United States Patent

La Vantine

[15] **3,645,606**

[45] **Feb. 29, 1972**

[54] MULTIFACET SUBSTANTIALLY PARABOLOIDAL COLLIMATOR AND METHOD FOR MAKING SAME

[72] Inventor: **Allan D. La Vantine,** Tarzana, Calif.

[73] Assignee: **TRW Inc.,** Redondo Beach, Calif.

[22] Filed: **Jan. 12, 1970**

[21] Appl. No.: **2,026**

Related U.S. Application Data

[62] Division of Ser. No. 656,093, July 26, 1967, Pat. No. 3,494,231.

[52] **U.S. Cl.**.....**350/292,** 29/407, 29/428, 350/296, 350/320

[51] **Int. Cl.**.....**G02b 5/10,** B23p 19/00

[58] **Field of Search** 350/292, 293, 296, 320; 29/407, 428

[56] **References Cited**

UNITED STATES PATENTS

3,009,391 11/1961 Zagieboylo et al. 350/292

OTHER PUBLICATIONS

Brunner " Process for Obtaining a Convex Surface" 1(1) IBM Tech. Disclosure Bulletin 22#6-1958

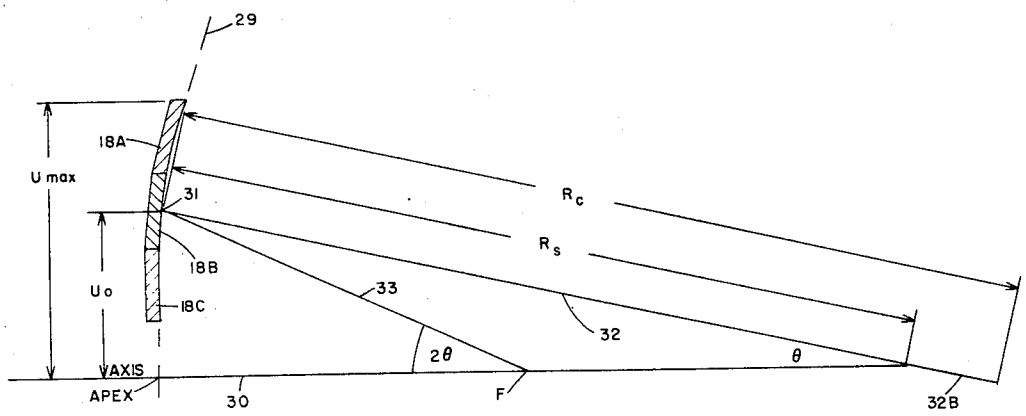
Primary Examiner—David Schonberg
Assistant Examiner—John W. Leonard
Attorney—Gerald Singer, Alfons Valukonis and Daniel T. Anderson

[57] **ABSTRACT**

A light reflecting collimator having a substantially paraboloidal surface and being formed of a plurality of juxtaposed facets each having a substantially paraboloidal surface.

A method for making such a collimator of a plurality of facets each having a substantially paraboloidal surface on individual plates and each facet formed on each plate being defined by two paraboloidal radii lying in orthogonal planes.

2 Claims, 12 Drawing Figures



Patented Feb. 29, 1972 3,645,606

5 Sheets-Sheet 1

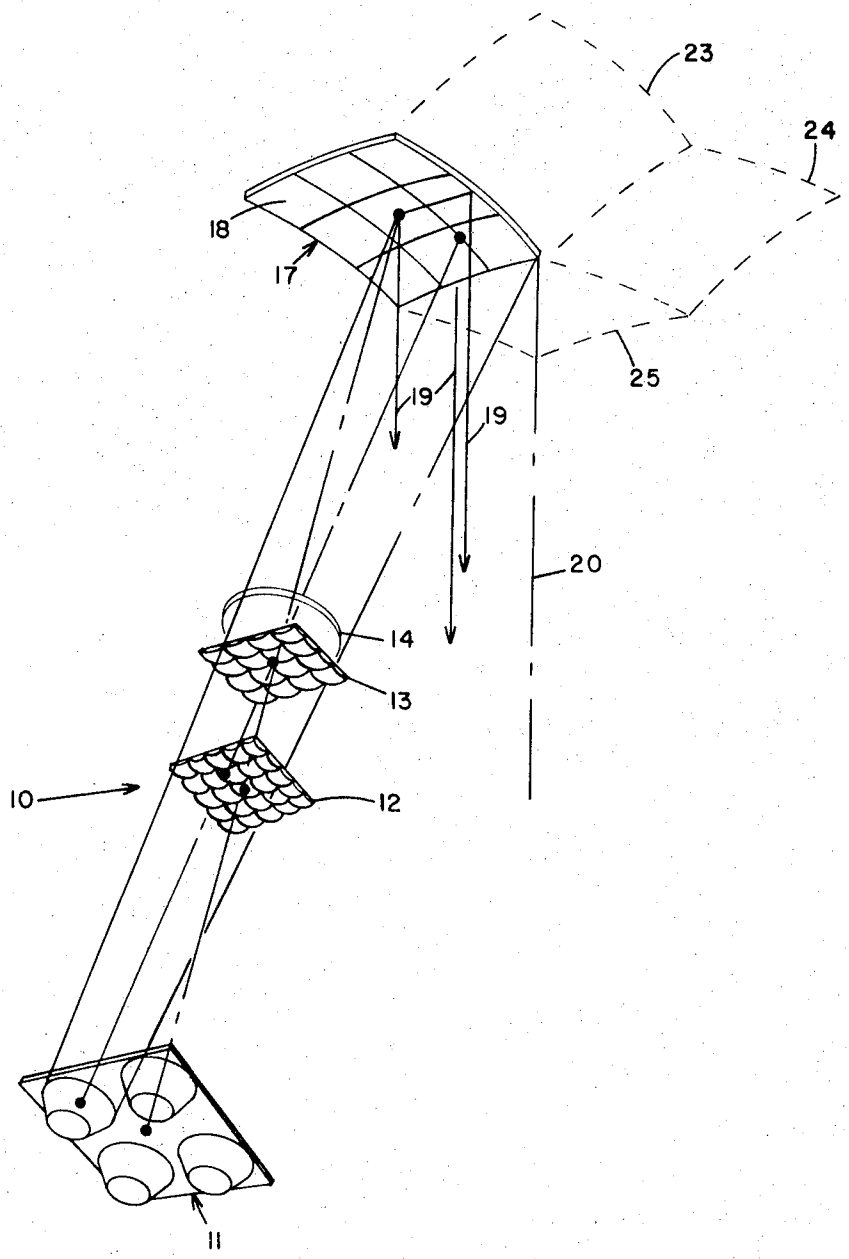


Fig. 1

Allan D. Le Vantine
INVENTOR

BY

AGENT

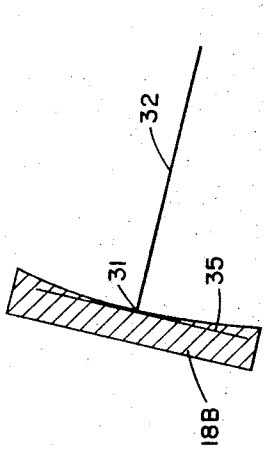


Fig. 2A

Fig. 2

Allan D. Le Vantine
INVENTOR.

BY

AGENT

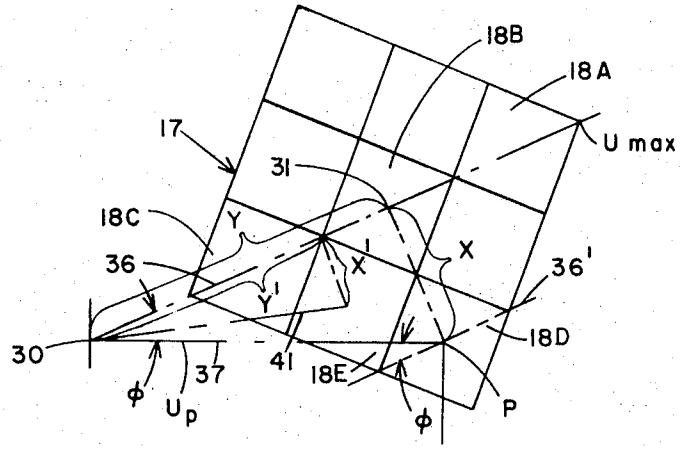


Fig. 3B

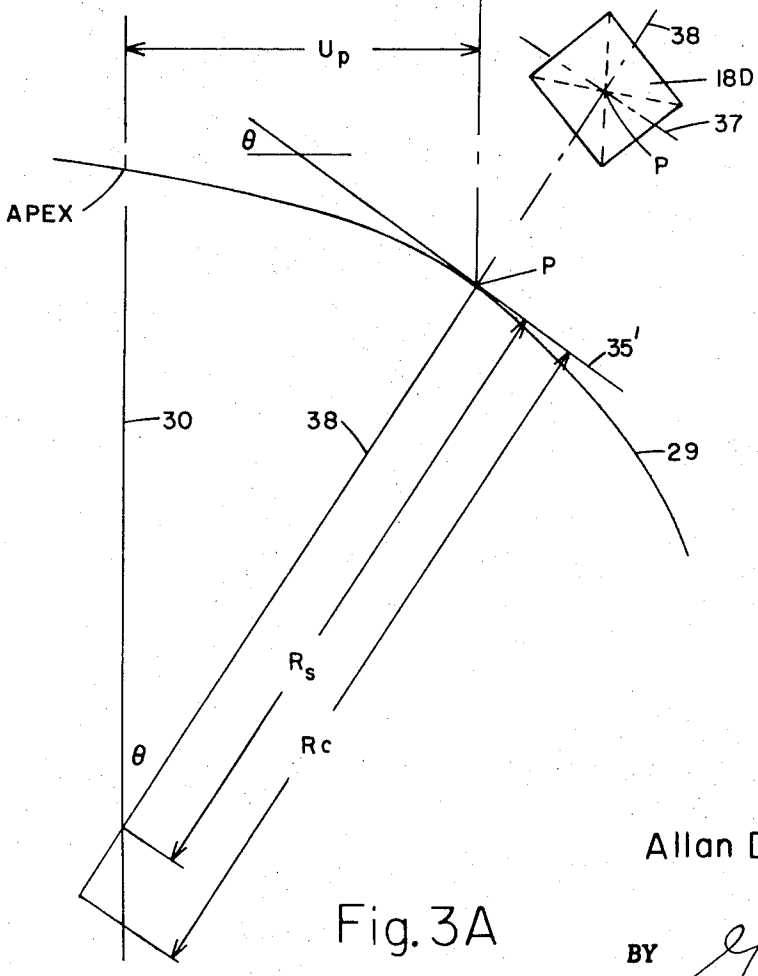


Fig. 3C

Fig. 3A

Allan D. Le Vantine
INVENTOR.
BY
AGENT

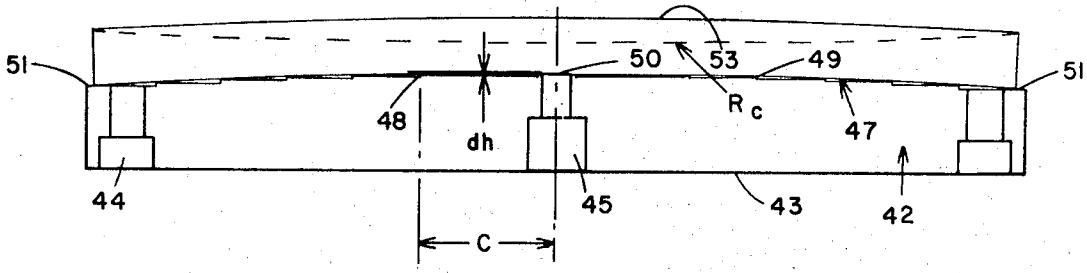


Fig. 4

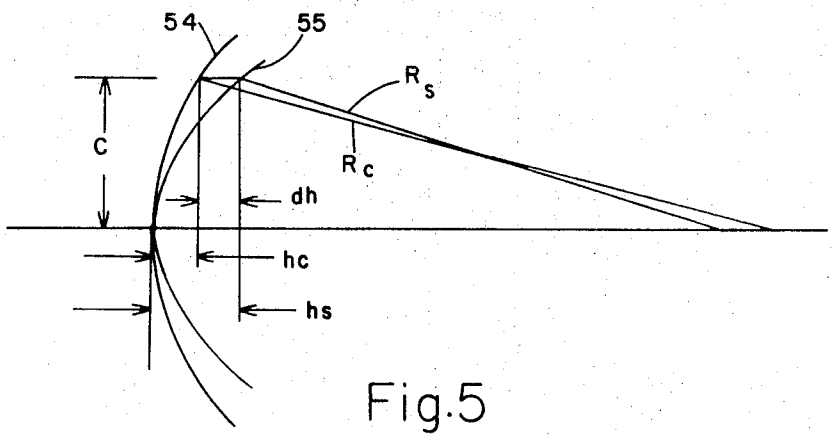


Fig. 5

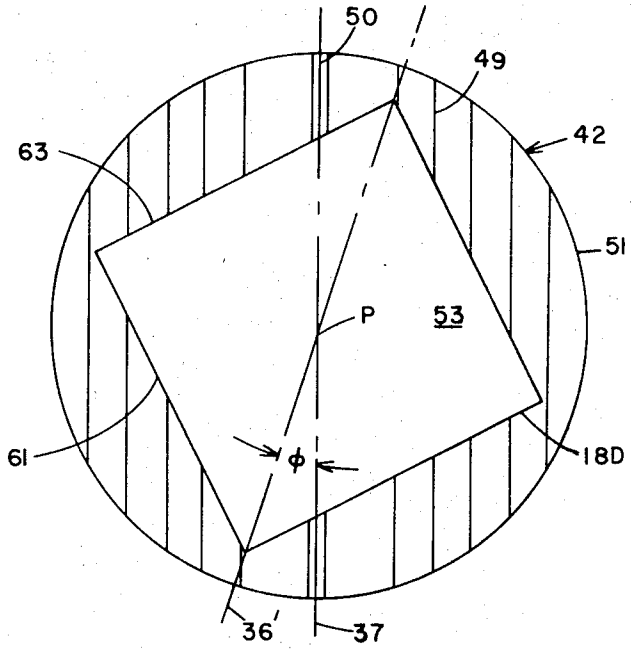


Fig. 6

Allan D. Le Vantine
INVENTOR.

BY

AGENT

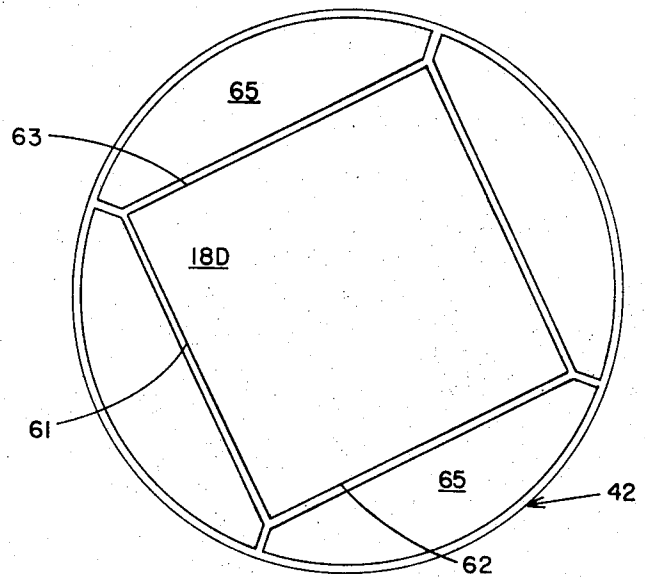


Fig. 7

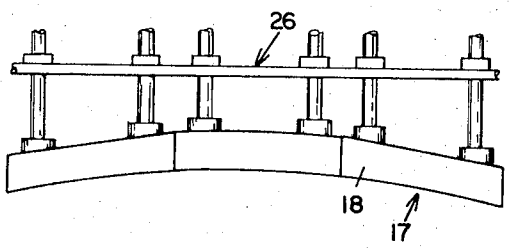


Fig. 9

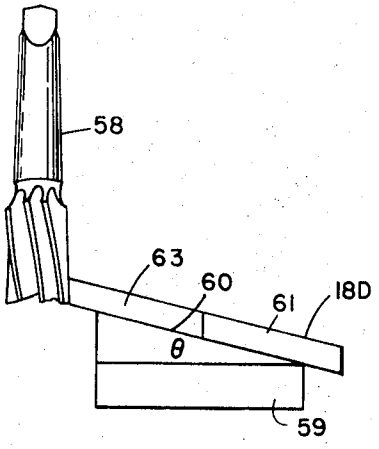


Fig. 8

Allan D. La Vantine
INVENTOR.

BY

AGENT

MULTIFACET SUBSTANTIALLY PARABOLOIDAL COLLIMATOR AND METHOD FOR MAKING SAME

This application is a division of application Ser. No. 656,093, now U.S. Pat. No. 3,494,231.

BACKGROUND OF THE INVENTION

In the prior art paraboloidal collimators have been generally small and formed as a single element. In a solar simulator, for example, where a relatively large reflecting collimator is required, it would be vary expensive to form the structure of a single element in that the material used is relatively rigid and heavy, and the paraboloidal surface would have to be ground into it. This would be an obviously difficult and time-consuming effort. By forming a substantially paraboloidal surface on a plurality of relatively small sections, great savings of time and expense have been accomplished. The invention provides a substantial simplification over that which would normally be used for grinding and polishing a surface of the required contour. This is especially true for producing the required surface upon a metal plate, such as aluminum which is used in solar simulators. In the manufacture of four collimators for a solar simulator, using the present invention, approximately three-fourths of a million dollars was saved over what the cost of grinding true paraboloidal surfaces would have been.

SUMMARY OF THE INVENTION

It is the object of the invention to provide a method for producing a surface on a flat metal or other relatively rigid plate, such as glass, defined by two radii of curvature in orthogonal planes.

Another object of the invention is to provide a jig for making a facet of a substantially paraboloidal collimator.

It is still another object of the invention to provide a method for making a collimator having a substantially paraboloidal surface formed of a plurality of paraboloidal facets upon individual plates, each facet being defined by two paraboloidal radii in orthogonal planes.

It is a further object of the invention to provide a collimator having a substantially paraboloidal surface and formed of a plurality of juxtaposed facets each having a paraboloidal surface.

Further objects and advantages of the invention may be brought out in the following part of the specification wherein small details have been described for the competence of disclosure, without intending to limit the scope of the invention which is set forth in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring to the accompanying drawings, which are for illustrative purposes:

FIG. 1 is a diagrammatic view of portions of a solar simulator employing paraboloidal collimators made according to the invention;

FIG. 2 is a side cross-sectional and diagrammatic view of a central row of facets of a collimator illustrating portions of the parabola geometry as they relate to the invention;

FIG. 2A is an enlarged view of the center facet shown in FIG. 2;

FIG. 3A is a side diagrammatic view illustrating the geometry of a paraboloid as it relates to the center point of a specific offcenter facet of the collimator according to the invention;

FIG. 3B is a plan view of a collimator, viewed along lines parallel to the axis of the parabola, projected from FIG. 3A;

FIG. 3C is a true view of the facet whose center point and a tangent thereto is illustrated in FIG. 3A, viewed normal to the tangent plane;

FIG. 4 is a side-elevational view of a jig for forming a facet according to the invention;

FIG. 5 is a diagrammatic view illustrating the geometry from which the jig calculations are determined for a single facet of a known parabola;

FIG. 6 is a plan view of the jig shown in FIG. 4 with the facet plate, shown in FIG. 3C, positioned thereon;

FIG. 7 is a plan view of the jig and plate shown in FIG. 6 with fill-in pieces arranged around the plate for obtaining a continuous mill cut on the face of the plate;

FIG. 8 is a side-elevational view of the facet plate, shown in FIG. 3C, in position for cutting the edges of the plate; and

FIG. 9 is a fragmentary view of a collimator illustrating means for securing the various facets together.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, there are shown portions of a solar simulator, generally indicated as **10**, diagrammatically illustrated. The solar simulator is comprised of a plurality of light sources and their collectors, generally indicated at **11**, in optical alignment with an input mosaic lens **12**, output mosaic lens **13** and an aligning lens **14**. The beams produced by the light sources, after passing through the lenses, are reflected by an off-axis, substantially paraboloidal collimator **17**, comprised of nine substantially paraboloidal facets **18**, each defined by two radii of curvature in orthogonal planes. The parallel light rays **19** are reflected downwardly from the collimator parallel to a centerline **20** of a test chamber, not shown. The test chamber has three other collimators **23**, **24** and **25**, forming reflective portions of a total solar simulator apparatus.

The facets **18** are made from aluminum alloy plates and are suspended in a nearly horizontal position from a rigid thermally stabilized rack, generally indicated as **26** in FIG. **9**. The rack is constructed of tubular members running generally horizontally with respect to the collimator and fluid is circulated through the tubular members to thermally stabilize the structure. The tubular members are adjustable to provide means to properly align each facet so as to form the substantially paraboloidal collimator. Thermal stabilization of the rack eliminates the possibility of any movement of aligned facets when the space simulation chamber is under a vacuum and having liquid nitrogen in the panels lining the walls of the chamber.

In FIG. **2** there is shown a cross-sectional view of the collimator **17** illustrating the reflective faces of the facets **18A**, **18B** and **18C** on a predetermined parabolic curve **29**. The parabola **29** has an axis **30** and a focus point F. In designing the solar simulator, it was determined that the center point **31** of the collimator should be off-axis, an angle equal to 20, specifically 26°, the angle being formed by the parabolic axis and the line **33** from the focus to the center point **31**. As is known, in a parabola a line **32** drawn normal to a tangent **35**, as shown in FIG. **2A**, to the point **31**, intersects the parabolic axis at an angle θ, half of 2θ. Similarly, the lines **32** and **33** also form an angle equal to θ.

In any paraboloid a line, such as **32**, has the length of a radius R_s in a plane perpendicular to the face of the drawing. The radius R_s defines the curvature of the paraboloid at point **31** in the aforesaid plane. A second radius R_c, longer then R_s as indicated by the extension **32B** of the line **32**, is in the plane of the face of the drawing, normal to the plane of the radius R_s, and together the two radii in the respective orthogonal planes determine the surface of a facet as **18B** at the point **31**. That is, at each such point, there are two radii in orthogonal planes that define that portion of the surface of a paraboloid. At locations off the point **31** in the facet **18B**, the radii vary slightly from R_s and R_c, but the size of **18B**, as well as that of the other facets, is selected so that the deviation is minor so as not to be of any consequence for purposes for the invention.

At the center **31** of the facet, the two radii defining the paraboloid can be defined as $R_{so}=2F/\cos O_o$, where F is the focal length and θ is the angle as indicated above; and $R_{co}=2F/\cos^3 O_o$. The angle θ is determined by the equation, $\theta_o=\tan^{-1}(U_o/2F)$, where U_o is the distance to the center of the facet from the paraboloid axis. At any other location the two radii of the paraboloid are:

$$R_s=\frac{2F}{\cos\theta},\ R_c=\frac{2F}{\cos^3\theta}\ \text{and}\ \theta=\tan^{-1}\left(\frac{U}{2F}\right),$$

where U is the distance of another point from the paraboloid axis. Each collimator facet, according to the invention, is defined by the two radii R_{so} and R_{co} at all points on the facet surface and the size of the facet must be chosen so that the deviation in the radii of curvature of the facet from those of a paraboloid or any location will be small and insignificant.

For example, a typical computation for these variations is indicated in the following, where $F=19.3$ feet, $U_o=10.3$ feet, and $U=11.7$ feet, then $\theta_o=14.9°$, $R_{so}=39.9$ feet, $R_{co}=42.75$ feet, $\theta=16.9°$, $R_s=40.35$ feet, and $R_c=44.15$ feet. However, the difference in illumination from that of the true paraboloid and the collimator made according to the invention is 0.043 which is insignificant for the illumination purposes required. Thus, as a matter of practice for the collimator according to the invention, it is sufficiently accurate to treat the radii of each facet for all points thereon as R_s and R_c, determined at each center point, the distance from the parabolic axis to the respective center points being considered to have a value equal to a respective U. It should be noted that U_{max}, as shown in FIGS. **2** and **3B**, is predetermined for the collimator in accordance with the area to be illuminated and is measured from the axis to the center point of the space simulator above the area illuminated.

Further, it should be noted that the intersection of the collimator facets are visible from the test zone of the simulator, the area to be illuminated, and these intersections block some of the light coming from the source image, the image appearing across the intersections on the collimator. This results in a local decrease of illumination in the test zone, but this decrease is made insignificant by closely butting the facets.

For each facet, F of the paraboloid being known, in order to determine the two radii, it is necessary to determine the angle θ from the equation, $\theta=\tan^{-1} U/2F$. The distance U for each center point may be determined in reference to FIGS. **3A**, **3B**, and **3C**. In FIG. **3B**, the axis **30** of the parabola is shown as a point, the axis being perpendicular to the surface of the drawing. The position of a vertical plane or line **36** is determined with respect to its position to the test zone or area to be illuminated by the collimator **17**. That is, the line **36** extends from the axis of the parabola to the point U_{max}, which is determined to be at the center of a test chamber having a solar simulator. Stated differently, the collimator is positioned so that it will provide the proper illumination upon the test zone or target. Thus, by using the line **36** as a diagonal through the center of the rectangular collimator its length and angular position are known.

The collimator in FIG. **3B** is shown to be comprised of nine facets, each 2 square feet, for example. The individual facets, as well as the collimator, are square only when viewed along lines parallel to the parabolic axis. In such an arrangement the center points of each facet are easily determined as being at the intersection of the diagnosis of known squares. To determine the distance, U_p, from the point P, the center of the facet **18D**, to the axis in the vertical plane **37** in FIG. **3B** and on the drawing surface in FIG. **3A**, it is necessary to determine the length of the lines indicated as X and Y, the two sides of the right triangle of which U_p, is the hypotenuse. The line X is equal to the length of the diagonal of two foot square and Y is equal to U_{max} minus the length of a diagonal and half of the 2 foot squares. Thus, the angle θ for the point P, shown in FIG. **3A**, for the known parabola and the radii R_s and R_c for the point P may be calculated from the equations above.

The radius R_c lies in the plane **37**. The radiuS R_s is in a plane indicated by the line **38**, the latter plane being normal to the plane **37**, the two being the orthogonal planes having the two radii which define the curvature of the facet **18D**. In FIG. **3A**, the tangent line or plane **35'** is perpendicular to the line **38** and is analogous to the tangent **35** in FIG. **2**. The facet **18D** is projected in FIG. **3C**, as viewed normal to the tangent plane **35'**. In this view the facet **18D** is a parallelogram having two long sides and two short sides and is not a rectangle, the lengths of the sides being 24.5297 and 24.1379 inches, for example.

To determine the values of U and the radii for the other facets, other than those on the line **36** where the distances to the center points are either known or obvious by subtracting diagonals or diagonal portions from U_{max}, the same method may be used as that for determining the value of U_p and the radii in the facet **18D**. Thus, for example, to determine the value of U for the facet **18E**, the value of X' is that of half of a diagonal and that the value of Y' is equal to U_{max} minus the length of two diagonals of squares. Thus, the length of the hypotenuse **41** is the value for U in the facet **18E** and it is in a vertical plane in FIG. **3B** in which its radius R_c extends. For this value of U, the angle θ may be determined in the vertical plane **41** so as to determine the respective values of R_s and R_c.

From the foregoing, it is clear how the value of U may be obtained for the other center points of the nine facets. It should be noted that each of the vertical planes in FIG. **3B**, passing through the axis and a center point, is at a corresponding angle ϕ with the plane represented by the line **36**.

After the radii for the facets are determined, they are used to determine the configuration of a facet jig **42**, shown in FIGS. **4** and **6**, on which facet surfaces are formed. There is a separate jig for each facet depending upon its radii, but the same jig may be used for corresponding left- and right-hand facets with respect to line **36**. Each jig is generally circular and has a flat bottom **43**. The upper face of the jig is formed so that a facet plate secured thereon by bolts, extending through holes **44** and **45** and threadedly engaged in tapped wells in the bottom of the plate, can be deformed within its elastic limit to mate with a cylindrical arc generally designated as **47**, the arc being formed by the flat bottom base of the facet when it is secured against the outer edges of each of the steps as **48** and **49**. That is, the arc **47** could be drawn so as to pass over each of the steps and the apex **50** as well as the opposite laterally outside nadirs as **51**. The steps are spaced at equal intervals on both sides of the axis of the cylindrical arc **47** or of the apex of the jig.

The arc **47** is determined for each facet according to its radii R_s and R_c. Each substantially paraboloidal face on the facet is formed by cutting a spherical contour on the facet face **53** on a facet as **18D** positioned on the jig. The spherical curvature is determined by the long radius, R_c. That is, the shape of the concave spherical cut into the facet face has a radius equal to R_c. When that has been accomplished, the facet is removed from the jig and it returns to its undeformed shape due to the energy stored therein when it was deformed on the jig within its elastic limit. The facet face **53**, after being removed from the jig, is no longer spherical but has a substantially paraboloidal face, defined by two radii in orthogonal planes. When the facet plate springs back to its undeformed shape, the second curvature is formed in the face **53** and its radius is equal to R_s. When the facet is removed from the jig, its bottom should be flat and if it is not, it must be cut to be flat. It is then put back on the jig and the spherical cut is made again. The jig is of sufficient thickness so that its deflection relative to that of the facet is insignificant.

The jig is prepared so that the proper radii and the orthogonal planes will define its substantially paraboloidal surface. The configuration of the jig is determined in reference to FIG. **5**. There the large arc **54** has a radius R_c and the small arc **55** has a radius R_s. The distance C is the distance laterally outwardly from the apex **50** for any step edge on the jig, or stated differently, the distance out from the apex at which a point on the cylindrical curve **47** will be formed so as to deform the facet plate. The distance h_s indicates the deformation that is required to form the arc **55** on the jig at a point C and the distance h_c indicates the deformation that is required on the jig to form the arc **54** at a point C on the jig. The distance dh is the difference in deformation required between the two arcs, or

$$dh=h_s-h_c=\frac{C^2(R_c-R_s)}{2R_cR_s},$$

determined from the right angle triangles in FIG. **5**.

When the radii are known, *dh*, the depth of any step downwardly from the apex **50** on the jig, is determined by selecting an arbitrary value for *C*, the distance laterally outwardly perpendicular to the axis of the jig or cylindrical surface to be formed. The values for *dh* are relatively small in the making of a 2-foot square facet. For example, where the radii are 482 and 525 inches, and *C* is 4 inches, *dh* is equal to 0.0014 inch, and where *C* is 15.5 inches, *dh* equals 0.0204 inch. The jigs also could be made to be concave, in which the spherical cut would be for the short radius R_s and the plate would be deflected into the concavity for the spherical cut.

The various facets are positioned on their respective jigs in accordance with the relationship of the central plane or line **36** which forms diagonals for the facets **18** A, B and C, and the angle ϕ for a respective facet. For the facets **18**A, B and C, the angle ϕ is 0. and they are positioned on a jig with their diagonals, along a plane **36**, directly above and parallel to the axis of the cylindrical arc **47**.

The other plates from which the facets are to be made are positioned on the jigs so that their center points are crossed by the axis of the arc of the cylinder. In FIG. **6**, for example, the plate **18**D is rotated on the jig so that the diagonal **36'**, parallel to the reference plane **3**B, through its center P forms the angle ϕ with the cylindrical axis of the jig arc which is in the position of the line **37** in FIG. 3B. The angle ϕ is determined for the facet **18**D, for example, as indicated in FIG. 3B, by the equation:

$$\phi = \tan^{-1} X/Y.$$

For facet **18**E, X' and Y' are used to solve for ϕ. In this situation, as shown in FIG. **6**, the angle ϕ is to the left of the cylindrical axis at the lower part of the drawing whereas for the facets on the left of the line **36** in FIG. **3**B, the angle ϕ would be formed to the right of the cylindrical axis.

Prior to fastening the plates to the jigs, the plates being somewhat larger than a 2 foot square, they must be milled along their edges to form a 2 foot square when viewed along a line parallel to the parabolic axis. As shown in FIG. **8**, this is accomplished by placing the plate on a support **59** having an upper surface **60** slanted at an angle θ equal to that for the respective facet as determined by the value of *U*. Further, the plate is rotated or positioned with respect to its angle ϕ in the same manner as it is on the jig with reference to the plane **36** and its corresponding plane, as **37** for facet **18**D. A milling cutter **58** is then applied to the outer edges as **61** and **63** of the plate, and moved to cut a 2 foot square, the cutter being in a position to make a vertical cut, or stated differently, in a position parallel to the axis of the parabola. This then makes a 2 foot square when viewed from a position parallel to the parabolic axis. When viewed as indicated in FIG. 3C, the plate, having finished edges, has the appearance of a parallelogram and not a square. Two of the sides of the facets as they would be viewed in FIG. 3C, except for the facets **18**A, **18**B and **18**C, are slightly longer than the other two sides. The facets **18**A, **18**B and **18**C have respective equal sides, as 24.5297, 24.3026 and 24.5297, 24.1379 inches.

After the edges of a facet plate are cut, the facet is positioned on its jig as indicated above, and sectors **65** are placed on the facet as shown in FIG. **7** so that when the spherical surface is cut, the cut across and around the facet will be continuous as the cutting tool passes back and forth over the outer edge of the facet plate.

After the surfaces of the nine facets have been cut and polished for reflective purposes, they are assembled in their specific locations as indicated in FIG. **3**B and put together to form the collimator as shown in FIGS. **1** and **9**.

It is clear that the foregoing method for making a substantially paraboloidal collimator from substantially paraboloidal facets is considerably less expensive in both time and money than the manufacture of a collimator in one piece formed to have a paraboloidal or a substantially paraboloidal face.

The invention and its attendant advantages will be understood from the foregoing description and it will be apparent that various changes may be made in the form, construction and arrangement of the parts of the invention without departing from the spirit and scope thereof or sacrificing its material advantages, the arrangement hereinbefore described being merely by way of example. I do not wish to be restricted to the specific forms shown or uses mentioned except as defined in the accompanying claims, wherein various portions have been separated for clarity of reading, not for emphasis.

I claim:

1. A collimator having a substantially paraboloidal surface and formed of a plurality of juxtaposed facets, each having a substantially paraboloidal surface, comprising:

a. each facet surface being defined by two paraboloidal radii in orthogonal planes;

b. the radii being calculated for a known paraboloid from the equations:

$$R_s = \frac{2F}{\cos\theta}, \quad R_c = \frac{2F}{\cos^3\theta};$$

where R_s is the short radius, R_c is the long radius, *F* is the focal length of the paraboloid, and θ is an angle between the parabolic axis and a line normal to a tangent through the center point of each facet, said line and axis being in a first of said orthogonal planes normal to a respective tangent: the angle being determinable from the equation:

$$\theta = \tan^{-1}(U/2F):$$

where *U* is the distance from the center point of each facet along a line normal to the parabolic axis, the latter line and axis being in the same plane:

c. each of said facets being predetermined squares when viewed along lines parallel to said parabolic axis, each square having at least one adjacent corner with another square;

d. at least one of said facets having a diagonal lying in its second orthogonal plane;

e. the distance of the center point of said last facet from the parabolic axis being predetermined;

f. the parabolic axis and the center point of each facet lying in the second orthogonal plane of the respective facet;

g. the position of the second orthogonal plane in each facet other than that second plane of said one facet being determinable by the equation;

$$\phi = \tan^{-1}(X/Y);$$

where ϕ is the angle between said second plane of said one facet and the plane to be determined; *X* is the length of a line normal to said second plane of said one facet to the center point of the respective facet and along a diagonal thereof and *Y* is the length of a line in said second plane from said parabolic axis to and normal to said last line, *X* and *Y* being determinable as diagonals or parts thereof of known squares.

2. A method for making a collimator having a substantially paraboloidal surface formed of a plurality of substantially paraboloidal facets on individual plates, each facet being defined by two paraboloidal radii in orthogonal planes, comprising:

a. determining the location of each facet to form said collimator having a predetermined paraboloidal surface;

b. determining the shape and dimensions of each facet plate along its edges viewed parallel to the parabolic axis;

c. determining the angles between the parabolic axis and lines normal to tangents through center points of each respective facet, each of said lines being in a first orthogonal plane normal to said tangent for each facet;

d. determining the position of the second orthogonal plane for each facet;

e. determining the respective radii for each facet;

f. preparing a respective jig face for each of said facets by putting steps on a jig plate from a central axial apex downwardly toward opposite sides symmetrically to nadir outer edge positions,

g. said steps extending in an axial position relative to the axis of a cylindrical curve adapted to extend transversely on the edges of said steps;

h. the depth of each step from the apex being determined from the equation;

$$dh = \frac{C^2(Rc - Rs)}{2R_sR_c};$$

where dh is the depth of each step; C is the transverse distance normal to said cylindrical axis from the axial apex to each step edge, arbitrarily selected; R_c is one of said respective radii for each facet to be used as a cutting radius to cut a spherical face as a part of a respective facet in each facet plate and which is in said second orthogonal plane; and R_s is the other of said respective radii which defines the finished facet and which is in said first orthogonal plane:

i. tilting each plate at an angle with the horizontal equal to the respective angle formed by the parabolic axis and the line normal to the tangent at the respective center point of each respective facet and positioning the plate in accordance with the respective orthogonal planes of the facet in relationship to a reference plane in the collimator so that the orthogonal planes will be in the proper positions in relation to the position of the facet in the collimator, then cutting the edges of each plate vertically to shape and dimension it according to the predetermined shape and dimensions viewed parallel to the parabolic axis:

j. placing each facet plate on a corresponding jig depending upon the radii of the respective facet;

k. positioning and securing each facet plate on its respective jig in accordance with the respective orthogonal planes of the facet in relationship to the cylindrical axis of the jig with respect to said reference plane so that the plate is deformed within its elastic limit on the curve of said steps and so that the planes will be in the proper positions in relation to the position of the facet in the collimator;

l. cutting said spherical surface on each facet using a respective R_c radius;

m. releasing each facet plate from its jig to permit the plate to return to its undeformed shape and thereby forming a second curved surface having the R_s radius in the first orthogonal plane, the R_c radius being in the second orthogonal plane;

n. finishing each facet to produce a highly reflective surface; and

o. securing said facets together to form said collimator in accordance with the predetermined location of each facet, and to have a substantially paraboloidal reflective surface.

* * * * *