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Continued on Last Page

(54) [Title of the Invention]

Stereolithographic Apparatus and Method

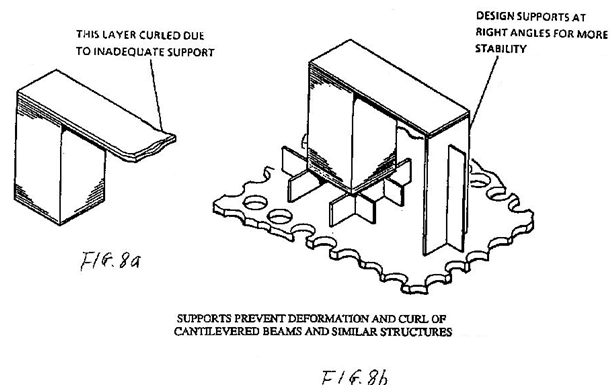
(57) [Abstract] (Amended)

[Problem]

In a stereolithographic method for forming three-dimensional objects, the structure that supports an object and the structure that secures the object to a stand are formed automatically.

[Solution]

A first means for defining a specially created object supporting structure for a three-dimensional object to be formed, and a second means for automatically forming the three-dimensional object in response to the specially created data are provided. Specially created data defines a web thin enough to make removal from an object easy after the object has been formed, or a web long enough to span a cross section of the object, or a support that secures the edges of a layer in place until a crosshatch vector has been drawn, or a support that prevents deformation of a cantilevered beam, or a support for attaching the section of a layer that would otherwise drift.



[Claims]

[Claim 1]

A stereolithographic apparatus, comprising: a first means for providing specifically created object defining data with respect to a three-dimensional object to be formed, the specifically created data specifying a support structure for the object; and a second means responsive to the specifically created data for automatically forming the three-dimensional object.

[Claim 2]

The stereolithographic apparatus according to claim 1, wherein the specifically created data specifies webs thin enough to facilitate removal from the object after the object is formed.

[Claim 3]

The stereolithographic apparatus according to claim 1, wherein the specifically created data specifies webs long enough to span the cross section of the object.

[Claim 4]

The stereolithographic apparatus according to claim 1, wherein the specifically created data specifies supports which anchor layer borders in place until crosshatch vectors are drawn.

[Claim 5]

The stereolithographic apparatus according to claim 1, wherein the specifically created data specifies supports for preventing deformation of cantilevered beams.

[Claim 6]

The stereolithographic apparatus according to claim 1, wherein the specifically created data specifies supports for attaching layer sections that would otherwise drift.

[Claim 7]

A stereolithographic method, comprising the steps of: providing specifically created object defining data with respect to a three-dimensional object to be formed, the specifically created data specifying a support structure for the object; and utilizing the specifically created data to stereolithographically form the three-dimensional object.

[Claim 8]

The stereolithographic method according to claim 7, wherein the step of providing specifically created data includes data which specifies webs thin enough to facilitate removal from the object after the object is formed.

[Claim 9]

The stereolithographic method according to claim 7, wherein the step of providing specifically created data includes data which specifies webs long enough to span the cross section of the object.

[Claim 10]

The stereolithographic method according to claim 7, wherein the step of providing specifically created data includes data which specifies supports which anchor layer borders in place until cross-hatch vectors are drawn.

[Claim 11]

The stereolithographic method according to claim 7, wherein the step of providing specifically created data includes data which specifies supports for preventing deformation of cantilevered beams.

[Claim 12]

The stereolithographic method according to claim 7, wherein the step of providing specifically created data includes data which specifies supports for attaching layer sections that would otherwise drift.

[Claim 13]

A stereolithographic method for forming a three-dimensional object, the method comprising the steps of:
providing data representing a cross section of the three-dimensional object to be formed;
providing data representing a cross section of a support structure used to form the three-dimensional object;
combining cross-sectional object data and cross-sectional support structure data to create structural data; and
using the structural data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[Claim 14]

A stereolithographic method for forming a three-dimensional object, the method comprising the steps of:
providing data representing a cross section of the three-dimensional object to be formed;
providing data representing a support structure used to form the three-dimensional object;
slicing the data representing the support structure to obtain cross-sectional support structure data indicating the support structure; and
using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[Claim 15]

A stereolithographic method for forming a three-dimensional object, the method comprising the steps of:
providing data representing a cross section of the three-dimensional object to be formed, each cross section including a boundary region and an interior region, and at least some of the boundary regions and interior regions of some of the cross sections facing downward during the formation of the object;
providing data representing a slender support structure used to support at least a section of the downward facing interior region of at least some cross sections of the three-dimensional object when the three-dimensional object is being formed; and using the object data and support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections, continuous cross sections being formed on top of already formed cross sections.

[Claim 16]

A stereolithographic method for forming a three-dimensional object, the method comprising the steps of:
providing data representing a cross section of the three-dimensional object to be formed;
defining a region under downward-facing surfaces of the three-dimensional object in which one or more support structures are to be located;
using the defined areas and hatch patterns to obtain data representing the one or more support structures; and
using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[Claim 17]

A stereolithographic method for forming a three-dimensional object, the method comprising the steps of:

providing data representing a cross section of the three-dimensional object to be formed;
automatically obtaining data representing one or more support structures that support the object when the object is being formed; and using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[Claim 18]

The method according to any of claims 13 to 17, wherein the object is formed from a medium that can be cured by exposure to a predetermined stimulus, and the steps of using the medium include forming a layer of fluid medium in preparation to forming a continuous section of the object and support structure, and exposing the layer to a predetermined stimulus to form and adhere a continuous cross section of the object and support structure.

[Claim 19]

The method according to claim 18, wherein the medium is a photopolymerizable polymer and the predetermined stimulus is selected from the group consisting of visible light, invisible light, and ultraviolet light.

[Claim 20]

A stereolithographic apparatus that forms a three-dimensional object, comprising:
a means for providing data representing a cross section of the three-dimensional object to be formed;
a means for providing data representing a cross section of a support structure used to form the three-dimensional object;
a means for combining cross-sectional object data and cross-sectional support structure data to create structural data; and
a means for using the structural data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[Claim 21]

A stereolithographic apparatus that forms a three-dimensional object, comprising:
a means for providing data representing a cross section of the three-dimensional object to be formed;
a means for providing data representing a support structure used to form the three-dimensional object;
a means for slicing the data representing the support structure to obtain cross-sectional support structure data indicating the support structure; and
a means for using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[Claim 22]

A stereolithographic apparatus that forms a three-dimensional object, comprising:
a means for providing data representing a cross section of the three-dimensional object to be formed, each cross section including a boundary region and an interior region, and at least some of the boundary regions and interior regions of some of the cross sections facing downward during the formation of the object;
a means for providing data representing a slender support structure used to support at least a section of the downward facing interior region of at least some cross sections of the three-dimensional object when the three-dimensional object is being formed; and
a means for using the object data and support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections, continuous cross sections being formed on top of already formed cross sections.

[Claim 23]

A stereolithographic apparatus that forms a three-dimensional object, comprising:
a means for providing data representing a cross section of the three-dimensional object to be formed;
a means for defining a region under downward-facing surfaces of the three-dimensional object in which one or more support structures are to be located;
a means for using the defined areas and hatch patterns to obtain data representing the one or more support structures; and
a means for using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[Claim 24]

A stereolithographic apparatus that forms a three-dimensional object, comprising:
a means for providing data representing a cross section of the three-dimensional object to be formed;
a means for automatically obtaining data representing one or more support structures that support the object when the object is being formed; and
a means for using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[Claim 25]

The apparatus according to any of claims 18 to 24, wherein the object is formed from a medium that can be cured by exposure to a predetermined stimulus, and the means for using the medium include a means for forming a layer of fluid medium in preparation to forming a continuous section of the object and support structure, and a means for exposing the layer to a predetermined stimulus to form and adhere a continuous cross section of the object and support structure.

[Claim 26]

The device according to claim 25, wherein the medium is a photopolymerizable polymer and the predetermined stimulus is selected from the group consisting of visible light, invisible light, and ultraviolet light.

[Detailed Description of the Invention]

[0001]

[Technical Field of the Invention]

This invention relates generally to improvements in methods and apparatus for forming three-dimensional objects from a fluid medium and, more particularly, to a new and improved stereolithography system involving the application of enhanced data manipulation and lithographic techniques to production of three-dimensional objects, whereby such objects can be formed more rapidly, reliably, accurately and economically. Specifically, this invention relates to stereolithographic supports for the object.

[0002]

[Background Art]

It is common practice in the production of plastic parts and the like to first design such a part and then painstakingly produce a prototype of the part, all involving considerable time, effort and expense. The design is then reviewed and, oftentimes, the laborious process is again and again repeated until the design has been optimized. After design optimization, the next step is production. Most production plastic parts are injection molded. Since the design time and tooling costs are very high, plastic parts are usually only practical in high volume production. While other processes are available for the production of plastic parts, including direct machine work, vacuum-forming and direct forming, such methods are typically only cost effective for short run production, and the parts produced are usually inferior in quality to molded parts.

[0003]

Very sophisticated techniques have been developed in the past for generating three-dimensional objects within a fluid medium which is selectively cured by beams of radiation brought to selective focus at prescribed intersection points within the three-dimensional volume of the fluid medium. Typical of such three-dimensional systems are those described in U.S. Pat. Nos. 4,041,476; 4,078,229; 4,238,840 and 4,288,861. All of these systems rely upon the buildup of synergistic energization at selected points deep within the fluid volume, to the exclusion of all other points in the fluid volume. Unfortunately, however, such three-dimensional forming systems face a number of problems with regard to resolution and exposure control. The loss of radiation intensity and image forming resolution of the focused spots as the intersections move deeper into the fluid medium create rather obvious complex control situations. Absorption, diffusion, dispersion and diffraction all contribute to the difficulties of working deep within the fluid medium on an economical and reliable basis.

[0004]

In recent years, "stereolithography" systems, such as those described in U.S. Pat. No. 4,575,330 entitled "Apparatus For Production Of Three-Dimensional Objects By Stereolithography," which is hereby fully incorporated by reference into this disclosure as though set forth in full herein, have come into use. Basically, stereolithography is a method for automatically building complex plastic parts by successively printing cross-sections of photopolymer (such as liquid plastic) on top of each other until all of the thin layers are joined together to form a whole part. With this technology, the parts are literally grown in a vat of liquid plastic. This method of fabrication is extremely powerful for quickly reducing design ideas to physical form and for making prototypes.

[0005]

Photocurable polymers change from liquid to solid in the presence of light and their photospeed with ultraviolet light is fast enough to make them practical model building materials. The material that is not polymerized when a part is made is still usable and remains in the vat as successive parts are made. An ultraviolet laser generates a small intense spot of UV. This spot is moved across the liquid surface with a galvanometer mirror X-Y scanner. The scanner is driven by computer generated vectors or the like. Precise complex patterns can be rapidly produced with this technique.

[0006]

The laser scanner, the photopolymer vat and the elevator, along with a controlling computer, combine together to form a stereolithography apparatus, referred to as an "SLA". An SLA is programmed to automatically make a plastic part by drawing a cross section at a time, and building it up layer by layer.

[0007]

Stereolithography represents an unprecedented way to quickly make complex or simple parts without tooling. Since this technology depends on using a computer to generate its cross sectional patterns, there is a natural data link to CAD/CAM. However, such systems have encountered difficulties relating to shrinkage, curl and other distortions, as well as resolution, accuracy and difficulties in producing certain object shapes.

[0008]

Supports are shown in the figures in Patent No. 4,575,330, and these supports attach the object to the platform.

[0009]

The original type of posts/supports used were actually formed by curing single points. These points were cured for specific lengths of time to give appropriate cure depths, with a corresponding cure width. This type of post is limited by its strength, and the associated cure time required to achieve this strength level if even possible to obtain the desired strength.

[0010]

Another type of post/support structure is based on the need to increase the adhesion strength between layers. The adhesion strength is proportional to the area of contact between layers. When curing a point the cure width quickly reaches a limit where additional cure width is impractical; therefore, another method of increasing contact area was implemented. Instead of curing supports that are point vectors in cross-section this next phase uses supports that are polygons in cross-section. These polygons can be triangles, rectangles, octagons, etc. These structures give us much greater contact area between layers (much greater adhesion strength), along with much greater structural strength against horizontal translation. These supports worked reasonably well but they still encountered some difficulties in that: 1) they were hard to remove from the object, 2) they offered support to only a limited number of object vectors, and 3) this type of support structure required the use of a base to support the polygons to insure attachment of the perforated platform.

[0011]

[Technical Problem]

Hence, there continues to be a long existing need in the design and production arts for the capability of rapidly and reliably moving from the design stage to the prototype stage and to ultimate production, particularly moving directly from the computer designs for such plastic parts to virtually immediate prototypes and the facility for large scale production on an economical and automatic basis.

[0012]

Accordingly, those concerned with the development and production of three-dimensional plastic objects and the like have long recognized the desirability for further improvement in more rapid, reliable, economical and automatic means which would facilitate quickly moving from a design stage to the prototype stage and to production, while avoiding the support problems of the previous three-dimensional production systems. The present invention clearly fulfills all of these needs.

[0013]

Briefly and in general terms, the present invention provides an object support system which solves several problems. It supplies a method of attaching an object to the platform. It allows easy removal of a cured part from the platform. It allows better control of the thickness of the first layer of the part. It improves liquid flow in and around the part. It decreases required dip time. It allows the part to drain faster and better. It anchors free floating boundaries (insures borders are held in place until cross-hatch is drawn). It prevents deformation due to curl, due to forces associated with dipping, and due to the weight of the part. It anchors part sections that otherwise would not attach to anything (until future layers are drawn).

[0014]

Basically, the present invention provides a new and improved stereolithography system for generating a three-dimensional object by forming successive, adjacent, cross-sectional laminae of that object at the face of a fluid medium capable of altering its physical state in response to appropriate synergistic stimulation, information defining the object being specially processed to provide necessary object supports, the successive laminae being automatically integrated as they are formed to define the desired three-dimensional object.

[0015]

[Solution to Problem]

The present invention is a stereolithographic apparatus, comprising: a first means for providing specifically created object defining data with respect to a three-dimensional object to be formed, the specifically created data specifying a support structure for the object; and a second means responsive to the specifically created data for automatically forming the three-dimensional object.

[0016]

Preferably, the specifically created data specifies webs thin enough to facilitate removal from the object after the object is formed, the specifically created data specifies webs long enough to span the cross section of the object, the specifically created data specifies supports which anchor layer borders in place until crosshatch vectors are drawn, the specifically created data specifies supports for preventing deformation of cantilevered beams, or the specifically created data specifies supports for attaching layer sections that would otherwise drift.

[0017]

The present invention is a stereolithographic method, comprising the steps of: providing specifically created object defining data with respect to a three-dimensional object to be formed, the specifically created data specifying a support structure for the object; and utilizing the specifically created data to stereolithographically form the three-dimensional object.

[0018]

Preferably, the step of providing specifically created data includes data which specifies webs thin enough to facilitate removal from the object after the object is formed, the step of providing specifically created data includes data which specifies webs long enough to span the cross section of the object, the step of providing specifically created data includes data which specifies supports which anchor layer borders in place until cross-hatch vectors are drawn, the step of providing specifically created data includes data which specifies supports for preventing deformation of cantilevered beams, or the step of providing specifically created data includes data which specifies supports for attaching layer sections that would otherwise drift.

[0019]

The present invention is a stereolithographic method for forming a three-dimensional object, the method comprising the steps of: providing data representing a cross section of the three-dimensional object to be formed; providing data representing a cross section of a support structure used to form the three-dimensional object; combining cross-sectional object data and cross-sectional support structure data to create structural data; and using the structural data to form the three-dimensional object and support structure from a plurality of combined cross sections. The present invention is also a stereolithographic method for forming a three-dimensional object, the method comprising the steps of: providing data representing a cross section of the three-dimensional object to be formed; providing data representing a support structure used to form the three-dimensional object; slicing the data representing the support structure to obtain cross-sectional support structure data indicating the support structure; and using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[0020]

The present invention is also a stereolithographic method for forming a three-dimensional object, the method comprising the steps of: providing data representing a cross section of the three-dimensional object to be formed, each cross section including a boundary region and an interior region, and at least some of the boundary regions and interior regions of some of the cross sections facing downward during the formation of the object; providing data representing a slender support structure used to support at least a section of the downward facing interior region of at least some cross sections of the three-dimensional object when the three-dimensional object is being formed; and the object data and support structure data are used to form the three-dimensional object and support structure from a

plurality of combined cross sections, continuous cross sections being formed on top of already formed cross sections.

[0021]

The present invention is also a stereolithographic method for forming a three-dimensional object, the method comprising the steps of: providing data representing a cross section of the three-dimensional object to be formed; defining a region under downward-facing surfaces of the three-dimensional object in which one or more support structures are to be located; using the defined areas and hatch patterns to obtain data representing the one or more support structures; and using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[0022]

The present invention is a stereolithographic method for forming a three-dimensional object, the method comprising the steps of: providing data representing a cross section of the three-dimensional object to be formed; automatically obtaining data representing one or more support structures that support the object when the object is being formed; and using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[0023]

In the stereolithographic methods for forming a three-dimensional object described above, the object is formed from a medium that can be cured by exposure to a predetermined stimulus, and the steps of using the medium include forming a layer of fluid medium in preparation to forming a continuous section of the object and support structure, and exposing the layer to a predetermined stimulus to form and adhere a continuous cross section of the object and support structure.

[0024]

Preferably, the medium is a photopolymerizable polymer, and the predetermined stimulus is selected from the group consisting of visible light, invisible light, and ultraviolet light.

[0025]

The present invention is also a stereolithographic apparatus that forms a three-dimensional object, comprising: a means for providing data representing a cross section of the three-dimensional object to be formed; a means for providing data representing a cross section of a support structure used to form the three-dimensional object; a means for combining cross-sectional object data and cross-sectional support structure data to create structural data; and a means for using the structural data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[0026]

The present invention is also a stereolithographic apparatus that forms a three-dimensional object, comprising: a means for providing data representing a cross section of the three-dimensional object to be formed; a means for providing data representing a support structure used to form the three-dimensional object; a means for slicing the data representing the support structure to obtain cross-sectional support structure data indicating the support structure; and a means for using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[0027]

The present invention is also a stereolithographic apparatus that forms a three-dimensional object, comprising: a means for providing data representing a cross section of the three-dimensional object to be formed, each cross section including a boundary region and an interior region, and at least some of

the boundary regions and interior regions of some of the cross sections facing downward during the formation of the object; a means for providing data representing a slender support structure used to support at least a section of the downward facing interior region of at least some cross sections of the three-dimensional object when the three-dimensional object is being formed; and a means for using the object data and support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections, continuous cross sections being formed on top of already formed cross sections.

[0028]

The present invention is also a stereolithographic apparatus that forms a three-dimensional object, comprising: a means for providing data representing a cross section of the three-dimensional object to be formed; a means for defining a region under downward-facing surfaces of the three-dimensional object in which one or more support structures are to be located; a means for using the defined areas and hatch patterns to obtain data representing the one or more support structures; and a means for using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[0029]

The present invention is also a stereolithographic apparatus that forms a three-dimensional object, comprising: a means for providing data representing a cross section of the three-dimensional object to be formed; a means for automatically obtaining data representing one or more support structures that support the object when the object is being formed; and a means for using the object data and cross-sectional support structure data to form the three-dimensional object and support structure from a plurality of combined cross sections.

[0030]

In addition, the web supports in the present invention are not limited to supports that extend perpendicular to the surface to be supported, but may also be supports that extend diagonally to the surface to be supported.

[0031]

"Stereolithography" is a method and apparatus for making solid objects by successively "printing" thin layers of a curable material, e.g., a UV curable material, one on top of the other. A programmed movable spot beam of UV light shining on a surface or layer of UV curable liquid is used to form a solid cross-section of the object at the surface of the liquid. The object is then moved, in a programmed manner, away from the liquid surface by the thickness of one layer, and the next cross-section is then formed and adhered to the immediately preceding layer defining the object. This process is continued until the entire object is formed.

[0032]

Of course, it will be appreciated that other forms of appropriate synergistic stimulation for a curable fluid medium, such as particle bombardment (electron beams and the like), chemical reactions by spraying materials through a mask or by ink jets, or impinging radiation other than ultraviolet light, may be used in the practice of the invention without departing from the spirit and scope of the invention.

[0033]

By way of example, in the practice of the present invention, a body of a fluid medium capable of solidification in response to prescribed stimulation is first appropriately contained in any suitable vessel to define a designated working surface of the fluid medium at which successive cross-sectional laminae can be generated. Thereafter, an appropriate form of synergistic stimulation, such as a spot of UV light or the like, is applied as a graphic pattern at the specified working surface of the fluid medium to form thin, solid, individual layers at the surface, each layer representing an adjacent cross-section

of the three-dimensional object to be produced. In accordance with the invention, information defining the object is specially processed to reduce curl and distortion, and increase resolution, strength, accuracy, speed and economy of reproduction.

[0034]

Superposition of successive adjacent layers on each other is automatically accomplished, as they are formed, to integrate the layers and define the desired three-dimensional object. In this regard, as the fluid medium cures and solid material forms as a thin lamina at the working surface, a suitable platform to which the first lamina is secured is moved away from the working surface in a programmed manner by any appropriate actuator, typically all under the control of a micro-computer of the like. In this way, the solid material that was initially formed at the working surface is moved away from that surface and new liquid flows into the working surface position. A portion of this new liquid is, in turn, converted to solid material by the programmed UV light spot to define a new lamina, and this new lamina adhesively connects to the material adjacent to it, i.e., the immediately preceding lamina. This process continues until the entire three-dimensional object has been formed. The formed object is then removed from the container and the apparatus is ready to produce another object, either identical to the first object or an entirely new object generated by a computer or the like.

[0035]

The data base of a CAD system can take several forms. One form consists of representing the surface of an object as a mesh of polygons, typically triangles. These triangles completely form the inner and outer surfaces of the object. This CAD representation also includes a unit length normal vector for each triangle. The normal points away from the solid which the triangle is bounding and indicates slope. Means are provided for processing CAD data, which may be in the form of "PHIGS" or the like, into layer-by-layer vector data that can be used for forming models through stereolithography. Such information may ultimately be converted to raster scan output data or the like.

[0036]

As previously indicated, stereolithography is a three-dimensional printing process which uses a moving laser beam to build parts by solidifying successive layers of liquid plastic. This method enables a designer to create a design on a CAD system, applying the concepts of the invention to reduce curl, stress, and provide suitable supports and build an accurate plastic model in a few hours. By way of example, a stereolithography may include the following steps.

[0037]

First, the solid model is designed in the normal way on the CAD system, without specific reference to the stereolithographic process.

[0038]

Model preparation for stereolithography involves selecting the optimum orientation, adding supports, building in appropriate stress relief, and selecting the operating parameters of the stereolithography system. The optimum orientation will (1) enable the object to drain, (2) have the least number of unsupported surfaces, (3) optimize important surfaces, and (4) enable the object to fit in the resin vat. Supports must be added to secure unattached sections and for other purposes, and a CAD library of supports can be prepared for this purpose. The stereolithography operating parameters include selection of the model scale and layer (slice) thickness.

[0039]

The surface of the solid model is then divided into triangles, typically "PHIGS". A triangle is the least complex polygon for vector calculations. The more triangles formed, the better the surface resolution and hence, the more accurate the formed object with respect to the CAD design.

[0040]

Data points representing the triangle coordinates and normals thereto are then transmitted typically as PHIGS, to the stereolithographic system via appropriate network communication such as ETHERNET. The software of the stereolithographic system then slices the triangular sections horizontally (X-Y plane) at the selected layer thickness.

[0041]

The stereolithographic unit (SLA) next calculates the section boundary, hatch, and horizontal surface (skin) vectors. Hatch vectors consist of cross-hatching between the boundary vectors. Several "styles" or slicing formats are available. Skin vectors, which are traced at high speed and with a large overlap, form the outside horizontal surfaces of the object. Interior horizontal areas, those within top and bottom skins, are not filled in other than by cross-hatch vectors. Details of the vector are explained in U.S. patent application numbers 182,830, 269,801, and 331,644.

[0042]

The SLA then forms the object one horizontal layer at a time by moving the ultraviolet beam of a helium-cadmium laser or the like across the surface of a photocurable resin and solidifying the liquid where it strikes. Absorption in the resin prevents the laser light from penetrating deeply and allows a thin layer to be formed. Each layer is made up of vectors drawn in the order of outline vector, cross-hatch vector, and outer skin vector.

[0043]

The first layer that is drawn by the SLA adheres to a horizontal platform located just below the liquid surface. This platform is attached to an elevator which then lowers the platform under computer control. After drawing a layer, the platform dips a short distance, such as several millimeters into the liquid to coat the previous cured layer with fresh liquid, then rises up a smaller distance leaving a thin film of liquid from which the second layer will be formed. After a pause to allow the liquid surface to flatten out, the next layer is drawn. Since the resin has adhesive properties, the second layer becomes firmly attached to the first. This process is repeated until all the layers have been drawn and the entire three-dimensional object is formed. Normally, the bottom 0.25 inch (6.33 mm) or so of the object is a support structure on which the desired part is built. Resin that has not been exposed to light remains in the vat to be used for the next part. There is very little waste of material.

[0044]

Post processing typically involves draining the formed object to remove excess resin, ultraviolet or heat curing to complete polymerization, and removing supports. Additional processing, including sanding and assembly into working models, may also be performed.

[0045]

In accordance with the invention, supports are provided in the form of "WEBS". Webs, in cross-section are long slender rectangular structures. The width of a web is designed thin enough to be easy to remove from the part after post curing. The length of a web is designed to meet two requirements: (1) long enough to give good adhesion to the elevator platform (without need of a base), and (2) long enough to span the cross-section of the object (to give support to cross-hatch and the boundaries enclosing it).

[0046]

All of these types of supports are used to attach objects to platforms (elevators), but they are also used to give critical areas of the object extra support. These critical areas may include upper edges of windows, cantilevers, etc. Webs may start at the elevator platform and work their way up to the section that requires support or they may actually start on one section of the part and work their way up to another section that needs support.

[0047]

[Effects of the Invention]

Using the technology of the present invention, it is possible to create almost any type of object shape. Complex shapes can be easily created by using computer functions to help create a program and send program signals to a three-dimensional modeling system.

[0048]

The new and improved stereolithographic system of the present invention has many advantages over currently used apparatus for producing plastic objects. The methods and apparatus of the present invention avoid the need of producing design layouts and drawings, and of producing tooling drawings and tooling. The designer can work directly with the computer and a stereolithographic device, and when he or she is satisfied with the design as displayed on the output screen of the computer, he can fabricate a part for direct examination. If the design has to be modified, it can be easily done through the computer, and then another part can be made to verify that the change was correct. If the design calls for several parts with interacting design parameters, the method of the invention becomes even more useful because all of the part designs can be quickly changed and made again so that the total assembly can be made and examined, repeatedly if necessary. Moreover, the data manipulation techniques of the present invention enable production of objects with reduced stress, curl and distortion, and increased resolution, strength accuracy, speed and economy of production, even for difficult and complex object shapes.

[0049]

After the design is complete, part production can begin immediately, so that the weeks and months between design and production are avoided. Stereolithography is particularly useful for short run production because the need for tooling is eliminated and production set-up time is minimal. Likewise, design changes and custom parts are easily provided using the technique. Because of the ease of making parts, stereolithography can allow plastic parts to be used in many places where metal or other material parts are now used. Moreover, it allows plastic models of objects to be quickly and economically provided, prior to the decision to make more expensive metal or other material parts. (Hereinafter "parts" are also referred to as "objects.") Thus, the new and improved stereolithographic apparatus and method of the present invention can be used to design and fabricate three-dimensional plastic parts with suitable supports that reduced stress and curl quickly, reliably, accurately, and economically.

[0050]

While not limiting the invention in any way, in preferred examples of the invention, the principles of computer graphic processing can be used in combination with three-dimensional modeling. In other words, stereolithography technology is applied to the production of three-dimensional objects in order to simultaneously perform computer-aided design (CAD) and computer-aided manufacturing (CAM) when manufacturing three-dimensional objects directly by computer instruction. The present invention can be applied for the purpose of producing models and prototypes in the design phase of product development, or for configuring manufacturing systems, or even for pure art forms.

[0051]

[Description of Embodiments]

The following is a detailed description of the present invention with reference to the drawings. Stereolithography parts are preferably built on structures known as supports, rather than directly on the elevator platform. One reason for using supports is to separate the part from the platform. A part cured directly to the platform would be difficult to remove, especially if the adhering surface is large. Furthermore, the thickness of the first layer formed on the platform cannot be accurately controlled and may even vary if the platform is warped or improperly installed. This could result in lines which are not cured deeply enough to adhere to the platform, a condition that could promote curl. Even

without these potential problems, the holes in the platform would create matching bumps on the bottom surface of any part made directly on it. Displacement of liquid as the platform is submerged can change the thickness of the first few layers, and these effects would be undesirable within the part itself.

[0052]

Another reason for using supports is to improve liquid flow around the part. This enables use of a shorter dip time, since the surface of the liquid will settle faster with improved flow. Additionally, excess resin will drain faster from the completed part to reduce post processing time.

[0053]

Supports are also used to anchor sections of a part which would otherwise have a tendency to move and to strengthen areas susceptible to curl or damage during dipping.

[0054]

Referring now to the drawings, and particularly to FIG. 1 thereof, there is shown a block diagram of an overall stereolithography system suitable for practicing the present invention. A CAD generator 2 and appropriate interface 3 provide a data description of the object to be formed, typically in PHIGS format, via network communication such as ETHERNET or the like to an interface computer 4 where the object data is manipulated to optimize the data and provide output vectors which reduce stress, curl and distortion, and increase resolution, strength, accuracy, speed and economy of reproduction, even for rather difficult and complex object shapes. The interface computer 4 generates layer data by slicing, varying layer thickness, rounding polygon vertices, filling, generating flat skins, near-flat skins, up-facing and down-facing skins, scaling, cross-hatching, offsetting vectors and ordering of vectors. This is detailed in U.S. Patent Application Nos. 182,830, 269,801 and 331,644. In summary, contour vectors are used to outline each section of the object, cross-hatch vectors are used to outline the inner portion of each section, and skin vectors are used to outline the outer surface of the object. These vectors are drawn in the following order: contour, cross hatch, and outer skin.

[0055]

The vector data and parameters from the computer 4 are directed to a controller subsystem 5 for operating the system stereolithography laser, mirrors, elevator and the like.

[0056]

FIGS. 2 and 3 are flow charts illustrating the basic system of the present invention for generating three-dimensional objects by means of stereolithography.

[0057]

Many liquid state chemicals are known which can be induced to change to solid state polymer plastic by irradiation with ultraviolet light (UV) or other forms of synergistic stimulation such as electron beams, visible or invisible light, reactive chemicals applied by ink jet or via a suitable mask. UV curable chemicals are currently used as ink for high speed printing, in processes of coating of paper and other materials, such as adhesives, and in other specialty areas.

[0058]

Lithography is the art of reproducing graphic objects, using various techniques. Modern examples include photographic reproduction, xerography, and microlithography, as is used in the production of microelectronics. Computer generated graphics displayed on a plotter or a cathode ray tube are also forms of lithography, where the image is a picture of a computer coded object.

[0059]

Computer aided design (CAD) and computer aided manufacturing (CAM) are techniques that apply the abilities of computers to the processes of designing and manufacturing. A typical example of CAD is in the area of electronic printed circuit design, where a computer and plotter draw the design of a printed circuit board, given the design parameters as computer data input. A typical example of CAM is a numerically controlled milling machine, where a computer and a milling machine produce metal parts, given the proper programming instructions. Both CAD and CAM are important and are rapidly growing technologies.

[0060]

A prime object of the present invention is to harness the principles of computer generated graphics, combined with UV curable plastic and the like, to simultaneously execute CAD and CAM, and to produce three-dimensional objects directly from computer instructions. This invention, referred to as stereolithography, can be used to sculpture models and prototypes in a design phase of product development, or as a manufacturing device, or even as an art form. The present invention enhances the developments in stereolithography set forth in U.S. Pat. No. 4,575,330, issued Mar. 11, 1986, to Charles W. Hull, one of the inventors herein.

[0061]

Referring now more specifically to FIG. 2 of the drawing, the stereolithographic method is broadly outlined. Step 8 calls for generation of CAD or other data, typically in digital form, representing a three-dimensional object to be formed by the system. This CAD data usually defines surfaces in polygon format, triangles and normals perpendicular to the planes of those triangles, e.g., for slope indications, being presently preferred, and in a presently preferred embodiment of the invention conforms to the Programmer's Hierarchical Interactive Graphics System (PHIGS) now adapted as an ANSI standard. This standard is described, by way of example in the publication "Understanding PHIGS", published by Template, Megatek Corp., San Diego, Calif.

[0062]

In Step 9, the PHIGS data or its equivalent is converted, in accordance with the invention, by a unique conversion system to a modified data base for driving the stereolithography output system in forming three-dimensional objects. In this regard, information defining the object is specially processed to reduce stress, curl and distortion, and increase resolution, strength and accuracy of reproduction

[0063]

Step 10 in FIG. 2 calls for the generation of individual solid laminae representing cross-sections of a three-dimensional object to be formed. Step 11 combines the successively formed adjacent laminae to form the desired three-dimensional object which has been programmed into the system for selective curing.

[0064]

Hence, the stereolithographic system of the present invention generates three-dimensional objects by creating a cross-sectional pattern of the object to be formed at a selected surface of a fluid medium, e.g., a UV curable liquid or the like, capable of altering its physical state in response to appropriate synergistic stimulation such as impinging radiation, electron beam or other particle bombardment, or applied chemicals (as by ink jet or spraying over a mask adjacent the fluid surface), successive adjacent laminae, representing corresponding successive adjacent cross-sections of the object, being automatically formed and integrated together to provide a step-wise laminar or thin layer buildup of the object, whereby a three-dimensional object is formed and drawn from a substantially planar or sheet-like surface of the fluid medium during the forming process.

[0065]

The technique described above and shown in FIG. 2 is more specifically outlined in the flowchart of FIG. 3, where again Step 8 calls for generation of CAD or other data, typically in digital form,

representing a three-dimensional object to be formed by the system. Again, in Step 9, the PHIGS data is converted by a unique conversion system to a modified data base for driving the stereolithography output system in forming three-dimensional objects. Step 12 calls for containing a fluid medium capable of solidification in response to prescribed reactive stimulation. Step 13 calls for application of that stimulation as a graphic pattern, in response to data output from the computer 4 in FIG. 1, at a designated fluid surface to form thin, solid, individual layers at that surface, each layer representing an adjacent cross-section of a three-dimensional object to be produced. In the practical application of the invention, each lamina will be a thin lamina, but thick enough to be adequately cohesive in forming the cross-section and adhering to the adjacent laminae defining other cross-sections of the object being formed.

[0066]

Step 14 in FIG. 3 calls for superimposing successive adjacent layers or laminae on each other as they are formed, to integrate the various layers and define the desired three-dimensional object. In the normal practice of the invention, as the fluid medium cures and solid material forms to define one lamina, that lamina is moved away from the working surface of the fluid medium and the next lamina is formed in the new liquid which replaces the previously formed lamina, so that each successive lamina is superimposed and integral with (by virtue of the natural adhesive properties of the cured fluid medium) all of the other cross-sectional laminae.

[0067]

The process of producing such cross-sectional laminae is repeated over and over again until the entire three-dimensional object has been formed. The object is then removed and the system is ready to produce another object which may be identical to the previous object or may be an entirely new object formed by changing the program controlling the stereolithographic system.

[0068]

FIGS. 4-5 of the drawings illustrate various apparatus suitable for implementing the stereolithographic methods illustrated and described by the systems and flow charts of FIGS. 1-3.

[0069]

As previously indicated, "Stereolithography" is a method and apparatus for making solid objects by successively "printing" thin layers of a curable material, e.g., a UV curable material, one on top of the other. A programmable movable spot beam of UV light shining on a surface or layer of UV curable liquid is used to form a solid cross-section of the object at the surface of the liquid. The object is then moved, in a programmed manner, away from the liquid surface by the thickness of one layer and the next cross-section is then formed and adhered to the immediately preceding layer defining the object. This process is continued until the entire object is formed.

[0070]

Essentially all types of object forms can be created with the technique of the present invention. Complex forms are more easily created by using the functions of a computer to help generate the programmed commands and to then send the program signals to the stereolithographic object forming subsystem.

[0071]

The data base of a CAD system can take several forms. One form, as previously indicated, consists of representing the surface of an object as a mesh of triangles (PHIGS). These triangles completely form the inner and outer surfaces of the object. This CAD representation also includes a unit length normal vector for each triangle. The normal points away from the solid which the triangle is bounding. This invention provides a means of processing such CAD data into the layer-by-layer vector data that is necessary for forming objects through stereolithography. Details of the various vector formats are

explained in U.S. Patent Application No. 182,830, its continuation application No. 269,801, and its continuation application Lyon & Lyon Case No. 186/195.

[0072]

For stereolithography to successfully work, there must be good adhesion from one layer to the next. Hence, plastic from one layer must overlay plastic that was formed when the previous layer was built. In building models that are made of vertical segments, plastic that is formed on one layer will fall exactly on previously formed plastic from the preceding layer, and thereby provide good adhesion. As one starts to make a transition from vertical to horizontal features, using finite jumps in layer thickness, a point will eventually be reached where the plastic formed on one layer does not make contact with the plastic formed on the previous layer, this causes severe adhesion problems. Horizontal surfaces themselves do not present adhesion problems because by being horizontal the whole section is built on one layer with side-to-side adhesion maintaining structural integrity. Therefore, means are provided for insuring adhesion between layers when making transitions from vertical to horizontal or horizontal to vertical sections, as well as providing a way to completely bound a surface, and ways to reduce or eliminate stress and strain in formed parts.

[0073]

A presently preferred embodiment of a new and improved stereolithographic system is shown in elevational cross-section in FIG. 4. A container 21 is filled with a UV curable liquid 22 or the like, to provide a designated working surface 23. A programmable source of ultraviolet light 26 or the like produces a spot of ultraviolet light 27 in the plane of surface 23. The spot 27 is movable across the surface 23 by the motion of mirrors or other optical or mechanical elements (not shown in FIG. 4) used with the light source 26. The position of the spot 27 on surface 23 is controlled by a computer control system 28. As previously indicated, the system 28 may be under control of CAD data produced by a generator 20 in a CAD design system or the like and directed in PHIGS format or its equivalent to a computerized conversion system 25 where information defining the object is specially processed to reduce stress, curl and distortion, and increase resolution, strength and accuracy of reproduction.

[0074]

A movable elevator platform 29 inside container 21 can be moved up and down selectively, the position of the platform being controlled by the system 28. As the device operates, it produces a three-dimensional object 30 by step-wise buildup of integrated laminae such as 30a, 30b, 30c.

[0075]

The surface of the UV curable liquid 22 is maintained at a constant level in the container 21, and the spot of UV light 27, or other suitable form of reactive stimulation, of sufficient intensity to cure the liquid and convert it to a solid material is moved across the working surface 23 in a programmed manner. As the liquid 22 cures and solid material forms, the elevator platform 29 that was initially just below surface 23 is moved down from the surface in a programmed manner by any suitable actuator. In this way, the solid material that was initially formed is taken below surface 23 and new liquid 22 flows across the surface 23. A portion of this new liquid is, in turn, converted to solid material by the programmed UV light spot 27, and the new material adhesively connects to the material below it. This process is continued until the entire three-dimensional object 30 is formed. The object 30 is then removed from the container 21, and the apparatus is ready to produce another object. Another object can then be produced, or some new object can be made by changing the program in the computer 28.

[0076]

The curable liquid 22, e.g., UV curable liquid, must have several important properties. (A) It must cure fast enough with the available UV light source to allow practical object formation times. (B) It must be adhesive, so that successive layers will adhere to each other. (C) Its viscosity must be low enough so that fresh liquid material will quickly flow across the surface when the elevator moves the object. (D) It should absorb UV so that the film formed will be reasonably thin. (E) It must be reasonably soluble in some solvent in the liquid state, and reasonably insoluble in that same solvent in the solid state, so

that the object can be washed free of the UV cure liquid and partially cured liquid after the object has been formed. (F) It should be as non-toxic and non-irritating as possible.

[0077]

The cured material must also have desirable properties once it is in the solid state. These properties depend on the application involved, as in the conventional use of other plastic materials. Such parameters as color, texture, strength, electrical properties, flammability, and flexibility are among the properties to be considered. In addition, the cost of the material will be important in many cases.

[0078]

The UV curable material used in the presently preferred embodiment of a working stereolithograph (e.g., FIG. 3) is DeSoto SLR 800 stereolithography resin, made by DeSoto, Inc. of 1700 South Mt. Prospect Road, Des Plaines, Illinois.

[0079]

The light source 26 produces the spot 27 of UV light small enough to allow the desired object detail to be formed, and intense enough to cure the UV curable liquid being used quickly enough to be practical. The source 26 is arranged so it can be programmed to be turned off and on, and to move, such that the focused spot 27 moves across the surface 23 of the liquid 22. Thus, as the spot 27 moves, it cures the liquid 22 into a solid, and "draws" a solid pattern on the surface in much the same way a chart recorder or plotter uses a pen to draw a pattern on paper.

[0080]

The light source 26 for the presently preferred embodiment of a stereolithography is typically a helium-cadmium ultraviolet laser such as the Model 4240N HeCd Multimode Laser, made by Liconix of Sunnyvale, Calif.

[0081]

In the system of FIG. 4, means may be provided to keep the surface 23 at a constant level and to replenish this material after an object has been removed, so that the focus spot 27 will remain sharply in focus on a fixed focus plane, thus insuring maximum resolution in forming a layer along the working surface. In this regard, it is desired to shape the focal point to provide a region of high intensity right at the working surface 23, rapidly diverging to low intensity and thereby limiting the depth of the curing process to provide the thinnest appropriate cross-sectional laminae for the object being formed.

[0082]

The elevator platform 29 is used to support and hold the object 30 being formed, and to move it up and down as required. Typically, after a layer is formed, the object 30 is moved beyond the level of the next layer to allow the liquid 22 to flow into the momentary void at the surface 23 left where the solid was formed, and then it is moved back to the correct level for the next layer. The requirements for the elevator platform 29 are that it can be moved in a programmed fashion at appropriate speeds, with adequate precision, and that it is powerful enough to handle the weight of the object 30 being formed. In addition, a manual fine adjustment of the elevator platform position is useful during the set-up phase and when the object is being removed.

[0083]

The elevator platform 29 can be mechanical, pneumatic, hydraulic, or electrical and may also use optical or electronic feedback to precisely control its position. The elevator platform 29 is typically fabricated of either glass or aluminum, but any material to which the cured plastic material will adhere is suitable.

[0084]

A computer controlled pump (not shown) may be used to maintain a constant level of the liquid 22 at the working surface 23. Appropriate level detection system and feedback networks, well known in the art, can be used to drive a fluid pump or a liquid displacement device, such as a solid rod (not shown) which is moved out of the fluid medium as the elevator platform is moved further into the fluid medium, to offset changes in fluid volume and maintain constant fluid level at the surface 23. Alternatively, the source 26 can be moved relative to the sensed level 23 and automatically maintain sharp focus at the working surface 23. All of these alternatives can be readily achieved by appropriate data operating in conjunction with the computer control system 28.

[0085]

FIG. 6 of the drawings illustrates the overall software architecture of a stereolithography system in which the present invention may be practiced.

[0086]

As an overview, the portion of our processing referred to as "SLICE" takes in the object that you want to build, together with any scaffolding or supports that are necessary to make it more buildable. These supports are typically generated by the user's CAD. The first thing SLICE does is to find the outlines of the object and its supports.

[0087]

SLICE defines each microsection or layer one at a time under certain specified controlling styles. SLICE produces a boundary to the solid portion of the object. If, for instance, the object is hollow, there will be an outside surface and an inside one. This outline then is the primary information. The SLICE program then takes that outline or series of outlines and says, but if you build an outside skin and an inside skin they won't join to one another, you'll have liquid between them. It will collapse. So let us turn this into a real product, a real part by putting in cross-hatching between the surfaces or solidifying everything in between or adding skins where there is so gentle a slope that one layer wouldn't join on top of the next, remembering past history or slope of the triangles (PHIGS) whichever way you look at it. SLICE does all those things and may use some lookup tables of the chemical characteristics of the photopolymer, how powerful the laser is, and related parameter to indicate how long to expose each of the output vectors used to operate the system. That output consists of identifiable groups. One group consists of the boundaries or outlines. A third group consists of skins and there are subgroups of those, upward facing skins, and downward facing skins which have to be treated slightly differently. These subgroups are all tracked differently because they may get slightly different treatment in the process. The output data is then appropriately managed to form the desired object and supports. These vector formats and formations are described in detail in U.S. patent applications Nos. 182,830, 269,801, and 331,644.

[0088]

After the three-dimensional object 30 has been formed, the elevator platform 29 is raised and the object is removed from the platform for post processing.

[0089]

In addition, there may be several containers 21 used in the practice of the invention, each container having a different type of curable material that can be automatically selected by the stereolithographic system. In this regard, the various materials might provide plastics of different colors, or have both insulating and conducting material available for the various layers of electronic products.

[0090]

As will be apparent from FIG. 5 of the drawings, there is shown an alternate configuration of a stereolithograph wherein the UV curable liquid 22 or the like floats on a heavier UV transparent liquid 32 which is non-miscible and non-wetting with the curable liquid 22. By way of example, ethylene

glycol or heavy water are suitable for the intermediate liquid layer 32. In the system of FIG. 4, the three-dimensional object 30 is pulled up from the liquid 22, rather than down and further into the liquid medium, as shown in the system of FIG. 3.

[0091]

The UV light source 26 in FIG. 5 focuses the spot 27 at the interface between the liquid 22 and the non-miscible intermediate liquid layer 32, the UV radiation passing through a suitable UV transparent window 33, of quartz or the like, supported at the bottom of the container 21. The curable liquid 22 is provided in a very thin layer over the non-miscible layer 32 and thereby has the advantage of limiting layer thickness directly rather than relying solely upon absorption and the like to limit the depth of curing since ideally an ultrathin lamina is to be provided. Hence, the region of formation will be more sharply defined and some surfaces will be formed smoother with the system of FIG. 5 than with that of FIG. 4. In addition a smaller volume of UV curable liquid 22 is required, and the substitution of one curable material for another is easier.

[0092]

A commercial stereolithography system will have additional components and subsystems besides those previously shown in connection with the schematically depicted systems of FIGS. 1-5. For example, the commercial system would also have a frame and housing, and a control panel. It should have means to shield the operator from excess UV and visible light, and it may also have means to allow viewing of the object 30 while it is being formed. Commercial units will provide safety means for controlling ozone and noxious fumes, as well as conventional high voltage safety protection and interlocks. Such commercial units will also have means to effectively shield the sensitive electronics from electronic noise sources.

[0093]

In accordance with the invention, part supports are provided by the user during CAD design. The following is an outline of the narrative description of the need for supports provided earlier in the application.

[0094]

The first need of a part support is separability of the part from the platform. This means that the cured part can be easily removed, the thickness of the first layer can be better controlled, and the holes in the platform match the pattern on the part.

[0095]

Second, the part support improves the flow of liquid in and around the part. This means that the liquid settles faster, dip time is minimized, and the part drains faster and better.

[0096]

Third, object supports are needed to anchor freely floating layer borders. This is because, in the case of spheres, the diameter of below layer border diameters increases rapidly, layer borders will drift, influenced by air flow and liquid convection, until the cross-hatch vectors are drawn. External supports are not needed above the equator, but internal supports may be needed. FIG. 7a and FIG. 7b show how supports anchor layer borders in place until cross-hatch vectors are drawn.

[0097]

Fourth, object supports are needed to strengthen layer sections that would otherwise be unsupported. In other words, supports can be used to prevent deformation during immersion due to increased part weight, and to prevent curling due to layer sections that cannot withstand stress but that can use small supports. FIG. 8a and FIG. 8b show how supports inhibit deformation and curl of cantilevered beams and similar structures.

[0098]

Fifth, object supports are needed to anchor unconnected layer sections. This prevents these layer sections from drifting during dipping. A support must exist at least one layer below the first unconnected section. FIG. 9a and FIG. 9b show how supports attach layer sections that would otherwise drift during dipping.

[0099]

The following is an overview of the web support that is provided later in this application.

[0100]

In the present invention, a "web" support is used. A web support is first of all a practical shape applicable to almost everything. In other words, it is easy to remove, does not fall through the platform, has back-to-back layer borders, and does not require cross-hatching or an outer skin, and does not take too long to draw.

[0101]

Second, web supports are characterized by the ability to create commonly used support style CAD libraries. This is because similar supports can be used for different parts, and it is faster to modify an existing support than to create a new one. The following is a description of examples.

[0102]

Example A

Near the bottom of the solid sphere shown in FIG. 7a and FIG. 7b, the layer border vectors consist of circles whose diameters increase rapidly with each successive layer. Until the cross-hatch vectors are drawn, many of the layer borders would float free on the surface of the liquid. Air currents or convection currents in the liquid could cause them to drift out of position. Adding supports which extend to the equator of the sphere, as shown in FIG. 7b solves this problem. Note that above the equator, the layer borders are formed directly on the cross-hatch vectors of the previous layer, and as such are firmly anchored without the need for further support.

[0103]

Example B

The first layer of the cantilevered beam shown in FIG. 8a and FIG. 8b (or any unsupported layer border) may be permanently deformed by the static resistance of the liquid when the part is dipped. In addition, the layer could curl upward when the next layer is formed. Both of these problems are solved by adding supports.

[0104]

Example C

The first layer of the teacup handle shown in FIG. 9a and FIG. 9b would be completely unattached when formed and would drift when the part is dipped. The support provides a surface, anchored to the elevator platform or to the body of the teacup, on which the handle can be built.

[0105]

The most practical type of support is the thin, vertical web shown in the previous illustrations. Web supports are easy to remove during post processing and, if they are designed properly, will not fall

through the holes in the elevator platform. Other shapes could provide the necessary support, but would take longer to draw.

[0106]

Generally, supports are designed together as a single CAD file separate from the part file. They are positioned relative to the solid model after the part is designed and oriented for stereolithography. The object and support files are merged and drawn as a single file later in the stereolithography process. A library of supports resident in the CAD is recommended, rather than designing unique supports for each application. In either case, supports should be designed and attached to the part in accordance with the following guidelines.

[0107]

Placement: Supports should be located as needed to provide a rigid foundation on which the part may be built. Supports should also be added to anchor or strengthen other surfaces, as discussed in the preceding examples. After the part is post-cured and the supports are removed, ridges will normally remain on the surface of the part. (The ridges can be cut and sanded or ground away.) Thus, if possible, avoid placing supports on surfaces that for aesthetic or functional reasons need to be smooth. Supports need not be attached to the elevator platform, but can instead be anchored to a strong section of the part.

[0108]

Spacing: In general, supports should be spaced at sufficiently close intervals so that no appreciable sag or curl occurs; however, drawing too many supports will slow the part building process. Web supports should typically be spaced 0.1 to 0.8 inch (2.54 to 20.32 mm) apart.

[0109]

Orientation: If all web supports for a part are aligned parallel to one another, as shown in FIG. 10a and FIG. 10b, the weight of the part could cause the webs to sag sideways while the part is being built. Subsequently layers would then be offset slightly (skewed) with respect to the previous layers. The addition of web supports more or less perpendicular to the parallel webs will prevent layer skewing.

[0110]

Height: To inhibit bending or sagging and to minimize drawing time, web supports should be no taller than required; however, the part must be suspended at least 0.25 inch (6.35 mm) above the elevator platform to ensure optimum liquid draining and settling (relaxing). If a tall web is needed, a second web perpendicular to the first should be added for additional support. In cross-section, the combined support would look like a plus sign, as shown in FIG. 10.

[0111]

Length: To minimize drawing time, supports should be only as wide as necessary. However, web supports built on the platform must be at least 0.65 inch (16.51 mm) wide where they contact the platform or they may droop or fall through the holes. Diagonal supports beginning and ending on the part should be designed as buttresses, as shown in FIG. 11, and should not extend into the corner of the part where they will be hard to remove.

[0112]

Width: Web supports should be designed as slabs of 1-2 mil (0.025 to 0.051 mm) CAD thickness. Since the width of the lines drawn with the laser is usually 10 to 20 mils (0.25 to 0.51 mm), the actual support will be considerably thicker than the CAD design. Supports designed as single surfaces with no CAD volume will confuse the software which creates cross-hatching, and should be avoided.

[0113]

Thickness: The thickness of the web support is formed by the looped reciprocating scan of the curing beam. Although the minimum thickness is reached when the beams are adjacent during that reciprocation, its thickness is less than two curing widths (the width of one beam curing) (see example below for details).

[0114]

If beam width compensation is used, the supports should be designed with the actual width desired, i.e., 10-20 mils, since the beam width compensation algorithm will compensate for the thickness of the lines drawn with the laser. Beam width compensation is described in more detail in U.S. Patent Application Nos. 182,830, 269,801 and 331,644.

[0115]

To ensure that the part is securely attached to the supports, design the web supports to overlap the part vertically by two or three layer thicknesses (typically 40 to 60 mils (1.02 to 1.52 mm)).

[0116]

Other common forms of support, in addition to the above, include the following.

[0117]

A "straight web" is generally an ultra-thin rectangular cross section less than 0.002 inches (0.051 mm) thick. This must be specified as a thickness, not a single surface. A "cross-shaped web" is a web consisting of two straight webs that intersect at right angles. It is stronger than a straight web. A "circular web" is a hollow tube tightly bonded to an object. It can support greater weights than straight and cross-shaped webs. However, they require more triangles and therefore use more space in a storage devices. A "triangular web" consists of three straight webs forming a triangle. It can be used in relation to straight webs that intersect each vertex. It is stronger than all other forms of web support.

[0118]

As mentioned earlier, supports are designed together in a single CAD file separate from the part file. These stereolithography (.STL) files are then sliced, or cross-sectioned, before being merged into one file. The features of the slicing software (SLICE) and merging software (MERGE) applicable to supports are described below. Details of commercial implementations of SLICE and MERGE software are described in U.S. patent applications Nos. 182,830, 269,801, and 331,644.

[0119]

SLICE has several options which are usually set to zero when slicing support files. Since web supports are thin, cross-hatching is unnecessary, so the X, Y and 60/120 hatch spacing values should be set to zero. For the same reason, supports do not need skins, so the X and Y skin fill values may also be zeroed. Minimum surface angle for scanned facets (MSA) and minimum hatch intersect angle (MIA) should be set to zero because web supports do not need near-flat skins and have no cross-hatching.

[0120]

The slice scale and Z spacing values selected for the support file must be compatible with the values chosen for the part file; that is, the support slice thickness must be evenly divisible by or identical to the slice thickness of the part file (in the overlap region). Otherwise, it will be impossible to draw lines for the supports and the part in the same layer.

[0121]

In forming the walls of the web support (one mil (0.0254 mm) apart), the layer border exposed while drawing the first wall will again be exposed while the second is drawn, because of the relatively broad laser line width. This effectively doubles the step period. For this reason, the step period obtained from the working curve may be divided by two before it is entered.

[0122]

The final operator action required to build supports is to use PREPARE menu options to increase the default step period value for the layer border vectors forming the first layer of the supports. Doing so increases the thickness (cure depth) of the layer. Normally, tripling the default support step period ensures adequate adhesion of the first layer of the supports to the platform.

[0123]

Another method of creating web supports is by creating a box with internal cross-hatching below the part being cured. In this latter approach, the already implemented SLICE algorithms for generating hatch vectors could be used to generate the web supports. This approach avoids the necessity of designing web supports in the CAD/CAM system, as described above. The box could be created in a separate .SLI file, placed into its own .SLI file, then merged with the .SLI file for the part after slicing. Specifically, a straight web could be created by hatching in the X or Y directions (not both). A crisscrossed web support could be implemented by hatching in the X and Y directions. A triangular web support could be implemented by hatching at 60/120 degrees and in either the X or the Y directions. In addition, the hatch spacing should be chosen to be 1/4" to 1" (6.35 to 25.4 mm) depending on the support needed.

[0124]

An example of a commercial system (SLA-1), provided by 3D Systems, Inc. of Sylmar, California, that embodies the present invention, is described below.

[0125]

The new and improved stereolithographic method and apparatus has many advantages over currently used methods for producing plastic objects. The method avoids the need of producing tooling drawings and tooling. The designer can work directly with the computer and a stereolithographic device, and when he is satisfied with the design as displayed on the output screen of the computer, he can fabricate a part for direct examination, information defining the object being tailored to provide supports to reduce curl and distortion, and increase resolution, strength and accuracy of reproduction. If the design has to be modified, it can be easily done through the computer, and then another part can be made to verify that the change was correct. If the design calls for several parts with interacting design parameters, the method becomes even more useful because all of the part designs can be quickly changed and made again so that the total assembly can be made and examined, repeatedly if necessary.

[0126]

After the design is complete, part production can begin immediately, so that the weeks and months between design and production are avoided. Ultimate production rates and parts costs should be similar to current injection molding costs for short run production, with even lower labor costs than those associated with injection molding. Injection molding is economical only when large numbers of identical parts are required. Stereolithography is particularly useful for short run production because the need for tooling is eliminated and production set-up time is minimal. Likewise, design changes and custom parts are easily provided using the technique. Because of the ease of making parts, stereolithography can allow plastic parts to be used in many places where metal or other material parts are now used. Moreover, it allows plastic models of objects to be quickly and economically provided, prior to the decision to make more expensive metal or other material parts.

[0127]

The present invention satisfies a long existing need in the art for a CAD and CAM system capable of rapidly, reliably, accurately and economically designing and fabricating three-dimensional plastic parts and the like.

[0128]

The objects and effects of the present invention described above, as well as others, will be further clarified by the detailed description of the following examples.

[0129]

(Examples)

The SLA-1 stereolithography system creates three-dimensional objects directly from a CAD system. The created objects, each up to 9 inches (22.86 cm) in length, width, and height, are created in photocured plastic. These can be widely used in various applications, for example, in industrial engineering, design engineering, architectural design, medicine, and science. The first embodiment of the SLA-1 stereolithography system is described in detail below.

[0130]

(First Embodiment)

1. Stereolithography Process

Stereolithography is a three-dimensional printing process which uses a moving laser beam to build parts by solidifying successive layers of liquid plastic. This method enables a designer to create a design on a CAD system and build an accurate plastic model in 2 to 3 hours. As shown in FIG. 12, the stereolithographic process is composed of eight steps: design solid model, prepare model for stereolithography, section model into triangles and reduce data for transmission, transmit data file to SLA-1 slice computer, slice triangle files horizontally, calculate vectors and add hatch and fill, and form object.

[0131]

The solid model is designed in the normal way on the CAD system, without specific reference to the stereolithographic process. A copy of the model is made for stereolithographic processing.

[0132]

Model preparation for stereolithography involves selecting the optimum orientation, adding supports, and selecting SLA-1 operating parameters. The optimum orientation will (1) enable the object to drain, (2) have the least number of unsupported surfaces, (3) optimize important surfaces, and (4) enable the object to fit in the resin vat. Supports must be added to secure unattached sections and for other purposes; a CAD library of supports can be prepared for this purpose. SLA-1 operating parameters include selection of the model scale and layer (slice) thickness.

[0133]

The surface of the solid model is then divided into triangles. A triangle is the least complex polygon for vector calculations. The Beta SLA-1 capability is approaching 200,000 triangles, with further improvements planned for the production SLA-1. The more triangles formed, the better the surface resolution and hence the more accurate the formed object with respect to the CAD design.

[0134]

Data points representing the triangle coordinates are then transmitted to the SLA-1 via Ethernet communication. The SLA-1 software slices the triangular sections horizontally (X-Y plane) at the selected layer thickness.

[0135]

The SLA-1 next calculates the section boundary, hatch, and horizontal surface (skin) vectors. Hatch vectors consist of cross-hatching between the boundary vectors. Several styles are available. Skin vectors, which are traced at high speed and with a large overlap, form the outside horizontal surfaces of the object. Interior horizontal areas, those within top and bottom skins, are not filled in other than by cross-hatch vectors.

[0136]

The SLA-1 forms the object one horizontal layer at a time by moving the ultraviolet beam of a helium-cadmium laser across the surface of a photocurable resin and solidifying the liquid where it strikes. Absorption in the resin prevents the laser light from penetrating deeply and allows a thin layer to be formed. Each layer is comprised of vectors which are drawn in the following order: border, hatch, and surface.

[0137]

The first layer that is drawn adheres to a horizontal platform located just below the liquid surface. This platform is attached to an elevator which then lowers it vertically under computer control. After drawing a layer, the platform dips several millimeters into the liquid to coat the previous cured layer with fresh liquid, then rises up a smaller distance leaving a thin film of liquid from which the second layer will be formed. After a pause to allow the liquid surface to flatten out, the next layer is drawn. Since the resin has adhesive properties, the second layer becomes firmly attached to the first. This process is repeated until all the layers have been drawn and the entire three-dimensional object is formed. Normally, the bottom 0.25 inch (6.35 mm) or so of the object is a support structure on which the desired part is built. Resin that has not been exposed to light remains in the vat to be used for the next part. There is very little waste of material.

[0138]

Post processing involves heating the formed object to remove excess resin, ultraviolet or heat curing to complete polymerization, and removing supports. Additional processing, including sanding and assembly into working models, may also be performed.

[0139]

2. Stereolithography Apparatus

The SLA-1 is a self-contained system that interfaces directly with the user's CAD system. The SLA-1, as shown in Figures 13a-13c, consists of four major component groups: the slice computer terminal, the electronic cabinet assembly, the optics assembly, and the chamber assembly. A block diagram of the SLA-1 is shown in FIG. 14.

[0140]

2.1 Electronic Cabinet Assembly

The electronic cabinet assembly includes the process computer (disc drive), keyboard, monitor, power supplies, AC power distribution panel, and control panel. The computer assembly includes plug-in circuit boards for control of the terminal, high-speed scanner mirrors, and a vertical (Z-stage) elevator. Power supplies for the laser, dynamic mirrors, and elevator motor are mounted in the lower portion of the cabinet. The control panel (FIG. 16a, FIG. 16b) includes a power on switch/indicator, a chamber light switch/indicator, a laser on indicator, and a shutter open indicator. Operation and maintenance parameters, including fault diagnostics and laser performance information, are displayed on the monitor. Operation is controlled by keyboard entries. Work surfaces around the keyboard and disc drive are covered with formica for easy cleaning and long wear.

[0141]

2.2 Optics Assembly

The helium cadmium (HeCd) laser and optical components are mounted on top of the electronic cabinet and chamber assembly as shown in FIG. 23a to FIG. 23c. The laser and optics plate may be accessed for service by removing separate covers. For safety reasons, a special tool is required to unlock the cover fasteners and interlock switches are activated when the covers are removed. The interlocks activate a solenoid-controlled shutter to block the laser beam when either cover is removed. An optics cleaning kit and interlock shorting tool are located under the optics cover (FIG. 19a to FIG. 19e). The cleaning kit includes cotton swabs, special cleaning tissues, and materials for cleaning the beam-turning mirrors and beam expander lenses. The interlock shorting tool is used to defeat the interlocks during servicing. This is necessary to enable optics alignment and servicing procedures which require operation of the laser with the optics and laser covers removed. The shutter assembly, two 90° beam-turning mirrors, beam expander, scanning mirror assembly, and optical window are mounted on the optics plate. The rotary solenoid-actuated shutters are installed at the laser output and rotate to block the beam when a safety interlock is opened. The 90° beam-turning mirrors reflect the laser beam to the next optical component. The beam expander enlarges and focuses the laser beam on the liquid surface. The high speed scanning mirrors direct the laser beam to trace vectors on the resin surface. A quartz window between the optics enclosure and reaction chamber allows the laser beam to pass into the reaction chamber, but otherwise isolates the two regions.

[0142]

2.3 Chamber Assembly

The chamber assembly (FIG. 24, FIG. 27) contains an environmentally-controlled chamber, which houses a platform, reaction vat, elevator, and beam profiler. The chamber in which the object is formed is designed for operator safety and to ensure uniform operating conditions. The chamber may be heated to approximately 45°C (140°F) and the air is circulated and filtered. An overhead light illuminates the reaction vat and work surfaces. An interlock on the glass access door activates a shutter to block the laser beam when opened. The reaction vat is designed to minimize handling of the resin. It is installed in the chamber on guides which align it with the elevator and platform. The part is formed on a platform attached to the vertical axis elevator, or Z-stage. The platform is immersed in the resin vat and is adjusted incrementally downward while the object is being formed. To remove the formed part, it is raised to a position above the vat. The platform is then disconnected from the elevator and removed from the chamber for post processing. Handling trays are provided to catch dripping resin. The beam profiler is mounted to one side of the reaction vat at the focal length of the laser. The scanning mirror is periodically commanded to direct the laser beam onto the beam profiler, which measures the beam intensity profile. The data may be displayed on the terminal either as a profile with intensity contour lines or as a single number representing the overall (integrated) beam intensity. This information is used to determine whether the mirrors should be cleaned and aligned, whether the laser should be serviced, and what parameter values will yield vectors of the desired thickness and width.

[0143]

3 Software. A software diagram of the SLA-1 is shown in FIG. 15. There are three computers needed to control the stereolithographic apparatus, a CAD system, a slice computer, and a process computer. Any CAD system can be used to design a part in three-dimensional space. This is identified as the object file. In order to generate the part, supports must be added to prevent distortion. This is accomplished by adding the necessary supports to the CAD part design and creating a CAD support file. The resultant two or more CAD generated files are then physically inserted into the slice computer through Ethernet. The stereolithography apparatus builds the part one layer at a time starting with the bottom layer. The slice computer breaks down the CAD part into individual horizontal slices. The slice computer also calculates where hatch vectors will be created. This is done to achieve maximum strength as each layer is constructed. The slice computer at the Beta Sites is a separate computer with its own keyboard and monitor. It is anticipated that in production models, the slice computer will be in the SLA-1 electronic cabinet and will share a common keyboard and monitor with the process

computer. The operator can vary the thickness of each slice and change other parameters of each slice with the User Interface program. The slice computer uses the Xenix machine language and is connected to the SLA-1 process computer by an Ethernet data bus. The sliced files are then transferred to the process computer through Ethernet. The process computer merges the sliced object and support files into a layer control file and a vector file. The operator then inserts the necessary controls needed to drive the stereolithography apparatus in the layer and parameter file. (The vector file is not usually edited.) The operator can strengthen a particular volume of the part by inserting rivets. This is accomplished by inserting the necessary parameters to the critical volume file prior to merging of the sliced files. The merge program integrates the object, support, and critical volume files and inserts the resultant data in the layer control file. The operator can edit the layer control file and change the default parameter file. The default parameter file contains the controls needed to operate the stereolithography apparatus to build the part. The process computer uses the MSDOS machine language and is directly connected to the stereolithography apparatus.

[0144]

4. Performance Specifications

Beta SLA-1 performance specifications are shown in Table 1-1.

[0145]

[Table 1]

Table 1-1. Beta SLA-1 Performance Specifications

Characteristic	Specification
Input Power	
Voltage and Frequency	115 Vac, 60 Hz
Current Drain	15 amperes
Functional Characteristics	
Laser Source	
Type	Helium Cadmium
Nominal Power	10 mW at 325
Warmup Time (to 90% power)	15 minutes
Expected Tube Lifetime	4000 hours (with 1000 hr. service intervals)
Dielectric Beam-Turning Mirrors	
Nominal Reflectivity	>99 percent at 325 nm
Incident Angle Range	0 to 45 degrees
Beam Expander Expansion Coefficient	4
Adjustable Axes	Y,Z (pitch and yaw)
Scanning Mirror	
Speed	
Minimum	0.001 inch/sec (0.025 mm/sec)
Maximum	20 inches/sec (51 cm/sec)
Drawing Area Width (X-axis)	9 inches (23 cm)
Length (Y-axis)	9 inches (23 cm)
Elevator (Z-stage)	
Maximum Travel	14 inches (36 cm)
Minimum Step Size	0.001 inch (0.025 mm)
Load Capacity	110 lbs (4.5 kg)

[0146]

[Table 2]

Characteristic	Specification
CAD Interface	Ethernet
Resin Characteristics	

Appearance and Odor	Clear amber liquid, milky odor
Vapor Density	Heavier than air
Specific Gravity (H ₂ O = 1)	1.18
Flash Point	> 200°F (93°C)
Extinguishing Method	National Fire Protection Association Class B Extinguishers (carbon dioxide, dry chemical, or foam)
Storage Temperature	+60° F to +80°F (+15°C to +26°C)
Physical Characteristics SLA-1	
Dimensions (maximum)	
Height	64 inches (163 cm)
Width	49 inches (124 cm)
Depth	27.5 inches (70 cm)
Shipping Weight	600 lbs (272 kg)
Resin Vat Dimensions	
Height	10 inches (25 cm)
Width	9 inches (23 cm)
Depth	9 inches (23 cm)
Operating Conditions	
Temperature	50°F to 104°F (10°C to 40°C)
Relative Humidity	0 to 90%

[0147]

5 Materials and Equipment

Materials and equipment that would enhance the operation of the SLA-1 system are listed in Table 3-1. Equivalent items may be used.

[0148]

[Table 3]

Table 3-1: Operation Materials and Equipment

Name	Model/Part No.	Application
Printer, Computer		Print out computer permanent record file.
Microscope		Make working curve measurements.
Oven, Heat Oven,		Post-cure green parts.
UV Applicator		Post-cure green parts.

[0149]

6. CAD Design for SLA-1 Parts

6.1 How to Design CAD Parts for SLA-1.

A part must initially be designed on a CAD system before it can be built on the SLA-1 system. This manual assumes that the operator knows how to design parts using a CAD system. In order to make the CAD design compatible with the SLA-1 system, the operator usually prepares two or more files on the CAD system, object files and support files. The object file is simply the CAD part. The support file is needed to add supporting structures to enable the part to keep its shape during construction on the SLA-1 system.

[0150]

6.2 Rules for Design of Parts

In order to prepare the CAD design for the SLA-1 system, the operator should modify the CAD object file as follows. First, the wall thicknesses should ideally be 0.020 to 0.150 inch. Second, rotate CAD parts into an orientation that satisfies the following conditions. These conditions are to minimize trapped volumes as the part builds, take advantage of nice up-facing skin surfaces, minimize visibility of down-facing skin surfaces, make support design easy and optimum, and make parts stable and strong as they are created. Third, design parts so that horizontal gaps and holes are larger than desired by one laser line width. Fourth, all solid parts must completely enclose a volume. Single surfaces will confuse the crosshatch algorithms.

[0151]

6.3 Design Method for SLA-1 Support Files

Supporting structures consist of bases, posts, and webs which are needed to properly support the part and prevent the part from being distorted during construction on the SLA-1 system. The supports should be designed on the CAD system in a separate support file.

[0152]

6.4 Rules for Design of Supports

The operator should create the CAD support file as follows. First, design a structure at the bottom of the CAD part which will rest on the elevator panel. This platform must have several horizontal legs which are at least 0.65 inch (16.51 mm) long (more than twice the diameter of the 1/4 inch (6.35 mm) holes in the platform). Second, design supports to intersect every outside corner of a part, as these are major stress areas. Third, arrange supports so that every unsupported downfacing border falls on a previously created support. Fourth, space supports at a minimum distance apart for best stress resistance. Fifth, design supports to have at least two layers of vertical overlap into the part for a strong attachment.

[0153]

7. SLICE Operation

7.1 How to Slice Files

The slice computer (Wyse PC 386) (FIG. 21a, FIG. 21b) automatically breaks down the object and support files into individual slices under user control. The user must choose the thickness of each slice and determine the shape and method of cross-hatching.

[0154]

7.2 Rules for Slicing

The operator should slice the CAD object and support files as follows. First, up-facing skin surfaces should only be in one dimension (X or Y) and should have a 0.002 inch offset (high overlap). Exposure must be low. Second, cross hatch should usually be as nearly perpendicular to the part border as possible. Cross hatches parallel to part borders increase production time and may increase stress. Third, slice support files without creating skin.

[0155]

7.3 How to Run User Interface

This procedure shows how to operate the slice computer to use the User Interface program to insert slice parameters and run the Slice program. This procedure assumes that the CAD file has been installed in the slice computer. An asterisk (*) in front of a step indicates that this is an optional step that only needs to be performed if a common keyboard is being used to operate the slice computer and process computer.

- a. Press ENTER - MAIN MENU is displayed.
- *b. Select Data Transfer (Slice) and press ENTER - Data Transfer menu is displayed.
- *c. Select TELNET, Terminal Utility and press ENTER.
- d. In response to \$ prompt, type UI (user interface) and press ENTER - SLICE USER INTERFACE Menu is displayed.
- e. Select option 1 (DATABASE File Name).
- f. In response to Enter Data File Name: prompt, type data file name followed by .stl (example - test.stl) and press ENTER.
- g. In response to Type File Binary or ASCII (B,A): prompt, type b (binary) or a (ASCII) as applicable and press ENTER.
- h. Select option 2 (Scale).
- i. In response to Enter Scale Value: prompt, type (scale value per CAD dimension unit) and press ENTER. (If 1000 is selected, 1000.000 is inserted in the Value column, which is 1/1000 of one CAD dimension unit.) (Example - for a part CAD designed in inches, a scale of 1000 makes each slice scale unit 1 mil.) (1 slice = 0.0254 mm)
- j. Select option 3 (Z Spacing).
- k. In response to Enter Fixed or Variable Spacing (F, V, or Q) value: prompt, type F (fixed) and press ENTER. Then type thickness in slice scale units (from option 2) (example - 20) and press ENTER. (To select variable thicknesses, refer to software manual.)
- l. Select option 4 (X hatch spacing).
- m. In response to Enter Hatch Spacing (hx) value: prompt, type X hatch spacing in slice scale units (example - 200 (5 hatches/inch)) and press ENTER. NOTE Do not use option 5 (Y hatch spacing) if option 6 (60/120 degree hatch spacing) is to be used.
- n. Select option 5 (Y hatch spacing).
- o. In response to Enter Hatch Spacing (hy) value: prompt, type Y hatch spacing in slice scale units (example - 200) and press ENTER.
- p. Select option 6 (60/120 degree hatch spacing).
- q. In response to Enter Hatch Spacing (60/120) value: prompt, type 60/120 hatch spacing in slice scale units (example - 20) and press ENTER.
- r. Select option 7 (X Skin fill for near flat surfaces).
- s. In response to Enter Skin fill for near flat surfaces (hfx) value: prompt, type X skin fill offset in slice scale units (example - 2) and press ENTER.
- t. SELECT option 8 (Y Skin fill for near flat surfaces). NOTE If x skin fill is used, Y should not be used, and vice versa.
- u. In response to Enter Skin fill for near flat surfaces (hfy) value: prompt, type Y skin fill in mils and press ENTER.
- v. Select option 9 (minimum Surface Angle for scanned facets).
- w. In response to Enter a Minimum Surface Angle prompt, type desired angle in degrees from vertical (example - 60) and press ENTER.
- x. Select option 10 (Minimum Hatch Intersect Angle).
- y. In response to Enter a Minimum Intersect Angle value: prompt, type intersect angle in degrees (example - 20) and press ENTER.
- z. Select option 11 (Segment Output File Name).
- aa. In response to Enter Segment File Name: prompt, type desired output file name followed by .sli (slice) (example - test.sli) and press ENTER.
- ab. After all slice parameters have been selected, selects (Save) and press ENTER. (This will save the parameters for future use and reference.)
- ac. In response to "Press (Enter) to Continue" prompt, press ENTER. Then select d (DoSlice) and press ENTER.
- ad. In response to Slice Version to use (Default XY) prompt, press ENTER. (The program now slices the files using the inserted slice parameters.)
- ae. After slicing is completed, DATA TRANSFER MENU is displayed.
- af. Press Q (Quit) and ENTER. (The sliced files are now ready to be transferred to the process computer.)

[0156]

8. SLA-1 Operation

8.1 Turn-On Procedure

- a. Set POWER ON switch to on (up). Verify that POWER ON indicator illuminates.
- b. Set OVEN LIGHT switch to on (up). Verify that OVEN LIGHT indicator illuminates and that overhead light in reaction chamber illuminates.

The SHUTTER OPEN and LASER ON indicators will illuminate during operation. The SHUTTER OPEN indicator will illuminate when the laser shutter is open and the LASER ON indicator will illuminate when the laser is operating.

- c. The MAIN MENU will be displayed on the monitor as the process computer boots up. Select "Power on sequence" and press ENTER.
- d. The POWER SEQUENCE menu will be displayed. Sequentially press function keys 1, 2, and 3 to power up the laser, mirror, and elevator drivers, and to open the laser shutters.
- e. Wait at least 15 minutes for the laser to stabilize in power before beginning to create a part. Other functions (file preparation, data transfer, etc.) can be performed during laser warm-up.

[0157]

8.2 How to Transfer Files from Slice Computer to Process Computer

This procedure shows how to transfer the sliced object and support files from the slice computer to the process computer (Wyse PC 286) in the SLA-1.

- a. Press ENTER - MAIN MENU is displayed.
- b. Select option 1 (Data Transfer).
- c. In response to (data transfer) prompt, type 2 (FTP) (file transfer program) and press ENTER.
- d. In response to (ftp) prompt, type OPEN and press ENTER.
- e. In response to (to) prompt, type address of slice computer and press ENTER.
- f. In response to Remote user prompt, type the name of your directory and press ENTER.
- g. In response to Password prompt, type your password and press ENTER.
- h. In response to (ftp) prompt, type GET and press ENTER.
- i. In response to (remote-file) prompt, type name of desired file usually followed by .sli (example - test.sli) and press ENTER.
- j. In response to (local-fill test .sli in default) prompt, press ENTER (unless you want to change name). (The FTP routine will now transfer the file to the process computer. It will prompt when the transfer is complete.)
- k. To exit from FTP, in response to (ftp) prompt, type BYE and press ENTER. (The sliced files have now been transferred to the SLA-1 process computer.)
- l. MAIN MENU is displayed after transfer is completed.

[0158]

8.3 How to Insert Critical Volumes

This procedure shows how to set up critical volumes. These critical volumes can be used to insert rivets, which are multiple passes of the laser beam over Crosshatch vectors to increase strength, or for other special treatment (This procedure can be skipped if the CAD part contains no critical volumes.)

- a. On CAD computer, call up CAD display of the part.
- b. Identify X, Y, and Z coordinates in CAD space for the four bottom corners of the rectangular solid (critical volume).
- c. On process computer, select option 5 (Edit System Files) and press ENTER.
- d. Select option to create a new file - Turbo Basic is displayed.
- e. Use arrow keys to select Write to and press ENTER.
- f. In response to New Name prompt, enter name of critical volume followed by .box (example - test.box) and press ENTER.
- g. Use arrow keys to select Edit and press ENTER,

- h. In response to C: Test .Box enter: prompt, insert the following:
 <type>, <base>, <height>, <x1>, <y1>, <x2>, <y2>, <x3>, <y3>, <x4>, <y4> (Be sure to insert commas between each item. Proper syntax is critical.)
 Here, <type> is "XV" to rivet cross-hatches in the enclosed area or "XI", to ignore cross-hatches
 <base> is the base of the box relative to the slice scale, <height> is the height of the box, <x1, y1>
 is the first coordinate of the box, <x2, y2> is the second coordinate, <x3, y3> is the third coordinate,
 <x4, y4> is the fourth coordinate.
- i. Press Esc (escape) key.
- j. Use arrow key to select File and press ENTER.
- k. Use arrow key to select Save and press ENTER.
- l. Use arrow key to select Quit and press ENTER. (The new <part> .box file has now been created to identify a critical volume.)

[0159]

8.4 How to Merge Sliced Files

This procedure shows how to combine (merge) the object and support files into vector and layer control files.

- Press ENTER - MAIN MENU is displayed.
- Select option 2 (MERGE) and press ENTER.
- In response to Slice File Names prompt, type names of files to be merged (include .SLI as part of the names) and press ENTER. (Be sure to include critical volume file, if applicable.)
- In response to Output File Name prompt, type desired name of output file and press ENTER. (No ".xxx" ending is necessary.)
- Press ENTER and wait for process computer to merge files (one slice at a time). (The program will prompt when it has completed the merge.)

[0160]

8.5 How to Operate SLA-1 to Build Parts

These procedures show how to use the process computer to actually build a part in the reaction vat. Included are procedures for setting up the reaction vat, modifying the merged vector and control files, preparing the default parameter files, and running the part making (supervisor) program.

[0161]

8.5.1 Rules for Building SLA-1 Parts

In order to prepare the SLA-1 to build a part, the operator must perform the operator's checklist, edit the layer control (.L) file (SUPER .PRM), prepare the default parameter files, and run the supervisor programs as follows. First, set speed of first support layer three times slower than normal layer drawing speed. This overcures the first layer to enable it to adhere firmly to elevator platform. Second, set dip speeds low to avoid undue stresses to part in progress. Third, use longer dip delays for fragile layers, lowest layers of supports near platforms, after layers with large area skins, areas with large trapped volumes of resin, and for shallow dip depths (thin layer thicknesses) Fourth, use single passes and choose exposure speeds from working curves which provide a 0.006 to 0.008 inch (0.15 to 0.20 mm) overcure into previously created layers. Fifth, record important parameters and comments in a Part Log (example in FIG. 17). (The user is encouraged to create his own custom Part Log to his special requirements.) If a printer is available, print out important parameters for a permanent record.

[0162]

8.5.2 How to Prepare Default Parameter Files

This procedure shows how to prepare the default -parameter (.PRM) files to control the part building access.

- a. Press ENTER - MAIN MENU is displayed.
- b. Select option 5 (Edit System Files) and press ENTER.
- c. In response to Load File Name prompt, enter file names (insert SUPER. PRM only) and press ENTER.
- d. Move arrow to Edit block and press ENTER. Values can now be inserted in default parameter (SUPER. PRM) files. (Refer to software manual for definitions of codes.)
- e. To quit editing files:
 1. Press Esc key.
 2. Use arrow key to select File and press ENTER.
 3. Use arrow key to select Save and press ENTER.
 4. Press Q key - MAIN MENU is displayed.

[0163]

8.5.5 How to Run Supervisor to Make a Part

Now that all of the preparatory work has been done, this procedure shows how to actually build a part.

- a. On process computer, press ENTER - MAIN MENU is displayed.
- b. Select option 4 (Supervisor) and press ENTER.
- c. In response to Part Prefix prompt:, type name of part files and press ENTER. This causes the laser to start tracing the first layer. Verify that SHUTTER OPEN and LASER ON indicators on operator control panel are illuminated.
- d. Watch the first layers form.
 1. Is the part centered on the elevator platform?
 2. Do the first layers stick to the platform?
 3. If not, abort the run and correct the problem.

[0164]

8.5.6 Post Processing of SLA-1 Parts

This procedure shows how to remove the finished part from the vat, drain the part, cure and dry the part, and remove supports.

- a. Updip and Preliminary Draining.
 1. On process computer, press ENTER - main menu is displayed.
 2. Select Utilities menu and press ENTER.
 3. Select Z-Stage Mover and press ENTER.
 4. Very slowly toggle t arrow until elevator is raised to 51 inches above edge of reaction vat level. Do not raise part quickly or distortion could occur.
 5. Wait approximately 15 minutes to allow excess resin to drip from part.
- b. Part/Platform Removal.
 1. Place a pad of absorptive material on the special drain tray.
 2. Slip the drain tray under the elevator platform and rest it on the shelves on either side of the vat.
 3. Toggle ↓ arrow on keyboard to lower the elevator platform until it is about 1/4 inch above the absorptive pad.
 4. Twist one of the elevator shaft knobs one turn CCW1. This will unscrew a threaded rod inside the elevator shaft from a threaded hole in one side of the elevator platform and partially release the platform.
 5. Repeat step (d) with the opposite elevator shaft knob.
 6. Repeat steps (d) and (e) alternately until the platform drops free from the shafts and falls a fraction of an inch to rest on the absorptive pad.
 7. Raise the elevator shafts, if necessary, with the ↑ arrow on keyboard.
 8. Remove the drain tray, platform, and attached part from the vat chamber. Keep the platform horizontal if possible to avoid putting side stresses on the green (uncured) part.
- c. Oven Draining.
 1. Place elevator platform and part in an oven.
 2. Set temperature to 80 to 90°C and wait 1 hour.
 3. Carefully wipe off excess liquid resin which adheres to up and down-facing surfaces with cotton swabs.

d. Post Curing.

1. Place elevator platform and part in an ultraviolet flood oven.
2. Flood the part with ultraviolet light until it is dry and no longer tacky.
3. Use a fine-tooth saw and remove the part from the elevator platform by sawing through the bottom supports that attach the part to the platform. Protect the part from stresses and inertial shocks during this procedure.
4. Clean all "sawdust" and fragments of support from the part before continuing.
5. Turn part upside down (or rest part on its side if this is not possible) and repeat steps 1 and 2.

e. Platform Replacement.

1. Scrape away any dry resin that is still sticking to elevator platform after removal of part. If may be necessary to tap out the threaded holes in the platform with a #10-32 tap.
 2. Place the empty platform on the drain tray.
 3. Place the drain tray in the SLA-1 vat chamber resting on the shelves and centered as well as possible over the vat.
 4. Very slowly toggle ↓ arrow on keyboard to lower the elevator shafts until the threaded rods are very close to the platform. Avoid running the shafts into the platform or tray as this can ruin the threads on the shaft.
 5. Adjust the tray and platform so that the threaded holes in the platform are exactly aligned beneath the threaded rods.
 6. Slowly toggle ↓ arrow on keyboard until the threaded rods contact the threaded holes gently.
 7. Twist one of the elevator shaft knobs one turn CEW. This will rotate the threaded rod inside the elevator shaft and cause it to engage the threaded hole in the panel.
 8. Repeat step 7 with the opposite elevator shaft knob.
 9. Repeats steps 7 and 8 alternately until the platform is lifted off of the drain tray and is in firm contact with the bottom of the elevator shafts.
 10. Snug up the elevator shaft knobs to secure the panel to the shafts. Do not overtighten as this can fracture the interior threaded rod.
 11. Toggle the ↑ arrow on the keyboard to raise the elevator.
 12. Remove the drain tray.
- f. Removing Supports and Finishing.
1. Carefully cut away supports with side cutting pliers.
 2. Carefully smooth off rough surfaces with appropriate files.
 3. Surface finish as required.

[0165]

8.5.7 Shutdown Procedures

- a. Set OVEN LIGHT switch to off (down). Verify that OVEN LIGHT indicator extinguishes.
- b. Set POWER ON switch to off (down). Verify that POWER ON and other indicators extinguish.

8.5.8 How to Create and Use Working Curves

The degree to which liquid plastic can be solidified is determined by three factors: (1) the type of resin used, (2) laser power, and (3) degree of laser focus. By creating a working curve, the operator can adjust the laser drawing speed to compensate for variations in these three factors. Therefore, a new working curve must be prepared each time a new batch of resin is used or there is a significant loss of laser power as shown on the Part Log. The working curve is then used to change the step period (laser drawing speed) and step size in the default parameter and layer control files.

- a. Toggle ↓ arrow on keyboard to lower elevator platform to 1 inch below resin surface. The banjo part used to create working curves will be prepared free floating on the resin surface.
- b. On process computer, press ENTER - main menu is displayed.
- c. Select Utilities menu and press ENTER.
- d. Select Banjo and press ENTER. Follow the menu to input the largest step period (SP) to be used. The SLA-1 will prepare the banjo part in the vat.
- e. After banjo part is completed, drain and cure it (subparagraph 8.5.6).
- f. Use a microscope and measure horizontal width of each string.

- g. Cut banjo part sideways and use microscope to measure thickness (depth) of each string.
- h. Plot height and width values on a working curve (sample in FIG. 18) at the step periods chosen (example - 40, 80, 160, 320, and 640). The lowest step period will create the thinnest banjo string and the highest step period will create the thickest banjo string.
- i. Another banjo can be created with different step periods to extend the range of the working curve.
- j. Connect the five or more points to form both working curves.
- k. The working curve can now be used to select the step period and step size for each slice.
- l. Insert the chosen step period and step size into the default parameter files (paragraph 8.5.2).

The following terms are used in the stereolithography process.

60/120 ANGLE HATCH This is one type of crosshatching pattern which supplements the standard X and Y hatching.

[0166]

BANJO This is a part which when built and measured provides line height and line width data for the working curve.

BASES (SUPPORTS) These are the structures generated by the CAD which provide structural support to the actual part when being built. (See webs).

BEAM PROFILE This is the spatial distribution of laser beam energy.

BORDER (BOUNDARY) The border is a block of vectors defining the walls of a sliced layer of a part.

[0167]

CAD Computer aided design.

CENTERING This is a SLICE routine which automatically centers the part in space. This can only be done if the part is defined by only one STL file. See software manual.

[0168]

CLIFF This is a software program which is used primarily in BASIC programming. It can also be used to move mirrors using direct commands from the DOS shell by transmitting data to STEREO.

[0169]

CRITICAL AREA This is an area within the part which has coordinates defined in a text file prior to merging. The area can have special attributes such as riveting. See software manual.

[0170]

CROSSHATCH This is a general interior vector type providing structural integrity to walls. The pattern used is defined during slicing. See software manual.

[0171]

CURL This is an effect sometimes encountered during part creation which can cause part inaccuracy.

[0172]

DIP ACCELERATION This is a part-building variable which defines the speed of elevator dipping. It can be modified on a layer by layer basis if needed.

[0173]

DIP DELAY This is a part-building variable defining the delay between the start of a dip routine and the start of next layer calculations (and laser movement). It can be modified on a layer by layer basis.

[0174]

DIP DEPTH This a part-building variable which defines the distance the elevator moves downward during a dipping sequence.

[0175]

DIP SPEED This is a part-building variable which defines the maximum speed that the elevator attains.

[0176]

DRAWING SPEED Laser drawing speed is defined by the Supervisor variables Step Period and Step Size. It is varied depending on layer thickness , type of resin, and laser power. The drawing speed to be used is typically generated by use of the working curve.

[0177]

DYNAMIC MIRRORS These are the galvanometer vector scanning mirrors which are controlled by SLA-1 software. Laser beam movement is defined by the rotation of these mirrors.

[0178]

ELEVATOR The elevator is the vertically moving device to which the elevator platform and part are attached.

[0179]

ETHERNET This is file transfer software system. It allows for easy movement of large files.

[0180]

FOOTPRINT The bottom of the support that adheres directly to the elevator platform.

[0181]

GREEN PART This is the laser cured part which has not undergone final post curing.

[0182]

HATCH SPACING This is the distance between crosshatching which is defined during slicing (see Crosshatch).

HeCd Helium Cadmium.

L FILE This is a merge generated control file which contains all the layer by layer vector block identification information. Individual layer parameters can be modified in the L file.

[0183]

LASER This is the laser controller software. It is also a device which provides the light energy required to polymerize the liquid photopolymer.

[0184]

LAYER THICKNESS This is the layer to layer dipping distance. It can be either one value for the whole part or changed many times throughout the part (see variable layer thickness).

LEVELING This is the time and temperature dependent process where the resin settles to a flat surface after being distributed by dipping. The time allowed for leveling is defined by the dip delay variable.

[0185]

LINE HEIGHT This the vertical thickness of a laser cured plastic line. It is variable depending on drawing speed and laser power/focus.

[0186]

LINE WIDTH This is the width of a laser cured plastic line. It is variable depending on drawing speed and laser power/focus.

[0187]

MERGE This is a software program which takes the individual sliced files for a part and combines them. It generates the L and V files which the Supervisor uses to make the part.

[0188]

MIA This is the minimum intersect angle and is used during slicing to delete hatch vectors which run parallel to layer boundaries. See software manual.

[0189]

MODULUS This is a physical attribute of a material which defines its overall toughness.

[0190]

MONOMER This is a chemical species which is generally low in molecular weight and is used as a building block for preparing polymers.

[0191]

MSA This is the minimum surface angle and is used during slicing. See software manual.

[0192]

MSHA Mine Safety and Health Administration.

NIOSH National Institute for Occupational Safety and Health.

PHIGS FORMAT This is the software program that defines the CAD surfaces by using triangles.

[0193]

PHOTOINITIATOR This is a chemical which transforms the laser energy into chemical energy and initiates the polymerization process.

[0194]

PHOTOPOLYMER This is a polymer which is formed using light as the energy source.

[0195]

POST CURE This is the process used to cure a green part. The post cure can be either ultraviolet light induced or thermal induced.

[0196]

POT LIFE This is the useful life expectancy of a pot of chemical and depends on the chemical stability and other factors.

[0197]

PRIMARY RADICAL This is the initial radical species formed when laser light is absorbed by the photoinitiator. The primary radicals initiate the polymerization process.

[0198]

RADIAL CROSSHATCH This is a specific type of crosshatch which generally provides the best overall strength and support (see Crosshatch).

RADIOMETER This is a device which allows for the measurement of the laser output power.

RESIN This is the liquid photopolymer.

RIVET This is a part making process which can be used in critical areas which may be prone to stress related inaccuracies.

[0199]

SCALE FACTOR This is a Supervisor variable which can be used to scale the xy space either larger or smaller. It does not affect the vertical dimension.

[0200]

SENSITIZATION This is an allergic response that some individual may obtain after repeated skin contact with a given chemical.

[0201]

SKIN (SKIN FILL) This is the coating of a horizontal (flat) or near horizontal (flat) area of the part.

[0202]

SLA Stereolithography Apparatus

SLICE This is the software that transforms the three-dimensional CAD designed part into a series of two-dimensional layers (slices).

[0203]

SMALLEY This is a stress relieving (decoupling) structure designed on the CAD.

[0204]

STEP PERIOD This is a Supervisor variable which helps to define the laser drawing speed. Increasing the step period slows the speed (increases the plastic line height and width) .

STEREO This is a memory resident portion of the laser controller software.

[0205]

STL FILE This is the PHIGS format CAD file used as input for slicing.

[0206]

SUPERVISOR This is the software which supervises all the passing of variables and data to drive the mirrors and move the Z stage up and down during part building.

[0207]

TENSILE STRENGTH This is an attribute of a material which defines the energy required to stretch it.

TRAPPED VOLUMES These are areas of the part from which resin cannot drain during dipping.

[0208]

USER INTERFACE This is the menu driven software which is used to control and run slicing programs.

[0209]

.V FILE This is a merge generated file which contains all the layer by layer vector information. See software manual.

[0210]

VARIABLE LAYER THICKNESS This is the process tool which allows use of differing dipping depths and layer thicknesses in order to achieve improved strength or accuracy. It is controlled within Slice.

[0211]

WEB This is a type of support structure designed by the CAD designer which can provide additional strength or support as needed.

[0212]

WORKING CURVE This is the plotted line height and line width data provided from a banjotop. It is used in with laser power to obtain drawing speed information.

[0213]

A second embodiment of a stereolithography apparatus (SLA) is shown below.

[0214]

(Second Embodiment)

A stereolithography apparatus (SLA) is a new CAP (computer-aided prototyping) product allowing a design engineer to quickly construct a three dimensional model designed and stored on a CAD/CAM/CAE system. The SLA, in conjunction with the designer's workstation, allows a convenient, easily installed, and truly integrated CAD/CAM/CAE environment.

[0215]

An overview of the procedure necessary to produce a part with the SLA is presented in FIG. 64.

[0216]

To manufacture a part with the SLA, a designer first uses the system to input a model of the part.

[0217]

Typically this part requires a wall thickness of approximately 0.1 inch (2.54 mm) and a support structure to ensure an accurate transfer of the CAD model to the plastic building material. This support structure may be added by the CAD designer or, in the near future, by the SLA user.

[0218]

Additionally, the model as input into the CAD system, may have surface and structural features which need special attention during construction. At first, the design engineer is required to manually flag these areas or to modify the part design. As our software matures, more and more of these special cases are expected to be incorporated into the SLA controller. To flag an area requiring special attention, the CAD designer identifies a volume which encloses a potential structural problem. Areas on the surface of the model may also be highlighted. These areas are now assigned attributes which are passed along to the SLA software for further processing.

[0219]

The model must now be translated from the internal format used by the CAD system to a planar faceted representation, or, in the near future, an IGES wire frame representation. However, the faceted representation is the only format currently supported by 3D Systems. This data structure loosely follows a graphics standard called PHIGS (Programmers Hierarchical Interactive Graphics Standard). FIG. 65a to FIG. 65b illustrate the format of this relatively verbose standard. The following paragraphs briefly outline the details of our facet representation. Further details are forthcoming.

[0220]

Included with each facet is a unit normal which is required to point away from the surface of the solid. For example, given a sphere with a wall thickness of 0.1 inch (2.54 mm), (typical for fabrication) the facets that describe the inner surface or wall would have their normals pointing inward, correspondingly, those on the outer surface, outward.

[0221]

Additionally, the vertices of the triangles should be ordered such that they give the direction of the triangle's normal according to the right hand rule. Note that the normal is specified first, followed by the three triangle vertices, followed by the facet attributes.

[0222]

Internally, the normal's i, j, and k components and the nine vertex coordinates are represented as 32 bit single precision floating point numbers, each with an eight bit exponent and a 24 bit mantissa. This translates into a floating point value with a mantissa of just under eight significant digits, thus giving an upper limit to the usable precision of the PHIGS standard.

[0223]

Because the number of facets is expected to exceed 100,000 for more exacting surface finish requirements, a compact form of the facet data will be implemented. This condensed data file requires the normal components and the vertex coordinates to be in a binary floating point format compatible with the Intel 80287 math coprocessor (See FIG. 66).

[0224]

This format uses three 32 bit values to specify the normal, a total of nine 32 bit values to specify the triangle vertices, and a 16 bit unsigned integer for the attributes, for a total of 50 bytes per triangular facet.

[0225]

Referring back to 3. regarding attributes, note that the model attributes identified by the designer are passed along to the SLA system at the facet level. For a large model, several hundred attributes are expected to completely define the model to the SLA software.

[0226]

The physical transfer of the faceted data and associated attributes from the CAD system to the SLA is made over a high speed data link. In-house the transfer is made over an Excellan Ethernet data link. This data could be transferred over a 19.2 Kbaud RS232 data link or even on floppy disks, but because of the large amounts of data to be transferred, a high speed data link is preferred.

[0227]

This faceted data file, which now resides on the SLA, is used as Input to a slicing program. The slices or layers of the model typically include crosshatching to strengthen the model walls, skins to surface the model, and special groups of building vectors to accommodate problem areas identified by the facet attributes.

[0228]

The sliced model is now transferred to the SLA supervisor. This program is responsible for actually building the model. By sending the sliced data to the mirrors which direct the SLA's laser, and by controlling the SLA elevator, the supervisor is able to build up the CAD model one layer at a time. Other functions of the supervisor include characterizing the SLA laser, matching the laser speed to the photosensitive properties of the plastic, and coordinating the construction of the more difficult attribute flagged areas.

[0229]

A CAD program must be able to produce a file with the specific format described below. Usually this file is quite large in size (several hundred thousand bytes) and is transferred over a high-speed data link such as Ethernet to the 386-based Stereolithography Computer. Transfers of smaller-size files using RS-232 and floppy diskettes are also possible but not recommended.

[0230]

The SLICE Input Format loosely follows a graphics standard called PHIGS (Programmers Hierarchical Interactive Graphics Standard), and improves on it in several ways. First, all the numeric data can be compressed into binary form, greatly reducing the size of storage files and reducing the data transfer time to the Stereolithography computer. Second, support of special part-building attributes allow certain features to be "attached" to facets and passed all the way down the pike to the Part-Making Supervisor. SLICE does not support negative or 0 values of vertices information.

[0231]

Files being submitted to SLICE should have the extension ".STL" that is, the name of the files should end in ".STL".

[0232]

The files can be stored in either ASCII or Binary. We recommend using the ASCII format while developing STL-file-making software and then switching to the binary format for release.

[0233]

An example of an ASCII STL file follows. It defines a simple tetrahedron.

[0234]

```

solid solid_Tetra. 2
  facet normal -100
    outer loop
      vertex 000
      vertex 001
      vertex 010
    endloop
  endfacet
  facet normal 0-10
    outer loop
      vertex 000
      vertex 100
      vertex 010
    endloop
  endfacet
  facet normal 00-1
    outer loop
      vertex 000
      vertex 010
      vertex 110
      attribute 16
      attribute 9
      attribute 22
    endloop
  endfacet
  :
endsolid solid_Tetra. 2

```

The important structure for an ASCII STL file which is different from the binary structure is its use of words to identify the type of numeric data. The facet normal and vertex information can be in floating point - numbers like 43.332382912 and 1.304E+3 are acceptable. Negative and 0 numbers are not accepted for vertices information. If the numbers are in scientific rotation, only E or e for exponent is supported (please do not use D for exponent). Facet normal must be a unit vector. There must be at least one space between two data fields.

[0235]

We assume a word is 16 bits and is equal to two bytes. The precise format for a binary STL file is the following.

[0236]

(top of file)

80 bytes - general information contains part names, comments, etc.

4 bytes

2 words - number of facet records each facet record defines one triangle

First facet record:

6 words - Normal Vector

2 words - i coordinate

2 words - j coordinate

2 words - k coordinate

18 words- Triangle Vertices

2 words - x1

```

2 words - y1} First vertex
2 words - z1
2 words - x2
2 words - y2} Second vertex
2 words - z2
2 words - x3
2 words - y3} Third vertex
2 words - z3
1 word - Number of Attributes
< special attributes >
This word must be set to zero.
: : :

```

The STL Binary Format is similar in structure to the ASCII format. One facet record follows another, and each facet record consists of a unit normal; three triangle vertices, and optionally some attributes. Since we don't as yet support attributes, the attribute count word should be set to zero.

[0237]

The binary format for the number of facet records and for each number of attributes is just an unsigned integer. The normal and triangle vertices are in four-byte 8087 real format, with a 3 byte mantissa and a 1 byte exponent.

[0238]

See the listing for file TEST0017.STL and FIG. 67.

[0239]

A third embodiment of a stereolithography apparatus is shown below.

[0240]

(Third Embodiment)

1. The Stereolithographic Process

The stereolithographic Process is composed of nine major steps performed on three hardware systems as shown in FIG. 33.

CAD System →	SLA-1 →	Post Curing Apparatus
1. CAD Design	4. Slice	9. Post Process
2. Orient & Support	5. Network	
3. CAD Interface	6. Merge	
	7. Prepare	
	8. Build	

CAD System

In CAD Design (Step 1), the part is designed as a solid or surface model on the CAD system without specific reference to stereolithography.

[0241]

In Orient & Support (Step 2), the CAD model is oriented in 3D space (within the CAD system) for stereolithography. A base, or support, is designed to attach and support the part while it is being built.

[0242]

In CAD Interface (Step 3), the CAD model is processed through an interface to generate files formatted for stereolithography. These .STL files are generic representations of all surfaces in the CAD design. The interfaces are supplied by CAD vendors.

Stereolithography Apparatus

In Slice (Step 4), the stereolithography (.STL) files representing three-dimensional objects are cross-sectioned on the Slice Computer to create layers of user defined thickness. In Network (Step 5), the sliced files are transmitted from the Slice Computer to the Control Computer via Ethernet or floppy disk. In Merge (Step 6), the sliced files for a part (i.e., all files for the supports and the part itself) are combined and reformatted to drive the SLA-1.

[0243]

In Prepare (Step 7), part-building parameters are specified by the user as required by the part's geometry and end use.

[0244]

In Build (Step 8), the part is built one layer at a time by moving a focused laser beam across the surface of photocurable resin, solidifying the liquid where it strikes. The first (lowest) layer adheres to a horizontal platform located just below the surface of the resin. The platform is attached to an elevator which then lowers it under computer control. After drawing a layer, the platform dips into the liquid, leaving a thin film from which the second layer will be formed. The next layer is drawn after a pause to allow the liquid surface to level. Since the resin has adhesive properties, the second layer becomes firmly attached to the first.

[0245]

This process is repeated until all layers have been drawn to form the three-dimensional object. Resin that has not been exposed to the laser beam remains in the vat to be used for the next part. There is very little waste of material.

[0246]

Post Curing Apparatus

In Post Process (Step 9), the part is drained to remove excess resin, ultraviolet cured to complete the polymerization process, and supports are removed. Optional finishing, such as sanding, assembly into working models and painting, may also be performed.

[0247]

2. Stereolithographic System (see FIG. 34a and FIG. 34b)

Stereolithography Apparatus

As shown in FIG. 35, the major components of the SLA-1 are a control computer, laser and optical system, process chamber, control panel, and slice computer.

[0248]

The control computer consists of a MSDOS standard 286 computer (single task for a single user), a monochrome terminal, a 40-megabyte hard disk with 36 to 38 megabytes of usable disk space, and an Ethernet interface. From networking to fabrication, the entire stereolithography process is operated by a control computer. Program and operating parameters are selected from a menu to make operation easier.

[0249]

The SLA-1 laser and optical system is mounted directly over the process chamber. These components generate and direct the laser beam under computer control onto the surface of the liquid resin.

[0250]

The SLA-1 uses a helium-cadmium (HeCd), multimode ultraviolet laser. The laser beam power varies, and is nominally 15 milliwatts at a wavelength of 325 nanometers.

[0251]

As shown in FIG. 36, the SLA-1 optical system is composed of a shutter assembly, two 90-degree beam-turning mirrors, a beam expander, and X-Y dynamic mirrors mounted on an optics plate. A 2-inch (50.8 mm) diameter precision optical window allows the laser beam to enter the process chamber while isolating optical components from the chamber environment.

[0252]

The solenoid-actuated shutter operates to block the laser beam when an interlock switch is activated. Interlock switches monitor removal of the laser and optics covers and opening of the process chamber door.

[0253]

The 90-degree beam-turning mirrors are specially coated for high reflectivity at 325 nanometers while transmitting most other wavelengths. The first turning mirror reflects the beam from the laser to the inlet aperture of the beam expander. The second mirror reflects the laser beam from the outlet beam expander aperture to the dynamic mirrors.

[0254]

Partially unmodified laser beams diverge slightly over distance. A highly focused beam is desired for stereolithography because it has higher power density and can therefore cure plastic at a greater depth or at a faster rate. The beam expander expands the divergent laser beam to four times its inlet diameter, then focuses it so that the beam converges to a small spot on the surface of the resin.

[0255]

The high-speed dynamic mirrors deflect the laser beam under computer control to trace vectors on the surface of the resin. Like the beam-turning mirrors, the dynamic mirrors are highly reflective at 325 nanometers and transmit most other wavelengths.

[0256]

The environmentally-controlled process chamber houses an elevator and platform, resin vat and beam profilers. This is where stereolithographic parts are created.

[0257]

The chamber is designed for operator safety and to ensure uniform operating conditions. Air is circulated and filtered through active charcoal. An overhead light illuminates the resin vat and work surfaces. An interlock on the access door activates a shutter to block the laser beam when the door is opened. The clear acrylic door blocks ultraviolet light for safe viewing by operators.

[0258]

The elevator raises and lowers the part under computer control. The platform supports the part while it is being built.

[0259]

The resin vat is 9 inches (228.6 mm) in every dimension. It is installed in the chamber on guides which align it with the elevator and platform. An overflow system channels excess resin to a removable container to maintain a constant liquid level.

[0260]

Two beam profilers are mounted in the process chamber, one on either side of the resin vat. The beam profilers measure laser power and intensity under computer control.

[0261]

The SLA-1 control panel includes a POWER ON switch, an OVEN LIGHT switch, a LASER ON, and a SHUTTER ON indicator.

[0262]

The POWER ON switch switches primary power to the laser, power supplies, process chamber and control computer.

[0263]

The OVEN LIGHT switch turns the overhead light in the process chamber on and off.

[0264]

The LASER ON indicator indicates that the laser is on when lit, and the SHUTTER ON indicator indicates that the shutter is open when lit.

[0265]

The slice computer used to cross-section .STL files to create .SLI files includes a UNIX based 386 Computer (multi-user, multi-task), a monochrome terminal, a megabyte hard disk with megabytes of available disk space, and an Ethernet Interface

[0266]

The post curing apparatus (PCA, see FIG. 34b) is used to cure parts produced by the SLA-1. This is done by exposing parts to ultraviolet radiation in an enclosed, vented chamber. The PCA can hold parts measuring 12 inches (404.8 mm) in every dimension. Its major components are shown in FIG. 37.

[0267]

Three 400 Watt metal-halide UV lamps, with reflectors, can be positioned in the chamber for optimum curing. The lamps have a rated service life of 750 hours. A one revolution per minute turntable is provided which rotates the part for uniform curing. Two doors, one at the front and one at the top, are provided for loading and unloading parts. Both doors are interlocked to turn off the UV lamps and turntable when they are opened, and have UV blocking windows to allow safe viewing of the parts. A 240 CFM (cubic feet per minute) cooling and ventilation fan and a control panel with power switch and timer are also provided.

[0268]

3. Stereolithography - From Start to Finish

3.1 CAD Design

Surfaces: The object must be represented as closed surfaces which unambiguously define an enclosed volume. That is, model data must specify what is inside the solid material of the object and what is not. This is required so that all horizontal cross-sections consist of closed curves which completely separate the inside and outside of the object.

[0269]

CAD Resolution: When generating objects with curved surfaces (e.g., spheres, cylinders), keep in mind that curved surfaces are approximated by a large number of polygons or facets. The larger the number, the more closely the surface is approximated, resulting in a smoother curve on the finished part. However, a larger number of polygons or facets also increases the slicing time and resultant file size. As a rule, use the lowest acceptable resolution.

[0270]

Wall Thickness: The minimum recommended wall thickness for curved objects is 0.020 inch (0.51 mm). Walls thinner than 0.020 inch (0.51 mm) are achievable only under special circumstances. The absolute minimum wall thickness is twice the width of the laser beam.

[0271]

3.2 Orientation and Support

A CAD part must reside entirely in the positive X Y Z quadrant for stereolithography. It should then be oriented to minimize the distance between the part and the CAD origin and minimize the height of the support structure.

[0272]

The part should be at least 0.25 inch (6.35 mm) above the platform for efficient draining. However, supports that are too tall take longer to build and may distort as the weight of the part increases while it is being built. Therefore, minimize the height of the object. This reduces the number of layers to be built, thereby reducing the run time. Also, to optimize part draining, minimize the number of slanted or sloping surfaces.

[0273]

These surfaces are constructed of overlapping layers so that the surface has a "stair-step" appearance, with the thickness of each layer being the height of the step. ensure that smooth or aesthetically important surfaces are either oriented vertically or upward-facing and horizontal. (Vertical and upward-facing horizontal surfaces are smoother than downward-facing surfaces.)

[0274]

Minimize the volume of liquid entrapped as the part is built. Entrapped liquid slows the part building process by requiring more time for the liquid resin to settle and level to a uniform height after the part is dipped.

[0275]

Ensure that the part fits in the resin vat. If the part is too large, it may be sectioned, built in several runs, then reassembled during post processing.

[0276]

The importance of each of these factors is determined by the objective for making the part.

[0277]

Stereolithographic objects are built on supports rather than directly on the elevator platform. The main reasons for using supports are the following. First, separating the object from the platform. This ensures that they are easily separated during post processing.

[0278]

Next, the first object layer is of uniform thickness, even if the platform is warped or improperly installed.

[0279]

Next, resin can drain quickly through the platform. This reduces the time required to build the part, since the surface of the resin levels faster after the part is dipped. Additionally, excess resin drains faster from the completed part to reduce post processing time.

[0280]

The following common types of supports can be used.

[0281]

Straight Webs are very thin rectangles or fins, generally less than 0.002 inch (0.051 mm) thick. Straight web supports must be defined by a volume, not single surfaces.

[0282]

Cross Webs are made from two straight webs which intersect at right angles. Cross web supports are stronger than straight webs.

[0283]

Circular Webs are hollow tubes strongly bonded to the object. Circular webs can support more weight than straight and cross web supports. However, they require more triangles, and thus use more memory.

[0284]

Triangular Webs are composed of three straight webs to form a triangle. These supports may be used in conjunction with straight webs which intersect the vertices. Triangular web supports are stronger than all other types of web supports.

[0285]

The following are examples of CAD model orientation and support.

[0286]

Example 1

Near the bottom of the solid sphere, as shown in FIG. 7a and FIG. 7b, layer border vectors consist of circles whose diameters increase rapidly with each successive layer. Until other vectors are drawn, many of the layer borders would float freely on the surface of the liquid. Air currents or convection currents in the liquid could cause them to drift out of position. Adding supports which extend to the equator of the sphere, as shown, would solve this problem. Note that above the equator the layer borders are formed directly on the crosshatch vectors of the previous layer, and as such are firmly anchored without the need for further support.

[0287]

Example 2

The first layer of the cantilevered beam, as shown in FIG. 8a and FIG. 8b, may be permanently deformed by static resistance of the liquid when the part is dipped. In addition, the layer could curl upward when the next layer is formed. Both of these problems are solved by adding supports.

[0288]

Example 3

The first layer of the teacup handle, as shown in FIG. 9a and FIG. 9b) would be completely unattached when formed and would drift when the part is dipped. The support provides a surface, anchored to the elevator platform or to the body of the teacup, on which the handle can be built.

[0289]

Note that supports must be completely contained in positive CAD space. Bottom supports should overlap the bottom layers of the object by approximately 0.040 to 0.060 inch (1.02 to 1.52 mm) (typically 2 to 3 layers). This ensures a strong bond between the supports and object. Side supports should also overlap the object to provide a stronger support structure.

[0290]

Generally, supports are designed together as a single CAD file separate from the object file. They are positioned relative to the object after it is designed and oriented for stereolithography. (The object and support files are merged and drawn as a single file later in the stereolithographic process.) A library of supports resident on the CAD system could reduce the need for designing unique supports for each object. In any case, supports should be designed and attached to the object in accordance with the following guidelines.

[0291]

Placement: Supports should be located as needed to provide a rigid foundation on which the object can be built. This includes supporting corners and edges. Supports should also be added to anchor or strengthen other surfaces, as discussed in the preceding examples. If possible, avoid placing supports on surfaces that for aesthetic or functional reasons need to be smooth. After the part is post-cured and the supports are removed, ridges will normally remain on the surface of the part. (The ridges can, however, be cut and sanded or ground away.) Supports can be attached to a strong section of the object, as well as to the elevator platform.

[0292]

Spacing: Supports typically are spaced 0.1 to 0.8 inch (2.54 to 20.32 mm) apart. In general terms, space supports at sufficiently close intervals so that no appreciable sag or curl occurs; however, drawing too many supports will slow the part building process.

[0293]

Orientation: As for the orientation of supports, use cross web supports to prevent layer skewing as shown in FIG. 8b. If straight web supports for a part are aligned parallel to one another, as shown in FIG. 8a, the weight of the part could cause the webs to sag sideways while the part is being built. Subsequent layers would then be offset slightly (skewed) with respect to the previous layers.

[0294]

Height: Hold parts at least 0.25 inch (6.35 mm) above the elevator platform to ensure optimum liquid draining and leveling. To inhibit bending or sagging and to minimize drawing time, supports should be no taller than required. If a tall support is needed, a cross, circular or triangular web should be used for additional strength.

[0295]

Width: Supports must be at least 0.65 inch (16.51 mm) wide where they contact the platform or they may droop or fall through the platform drain holes. However, to minimize drawing time, supports should be only as wide as necessary. Diagonal supports beginning and ending on the part should be designed as buttresses, as shown in FIG. 11, and should not extend into the corner of the part where they will be hard to remove.

[0296]

Thickness: Supports should be designed with minimum thickness (web supports should be 1 mil (0.0254 mm) thick). Since the thickness of lines drawn with the laser is usually 10 to 20 mils (0.25 to 0.51 mm), the actual support will be considerably thicker than the CAD design. Supports designed as single surfaces with no CAD volume are not allowed.

[0297]

Attachment: To ensure that the object attaches securely to the supports, design supports to overlap the object vertically by 0.040 to 0.060 inch (1.02 to 1.52 mm) (typically 2 to 3 layers).

[0298]

3.3 CAD Interface

Many CAD and solid modeling systems represent surfaces of parts as a set of triangles. Triangles are the simplest polygon for computations and, if enough are used, can closely approximate all surfaces.

[0299]

The easiest geometric shape to represent, other than a triangle, is a rectangle. The most difficult is a curve. As shown in FIG. 40, a rectangle can be created by two back-to-back triangles. Curved surfaces, on the other hand, can be closely approximated only by a large number of triangles. The SLA-1 can process up to 14,000 triangles per stereolithography (.STL) file to produce very accurate circles and other curved surfaces.

[0300]

As shown in FIG. 41, CAD triangles are classified for stereolithography as flat (horizontal), near-flat and steep (vertical or near-vertical). The roof of the simplified automobile is composed of flat triangles. The hood and trunk are made up of near-flat triangles. The front, sides and back are steep triangles.

[0301]

3.4 STL Format Files

The .STL file required as input to SLICE is composed of triangular facets with outward facing (away from solid) unit normals. This format specifies the X, Y and Z coordinates of each vertex and the unit normal for each triangle. Interfaces used to generate .STL files are supplied by CAD vendors. The .STL file can be in either ASCII or binary format. Binary is preferred for space and performance considerations. ASCII is used at times because it allows easy debugging of interfaces.

[0302]

3.5 SLICE

Stereolithography (.STL) files generate Slice (.SLI) files consisting of cross-sections in the X-Y plane layered one on top of another to create a three-dimensional object, as shown in FIG. 43.

[0303]

Logon UNIX directly at the Slice Computer or remotely at the Control Computer via REMOTE USER. Execute SLICE at the UNIX prompt (\$).

[0304]

The next step is to alter standard options and enter extra parameters, as needed. These options control slicing and have a strong impact on part building later in the stereolithographic process. They can be saved to disk in an options file (.UII) to be used for later runs of the same or similar parts.

[0305]

The final step is to slice the .STL file, in accordance with the Slice options, to create a Slice (.SLI) file.

[0306]

Layer Borders, Crosshatches and Skin Fill (see FIG. 43)

Layer Borders Layer border vectors define surface boundaries. Crosshatches Crosshatch vectors are created internally by SLICE to partially solidify and strengthen the liquid area between layer borders (walls). The spacing between crosshatches and the type used are selected prior to running SLICE. (See FIG. 47.) Skin Fill Horizontal (top and bottom) surfaces are covered by a series of closely spaced parallel vectors which form a type of skin. The layers between the skins are generally cross-hatched for added strength. (See FIG. 47.) Layer thickness is a SLICE parameter which allows users to choose and vary layer thicknesses, thus determining the vertical resolution of the part. Use thinner layers are to improve accuracy and resolution in the vertical (Z) axis. Vertical dimension accuracy and resolution are limited to one layer thickness. Sloping (near-flat) surfaces are approximated with smaller horizontal and vertical surfaces which appear as stair-steps. The chosen layer thickness determines the height of each step. Gaps between layer borders are skin filled. Other areas may be crosshatched, if necessary. Decreasing the layer thickness in near-flat regions results in smoother surfaces, since the height of each step is reduced. Thicker layers can be used to strengthen parts and in some cases reduce the time required to build parts. However, the laser must trace at a slower rate over the resin surface to draw thicker layers, so the time saved by drawing thicker and thus fewer layers is partially offset by the reduced drawing speed (scan speed).

[0307]

SLICE creates vector blocks for a variety of two-point vectors. The block identifiers follow the mnemonic rule shown below.

[0308]

[Table 4]

Block Mnemonic	Description
LB	Layer Border
LH	Layer Hatch
FUB	Flat Up Border
FUF	Flat Up Skin Fill
FDB	Flat Down Border
FDF	Flat Down Skin Fill
NFUB	Near-Flat Up Skin Border
NFUF	Near-Flat Up Skin Fill
NFDB	Near-Flat Down Skin Border
NFDH	Near-Flat Down Skin Hatch
NFDF	Near-Flat Down Skin Fill

[0309]

Slice resolution translates .STL files from CAD space to Slice space by specifying the number of slice units contained in each CAD unit.

[0310]

Slice Resolution = # of slice units/CAD unit

[0311]

Slice Main Menu (Omitted)

Alter alters standard slicing parameters.

[0312]

Extra selects extra parameters not listed on the Alter Menu. These extra parameters currently specify the vertical axis for part building, the (default) slice part along the Z-axis, the X slice part along the X-axis, and the -Y slice part along the Y-axis.

[0313]

Save saves the options displayed on the screen, variable layer thickness table and extra parameters in the current options file.

[0314]

DoSlice runs SLICE using the current options.

[0315]

Quit quits SLICE. QUIT does not save the options file (use SAVE first).

[0316]

Alter Menu (Omitted)

DATABASE File Name specifies the .STL file to be sliced and whether the file is ASCII or binary. Enter the filename only; the .SLI extension is assumed.

[0317]

Resolution divides the CAD unit into smaller slice units, in essence creating a three-dimensional grid. Thus, if the CAD model were designed in inches (1 inch = 25.4 mm), and slice resolution was set to 1000, each inch (25.4 mm) of the part would be divided into 1000 slice units, each 0.001 inch (0.0254 mm) long. Note the following. First, larger resolution values distort triangles less and reduce the possibility of crosshatching errors. Second, all files comprising a single part (all support and object files) should be sliced with the same resolution. Third, the largest X, Y or Z coordinate of the CAD model determines the maximum acceptable value for slice resolution. (Highest coordinate) * slice res. < 65,535. Use round numbers (i.e., 1000, 2000, 5000 etc.).

[0318]

Layer Thickness Defines the vertical slice thickness in CAD units. (Layer thickness is displayed later in both CAD units and slice units, but is entered in CAD units.) Layer thickness may be fixed for an entire file (i.e., all layers assigned the same layer thickness) or varied (groups of layers having different layer thicknesses). Typical values range from 0.002 inch to 0.030 inch (0.051 to 0.76 mm). Type Thicknesses include Fine 0.005 inch (0.13 mm), Medium 0.010 inch (0.25 mm), Coarse 0.020 inch (0.51 mm). For example, if you want a part designed in inches to be built of layers 0.01 inch (0.25 mm) thick, enter .01. The layer thickness in slice units will be displayed on the screen automatically under the SLICE UNITS heading. The maximum number of layers which can be used is 16384 (this corresponds to 0.0005 inch (0.013 mm) thick layers on an 8.0 inch (203.2 mm) part).

[0319]

In Hatch Spacing, options (4), (5) and (6) specify the perpendicular distance, in CAD units, between adjacent hatch vectors drawn parallel to the X axis, parallel to the Y axis, or 60 and 120 degrees from the X axis, respectively. However, note the following. Typical hatch spacing values are 0.05 to 0.10 inch (1.27 to 2.54 mm). Use zero for web supports. (Web supports are designed as two back-to-back vertical surfaces and thus do not need cross-hatches.) A zero means no crosshatches are generated. X and Y crosshatches are commonly used together to form a grid of squares. X and 60/120 crosshatches are most often used since they produce a more rigid structure than X and Y crosshatches alone.

[0320]

In Fill Spacing, options (7) and (8) specify the perpendicular distance, in CAD units, between skin vectors drawn parallel to the X or Y axis, respectively. Note the following. Typical fill spacing values are 0.001 to 0.004 inch (0.025 to 0.10 mm). Never use both X and Y fill at the same time as this tends to stress and deform surfaces. Use zero for supports.

[0321]

Output Filename is the filename that will be assigned to the slice output file.

[0322]

Quit returns control to the Slice Main Menu.

[0323]

Procedures (Lab 2 - Slice)

Before You start, first transfer .STL files to the Slice Computer Logon UNIX

Step 1) At the UNIX prompt, execute SLICE and enter the object filename. \$slice^cam_part
ENTER ↵

Step 2) [Table Omitted]

At the Slice Main Menu, press A to alter standard options.

Step 3) [Table Omitted]

At the Alter Menu, update or verify the following options.

[0324]

[Table 5]

DATABASE Filename	cam_part ascii
Resolution	5000
Layer thickness	Fixed .010
X hatch spacing	.050
60/120 degree hatch spacing	.050
X skin fill spacing	.003
Minimum surface angle for scanned facets	50

[0325]

Press Q to return to Slice Main Menu.

Step 4) Press E to set extra parameters and enter -y.

Step 5) Press s to save options file as cam_part.UII.

Step 6) [Table Omitted]

At the Slice Main Menu, press D to slice the cam_part file.

Step 7) [Table Omitted]

When SLICE is finished, press ENTER ↵ to return to the Slice Main Menu.

Step 8) At the Slice Main Menu, press A to alter the following options

[0326]

[Table 6]

DATABASE Filename	cam_base ascii
Resolution	5000
Layer thickness	Fixed .010

[0327]

Set hatch, skin fill and MSA values (options 4 through 9) to zero.

Step 10) Press E and set extra parameters to -y.

Step 11) Press S to save options file as cam_base.UII.

step 12) At the Slice Main Menu, press D to slice cam_base file.

Step 13) At the Slice Main Menu, press Q to quit SLICE. This will return you to the UNIX prompt.

Slice Main Menu [Table Omitted]

Load loads another file. The options previously listed on the screen are not automatically saved (you must use the SAVE command).

[0328]

Write Writes the options into another object's options file.

[0329]

Copy copies options from a previously saved object's options file into the current options file. COPY saves having to re-enter options which are similar to those entered during an earlier run.

[0330]

Alter Menu Variable Layer Thickness [Table Omitted]

Variable layer thickness allows sets of layers (ranges) in the file to be created in which layer thickness can be individually specified. Thinner layers are commonly used to minimize the stair-step appearance of sloping surfaces and improve accuracy of critical vertical dimensions and details. Thicker layers are occasionally used to strengthen unsupported regions or to produce stronger, rigid layers.

[0331]

Layer Thickness Commands [Table Omitted]

A adds a new Z Level to the table. The Z Level specifies the vertical dimension to begin slicing at the specified thickness. The starting dimension and thickness are both entered in CAD units. Slicing will continue at this spacing until another Z Level is defined. The first (lowest) Z Level must start at or lower than the bottom of the object to be sliced. D deletes a Z Level from the table. S saves the table and returns control to the Alter Menu. Q returns to the Alter Menu without saving the table. H Prints a help message similar to this listing.

[0332]

MSA

SLICE parameter MSA (Minimum Surface Angle for scanned facets) defines the angle at which a triangle classification changes from near-flat to steep. As shown in FIG. 44, near-flat triangles are at an angle greater than zero (horizontal), but less than or equal to the MSA. Steep triangles are at an angle greater than the MSA, but less than or equal to 90 degrees. Note the following. Triangles inclined at less than the MSA are classified as near-flat. For these triangles, SLICE generates near-flat skin to fill gaps between layer borders on adjacent layers. Too large an MSA will cause SLICE to generate more skin vectors than necessary, increasing the run time and file size. Too small an MSA will cause gaps in the finished part resulting in liquid draining out of the object's walls. The correct MSA depends on the layer thickness used, but the following values are preferred.

[0333]

[Table 7]

Layer Thickness	MSA
0.005	40
0.010	50
0.015	55
0.020	60

[0334]

Use zero for web supports.

[0335]

MIA

MIA allows removal of specific hatch vectors which may cause part building problems.

[0336]

Procedures (Lab 3-Slice)

Variable Layer Thickness

Step 1) [Table Omitted]

At the Alter Menu, press 3 to select LAYER THICKNESS.

Step 2) Press V to select variable thickness. [Table Omitted]

Step 3) Add or delete Z Levels as needed.

Command? A^1.00^.010 ENTER ↵

Command? A^2.60^.005 ENTER ↵

NOTE: The first Z Level must start at or below the bottom of the part.

Step 4) Press S to save Layer Thickness table. [Table Omitted]

Step 5) Press Q to return to Alter Menu.

Step 6) Alter other standard options, X hatch spacing to .050, MSA to 55 as needed.

Step 7) Press E and set extra parameters to -y.

Step 8) Press S to save options file as spike_p.UII.

Step 9) At the Slice Main Menu, press D to slice spike_p file.

Step 10) Repeat to set parameters and slice spike_p file.

[0337]

3.6 Control Computer

All stereolithographic process steps from MERGE through BUILD are run on the Control Computer. This encompasses all functions from transmitting and merging slice files, through controlling the elevator and dynamic mirrors to build the part.

[0338]

Programs and operating parameters are selected from menus for ease of operation. The top-down hierarchy begins at the Main Menu, and continues through submenus, data entry screens, and status/information screens. Select options from menus by pressing the option number on the keyboard, or use the up and down arrow keys on the numeric keypad to position the pointer, then press ENTER ↵

[0339]

The SLA-1 menu hierarchy is illustrated in FIG. 45 and in the following figure. Note that each menu includes an exit or quit option to return to a next higher menu. The exit option from the Main Menu takes you out of the SLA-1 operating system and into MSDOS.

[0340]

3.7 Utilities

Utility menu options are used throughout the part-building process. Their functions include turning on and off SLA-1 hardware, measuring laser beam intensity and focus, moving the elevator platform before and after building a part, entering cure depth and linewidth data measured from banjotops, editing text files, making test parts Utility Menu. [Table Omitted]

[0341]

Power Sequencer [Table Omitted]

Turns on and off the laser, dynamic mirrors and elevator drivers, and opens and closes the laser shutter, directly from the Control Computer keyboard. The current status of each component is listed at the bottom of the screen.

[0342]

Beam Analysis [Table Omitted]

Measures laser beam intensity and focus, and enables Field Engineers to maintain and calibrate the laser.

[0343]

Beam Power points the laser beam at two beam profilers mounted in the Process Chamber and then calculates the average laser power. The current laser power is needed when Prepare Menu option MATERIAL MANAGER is run to calculate cure depths.

[0344]

Elevator Mover [Table Omitted]

Elevator Mover enables positioning of the elevator platform using up and down arrow keys on the Control Computer numeric keypad. Press the space bar to stop elevator motion.

[0345]

D moves the elevator platform a specified distance in inches (1 inch = 25.4 mm). Positive values move the platform downward, negative up.

[0346]

T toggles parameter information displayed at the bottom of the screen on and off.

[0347]

Procedures (Lab 2 - Utilities)

Power Sequencer

Step 1) [Table Omitted]

At the Utility Menu, press 1 to select POWER SEQUENCER.

Step 2) [Table Omitted]

At the Power Sequencer Menu, press the appropriate number key. The status display at the bottom of the screen will automatically update.

Beam Analysis

Step 1) [Table Omitted]

At the Utility Menu, press 2 to select BEAM ANALYSIS.

Step 2) [Table Omitted]

At the Beam Analysis Menu, press 1 to select DISPLAY PROFILE or 4 to select BEAM POWER.

Display Profile Review profile then press ENTER ↵ to return to Beam Analysis Menu.

Beam Power

Sensor #1 has an average reading of 8.08 mW (7.99 mW unfiltered), and sensor #2 has an average reading of 7.73 mW (7.65 mW unfiltered). Press 1 to 3 to select sensor #, press Q to quit. After power readings settle, write down average and press Q to return to Beam Analysis Menu.

Elevator Mover

Step 1) [Table Omitted]

At the Utility Menu, press 3 to select ELEVATOR MOVER.

Step 2) [Table Omitted]

Press the up and down arrow keys on the numeric keypad to raise and lower the elevator platform and Press the space bar to stop elevator motion, or Press D to specify a distance (in inches) for the elevator to move (positive values lower the elevator). EDIT A FILE is used to edit text files. MAKE TEST PARTS is used to build banjotops.

Material Manager [Table Omitted]

Load Material Data lists material (.MAT) files and prompts for the file to be loaded. View Material Data displays material data on the screen. Input New Material Data inputs material data measured from banjotops. These data include Step Period (SP) values, the line height of each banjotop string, and the minimum and maximum line width measurement from each banjotop string. INPUT NEW MATERIAL DATA then calculates a working curve and displays the slope and Y-intercept of the curve on the screen. (Refer to subsection 5.3 for further discussion of banjotops, working curves and related topics.)

[0348]

Procedures (Lab 3 - Utilities)

Material Manager

Step 1) [Table Omitted]

At the Utility Menu, press 4 to select MATERIAL MANAGER.

Step 2) [Table Omitted]

At the Material Manager Menu, press the appropriate option number.

Step 3) Load Material Data [Table Omitted]

Enter the material (.MAT) filename.

Name of data file to read: test.mat

ENTER↵

Input new material data [Table Omitted]

Enter the average laser power reading from BEAM POWER. [Table Omitted]

Enter the material test laser power reading (mW)

ENTER↵ [Table Omitted]

Enter the number of data pairs measured from the banjo top:

How Many Step Period/Line HeightData Pairs? 3

ENTER↵ [Table Omitted]

Input measured step period (SP), line height (LH), and minimum and maximum line width (WMIN, WMAX) data from the banjotop.

If no WMIN and WMAX data were measured, enter zero.

[0349]

3.9 Merge

MERGE combines all Slice files for a part (support and object files) and generates Layer (.L), Vector (.V) and Range (.R) files, as shown in FIG. 48. Layer (file.L) File defines the types of vector blocks in each layer. Vector (file.V) File contains vector data used by BUILD to draw each layer. Range (file.R) File specifies range, drawing parameters and dipping parameters for BUILD. It is this file which may be modified with the Prepare option to add part fabrication parameters.

Merge Information Screen [Table Omitted]

The MERGE information screen is used to enter file information. It displays the following status information as MERGE is running. Starting and ending Z Level values for each layer thickness range. The Z Level currently being merged. At completion of the run, the total number of ranges processed and the number of merged layers in each range.

[0350]

Procedures (Lab 2 - Merge)

Before you start, run Network Menu option FTP to transfer all required Slice files to the Control Computer working directory.

Step 1) [Table Omitted]

At the Main Menu, select MERGE2 or locate pointer, and ENTER↵

Step 2) Enter the files to be merged.

Slice File Name: cam_part^cam_base

ENTER↵

Step 3) Enter a filename for the layer, vector and range files, or press ENTER↵ to select the default filename.

Output File Name Prefix

[CAM_PART]:cam

ENTER↵

Step 4) At the prompt, press ENTER↵; ENTER↵ to select the default layer thickness.

Layer thickness in mils [10]?

ENTER↵

Step 5) [Table Omitted]

Watch the screen to determine when MERGE is completed. (Note that slice files with revisions earlier than 3.0 may prompt for Z-spacing.)

Merge Options

/Z adjusts the vertical position of one file relative to another. This option is used to align objects vertically. Enter the offset in slice units following the file to be adjusted.

Slice File Names: cam_part^cam_base/Z100

/X adjusts the X direction position of one file relative to another. /Y adjusts the Y direction position of one file relative to another.

[0351]

3.11 PREPARE

Prepare Menu options are used to specify part building parameters such as laser drawing speed and elevator dipping times, as well as to edit the Range (.R) file.

[0352]

Layer overlap, that is, good adhesion between layers is normally attained by giving each layer a 0.006 inch (0.15 mm) overcure (i.e., the cure depth used for 0.020 inch thick (0.51 mm) layers is 0.026 inch (0.66 mm). Dip delay, that is, the amount of time required for the surface of the resin to level and settle after a part is dipped is dependent on the geometry of the part and many other factors.

[0353]

SS (Step Size) The SLA-1 only appears to draw vectors in continuous motion. The dynamic mirrors actually move the beam in discrete steps followed by short delays. Step size is the size of the move in mirror bits.

[0354]

In general, step size for borders and crosshatches is set to 2 (the minimum allowable). Step size for skin fill vectors is typically set to 16.

[0355]

SP (Step Period) is the length of the delay following each laser step. The larger the SP, the slower the laser drawing speed, and thus the greater the depth of cured plastic.

[0356]

ZW specifies the leveling time for the resin surface to settle and level after dipping. Generally, ZW is set to between 30 and 60 seconds for supports. Set ZW to 45 to 130 seconds for normal part building.

[0357]

Ranges

A range is a group of one or more horizontal slice layers defined by lower and upper dimensions entered in CAD units or slice units. A range is created whenever a part building parameter value needs to be specified for a group of layers. For example, if a dip delay of 30 seconds is required for support layers, and 60 seconds will be used for all remaining layers, two ranges have to be defined. The first would contain the layers of the part with a ZW of 30, the second all layers with a delay of 60. Another example where ranges are often used is in varying layer cure depths. A range comprised of the first few support layers would be created with larger cure depths than those specified for the rest of the layers. Prepare Menu options are used to create the necessary ranges.

[0358]

Prepare Menu [Screen Omitted]

Parameters Manager Menu [Screen Omitted]

Parameters Manager is used to add or modify part building parameters.

1. Z-Pitch

This parameter controls scaling of the part in the vertical dimension.

2. XY- Only Scale Factor

XY-only scale factor converts a distance in slice units into movement of the laser beam on the surface of the resin.

[0359]

A characteristic of the dynamic mirrors is that the laser beam will move 1 inch (25.4 mm) on the resin surface for every 3556 mirror bits sent to the mirror drivers (or 140 bits for every mm). Since 3556 is an inconvenient number to use for slice resolution, a conversion factor is used.

[0360]

For example, if you slice a CAD file designed in inches (1 inch = 25.4 mm) with a resolution of 1000, every inch of the object will be represented by 1000 slice units, instead of 3556. Therefore, every vector in the .V file will be too short, by a factor $1000/3556 = .3556$, and if it were used without modification, the final part would be too small. BUILD multiplies all vector coordinates in the .V file by the XY- only scale factor. Therefore, this parameter should be set to $3556/1000 = 3.556$ to rescale the vectors to their proper lengths. In general, the formula is the following.

[0361]

XY-Only Scale = 3556 mirror bits/# slice units per inch

Note that you can also resize your part using XY-only scale factor. For example, to increase the horizontal dimensions of the part described above by 10 percent, use the following scale factor.

$$3.556 * 1.10 = 3.912$$

To reduce the horizontal dimensions by 50 percent, use the following.

$$3.556 * 0.50 = 1.778$$

3. Maximum Vector Count

This parameter specifies the maximum number of vectors to be loaded into the dynamic mirrors buffer before they begin moving to build the part.

4/5. Minimum/Maximum Viewport Coordinates

BUILD viewport coordinates specify the minimum and maximum coordinates (in mirror bits) of the window display of the vat shown on the BUILD status screen. The coordinate limits are (0,0) and (65535,65535).

[0362]

For example, if you would like to view the cam while it is being built, use viewport coordinates. (The cam is approximately 1 inch (25.4 mm) in diameter.)

$$\begin{aligned} (Xmin, Ymin) &= \text{vat center} - 1/2 \times \text{part width} \\ &= 32767 - 0.5 * 3556 \\ &= 30989 \end{aligned}$$

$$\begin{aligned} (Xmax, Ymax) &= \text{vat center} + 1/2 \text{ part width} \\ &= 32767 + 0.5 * 3556 \\ &= 30989 \end{aligned}$$

Note that since the coordinates calculated for the X-Y offsets are for the center of the part, you must subtract enough mirror bits from the offsets to display the entire part. You must add a similar number, at least equal to one-half the part width, to the maximum offsets.

[0363]

To show the entire 9 inch by 9 inch working surface, enter the following.

$$\begin{aligned} (X_{\min}, Y_{\min}) &= 32767 - 4.5 * 3556 \\ &= 16765 \end{aligned}$$

$$\begin{aligned} (X_{\max}, Y_{\max}) &= 32767 + 4.5 * 3556 \\ &= 48769 \end{aligned}$$

6. Multiple Part Positioning

These parameters are used to both position the part on the elevator platform and to make multiple parts in the same BUILD run.

[0364]

To calculate the coordinates needed to position a part in the center of the resin vat, you need to know the coordinates of the center of the part in CAD space. [The coordinates of the center of the vat, which are about (32767,32767). If necessary, exact coordinates can be obtained.]

[0365]

For example, if the part X-Y center is (2.3 inch (58.42 mm), 4.1 inch (104.14 mm)), and the center of the vat is (32767, 32767), then

$$\begin{aligned} \text{X-offset} &= \text{vat center} - (\text{CAD center} * 3556) \\ &= 32767 - (2.3 * 3556) \\ &= 24588 \end{aligned}$$

$$\begin{aligned} \text{Y-offset} &= \text{vat center} - (\text{CAD center} * 3556) \\ &= 32767 - (4.1 * 3556) \\ &= 18187 \end{aligned}$$

Multiple part positioning coordinates can also be used to make multiple copies of the part in the same run. For example, if you want to make four copies of the part used in the above example, you will calculate four sets of coordinates (X1/Y1, X2/Y2, X3/Y3 and X4/Y4) representing the center of each of the four parts.

[0366]

If you want all four copies of the part clustered about the center of the resin vat and separated from each other by two inches (50.8 mm) in both the X and Y directions, calculate the coordinates for the vat center first, as in the previous example, then add and subtract mirror bits equal to half the distance desired between each part.

$$\text{Separation} = 2 \text{ inches} / 2 = 3556 \text{ bits}$$

$$X1 = X_c + 3556 = 24588 + 3556 = 28144$$

$$Y1 = Y_c + 3556 = 18187 + 3556 = 21743$$

$$X2 = X_c - 3556 = 21032$$

$$Y2 = Y_c - 3556 = 14631$$

$$X3 = X_c + 3556 = 28144$$

$$Y3 = Y_c - 3556 = 14631$$

$$X4 = X_c - 3556 = 21032$$

$$Y4 = Y_c + 3556 = 21743$$

7. Build Options Line

These parameters define the orientation of the BUILD viewport.

[0367]

U. Update Build Parameters On Disk

This command saves all other PARAMETERS MANAGER entries to disk in the build.prm file.

[0368]

Range Manager Menu [Screen Omitted]

RANGE MANAGER is used to add or delete ranges, calculate step periods (laser drawing -speed), and edit ranges to modify dip delays save the Range (.R) file

[0369]

The RANGE MANAGER Menu lists: the Range (.R) filename, the range numbers assigned when ranges are added, and the starting and ending range dimensions in both CAD units and slice units, [in the screen shown, the slice resolution is 5000, so CAD dimensions 0.73 inch (18.54 mm) (bottom of the part) and 1.37 inches (34.8 mm) (top of the part) correspond to slice units 3650 and 6850], the layer thickness in both CAD units and slice units, the total number of layers in each range, and the commands used to modify and save the .R file.

[0370]

Range Manager Commands

[The commands that appear in the RANGEMANAGER menu are as follows.]

A (add range) - add range
 D (delete range) - delete range
 E (edit range) - edit range
 V (verify blocks) - verify blocks
 R (make a report) - make s report
 C (calcSPs) - s\Sp calculation
 X (exit) - exit
 S (save changes on disk) - save changes to disk

A adds a range to a temporary range file; the .R file is not changed until the SAVE command is used. The starting range layer can be entered in either slice units or CAD units. The break point is the first layer of the range. D deletes a range from the screen. If there is more than one range left, the range will be combined into the next higher range if one exists (for example, data from deleted range 2 will be incorporated into range 3; if there is no range 3, the data will be incorporated into range 1). E lists (for editing) each vector block in a specified range. This command is primarily used to add dipping parameters to ranges. [Screen Omitted]

V verifies through the Layer (.L) file that only the vector blocks contained in each range are listed for editing in the temporary .R file. It is these blocks which are edited to control step periods, step sizes and other part building parameters. The vector blocks and ranges are not written to the .R file on disk until the file is saved using the S command, R displays the vector blocks in each range on the screen or prints a hard-copy via the optional printer port. [Screen Omitted]

X exits RANGE MANAGER and returns to the Prepare Main Menu. The .R file is not saved using this command.

S saves the .R file permanently on disk, including all information entered using RANGE MANAGER. calculates step periods and enters cure depth/step period information into the temporary range file. CALC SP commands are as follows. [Screen Omitted]

R (read material data) - read material data
 S (save new range command) - save new range command
 P (change power rating) - change power rating
 E (edit cure depth/step) - edit cure depth/step period
 V (view material data) - view material data
 Q (quit program) - quit program
 X (exit) - exit

R to read line height and width data from a material data (.MAT) file. The .MAT files in the working directory are listed on the screen for convenience. P to change the laser power reading shown on the screen to the latest reading measured by utility BEAM ANALYSIS. E to edit the cure depth and estimated step period values shown on the screen. V to display material data from a material data (.MAT) file. Q to quit the CALC SP function and return to the Main Menu. No changes entered using Prepare Menu options are saved. S adds SP and SS laser drawing parameters to appropriate vector blocks in the temporary range file. The parameters can be added to all vector blocks in the file, to only border and hatch blocks, or only to fill blocks. In addition, you can choose to update only specific merge-sets. (A merge-set is comprised of vector blocks from only one of the Slice files input to MERGE. Merge-sets are delineated by the number appended to each vector block (i.e., LB2)). Note that this update command does not update the .R file, only the temporary range file. Use the Range Manager Menu SAVE command to save the .R file to disk. [Screen Omitted]

X ++ CALC SP to the Range Manager Menu.

[0371]

Procedures (Lab 2 - PREPARE)

PARAMETERS MANAGER

Step 1) At the Main Menu, press 4 to select PREPARE.

Step 2) At the prompt, enter the part file name prefix. Part Prefix: cam

ENTER ↵

[Screen Omitted]

Step 3) At the Prepare Main Menu, press 1 to select PARAMETERS MANAGER.

Step 4) Set XY-only scale factor to .7112 (3556/5000).

Step 5) Set X Offset to 17000 (32767 - (4.5 * 3556)).

Step 6) Set Y offset to 17000.

Step 7) (Optional) To make two parts, set (X₁, Y₁) to (15000, 15000) and (X₂, Y₂) to (15000, 25000).

Step 8) Set viewport coordinates to Xmin, Ymin = 5000, 5000 and Xmax, Ymax = 35000, 35000.

Step 9) Press U to update file to disk.

RANGE MANAGER

Before you start, run utility BEAM ANALYSIS to measure current laser power. Record average of sensor 1 and 2 readings.

Step 1) At the Prepare Main Menu, press 2 to select RANGE MANAGER. [Screen Omitted]

Adding Ranges

Step 1) At the Range Manager Menu, press A to add range. [Screen Omitted]

Step 2) Press Z to add range dimensions in slice units, or C to enter dimensions in CAD units.

Adding Range

Press Z to enter Z-Layer ... Number: 2

ENTER ↵

Step 3) Enter start of range in slice units. Enter break point, in Z-Layer units: 3750

ENTER ↵

Step 4) Check screen to verify that range was added properly. [Screen Omitted]

Step 5) Add another range starting at 4950.

Step 6) Add a fourth range starting at 6000.

Deleting Ranges

Step 1) At the Range Manager Menu, press D to delete range. [Screen Omitted]

Step 2) Enter the range number to be deleted.

Delete what range: 3

ENTER ↵

Step 3) Check screen to ensure that range was deleted. [Screen Omitted]

[0372]

Verifying Ranges

Step 1) At the Range Manager Menu, press V to verify blocks. [Screen Omitted]

Step 2) Enter y at the caution message. Verifying . . . command. Continue? Y

ENTER ↵

Reporting

Step 1) At the Range Manager Menu, press R for report. [Screen Omitted]

Step 2) Press V to view report on screen, or P to print report on printer. The report will not be shown on the screen if the printer option is selected.

Step 3) Press ENTER to continue. [Screen Omitted]

Calculating Step Periods

Step 1) At the Range Manager Menu, press C to calculate step periods. [Screen Omitted]

Step 2) At the CALC SP Menu, press P to change laser power reading. [Screen Omitted]

Step 3) Enter average laser power from BEAM ANALYSIS.

Enter new laser power reading (mW): _____ ENTER ↵

Step 4) At the CALC SP Menu, press E to edit cure depth/step period data.

Step 5) Enter the cure depth necessary to adhere "roast" the first range (containing the first two layers of the supports) to the platform by entering C followed by the range number and new cure depth.

C1, 35 ENTER ↵

Note that the cure depth selected should be at least 6 mils (0.15 mm) greater than the layer thickness for adequate bonding between layers. The cure depth for the first few layers of supports should be deeper for strong bonding to the platform. In this case, the required cure depth is 35 mils (0.89 mm).

Step 6) Enter cure depths of 16 for all layer borders and hatches in ranges 2 and 3.

C2, 16 ENTER ↵

C3, 16 ENTER ↵

Step 7) At the CALC SP Menu, verify the changes. [Screen Omitted]

Step 8) At the CALC SP Menu, press S to save ranges.

Step 9) Specify which vector block group to update, or press ENTER ↵ to select the default group shown in the brackets.

Use which block group [1] ? ENTER ↵ [Screen Omitted]

Step 10) Specify the merge set(s) to be updated, or press ENTER ↵ to select the default shown in the brackets.

Update which merge-sets [all]? ENTER ↵

Step 11) Begin editing skin cure depths by pressing E then entering a cure depth of 26 mils (0.66 mm) (this is 6 mils (0.15 mm) greater than the selected 20 mil (0.51 mm) layer thickness).

C2, 26 ENTER ↵

Step 12) Divide the resultant step period (90) in half, then press E and enter that value for the skin fill SP in ranges 2 and 3.

S2, 45 ENTER ↵

S3, 45 ENTER ↵

Step 13) Press S to save the file.

Step 14) At the prompt, specify update of skin fill blocks (block group 2).

Use which block group [1]? ENTER ↵

Step 15) At the prompt, press ENTER ↵ to update all merge sets.

Update which merge sets [all]? ENTER ↵

Step 16) At the CALC SP Menu, press X to exit the CALC SP function.

Step 17) At the Range Manager Menu, press E to edit a range to add dip delays.

Step 18) At the prompt, enter 1 to edit range 1. Edit what range? 1

ENTER ↵

Step 19) At the prompt, add a dip delay of 30 seconds to the #BTM record. Enter commands for #BTM: ZW30

ENTER ↵

Step 20) Edit range 2 to add a 30 second dip delay.

Step 21) Edit range 3 to add a 120 second dip delay.

Step 22) At the Range Manager Menu, press S to save the .R file to disk. [Screen Omitted]

[0373]

Layer Manager Menu [Screen Omitted]

LAYER MANAGER is used primarily to find specific vector blocks in the .L file. Its other capabilities, edit and update, are advanced features. The LAYER MANAGER screen shown above lists the .L filename, the number of ranges specified in the .R file, the starting and ending range dimensions in slice units, the layer thickness in slice units, the total number of layers in the range, and operating commands.

Layer Manager Commands

F finds specific vector blocks in the .L file and lists the layer numbers. For example, if you would like to determine where merge-set 3 starts in Z space, press F to find blocks then enter L3 and ALL at the prompts. LAYER MANAGER will list all slice layers containing vector block L3 on the screen. This is fast and convenient, when compared to exiting the Prepare Menu and running VIEW to locate particular vector blocks.

STATISTICS [Screen Omitted]

STATISTICS lists layer, range and vector file information, including, file sizes in bytes, dates and times files were created, and free disk space.

[0374]

Procedures (Lab 3 - PREPARE)

STATISTICS

Step 1) At the Prepare Main Menu, press 4 to select STATISTICS.

Step 2) Press ENTER ↵ to continue.

[0375]

3.12 BUILD

Overview

BUILD supervises the part-making process by reading the Vector (.V) and Range (.R) files and sending appropriate commands and parameters to the dynamic mirrors and elevator driver. This includes, deflecting the laser beam to trace vectors on the surface of the resin vat, controlling the speed of the laser pass to ensure appropriate cure depths, and controlling the dipping sequence between layers (dip, raise, and level).

BUILD Options screen [Screen Omitted]

This screen is used to enter the part filename and to display part building information. Items displayed on the screen include Options (see Intermediate Topics or Prepare Menu option PARAMETERS MANAGER), XY-Scale listing the XY-only scale factor, #Parts showing the number of duplicate parts to be built, X,Y listing the multiple part positioning coordinates, Parts Directory Listing listing the files in the working directory, and Part Filename specifying the part to be built.

[0376]

BUILD Status Screen (see FIG. 52)

This screen displays current status information while the part is being built. Items shown in the screen include Part showing the name of the part being built, Control specifying the range control (default), Action listing the current BUILD, Time listing the number of seconds remaining in the dip delay, Start/End Times listing BUILD starting and ending times and dates, Start/On/End Layer listing starting and ending part layer numbers, and the layer currently being drawn, Block listing the mnemonic of the vector block currently being processed, Viewport showing a top view of the resin vat and part cross-section (vectors are traced on the screen as they are drawn on the surface of the resin), Loading indicating if data for laser beam positioning are being loaded into the buffer, Leveling indicating if BUILD is dipping or waiting for resin to settle and level following dipping, Drawing indicating if vectors are being traced on the surface of the resin vat, and Analyzing indicating if BUILD is analyzing or correcting laser mirror drift.

[0377]

PROCEDURES (LAB 2 - BUILD)

Before, you start, position the elevator platform slightly below the surface of the resin using ELEVATOR MOVER, open the resin spillway valve on the front of the vat to allow resin displaced by the platform support rods to flow into the overflow container, and raise the elevator until the top surface of the platform is slightly above the resin level. Close the door to the process chamber. Verify that the LASER ON and SHUTTER OPEN indicators are on. Use POWER SEQUENCER to turn on the laser or close the shutter, as required.

Step 1) At the Main Menu, select BUILD. 5 or locate pointer and press ENTER ↵

Step 2) Enter the part file name from the files listed. [Screen Omitted]

Part Filename: cam

ENTER ↵

Step 3) (See FIG. 53)

Check the status screen and part periodically to verify that the first few layers adhere to the elevator platform, that the part is centered in the resin vat, and that layers with different layer thickness values adhere to one another. Abort BUILD, by pressing SPACE BAR if there are part making problems. This will return you to the Main Menu.

[0378]

KEYBOARD COMMANDS

During the leveling action, BUILD accepts three keyboard commands. P pauses BUILD until any other key is pressed. The leveling time will continue to count down to zero. A pause message is displayed in the command line at the bottom of the screen. C continues the part building process by overriding the remaining leveling time period and immediately starting the next layer. S skips to a specified Z level. The first layer at or above that Z level will be drawn. This command works only in the direction from lower to higher Z levels.

[0379]

COMMAND LINE OPTIONS

/LOFF turns off the dynamic mirrors driver. This option is used in conjunction with /ZOFF to run BUILD without making a part. /ZOFF turns off the elevator driver. This option is used in conjunction with /LOFF to run BUILD without making a part. /START specifies a starting Z level for part building. All lower layers are skipped. Use /START to start building in the middle of a part. For example, to start building the sample part at Z level 5000, enter the following.

Part Filename: cam/start^5000

ENTER ↵

/STOP specifies an ending level for part building. All upper layers are skipped. Use this option, in conjunction with /START, to build a cross-section of the part. For example, to build all layers between Z levels 5000 and 5500, enter the following.

Part Filename: cam/start^5000/stop^5500

ENTER ↵

The elevator will not dip after the last layer is drawn. The /LOFF and /ZOFF commands are commonly used with /START and /STOP to check if the part fits in the viewport. For example, enter the following.
Part Filename: cam/zoff/loff/start^5000/stop^5050

ENTER ↵

The mirrors will not draw the layer and the elevator will not move. If the part is displayed on the viewport properly, restart BUILD with no command line options to build the part. Otherwise, edit the viewport coordinates using PARAMETERS MANAGER.

[0380]

3.13 POST PROCESS

Post process involves curing and finishing green stereolithographic parts. Green parts are composed of semi-hard plastic and liquid with the exact composition dependent on several factors, including the resin being used and the type of crosshatching selected.

[0381]

The major post process steps are draining excess resin into the resin vat, wicking to remove resin from corners and other part details, UV curing to solidify uncured portions of the part, removing supports, and Optional finishing such as sanding, sandblasting, and painting.

[0382]

Drains liquid resin from the part back into the resin vat. Draining times generally range from 30 minutes to 24 hours. Note, however, that longer exposure to air will weaken the part structure and may inhibit UV curing. Thermal ovens do speed up the process, but may adversely affect the dimensional accuracy of the part.

[0383]

Use care when tilting and otherwise handling green parts. Layers can peel or deform readily before UV curing. Removes excess liquid trapped in corners and around small details of the part.

[0384]

Finish the polymerization process to produce a hard plastic part. Test for surface tackiness to ensure complete curing. The general procedure is to cure all exposed surfaces while the part is attached to the platform, then remove the platform and cure all remaining surfaces.

[0385]

In the air, is the most common curing method. Cure parts within 12 hours of exposure to air to maintain structural soundness. The disadvantages to air curing are that parts may yellow and distort due to excess heating.

[0386]

Curing times can be reduced dramatically by immersing parts in water, since water does not absorb UV light and acts as a "heat sink" to cool the part and minimize heat distortion. Remove all air bubbles, since they may cause blistering. Short, rapid curing sessions (i.e., 5 minutes) work best.

[0387]

Remove supports from the part by clipping or sanding.

[0388]

Procedures (Lab 2 - POST PROCESS)

DRAINING

Step 1) At the Main Menu, select UTILITIES. Press 6 or locate pointer over UTILITIES and press ENTER
⇐ [Screen Omitted]

Step 2) At the Utility Menu, press 3 to select ELEVATOR MOVER. [Screen Omitted]

Step 3) Using the up arrow key on the numeric keyboard, slowly raise the elevator 3 inches (76.2 mm). (Go slow to avoid distorting the part.)

Step 4) Wait about 30 minutes for excess resin to drain into resin vat.

Part and Platform Removal From Chamber

Step 1) Place a drain pad in the drain tray.

Step 2) Place the drain tray on top of the resin vat and below the elevator platform. Caution: do not run the elevator into the drain tray when removing the platform from the elevator rods. This may damage the elevator.

Step 3) Toggle the down arrow key to lower the elevator platform until it is about 1/4 inch (6.35 mm) above the drain pad.

Step 4) Alternately turn the elevator shaft knobs one turn CCW. This will unscrew the threaded end of the shafts from the platform. Repeat this step until the platform drops free from the shafts onto the drain pad.

Step 5) Toggle the up arrow key to raise the elevator shafts, as necessary for removal of the drain tray and platform.

Step 6) Remove the drain tray and elevator platform with attached part from the process chamber. Hold the platform level to avoid damaging the part.

[0389]

WICKING

Step 1) Place the drain tray and elevator platform with attached part on a work surface.

Step 2) Using swabs, gently remove excess resin from corners, details and other areas that did not drain fully. Wait and repeat as necessary.

[0390]

Wear gloves when performing the following steps.

Step 1) Place the drain tray and elevator platform with attached part in the PCA. WARNINGS Do not put drain pads or any other flammable material in the PCA.

Step 2) Post cure the part until all surfaces exposed to the UV lamps are no longer tacky. Use short cure periods (5 to 10 minutes).

Step 3) Using a fine tooth saw, carefully cut the supports near where they attach to the platform.

Step 4) Clean the part to remove sawdust and fragments before continuing. Properly dispose of residue.

Step 5) Turn the part upside down (or rest it on its side) as needed to expose uncured surfaces to the UV lamps in the PCA.

Step 6) Post cure the part until all surfaces are no longer tacky. This may take several separate runs.

[0391]

PLATFORM REPLACEMENT

Step 1) Scrape resin residue from the platform. Tap out threaded holes in platform with a #10-32 tap.

Step 2) Hold the platform under the elevator rods so that threaded holes in the platform line up with the threaded ends of the rods. Step 3) Alternately turn the shaft knobs CW one turn. Repeat this step until the platform is securely installed on the elevator shafts.

[0392]

REMOVING SUPPORTS AND FINISHING

Step 1) Carefully cut away supports with files, grinding tools, side cutting pliers or other appropriate tools. Step 2) Smooth surfaces using files.
 Step 3) Sand, sandblast and paint part as required.

[0393]

OPERATING THE PCA

Step 1) Place part, still attached to platform, in center of oven, as shown in FIG. 54a. Orient lamps for even exposure (as close to 90 degrees as possible) of the greatest number of surfaces.
 Step 2) Set timer to 10 to 20 minutes. Step 3) After time expires, set MAIN POWER switch to OFF.
 Step 4) Remove part and platform from oven and separate part from platform. Use care to avoid distorting uncured surfaces.
 Step 5) Reorient part on turntable to expose most of the remaining surfaces, as shown in FIG. 54b.
 Step 6) Repeat steps 2 and 3.
 Step 7) Reorient part and lamps to best position to cure all remaining surfaces, as shown in FIG. 54c. This may take several runs.

[0394]

3.14 PART BUILDING CHECKLIST SCOPE

This checklist is a step-by-step guide to building stereolithographic parts. The starting point is a CAD design made without reference to stereolithography. All required hardware and software systems are assumed to be installed and operational.

1. CAD DESIGN

- Verify that objects define enclosed volume
- Select required CAD resolution

2. ORIENT PART

- Position part entirely in positive CAD space, as close to origin as possible
- Optimize orientation in order to:

Enable part to fit in resin vat

Minimize number of unsupported surfaces

Maximize vertical and up facing horizontal surfaces

Minimize slanted or sloping surfaces Optimize draining Minimize volume of entrapped liquid

3. DESIGN AND ORIENT SUPPORTS

-Design Supports

Placement

Spacing

Orientation

Height

Width

Thickness

- Overlap Supports 2 to 3 Layers into Object

4. CAD INTERFACE

- Create stereolithography files
- Transfer .STL files to Slice Computer

5. SLICE

- Alter standard options

DATABASE Filename

Resolution

Layer Thickness

Hatch Skin Fill Vector Spacing

Minimum Surface Angle for Scanned Facets

Minimum Hatch Intersect Angle

Output Extra Parameters

- Specify extra parameters
- Save options file
- Run DoSlice to slice file
- Repeat to slice all object and support files
- 6. TRANSFER SLICE FILES TO CONTROL COMPUTER
 - Select NETWORK From Main Menu
 - Run FTP
 - GET or MGET Files
 - Check Control Computer working directory to verify transfer
- 7. MERGE
 - Select MERGE from Main Menu
 - Enter input and output filenames
 - Record filenames and sequence entered
 - Check MERGE screen to verify complete Run
- 8. MEASURE LASER POWER
 - Select UTILITIES from Main Menu
 - Run BEAM ANALYSIS
 - Record average power from both sensor readings
- 9. PARAMETERS MANAGER
 - Calculate and enter X-Y only scale factor
 - Calculate and enter minimum/maximum viewport coordinates-
 - Calculate and enter multiple part positioning coordinates
- 10. PREPARE RANGE FILE
 - Add ranges
 - Verify blocks
 - Edit cure depths to calculate step periods
 - Edit dipping parameters
 - Save range file
- 11. CHECK SYSTEM
 - Top off vat with resin
 - Open overflow valve
 - Check indicators for laser and shutter status
 - Position elevator platform using ELEVATOR MOVER
- 12. BUILD PART
 - Select BUILD from Main Menu
 - Check first few layers for adherence to platform and proper location in vat
- 13. POST PROCESS
 - Raise part and drain excess resin into vat
 - Remove remaining resin by wicking UV cure part on platform
 - Finish curing and separate part from platform
 - Remove supports from part
 - (Optional) refinishing
 - Clean and reinstall platform
- 14. (OPTIONAL) VIEW STEREO LITHOGRAPHY AND SLICE FILES
 - If viewing .STL File, transfer file using FTP.
 - Select VIEW from Main Menu
 - Input filenames and specify viewing parameters SECTION

[0395]

4. PART BUILDING PROBLEMS AND REMEDIES

Common part building problems are summarized in the following table along with remedial actions.

[0396]

[Table 8]

PROCESSING STAGE	PROBLEM	REMEDY
CAD Design	The CAD model does not become a closed volume. The 3D modeling file is not sliced.	Redesign the model so that the horizontal cross-section is composed of a closed curve that completely separates the inside and outside of the part.
Orientation and Support	The entire part is not in positive CAD space. The 3D modeling file is not sliced.	Convert the object to a positive XYZ space. Position it as close to the origin as possible.
	Liquid resin is trapped when the object is made. This slows down the production of the part.	Change the orientation of the part so that the excess liquid can be drained as the part is being produced. If this is not possible, divide the part into sections, manufacture each section separately, and then assemble the sections in a post-processing stage. Another method is to add drainage holes to the surface as needed.
	The support is hanging from holes in the platform.	Redesign the support so that the width of the part that touches the platform is at least 0.65 inches (16.51 mm).
	The part did not properly bond to the support.	Redesign the support so that it overlaps the part vertically by a few layers (usually 40-60 mils (1.02-1.52 mm)). The layers of the overlapping part and support must be the same or have a thickness that can be divided evenly.

[0397]

[Table 9]

SLICE	Layers are so loose that the part becomes skewed. Drooping or curling of layers of the part.	Add orthogonal, cylindrical, or triangular web supports. Add more supports (supports are generally spaced 0.1 to 0.8 inches (2.54 to 20.32 mm) apart.
	When the part was immersed, a portion of it was misaligned.	Add a support to anchor the portion that is misaligned.
	A file sliced along the wrong axis. The part is directly manufactured on the platform.	Re-run the slice and change the slice vertical axis (extra parameter) to match the vertical CAD axis.
	The wrong unit was used for the layer thickness (inches instead of millimeters).	Re-run SLICE with the correct layer thickness.
	The triangles are distorted due to the low slice resolution, causing deformation of the part.	Re-run SLICE with high resolution.
	A near-flat surface is too rough (it has a stair-step appearance).	Re-run SLICE with a thinner layer or apply paper finish to the finished part.
	There is a gap in the surface of the part.	Re-run SLICE to increase the MSA (minimum surface angle of the scanning plane). However, if the MSA is too large, SLICE will generate more skin vectors than necessary, causing an increase in execution time and file size.
Network and Merge	Insufficient disk space.	Delete or save old files.

[0398]

[Table 10]

PREPARE	Separation or curling of layers due to improper interlayer merging.	First, check whether the current laser power was used when CALC SP was executed. If it was not being used, run the utility BEAM ANALYSIS, and after measuring the laser power, re-execute the CALS SP option in the RANGE MANAGER to recalculate the step period. If the current laser power was used, re-run CALC SP to ensure an extra depth of 6 mils (0.15 mm).
	The first layer of the support did not adhere to the platform.	Use CALC SP, an option in RANGE MANAGER, to increase the step height to three times the recommended value and/or adjust the starting height of the elevator platform.
	A bulge occurs on a horizontal surface.	Use RANGE MANAGER to increase the dip delay (parameter ZW) or increase the height of the part so that it is at least 0.25 inches above the platform. If a new layer is created on excess resin that did not have enough time to flow over the edges, the surface is likely to bulge.
	The final object does not have the same dimensions as the CAD model.	Use the PARAMETERS MANAGER to correct the XY-specific scale factor and re-execute BUILD.
	The object is not shown at all on the BUILD viewport, or is only partially shown.	Use the PARAMETERS MANAGER to enter new viewport coordinates and then execute BUILD.

[0399]

5. Chemistry of Stereolithography

Stereolithography is made possible by a process called photopolymerization in which a liquid resin monomer is converted to a solid polymer upon exposure to ultraviolet light. The degree to which polymerization occurs, and thus the solidity of the material, is dependent on the total light energy absorbed.

[0400]

The polymerization of liquid resins is not a new technology, having been used in such applications as ultraviolet inks, coatings, varnishes, and printed circuits for more than twenty years. The use of lasers as the light energy source is, however, a more recent innovation that has been used to date primarily in basic academic research programs.

[0401]

Photopolymers

The photopolymers used in Stereolithography are composed of two basic materials. The first is a photoinitiator which absorbs the laser energy and forms reactive radical species which initiate the polymerization process. The photopolymers also contain acrylic functionalized monomers and oligomers which polymerize upon exposure to a free radical source.

[0402]

Certain polymers contain thermoset materials which are sensitive to heat, and thus allow thermal curing of the finished part. Totally UV curable polymers do not appreciably polymerize when heated after being cured by the laser, but in the liquid form can polymerize uncontrollably when overheated.

[0403]

The preceding discussion of photopolymers, and the following discussion of the photopolymerization process, provide only a basic overview as needed to better understand Stereolithography. Detailed information on both topics can be found in the following reference: UV Curing, Volumes 1 & 2: Editor S. Peter Pappas, Science and Technology Marketing Corporation, Norwalk, Connecticut (1980).

The Photopolymerization Process

The sequence of events in the photopolymerization process is as follows.

Photoinitiator molecules (PI) absorb UV light from the laser and are converted to an excited state (the singlet state $^1P1^*$). This short-lived, high energy species quickly relaxes to a lower energy excited state (the triplet state $^3P1^*$), as shown in FIG. 56.

[0404]

The excited $^3P1^*$ molecules catalyze formation of one or more (generally one) species called primary radicals ($R\cdot$), with the formation reaction and number dependent on the photoinitiator used.

[0405]

[Equation 1]



[0406]

The primary radical reacts with an acrylic monomer (M) to form a new radical species ($RM\cdot$). This starts a chain propagation process (polymerization) in which the reaction is repeated over and over again to form a polymer chain.

[0407]

[Equation 2]



[0408]

The polymer quickly increases in molecular weight until it is evident as a solid. The reaction will immediately stop if the light energy is removed. The reaction will slow down and eventually stop as the available monomer concentration decreases. The overall dimensions of the solid polymer formed when a UV laser is focused on the surface of a photopolymer are controlled by the intensity of the laser beam and the period of exposure. A longer exposure or increased laser energy will increase the depth and width of the solid region.

[0409]

The physical properties of Desolite SLR 800, both as a liquid and as a solid, are summarized below.

[0410]

In liquid form, it has a viscosity (Brookfield cps at 25°C) of 1350 centipoise, a solids content (reactive material) of over 99%, and low volatility.

[0411]

In solid form, the extractables (in a methyl ethyl ketone solvent) are less than 5%, the tensile modulus is 140 kpsi, the tensile strength is 6.7 kpsi, and the tensile elongation at break is about 7%.

[0412]

Plastic parts prepared using SLR 800 resin tend to be somewhat brittle after UV post curing. Even so, post cured parts can be sanded, sandblasted and drilled using sufficient care.

[0413]

Surfaces of completed parts can be smoothed to a glass-like finish by sanding followed by application and UV curing of a thin layer of diluted resin (a 1:1 mixture of resin and methyl ethyl ketone). Defects in parts (e.g., cracks, chips and holes) can usually be eliminated by using a similar resin/UV curing technique. Finished parts have shown adhesion properties typical of acrylics, thus allowing the use of standard epoxy glues to join parts together. One of the best glues found thus far is the resin itself, with curing by UV.

[0414]

As shown in FIG. 57, a relatively small change in temperature will cause a large change in the viscosity of the liquid resin, with the viscosity decreasing as the temperature increases and vice versa. Higher temperatures, and thus reduced viscosity, will result in a thinner liquid that would settle faster during dipping and drain faster during post processing.

[0415]

This seems like an attractive option, except that higher process temperatures may decrease the structural integrity of the part while it is being built and may cause uncontrolled polymerization of the liquid resin.

[0416]

6. Bullets, Banjotops, and Working Curve Bullets

An ultraviolet laser beam focused on the surface of a photopolymer will solidify or cure a small, bullet-shaped volume of liquid. This characteristic can be explained as follows. The intensity profile of a laser beam, as shown in FIG. 58 where the larger values indicate higher intensity, varies from point to point with a maximum near the center of the beam. The liquid can be thought of as consisting of very thin horizontal sheets, each of which will absorb a fraction (for example, 1/2) of the laser light and transmit the rest to the next lower sheet. If the laser beam strikes the liquid vertically for one second, and during this time X units of light strike the top sheet, then X/2 units will be absorbed by that sheet and the remaining X/2 transmitted to a point in the second sheet, X/4 to a point in the third, and so on. Since the more light absorbed the more polymerization, the top sheet will be the most solid, the second one less so, and so on until a sheet has absorbed so little energy that it is no more solid than the surrounding liquid. If the solid plastic is pulled from the liquid, this last sheet will remain behind, since its bonding force to the solid plastic is no greater than that to the liquid below.

[0417]

The depth of the cured plastic will vary as X is increased or decreased, and will also vary across the width of the laser beam since the beam front is not uniform (as shown by the intensity profile). Thus, the center of the beam will cure to the greatest depth because it is the area of highest intensity, and the surrounding areas will cure to lesser depths. The maximum solid depth achieved (after post-curing) is known as the cure depth. A second factor also plays a role in the development of the bullet shape. Since the refractive index of solid plastic is slightly higher than that of the liquid, the laser light will be refracted inward to varying degrees as the liquid changes to solid. At certain angles, light may be reflected as well from the interface. This characteristic, illustrated in FIG. 59, tends to give the bullet a narrower shape than if beam intensity was the only consideration.

[0418]

Bullets are the building blocks of Stereolithography, for the overlap of successive bullets form lines and the overlap of lines form surfaces. As discussed earlier, the shape of the bullets is determined largely by the beam profile and optical effects. It follows that their overall dimensions should be determined by how much laser energy enters the liquid; this quantity is known as exposure. Exposure is proportional to the product of laser intensity and step period, an operating parameter that specifies the number of 10-microsecond increments between movements of the laser when forming a line. Thus, step period is a measure of the time the laser is focused on a particular location and the brief transit time required to move to the next location. In practice, the laser intensity is not adjusted, and exposure is controlled by choice of step period value.

[0419]

Measurements taken of actual bullets produced by the SLA-1 show that in addition to varying the dimensions of the bullets, large step period values (a range of 5 to 4000 is available) will also affect the shape of the bullets. Sample bullet shapes and relative dimensions at various step period values are shown in FIG. 60.

[0420]

As shown in FIG. 61, bullets overlap to form lines. The distance that the laser moves between forming bullets is a parameter known as step size. If the step size is less than or equal to the maximum diameter of the bullets (i.e., measured across the top of the bullet), the bullets will overlap and a continuous line will be formed. Depending on the step size selected, many points in the liquid along the path of the drawn line will be exposed for more than one step period. These points, as shown in the lower figure, will be more heavily cured than surrounding points.

[0421]

The thickness of a line is the cumulative cure depth of the bullets from which it is formed. When lines in successive layers are intended to adhere or bond to one another, the thickness of the upper line must be greater than the separation (slice thickness) between the layers, so that the layers overlap vertically.

[0422]

Layer-to-layer bonding occurs because while the top layer is being formed, the lower layer is near enough to the surface to absorb light and cure further. Thus, chemical bonds are formed between the lower layer and the freshly-formed top layer.

[0423]

Strong layer-to-layer bonding and therefore sufficient overlap are needed to build strong parts. Equally important, too large an overlap may cause a layer to curl. An overlap of 6 to 8 mils (0.15 to 0.20 mm) typically gives good results with layer thicknesses between 5 and 30 mils (0.13 to 0.7 mm).

[0424]

To obtain an appropriate overlap, you will need to know which step period values will produce which cure depths. You will also need to know the width of lines produced at different step period values, especially when building a thin vertical wall or when trying to determine the angle at which a sloping (near-flat) surface will need skin fill in order to avoid gaps. Working curves provide this information.

[0425]

Working Curves Defined

A working curve is a graph that shows line height (cure depth) and line width as functions of the step period value. As shown in FIG. 62, these relationships are not linear, but logarithmic. That is, if the step period is multiplied by a value X, the resulting line height or width is not X times as large, but considerably less. The working curve demonstrates that when the logarithm of the step period is plotted versus line height or width, the points will fall more or less on a straight line. Therefore, a line can be fit to the points to obtain a linear equation which approximately relates line height or width to the step period value.

[0426]

Several variables affect the slope and intersect points of working curves. Different resins have different sensitivities to the ultraviolet light of the laser. Laser power also varies from one SLA to another, and even from day-to-day in the same SLA. Finally, the degree to which the laser is focused on the liquid surface (i.e., whether the optics are properly aligned and if they are clean) can affect working curves.

[0427]

Obtaining Data for Working Curves

Line height and width data at various step period values, for the specific resin and laser in use, are obtained by creating and measuring a small, single-layer part known as a banjotop. Banjotops are created on the surface of the liquid and do not attach to the elevator platform. As shown in FIG. 63, a banjotop has five strings (lines) formed using different step periods and a fixed step size of 2.

[0428]

After the banjotop is drained and post-cured, the string heights and widths are measured. Two banjotops are generally made, with one common step period, in order to evaluate a wide range of step periods. The SLA-1 allows step periods from 5 to 4000. One banjotop is typically made with step periods of 2560, 1280, 640, 320 and 160, and the second with step periods of 160, 80, 40, 20 and 10.

[0429]

Measuring Banjotop Strings

Draw banjotops using Utility Menu option MAKE TEST PART. Measuring banjotop string height and width as follows.

[0430]

Step 1) Place the banjotop with top surface facing upward on the stage of a measuring microscope or other non-contact measuring device.

Step 2) Orient the first string to be measured perpendicular to the axis of stage movement and with the center of the string near the center of the visual field.

Step 3) Move the stage to center the cross hairs along one edge of the string. Note that the stage should always be moved to the position where measurements are taken from one direction only in order to minimize the effect of backlash in the positioning screw.

Step 4) Zero the counter that measures stage movement or record the stage position.

Step 5) Move the stage until the cross-hairs are centered on the opposite edge of the string and record the value. If the Stage is moved too far, reverse it past the correct position and try again.

Step 6) Repeat steps 2 through 5 to measure the width of the remaining strings. Compile all line width data in a table relative to step period value.

Step 7) Clamp the first banjotop short edge up and repeat steps 2 through 5 to measure the line height. Cut away each string after it is measured to reveal the next string.

Step 8) Repeat step 7 for each remaining string. Compile all line height data in a table relative to step period value.

Data measured from banjotops are entered using the Utility Menu MATERIAL MANAGER. It will then fit a line to the data points using the method of least squares and calculate the slope and Y-intercept of each line. Equations can be written in terms of line height or width relative to step period using the slope and Y-intercept from the working curve. These equations are as follows.

(1) Height = slope logSP + Y intercept or

$$SP = 10^{((\text{height} - Y \text{ intercept})/\text{slope})}$$

(2) Width = slope log SP + Y intercept or

$$SP = 10^{((\text{width} - Y \text{ intercept})/\text{slope})}$$

As an example of how such equations are used by MATERIAL MANAGER, let us find the correct step period for a layer thickness of 20 mils (0.51 mm). Keep in mind that a cure depth of 26 mils (0.66 mm) is required to ensure adequate adhesion between layers. We'll use a slope for the height curve of 13.76 and a Y-intercept of -6.50. Using the second form of equation (1), the proper step period is as follows.

$$\begin{aligned} SP &= 10^{[(26.00-6.5)/13.76]} \\ &= 10^{2.36} \\ &= 230 \end{aligned}$$

We can calculate the line width at a step period of 230 using the first form of equation (2). Assuming a slope for the width curve of 6.52 and Y-intercept 2.91, the line width is as follows.

$$\begin{aligned} \text{Width} &= 6.52 \log 230 + 2.91 \\ &= 6.52(2.36) + 2.91 \\ &= 18.3 \text{ mils (0.46 mm)} \end{aligned}$$

Line widths are of particular interest when designing near-flat surfaces, where you need to know the surface angle at which skin will be needed to fill gaps between the layer borders.

[0431]

Another situation in which line widths are of particular interest is when step periods are calculated for skin vectors. Skin vectors are spaced 1 to 4 mils (0.0254 to 0.10 mm) apart and overlap a great deal. (For example, if a skin fill spacing of 2 mils (0.051 mm) is used, within the width of an 8 mil (0.20 mm) wide line there would be four overlapping exposures.) Thus, if the desired skin thickness is to be obtained, the step period value that would be used for a single line of this thickness must be reduced by the ratio of the line width to fill vector spacing. In our example, this would be $8/2 = 4$ for a 2 mil (0.051 mm) spacing.

[0432]

Normally, a working curve is made only once to characterize the laser and optics with the resin type. However, variations in laser power require that the current power be measured before a part is made. Prepare Menu option RANGE MANAGER is used to update the step period values in the .R Range file when the laser power has changed.

[0433]

The following is a brief explanation of the terms used in this document.

[0434]

60/120 HATCH VECTOR Crosshatch vectors drawn 60 and 120 degrees from the X axis.

[0435]

BANJOTOP A floating, single-layer part with five strings (lines), each drawn at a different step period value. Banjotops provide cure depth and line width data for working curves.

[0436]

BEAM ANALYSIS A Utilities Menu option which focuses the laser beam on beam profilers mounted in the process chamber to measure laser power and intensity.

[0437]

BEAM EXPANDER The lens assembly mounted on the optics plate which expands the laser beam, enabling it to be focused so that the beam converges to a small, high energy spot on the surface of the resin.

[0438]

BEAM PROFILE A pattern of numbers or dots representing the spatial distribution of laser beam energy. Beam profiles are used to determine whether the laser should be adjusted or replaced, or whether the optics should be cleaned.

[0439]

BEAM PROFILER A device (radio-meter) which measures laser power and intensity. Two beam profilers are mounted on either side of the vat in the process chamber.

[0440]

BEAM-TURNING MIRRORS Specially-coated mirrors mounted on the optics plate which reflect 325 nm ultraviolet light and transmit all other wave-lengths. Beam-turning mirrors reflect the laser beam from the laser outlet to the inlet aperture of the beam expander, and then from the beam expander outlet aperture to the dynamic mirrors.

[0441]

BUILD A Main Menu option which supervises the building of stereolithographic parts and controls the dynamic mirrors and elevator.

[0442]

BULLET The characteristic shape of the solid plastic created by a stationary laser beam on the surface of photo-curable resin.

CAD Computer-aided design.

[0443]

CAD RESOLUTION The internal approximation of surfaces within a CAD system.

[0444]

CIRCULAR WEB SUPPORT A hollow tube structure which can support large, heavy parts.

[0445]

CONTROL COMPUTER The computer mounted in the SLA-1 cabinet which controls the building of stereolithographic parts.

[0446]

CROSS WEB SUPPORT Two straight web supports which intersect at right angles.

[0447]

CROSSHATCH A vector created during slicing which is drawn between layer borders to strengthen part surfaces. The Crosshatch type and spacing are user specified.

[0448]

CURE DEPTH The thickness or depth of a cured line of resin. The cure depth of any line is determined by the step period and step size values used to draw the line.

[0449]

CURL A characteristic type of deformation (curling of layers).

[0450]

DIP DELAY A part-building parameter which defines the time between the start of a dip and the first laser movement to draw the next layer. The dip delay allows the resin surface to level.

[0451]

DRAWING SPEED The speed at which the laser traces over the surface of the resin to form solid plastic lines and surfaces. The laser drawing speed varies depending on the layer thickness specified and laser power.

[0452]

DYNAMIC MIRRORS Galvanometer-controlled scanning mirrors which direct the laser beam to any point on the surface of the resin.

[0453]

EDIT A FILE A Utility Menu option used to modify text files.

[0454]

ELEVATOR The hardware component that raises and lowers the platform and part in the vertical (Z) axis.

[0455]

ELEVATOR MOVER A Utilities Menu option used to position the elevator platform using the up and down arrow keys on the Control Computer numeric keypad.

[0456]

ELEVATOR PLATFORM The perforated aluminum base which attaches to the elevator and supports parts being built by the SLA-1.

[0457]

ENTRAPPED VOLUME A volume in the part from which the liquid resin cannot drain during dipping.

[0458]

ETHERNET A high-speed, inter-computer communications system jointly developed by Digital, Intel and Xerox. Ethernet is used to transfer files between the Slice and Control Computers.

[0459]

EXPOSURE The product of laser intensity and step period.

[0460]

FILL Overlapping parallel vectors which comprise the horizontal surfaces (skins) of stereolithographic parts.

[0461]

FLAT TRIANGLE A horizontal stereolithography (.STL) file triangle.

[0462]

FTP FILE TRANSFER PROGRAM A Network Menu option which moves files between the Slice and Control Computers.

[0463]

GREEN PART A stereolithography part prior to UV post curing.

[0464]

HATCH SPACING A SLICE parameter which specifies the perpendicular spacing, in CAD units, between cross-hatches.

[0465]

LASER The device which generates the light energy required to polymerize photocurable resin. The SLA-1 Helium-Cadmium laser has a nominal power of 15 MW at a wavelength of 325 nanometers.

[0466]

LAYER (.L) FILE A MERGE output file which defines the types of vector blocks in each layer of the part.

[0467]

LAYER BORDER (LB) VECTOR A vector which defines the perimeter of a layer. Crosshatch and fill vectors are drawn between layer borders where needed.

[0468]

LAYER MANAGER A Prepare Menu option used to find vector blocks in a particular range or in the entire Layer (.L) file.

[0469]

LAYER THICKNESS The depth of a cured layer of plastic and the SLICE parameter used to specify fixed or variable layer thickness. Layer thickness may be varied for one layer or a group of layers, or set at one value for the entire part.

[0470]

LEVELING The process whereby the surface of the resin settles and levels after a part is dipped. The time allowed for leveling is defined by the ZW (dip delay) part building parameter.

[0471]

LINE A line of cured plastic generated by overlapping bullets.

[0472]

LINE HEIGHT The depth of a laser-cured resin line. Line height is a variable dependent on exposure and is controlled by selection of step period.

[0473]

LINE WIDTH The horizontal width of a laser-cured resin line. Line width is a variable dependent on exposure.

[0474]

MATERIAL (.MAT) FILE A file containing cure depth and line width data measured from banjotops.

[0475]

MAKE TEST PARTS A Utilities Menu option used to create banjotops.

[0476]

MATERIAL MANAGER A Utilities Menu option used to input new material data from banjotops.

[0477]

MERGE A Main Menu option which combines all object and support Slice (.SLI) files to create Layer (.L), Range (.R) and Vector (.V) files.

[0478]

MIA (MINIMUM HATCH INTERSECT ANGLE) A SLICE parameter which defines the minimum angle allowed between a crosshatch and a layer border vector.

[0479]

MONOMER A low molecular weight chemical species which is a building block of polymers.

[0480]

MSA (MINIMUM SURFACE ANGLE) A SLICE parameter which defines the angle from the horizontal below which a triangle is classified as near-flat rather than steep. Near-flat triangles may have skin fill but steep triangles cannot.

[0481]

MSDS Material safety data sheet.

MSDOS (Microsoft Disk Operating System) The operating system used in the Control Computer.

[0482]

MULTIPLE PART POSITIONING COORDINATES Build parameters used to position the part on the platform and/or to make multiple parts in the same BUILD run.

[0483]

NEAR-FLAT TRIANGLE A stereolithography (.STL) file triangle at an angle greater than zero and less than or equal to the MSA.

[0484]

OPTICAL WINDOW The quartz window just below the dynamic mirrors which allows laser light to enter the process chamber while isolating the optics plate from the chamber environment.

[0485]

OPTICS PLATE The aluminum plate above the process chamber which supports the laser and optical components in precise alignment.

[0486]

PARAMETERS MANAGER A Prepare Menu option used to edit the .R file to add part building parameters.

[0487]

PCA Post curing apparatus.

[0488]

PHOTOINITIATOR A chemical in photopolymers which transforms the laser energy into chemical energy and initiates the photopolymerization (solidification) process.

[0489]

PHOTOPOLYMER A chemical substance composed of photoinitiators, monomers and oligomers which polymerizes when exposed to light energy.

[0490]

PHOTOPOLYMERIZATION The process whereby light energy converts a monomer or oligomer substance into a polymer.

[0491]

POST CURING APPARATUS An ultraviolet device used to cure green stereolithographic parts.

[0492]

POST PROCESS The process to cure and finish stereolithographic parts.

[0493]

POWER SEQUENCER A Utilities Menu option which is used to turn SLA-1 hardware on and off directly from the Control Computer keyboard.

[0494]

PREPARE A Main Menu option used to specify part building parameters and to edit the Range (.R) file.

[0495]

PROCESS CHAMBER The chamber in which the resin vat, elevator, and beam profilers are mounted.

[0496]

RANGE A set of one or more horizontal slice layers defined by upper and lower dimensions either in CAD units or slice units. A new range must be created any time a part building parameter value changes.

[0497]

RANGE (.R) FILE A MERGE output file which is used to specify part building parameters by range.

[0498]

RANGE MANAGER A Prepare Menu option which is used to add or delete ranges, calculate step periods, edit ranges to modify dip delays, and update the Range (.R) file.

[0499]

REMOTE USER A Network Menu option used to remotely operate the Slice Computer from the Control Computer keyboard.

[0500]

RESIN Another name for the photopolymer chemical used in stereolithography.

[0501]

RESIN VAT The container of resin in which the object is formed.

[0502]

SENSITIZATION An allergic response to the photo-curable resins generally resulting from repeated skin contact.

[0503]

SHUTTERS Solenoid-actuated vanes which block the laser beam when an interlock switch is activated.

[0504]

SKIN (SKIN FILL) Thin, overlapping lines drawn to fill in or create horizontal surfaces.

[0505]

SLA Stereolithography apparatus.

[0506]

SLICE A program run on the Slice Computer which cross-sections the stereolithography (.STL) file and generates vector data.

[0507]

SLICE FILE (.SLI) The SLICE output file which contains vector data used to build the part.

[0508]

SLICE COMPUTER The computer used to run SLICE. The Slice Computer operates under UNIX and is linked to the Control Computer via Ethernet.

[0509]

SLICE RESOLUTION A SLICE parameter which specifies the number of slice units assigned to each CAD unit of measure.

[0510]

STEEP TRIANGLE A vertical or near-vertical stereolithography (.STL) file triangle.

[0511]

STEP PERIOD A part building parameter which defines the length of the delay following each laser step.

[0512]

STEP SIZE A part building parameter which defines the size of the step, in mirror bits, that the laser makes between forming bullets of cured plastic.

[0513]

STEREOLITHOGRAPHY A three-dimensional printing or drawing process that forms plastic objects by solidifying successive layers of photocurable resin.

[0514]

STEREOLITHOGRAPHY (.STL) FILE A tessellated CAD file input to SLICE.

[0515]

VIEW A Main Menu option used to display stereolithography (.STL) and Slice (.SLI) files on the Control Computer screen.

[0516]

VIEW PORT COORDINATES Minimum and maximum coordinates which define, in mirror bits, the dimensions of the viewport in the BUILD status screen.

[0517]

WEB A style of support recommended for use in stereolithography because of its ease of creation and removal.

[0518]

WORKING CURVE A plot of line height and line width versus step period at a particular laser power which characterizes the SLA-1 laser and optics with a particular resin to define part building parameters. The data used to make working curves are taken from banjotops.

[0519]

XY-ONLY SCALE FACTOR A part-building parameter which converts vector data from slice units to mirror bits. The X-Y only scale factor can be used to cross-section the part smaller or larger in the X and Y dimensions. It does not affect the vertical (Z) dimension.

[0520]

STRAIGHT WEB SUPPORT A thin rectangle or fin structure defined by a minimum of six surfaces.

[0521]

SUPPORTS Structures designed on the CAD system to support the object above the elevator platform, provide a rigid foundation on which the part may be built, and attach and support layer sections. Supports may be processed in a separate file until combined with the object files by MERGE.

[0522]

TEM Transverse electromagnetic mode.

[0523]

TESSELLATE The representation of CAD surfaces by triangles or other polygons.

[0524]

TRIANGULAR WEB SUPPORT A triangular shaped support structure.

[0525]

UNIX A multi-tasking, multi-user operating system used in Slice Computer.

[0526]

VECTOR A directed line segment represented by starting and ending coordinates.

[0527]

VECTOR (.V) FILE A MERGE output file which contains layer-by-layer vector data for all merged files.

VECTOR BLOCK A set of like vectors (that is, layer borders, crosshatches, or fill)

[Brief Description of the Drawings]

[FIG. 1]

FIG. 1 is an overall block diagram of a stereolithography system for embodying the present invention.

[FIG. 2]

FIG. 2 is a flowchart showing a basic concept used when performing the stereolithography of the present invention.

[FIG. 3]

FIG. 3 is a flowchart showing another basic concept used when performing the stereolithography of the present invention.

[FIG. 4]

FIG. 4 is a combination of a schematic elevational cross section and a block diagram of a system suitable for embodying the invention

[FIG. 5]

FIG. 5 is an elevational sectional view of another embodiment of a system for embodying the present invention.

[FIG. 6]

FIG. 6 is a software architectural flowchart showing in more detail the overall data flow, data manipulation and data management of the stereolithography system.

[FIG. 7]

FIG. 7a and FIG. 7b shows how the anchor layer borders are held in place until crosshatch vectors are drawn.

[FIG. 8]

FIG. 8a and FIG. 8b show how the support prevents deformation and curling of cantilevers and similar structures.

[FIG. 9]

FIG. 9a and FIG. 9b show how temporary unsupported layer sections are secured while a part is being produced.

[FIG. 10]

FIG. 10a and FIG. 10b show how a vertical web support prevents layer distortion.

[FIG. 11]

FIG. 11 shows the use of a diagonal support.

[FIG. 12]

FIG. 12 is a diagram showing important steps in the three-dimensional production method.

[FIG. 13]

Fig. 13a to FIG. 13c show the main components of the stereolithography system.

[FIG. 14]

FIG. 14 is a block diagram of a stereolithography system.

[FIG. 15]

FIG. 15 is a software diagram for a stereolithography system.

[FIG. 16]

FIG. 16a and FIG. 16b shows switches and indicators on the control panel.

[FIG. 17]

FIG. 17 is a diagram showing a sample component record.

[FIG. 18]

FIG. 18 shows a sample working curve.

[FIG. 19]

Fig. 19a to FIG. 19e show a recommended cleaning technique for the optical apparatus.

[FIG. 20]

FIG. 20 is a diagram showing replacement of an air filter.

[FIG. 21]

FIG. 21a and FIG. 21b show the components of a SLICE computer.

[FIG. 22]

FIG. 22a and FIG. 22b show components of an electronic device cabinet.

[FIG. 23]

FIG. 23a and FIG. 23c show components of an optical apparatus.

[FIG. 24]

FIG. 24 is a diagram showing components of a chamber.

[FIG. 25]

FIG. 25a and FIG. 25b show the alignment of laser resonators.

[FIG. 26]

FIG. 26a and FIG. 26b shows the arrangement of an optical apparatus.

[FIG. 27]

FIG. 27 shows an arrangement of a chamber.

[FIG. 28]

FIG. 28 shows an SLA-1 stereolithography system.

[FIG. 29]

FIG. 29a and FIG. 29b show the arrangement of an electronic cabinet assembly.

[FIG. 30]

FIG. 30 is a view showing an arrangement of an optics assembly.

[FIG. 31]

FIG. 31a and FIG. 31b show the arrangement of a chamber assembly.

[FIG. 32]

FIG. 32 shows an SLA-1 wiring diagram.

[FIG. 33]

FIG. 33 is a view showing a stereolithographic process.

[FIG. 34]

FIG. 34a and FIG. 34b shows an SLA-1 laser post curing apparatus.

[FIG. 35]

FIG. 35 shows the main components of SLA-1.

[FIG. 36]

FIG. 36 shows an SLA-1 laser optical apparatus.

[FIG. 37]

FIG. 37 is a diagram showing a post curing apparatus.

[FIG. 38]

FIG. 38a and FIG. 38b shows the location of the laser warning and safety information label

[FIG. 39]

FIG. 39 shows a test part.

[FIG. 40]

FIG. 40 shows how a curved surface requires a large number of triangles for approximation of the surface.

[FIG. 41]

FIG. 41 shows how any (CAD) object can be completely drawn by flat triangles, near-flat triangles, and steep triangles.

[FIG. 42]

FIG. 42 shows how SLICE cross-sectional three-dimensional "stereolithography" (.STL) generates files using Slice (.STL) files.

[FIG. 43]

FIG. 43 shows how the form of a triangle determines whether the area between layer boundaries is cross-hatched or skin filled.

[FIG. 44]

FIG. 44 shows how the angle at which a triangle classification changes from near-flat to steep is defined by the SLICE parameter MSA.

[FIG. 45]

FIG. 45 shows the SLA-1 menu system.

[FIG. 46]

FIG. 46 shows how NETWORK transfers files between a control computer and a slice computer via Ethernet.

[FIG. 47]

FIG. 47 shows how TERMINAL UTILITY enables a user to remotely control SLICE from a control computer.

[FIG. 48]

FIG. 48 shows how MERGE combines all of the components (support and object files) to create a layer file (.L), vector file (.V) and range file (.R)

[FIG. 49]

FIG. 49 shows how VIEW displays STL files and .SLI files on the control computer screen.

[FIG. 50]

FIG. 50 shows an .STL file.

[FIG. 51]

FIG. 51 shows an .SLI file.

[FIG. 52]

FIG. 52 is a BUILD status screen.

[FIG. 53]

FIG. 53 shows a BUILD state screen in another aspect of the invention.

[FIG. 54]

FIG. 54a to FIG. 54c show the PCA at each stage of the operation.

[FIG. 55]

FIG. 55 shows a helium-cadmium laser for SLA-1.

[FIG. 56]

FIG. 56 shows excitation and relaxation of photopolymerization initiator molecules.

[FIG. 57]

FIG. 57 shows how a small change in temperature results in a large change in viscosity.

[FIG. 58]

FIG. 58 shows an intensity distribution indicating the maximum value near the center of the beam.

[FIG. 59]

FIG. 59 shows how a change in refractive index promotes a bullet shape.

[FIG. 60]

FIG. 60 shows how step duration values determine the overall size of a bullet.

[FIG. 61]

FIG. 61 shows how a point is cured more when the step size is less than the maximum bullet diameter.

[FIG. 62]

FIG. 62 shows a working curve.

[FIG. 63]

FIG. 63 shows a banjotop.

[FIG. 64]

FIG. 64 shows an overview of the procedure necessary for producing a part by SLA.

[FIG. 65]

FIG. 65a and FIG. 65b show a faceted representation of a part according to the PHIGS graphics processing standard.

[FIG. 66]

FIG. 66 show a binary floating point format compatible with the Intel 80287 math coprocessor.

[FIG. 67]

FIG. 67 shows a box represented by a TEST0017.STL file.

[FIG. 68]

FIG. 68a and FIG. 68b shows the specifications for a test part.

[FIG. 69]

FIG. 69a and FIG. 69b show a spatial arrangement of the test part.

[FIG. 1]

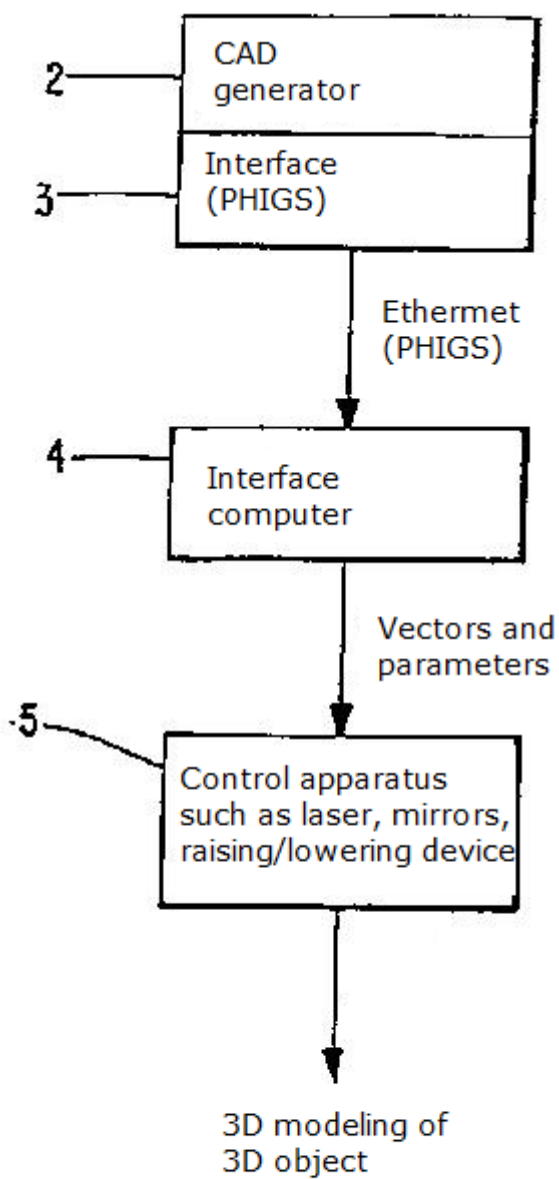
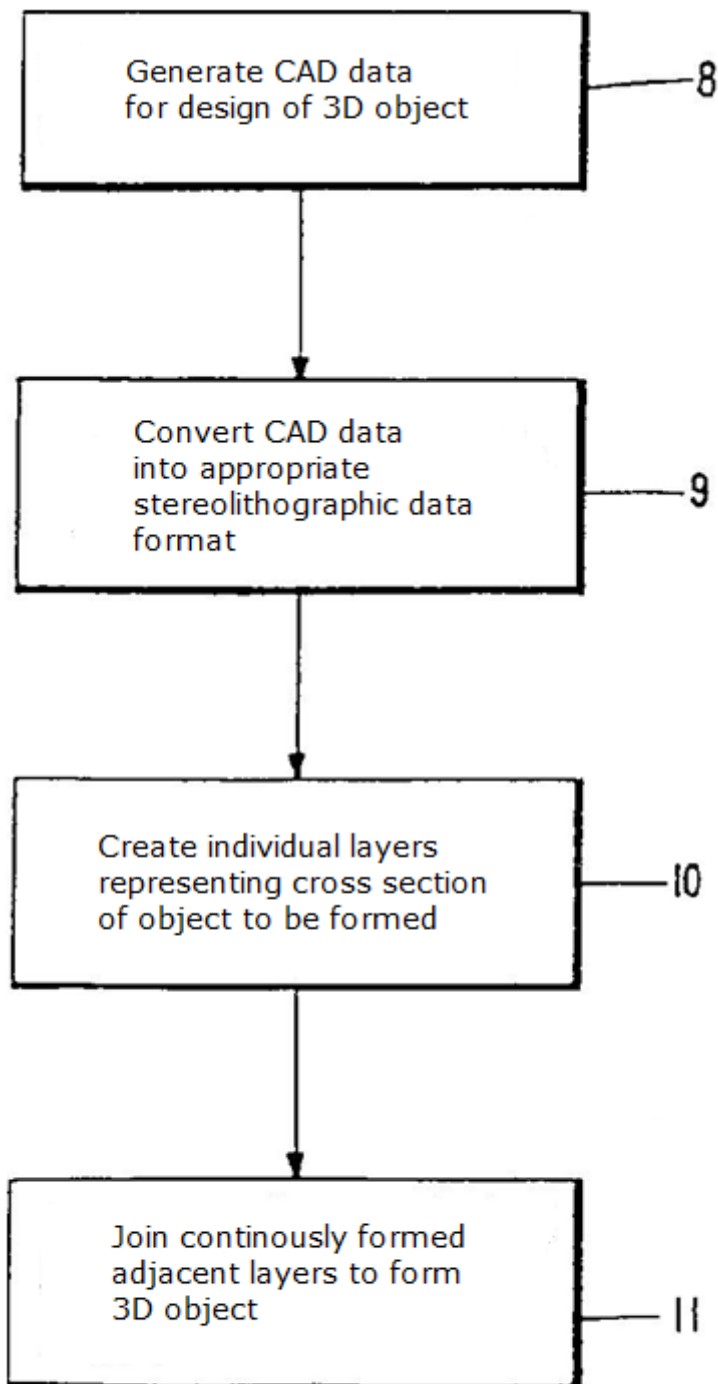
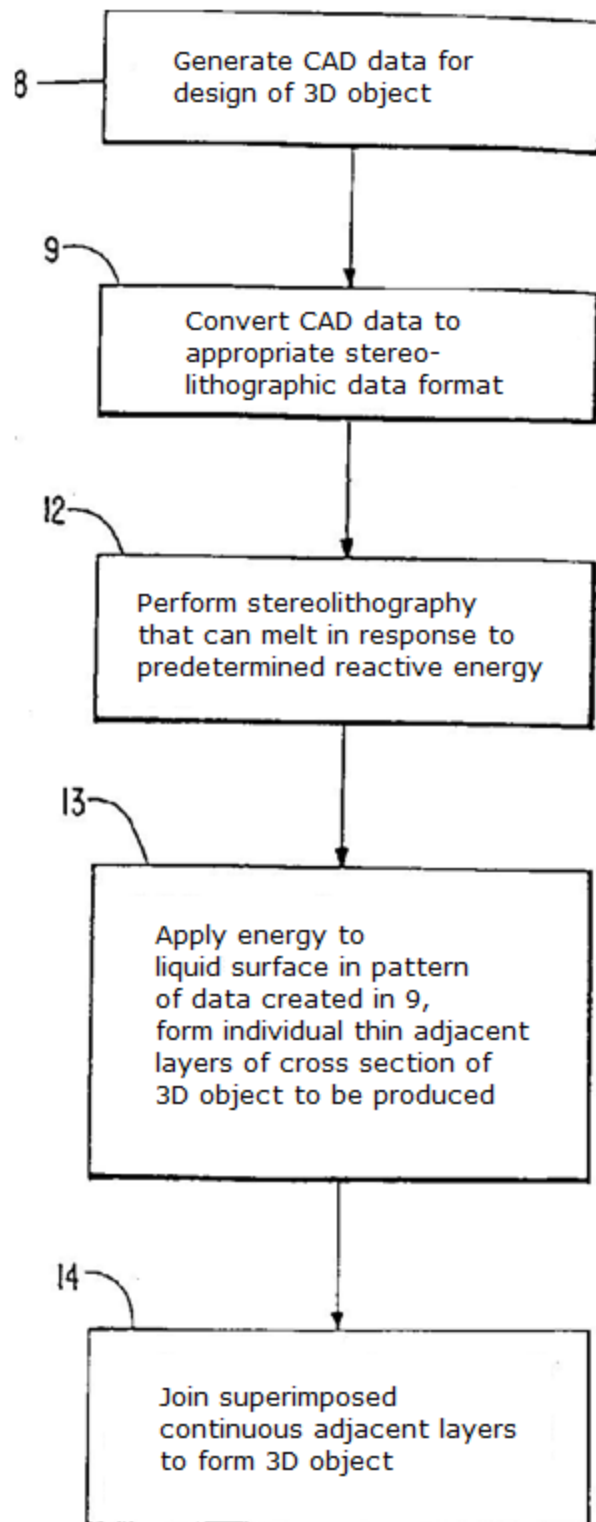


FIG. 1.

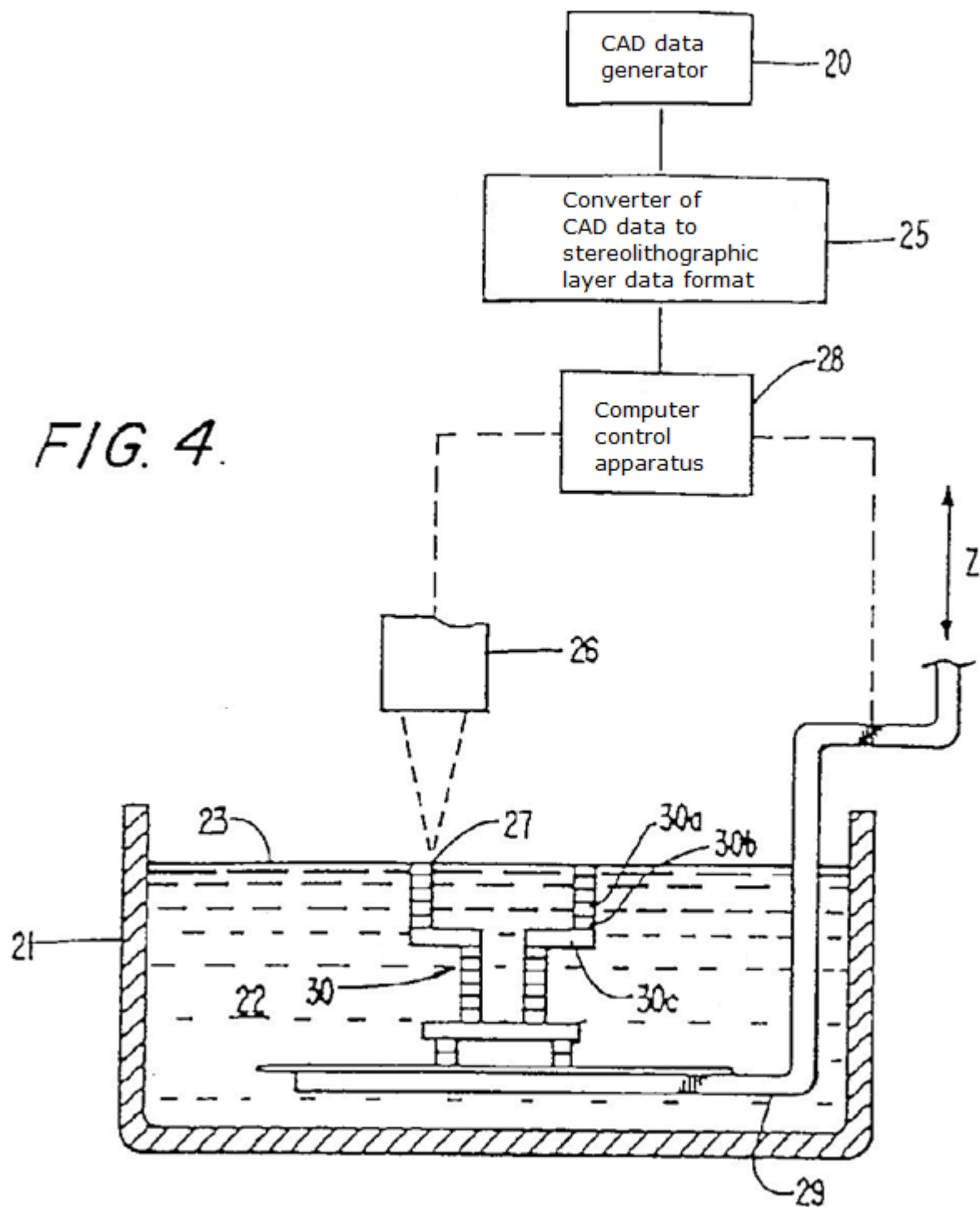
[FIG. 2]

*FIG.2*

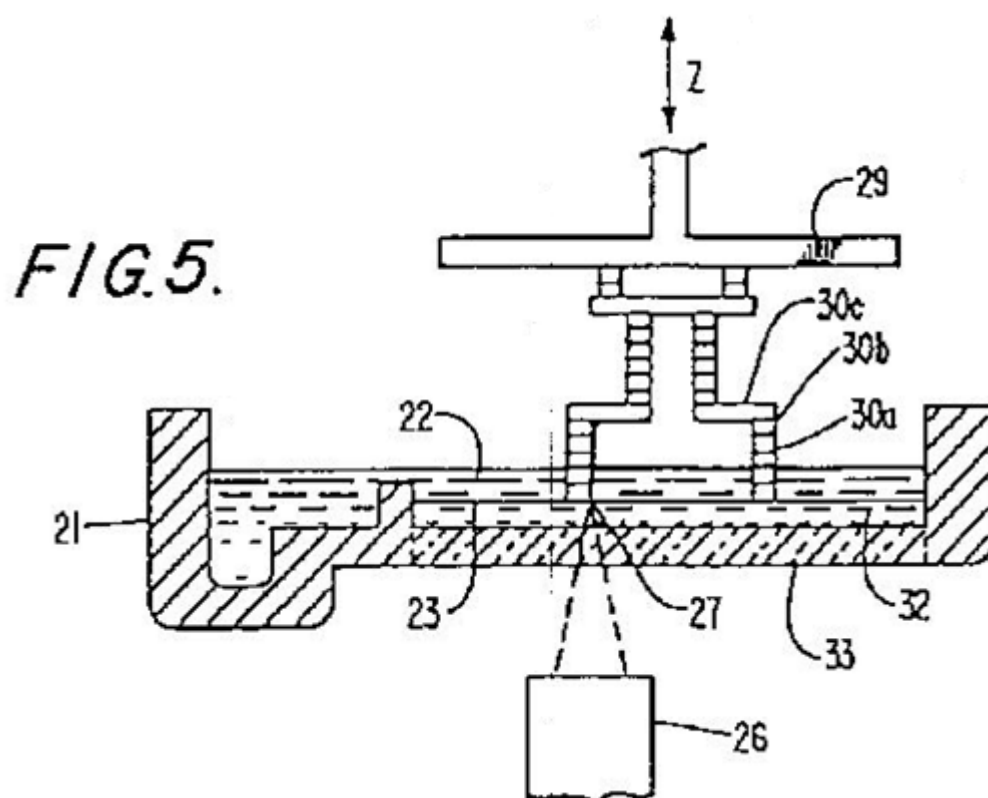
[FIG. 3]

*FIG. 3.*

[FIG. 4]



[FIG. 5]



[FIG. 6]

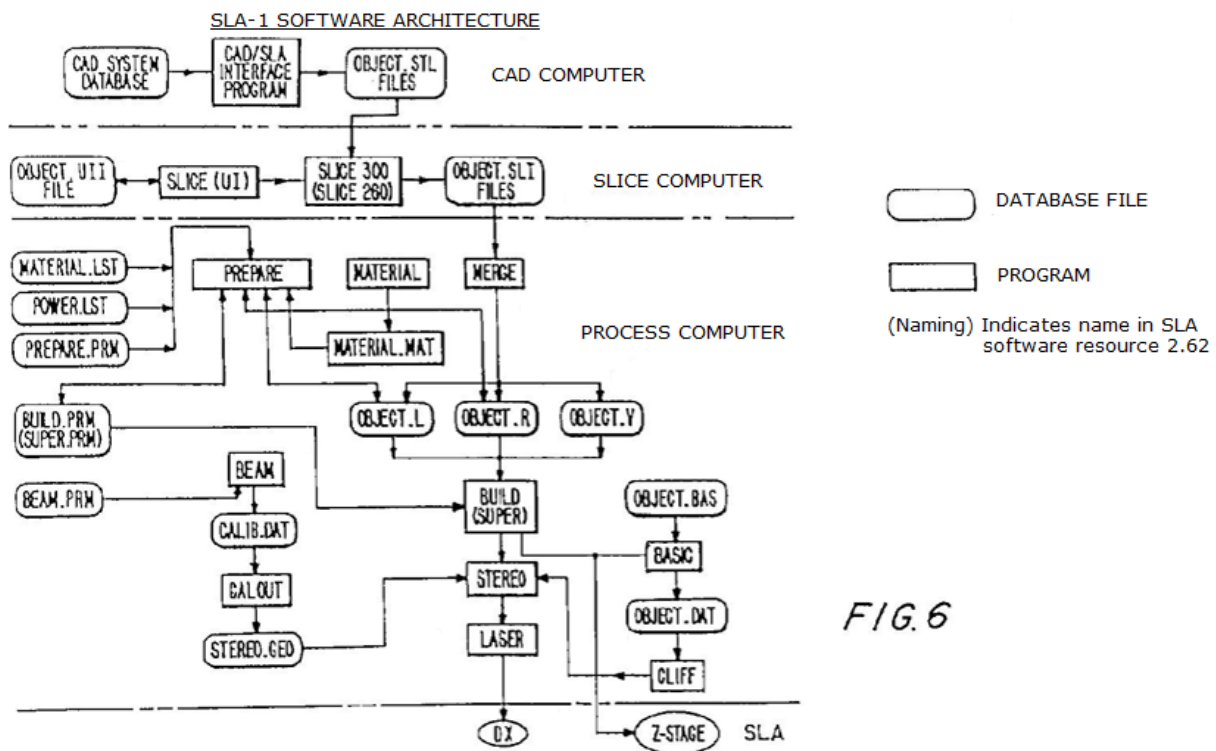


FIG. 6

[FIG. 7a, 7b]

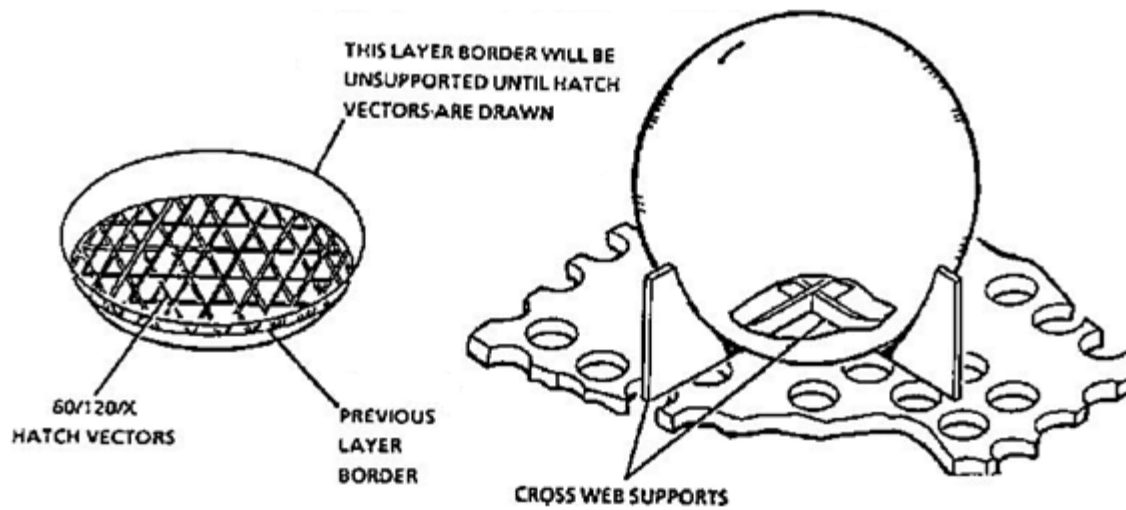


FIG. 7a

SUPPORTS ANCHOR LAYER BORDERS IN PLACE
UNTIL CROSSHATCH VECTORS ARE DRAWN

FIG. 7b

[FIG. 8a, 8b]

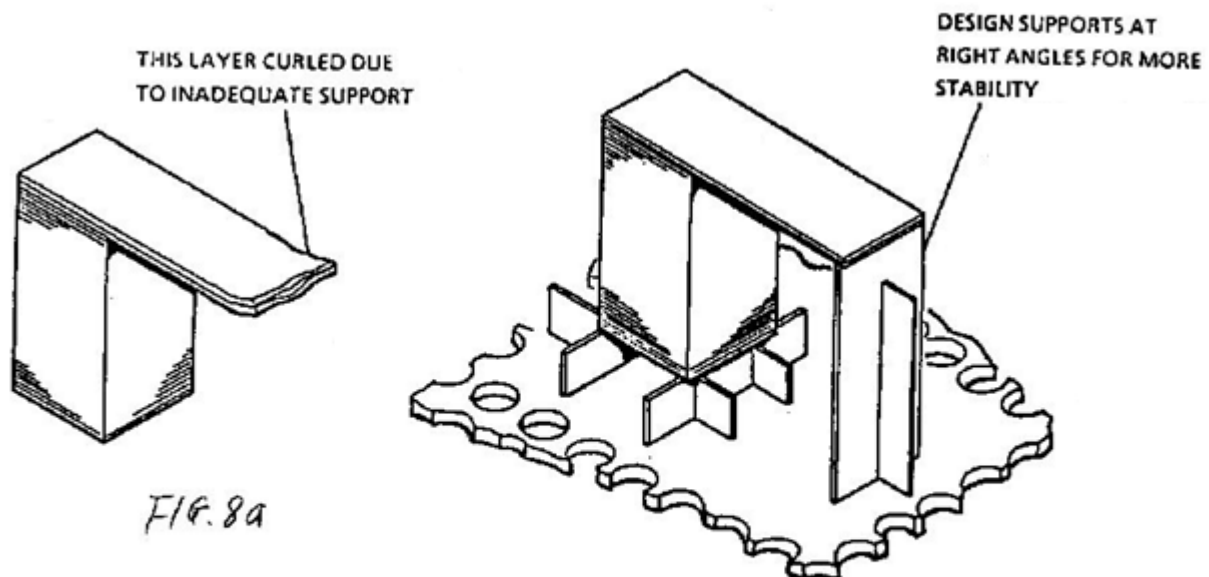


FIG. 8a

SUPPORTS PREVENT DEFORMATION AND CURL OF
CANTILEVERED BEAMS AND SIMILAR STRUCTURES

FIG. 8b

[FIG. 9a, 9b]

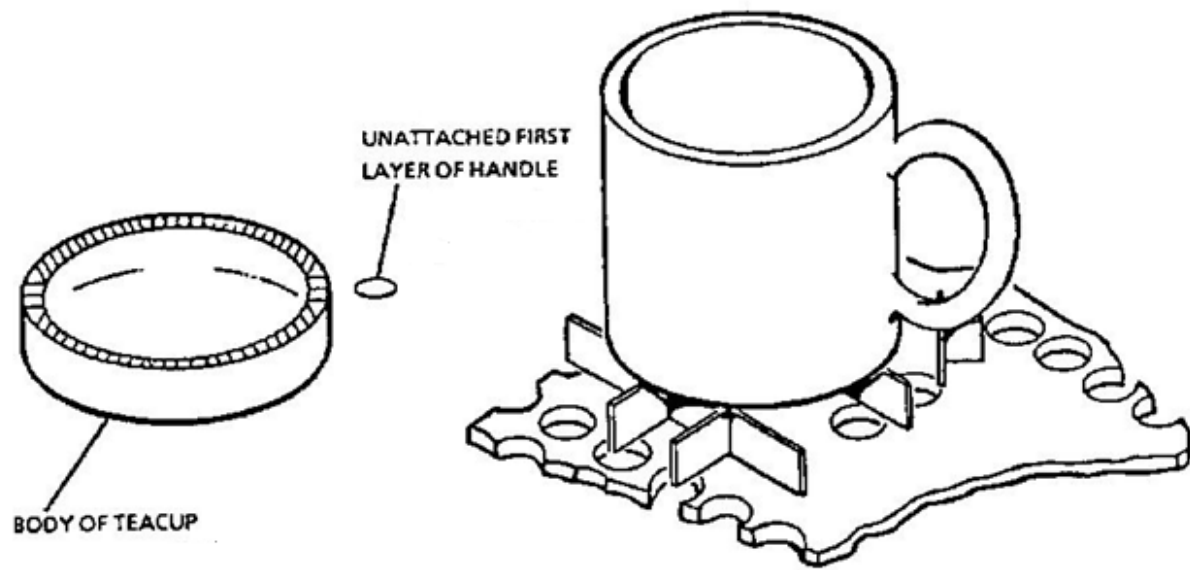


FIG. 9a

SUPPORTS ANCHOR UNATTACHED LAYER SECTIONS

FIG. 9b

[FIG. 10a, 10b]

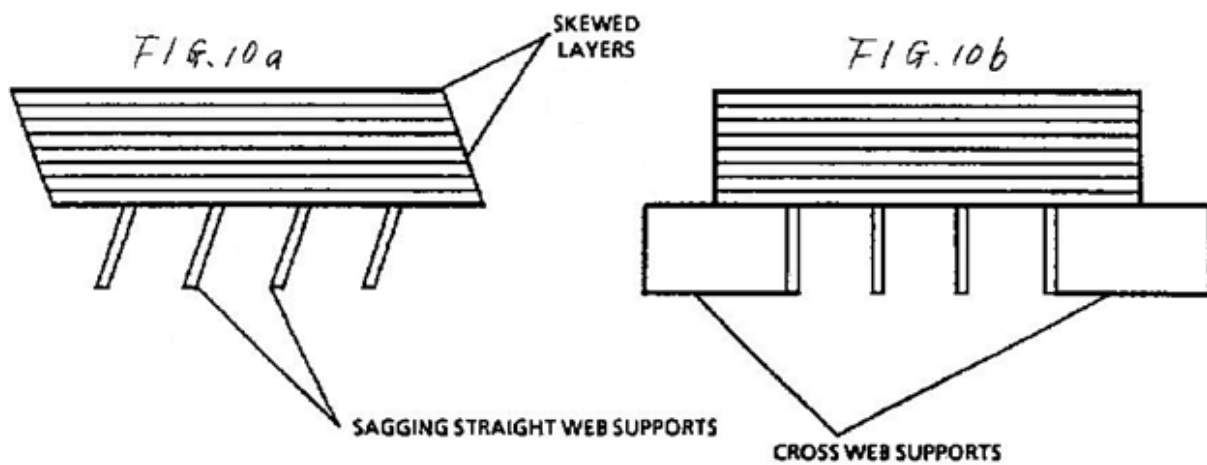


FIG. 10a

SKEWED
LAYERS

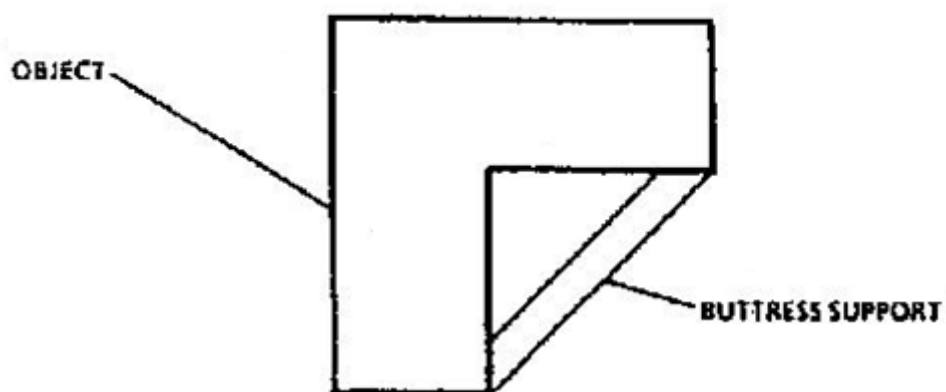
FIG. 10b

SAGGING STRAIGHT WEB SUPPORTS

CROSS WEB SUPPORTS

CROSS WEB SUPPORTS PREVENT LAYER SKEWING

[FIG. 11]



DIAGONAL SUPPORTS SHOULD NOT EXTEND INTO INTERIOR CORNERS
FROM WHICH THEY WILL BE DIFFICULT TO REMOVE

FIG. 11

[FIG. 12]

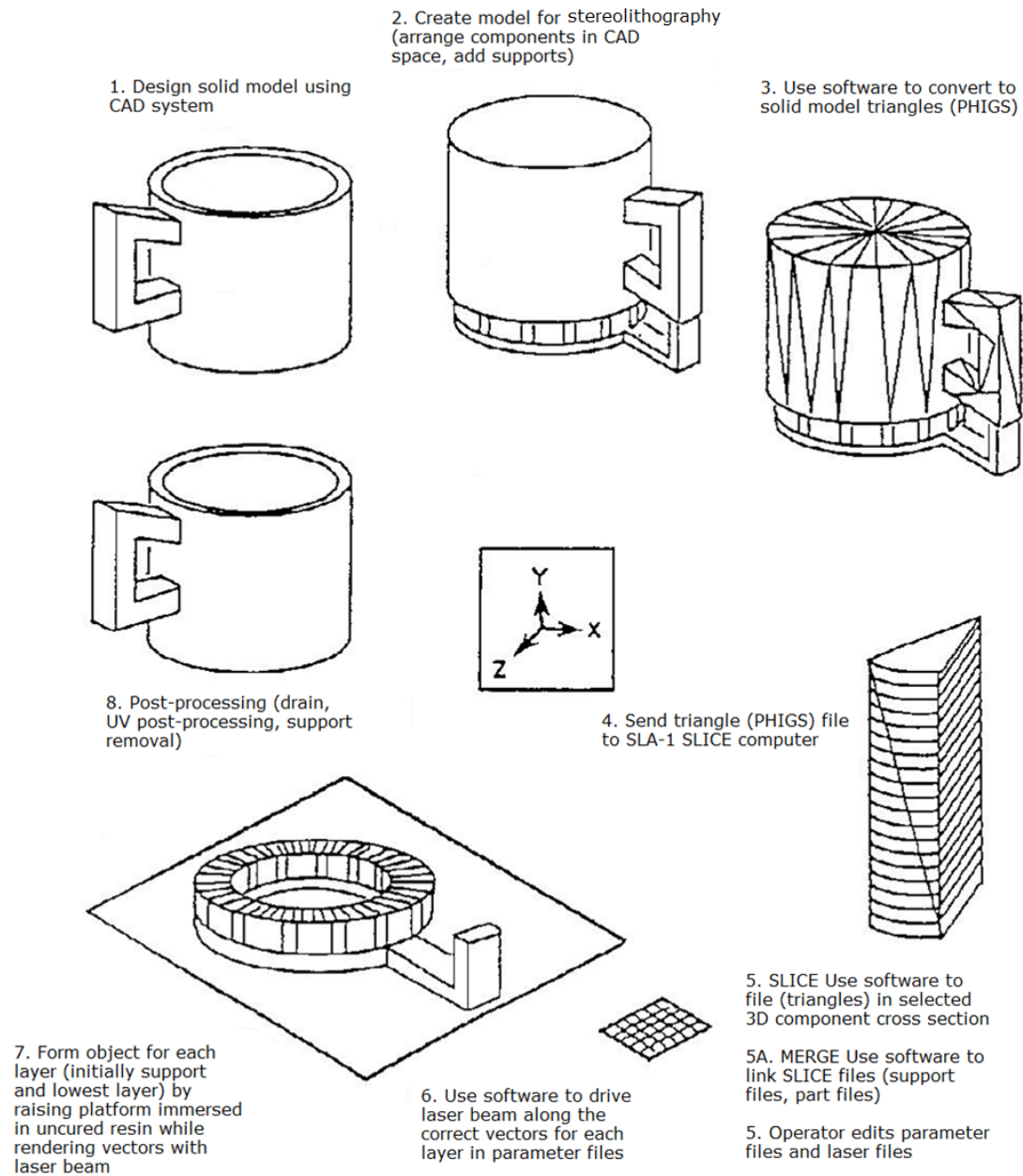
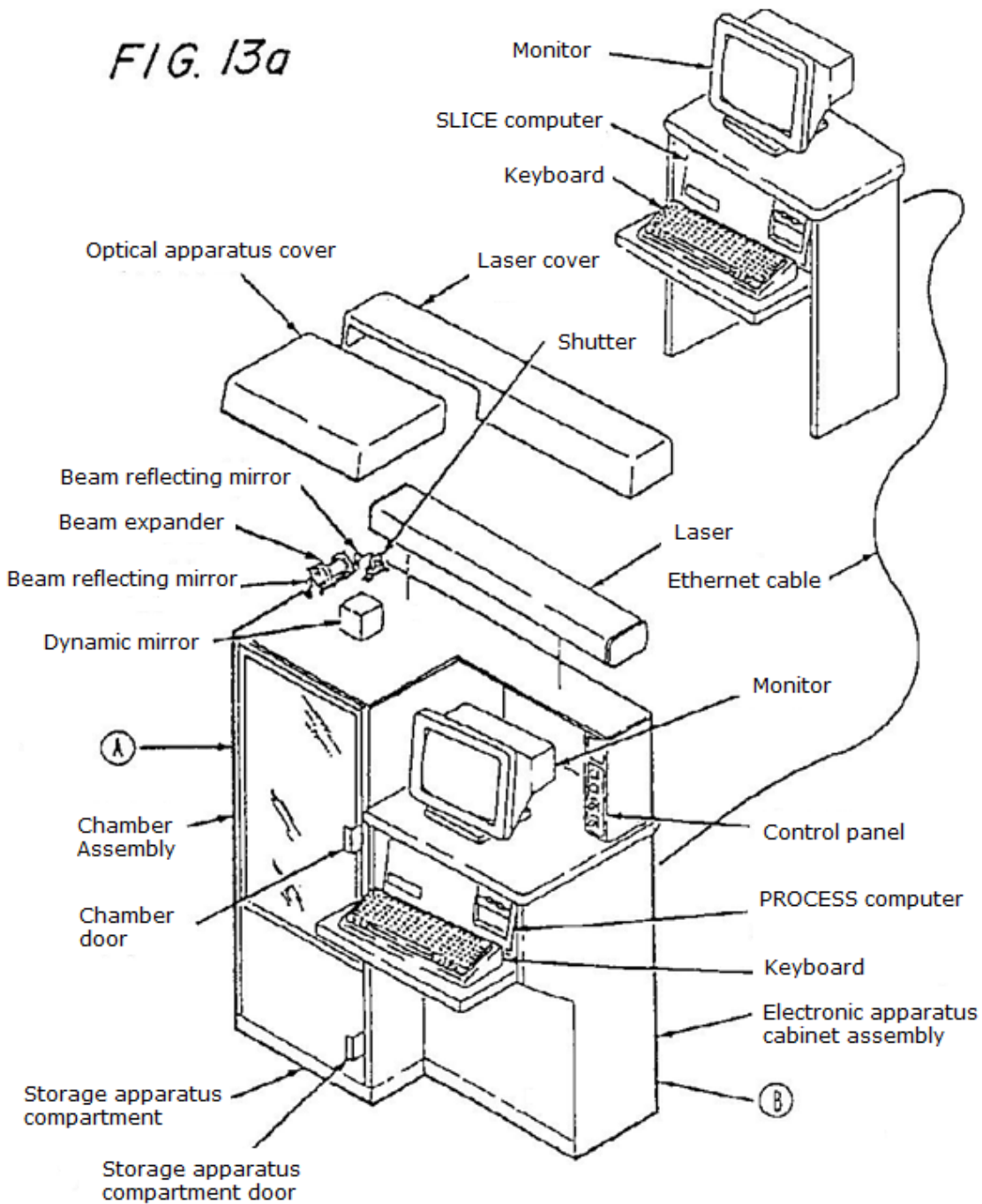


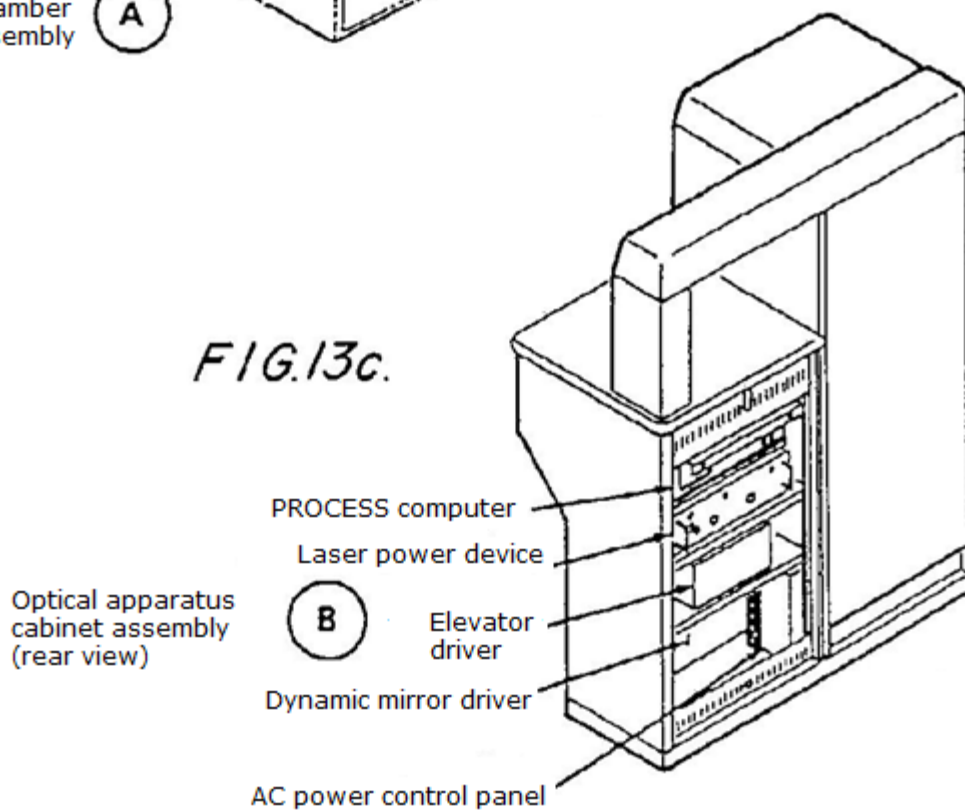
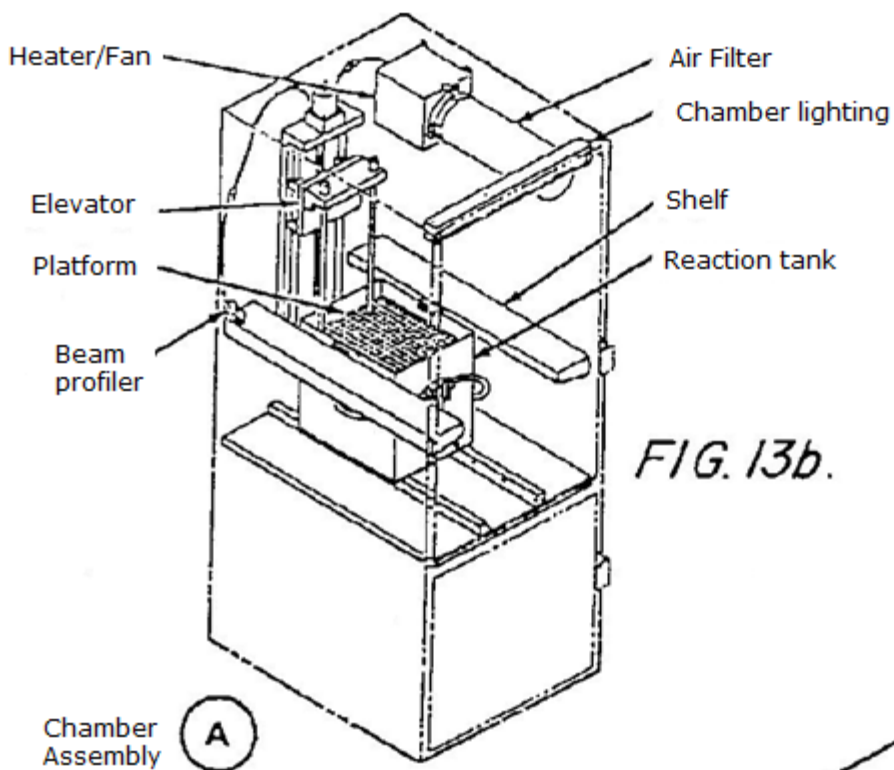
FIG. 12

[FIG. 13a]

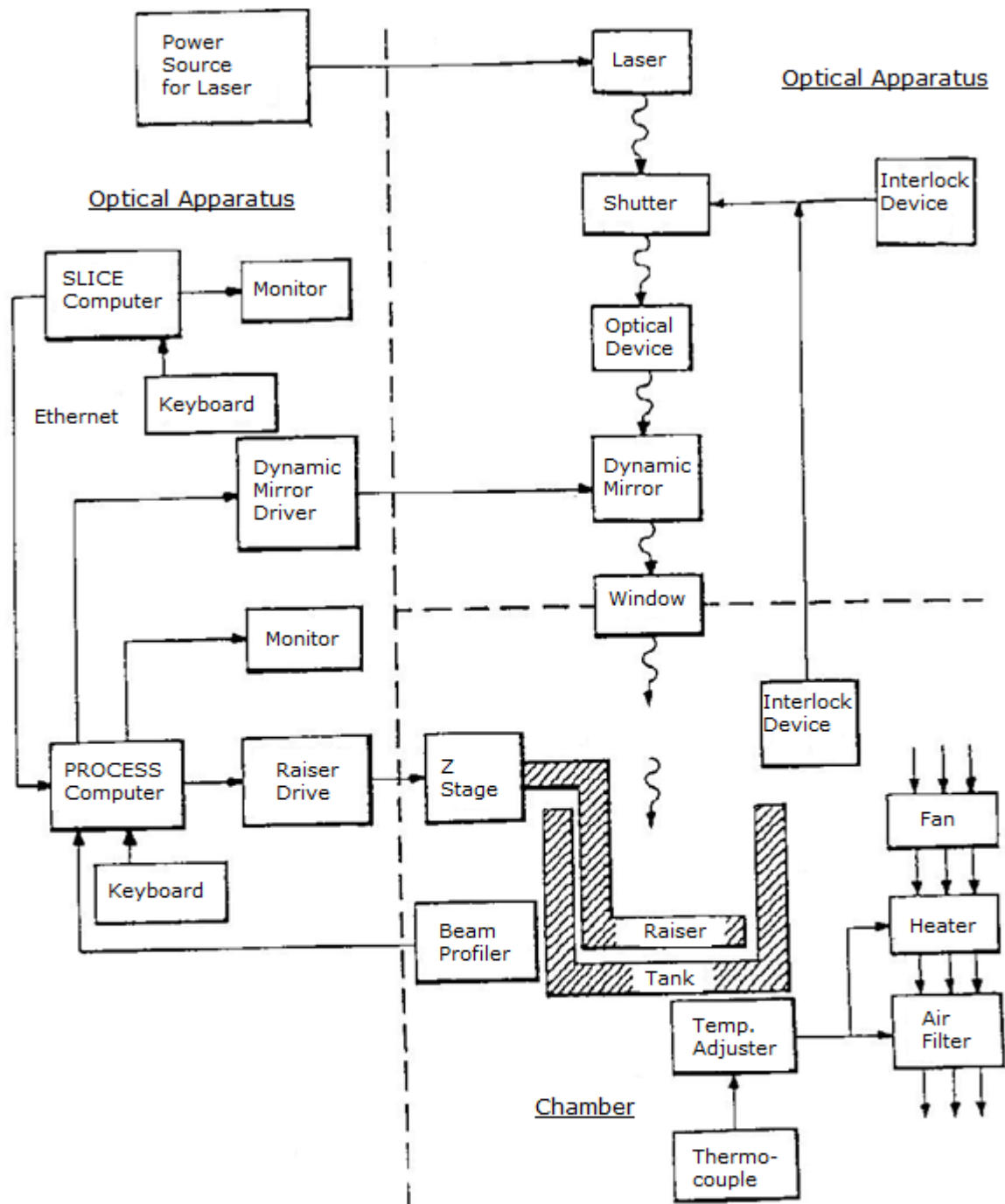


Main Components of the Stereolithography Apparatus

[FIG. 13b,13c]



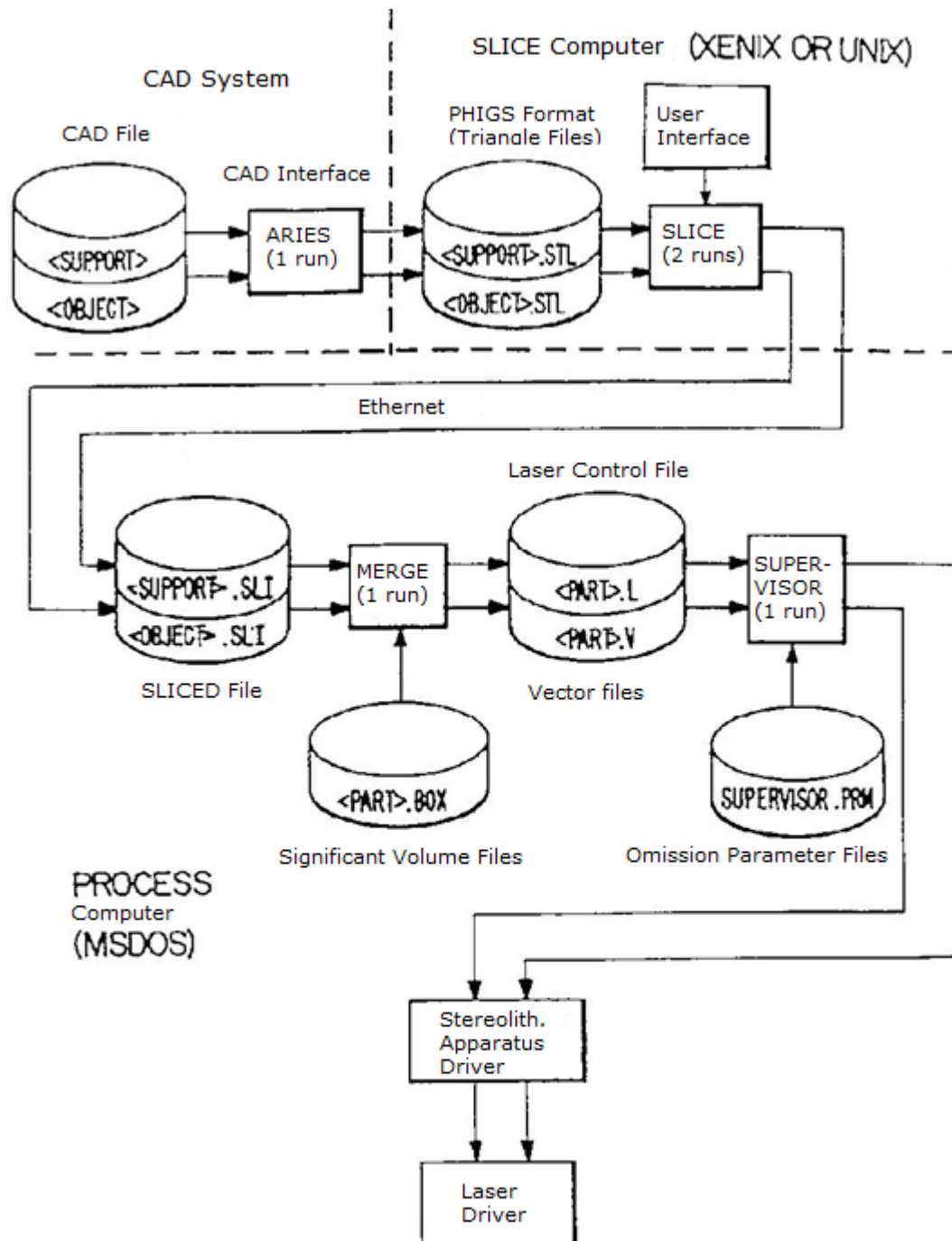
[FIG. 14]



Stereolithography Apparatus Block Diagram

FIG. 14.

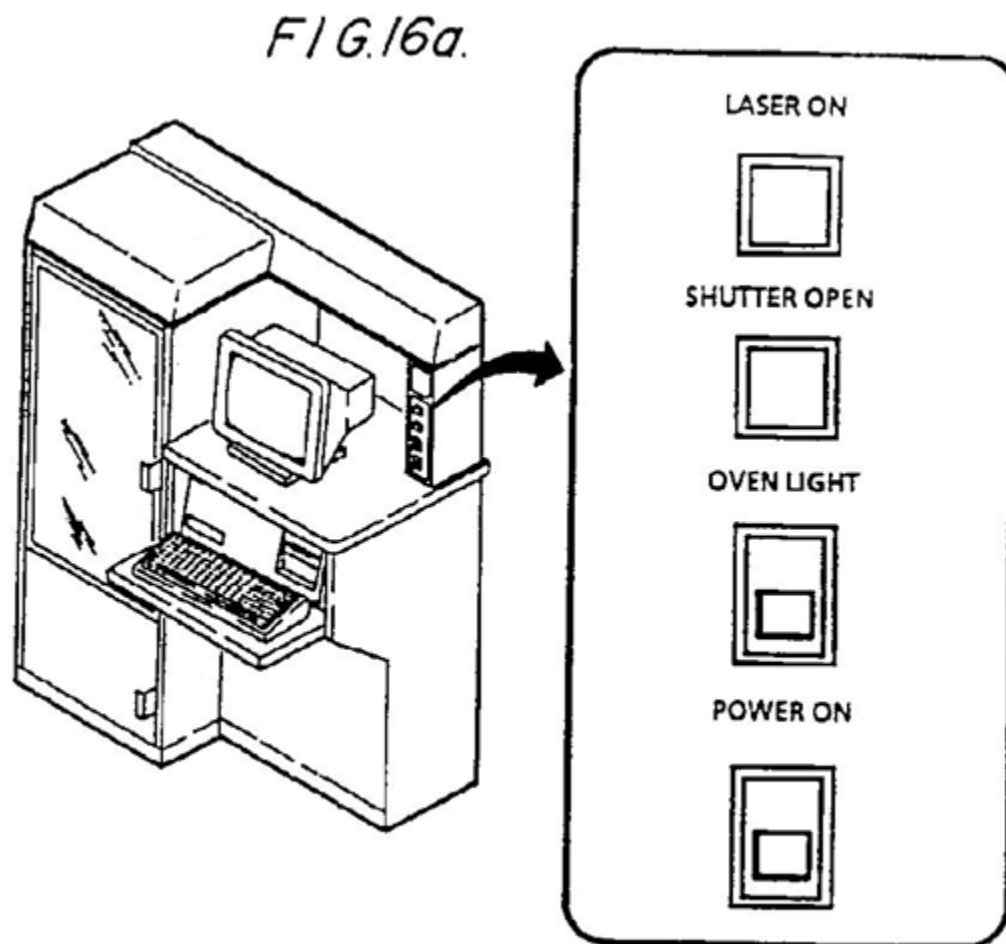
[FIG. 15]



Stereolithography Apparatus Software Diagram

FIG. 15.

[FIG. 16a,16b]



Name	Function
Laser ON Display	Blue light indicates that the laser is operating
Shutter Open Light	Green light indicates the laser shutter is open
Light ON Toggle Switch/Light	Switches reaction chamber ceiling light ON/OFF
Power ON Toggle Switch/Light	Controls primary power supply to laser, power supply, reaction chamber, filter/heater, and PROCESS computer

Control Panel Switches and Lights

Sample Component Record

[illegible]

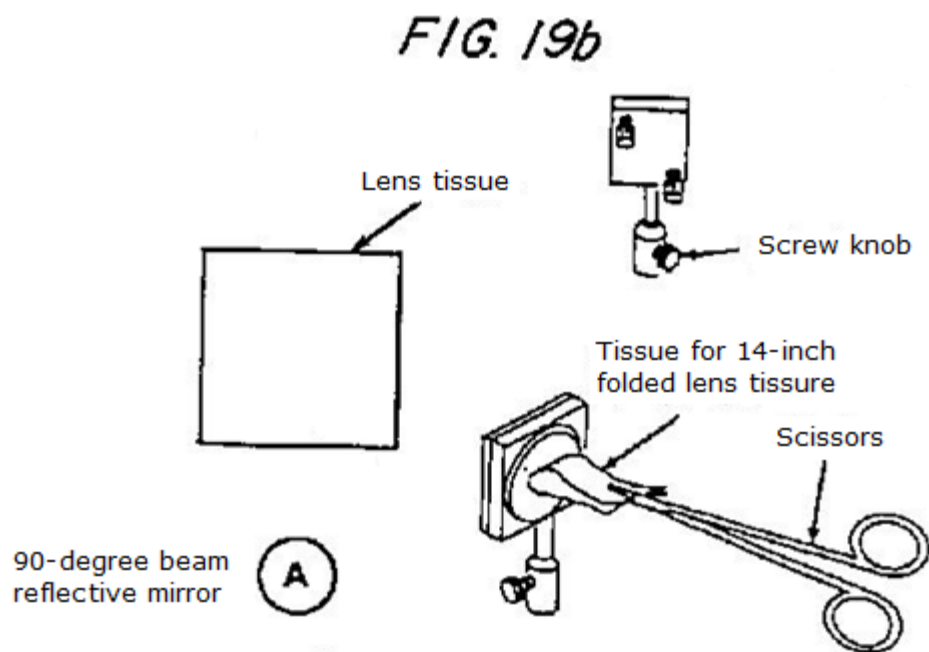
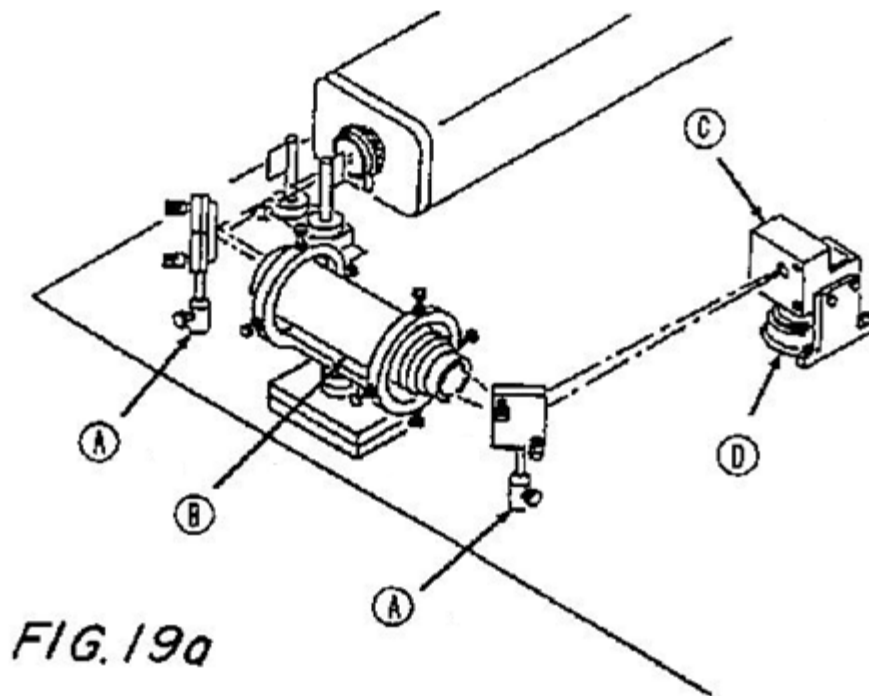
[FIG. 18]

The graph plots Line Dimensions in mils on the y-axis (ranging from 20 to 40) against Step Period in microseconds on the x-axis (logarithmic scale from 20 to 1000). Two data series are shown: Height (represented by solid circles) and Width (represented by solid triangles). Both series show an upward trend as the step period increases.

Step Period (μs)	Height (mils)	Width (mils)
40	18.5	11.5
80	23.0	12.5
160	28.0	13.5
320	32.5	14.5
640	35.5	15.5

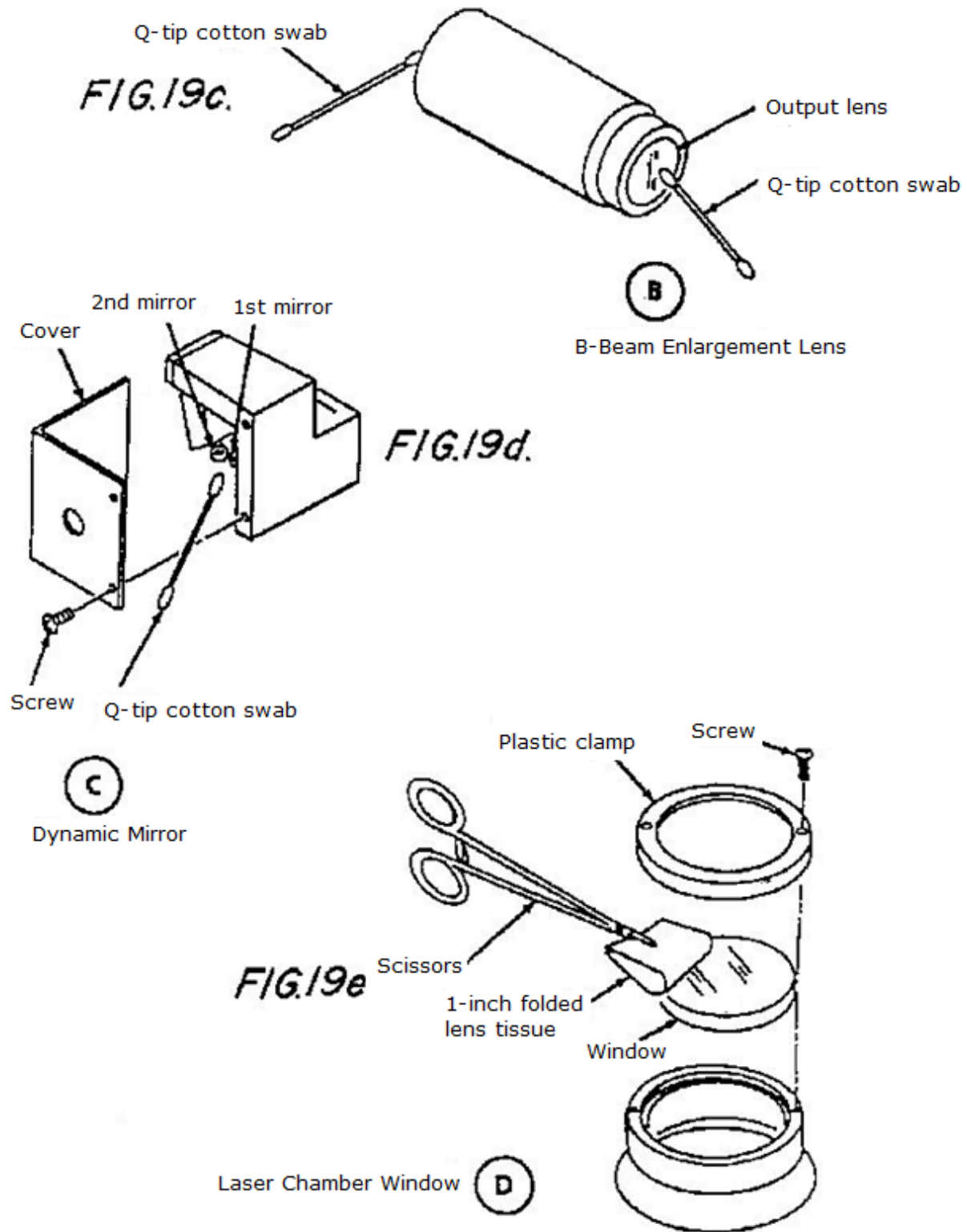
109

[FIG. 19a, 19b]

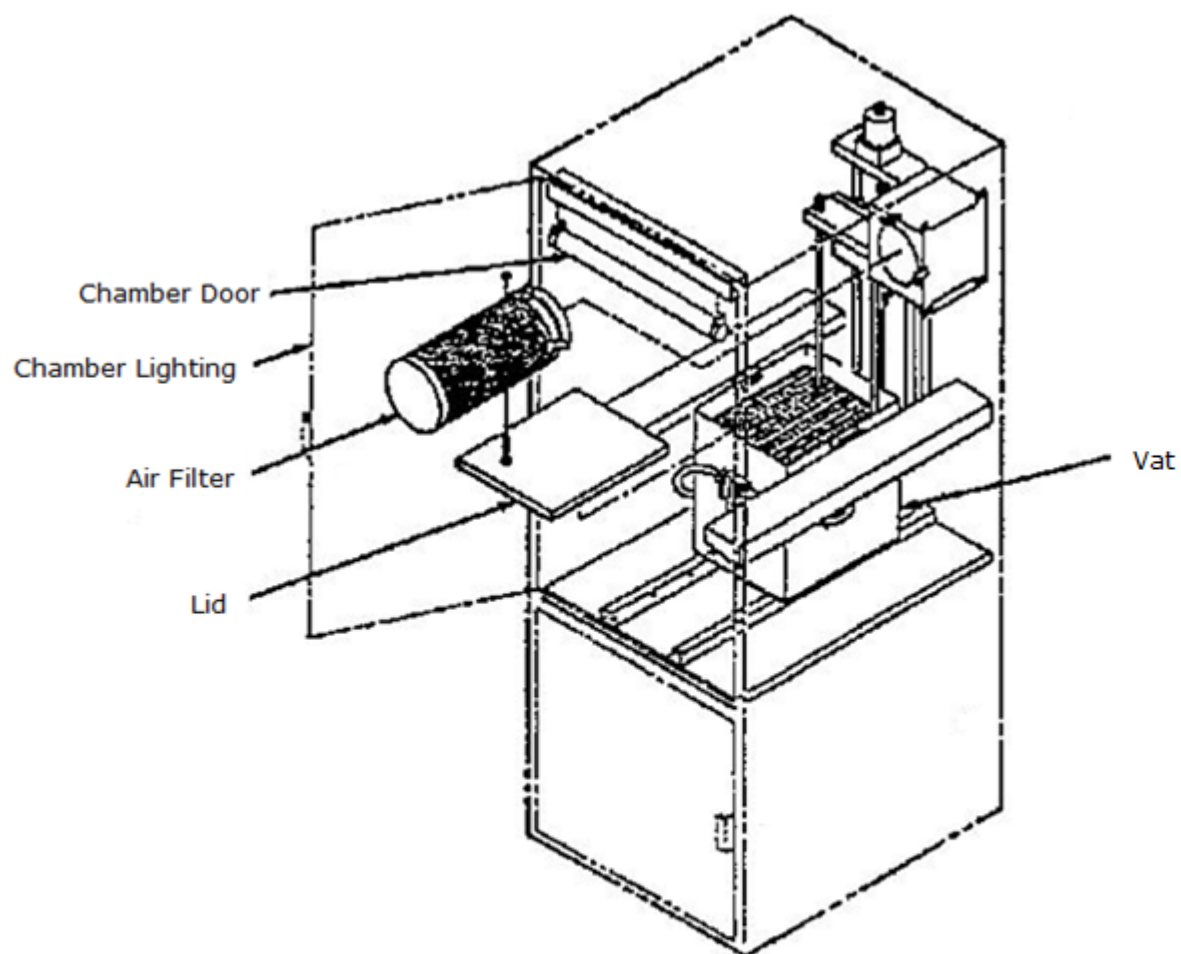


RECOMMENDED OPTICAL APPARATUS CLEANING TECHNIQUE

[FIG. 19c to 19e]



[FIG. 20]



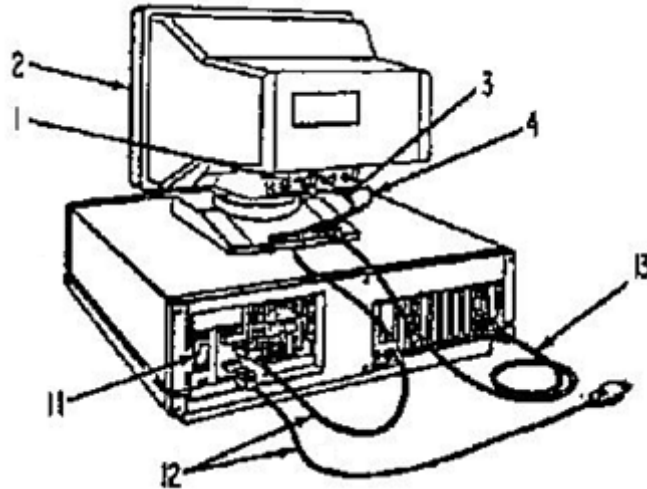
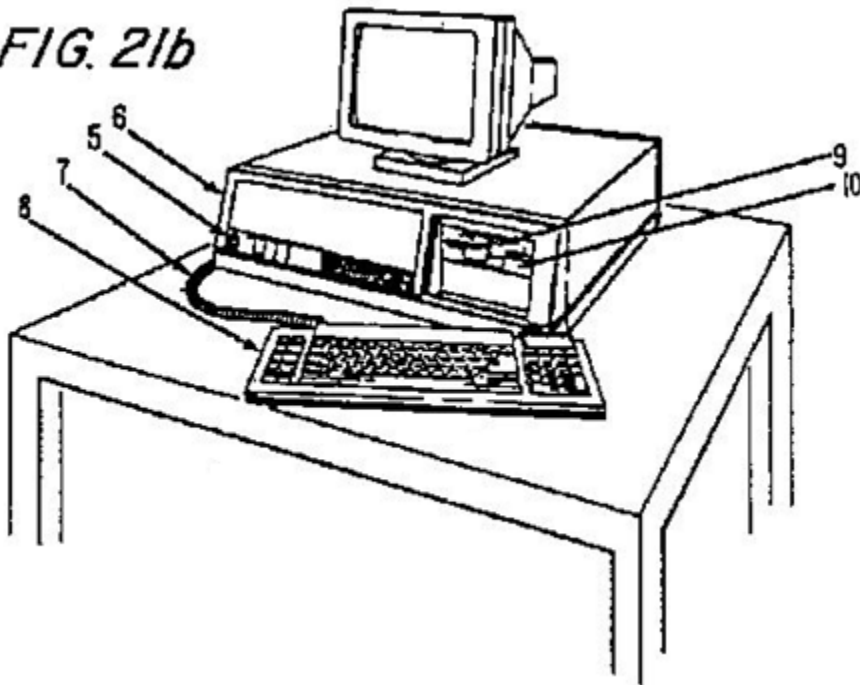
Air Filter Replacement

FIG. 20.

[FIG. 21a,21b]

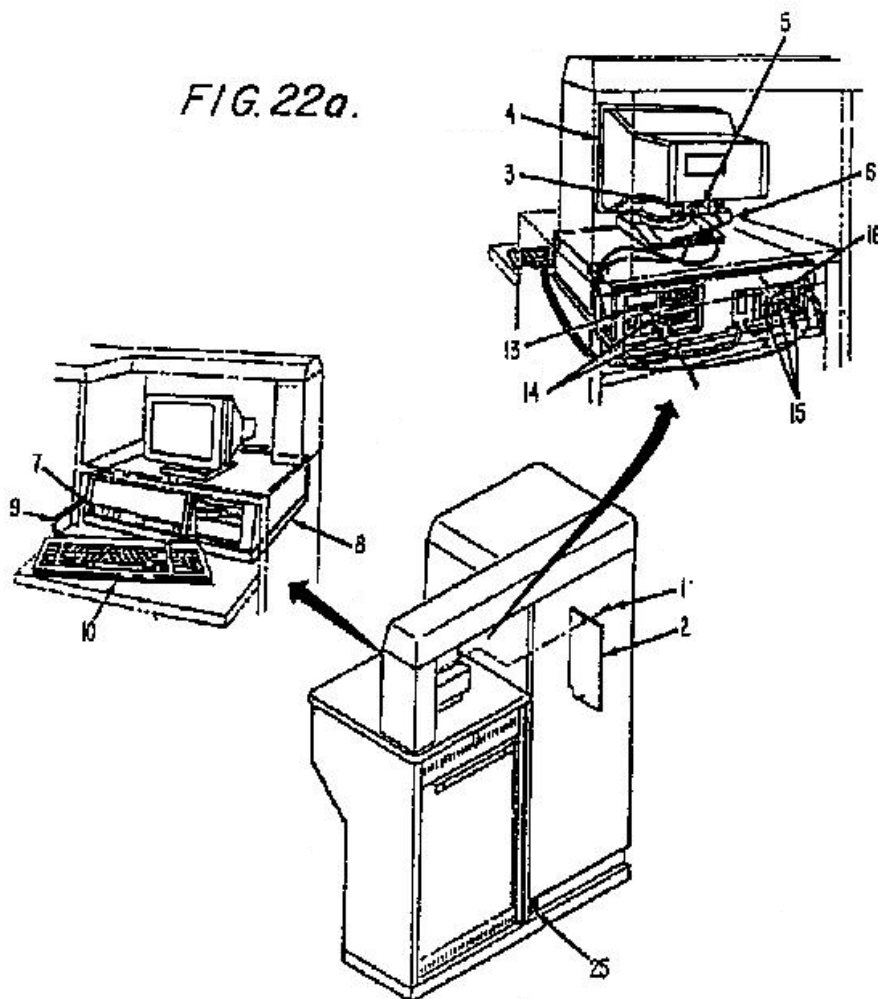
SLICE Computer

1. Power switch
2. Monitor
3. Power cable
4. Signal cable
5. Lockout switch
6. SLICE computer
7. Signal cable
8. Keyboard
9. Diskette
10. Disk drive
11. Power switch
12. Power cable (2EA)
13. Signal cable

*FIG. 21a.**FIG. 21b*

[FIG. 22a]

- | | |
|------------------------|----------------------------|
| 1. Screw (2EA) | 19. Cable (3EA) |
| 2. Cable access panel | 20. Cable (2EA) |
| 3. Power switch | 21. Power switch |
| 4. Monitor | 22. Raiser driver |
| 5. Power cable | 23. Cable (2EA) |
| 6. Signal cable | 24. Cable |
| 7. Lockout switch | 25. Light shield |
| 8. PROCESS computer | 26. Power cable (4-6EA) |
| 9. Signal cable | 27. AC power control panel |
| 10. Keyboard | 28. Cable (4EA) |
| 11. Screw (4EA) | 29. Screw (4EA) |
| 12. Access panel | 30. Cover |
| 13. Power switch | 31. Terminal board |
| 14. Power cable (2EA) | 32. Screw (4EA) |
| 15. Signal cable (3EA) | 33. Screw (8EA) |
| 16. Coaxial cable | 34. Dynamic mirror driver |
| 17. Power switch | 35. Cable (4EA) |
| 18. Laser power supply | 36. Power switch |



Electronic Apparatus Cabinet Components

[FIG. 22b]

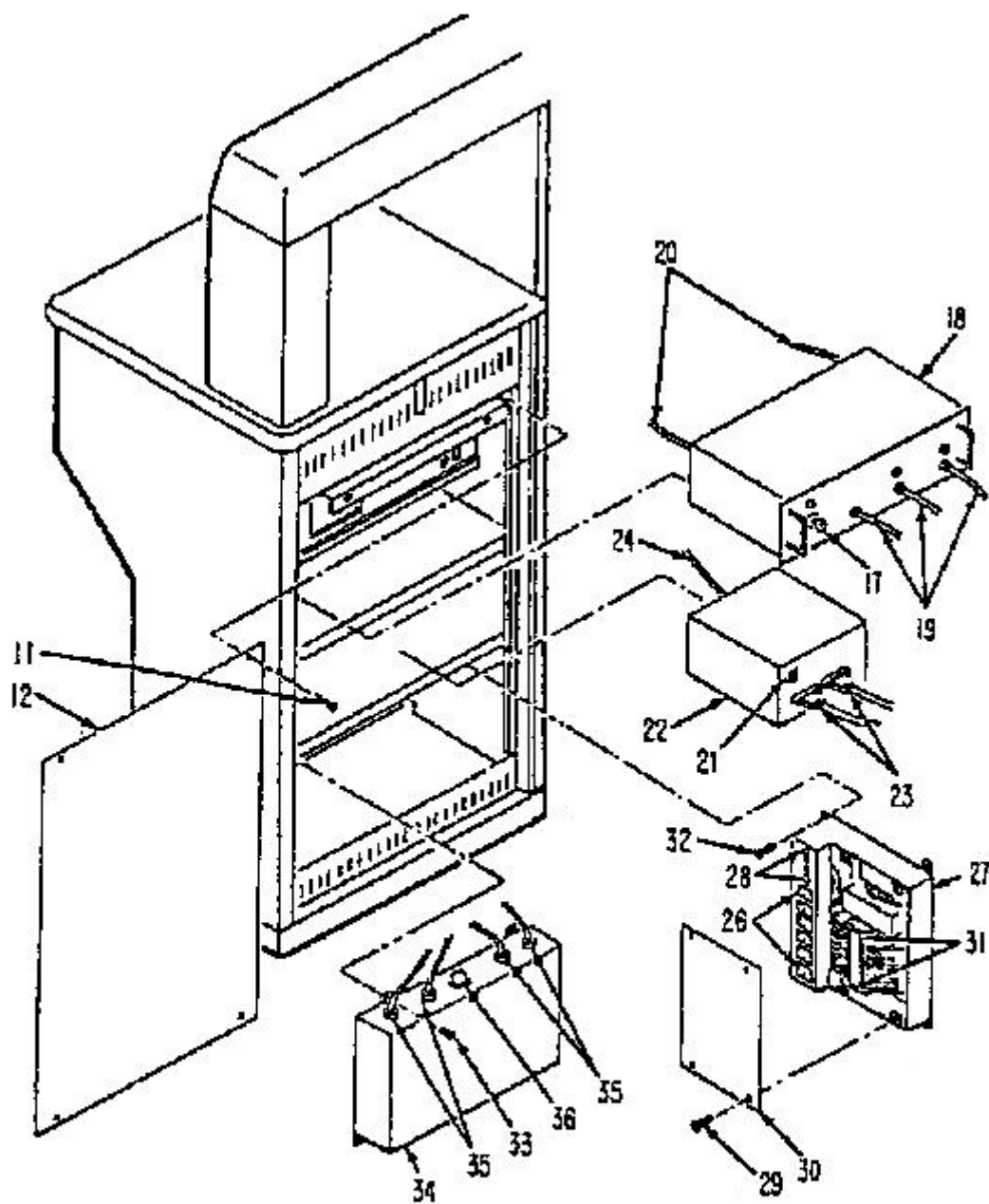
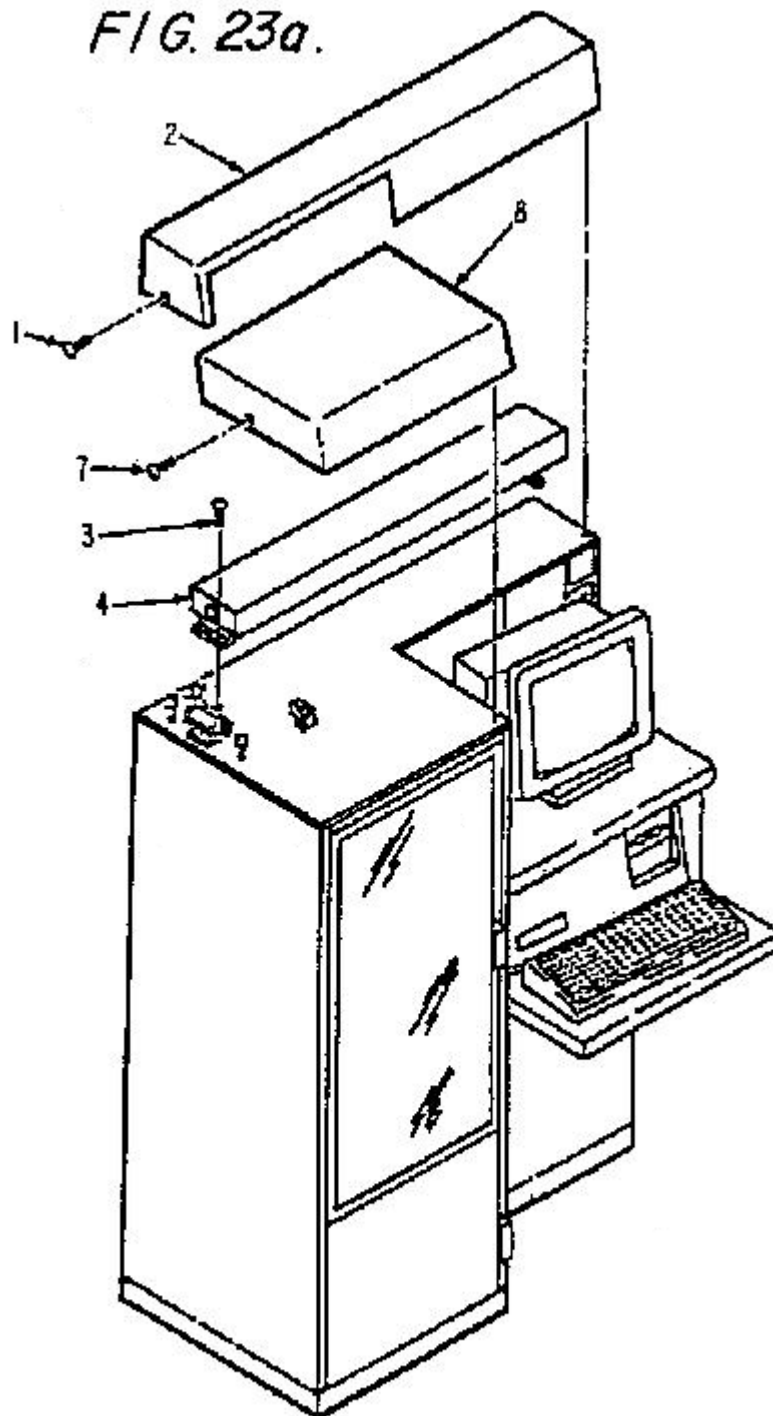


FIG. 22b.

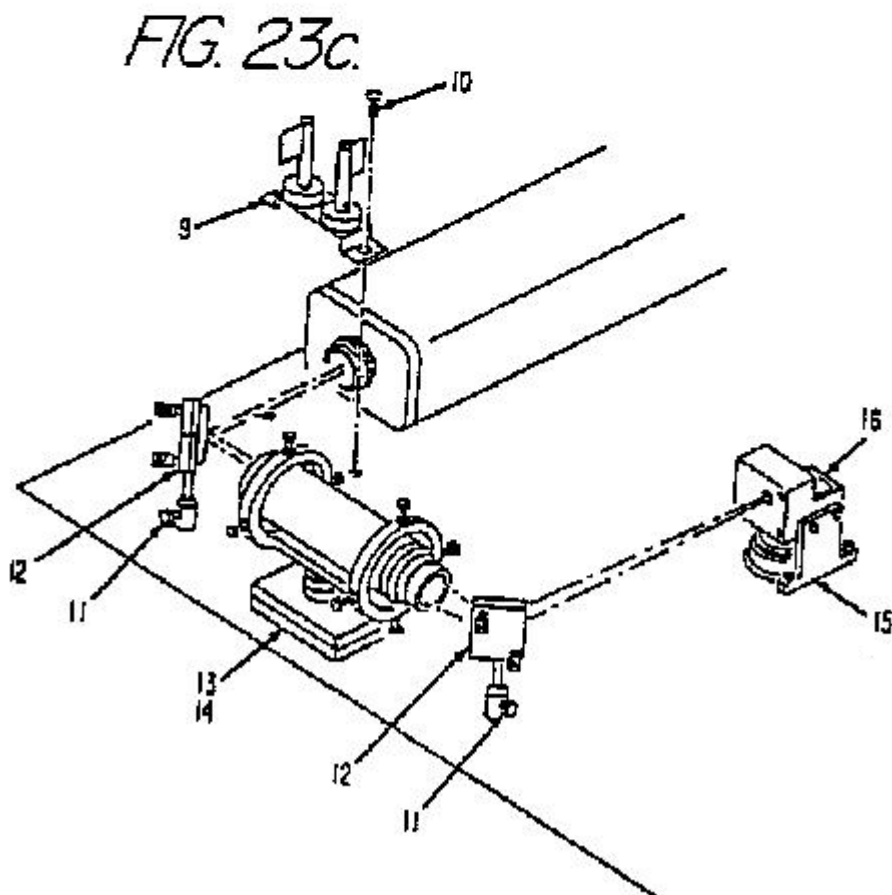
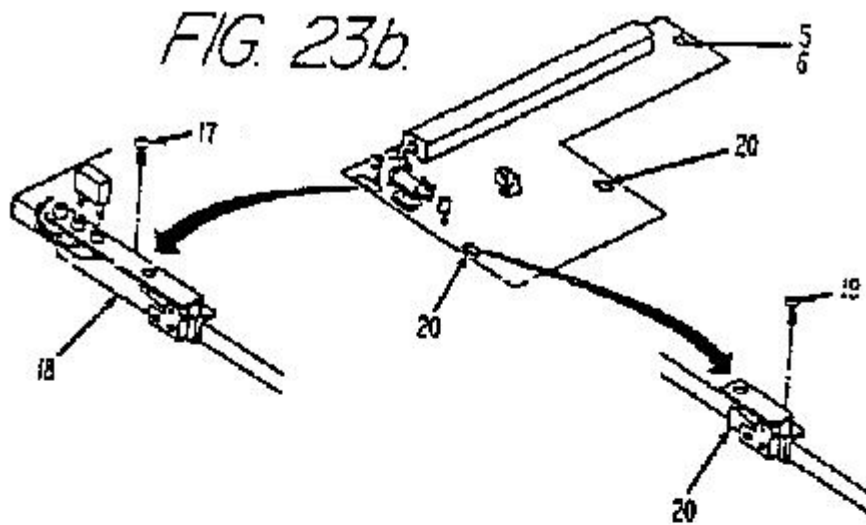
[FIG. 23a]

1. Screw (2EA)
2. Laser cover
3. Screw (4EA)
4. Laser
5. Screw
6. Interlocking switch
7. Screw (2EA)
8. Optical apparatus cover
9. Shutter
10. Screw (2EA)
11. Knob screw
12. Beam reflecting mirror
13. Screw (2EA)
14. Beam expander
15. Screw (2EA)
16. Dynamic mirror
17. Screw (2EA)
18. Interlocking switch
19. Screw (2EA)
20. Drive switch (2EA)

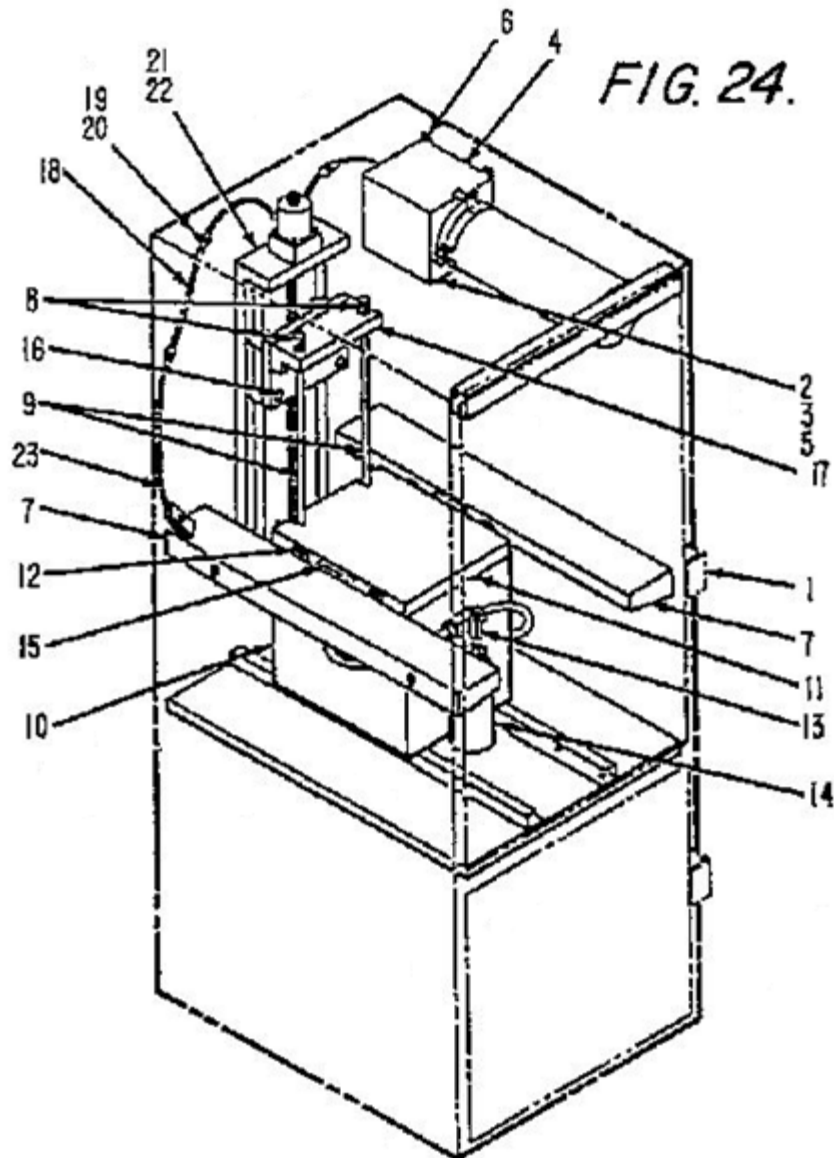


Optical Apparatus Components

[FIG. 23b, 23c]



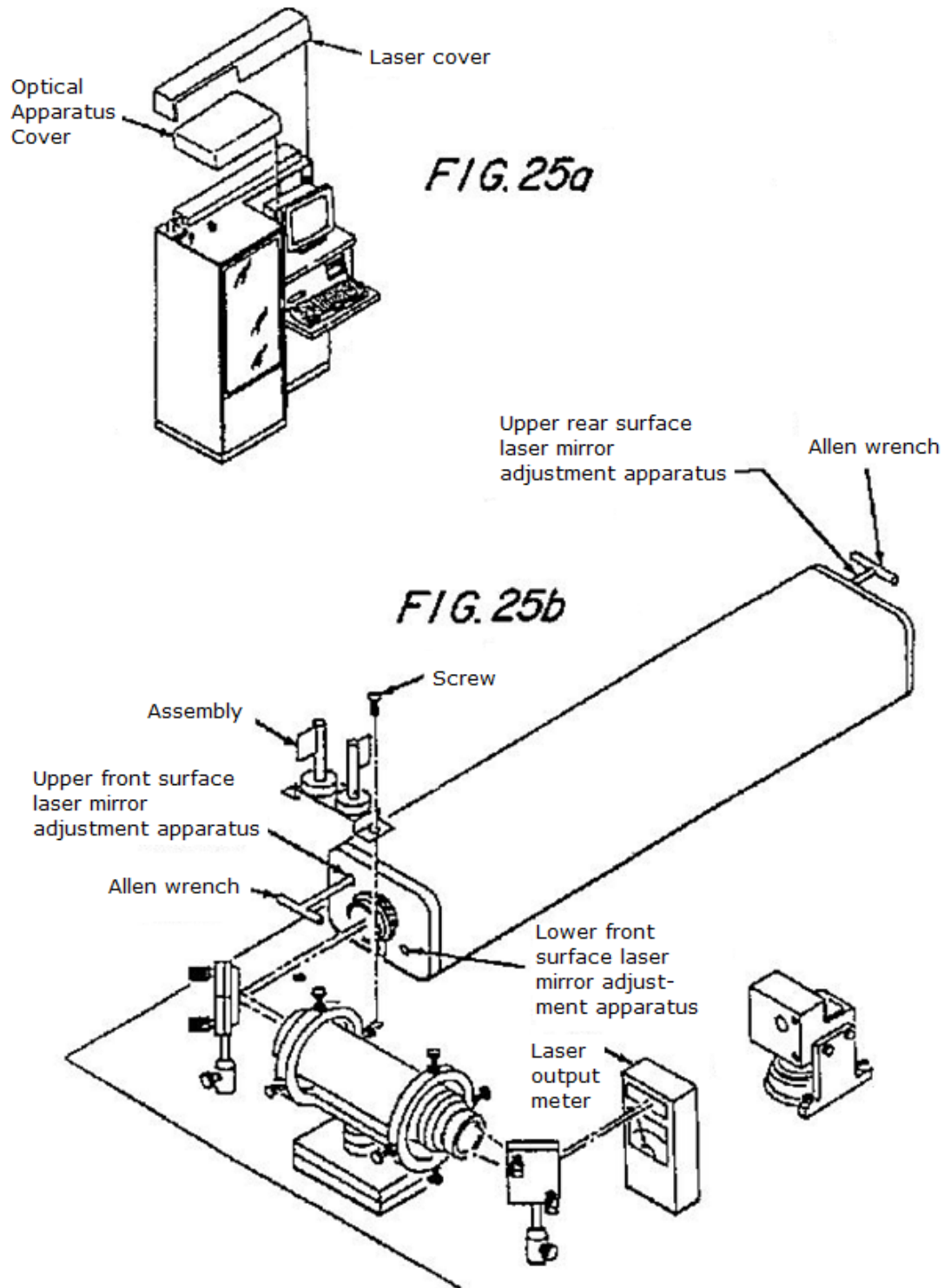
[FIG. 24]



- | | |
|-----------------------|-----------------------|
| 1. Chamber door | 13. Drain valve |
| 2. Screw (2EA) | 14. Rotating bottle |
| 3. Bottom cover | 15. Side handle (2EA) |
| 4. Heater/fan | 16. Screw (2EA) |
| 5. Terminal board | 17. Platform |
| 6. Screw (4EA) | 18. Cable |
| 7. Side panel (2EA) | 19. Screw |
| 8. Knob (2EA) | 20. Cable clamp |
| 9. Platform rod (2EA) | 21. Screw (4EA) |
| 10. Reaction vat | 22. Elevator |
| 11. Lid | 23. Chamber cable |
| 12. Latch (4EA) | |

Chamber Components

[FIG. 25a, 25b]



[FIG. 26a,26b]

FIG. 26a.

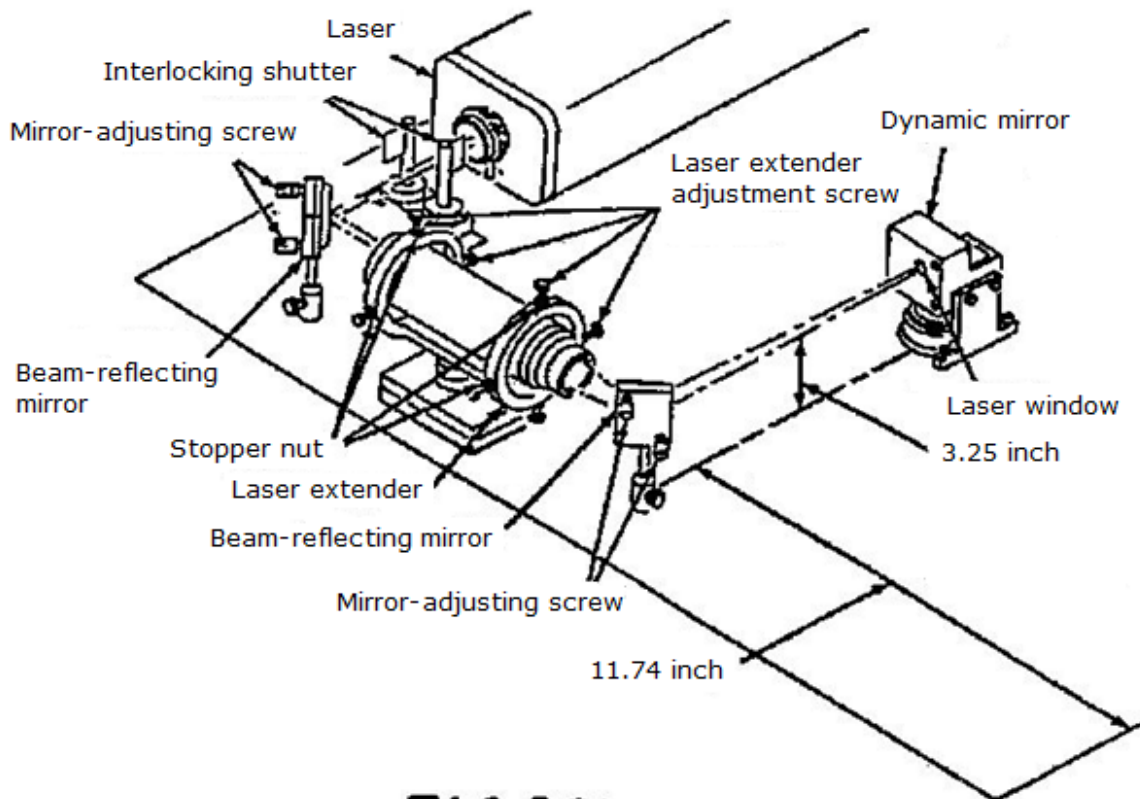
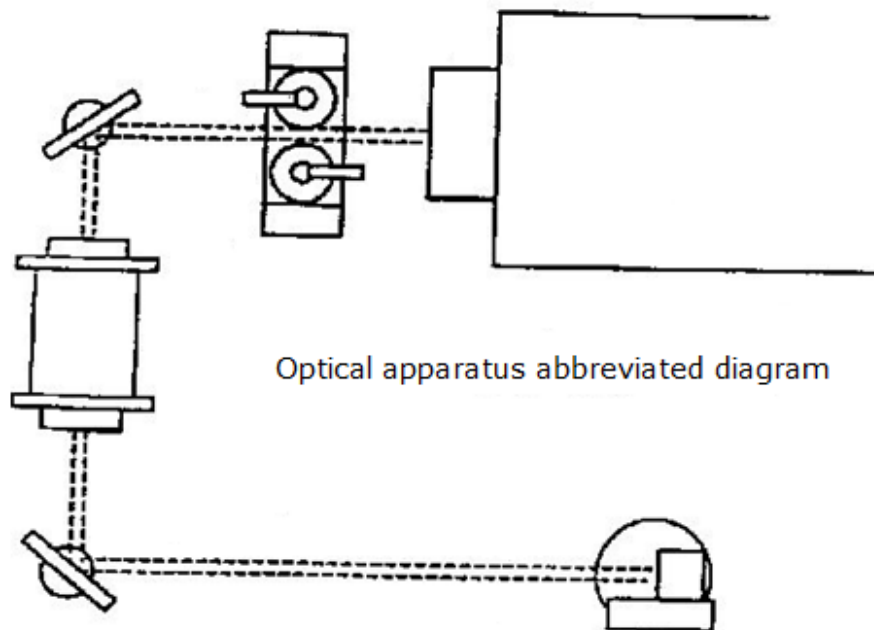
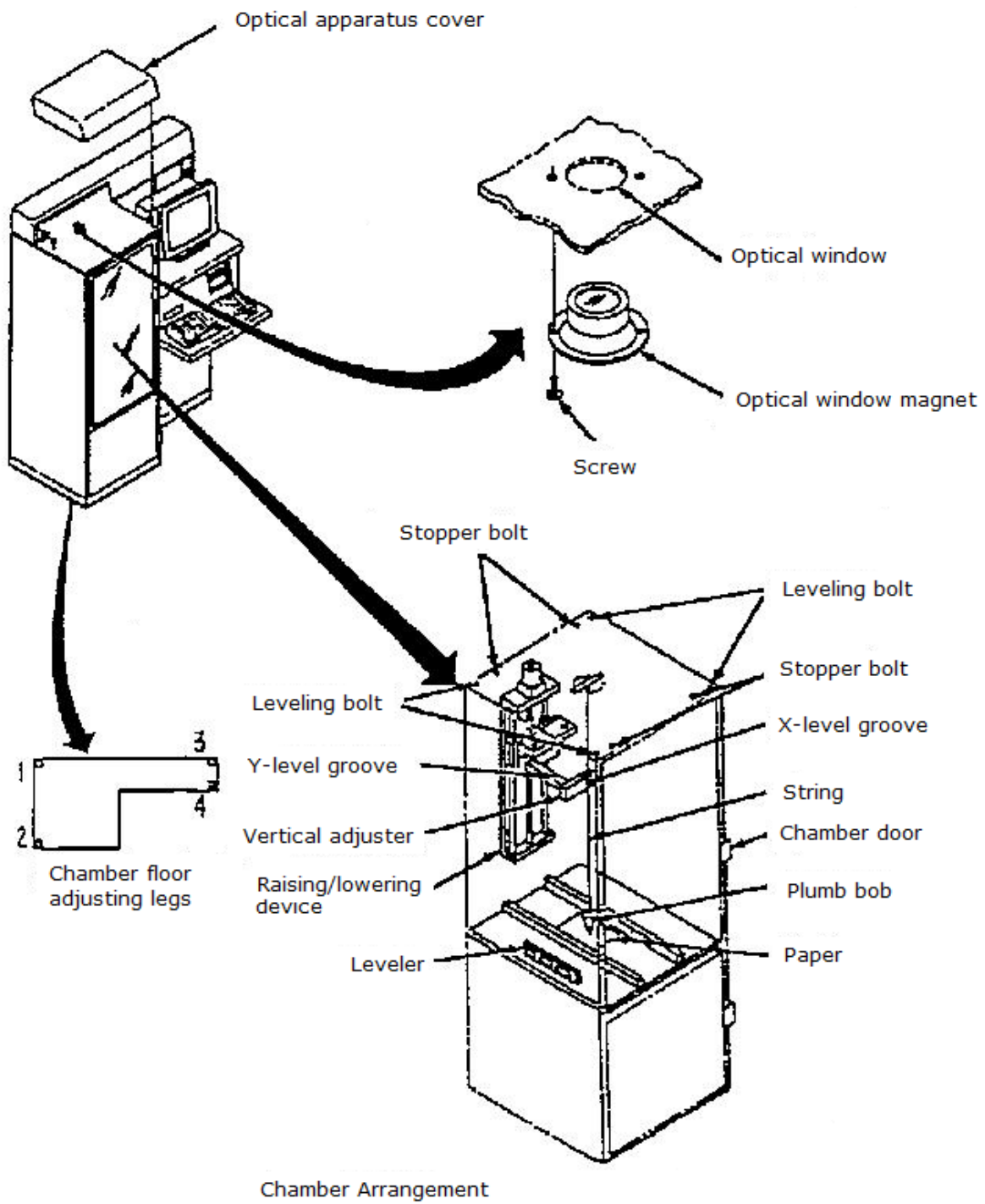


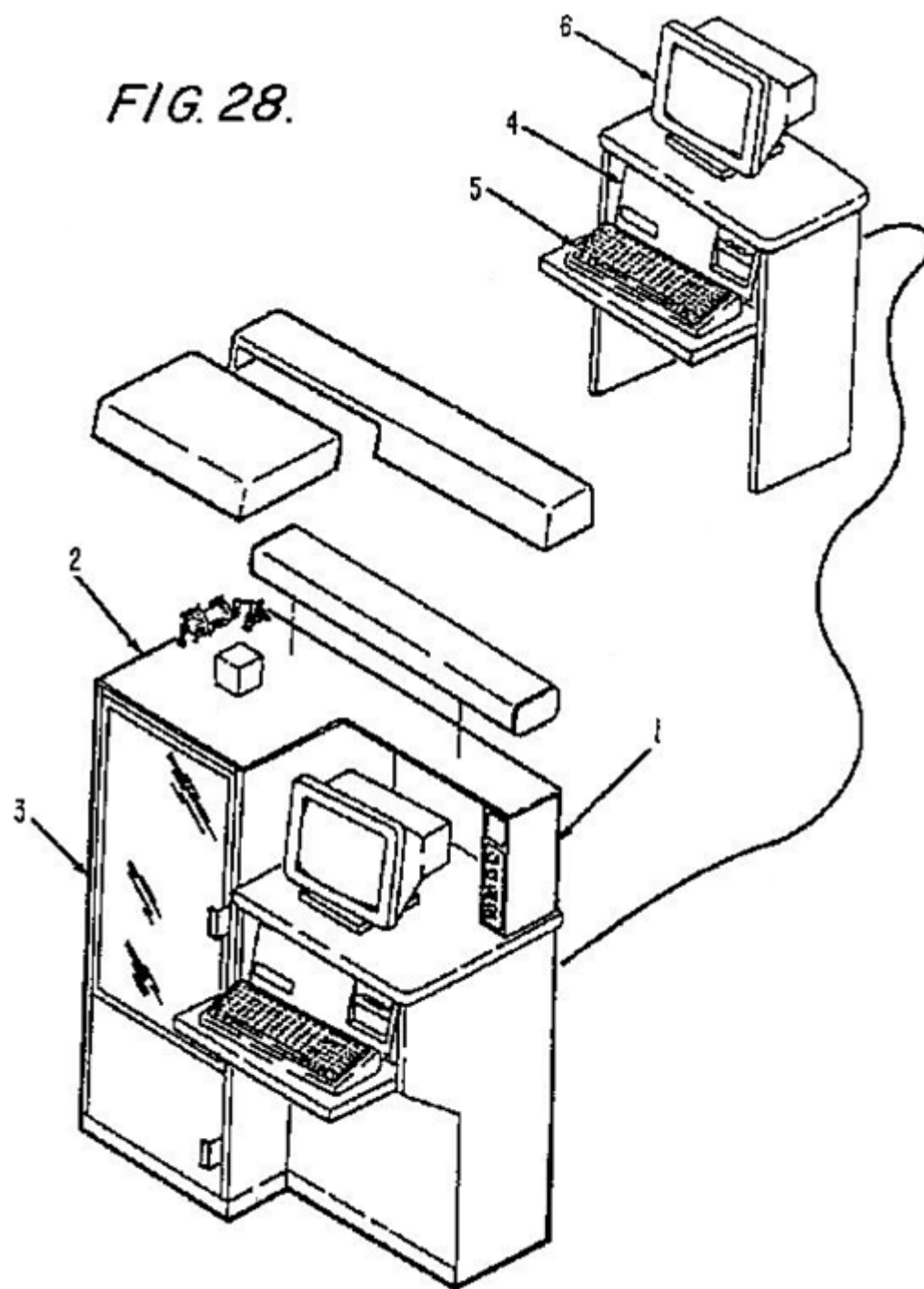
FIG. 26b.



[FIG. 27]

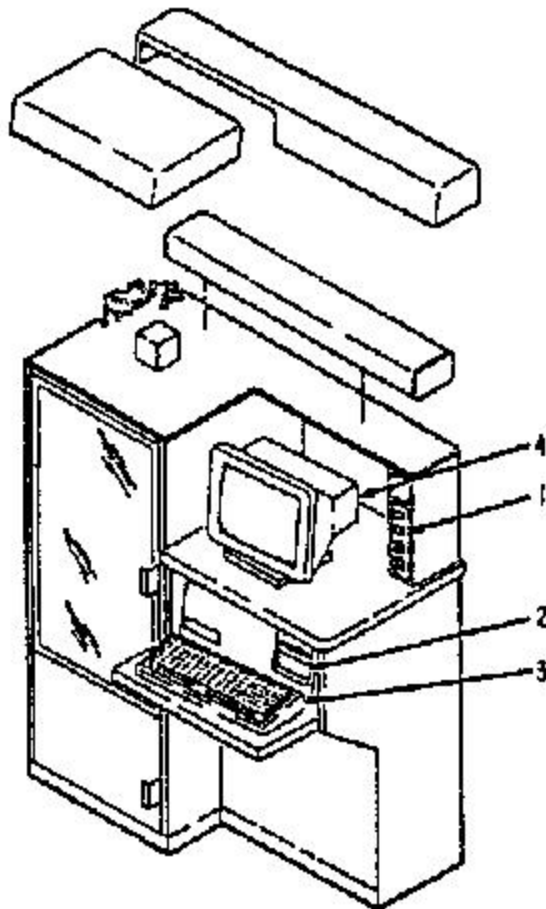
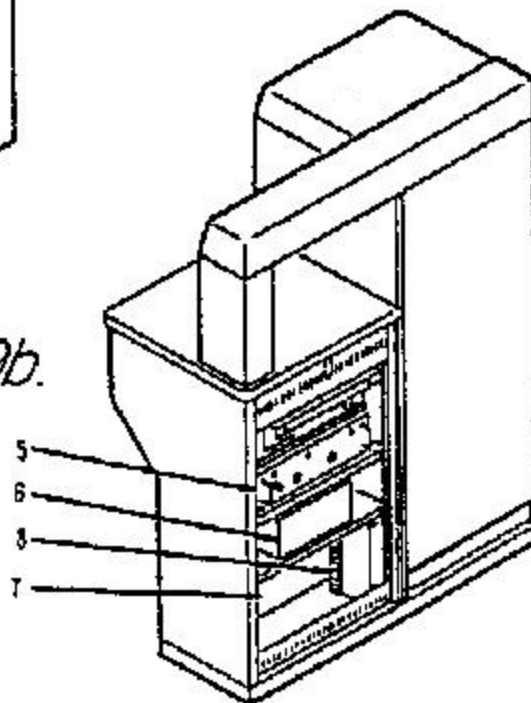
FIG. 27.

[FIG. 28]

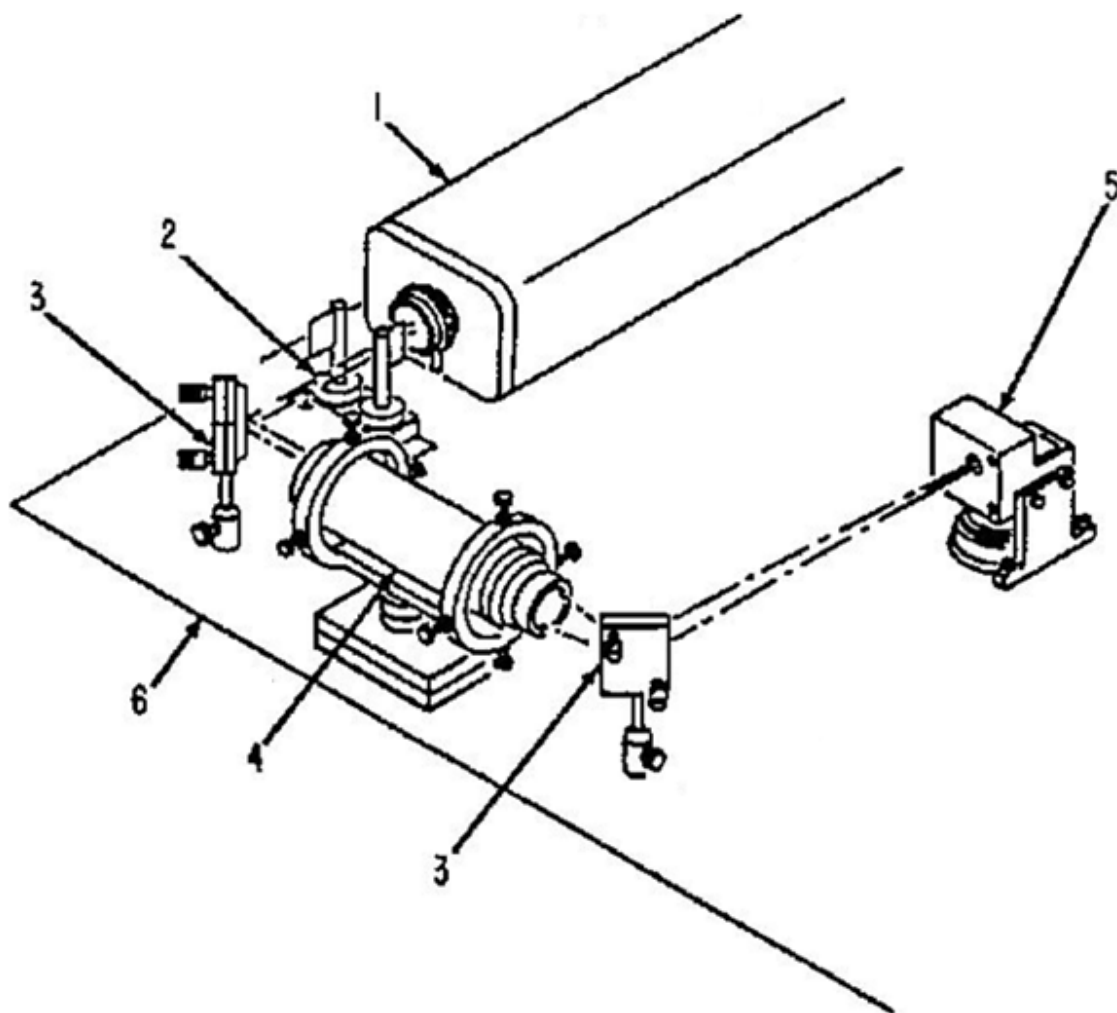


SLA-1 Stereography Apparatus

[FIG. 29a, 29b]

*FIG. 29a.**FIG. 29b.*

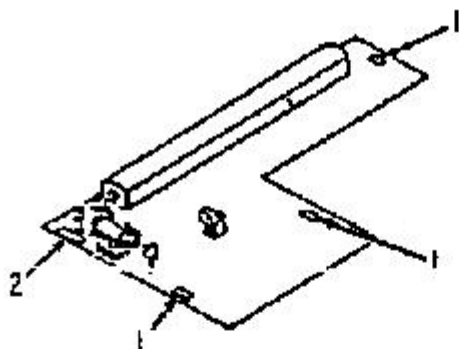
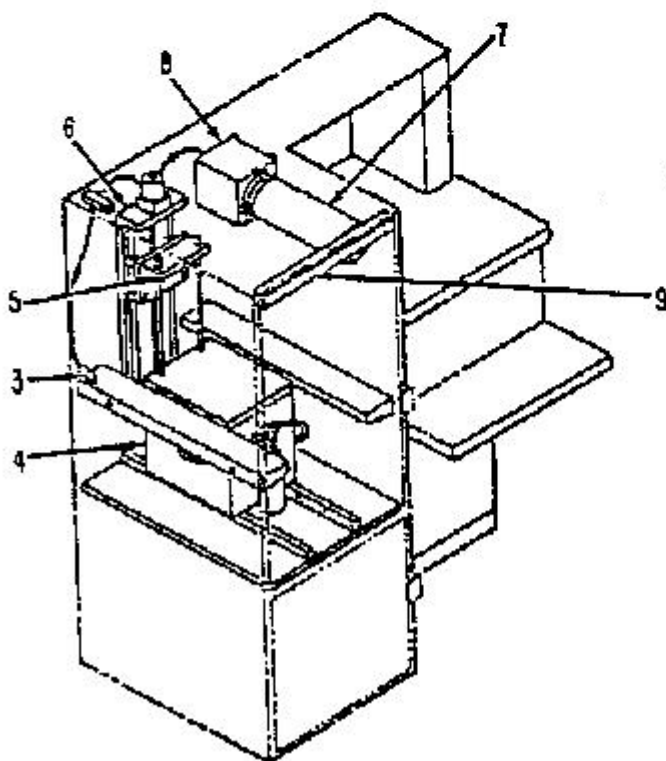
[FIG. 30]



Optical Apparatus Assembly

FIG. 30

[FIG. 31a, 31b]

*FIG. 31a.**FIG. 31b.*

[FIG. 32]

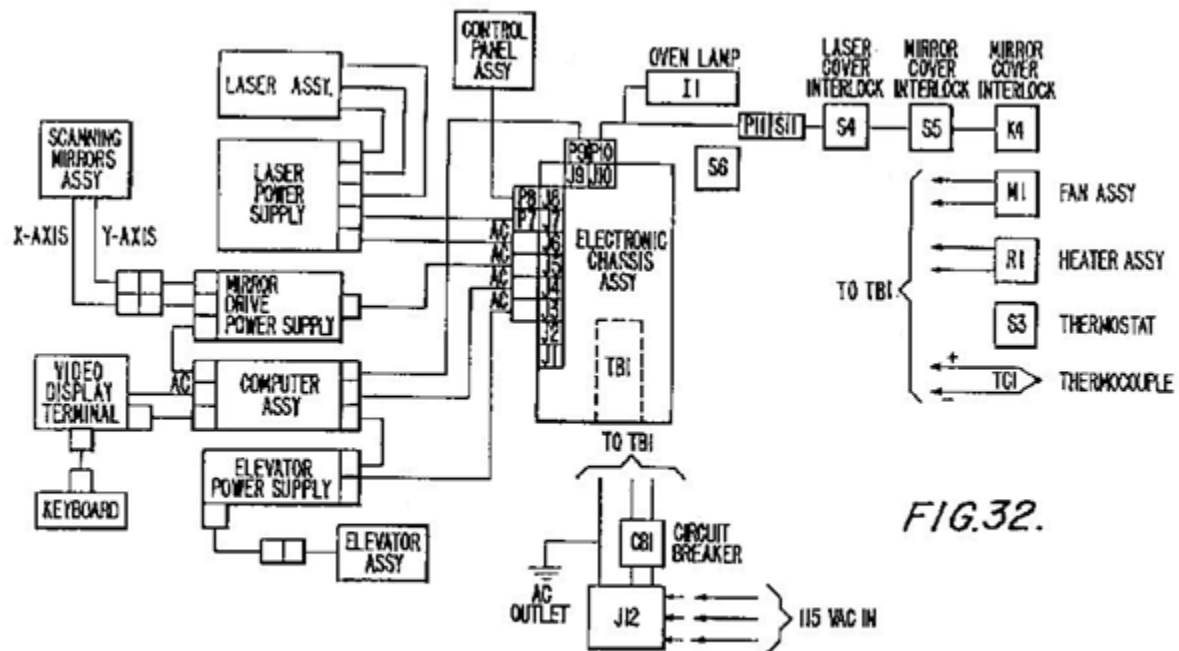


FIG.32.

SLA-1 Wiring Diagram

[FIG. 33]

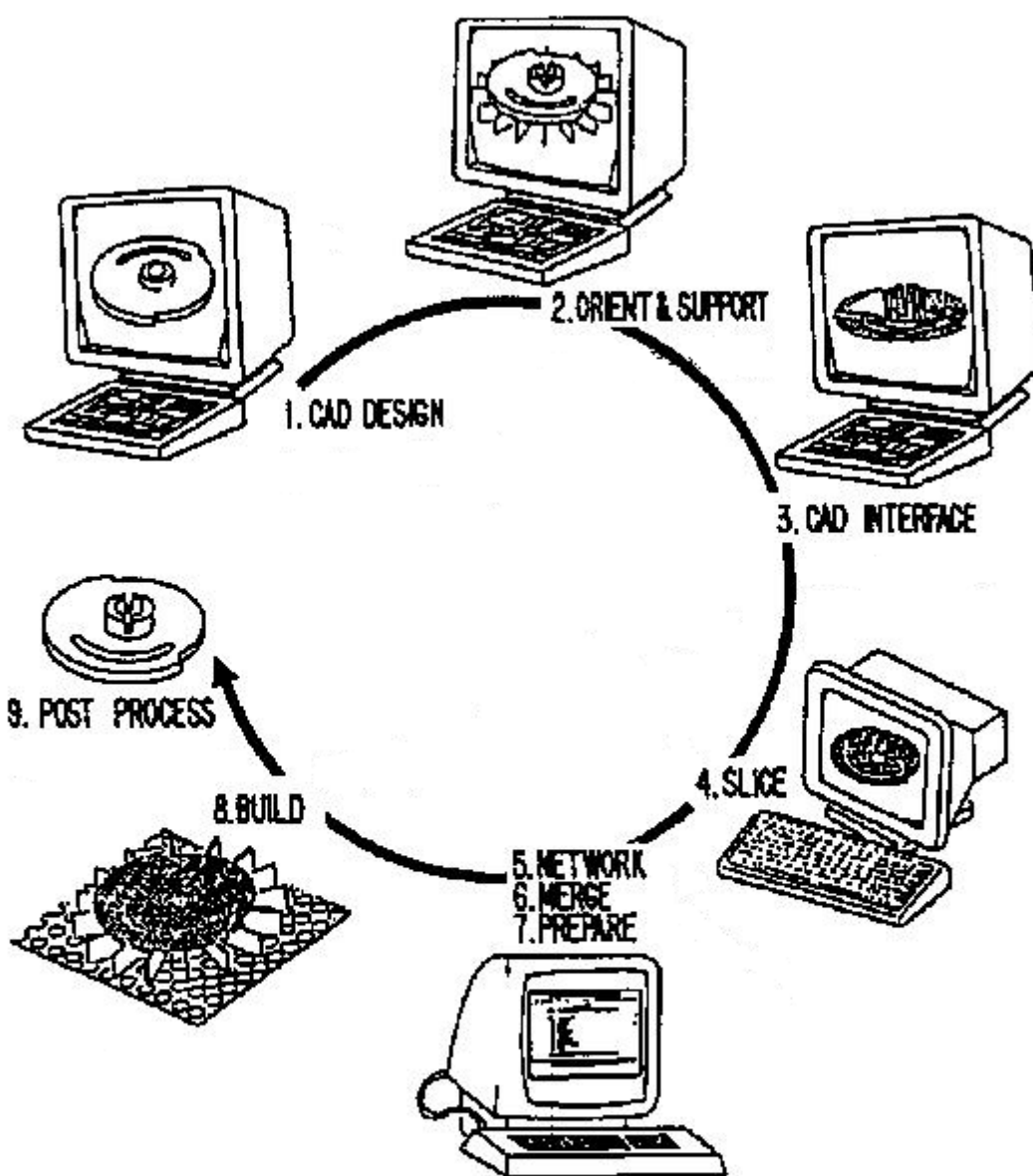
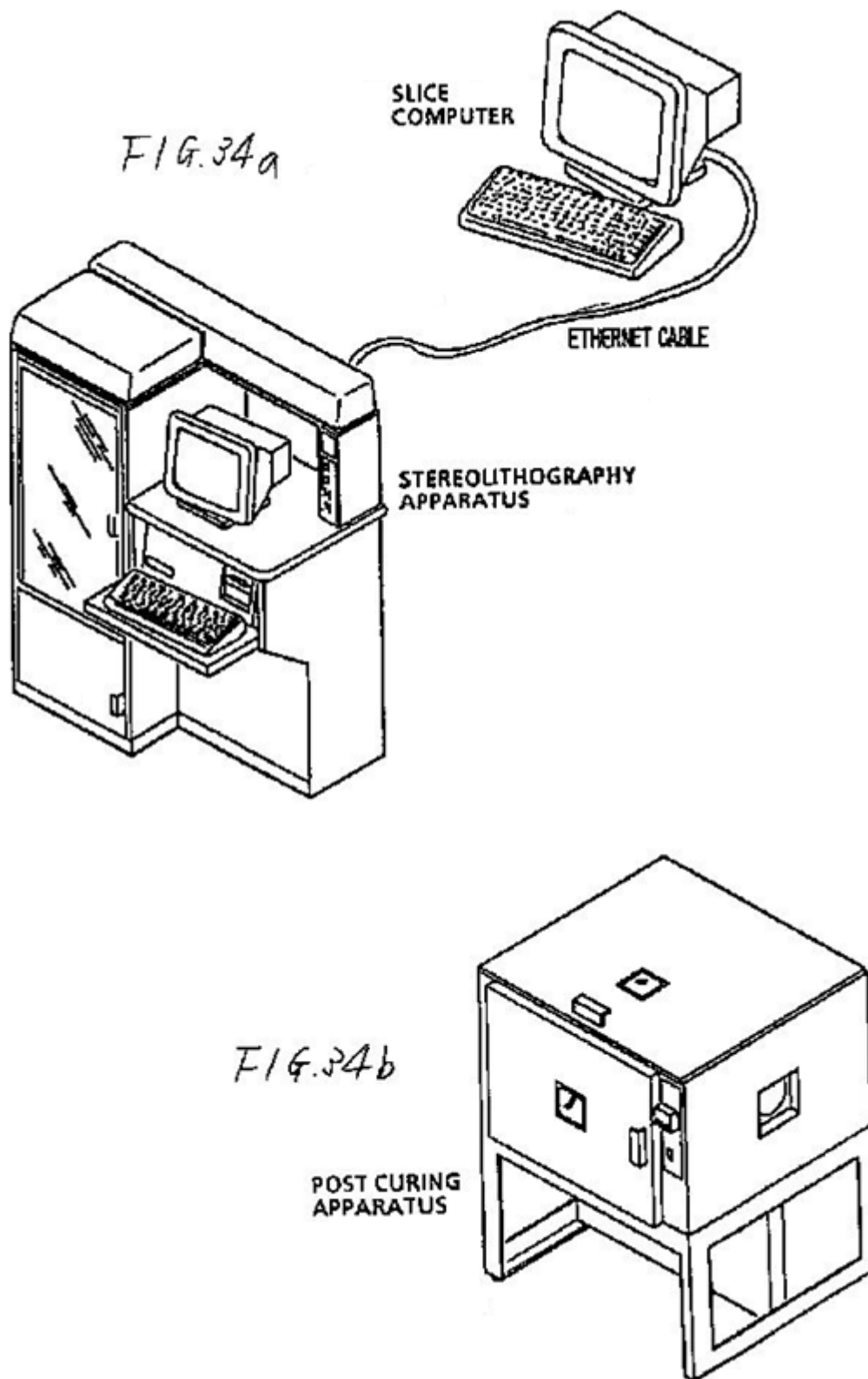
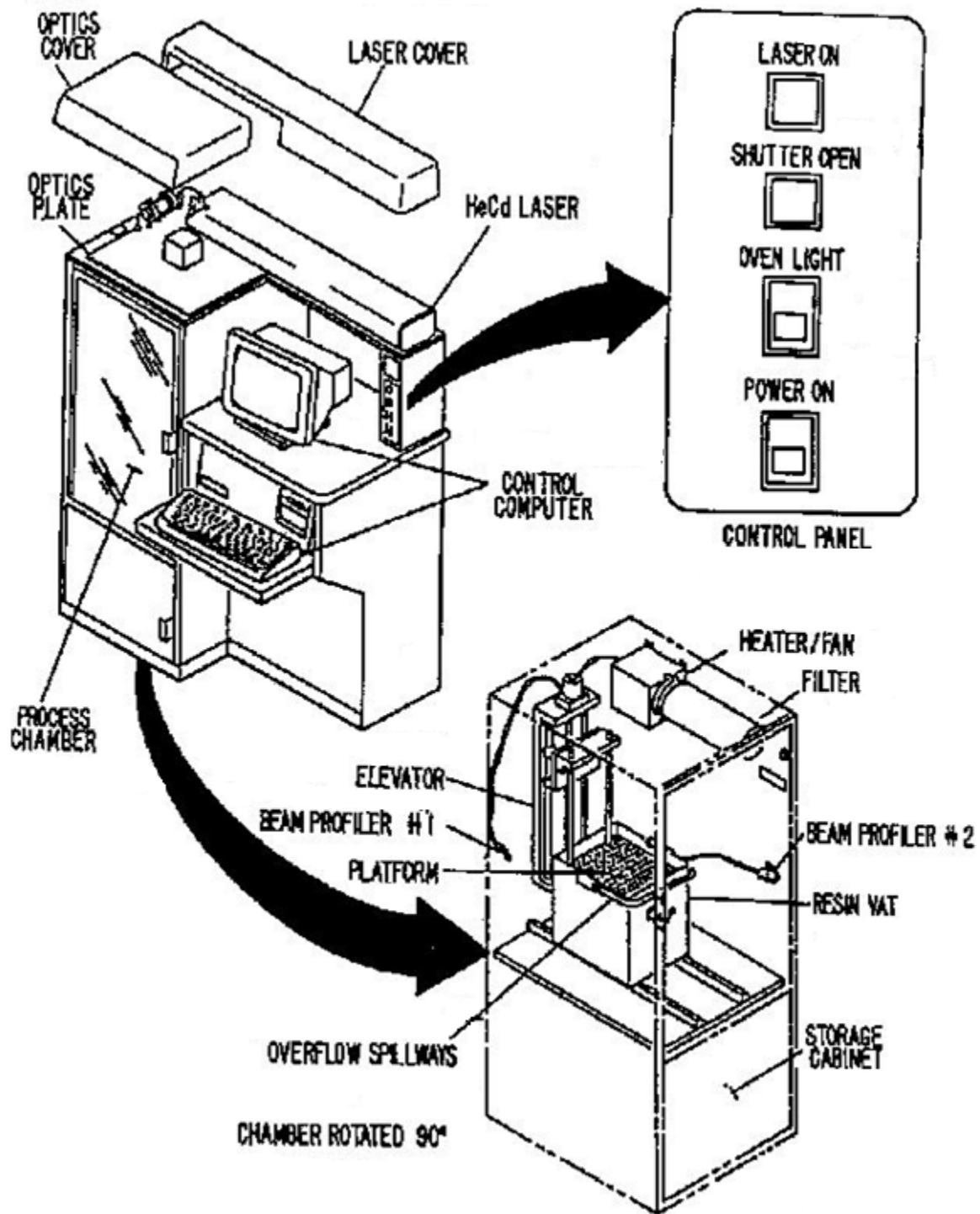


FIG. 33

[FIG. 34a, 34b]



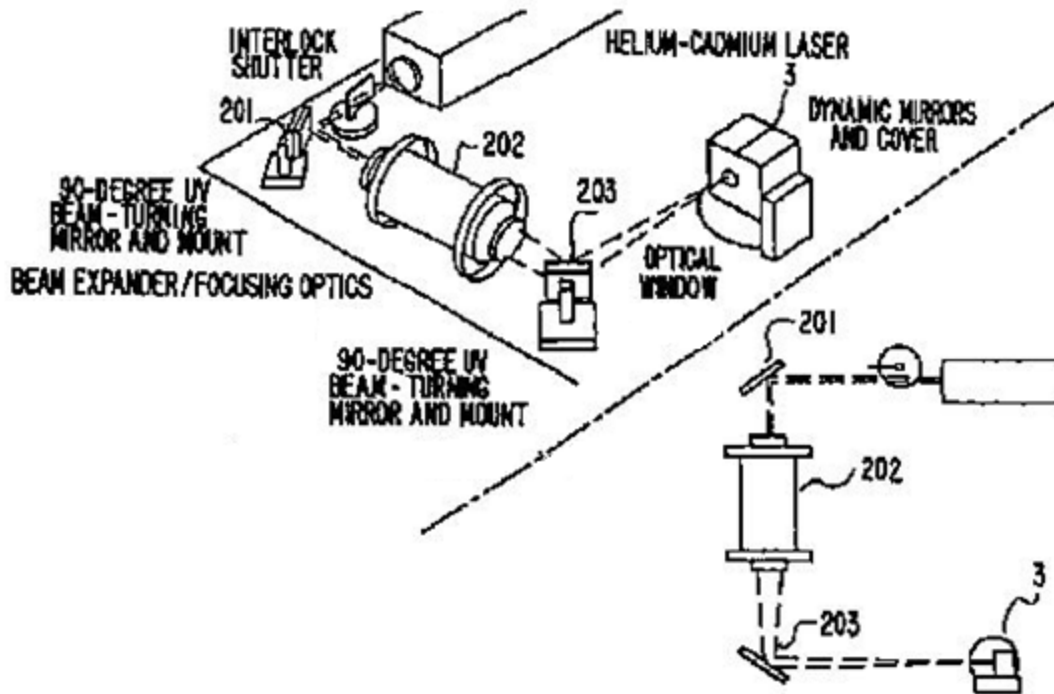
[FIG. 35]



MAJOR COMPONENTS OF THE SLA-1

FIG. 35

[FIG. 36]



THE SLA-I LASER AND OPTICAL SYSTEM

FIG. 36

[FIG. 37]

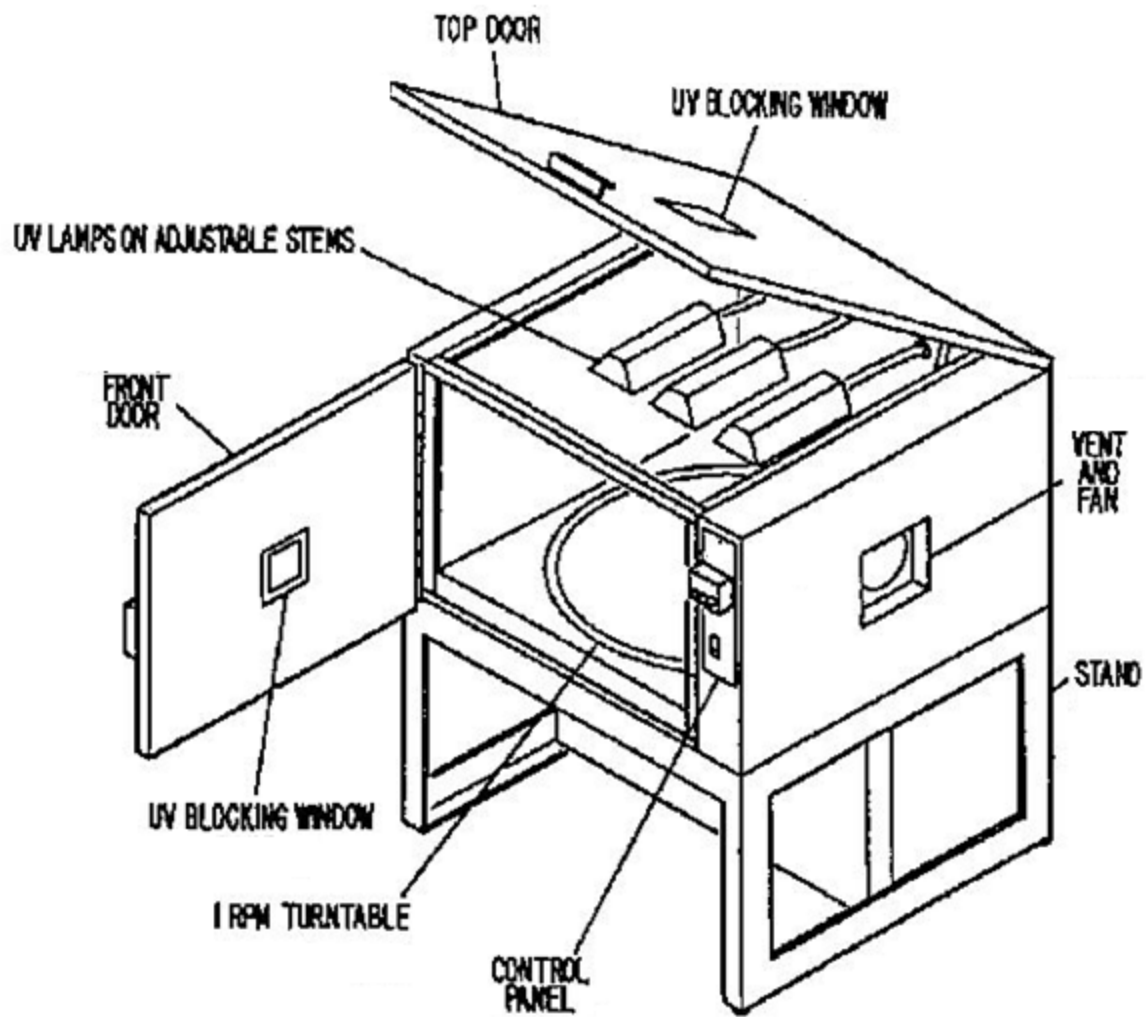
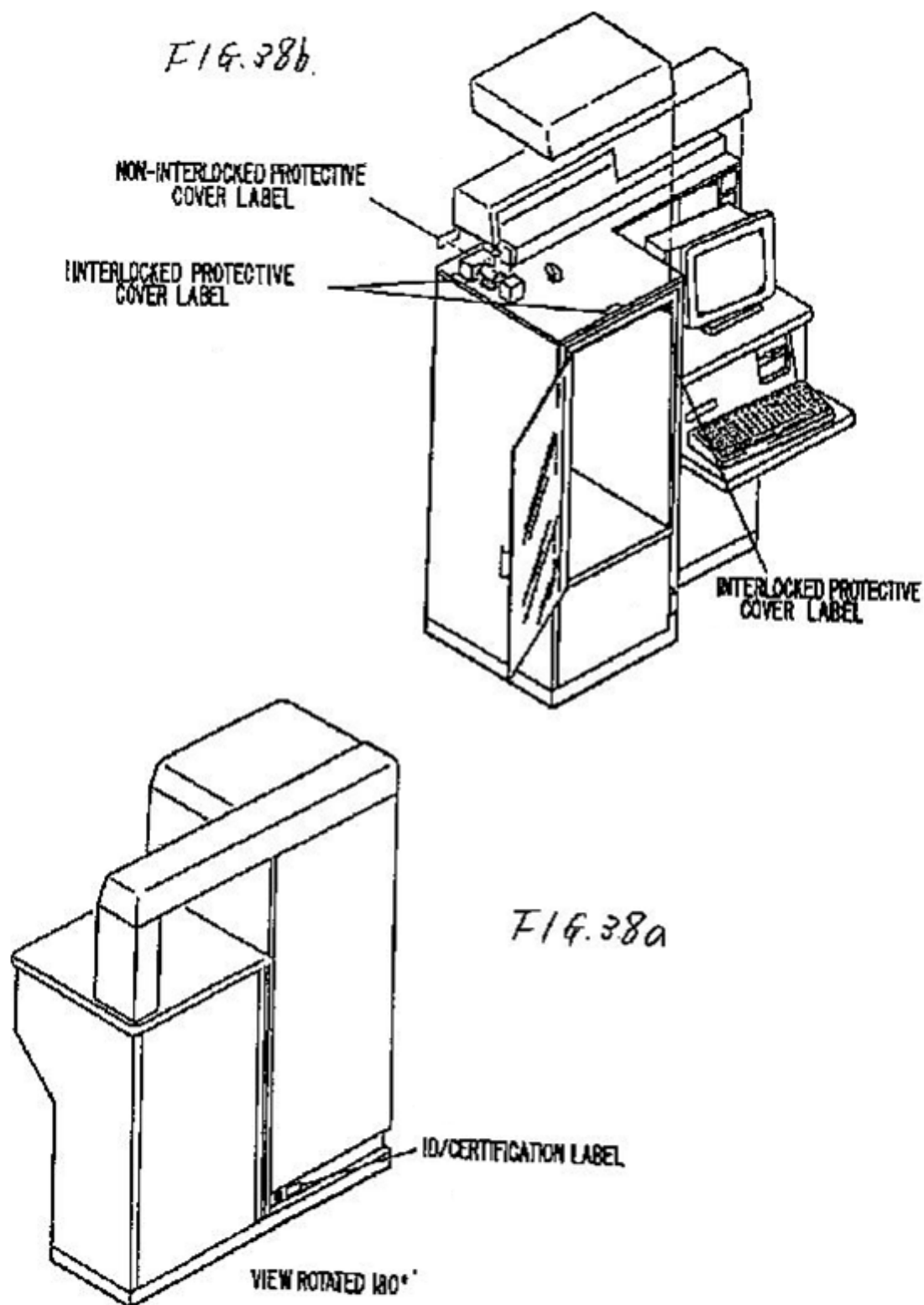


FIG. 37

[FIG. 38a, 38b]



LOCATIONS OF LASER WARNING AND SAFETY INFORMATION LABELS

[FIG. 39]

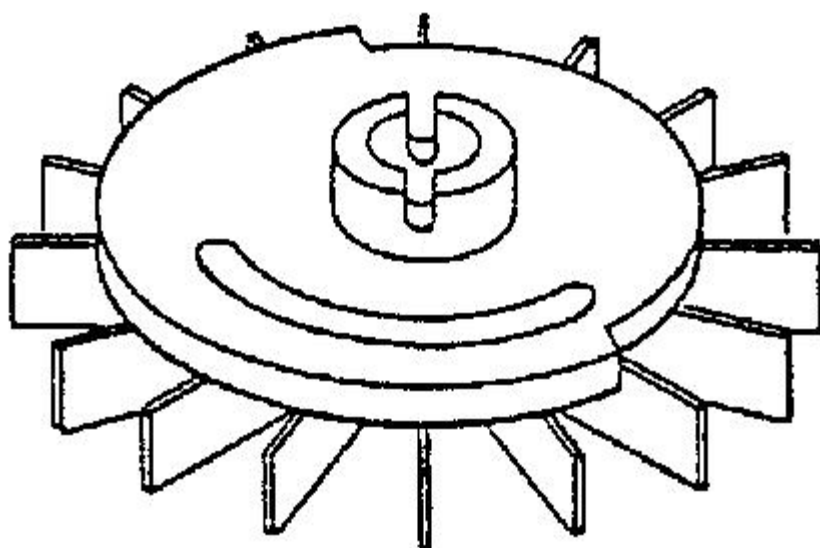
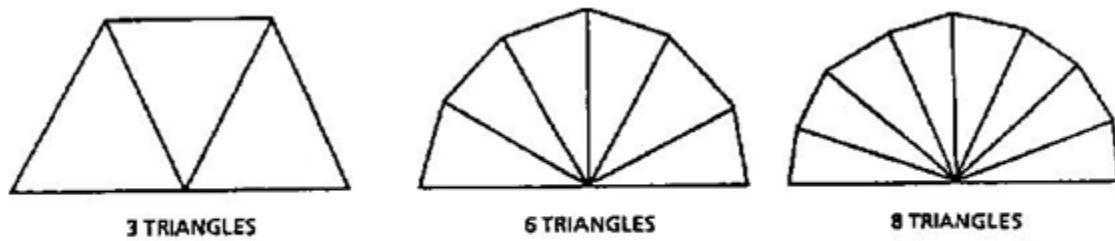


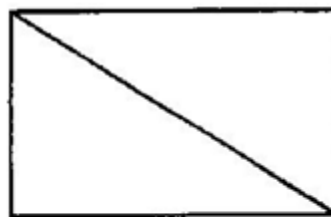
FIG. 39

[FIG. 40]



APPROXIMATING CURVED SURFACES

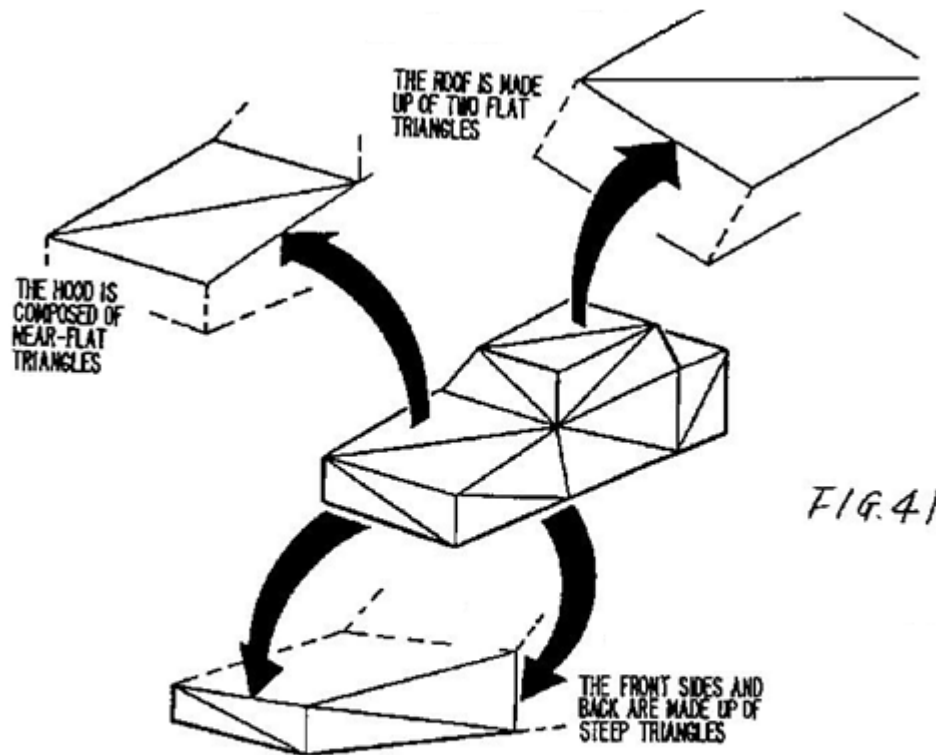
FIG. 40



APPROXIMATING A RECTANGULAR SURFACE

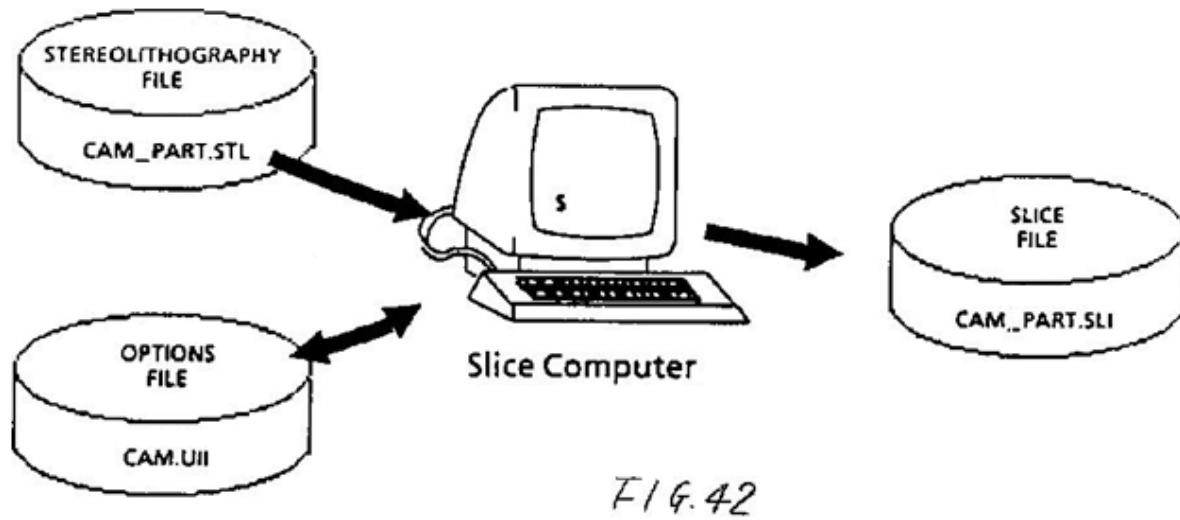
CURVED SURFACES REQUIRE MANY TRIANGLES TO APPROXIMATE
WHILE RECTANGLES ARE FULLY DESCRIBE BY ONLY TWO

[FIG. 41]

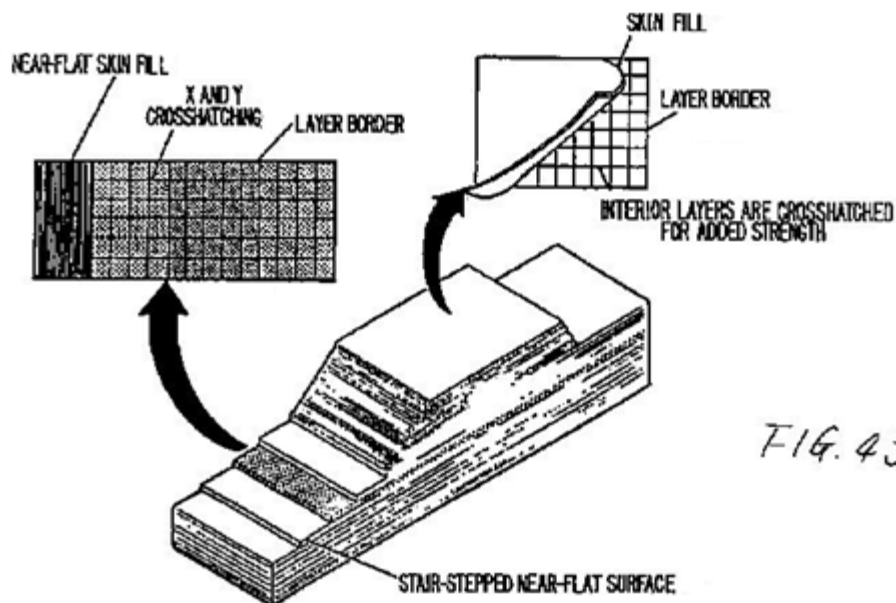


ANY CAD OBJECT CAN BE COMPLETELY DESCRIBED
BY FLAT, NEAR-FLAT AND STEEP TRIANGLES

[FIG. 42]

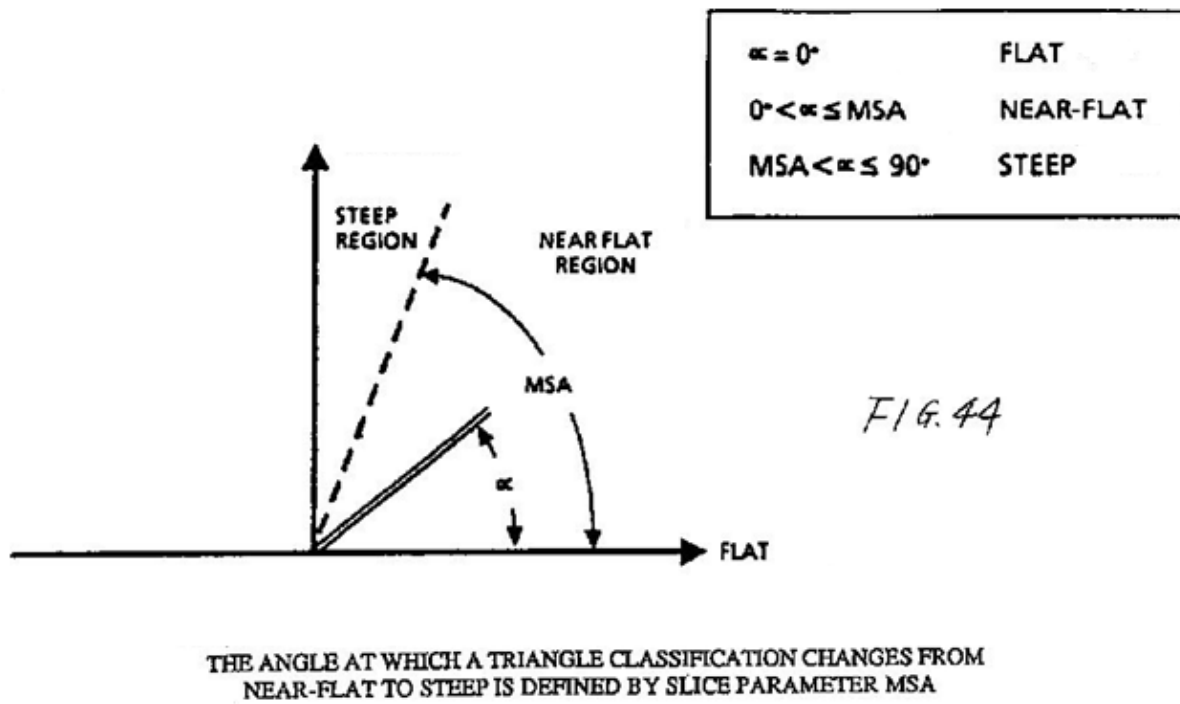


[FIG. 43]



THE TYPE OF TRIANGLE SLICED DETERMINES WHETHER THE AREA BETWEEN THE LAYER BORDERS IS CROSSHATCHED OR SKIN FILLED.

[FIG. 44]



[FIG. 45]

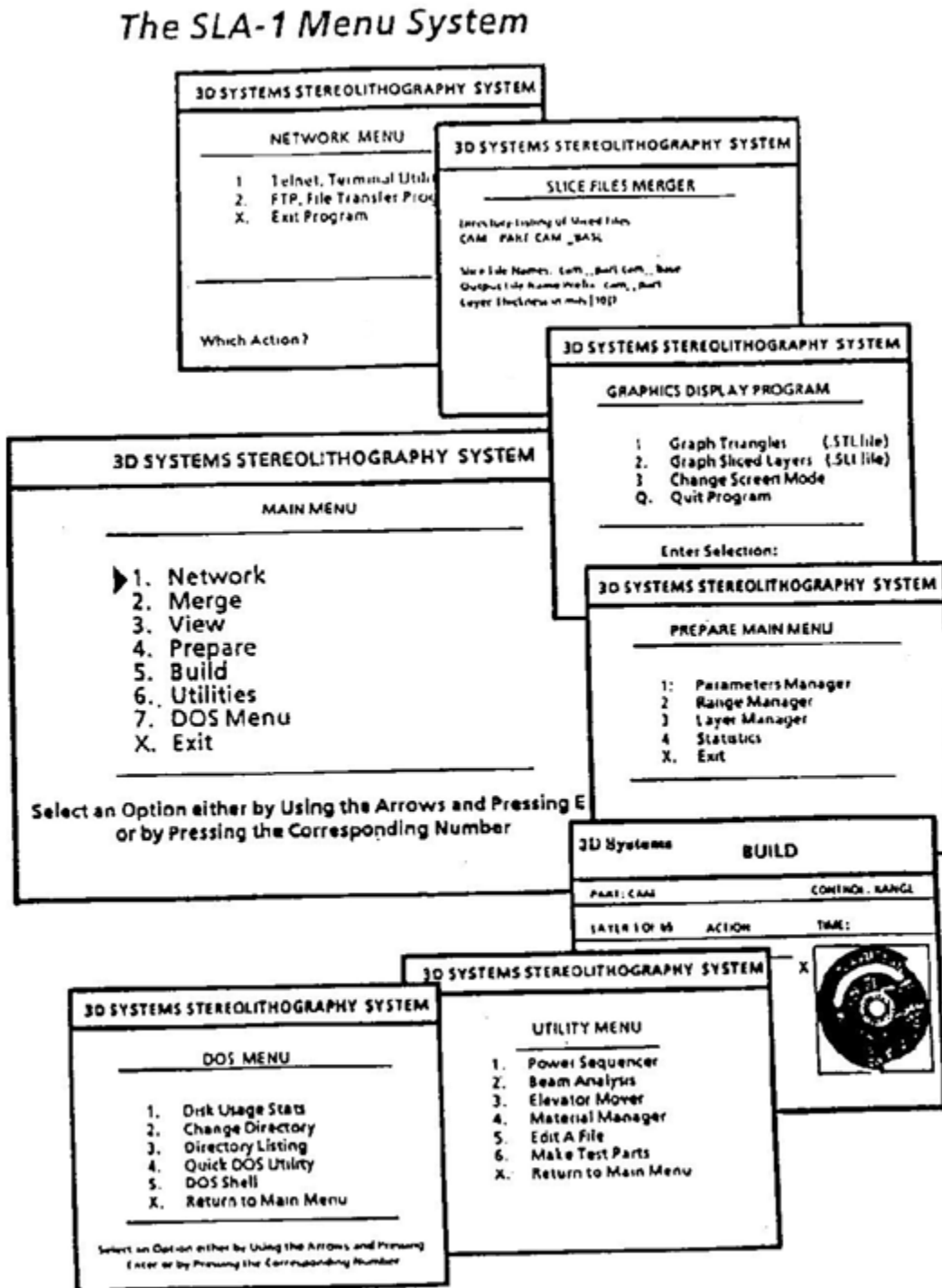


FIG. 45

[FIG. 46]

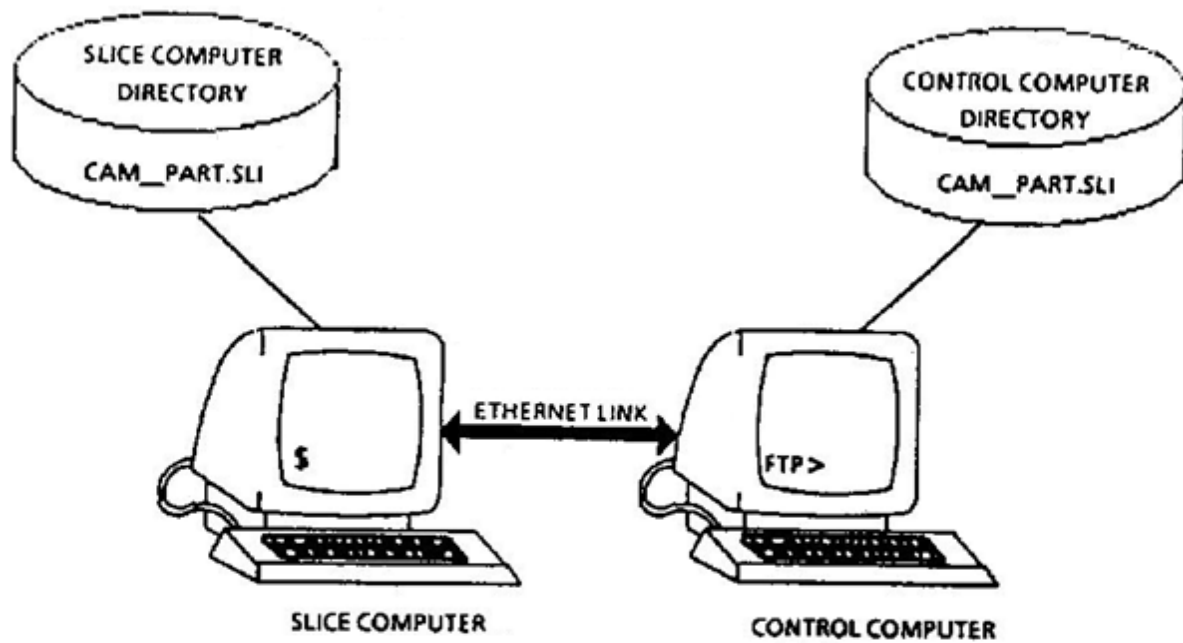


FIG. 46

[FIG. 47]

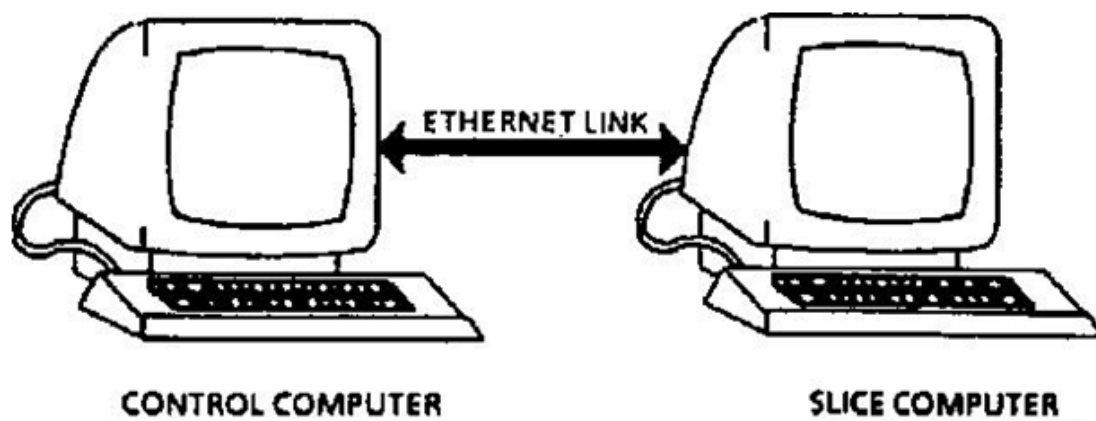
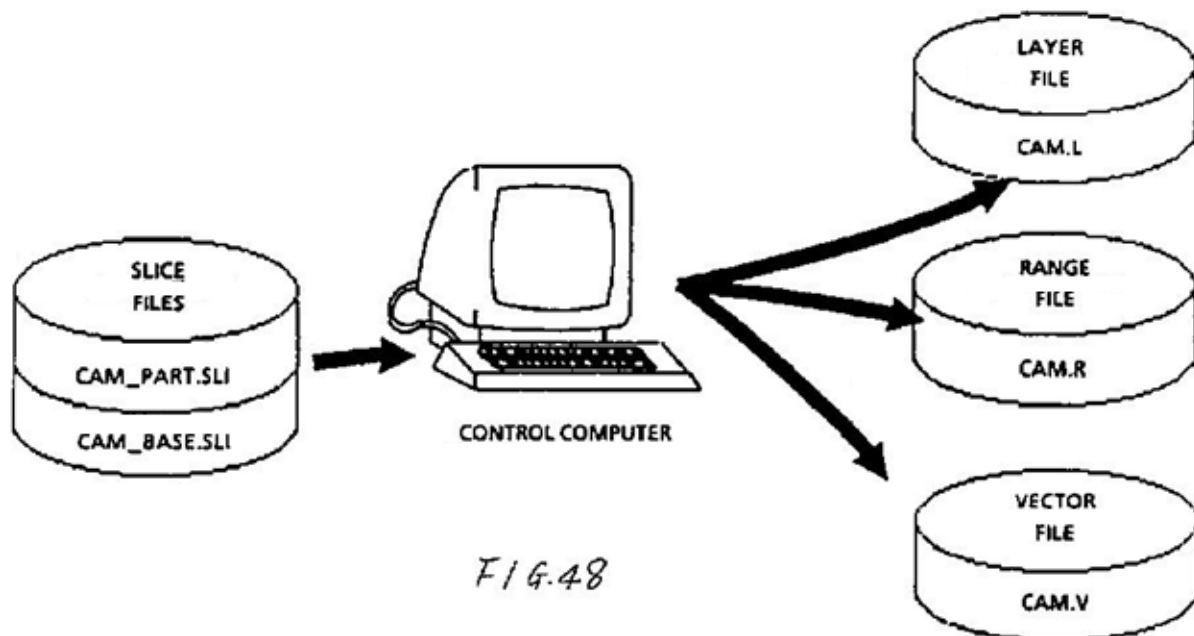
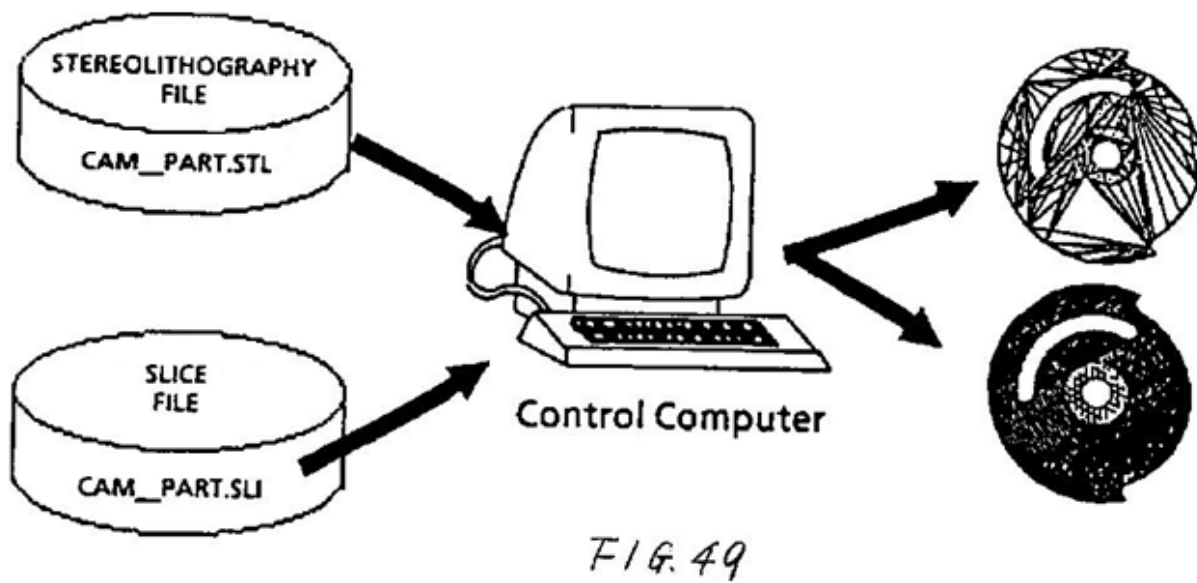


FIG. 47

[FIG. 48]



[FIG. 49]



[FIG. 50]

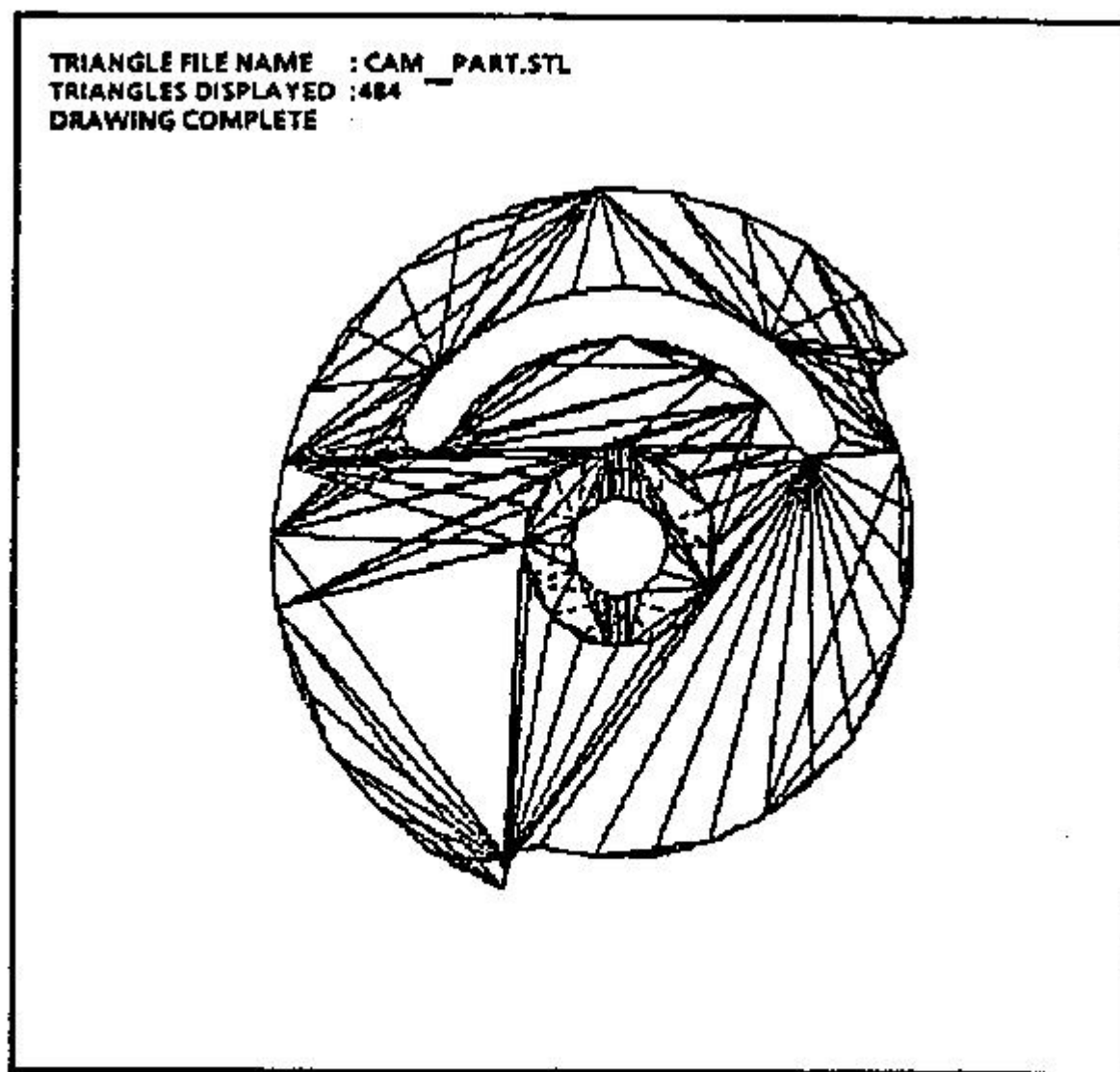
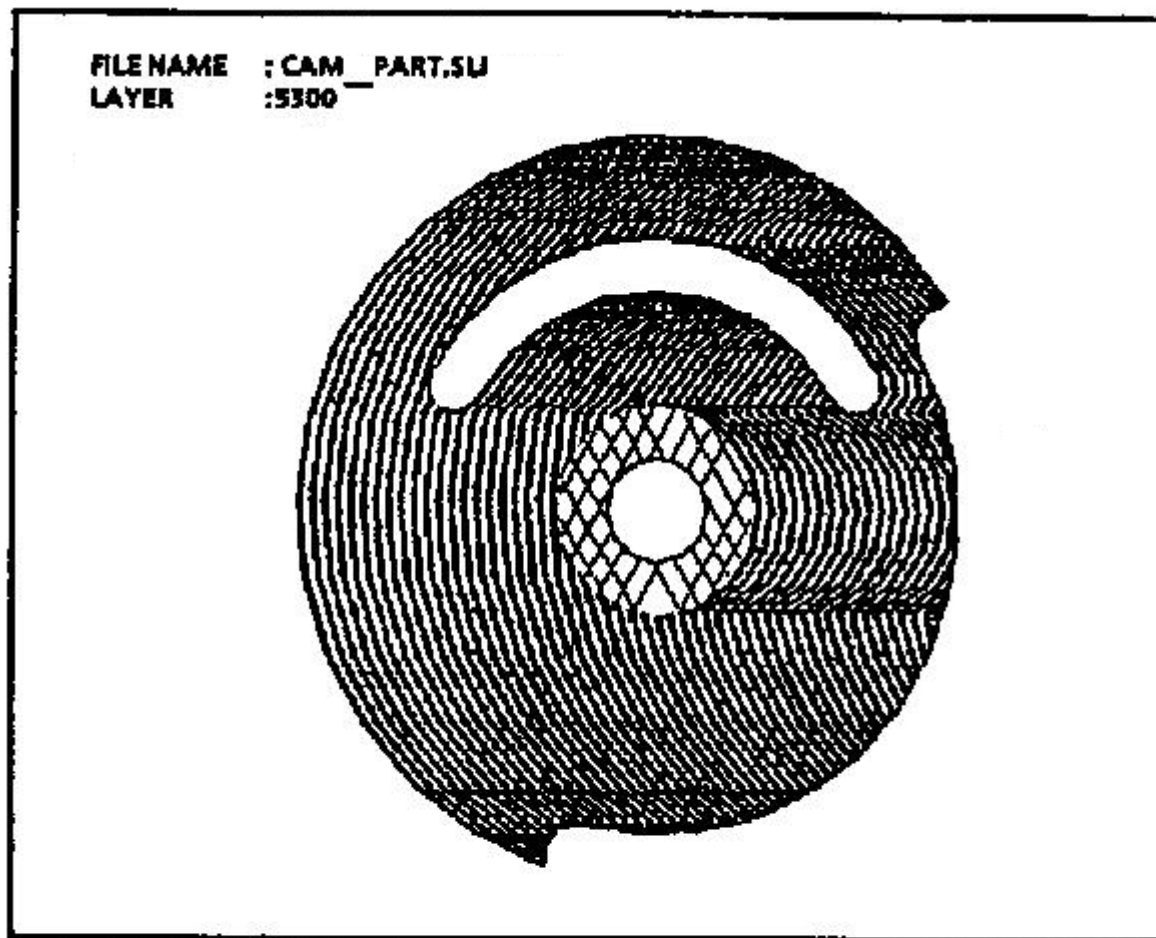


FIG. 50

[FIG. 51]

*FIG. 51*

[FIG. 52]

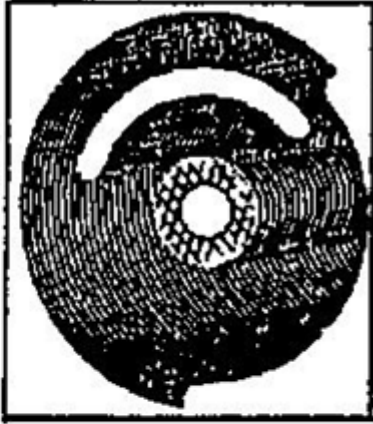
3D Systems		BUILD	
PART: CAM		CONTROL: RANGE	
LAYER 28 OF 65		ACTION: TIME:	
START TIME: MON 3/23/88 11:15 AM END TIME:			
START LAYER: 3650 ON LAYER: 5000 END LAYER: 6850	BLOCK LB1		
PART FILENAME:			

FIG. 52

[FIG. 53]

3D Systems		BUILD	
PART: CAM		CONTROL: RANGE	
LAYER 1 OF 65		ACTION: DRAWING	
TIME:			
START TIME: MON 3/23/88 11:15 AM			
END TIME:			
START LAYER: 3650 ON LAYER: 3650 END LAYER: 6850	BLOCK LB2		

FIG. 53

[FIG. 54a]

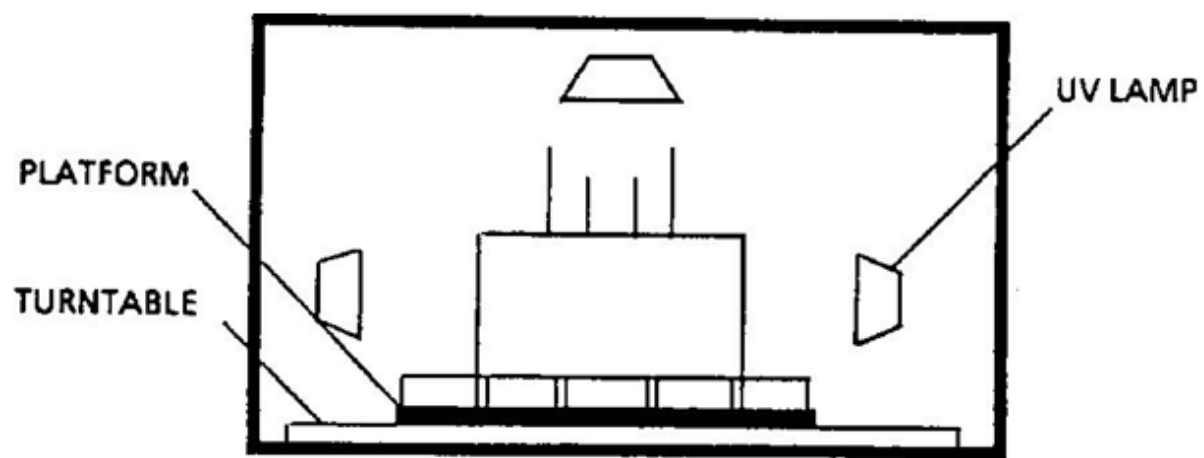


FIG. 54

[FIG. 54b, 54c]

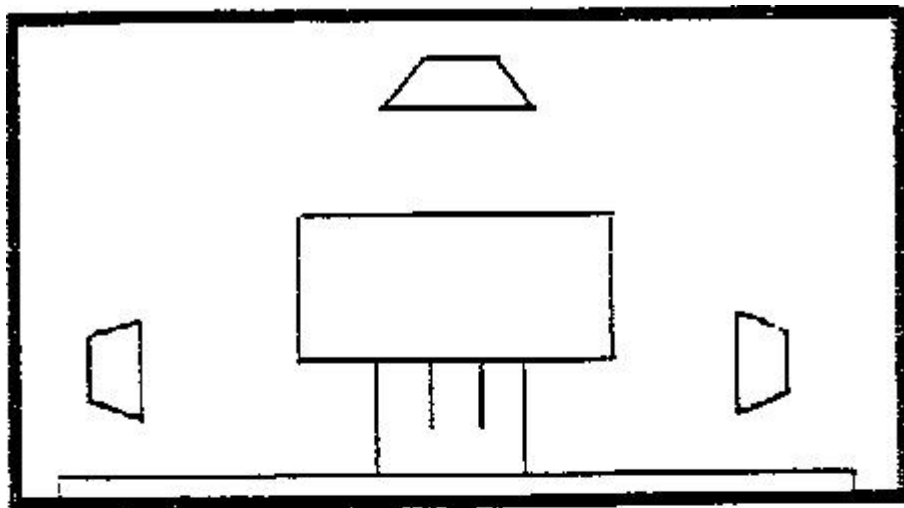
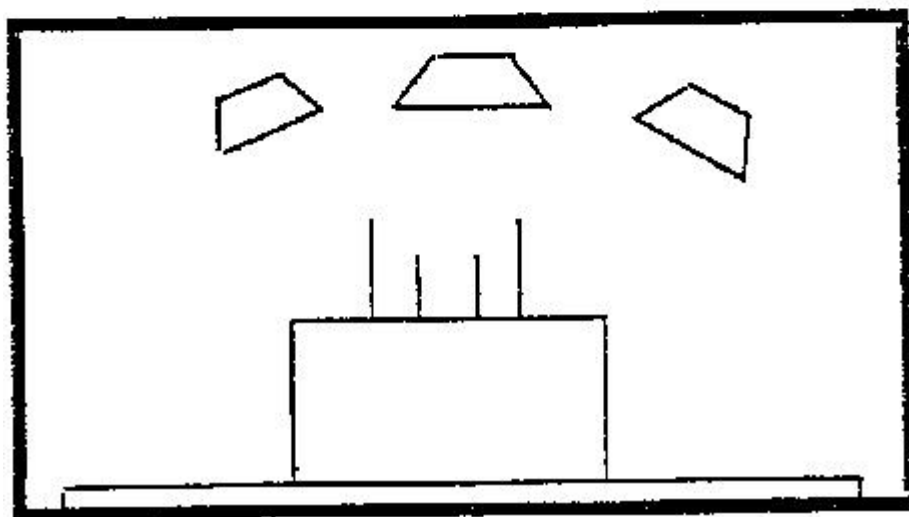


FIG. 54b.

FIG. 54c.



[FIG. 55]

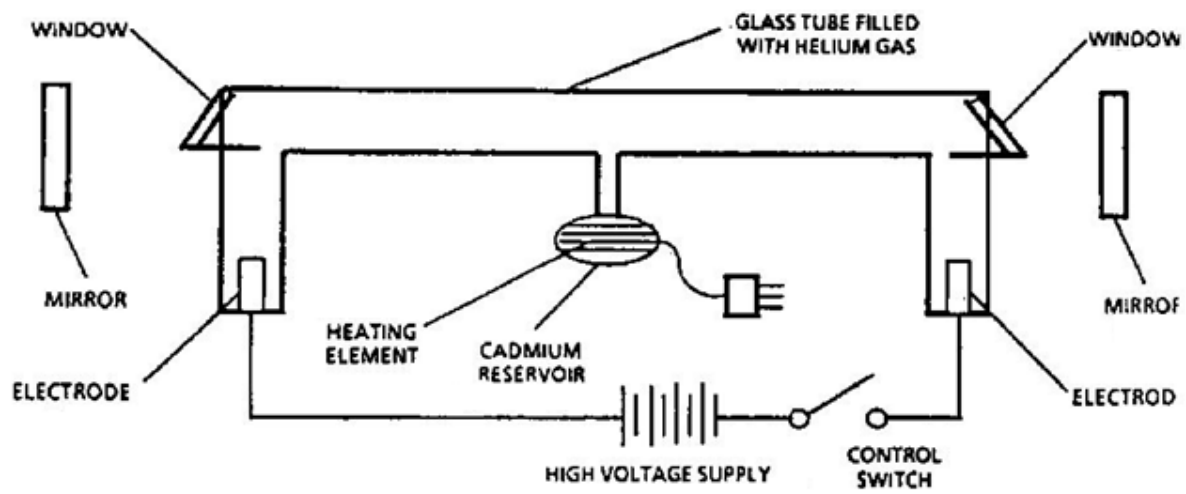


FIG. 55

[FIG. 56]

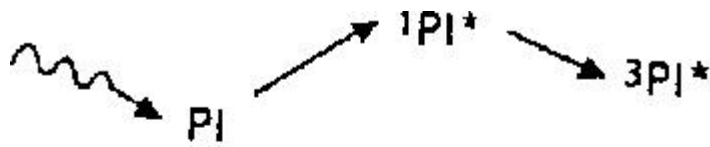
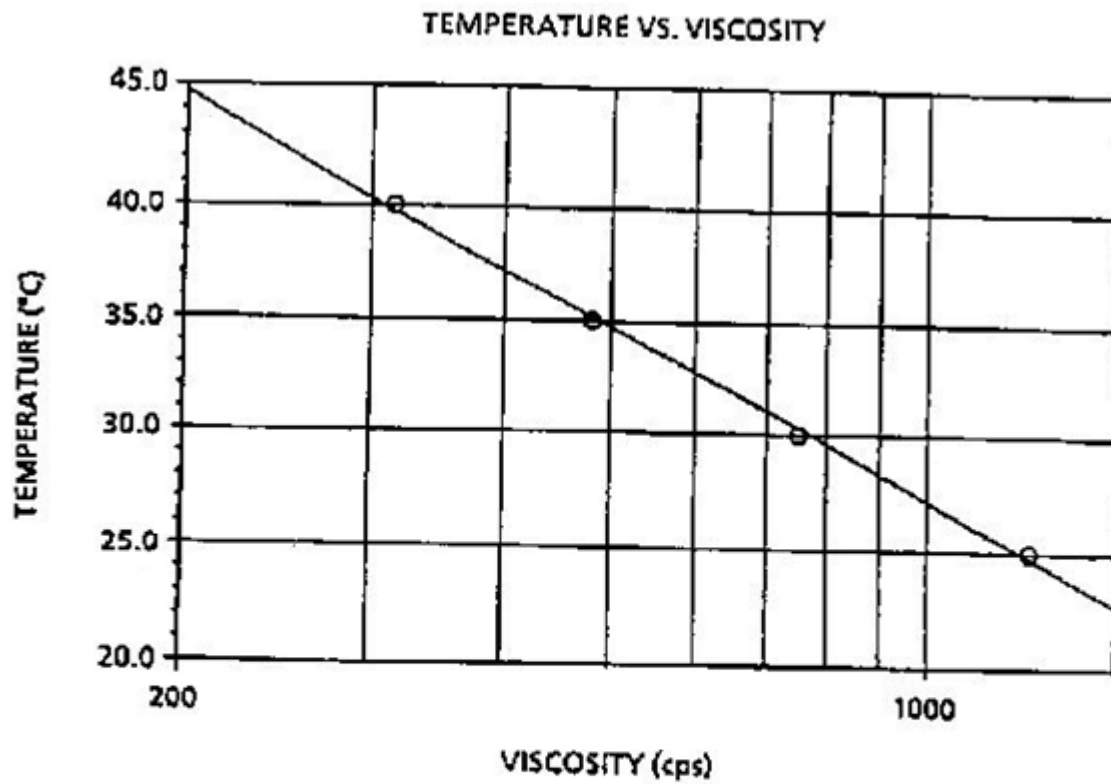


FIG. 56

[FIG. 57]

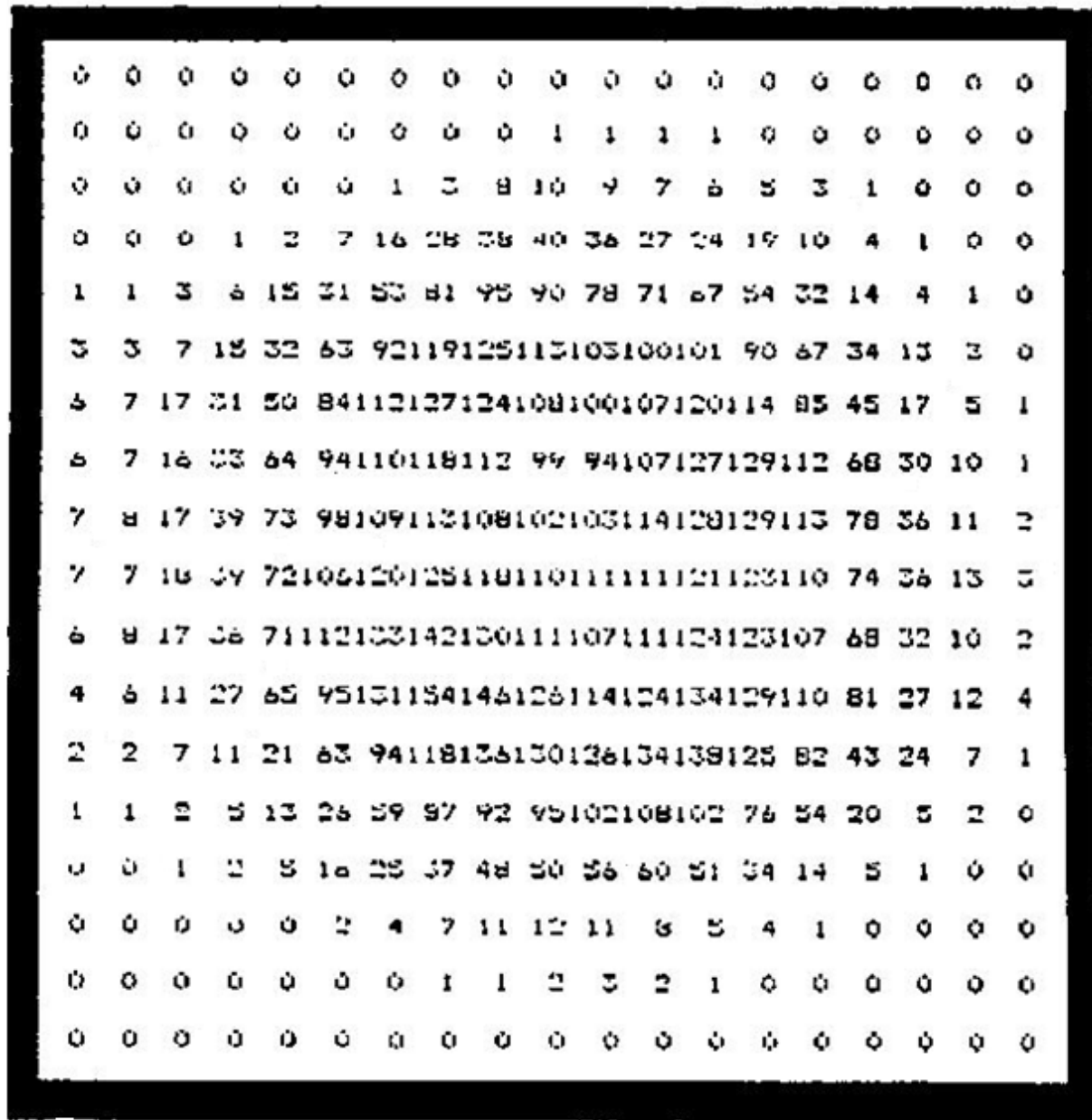


A SMALL CHANGE IN TEMPERATURE CAUSES
A LARGE CHANGE IN VISCOSITY.

FIG. 57

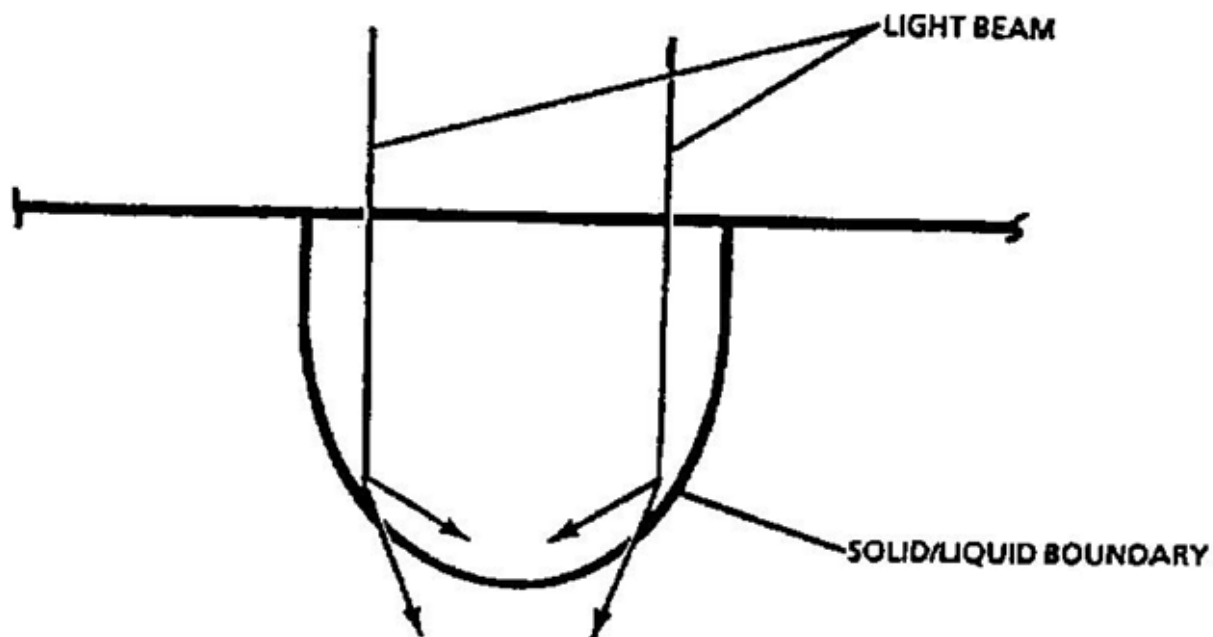
[FIG. 58]

FIG. 58



AN INTENSITY PROFILE SHOWING A MAXIMUM
NEAR THE CENTER OF THE BEAM.

[FIG. 59]



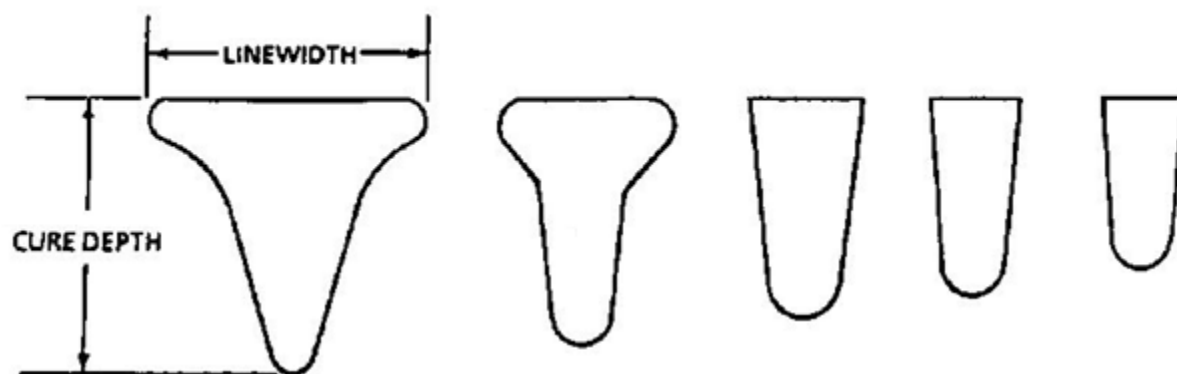
THE CHANGE IN REFRACTIVE INDEX OF THE RESIN AS IT
TRANSFORMS FROM LIQUID TO SOLID ENHANCES THE BULLET SHAPE

FIG. 59

(150)

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[FIG. 60]

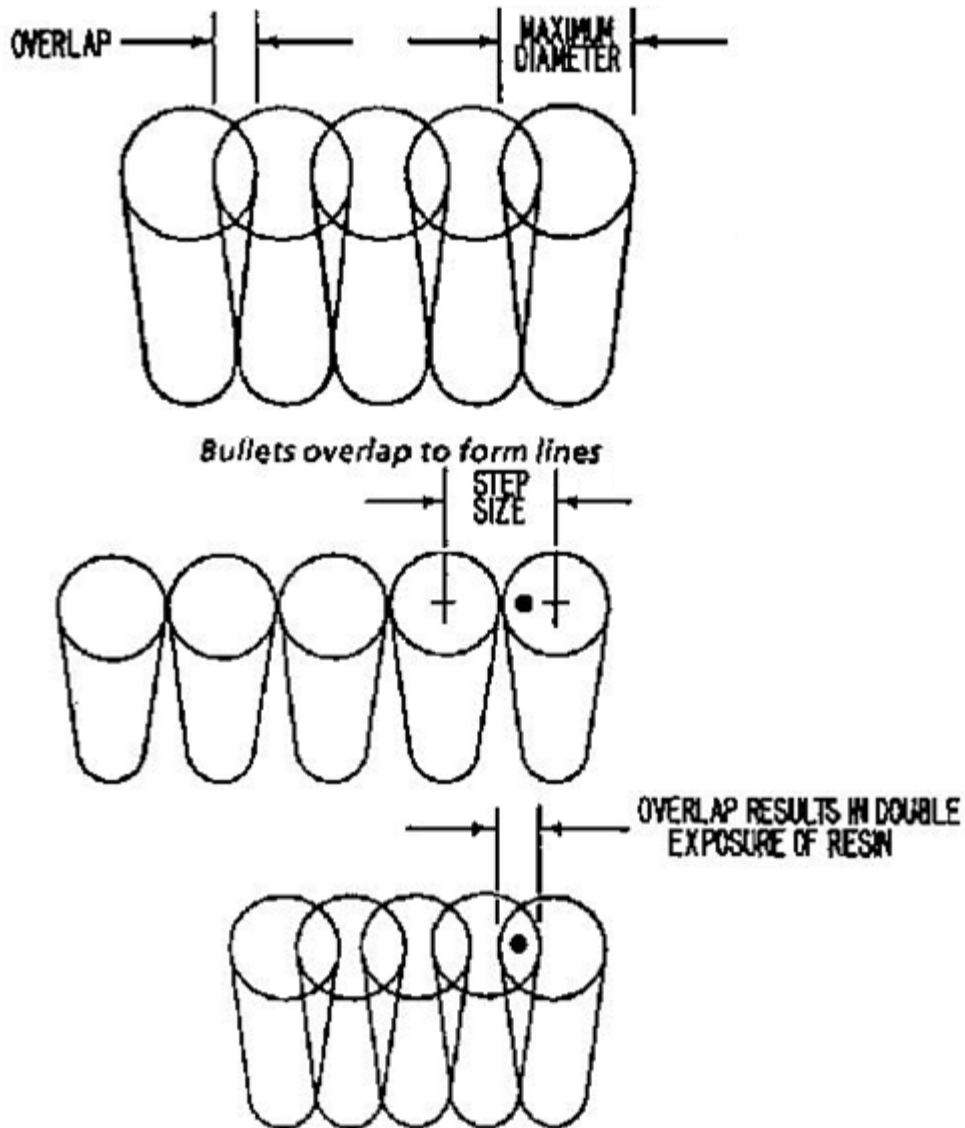


STEP PERIOD VALUES DETERMINE THE OVERALL DIMENSIONS
OF BULLETS AND ALSO AFFECT BULLET SHAPE

FIG. 60

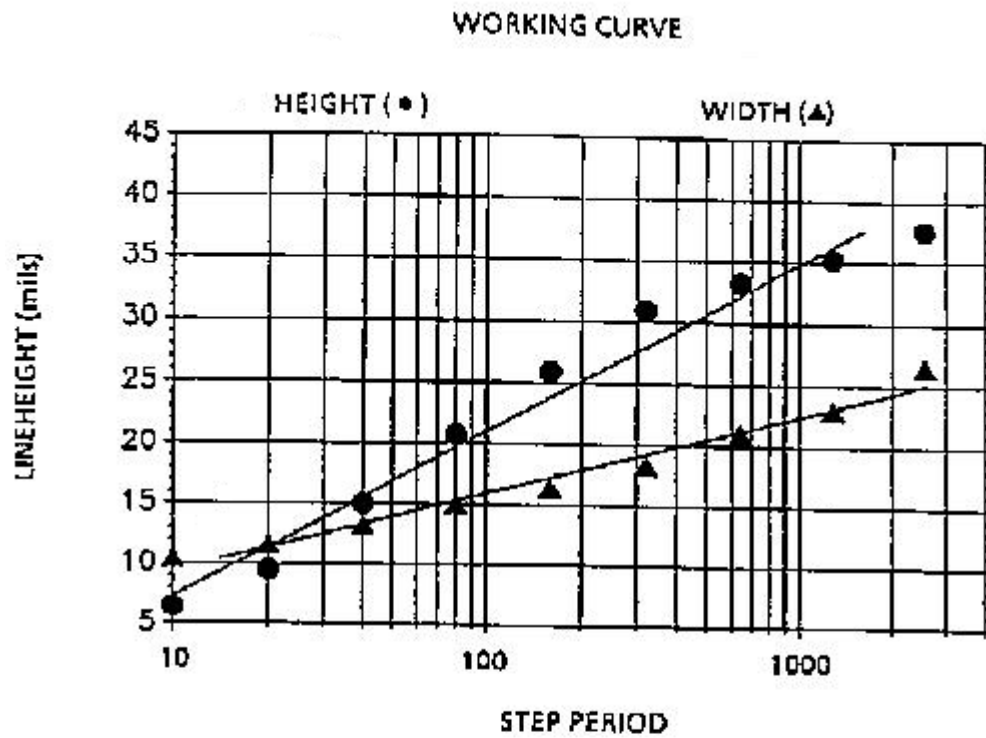
[FIG. 61]

F1G. 61



CERTAIN POINTS WILL BE MORE HEAVILY CURED IF THE STEP SIZE IS LESS THAN OR EQUAL TO THE MAXIMUM DIAMETER OF THE BULLETS

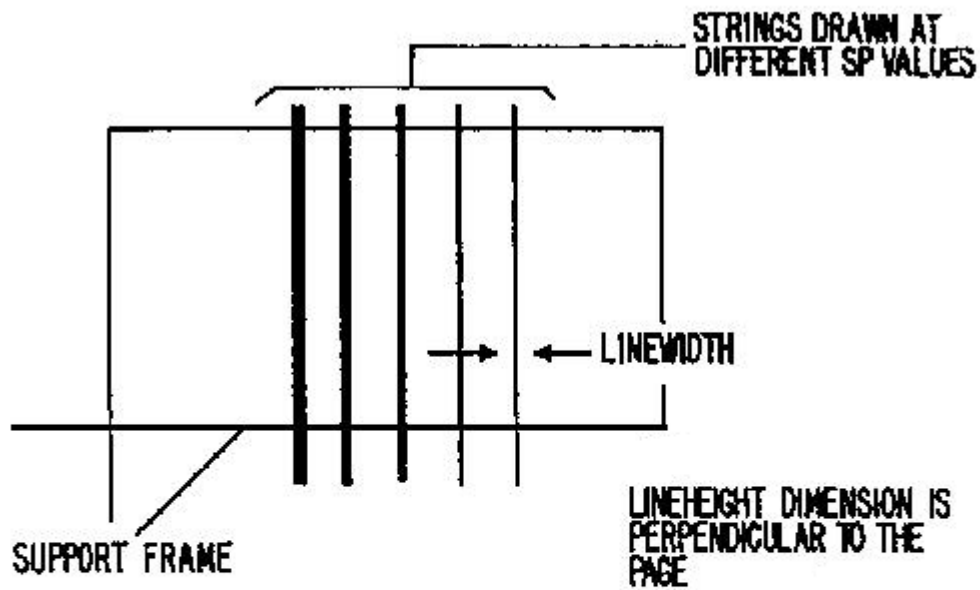
[FIG. 62]



CURVE IS A GRAPH THAT SHOWS LINEHEIGHT
AND LINEWIDTH PORTION OF STEP PERIOD

FIG. 62

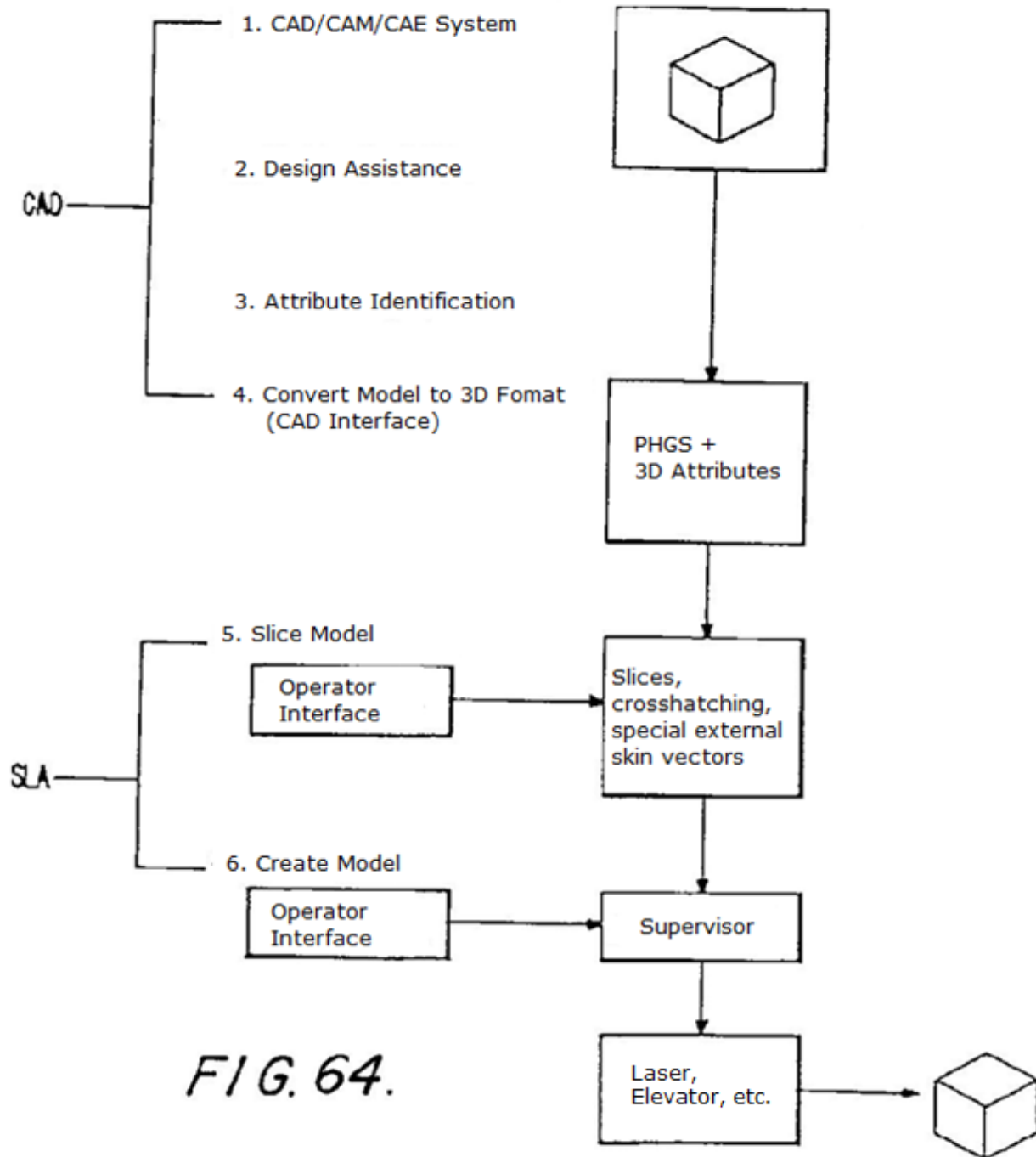
[FIG. 63]



BANJOTOPS HAVE FIVE STRINGS FORMED USING
DIFFERENT STEP PERIODS AND A FIXED STEP SIZE

FIG. 63

[FIG. 64]



[FIG. 65a, 65b]

SLA Overview

```

solid Solid_Tetra.2
  facet normal -1 0 0
    outer loop
      vertex 0 0 0
      vertex 0 0 1
      vertex 0 1 0
    endloop
  endfacet
  facet normal 0 -1 0
    outer loop
      vertex 0 0 0
      vertex 1 0 0
      vertex 0 1 0
    endloop
  endfacet
  facet normal 0 0 -1
    outer loop
      vertex 0 0 0
      vertex 0 1 0
      vertex 1 0 0
    endloop
  endfacet
  facet normal n1 n2 n3
    outer loop
      vertex 1 0 0
      vertex 0 1 0
      vertex 0 0 1
    endloop
  endfacet
endsolid Solid_Tetra.2

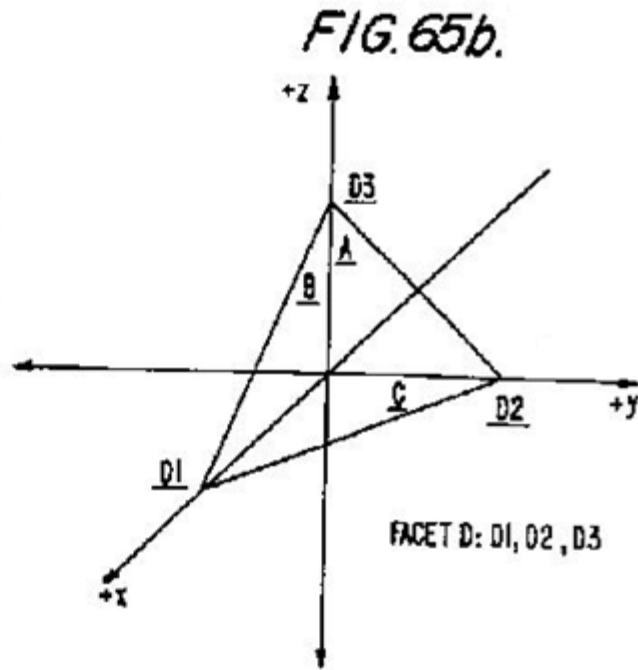
```

A

B

C

D

**FIG. 65a.**

Note: ASCII floating point notation is expected for dimensions and point coordinates.
e.g., "6.58537e-10"

[FIG. 66]

Data Format	Range	Precision	Top Byte: Highest Addressed Byte											
			7	0	7	0	7	0	7	0	7	0	7	0
Word Integer	10^4	16 BITS	(Complement of 2)											
			15										0	
Short Word	10^9	32 BITS	(Complement of 2)											
			31										0	
Long Word	10^{19}	64 BITS	(Complement of 2)											
			63										0	
Pack BCD	10^{18}	18 DIGITS	S	X	d ₁₇	d ₁₆	d ₁₅	d ₁₄	d ₁₃	d ₁₂	d ₁₁	d ₁₀	d ₉	d ₈
			79	72										
Short Real Number	10^{+38}	24 BITS	S	Biased Exponent		Significant Digit								
			31		23									0
Long Real Number	10^{+308}	53 BITS	S	Biased Exponent		Significant Digit								
			63		52									0
Transient Number	10^{+1632}	64 BITS	S	Biased Exponent		Significant Digit								
			79		64	63								

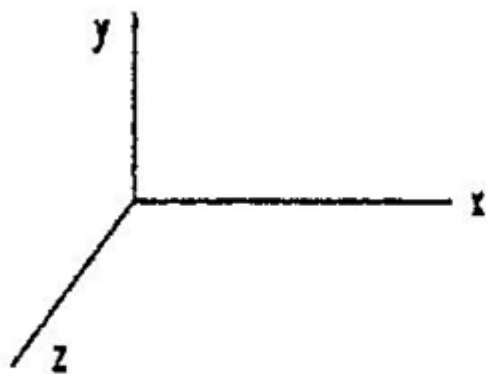
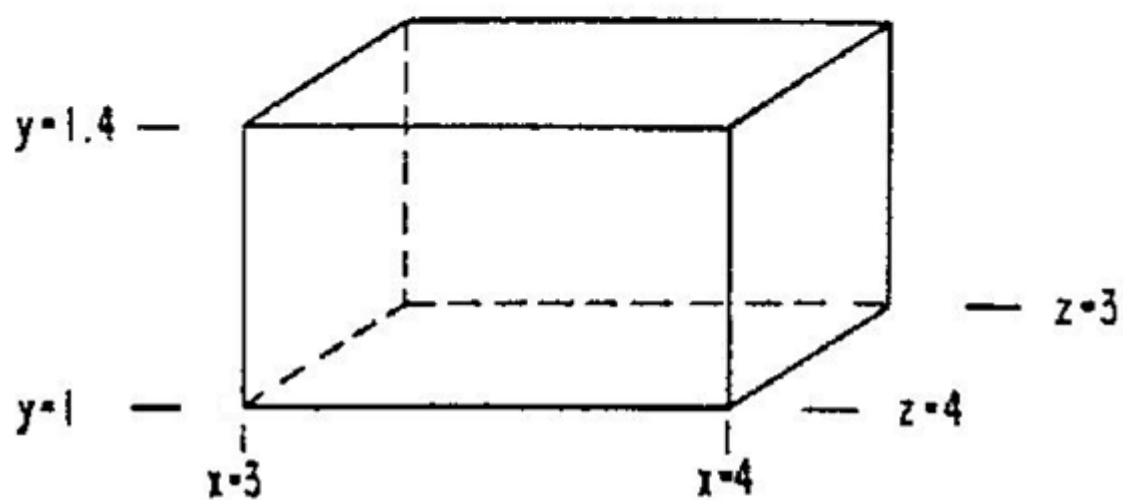
Notes:

- (1) S: Code bit (0 = positive, 1 = negative)
- (2) d: Base 10 (2 each byte)
- (3) X: Unweighted bits: 8087 are ignored during loading and zeroed out when stored
- (4) ▲: Position of binary point of entry
- (5) I: Integer bits of significant digits: stored in short and long real numbers, stored in transient real numbers
- (6) Exponent bias (Normalized values): Short real numbers: 127 (7FH)
Long real numbers: 1023 (3FFH)
Transient real numbers: 16383 (3FFFH)
- (7) Pack BCD: $(-1)^3 (D_{17} \dots D_0)$
- (8) Real numbers: $(-1)^2 (2\text{-exponent bias}) (F_0 F_1 \dots)$

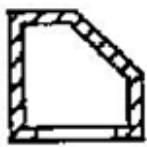
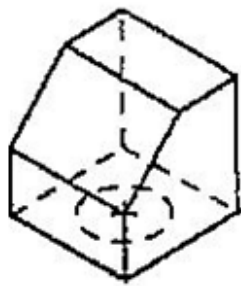
FIG. 66.

[FIG. 67]

TEST0017.STL

*FIG. 61.*

[FIG. 68a, 68b]



A-A Diagram

Thickness of
all walls is
usually 0.10

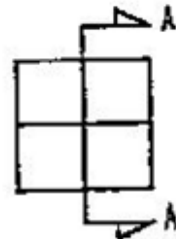
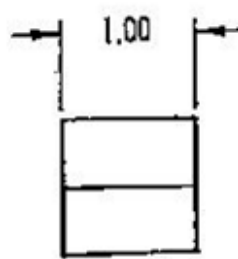
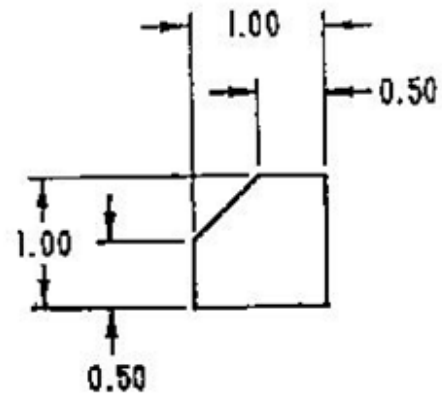
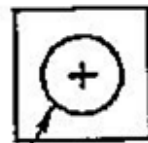


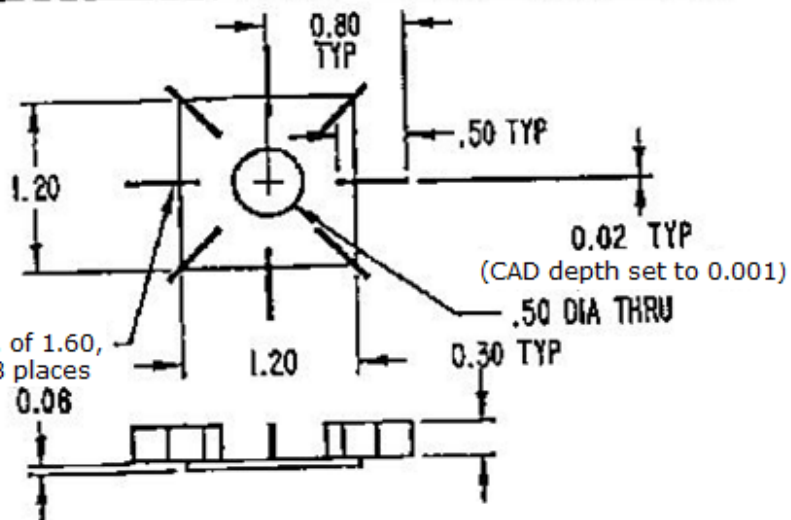
FIG. 68a



Note: 1. Units are all in inches
2. Not to scale



0.60 dia. through-hole

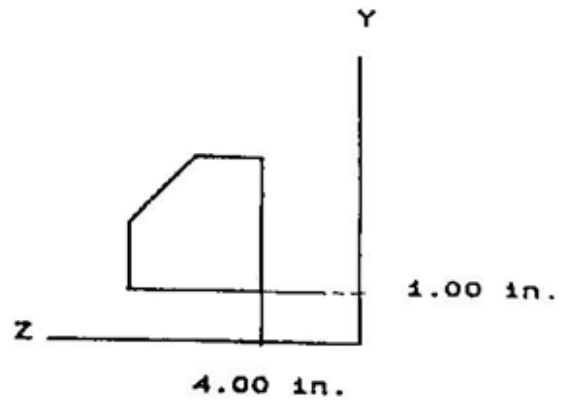
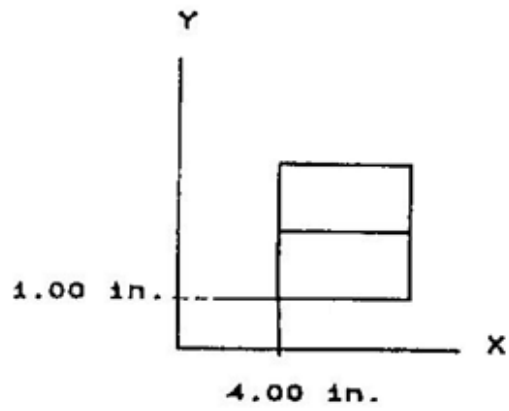


Each web has ext. dia. of 1.60,
45-degree contact at 8 places

FIG. 68b

[FIG. 69a, 69b]

Spatial Arrangement of Test Box



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Continued From Front Page

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