



US006923634B2

(12) **United States Patent**
Swanson et al.

(10) **Patent No.:** **US 6,923,634 B2**
(45) **Date of Patent:** **Aug. 2, 2005**

(54) **FILAMENT LOADING SYSTEM IN AN
EXTRUSION APPARATUS**

(75) Inventors: **William J. Swanson**, St. Paul, MN
(US); **Minea A. Popa**, Roseville, MN
(US); **Patrick W. Turley**, Eden Prairie,
MN (US); **Paul E. Hopkins**, Savage,
MN (US); **Steve Brose**, Belle Plaine,
MN (US); **Daniel I. Kimm**, Leucadia,
CA (US); **David L. Pollard**, Mountain
Center, CA (US); **Andrew M. Hahn**,
Anaheim, CA (US)

(73) Assignee: **Stratasys, Inc.**, Eden Prairie, MN (US)

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 57 days.

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(21) Appl. No.: **10/736,360**

(22) Filed: **Dec. 15, 2003**

(65) **Prior Publication Data**

US 2004/0126452 A1 Jul. 1, 2004

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Related U.S. Application Data

(60) Division of application No. 09/804,401, filed on Feb. 27, 2001, now Pat. No. 6,776,602, which is a continuation-in-part of application No. PCT/US00/17363, filed on Jun. 23, 2000.

(60) Provisional application No. 60/218,642, filed on Jul. 13, 2000, and provisional application No. 60/140,613, filed on Jun. 23, 1999.

(51) **Int. Cl.⁷** **B29C 41/02**; B29C 41/36

(52) **U.S. Cl.** **425/169**; 425/190; 425/375;
425/376.1

(58) **Field of Search** 425/169, 190,
425/375, 376.1

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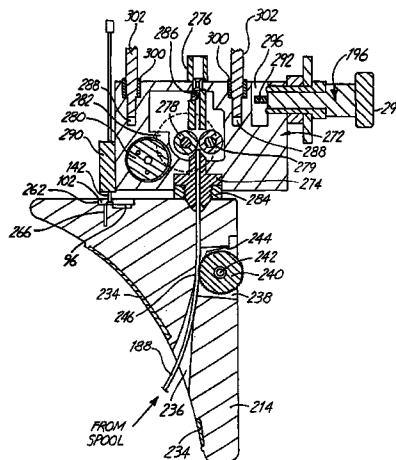
Primary Examiner—Robert B. Davis

(74) *Attorney, Agent, or Firm*—Kinney & Lange, P.A.

(57) **ABSTRACT**

An apparatus which extrudes flowable material from a liquifier includes a system for loading filament supplied in a cassette. The cassette is loaded into a loading bay of the apparatus. A strand of filament from the cassette is engaged and advanced along a path to the liquifier using a drive wheel or roller pair. A conduit having an entrance in the loading bay guides the filament as it is advanced. The filament loading system of the present invention provides a convenient manner of loading and unloading filament in a three-dimensional modeling machine, and can be implemented in a manner that protects the filament from environmental moisture.

28 Claims, 20 Drawing Sheets



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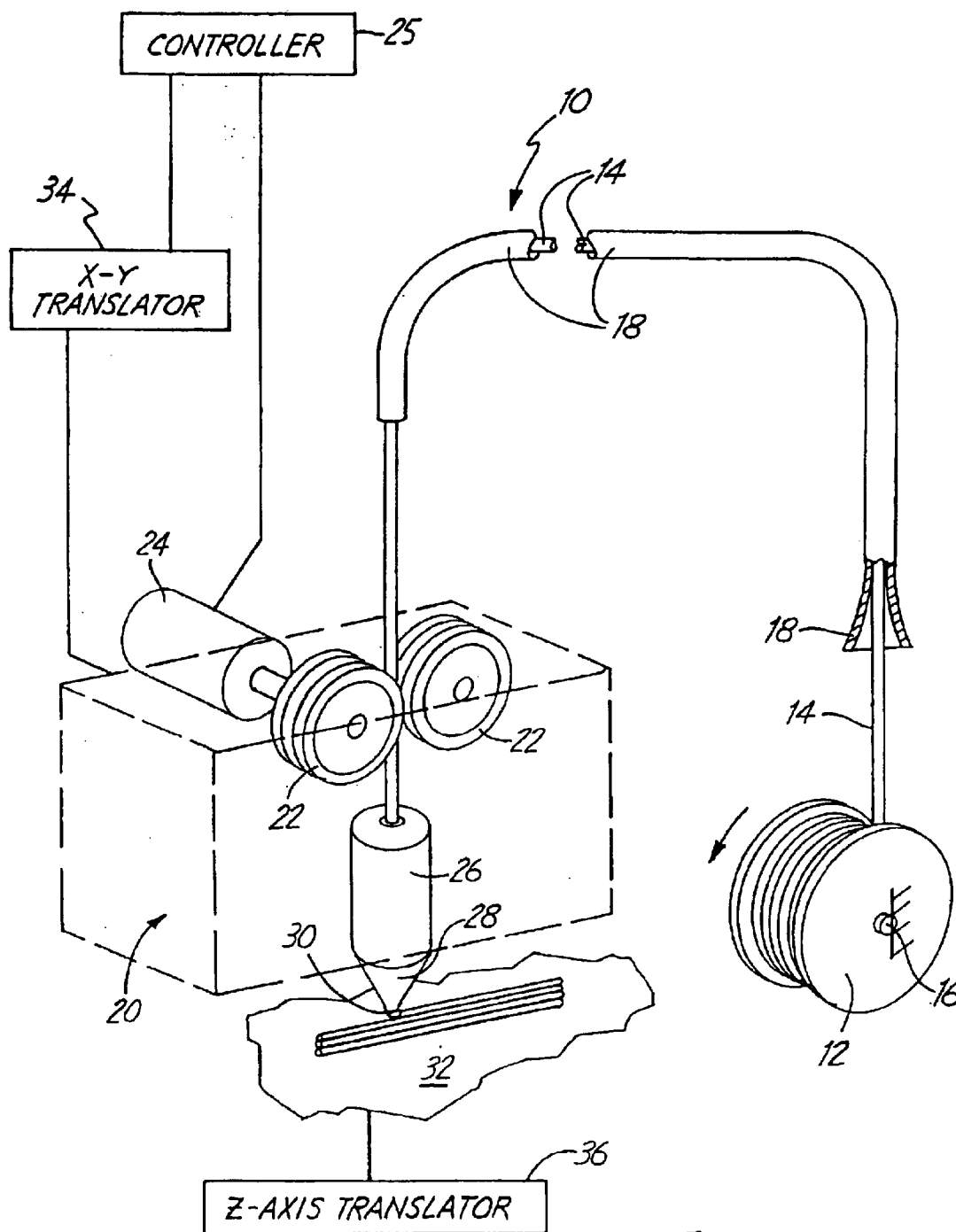


FIG. 1

PRIOR ART

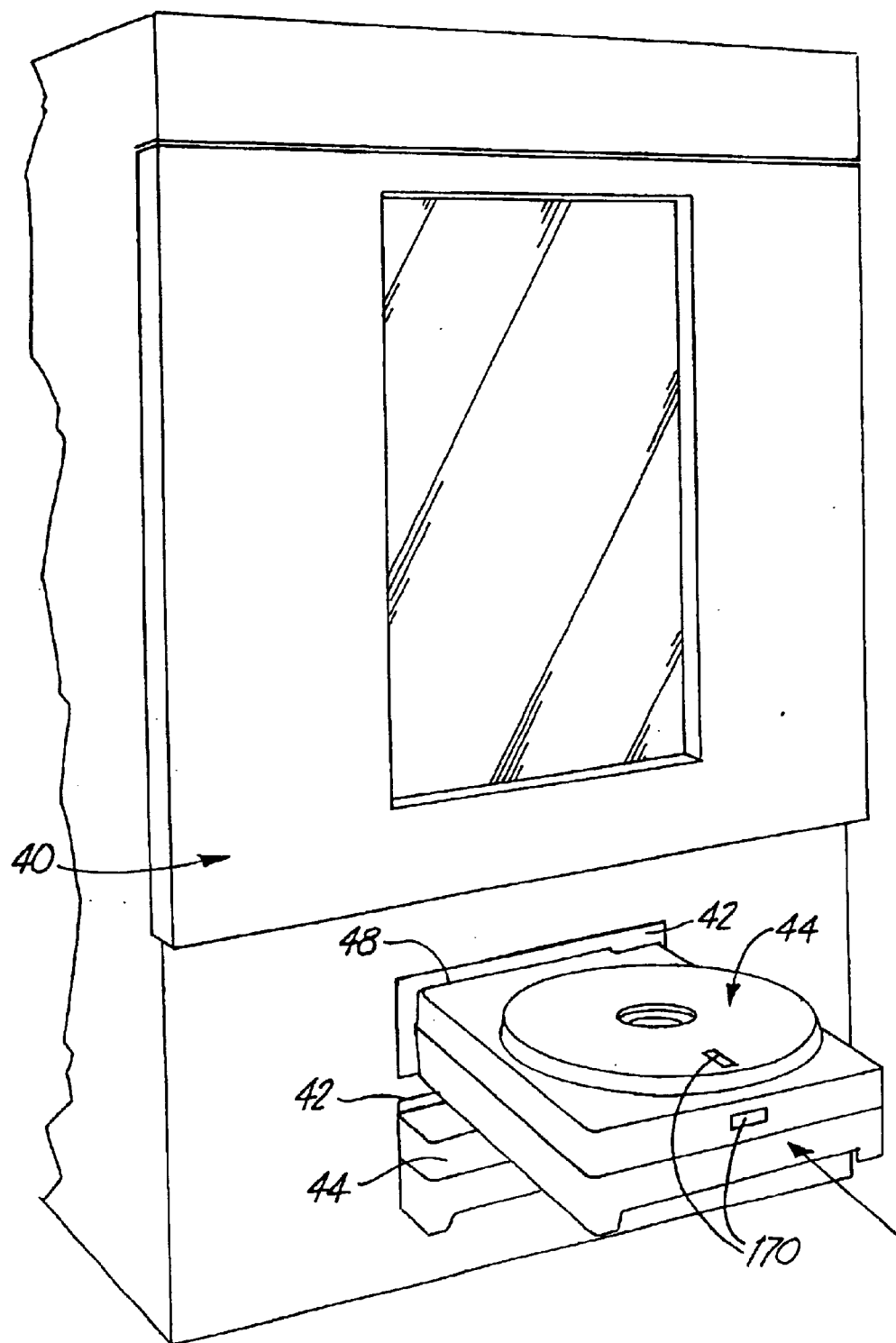
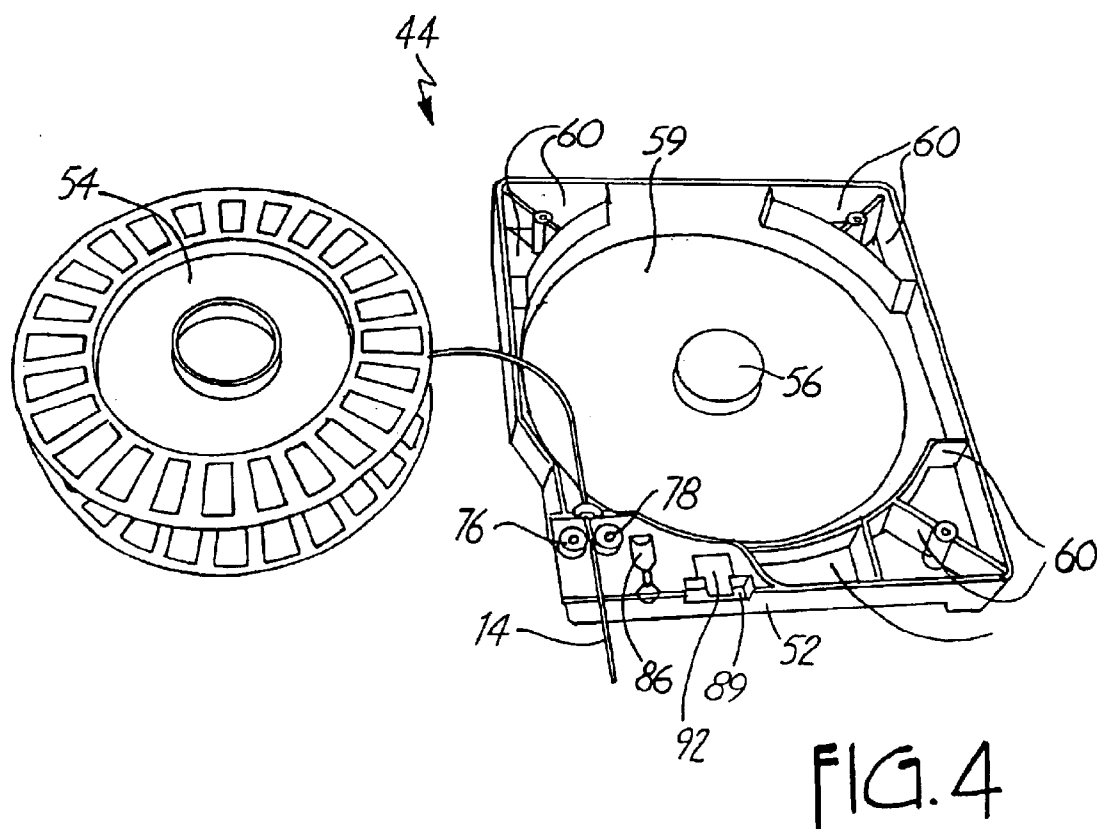
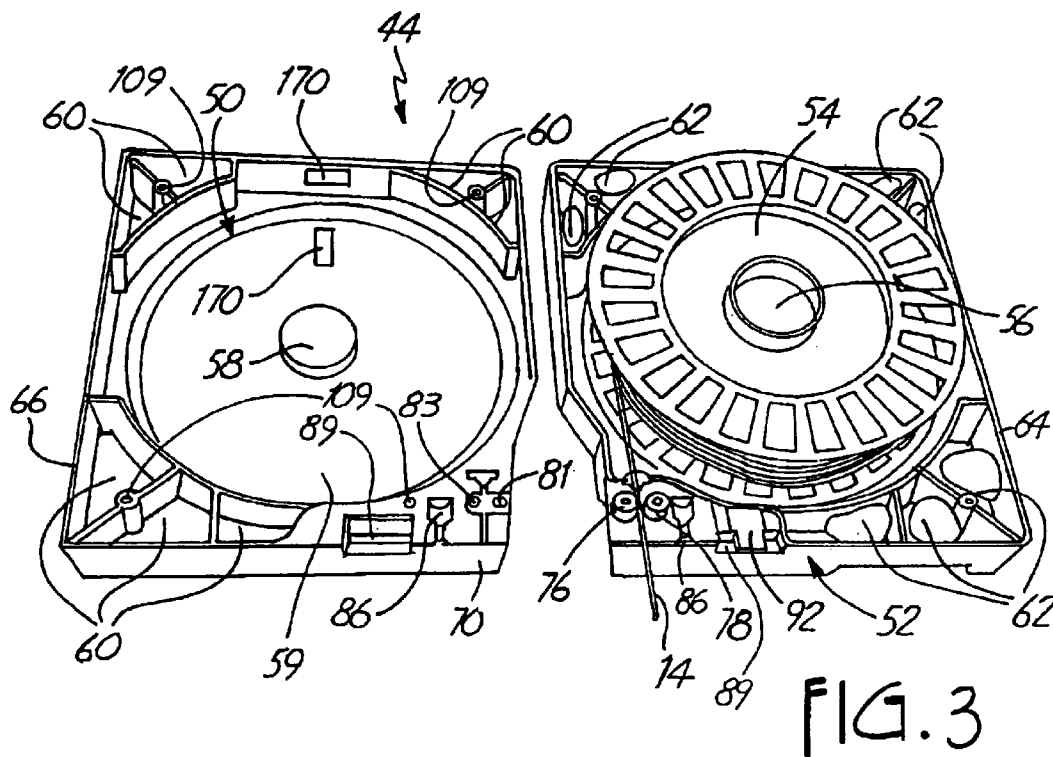
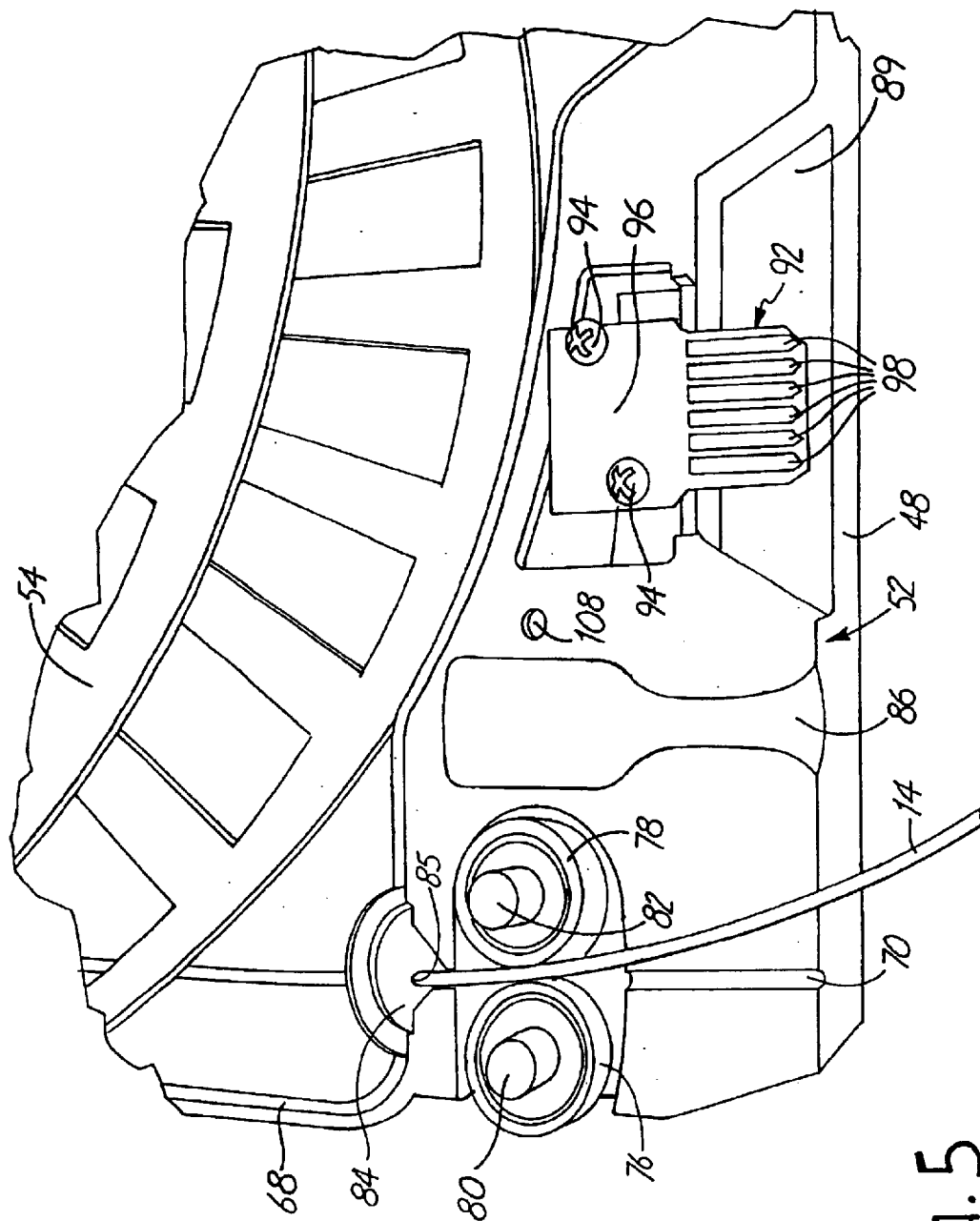


FIG. 2





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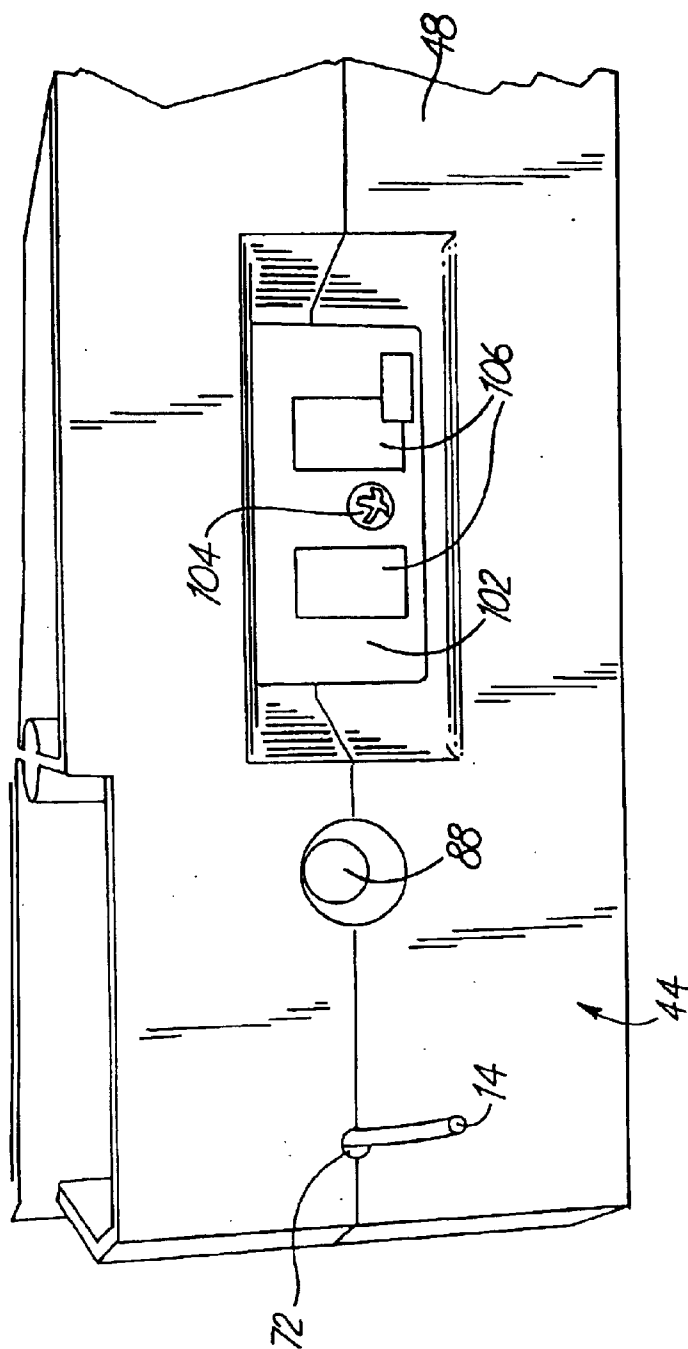


FIG. 5A

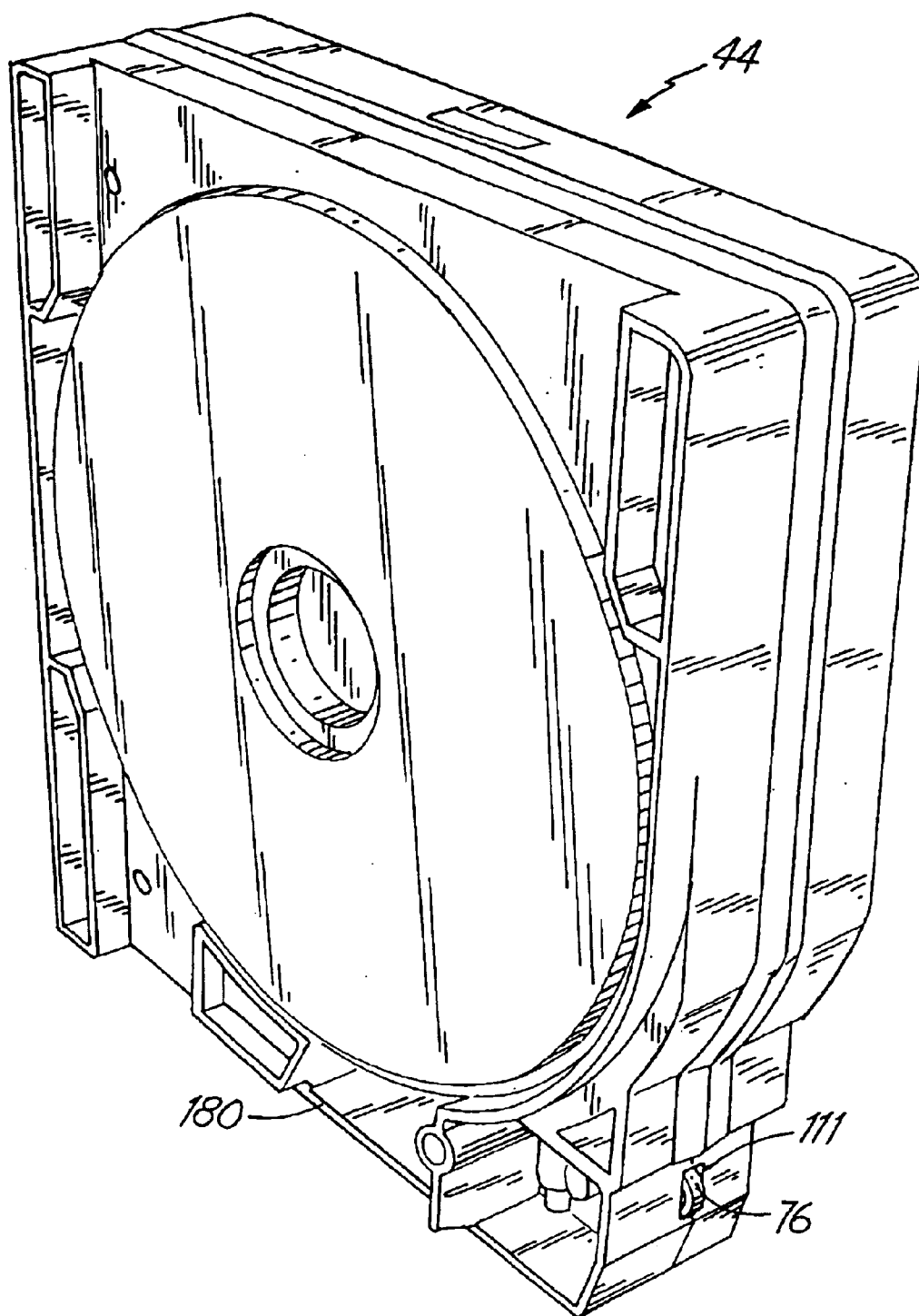


FIG. 6

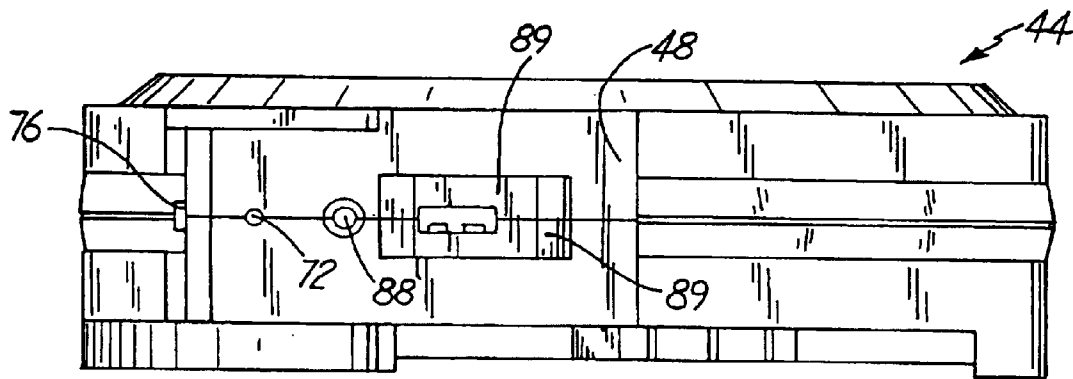


FIG. 7

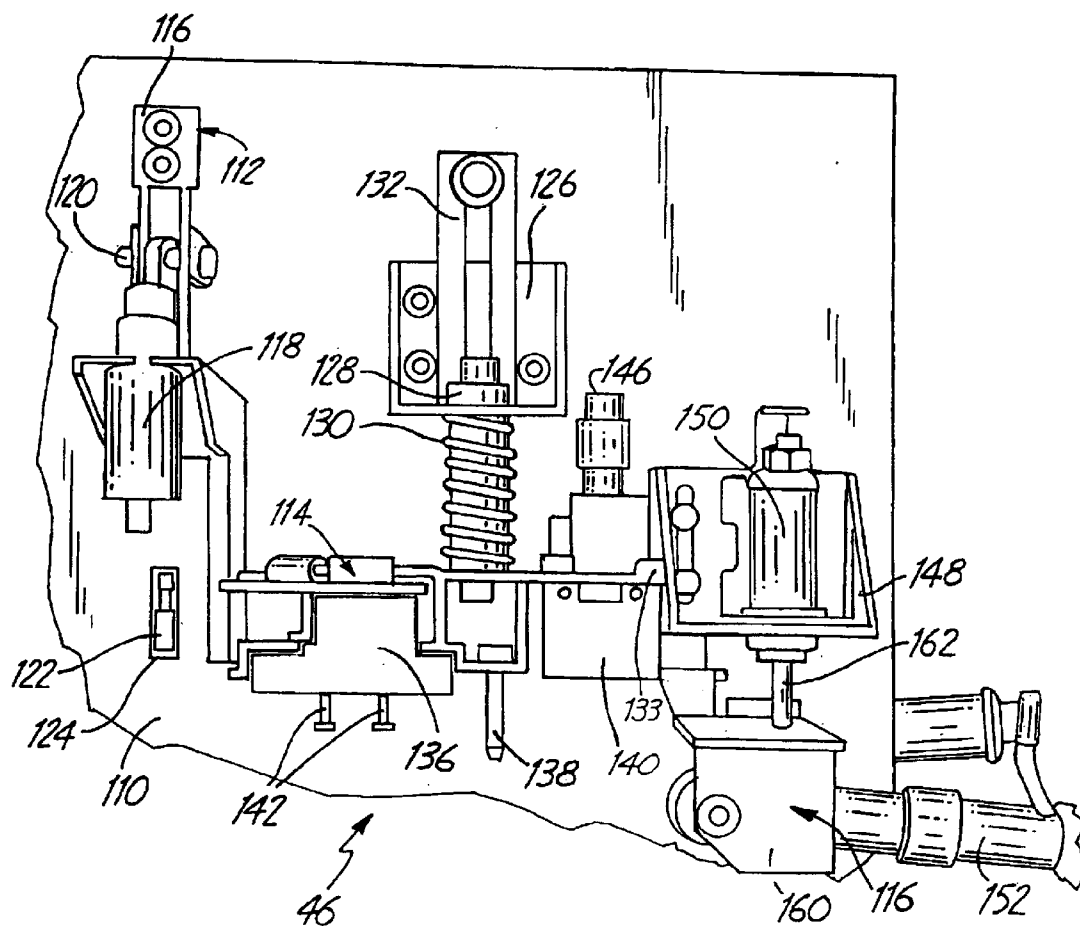


FIG. 8

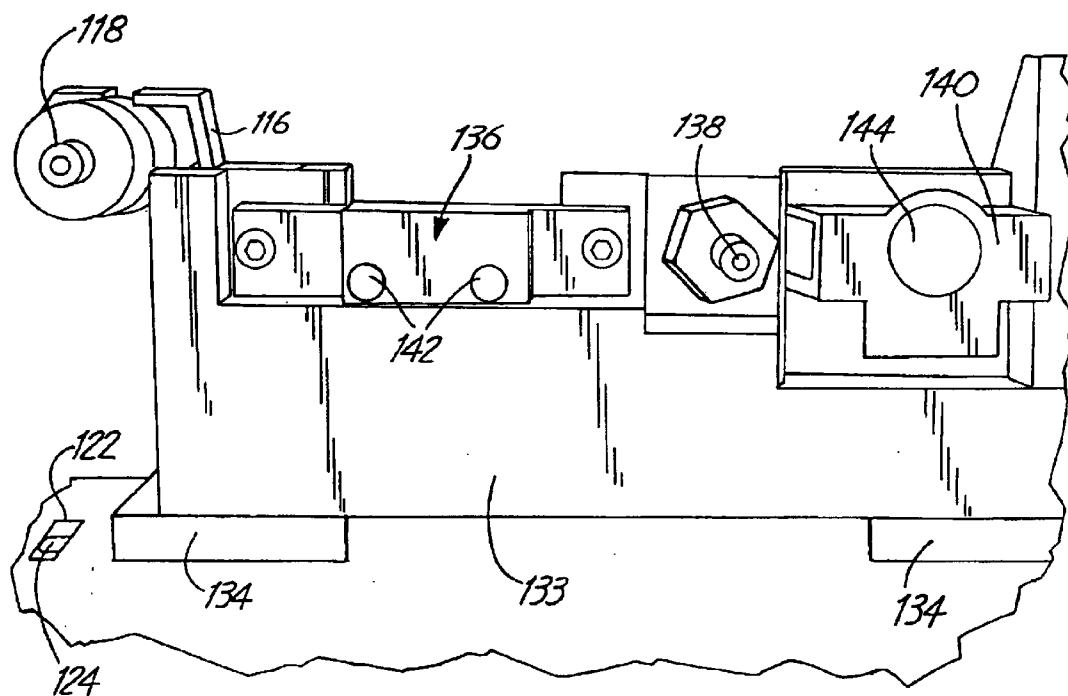


FIG. 9

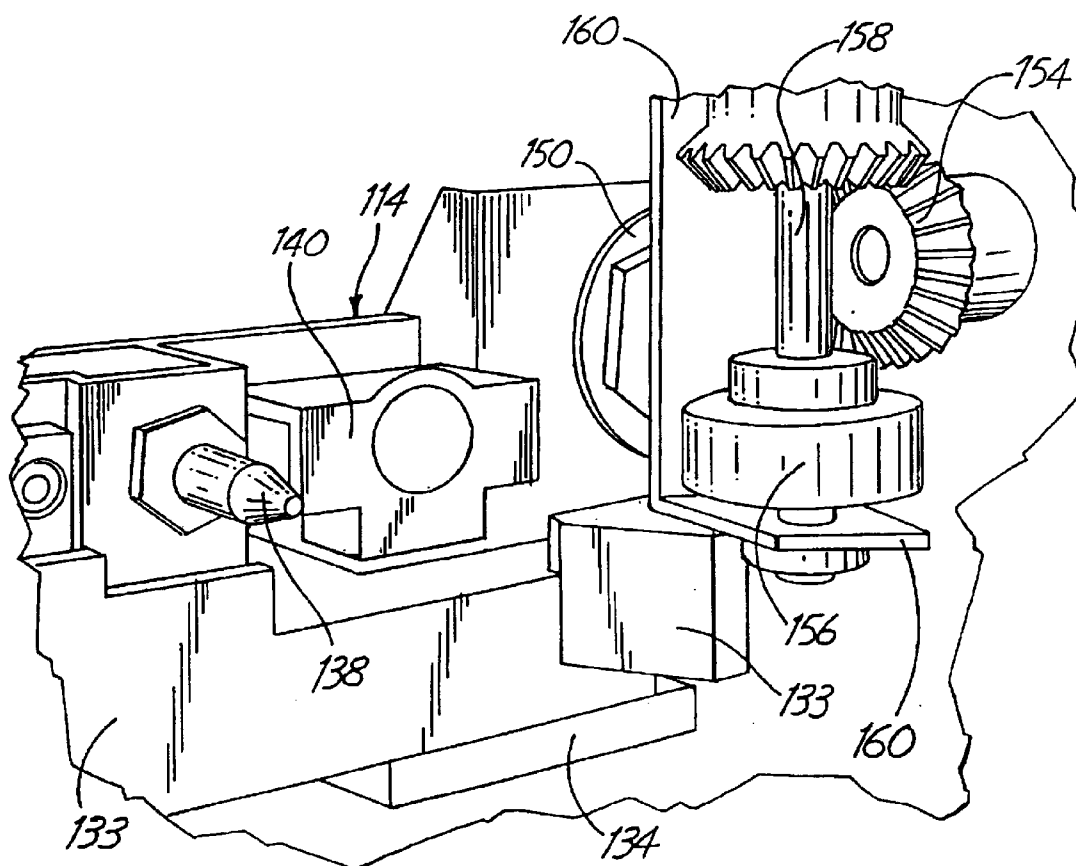


FIG. 10

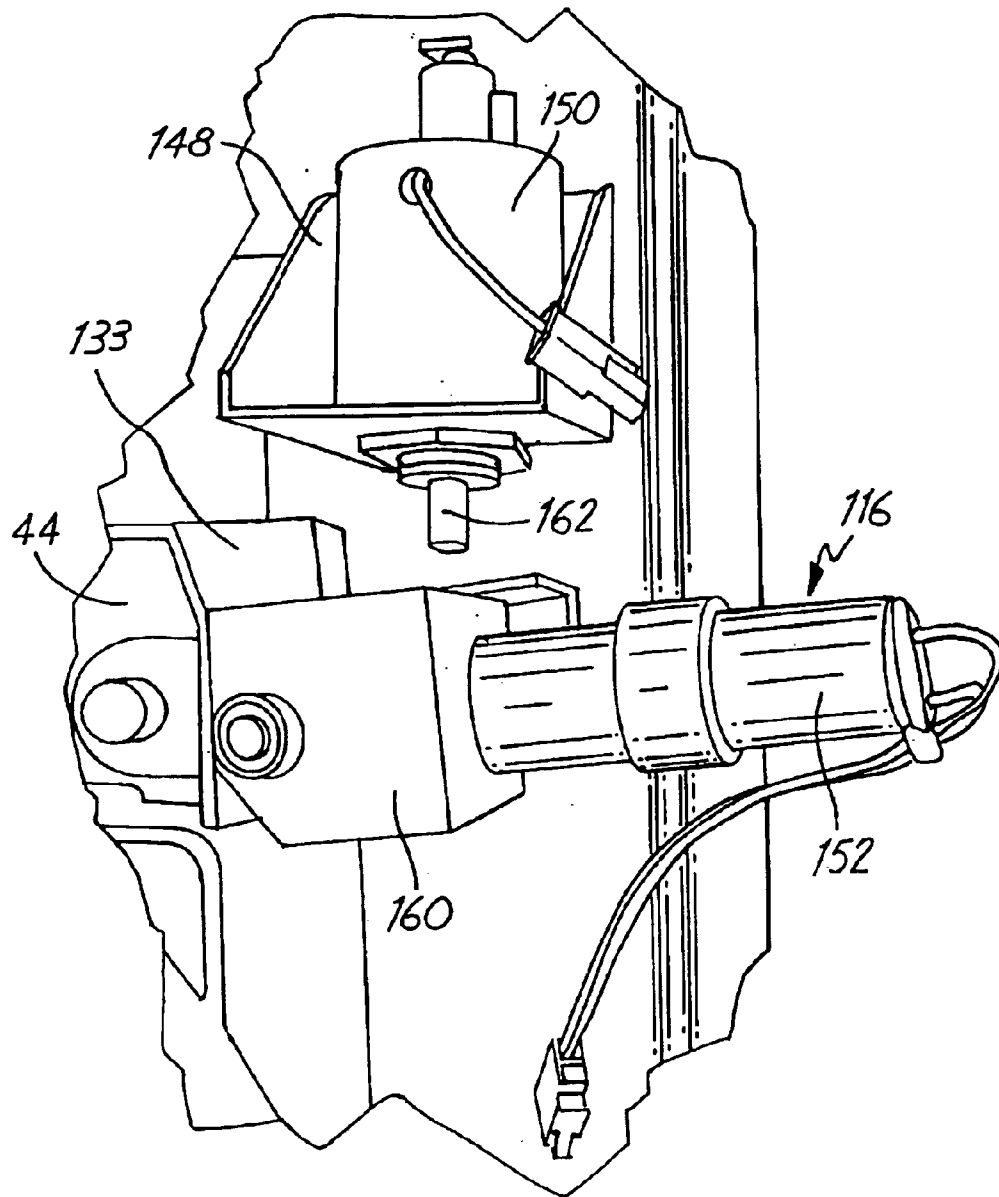


FIG. 11A

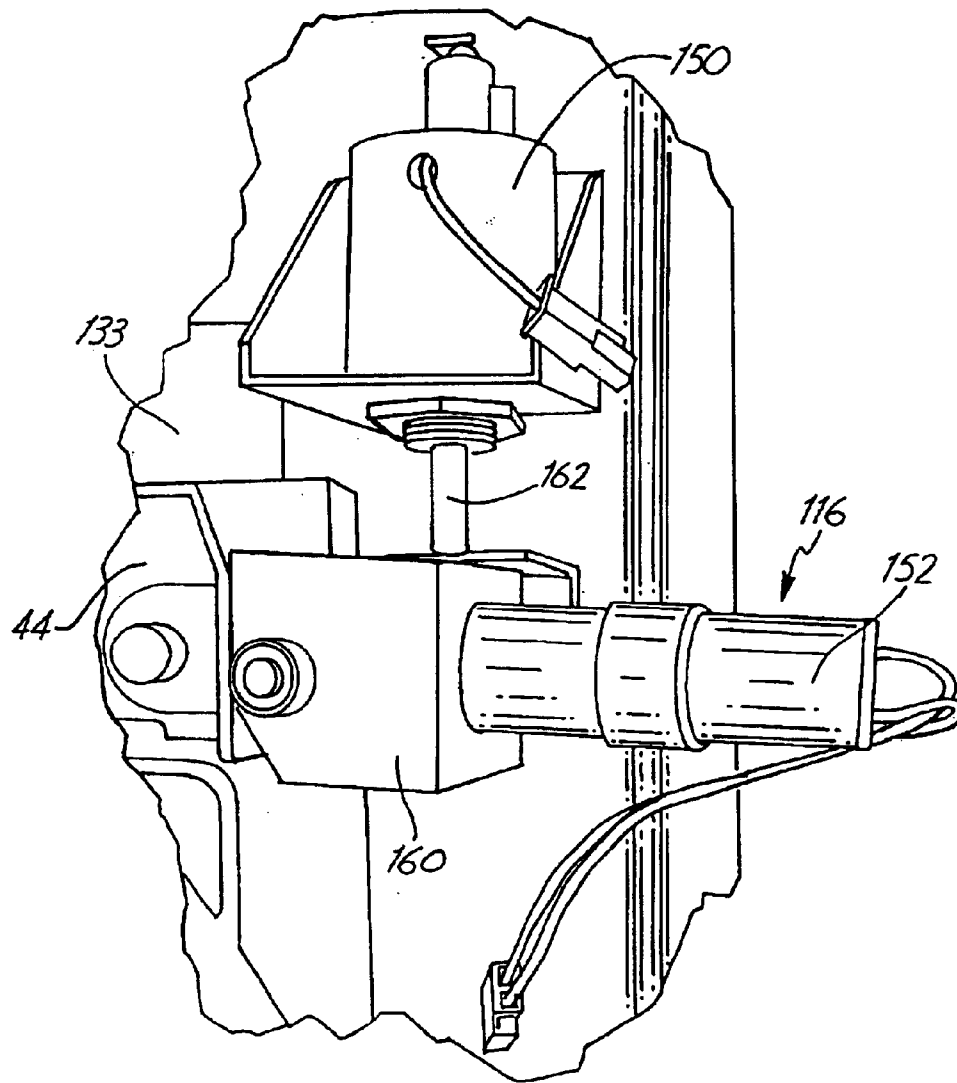


FIG. 11B

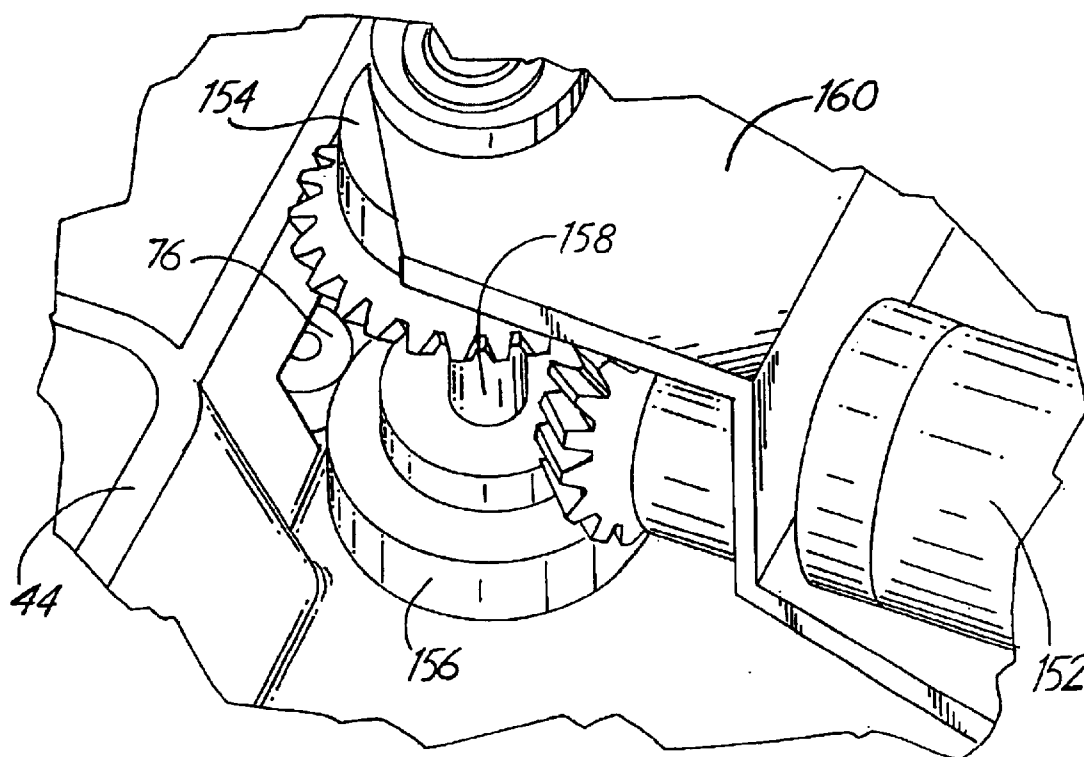


FIG. 12

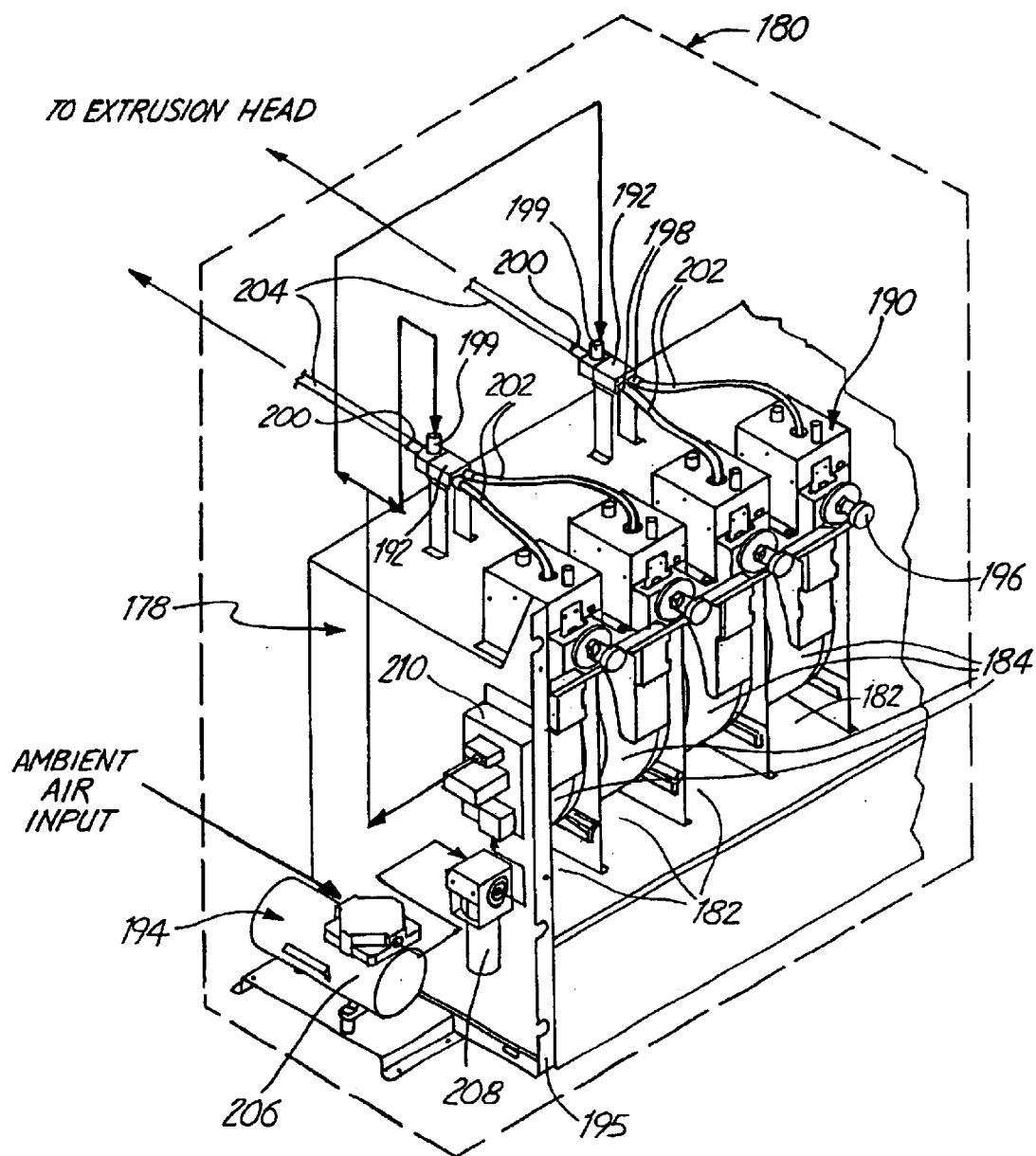


FIG. 13

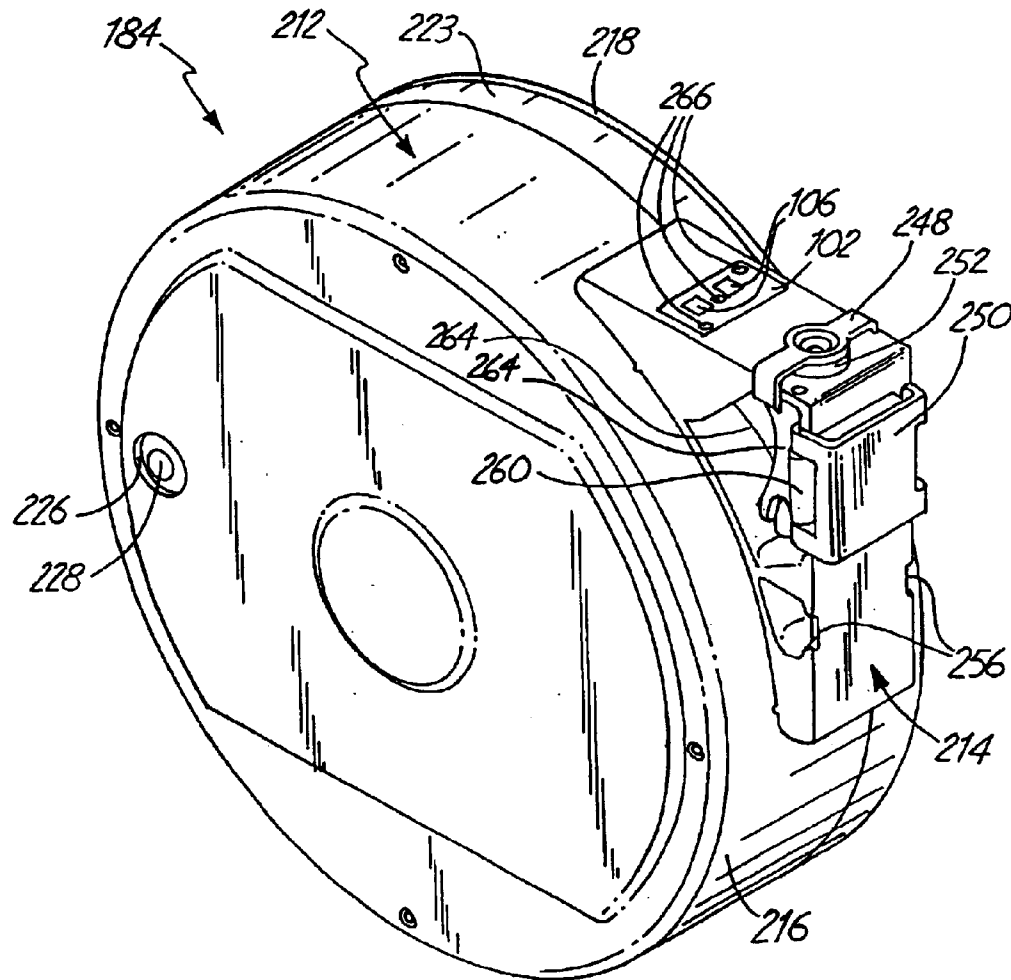
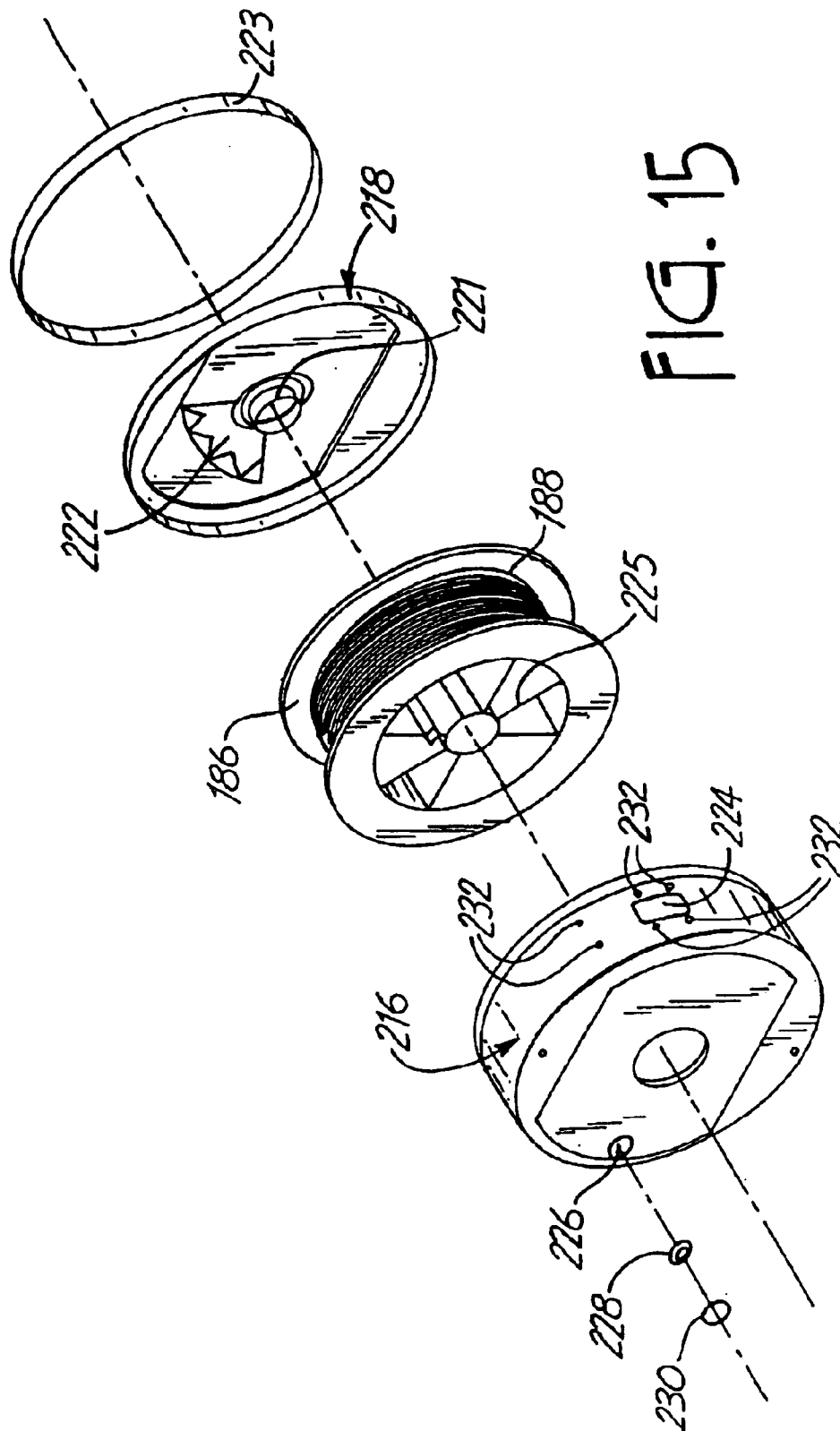


FIG. 14



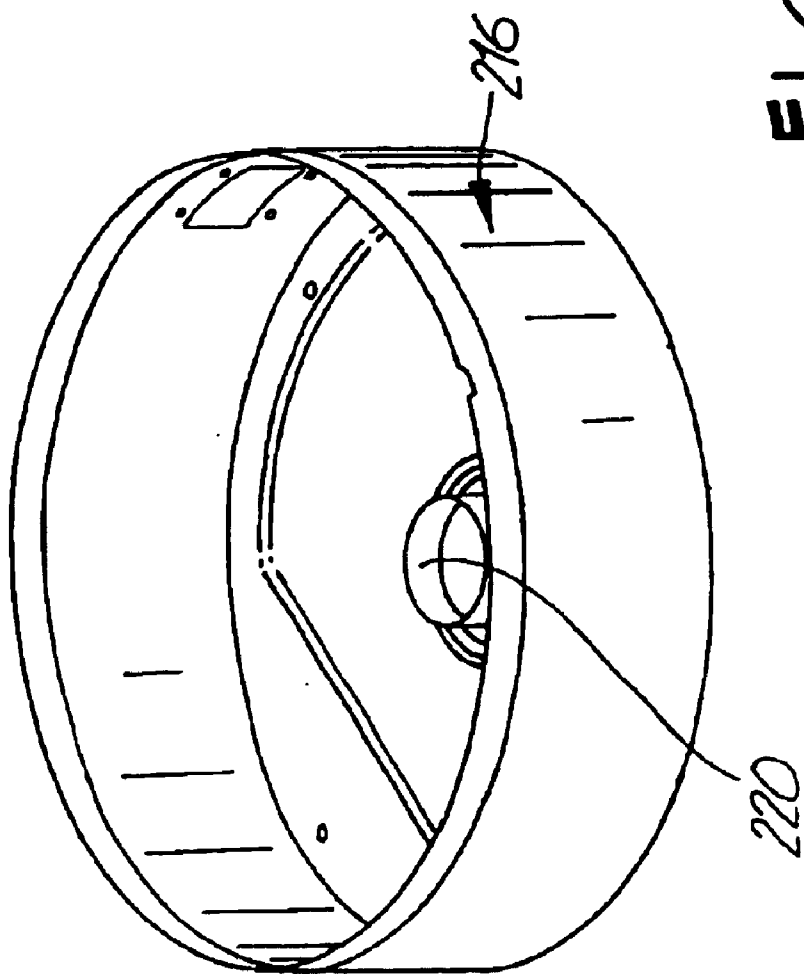
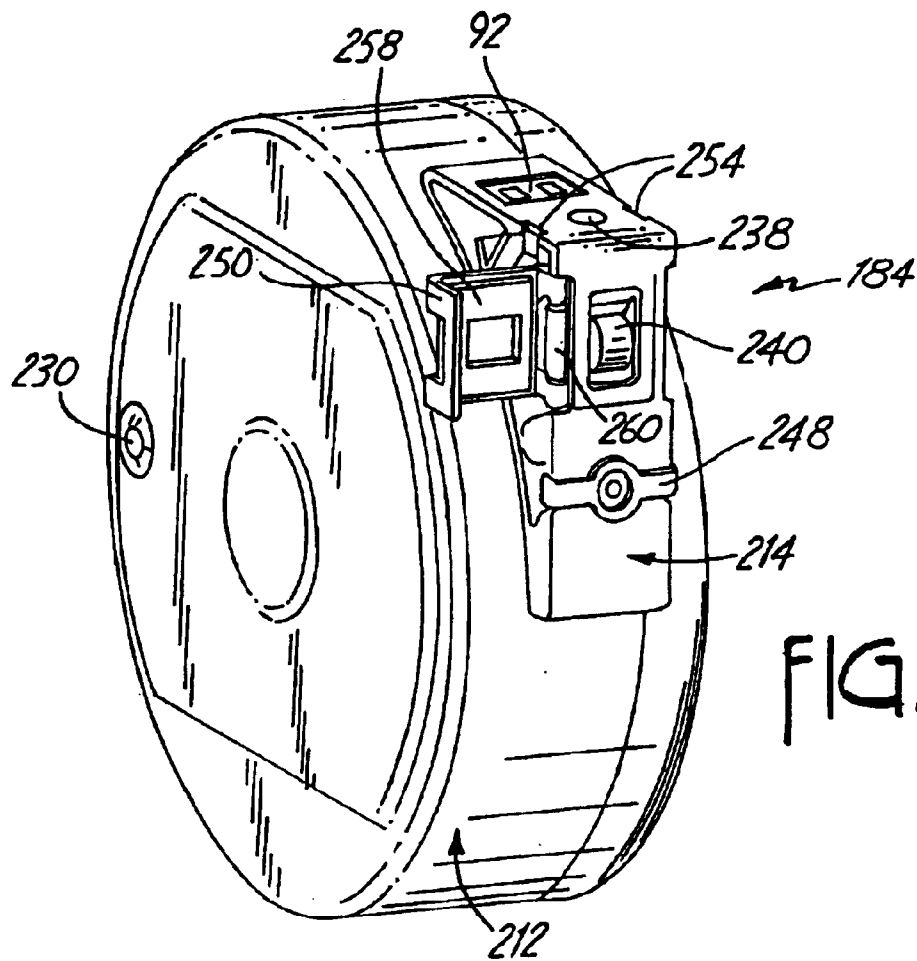


FIG. 16



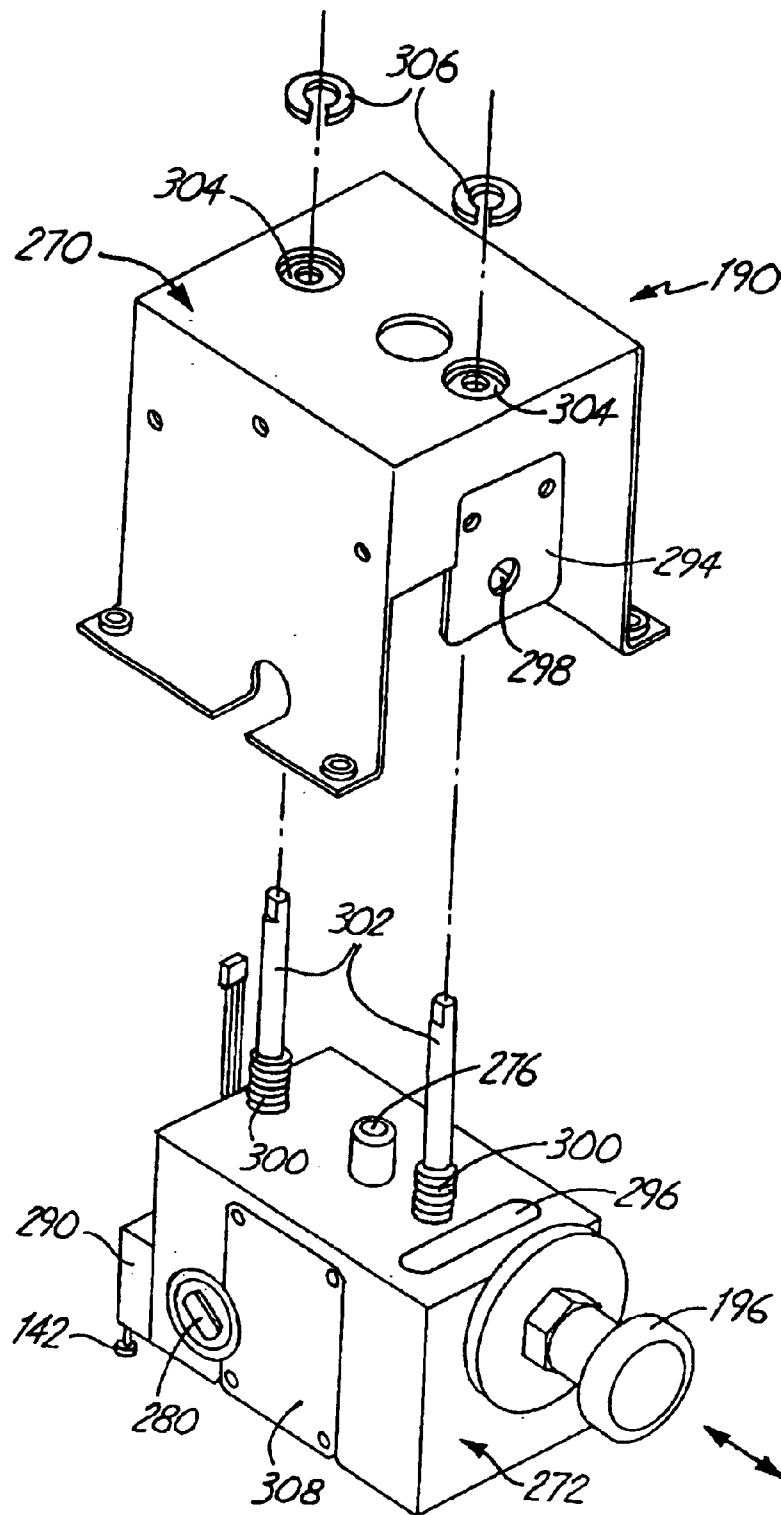


FIG. 18

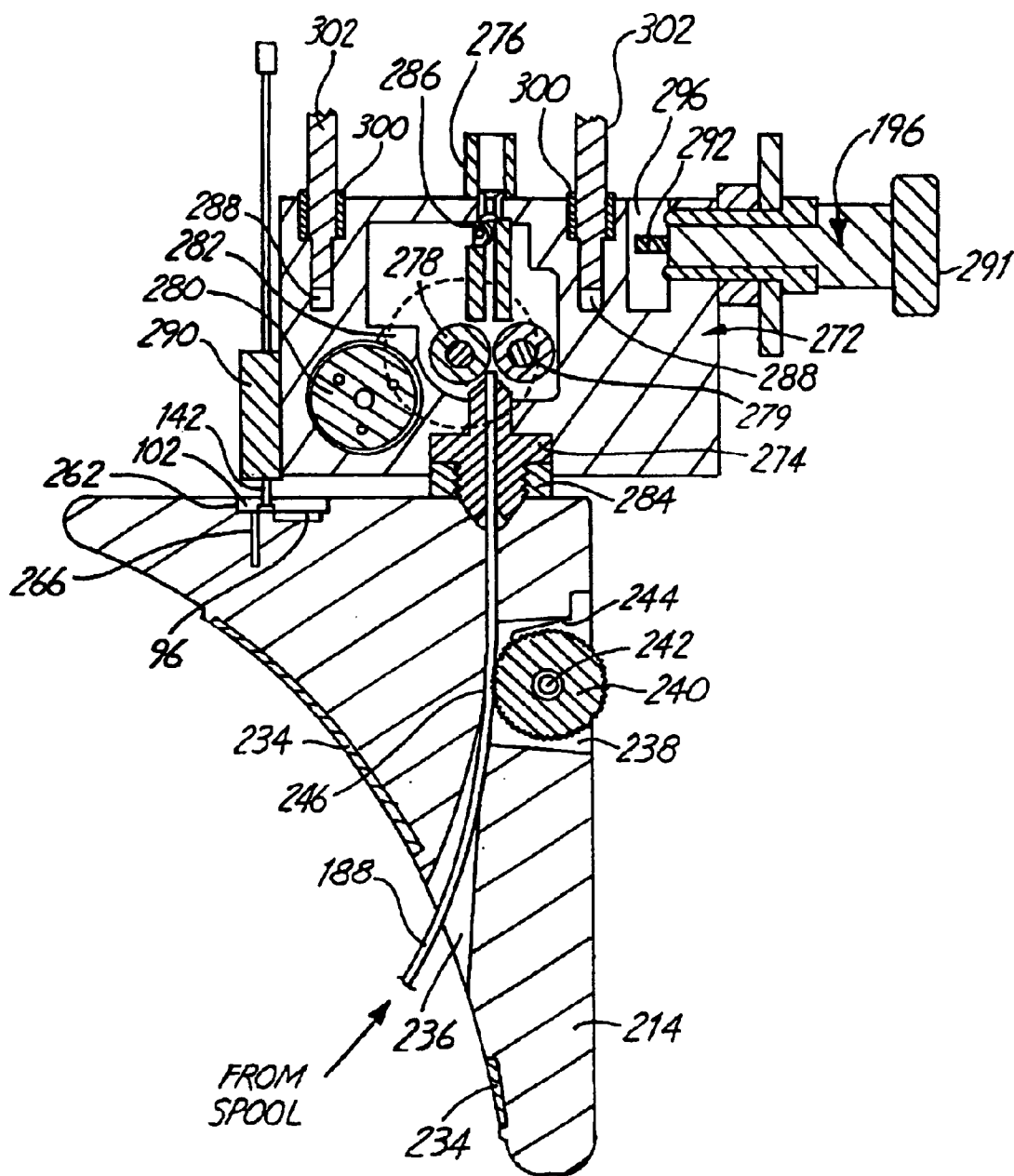


FIG. 19

FILAMENT LOADING SYSTEM IN AN EXTRUSION APPARATUS

CROSS-REFERENCE TO RELATED APPLICATION(S)

This application is a divisional of application Ser. No. 09/804,401, filed on Feb. 27, 2001 and now U.S. Pat. No. 6,776,602, which claims priority to provisional application Ser. No. 60/218,642, filed Jul. 13, 2000, and which is also a continuation-in-part of PCT International Application No. US00/17363, filed Jun. 23, 2000 (designating the United States), which is hereby incorporated by reference as if set forth fully herein, and which is a non-provisional of provisional application Ser. No. 60/140,613, filed Jun. 23, 1999.

BACKGROUND OF THE INVENTION

This invention relates to the fabrication of three-dimensional objects using extrusion-based layered manufacturing techniques. More particularly, the invention relates to forming three-dimensional objects by extruding solidifiable modeling material in a flowable state in three dimensions with respect to a base, wherein the modeling material is supplied in the form of a filament.

Three-dimensional models are used for functions including aesthetic judgments, proofing the mathematical CAD model, forming hard tooling, studying interference and space allocation, and testing functionality. Extrusion-based layered manufacturing machines build up three-dimensional models by extruding solidifiable modeling material from an extrusion head in a predetermined pattern, based upon design data provided from a computer aided design (CAD) system. A feedstock of either a liquid or solid modeling material is supplied to the extrusion head. One technique is to supply modeling material in the form of a filament strand. Where the feedstock of modeling material is in solid form, a liquifier brings the feedstock to a flowable temperature for deposition.

Examples of extrusion-based apparatus and methods for making three-dimensional objects are described in Valavaara U.S. Pat. No. 4,749,347, Crump U.S. Pat. No. 5,121,329, Crump U.S. Pat. No. 5,340,433, Crump et al. U.S. Pat. No. 5,503,785, Danforth, et al. U.S. Pat. No. 5,900,207, Batchelder, et al. U.S. Pat. No. 5,764,521, Dahlin, et al. U.S. Pat. No. 6,022,207, Stuffle et al. U.S. Pat. No. 6,067,480 and Batchelder, et al. U.S. Pat. No. 6,085,957, all of which are assigned to Stratasys, Inc., the assignee of the present invention.

In the modeling machines employing a filament feed, modeling material is loaded into the machine as a flexible filament wound on a supply reel, such as disclosed in U.S. Pat. No. 5,121,329. A solidifiable material which adheres to the previous layer with an adequate bond upon solidification and which can be supplied as a flexible filament is used as the modeling material. The extrusion head, which includes a liquifier and a dispensing nozzle, receives the filament, melts the filament in the liquifier, and extrudes molten modeling material from the nozzle onto a base contained within a build envelope. The modeling material is extruded layer-by-layer in areas defined from the CAD model. The material being extruded fuses to previously deposited material and solidifies to form a three-dimensional object resembling the CAD model. In building a model from a modeling material that thermally solidifies upon a drop in temperature, the build envelope is preferably a chamber which is heated to a temperature higher than the solidification temperature of the modeling material during deposition, and then gradually

cooled to relieve stresses from the material. As disclosed in U.S. Pat. No. 5,866,058, this approach anneals stresses out of the model while it is being built so that the finished model is stress free and has very little distortion.

In creating three-dimensional objects by depositing layers of solidifiable material, supporting layers or structures are built underneath overhanging portions or in cavities of objects under construction, which are not supported by the modeling material itself. For example, if the object is a model of the interior of a subterranean cave and the cave prototype is constructed from the floor towards the ceiling, then a stalactite will require a temporary support until the ceiling is completed. A support structure may be built utilizing the same deposition techniques and apparatus by which the modeling material is deposited. The apparatus, under appropriate software control, produces additional geometry acting as a support structure for the overhanging or free-space segments of the object being formed. Support material is deposited either from a separate dispensing head within the modeling apparatus, or by the same dispensing head that deposits modeling material. A support material is chosen that will adhere to the modeling material during construction, and that is removable from a completed object. Various combinations of modeling and support materials are known, such as are disclosed in U.S. Pat. No. 5,503,785.

In Stratasys FDM® three-dimensional modeling machines of the current art which embody a filament feed as disclosed in the above-referenced patents, a coil of modeling filament wrapped on a spool is loaded into the machine by mounting the spool onto a spindle. The filament is made of a thermoplastic or wax material. The user manually feeds a strand of the filament through a guide tube made of low friction material, unwinding filament from the spool until the filament strand reaches a pair of motor-driven feed rollers at the extrusion head. The filament strand is advanced by the feed rollers into a liquifier carried by the extrusion head. Inside the liquifier, the filament is heated to a flowable temperature. As the feed rollers continue to advance filament into the extrusion head, the force of the incoming filament strand extrudes the flowable material out from the dispensing nozzle where it is deposited onto a substrate removably mounted to a build platform. The flow rate of the material extruded from the nozzle is a function of the rate at which the filament is advanced to the head and the size of the dispensing nozzle orifice. A controller controls movement of the extrusion head in a horizontal x, y plane, controls movement of the build platform in a vertical z-direction, and controls the rate at which the feed rollers advance filament into the head. By controlling these processing variables in synchrony, the modeling material is deposited at a desired flow rate in "beads" or "roads" layer-by-layer in areas defined from the CAD model. The dispensed modeling material solidifies upon cooling, to create a three-dimensional solid object.

The Stratasys FDM® modeling machines use modeling filaments which are made from moisture sensitive materials, e.g., ABS thermoplastic. In order for the machines to function properly and to build accurate, robust models, the material must be kept dry. Therefore, filament spools for use in the machines are shipped, together with packets of desiccant, in moisture-impermeable packages. Each filament spool is to remain in its package until it is loaded into a modeling machine. The spindle onto which the spool is mounted is contained in a "drybox", an area of the machine maintained at low humidity conditions. The user is instructed to place the desiccant packets packaged with the filament spool into the drybox, and to remove any desiccant

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packets placed in the machine with prior spools. After manually feeding the filament to the feed rollers, the user latches a door of the drybox and may instruct the machine to begin building a model. To unload the filament spool from the machine, the user manually winds the filament back onto the spool. U.S. Pat. No. 6,022,207 shows and describes a spool of the current art loaded into the drybox of a three-dimensional modeling machine.

Manually feeding filament to the head, as is presently done, can be tedious. Additionally, as a practical matter, users often leave old desiccant in the drybox and fail to replace it with new desiccant, allowing humidity in the drybox to reach unacceptable levels. Further, frequent switching of spools results in moisture-contaminated material. Opening and closing the drybox door allows humid air to get trapped inside of the sealed area. A partially used spool unloaded from the machine is exposed to moisture and becomes contaminated as well. These moisture contamination problems result in wasted material when the user switches the type or color of modeling material. Moreover, some materials desirable for use as modeling materials in the Stratasys FDM® machines are highly vulnerable to moisture and can get contaminated within minutes. The time during which the drybox door is opened for loading and unloading filament introduces a level of moisture into the drybox unacceptable for some desirable materials, limiting the choice of modeling materials for use in these machines.

It would be desirable to provide modeling filament to a three-dimensional modeling machine in a manner that would simplify the loading and unloading operation, and that would reduce the moisture introduced into the machine. Additionally, it would be desirable to be able to readily remove unused filament from the machine and store it for later use.

BRIEF SUMMARY OF THE INVENTION

The present invention is an extrusion apparatus which includes a system for loading filament supplied in a cassette. The extrusion apparatus, such as a three-dimensional deposition modeling machine, has a liquifier that receives a feedstock of material in filament form and delivers the material in a flowable state. The apparatus includes a loading bay which receives the filament cassette and means for advancing a strand of the filament from the cassette towards the liquifier. In the exemplary embodiments, a conduit is provided for guiding the filament strand along the path towards the liquifier. Optionally, an entrance of the conduit makes an airtight seal with an exit orifice of the cassette, and the filament is protected from environmental moisture as it is advanced to the liquifier.

An extrusion apparatus may include multiple loading bays, each receiving a filament cassette. In the exemplary embodiments, a latching means engages and disengages the filament cassette in the loading bay and a registration means aligns the exit orifice of the cassette with the entrance of the conduit. The filament loading system of the present invention provides a convenient manner of loading and unloading filament in a three-dimensional modeling machine.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective, diagrammatic view of a generic filament-feed used in an extrusion-based three-dimensional modeling machine.

FIG. 2 shows a first embodiment of a filament cassette being loaded into a first embodiment of a three-dimensional modeling machine.

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FIG. 3 is a partially exploded view of the first embodiment of a filament cassette.

FIG. 4 is an exploded view of the spool and lower shell of the filament cassette shown in FIG. 3.

FIG. 5 is a detailed view of the (partially) exploded filament cassette shown in FIG. 3, showing a strand of filament in the filament path and a mounted circuit board.

FIG. 5A is a detailed view of an alternative configuration of a circuit board mounted onto the first embodiment of a filament cassette.

FIG. 6 is a perspective view of the first embodiment of the filament cassette, showing the bottom surface, side and trailing edge of the cassette.

FIG. 7 is a front elevation of the first embodiment of the filament cassette.

FIG. 8 is top plan view of a first embodiment of a filament cassette receiver of the present invention.

FIG. 9 is a front elevation of the first embodiment of the filament cassette receiver.

FIG. 10 is a perspective, detailed view of the filament drive shown in FIG. 8 as part of the filament cassette receiver.

FIG. 11A is a top plan view of the first embodiment of a filament cassette loaded into the filament cassette receiver of FIG. 8, showing the filament drive assembly in a disengaged position.

FIG. 11B is a top plan view of a filament cassette loaded into the cassette receiver of FIG. 6, showing the filament drive assembly in an engaged position.

FIG. 12 is a perspective detailed view of the filament drive assembly of FIG. 11B engaging a roller on the first embodiment of the filament cassette.

FIG. 13 is a perspective view of a filament loading assembly in a second embodiment of the three-dimensional modeling machine.

FIG. 14 is a perspective view of a second embodiment of the filament cassette.

FIG. 15 is an exploded view of the second embodiment of the filament cassette (guide block not shown).

FIG. 16 is a perspective view of the canister base of the second embodiment of the filament cassette.

FIG. 17 is a perspective view of the guide block shown in FIG. 14, with the access door open.

FIG. 18 is an exploded view of the filament cassette receiver shown in FIG. 13.

FIG. 19 is a sectional view of the filament loading assembly of FIG. 13, taken along a line 19—19 thereof.

DETAILED DESCRIPTION

A filament feed 10 used generally to feed filament to an extrusion head 20 in an extrusion-based three-dimensional modeling machine is shown in FIG. 1. A spool 12 carrying a coil of filament 14 is mounted on a spindle 16. The filament 14 is made up of a modeling material from which a three-dimensional model (or a support structure for the three-dimensional model) is to be built. Typically, the filament has a small diameter, such as on the order of 0.070 inches.

A strand of the filament 14 is fed through a guide tube or tubes 18, made of a low-friction material, which also preferably provides a moisture barrier, such as Teflon™. The guide tube 18 routes the strand of filament 14 to the extrusion head 20. A pair of feed rollers 22, shown mounted

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on the extrusion head **20**, receive the strand of filament **14** and feed the strand of filament **14** to a liquifier **26** carried by the extrusion head **20**. As shown, the feed rollers **22** are rubber-coated so as to grab the strand of filament **14** therebetween. Also as shown, one of feed rollers **22** is a drive roller, driven by a motor **24** under the control of a controller **25**. The other roller **22** is an idler roller. The liquifier **26** is heated so as to melt the filament **14**. The liquifier **26** terminates in a nozzle **28** having a discharge orifice **30** for dispensing the molten modeling material. The liquifier **26** is pressurized by the "pumping" of the strand of filament **14** into the liquifier **26** by feed rollers **22**. The strand of filament itself acts as a piston, creating a "liquifier pump". The pressurization impels the molten modeling material out of the orifice **30** at a volumetric flow rate. The volumetric flow rate is a function of the size of the dispensing orifice **30** and the rate of rotation of the feed rollers **22**. By selective control of the motor **24**, the rate of advancement of the strand of filament **14**, and thus the volumetric dispensing rate of the molten modeling material, can be closely controlled.

The extrusion head **20** is driven in a horizontal x,y plane by an x-y translator **34**, which receives drive signals from the controller **25** in accordance with design data derived from a CAD model. As the extrusion head **20** is translated in the x-y plane, molten modeling material is controllably dispensed from the orifice **30** layer-by-layer onto a planar base **32** (shown in part in FIG. 1). After each layer is dispensed, the base **32** is lowered a predetermined increment along a vertical z-axis by a z-axis translator **36**, which also receives drive signals from the controller **25**. The dispensed material fuses and solidifies to form a three-dimensional object resembling the CAD model. Support material may be dispensed in a like fashion in coordination with the dispensing of modeling material, to build up supporting layers or a support structure for the object.

As will be understood by those in the art, many variations of the modeling machine and process are possible. For example, any relative movement in three-dimensions between the extrusion head **20** and the base **32** may be used to build up the object. The feed rollers and the motor may take various forms. For example, as is disclosed in U.S. Pat. No. 5,121,329, both rollers may be driven (such as by coupling the rollers by a timing belt), more rollers be added, or the rollers may be spring-biased towards each other, rather than rubber coated, to maintain gripping frictional contact on the filament. Any type of motor that can drive the feed rollers at a controlled rate may be employed, for instance a servo motor or a stepper motor. Likewise, different arrangements of extrusion heads may be utilized for receiving and dispensing different types or colors of filament from separate filament feeds. For example, the extrusion head may carry two sets of feed rollers, each driven by its own motor, for advancing two different filament strands from two different spools, such is disclosed in U.S. Pat. Nos. 5,121,329; 5,503,785; and 6,004,124.

Embodiment One

In the present invention, the spool carrying a coil of filament is contained within a filament cassette. FIG. 2 shows a first exemplary embodiment of a modeling machine **40** which has two loading bays **42** stacked vertically, each for receiving a first embodiment of a filament cassette **44**. As shown, one filament cassette **44** is loaded into the lower loading bay. A second cassette **44** is being loaded into the upper loading bay **42**. Each filament cassette contains a spool carrying a coil of filament. Preferably, one cassette **44** supplies filament formed of modeling material, while the

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other cassette **44** supplies filament formed of support material. The modeling machine **40** has two liquifiers **26**, such as shown in FIG. 1, which each receive a strand of filament from one of the cassettes **44**.

As will be described in detail below, each loading bay **42** contains a cassette receiver **46** which engages the filament cassette **44** and advances a strand of the filament **14** from the cassette **44** into the guide tube **18** of filament feed **10**. A user loads the filament cassette **44** into the modeling machine **40** by holding the cassette **44** in an upright position and lining up a leading edge **48** of the cassette **44** with one of the loading bays **42**. The user pushes the cassette **44** into the loading bay **42** until a hard stop is reached. At such time, the cassette **44** is engaged by the cassette receiver **46**.

Detail of the filament cassette **44** is shown in FIGS. 3-7. As shown in FIGS. 3 and 4, the filament cassette **44** is comprised of an upper shell **50**, a lower shell **52**, and a spool **54** carrying the filament **14**. The upper shell **50** and lower shell **52** fasten together, with the spool **54** between them, by a set of four screws **55** (not shown). The lower shell **52** has a hub **56** and the upper shell **50** has a hub **58**. A circular recess **59** within upper shell **50** and lower shell **52** surrounds each of hubs **56** and **58**. The upper shell **50** and lower shell **52** each have seven compartments **60** along the periphery of the recess **59**. Together, hubs **56** and **58** form a spindle on which the spool **54** rotates within a chamber defined by the circular recesses **59**. Packets of desiccant **62** are placed in the compartments **60** so as to maintain dry conditions in the chamber of cassette **44**. A narrow channel **64** is routed in lower shell **52** in a closed-loop around the periphery of the circular recesses **59** and the compartments **60**. A gasket **68** is seated in the channel **64**, and a ridge **66** in the upper shell **50** mirrors the channel **64**. The gasket **68** blocks air from reaching the spool **54** within the cassette **44** when the upper shell **50** and the lower shell **52** are fastened together.

Each of shells **50** and **52** have a narrow channel **70** leading from the circular recess **59** to the leading edge **48** of the cassette **44**, as best shown in FIG. 5. Together, the channels **70** define a filament path which terminates in an exit orifice **72** of the cassette **44**, as shown in FIG. 7. As is best shown in FIG. 5, a roller **76** is mounted opposite a roller **78** along the channel **70** of the lower shell **52**. As shown, roller **76** rotates on a floating axle **80**, while roller **78** rotates on a fixed axle **82**. The floating axle **80** is seated in an oblong depression **81** of the upper and lower shells **50** and **52**, oriented perpendicular to the filament path. The fixed axle **82** is seated in a cylindrical depression **83** of the upper and lower shells **50** and **52**. A force applied against roller **76** will force roller **76** towards roller **78** to grip a strand of filament **14** in the filament path. Alternatively, both rollers could have a fixed axle, and be positioned close enough to one another to grip a filament strand in the path. The rollers may have an elastomeric surface, to aid in gripping the strand of filament **14**.

The channel **70** of lower shell **52** forming the filament path crosses the channel **64** at a position located between the circular recess **59** and the roller pair **76** and **78**. A retainer **84**, which is integral with the gasket **68**, is positioned at this location. The retainer **84** has a center hole **85** of a diameter approximately equal to the filament diameter.

Each of shells **50** and **52** have another channel **86** which runs parallel to the channel **70**. Together, the channels **86** define a registration pin receiving cavity **88**, which begins at the leading edge **48** of the cassette **44** and terminates before reaching the gasket **68**. Cavity **88** has a flared mouth followed by a narrow neck. The mouth of cavity **88** is shown

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in FIG. 7. Each of upper shell 50 and lower shell 52 have a recess 89 to the right of the channel 86, which together form a recess in the leading edge 48 of the cassette 44. On the lower shell 52, a circuit board is mounted in the recess 89.

In one embodiment, as shown in FIG. 5, a circuit board 92 is mounted horizontally at the base of the recess 89 by two screws 94, and carries an EEPROM 96 on its upper surface. The circuit board 92 has conductive tabs 98 on a portion thereof which extends across the recess 89, so that it may be received by a card-edge connector. In an alternative embodiment, shown in FIG. 5A, a circuit board 102 is mounted vertically in the recess 89 by screws 104. The circuit board 102 has an inner face (not shown) which carries the EEPROM 96 and an outer face which carries a pair of electrical contacts 106.

The EEPROM 96 acts as an electronic tag for the cassette 44. The EEPROM 96 contains information identifying the cassette 44 and the filament 14, such as the type of material from which the filament is formed. The EEPROM 96 additionally may keep a count of the lineal feet of filament 14 that is in the cassette 44. When the cassette 44 is loaded into the modeling machine 40, the EEPROM 96 is electrically connected to the controller 25, as described below. As filament 14 is advanced from the cassette 44 into the modeling machine 40, the controller 25 continually updates the lineal feet count of the filament 14 remaining in the cassette 44. This allows the controller 25 to prevent the machine 40 from attempting to model without filament. EEPROM 96 may be any electronically readable and writable data store. The use of such a data store as a filament tag is described in U.S. Pat. No. 5,939,008.

The filament cassette 44 is assembled by placing the spool 54 carrying the filament 14 on the hub 56 of the lower shell 52. The lower shell 52 is prepared by pressing the gasket 68 into the channel 64, so that the center hole 85 of the retainer is aligned in the channel 70. One of the circuit boards 92 or 102 is fastened to the lower shell 52. The fixed axle 82 carrying roller 78 is placed into the cylindrical depression 82 of the lower shell 52, while the floating axle 80 carrying roller 76 is placed into the oblong depression 81 of the lower shell 52. A strand of the filament 14 from the spool 54 is threaded through the hole in retainer 84, and placed in the channel 70 of lower shell 52 between the rollers 76 and 78. A packet of desiccant is placed in each of the compartments 60. Once each of these items are in position on the lower shell 52, the upper shell 50 and lower shell 52 are fastened together by the four screws 55 (alternatively, any known fastening device could be used). The screws 55 are set into four screw holes 108 of the lower shell 52, and extend into four threaded screw holes 109 of the upper shell 50. The cassette 44 is then ready for loading into the modeling machine 40.

Once the cassette 44 is assembled, it may be placed in a moisture-impermeable package, which package may then be vacuum sealed, for shipping or later use. Vacuum sealing is desirable where the filament 14 is made from a moisture sensitive material. Additionally, for moisture sensitive materials, the chamber of the cassette 44 containing the spooled filament should be dried just prior to the vacuum sealing. The cassette 44 then remains in the package until a user is ready to load the cassette 44 into the modeling machine 40.

After the filament 14 contained within the cassette 44 is depleted or otherwise becomes unusable, the cassette 44 can be refilled and reused by detaching the shells 50 and 52 and replacing the filament 14 on the spool 54. The EEPROM 96

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carried by circuit board 92 or 102 can be reset or the circuit board replaced to provide a new EEPROM 96.

FIG. 6 shows the bottom surface, trailing edge and right side of filament cassette 44. As shown, the roller 76 protrudes from an opening 111 in the right side of the cassette 44 so that it may receive an external rotational force. As will be described in more detail below, the roller 76 is preferably driven by a drive wheel 156 on the cassette receiver 46 to advance the strand of filament 14 out of the exit orifice 72.

The cassette receiver 46 which engages filament cassette 44 is shown in FIGS. 8-12. The cassette receiver 46 is mounted on the floor 110 of each loading bay 42. Preferably, the loading bay floor 110 is made of sheet metal. The cassette receiver 46 comprises a latching mechanism 112, a reciprocating assembly 114 and a drive assembly 116. The latching mechanism 112 is mounted to the floor 110 by a bracket 116. The latching mechanism 112 is comprised of a solenoid 118, an arm 120 and a latch 122. The arm 120 is coupled to the solenoid 118 at one end thereof and is integral with the latch 122 at the other end thereof. The arm 120 extends downward from the solenoid 118 through an opening in the floor 110, sits below and generally parallel to the floor 110, and then angles upward so that it will pivot to position the latch 122 alternately above and below the floor 110. The latch 122 moves up and down through a cutout 124 in the floor 110.

The solenoid 118, operating under control of the controller 25, alternately rocks the arm 120 up and down to engage and disengage the latch 122. When the solenoid 118 is energized, the arm 120 rocks upward at the latch end, placing the latch 122 in an engaged position. When the solenoid 118 is de-energized, the latch end of arm 120 rocks downward, moving the latch 122 to a disengaged position.

The reciprocating assembly 114 is fastened to the loading bay floor 110 by a bracket 126. The reciprocating assembly 114 comprises a piston 128, an ejection spring 130, a track 132 and a frame 133. The piston 128 sits parallel to and above the floor 110. The piston 128 extends through a hole in the bracket 126 and moves forward and back in the loading bay 42, guided by track 132. The forward end of the piston 128 is coupled to the frame 133, which extends generally perpendicular to the piston 128. The frame 133 moves back and forth with the motion of piston 128. The ejection spring 130 is coiled around the piston 128, connecting to the bracket 126 at the rearward end thereof and connecting to the frame 133 at the forward end thereof. A horizontal force applied against the frame 133 will compress the ejection spring 130. When said force is released, the spring 130 will decompress, causing the frame 133 and piston 128 to move forward. A pair of bearings 134 are mounted to the floor 110 underneath the frame 133. The bearings 134 provide a low friction surface which supports frame 133 in a plane parallel to the floor 110, while allowing the frame 133 to slide back and forth.

Attached to the frame 133 are an electrical connector 136, a registration pin 138 and a conduit 140. The electrical connector 136 is configured to mate with the circuit board of the filament cassette 44 on a forward face thereof and is configured to provide an electrical connection to the controller 25 at a rear face thereof. As shown, the forward face of electrical connector 136 carries two pogo pins 142 configured to mate with the electrical contacts 106 of circuit board 102 carried by the cassette 44. (Alternatively, the electrical connector could be a card-edge connector for receiving the conductive tabs 98 of circuit board 92). The registration pin 138 is mounted on the frame 133 to the right

of the electrical connector 136. The registration pin 138 extends forward in the loading bay 42 and has a diameter approximately equal to the diameter of the neck of cavity 88 within the filament cassette 44. The conduit 140 is located to the right of the registration pin 138. The conduit 140 has an entrance 144 which faces forward in the loading bay 42, and an exit 146 facing to the rear of the loading bay 42. The entrance 144 of the conduit 140 is configured to align with the exit orifice 72 of the cassette 44, and to receive the strand of filament 14 from the exit orifice 72. Optionally, the conduit 140 may make an airtight seal with the exit orifice 72 and the guide tube 18. A strand of the filament 14 fed into the conduit entrance 144 will exit through the conduit exit 146 where it can then be provided into the guide tube 18 and routed to the liquifier 26.

The drive assembly 116 is mounted to the loading bay floor 110 by a bracket 148. The drive assembly 116 comprises a solenoid 150, a motor 152, a gear train 154, a drive wheel 156 which rotates on a shaft 158, and a housing 160. The drive assembly 116 is shown in detail in FIGS. 10–12. The solenoid 150 having an actuator 162 is mounted in the bracket 148 so that the actuator 162 reciprocates forward and back in the loading bay 42. Energization of the solenoid 150 is controlled by the controller 25. The actuator 162 moves forward in the loading bay 42 when the solenoid 150 is actuated, and moves towards the back of the loading bay 42 when the solenoid 150 is deactuated. The housing 160, which carries the motor 152, the gear train 154 and the drive wheel 156, is pivotably mounted onto the floor 110 in front of the actuator 162. When the solenoid 150 is energized, the actuator 162 pivots the housing 160 in a clockwise rotation. Absent a force imparted against the housing 116 by the actuator 162, the housing 160 is in an upward resting position. When the actuator 162 rotates the housing 116 in a counterclockwise direction, the drive wheel 156 is placed in an actuated position at which it will press against the floating-axis roller 76 of the cassette 44 when the cassette 44 is loaded in the loading bay 42.

The motor 152, in response to control signals from the controller 25, causes rotation of the shaft 158 via gear train 154, as best shown in FIG. 10. Rotation of the shaft 158 rotates the drive wheel 156. When in its actuated position, the drive wheel 156 will then rotate the cassette roller 76. Release of the actuator 162 from the housing 160 allows the housing 160 to rotate back into a resting position. In an alternative embodiment wherein the cassette roller has a fixed axis, the solenoid 150 could be eliminated and the drive wheel 156 could remain fixed in the actuated position where it would impart a constant force against the cassette roller.

As mentioned above, a user loads the cassette 44 into the modeling machine 40 by pushing the cassette 44 into one of the loading bays 42 until a hard stop is reached. The hard stop is provided by a backstop 164, which is mounted to the loading bay floor 110 (as shown in FIG. 8), and the compression of the ejection spring 130. As the user releases the cassette 44, it moves back until the latch 122 catches on a ridge 180 on the bottom surface of the cassette 44 (shown in FIG. 6). The latch 122 is set in an upward position prior to loading the cassette 44, under commands from the controller 25 to the solenoid 118, so that it is ready to catch the cassette 44. The latch 122 remains in this upward position until the user desires to remove the cassette 44, at which time the controller 25 de-energizes the solenoid 118 to lower the latch 122.

As the cassette 44 is pushed into the loading bay 42, the registration pin 138 slides into the cavity 88 of the cassette

44. The registration pin 138 serves to properly align the cassette 44 with the cassette receiver 46, and specifically to counteract a torque imparted against the cassette 44 by engagement of the drive system 116. With the cassette 44 properly aligned with the cassette receiver 46, the pogo pins 142 mate with the electrical contacts 106 of the circuit board 102. Electrical contact is then established between the cassette 44 and the controller 25. The controller 25 knows that the cassette 44 is loaded when it senses that the EEPROM 96 is present. The controller 25 reads the count that is stored on the EEPROM 96. If the count indicates that the amount of filament 14 contained in the cassette 44 is below a set "cassette empty" threshold value, the user is alerted to load a new cassette 44.

When the controller 25 senses that the cassette 44 is loaded, it energizes the solenoid 150 of the drive assembly 116. As described above, actuation of the solenoid 150 rotates the housing 160 such that the drive wheel 156 moves to its actuated position, at which it presses against the roller 76 of the cassette 44. The drive wheel 156 imparts a force against the roller 76, pushing the roller 76 towards the roller 78, thus pinching the strand of filament 14 that is in the filament path. When the drive wheel 156 is driven in a counterclockwise rotation by the motor 152, the roller 76 is driven in a clockwise-rotation so as to advance the strand of filament 14 into the conduit 140, and then into the guide tube 18.

The cassette receiver 46 continues to advance the strand of filament 14 until it reaches the feed rollers 22. The controller 25 senses presence of the filament 14 at the feed rollers 22. Preferably, motor 24 is a DC servo motor, and the sensing is achieved by monitoring the current load of the motor 24. To monitor the current load, the controller 25 activates the motor 24 at the start of the auto-load process. When filament is present between the rollers 22, the current load will increase. When the controller 25 senses the increase in motor current load, the controller 25 signals the motor 24 and the cassette receiver 46 to stop. Additionally, the controller 25 de-energizes the solenoid 150 to remove the force of drive wheel 156 against the roller 76. This serves to remove the frictional force of the rollers from the filament 14 during modeling. Filament 14 from each of the cassettes 44 is loaded in a like manner. Once both materials have been loaded, modeling may begin.

Optionally, as mentioned above, the drive assembly 116 could be designed so that the drive wheel 156 remains in a fixed position where it applies a constant force. In such an arrangement, it would be possible to eliminate the roller pair 22, and instead use the roller pair on the cassette 44 to feed the filament 14 into the liquifier 26. Then, the drive wheel 156 would be driven at a controlled rate to control the rate of advancement of the filament 14 into the liquifier 26.

To unload the filament, a controller 25 drives the motor 24 backwards for a short time sufficient to pull the strand of filament 14 out of the liquifier 26 and feed rollers 22. The controller 25 then disengages the cassette receiver 46 from the cassette 44, allowing the user to remove the cassette 44 from the loading bay 42. To eject the cassette 44 from the machine 40, the user pushes the cassette 44 to the hardstop to allow disengagement of the latch 122. The spring 130 then forces forward the reciprocating assembly 114, ejecting the cassette 44.

The top surface and trailing edge of cassette 44 each have a window 170 which allow the user to visually inspect the amount of filament 14 contained within the cassette 44 when the cassette 44 is loaded or unloaded. If a useable amount of

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filament 14 remains in the cassette 44 when it is removed from the loading bay 42, the cassette can be stored for later use. If there is not a usable amount of filament remaining, the cassette 44 can be refilled and reused.

Embodiment Two

FIG. 13 shows a filament loading assembly 178 in a second embodiment of a modeling machine 180, which builds models from filament supplied from a second exemplary embodiment of a filament cassette 184. The filament loading assembly 178 and the filament cassette 184 are particularly suited for building models from moisture-sensitive materials. The filament loading assembly 178 comprises four loading bays 182, four filament cassettes 184 each containing a spool 186 carrying a coil of filament 188, four filament cassette receivers 190, two junction blocks 192 and a drying system 194. The four loading bays 182 are aligned horizontally across the front of the modeling machine 180. Each loading bay 182 receives one filament cassette 184 and has associated with it one filament cassette receiver 190, mounted in a ceiling thereof. The junction blocks 192 are mounted to a frame 195 of the filament loading assembly 178, and are each associated with a pair of cassette receivers 190.

A user loads the filament cassette 184 into the modeling machine 180 by holding the cassette 184 in an upright position, pushing the cassette 184 into one of the loading bays 182, grasping a latch 196 on the filament cassette receiver 190, and pulling the latch 196 forward to drop the filament cassette receiver 190 to a lowered position. In the lowered position, the filament cassette receiver 190 mates with the filament cassette 184 and latches the cassette 184 into place. A strand of filament is manually fed from each filament cassette 184 to the associated cassette receiver 190 (as will be described in detail below). The cassette receiver 190, under control of the controller 25, then automatically advances the filament strand through tubing 202 and the associated junction block 192 toward the extrusion head 20.

Each junction block 192 has two input ports 198, one air port 199, and one output port 200. The input ports 198 are coupled to the associated cassette receivers 190 by lengths of tubing 202, which provides a path for filament strands from the receivers 190 to the associated junction block 192. The output ports 200 of each junction block 192 are connected to lengths of tubing 204. Tubing 204 provides a filament path from each junction block 192 to a liquifier 26 (such as shown in FIG. 1). For filament 188 that is made of a moisture sensitive material, the drying system 194, which comprises a compressor 206, a filter 208, and a regenerative dryer 210, is used to maintain dry conditions in the path of the filament strand as it travels from the cassette 184 to the liquifier 26, as will be described in more detail below.

At a given time, only one strand of filament is provided to each junction block 192 and to each pair of feed rollers 22. The other filament strands remain in the associated cassette receivers 190. A cassette 184 that provides the filament strand to the junction box 192 is termed a primary material supply cassette, while a cassette 184 which provides the filament strand that remains in the cassette receiver 190 is termed a standby material supply-cassette. The machine 180 can switch from the primary to the standby material supply cassette 184 without user intervention, by winding the filament strand from the primary cassette 184 back towards its receiver 190, and advancing the filament strand from the standby cassette 184 through the junction block 192 to the feed rollers 22. The standby cassette then becomes the

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primary cassette. In a typical modeling application, it will be preferable for one junction block 192 to receive modeling material filament and the other junction block 192 to receive support material filament. Then, the machine 180 can automatically switch to the standby supply when the primary supply is depleted, and no modeling time will be lost. The depleted cassette can be replaced at the user's convenience while the modeling machine 180 continues to run. Alternatively, if the primary and standby cassettes 184 contain different types of filament 188, switching can be done before depletion of material to allow building from a different material type or color.

The filament cassette 184 is shown in detail in FIGS. 14-17. As shown, the filament cassette 184 is comprised of a canister 212, a guide block 214, and spool 186 carrying a coil of the filament 188. The canister 212 is formed of a body 216, and a lid 218 that presses onto the body 216. The interior of canister 212 defines a chamber containing the spool 186. The spool 186 rotates on a hub 220 of the body 216 and a hub 221 of the lid 218. Optionally, a spring plate 222 is attached to the inside of the lid 218. The spring plate 222 has spiked fingers which are bent so as to allow rotation of the spool 186 in only the direction that will advance filament out of the cassette 184. The guide block 214 is attached to the body 216 at an outlet 224, and provides a exit path for the filament 188. The guide block 214 is fastened to the canister body 216 by a set of screws (not shown) which extend through six screw holes 232 in the body 216 (shown in FIG. 15).

For filament 188 made of moisture sensitive material, the cassette 184 is made air tight. The canister 212 and guide block 214 are made of materials that block water vapor transmission, such as sheet metal and polypropylene, respectively. A strip of moisture-impermeable tape 223 seals the lid 218 to the body 216. Moisture can be withdrawn from the interior chamber of canister 212 through a hole 226 in the canister body 216, and the hole 226 sealed with a plug 228. Preferably, a piece of moisture-impermeable tape 230 is placed over the plug 228 to further seal the hole 226.

As shown in FIG. 19, a strand of the filament 188 inside the canister 212 is fed through outlet 224 into a filament path 236 in the guide block 214. The filament path 236 extends through the guide block 214, terminating in an exit orifice 238. Adjoining the filament path 236, the guide block 214 has a chamber 238 in which a knurled roller 240 is mounted on a pin 242. The pin 242 is mounted so that the knurled roller 240 pinches the strand of filament in the path 236 against a wall 246. A user can advance the filament strand out of the exit orifice 238 and along the filament path 236 by manually rotating the roller 240 in a clockwise direction. To prevent a counterclockwise rotation of roller 240 (which would push the filament strand towards the canister 212 where it could be accessed only by opening the canister), an anti-rotation plate 244 is preferably mounted in the chamber 238, juxtaposed with the roller 240. It will be apparent to those skilled in the art that the knurled roller 240 could be replaced with some other means for advancing the filament strand. For example, the wall 246 could have a raised contour allowing a user to apply a manual propulsion force to the filament over the contour. Further, the raised counter could be defined by an idler rollers or an idler roller could be used in combination with the knurled roller 240.

For filament 188 formed of moisture sensitive material, air flow to the filament path 236 is prevented. The guide block 214 has a removable plug cap 248 that seals the exit orifice 238, and a door 250 that encloses the chamber 238. The plug cap 248 snap-fits onto a pair of grooves 254 on the

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guide block **214**, so that a compressible seal **252** on the underside of the plug cap **248** covers the exit orifice **238**. The plug cap **248** is removed by the user at the time of inserting the cassette **184** into the machine **180**. Preferably, the guide block has a second set of grooves **256** on which the plug cap **248** may be parked when it is removed from the first set of grooves **254**. The door **250** has a compressible seal **258** on an interior surface thereof, and pivots on a hinge **260**. When the door **250** is open, the roller **240** is accessible to a user. The door **250** is opened by a user to load filament into the machine **180**, and kept closed otherwise. A compressible seal **234** is placed between the guide block **214** and the canister body **216** to further seal the cassette **184**.

The guide block **214** may carry an EEPROM **96** (described with respect to embodiment one above). The circuit board **102** carrying EEPROM **96** is mounted in a depression **262** of the guide block **214**, with the pair of electrical contacts **106** facing out and the EEPROM **96** facing in. The circuit **102** is fastened to the guide block **214** by three screws **266**. For ease of use, the guide block **214** preferably functions as a handle for the cassette **184**. In the embodiment shown, the guide block **214** includes a pair of grips **264** (shown in FIG. 14) on opposite sides thereof.

The filament cassette **184** is assembled by placing the spool **186** carrying the filament **188** on the hub **220** of the body **216**, and feeding a filament strand into the guide block **214**. The filament strand is positioned along the filament path **236** so that it contacts the roller **240**. Optionally, packets of desiccant **62** (such as shown in regards to embodiment one) may be placed in compartments defined by spokes **225** of the spool **186**. Then, the lid **218** is pressed onto the body **216**, and the tape **223** is applied. It is then ready for use. The cassette **184** may likewise be refilled and reused after the filament **188** that it contains becomes depleted or unusable, by removing the lid **218** of the canister **212** and replacing the filament **188** on the spool **186**. When refilling a cassette **184**, the EEPROM **96** carried by circuit board **102** can be reset or the circuit board replaced to provide a new EEPROM **96**.

For moisture sensitive materials, the cassette **184** containing the spooled filament should be dried to a level at which the moisture content will not impair model quality. For most high-temperature thermoplastics, for example polycarbonate, polyphenylsulfone, polycarbonate/ABS blend and Ultem™, an acceptable moisture content is a level less than 700 parts per million (ppm) water content (as measured using the Karl Fischer method). Multiple techniques may be used to dry the filament.

The material may be dried by placing the cassette **184** containing spooled filament in an oven under vacuum conditions. The cassette **184** is placed in the oven prior to attaching the circuit board **102** and prior to plugging the hole **226**. The oven is set to a temperature suitable to the specific modeling material type. For high-temperature thermoplastics, a temperature of between 175–220° F. is typical. The oven has a vacuum pump which maintains a dry environment in the oven. The hole **226** in canister **212** facilitates bringing the chamber of the canister **212** to the oven environment, so that the modeling material will be dried. When the moisture content of the material reaches a level desirable for the modeling material, the hole **226** is promptly sealed and the cassette **184** removed from the oven. For high-temperature thermoplastics, an expected drying time is between 4–8 hours to reach less than 300 ppm water content. The circuit board **102** is then attached. The fully-assembled cassette **184** may be vacuum-sealed in a moisture-impermeable package, until its installation in a machine.

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Alternatively, the packets of desiccant **62** alone may be used to dry the material in the chamber of canister **212** without use of the oven. It has been demonstrated that placing packets **62** containing Tri-Sorb-molecular sieve and calcium oxide (CaO) desiccant formulations in the cassette **184** and sealing the cassette **184** in a moisture-impermeable package will dry the material to a water content level of less than 700 ppm, and will dry the material to the preferred range of 100–400 ppm. This desiccant-only drying method has advantages over the oven-drying method in it requires no special equipment, and is faster, cheaper and safer than oven drying. Suitable Tri-Sorb-molecular sieve desiccant formulations include the following: zeolite, NaA; zeolite, KA; zeolite, CaA; zeolite, NaX; and magnesium aluminosilicate.

Modeling filament in the cassette **184** can later be re-dried by oven-drying or by replacing the desiccant packets if the cassette **184** becomes moisture contaminated while a usable amount of filament **188** remains. Moisture contamination may occur, for example, if the access door **250** is left open for a prolonged time period, if the cassette **184** is removed from the machine **180** without replacing the plug cap **248**, or if the cassette **184** is opened by a user.

The filament cassette receiver **190**, which engages filament cassette **184**, is shown in detail in FIGS. 18 and 19. Each cassette receiver **190** comprises a lift **270** and a drive block **272**. As shown in FIG. 19, drive block **272** houses an entry conduit **274**, an exit conduit **276**, a pair of rollers **278** and **279**, a motor **280** and the latch **196**. Roller **278** is a drive roller and roller **279** is an idler. The drive roller **278** is driven by the motor **280**. The motor **280** is preferably a DC motor with a current supply controlled by the controller **25**. Motor **280** extends laterally through the drive block **272** and couples to the drive roller **278** by a drive gear **282** attached to the shaft of the roller **278**.

The exit conduit **276** is connected to the tubing **202**. The filament strand provided from the guide block **214** passes through the entry conduit **274** to the rollers **278** and **279**. The entry conduit **274** mates with the exit orifice **238** of the guide block **214** when the cassette **184** is loaded and latched into modeling machine **180**. To provide an airtight path for the filament strand entering the drive block **272**, a seal **284** surrounds the entry conduit **274** near the entrance thereof, and compresses against the guide block **214** of the loaded cassette **184**. From the rollers **278** and **279**, the filament strand is provided to the exit conduit **276**, and from there to the tubing **202**. The tubing **202** makes an airtight seal with the exit conduit **276**. Likewise, tubing **202** and tubing **204** make an airtight seal with the ports **198** and **200** of the junction block **192**, providing an airtight filament path from the cassette **184** to the feed rollers **22**.

The drive roller **278** and idler roller **279** must maintain gripping, frictional contact on the filament strand to advance it along the filament path. To grip the filament strand, the rollers **278** and **279** may be have elastomeric surfaces, or idler roller **279** may be spring-biased towards the drive roller **278**, such as is described in U.S. Pat. No. 5,121,329. An advantage of a spring-biased configuration is that the roller surfaces can be hard and more wear resistant. Preferably, the surfaces of rollers **278** and **279** each also have a groove around the circumference thereof to align the filament strand on its course from the entry conduit **274** to the exit conduit **276**. The rollers **278** and **279** are accessible to a user for maintenance through cover plate **308**.

The drive block **272** also contains a filament sensor **286**, which is positioned along the filament path between the

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roller pair 278 and 279 and the exit conduit 276. Sensor 286 is electrically connected to the controller 25, and provides a signal indicating whether or not filament is present at the position of the sensor 286. In the exemplary embodiment shown, the sensor is a floating axis microswitch sensor. The drive block 274 further carries an electrical connector 290. The electrical connector 290 has two pogo pins 142 that mate with the electrical contacts 106 of circuit board 102, connecting the EEPROM 96 carried by circuit board 102 to the controller 25. The EEPROM 96, when contacted by the pogo pins 142, signals the controller 25 that the cassette 182 is present. In this manner, the machine 180 knows whether or not each cassette 184 has been loaded.

The drive block 272 is manually raised and lowered by the use of the latch 196. The latch 196 has a handle 291 at one end thereof and a latch pin 292 at the other end thereof. The latch 196 extends through the drive block 272 such that the handle 291 is accessible to a user and the latch pin 292 projects into a vertical slot 296 of the drive block 272. The slot 296 receives a latch plate 294 which extends vertically downward from the lift 270. The latch plate 294 has a hole 298 for receiving the latch pin 292. Pulling on the handle 291 of the latch 196 retracts the latch pin 292, allowing insertion and removal of the pin 292 from the hole 298. When the latch pin 292 is inserted into the hole 298, the drive block 272 is maintained in a raised position, allowing loading and unloading of the cassette 184 from the loading bay 182. When the latch pin 292 is removed from the hole 298, the drive block 272 drops to its lowered position where it engages the cassette 184 in the loading bay 182. A user manually raises or lowers the drive block 272 by grabbing the latch handle 291, pulling forward, and either lifting or lowering the latch 196.

A pair of guide rods 302 are provided on the drive block 272, which couple the drive block 272 to the lift 270, and align the latch plate 294 in the slot 296. The guide rods 302 are mounted in two receptacles 288 on a top surface of the drive block 272. The guide rods 302 extend vertically upward from the drive block 272 and through a pair of guide bearings 304 in the lift 270. A pair of e-clips 306 clip to the guide rods 302 above the lift 270 to support the drive block 272 in its lowered position. Preferably, a pair of springs 300 surround the guide rods 302 in the receptacles 272. In the raised position, the springs 300 compress beneath the lift 270. When the latch 196 is pulled to remove the pin 292 from the hole 298, springs 302 force the drive block 272 to its lowered position.

The drying system 194 creates an active moisture barrier along the filament path, keeping the filament 188 dry while in the machine 18. In the exemplary embodiment, the drying system 194 is a dry-air purge system which provides dry air under pressure into air port 199 of the junction blocks 192. The dry air flows through the tubing 204 and exits the tubing 204 near the liquifier 26. If the feed rollers 22 are used to advance the filament strand into the liquifier 26, the filament will exit the tubing 204 as it enters the feed rollers 22. Alternatively, the feed rollers 22 can be eliminated by using the roller pair 278 and 279 in the drive block 272 to advance filament into the liquifier 26 at a controlled rate. The exit of tubing 204 serves as a vent through which any moisture that may have been trapped along the filament path is released. For instance, the air flow provided by drying system 194 will purge any humid air that enters the drive block 272 during the time that the entry conduit 274 of the drive block 272 is not sealed to a filament cassette 184. Additionally, the positive pressure maintained in the tubing 204 prevents humid air from entering the open end of the tubing 204. By

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maintaining a positive pressure in the tubing 202 and 204 and purging the filament path of any moisture, the drying system 194 allows use of the modeling machine 180 in a humid environment with moisture sensitive modeling material.

As mentioned above, the drying system 194 of the exemplary embodiment comprises a compressor 206, a filter 208 and a regenerative dryer 210. The compressor 206 intakes ambient air and provides the air under pressure to filter 208. Filter 208 removes water particles from the air. A Norgren™ F72G general purpose filter is suitable for this application. From the filter 208, the air under pressure flows to the dryer 210, which is preferably a regenerative dryer, such as an MDH Series dryer available from Twin Tower Engineering, Inc. of Broomfield, Colo. Dry air under pressure flows from the dryer 210 into each junction block 192. In alternative embodiments of the drying system, any source of dry air under pressure may be utilized successfully to purge moisture from the filament path, and other dry gases may be utilized as well. Importantly, the drying system should continuously feed dry air or other gas under pressure to the filament path, disallowing humid air from remaining in or entering the filament path, and should be vented at or near the end of the filament path. One alternative to drying system 194 is to provide a compressed nitrogen tank as the dry gas source. Another alternative is a regenerative drying system, such as a hot air desiccant dryer having an output of less than or equal to about -40° F. dew point.

To install one of the cassettes 184 into the modeling machine 180, the machine 180 is first turned on. The user then removes the plug cap 248 from the filament cassettes 184, and promptly inserts the cassette 184 into one of the loading bays 182. The plug cap 248 can be parked on the grooves 256 of the guide block 214, saving it for later use. The user latches the cassette 184 into place by pulling on latch 196, as has been described. Once latched, the pogo pins 142 will contact the circuit board 102, thereby connecting the EEPROM 96 to the controller 25. Once the controller 25 senses that the cassette 184 is loaded, the controller 25 will turn on the motor 280. The drive roller 278 will then begin turning.

The user next opens the door 250 of the guide block 214 to access the roller 240, and manually turns roller 240 by exerting a downward force on the roller. The rotation of roller 240 will advance the strand of filament 188 out of the guide block 214 and into the entry conduit 274 of the drive block 272. When the filament strand reaches the already rotating drive roller 278, the roller pair 278 and 279 will grab the filament strand and take over advancement of the strand from the user. The user promptly shuts the door 250 to seal the filament path. The roller pair 278 and 279 then advance the filament strand at least as far as the position of the filament sensor 286. If the filament cassette 184 is to be a standby cassette, the controller 25 will signal the motor 280 to stop turning, so that advancement of the filament strand ceases at the sensor 286. Alternatively, if the cassette 184 is to be a primary cassette, the roller pair 278 and 279 feed the filament strand through the junction block 192 to the feed rollers 22 (or alternatively to the liquifier 26). When the filament strand reaches the feed rollers 22, the feed rollers 22 take over control of the filament strand advancement. If the current on the motor 280 is set low enough and the filament is rigid enough, the motor 280 may be allowed to remain on and continue supplying a constant push, but will stall out when the feed rollers 22 are not in motion. This arrangement avoids having to turn the motor 280 on and off in synchrony with the operation of the feed rollers 22. In an alternate

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embodiment, the roller pair **278** and **279** may serve as the material advance mechanism in place of the feed rollers **22**. In such a case, the operation of motor **280** would be closely controlled by controller **25** to control advancement filament into the extrusion head **20**.

During modeling, the controller **25** can keep track of the amount of filament remaining in each cassette **184** by use of a count maintained by each EEPROM **96**. When one of the primary cassettes **184** becomes depleted of filament, the modeling machine **180** will automatically switch to the standby cassette **184** without operator intervention. To unload the filament, the controller drives the motor **24** backwards for a short time sufficient to pull the strand of filament **188** out of the liquifier **26** and feed rollers **22**. The controller **25** then drives the motor **280** backwards to pull the filament strand out of the tubing **204**, the junction block **192**, the tubing **202**, and past the sensor **286**. The machine **180** knows that the junction block **192** is clear to receive filament from the standby cassette **184** when the sensor **286** of the primary cassette drive block **272** indicates that filament is no longer present. The machine **180** then loads filament from the standby cassette **184** to the extrusion head **20**. This auto-unload/reload process is particularly beneficial for modeling of large objects and when the modeling machine **180** is operated beyond business hours. The user can replace the depleted cassette **184** while the machine **180** continues to build a model. The depleted cassette **184** can then be refilled and reused.

In the case that the user desires to remove one of the cassettes **184** from the machine **180** before the cassette **184** is depleted of filament, the user may command the machine **180** to execute the unload process. If a useable amount of filament **188** remains on cassette **184** when it is removed from the modeling machine, the cassette **184** may be stored for later use without contamination. In such a case, the user should seal the exit orifice **238** with the plug cap **248**. If the cassette **184** has a useable amount of filament **188** remaining but the filament has been moisture contaminated, the cassette **184** may be re-dried as described above.

As disclosed in U.S. Pat. No. 5,866,058, in building a model from a thermally solidifiable material, it is preferable to build the model in a chamber heated to a temperature higher than the solidification temperature of the modeling material, and to cool the material gradually following deposition so as to relieve stresses from the material. A number of desirable thermoplastic modeling materials have high melting points, for example, polycarbonate, polyphenylsulfone, polycarbonate/ABS blend and Ultem™, and additionally are moisture sensitive. A deposition modeling apparatus which is particularly suitable for building models at a high temperature is disclosed in PCT Application No. US00/17363, which has been incorporated by reference herein. The modeling machine **180** which uses a moisture-sealed material delivery apparatus according to the second embodiment of the present invention may be an apparatus of the type that is a subject of PCT Application No. US00/17363, thereby providing a dry, high temperature modeling environment. Various high-temperature, moisture sensitive thermoplastics have been successfully utilized in such a machine, namely, polycarbonate, polyphenylsulfone, polycarbonate/ABS blend and Ultem™ having a viscosity at the modeling temperature of less than 1200 Pa/sec at a shear rate of $10 \text{ E}^{-1} \text{ sec}^{-1}$ and having a water content ranging between 100–400 ppm. These materials are stronger than ABS thermoplastic and have suitable thermal properties, melt viscosity, shrink characteristics and adhesion for use in three-dimensional deposition modeling.

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Although the present invention has been described with reference to exemplary embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention. For example, the various features of embodiment 1 may be used and interchanged with the features of embodiment 2, and vice-versa. For example, the drying system of embodiment 2 may be used with the design of embodiment 1, and embodiment 1 may be used to provide primary and standby cassettes as disclosed with respect to embodiment 2. Additionally, it will be apparent to those in the art that the filament cassette and loading system of the present invention may be used to advantage in extrusion applications other than the building of three-dimensional models by a fused deposition process. Other changes may be made as well in keeping with the scope of the invention. As an example, the motor for driving a roller carried by a filament cassette may be carried by the cassette rather than mounted on the modeling machine. These and other changes will be apparent to one skilled in the art.

What is claimed is:

1. An extrusion apparatus having a liquifier that receives a feedstock of material in filament form and delivers the material in a flowable state, comprising:

a loading bay;

a substantially enclosed cassette containing spooled filament, inserted in the loading bay; and

means for engaging a strand of the filament in the loading bay and advancing the filament strand along a path to the liquifier.

2. The extrusion apparatus of claim 1, and further comprising:

a conduit having an entrance in the loading bay for guiding the filament strand as it is advanced.

3. The extrusion apparatus of claim 2, wherein the entrance of the conduit makes an airtight seal with an exit orifice of the cassette.

4. The extrusion apparatus of claim 2, and further comprising:

registration means for aligning the cassette with the conduit.

5. A three-dimensional modeling machine having a liquifier that receives modeling material in filament form and delivers the material in a flowable state, comprising:

a loading bay for receiving a cassette containing spooled filament;

means for engaging a strand of the filament in the loading bay; and

means for automatically advancing the filament strand along a path to the liquifier.

6. The three-dimensional modeling machine of claim 5, and further comprising:

a conduit having an entrance in the loading bay for guiding the filament strand as it is advanced.

7. The three-dimensional modeling machine of claim 5, and further comprising:

registration means for aligning the cassette with the conduit.

8. The three-dimensional modeling machine of claim 5, and further comprising:

latching means for engaging and disengaging the cassette in the loading bay.

9. The three-dimensional modeling machine of claim 5, and further comprising:

means for ejecting the cassette from the loading bay.

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10. A three-dimensional modeling machine having a liquifier that receives modeling material in filament form and delivers the material in a flowable state, comprising:

a loading bay for receiving a cassette containing spooled filament; and

a filament cassette receiver for engaging the cassette in the loading bay, said receiver comprising:

a conduit for receiving a filament strand from the cassette and guiding the filament strand along a path to the liquifier; and

means for advancing the filament strand through the conduit.

11. The three-dimensional modeling machine of claim **10**, wherein the means for advancing comprises:

a pair of feed rollers having a nip therebetween for receiving the filament strand; and

a drive mechanism coupled to the feed rollers.

12. The three-dimensional modeling machine of claim **11**, wherein the feed rollers are in the conduit.

13. The three-dimensional modeling machine of claim **10**, wherein the means for advancing comprises:

a drive wheel configured to mate with a follower wheel on the cassette; and

a drive mechanism coupled to the drive wheel.

14. The three-dimensional modeling machine of claim **13**, wherein the filament cassette receiver further comprises:

a drive engagement means for engaging and disengaging the drive wheel.

15. The three-dimensional modeling machine of claim **10**, and further comprising:

a sensor for detecting presence of the filament strand at a sensing position of the path approaching the liquifier;

wherein the means for advancing is disabled in response to a detection indication provided by the sensor.

16. The three-dimensional modeling machine of claim **15**, and further comprising:

a pair of feed rollers located proximate the sensing position.

17. The three-dimensional modeling machine of claim **10**, wherein the filament cassette receiver further comprises:

registration means for aligning an exit orifice of the cassette with an entrance of the conduit.

18. The three-dimensional modeling machine of claim **10**, wherein an entrance of the conduit is configured to make an airtight seal with an exit orifice of the cassette.

19. A three-dimensional modeling machine having a liquifier that receives modeling material in filament form and delivers the material in a flowable state, comprising:

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a loading bay for receiving a cassette containing spooled filament;

a conduit configured to mate with an exit orifice of the cassette for receiving a filament strand from the cassette and guiding the filament strand along a path to the liquifier; and

a drive roller for advancing the filament strand through the conduit.

20. The three-dimensional modeling machine of claim **19**, and further comprising:

a latch for engaging and disengaging the cassette in the loading bay.

21. The three-dimensional modeling machine of claim **19**, wherein the entrance of the conduit makes an airtight seal with an exit orifice of the cassette.

22. The three-dimensional modeling machine of claim **19**, and further comprising:

registration means for aligning the cassette with the conduit.

23. The three-dimensional modeling machine of claim **19**, and further comprising:

means for ejecting the cassette from the loading bay.

24. The three-dimensional modeling machine of claim **19**, and further comprising:

a follower roller positioned opposite the drive roller.

25. The three-dimensional modeling machine of claim **24**, wherein the drive roller and the follower roller are in the conduit.

26. The three-dimensional modeling machine of claim **19**, wherein the drive roller is a wheel configured to engage a follower wheel on the cassette.

27. The extrusion apparatus of claim **26**, and further comprising:

drive engagement means for engaging and disengaging the drive roller from the cassette.

28. The extrusion apparatus of claim **27**, and further comprising:

a pair of feed rollers positioned along the path proximate the liquifier; and

a sensor for detecting presence of the filament strand between the feed rollers and providing a detection indication;

wherein the drive engagement means disengages the drive roller in response to the detection indication.

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