve or line.

In Fig. 4 D and ω are defined and represented for both concave and convex spherical surfaces. D is the distance from the source to the vertex V . ω is the angle formed by the line D and the optical axis X of the spherical element. From a knowledge of the location of the source S , the center C of the spherical surface element and its vertex V , ω may be computed. For computing the variation of the deposit on concave surfaces, we have derived the following equations:

$$J = \frac{D(z - D \cos \omega \cos \delta)}{4z \sin^2 \omega \cos \omega} U$$

$$U = 1 + \frac{K+L}{\sqrt{A^2 - B^2}} + \frac{KLA}{(A^2 - B^2)^{3/2}}$$

$$A = D^2 + 2(1 - D \cos \omega)(1 - \cos \theta)$$

$$K + A = 2D^2 \sin^2 \omega \frac{z - \cos \delta (1 - \cos \theta)}{z - D \cos \omega \cos \delta}$$

$$B = 2D \sin \omega \sin \theta$$

$$L = -D(D - 2 \cos \omega)$$

In the above formula all distances D and z are measured in terms of the length of the radius of the concave spherical surface. In the above formula

J =ratio of thickness of deposit at the vertex V (Fig. 3) to the thickness at an arbitrary zone Z ;

D =the distance from the source to the vertex of the surface;

z =the height of the vertex above the horizontal plane of the zone;

ω =the angle between the axis of rotation and the radius vector from source to vertex;
 δ =the angle between the normal to the source and axis of rotation; and
 θ =the angle between the optic axis X and a line from center C to an arbitrary point Q upon zone Z. This angle is used to distinguish the zone for which the thickness of the coating is to be computed.

For computing the variation of the deposit on convex surfaces we have derived the following equations

$$J = \frac{D(D \cos \omega \cos \delta - z)}{4z \sin^2 \omega \cos \omega} V(\phi)$$

$$\phi = \pi \text{ if } \left| \frac{L+A}{B} \right| > 1; \cos \phi = \frac{L+A}{B}$$

otherwise

$$V(\phi) = \frac{1}{\pi}$$

$$\left[\phi + 2(U-1) \arctan \frac{(A+B) \sin \phi}{\sqrt{A^2 - B^2(1 + \cos \phi)}} - \frac{BK \sin \phi}{A^2 - B^2} \right]$$

$$A = D^2 + 2(1 + D \cos \omega)(1 - \cos \theta)$$

$$B = 2D \sin \omega \sin \theta$$

$$L = -D(D + 2 \cos \omega)$$

$$K + A = 2D^2 \sin^2 \omega \frac{z + \cos \delta(1 - \cos \theta)}{z - D \cos \omega \cos \delta}$$

Further,

$$V(\phi) = U = 1 + \frac{K+L}{\sqrt{A^2 - B^2}} + \frac{KLA}{(A^2 - B^2)^{3/2}}$$

when

$$\phi = \pi, \text{ i. e. } \left| \frac{L+A}{B} \right| > 1$$

In the above formula all distances D and z are measured in terms of length of the radius of the convex spherical surface.

The variables δ and ω are selected in the concave and convex cases so that $\cos \omega$ and $\cos \delta$ are numerically positive, that is, such that the acute angle is taken in either case.

It is pointed out that in all the cases illustrated the axis of rotation of the element is the optical axis of surface to be coated.

Referring to Figs. 3 and 5, the normal N to the source and the optic axis X do not necessarily intersect but are merely shown as intersecting for convenience of illustration.

We have considered the whole sphere in carrying out the theory for the convex case as shown in Fig. 5. In this figure the cross hatched section H of the sphere bounded by the line G may be taken as a lens element for the purpose of illustration. In this figure the curve FE represents the boundary of what is called the shadow zone. The dotted area of Fig. 5 indicates this shadow zone. This shadow zone is the portion of the complete sphere which does not receive molecules of the coating material from the source. As the lens element H is rotated about its axis X points upon its surface in general pass from the shadow zone and into the region which receives molecules of the coating material from the source. The fact that this happens plays a profound effect in convex surfaces upon the final result and must be taken into account. This is necessary in the case of convex surfaces which are more difficult because one has to go to higher angles δ of inclination of the axis of rotation X to obtain sub-

stantially uniform distribution of the coating material. In the case of concave surfaces uniform distribution can be obtained with the inclination of the axis of rotation X at smaller angles δ for which no shadowing takes place, and hence the shadow effect has been omitted in the above formula for the concave case.

As will be seen in Figs. 3 and 4, z is the distance of the point V or the vertex of the lens element above the horizontal plane of the source S.

In Fig. 7 we give the curves for the special case of convex spherical surfaces where the vertex falls upon the normal to the source, the radius of the sphere is 2 inches and the distance from source to vertex is 10 inches. In this special convex case the equations given above for convex cases are simplified to

$$A = D^2 + 2(1 + D \cos \omega)(1 - \cos \theta)$$

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$$B = 2D \sin \omega \cos \theta$$

$$L = -D(D + 2 \cos \omega)$$

$$K = D^2 - 2(1 - \cos \theta)$$

25

$$J = \frac{D}{4 \cos \omega} V(\phi)$$

For this special case the variation in the deposit from one zone to another, that is, from one value of θ to another is given in Fig. 7. For the instance in which $\delta=0$, that is, the usual prior art situation, the thickness of the deposit decreases rapidly for the outer zones. As δ is increased, the deposit becomes more uniform until for $\delta=60^\circ$ great improvement in uniformity has resulted. As δ is increased the thickness of the deposit upon the outer zones actually becomes greater than the thickness of the deposit upon the inner zones. Further, by proper choice of δ the variation in this deposit may be systematically varied. By varying other variables namely ω , z and D, the possibilities of adapting the distribution of the coating material to any requirements are greatly increased.

In Fig. 6 there is shown diagrammatically one form of apparatus for carrying out this invention. In this view N is the normal to the source S, U is an upright adapted to support the parts herein-after described. It will be noted that as shown by the arrows the upright U is adjustable both vertically and horizontally to alter the position of the parts as necessary.

In this view there is shown at the upper end of the upright U a pivot W having a protractor or angle scale to allow the support P to be set at any desired angular relation T with reference to said upright U such as the angle T as shown in the drawings.

On the support P is mounted the plate holder Y on which is mounted the plate L. The motor M and gear G are provided for rotating said plate holder Y and therefore causing rotation of the plate L during the coating process.

The support P is also so connected with the upper end of the upright U as to allow its tilting in two planes at right angles to each other, that is, it is practically a universal connection.

While the plate L has been shown and described throughout the various figures as a single plate it will be understood that this might instead consist of a plurality of elements secured in a plate holder. The elements may be spherical or planar or of any desired contour.

It is also pointed out that while in Figs. 3, 4 and 5 the vertex V of the plate L is not shown as coin-

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ciding with the normal N to the source S, in practice it would probably be the best plan to have this vertex V on the said normal to the source N such as diagrammatically illustrated in Fig. 1. It is also pointed out that the charts shown in Fig. 2 and in Fig. 7 were computed with the vertex V on the normal as described above.

In operation the mechanism shown in Fig. 6 may or may not be placed in an evacuated chamber such as a bell jar, depending on the coating material to be applied, and if the apparatus is placed in the bell jar the adjustable upright U may assume the form of a bellows or other forms that can be adjusted from without the evacuated chamber.

The motor M may be a motor placed in the vacuum and operated entirely therein or may be magnetically operated by means of auxiliary magnets from without.

In operation the source of the coating material is placed at the point S and the article or articles having the surface or surfaces to be coated are placed in the adjustable holder Y. This adjustable holder is then tilted or oriented to place the surface at the necessary angle to give the desired coating to the articles. That is, the axis X of the plate L is adjusted in accordance with the computations outlined above to so relate the plate L with the source S as to give the desired controlled coating on the surface of the plate L which is toward said source S. If the source does not obey the cosine law of emission, minor deviations from this orientation may be necessary in order to obtain the desired control in thickness in the applied coating.

Another application of the invention is that it might be used for providing non-reflective coatings or other coatings on articles having aspheric surfaces such as lenses. This would only require the computation of the correct location of the axis X during the coating operation.

Another possible application of this invention would be to place coatings of controlled thickness on related surfaces, for example, to a plurality of plane surfaces held in fixed relation with each other.

Another and important advantage of the invention is that by employing the same, plane or spherical lens surfaces may be so altered or varied as to transform the same into aspheric surfaces and this would allow a simple, efficient and economical method of manufacturing lenses or the like with aspheric surfaces and allowing a definite predetermined control in the degree of asphericity of the completed lens or article.

It is pointed out that by employing the method outlined above for transforming plane or spherical surfaces into aspheric surfaces, lens systems may be considerably transformed or redesigned to produce new systems having greatly improved optical properties as regards image definition and speed. Thus, for example, in a Cooke triplet it would be possible to decrease the curvature of field and then eliminate residual aberration by means of an applied aspheric film to the surfaces of certain of the lens elements. In fact, entirely new lens systems may be built around this principle.

It is also pointed out that while the method and apparatus described herein have shown a single source of coating material, any desired number of such sources, including ring shaped sources, may be employed as is necessary. These, however, will require corresponding changes in the formula.

The coating material for forming non-reflective films may be magnesium or calcium fluoride

or cryolite or other suitable substance or a layer of quartz over a layer of titanium dioxide, beryl, aluminum oxide, or other suitable coating material.

The coating material for transforming plane or spherical surfaces into aspheric surfaces may be beryl, quartz, magnesium fluoride, cryolite or other suitable material.

During the coating of the plane or spherical lens elements to form an aspheric surface thereon, the element is preferably rotated numerous times as described above.

The method described above may also be employed where the coating material is metal, such as in the forming of reflectors or reflective surfaces.

Another possible use of the invention is that by properly controlling the position of the plate, aspheric surfaces may be altered or corrected so that they will become plane or spherical.

It is also pointed out that while we have shown and described the plate to be coated as rotatable and the source fixed relative thereto, it might be possible to maintain the plate in fixed position and movably mount the source and have the source move relative to said fixed plate.

From the foregoing it will be seen that we have provided simple, efficient, convenient and economical means for obtaining all of the objects and advantages of the invention.

Having described our invention, we claim:

1. The method of forming a coating on a surface of an article comprising rotatably mounting said article in an evacuated chamber relative to the source of coating material and spaced therefrom, with the surface to be coated being substantially entirely exposed toward said source of coating material, causing emission of said coating material from said source, and rotating said article about an axis which is inclined with relation to a vertical line passing through the source of coating material, with said inclination being controlled according to the formula

$$J = \frac{\left(1 + \frac{r^2}{d^2} \cos 2\delta\right)}{\left(1 + \frac{r^2}{d^2} + 2\frac{r^2}{d^4} \cos 2\delta\right)^{3/2}}$$

where J is the ratio of thickness of deposit at zone r, r is the distance from the center of the article to an arbitrary point thereon, d is the distance from the source to the center of the article and δ is the angle between the vertical line passing through the source and the axis of the article to give a coating of controlled thickness on said article with the angle δ being varied according to the resultant characteristics required of the surface coating and according to the shape of the surface being coated.

2. The method of forming a coating on a surface of an article comprising rotatably mounting said article in an evacuated chamber relative to the source of coating material and spaced therefrom, with the surface to be coated being substantially entirely exposed toward said source of coating material, causing emission of said coating material from said source, and rotating said article about an axis which is inclined with relation to a normal to the source of coating material, with said inclination being controlled according to the formula

$$J = \frac{\left(1 + \frac{r^2}{d^2} \cos 2\delta\right)}{\left(1 + \frac{r^2}{d^2} + 2\frac{r^2}{d^4} \cos 2\delta\right)^{3/2}}$$

zone r , r is the distance from the center of the article to an arbitrary point thereon, d is the distance from the source to the center of the article and δ is the angle between the normal to the source and the axis of the article to give a coating of controlled thickness on said article with the angle δ being varied according to the resultant characteristics required of the surface coating and according to the shape of the surface being coated.

3. The method of forming a coating on a surface of an article comprising rotatably mounting said article in an evacuated chamber relative to the source of coating material and spaced therefrom, with the surface to be coated being substantially entirely exposed toward said source of coating material, causing emission of said coating material from said source, and rotating said article about an axis which is inclined with relation to the axis of the emitted coating material,

with said inclination being controlled according to the formula

$$J = \frac{\left(1 + \frac{r^2}{d^2} \cos 2\delta\right)}{\left(1 + \frac{r^2}{d^2} + \frac{2r^2}{d^4} \cos 2\delta\right)^{3/2}}$$

where J is the ratio of thickness of deposit at zone r , r is the distance from the center of the article to an arbitrary point thereon, d is the distance from the source to the center of the article and δ is the angle between the axis of the emitted coating material and the axis of the article to give a coating of controlled thickness on said article with the angle δ being varied according to the resultant characteristics required of the surface coating and according to the shape of the surface being coated.

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