

Fig. 1

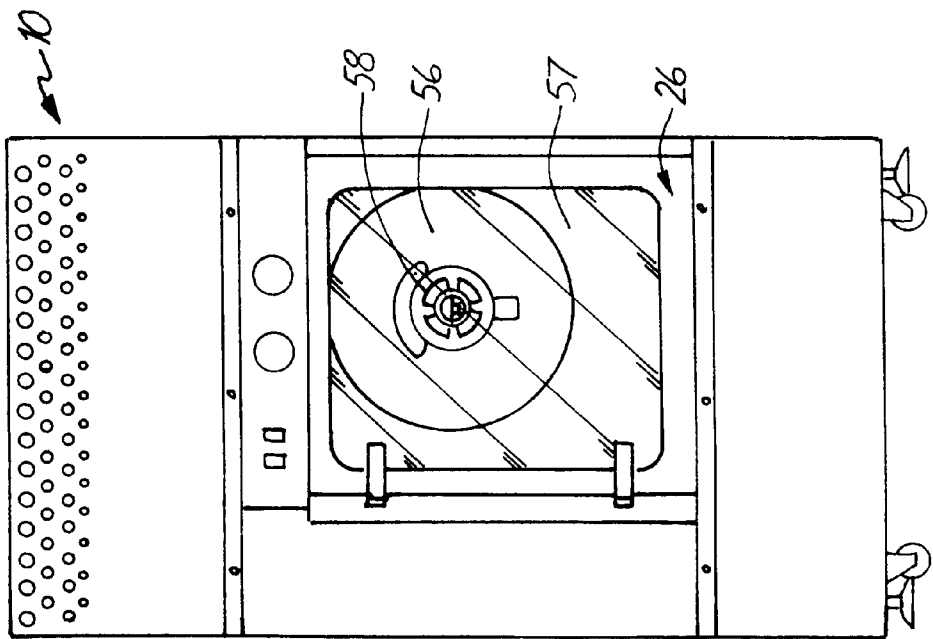


Fig. 3

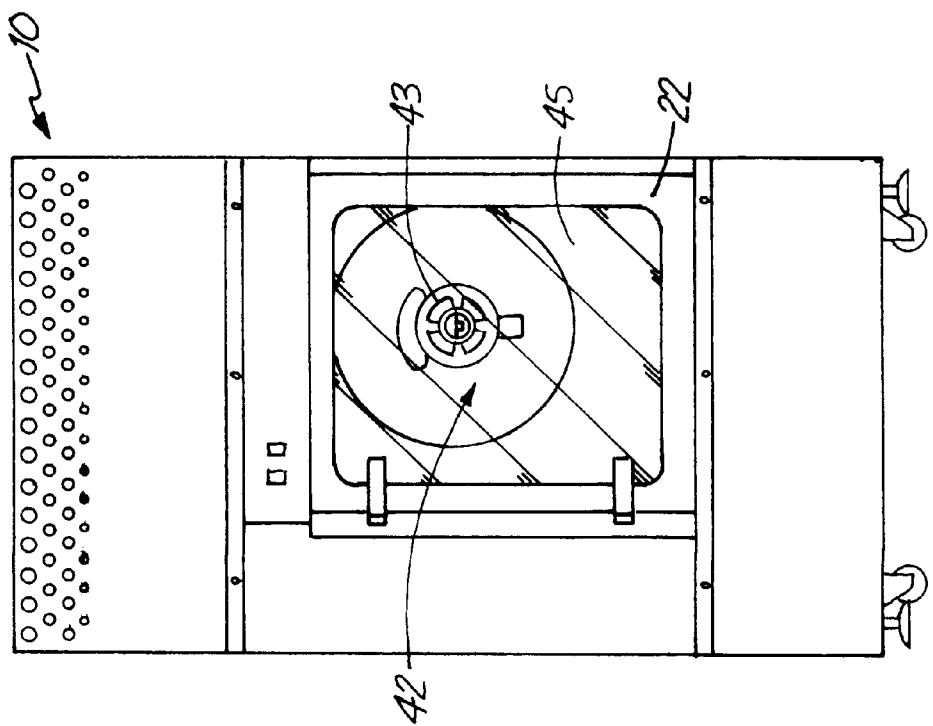
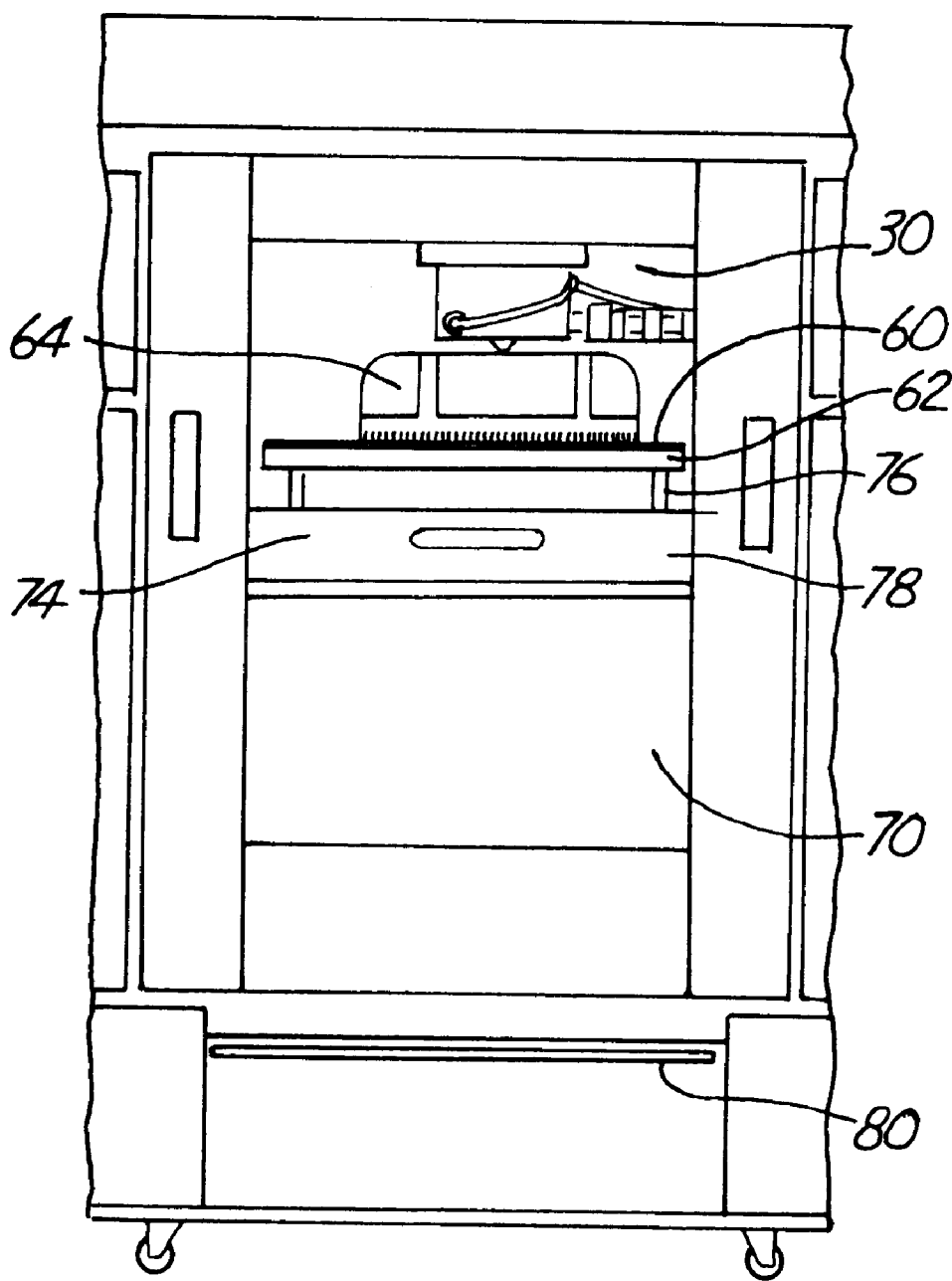
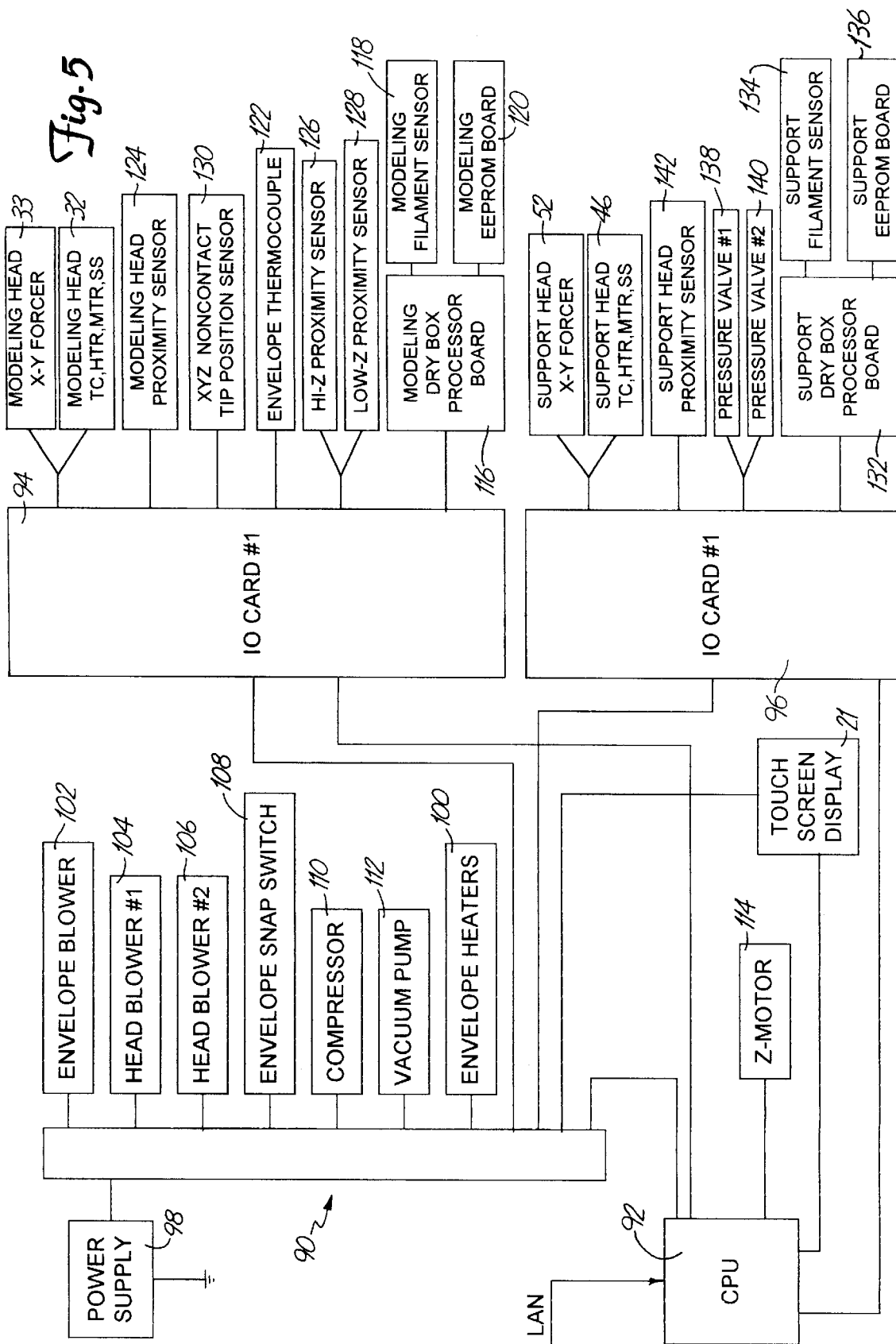
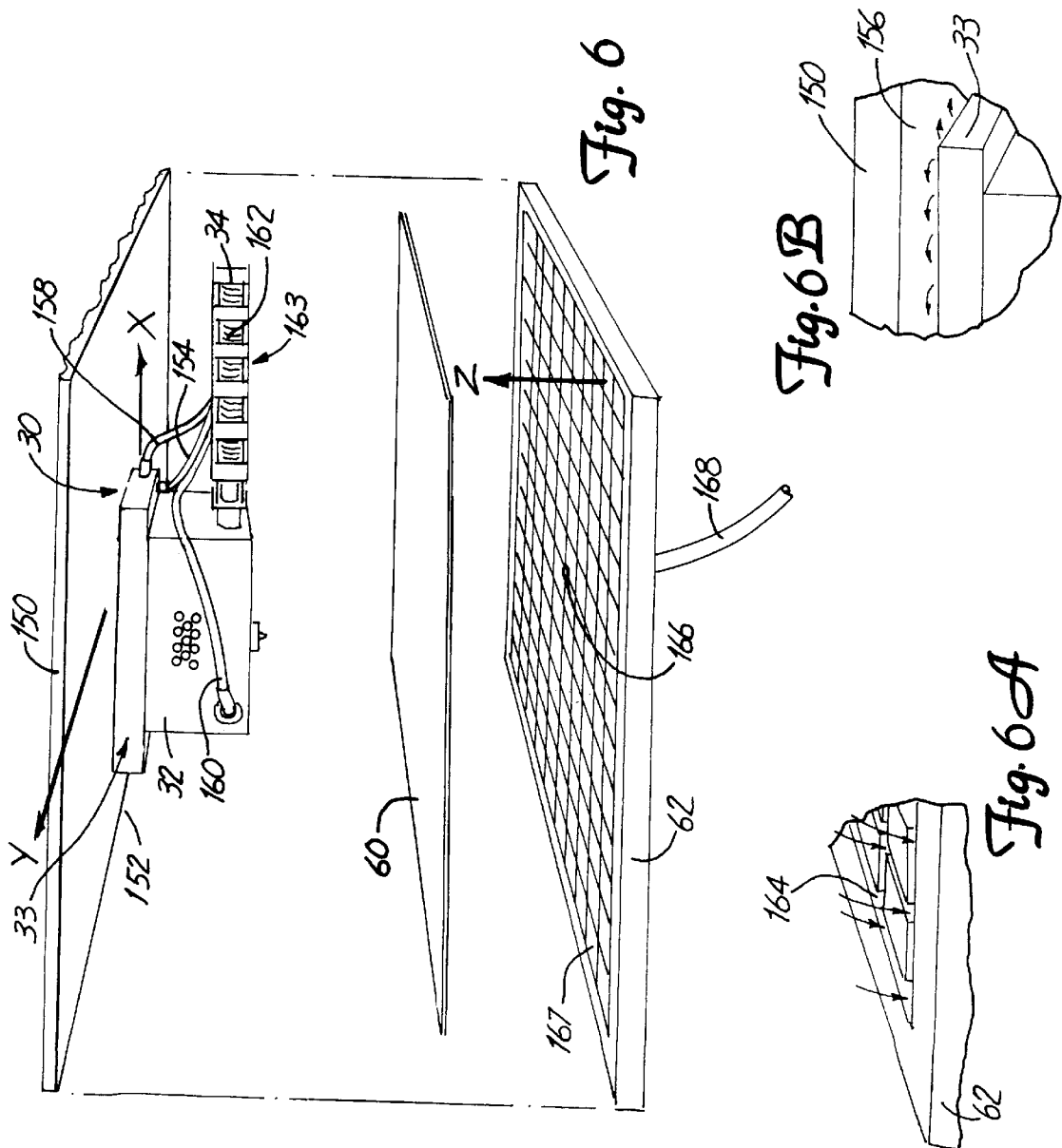


Fig. 2

Fig. 4







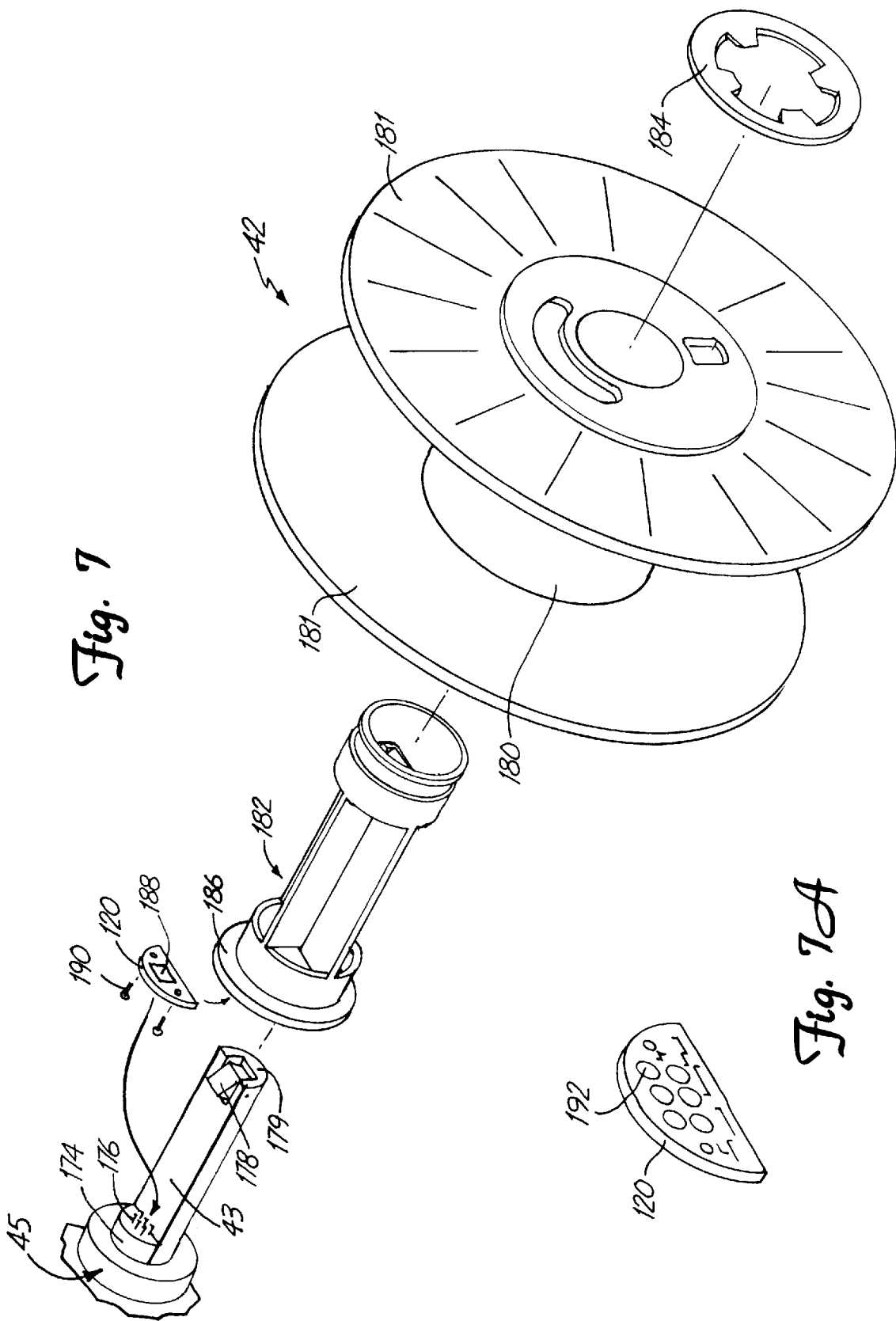
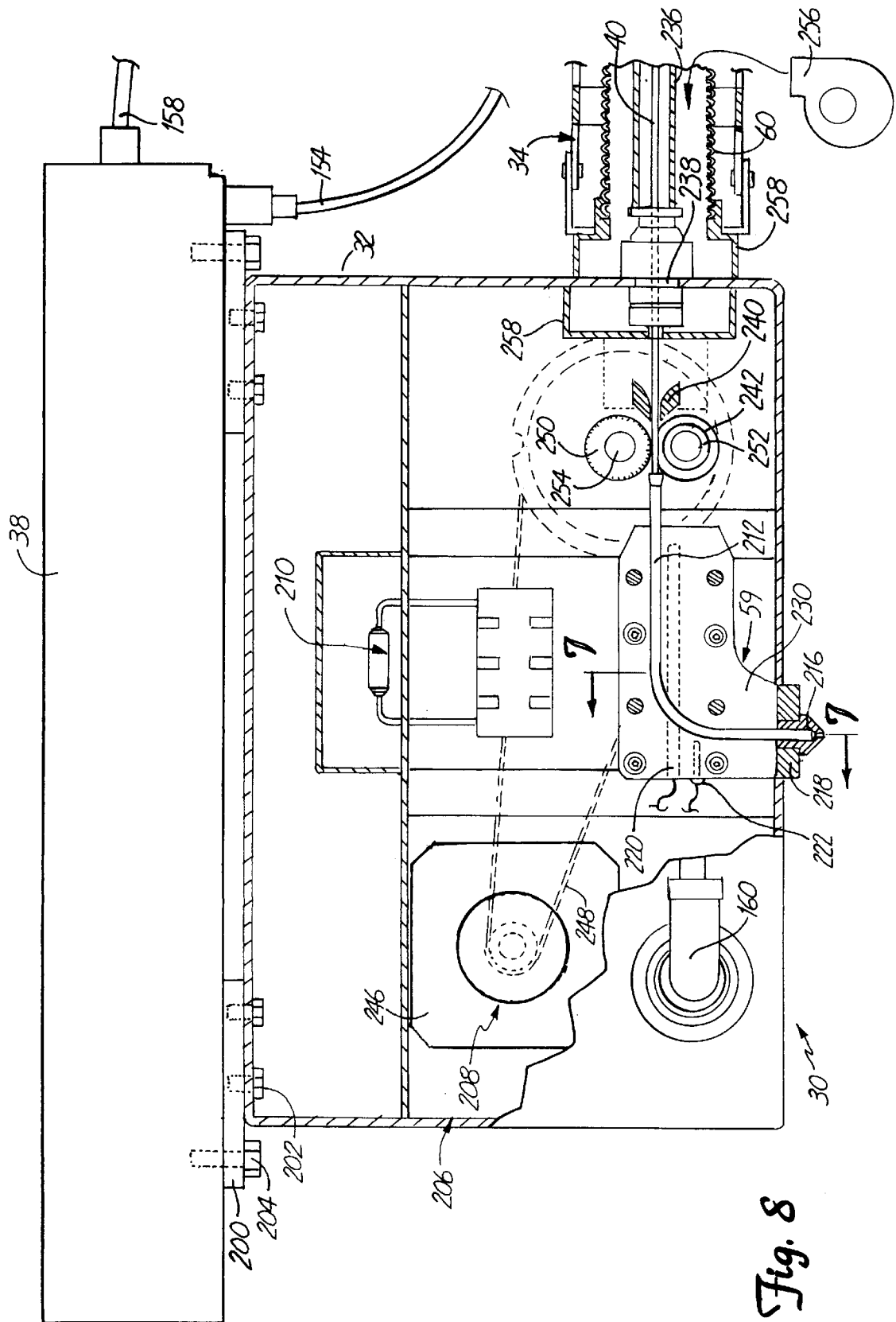
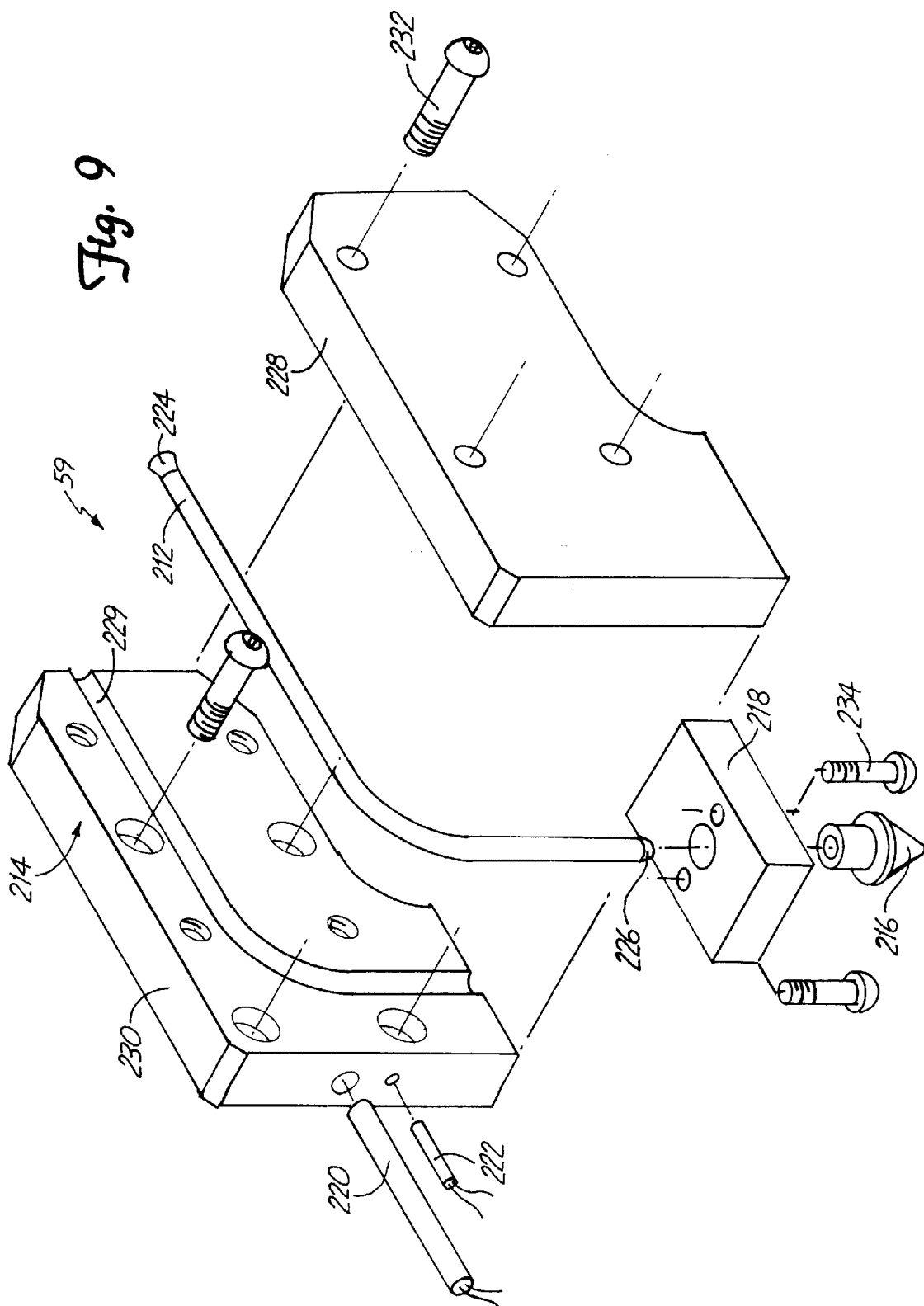
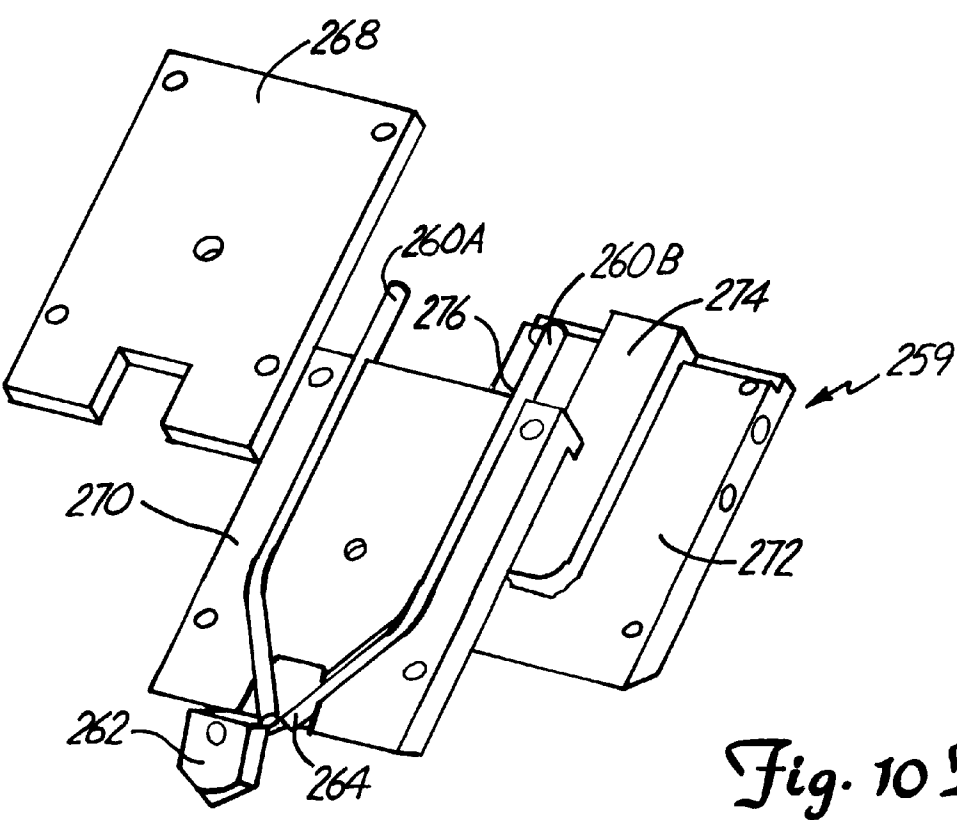
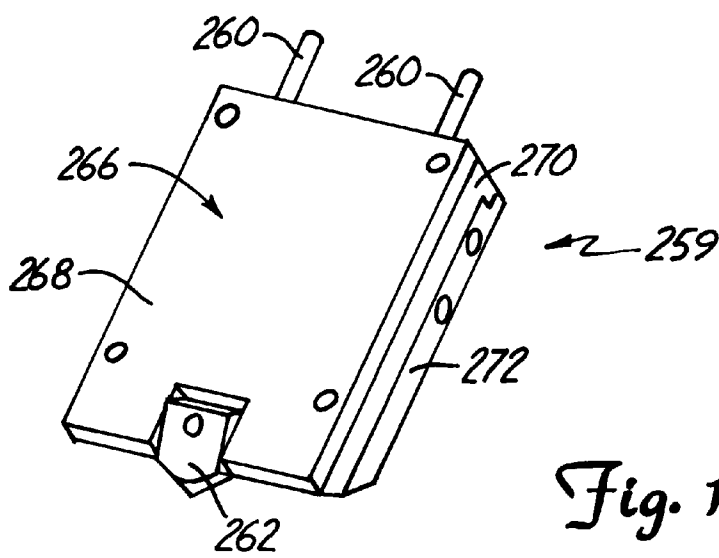


Fig. 7

Fig. 7A







THIN-WALL TUBE LIQUIFIER

BACKGROUND OF THE INVENTION

This invention relates to a dispensing head for depositing layers of solidifying material in a desired pattern to form three-dimensional physical objects. One useful application for such a device is rapid prototyping of models or objects. The modeling material is selected and its temperature is controlled so that it solidifies upon extrusion from the dispensing head onto a base, with the build-up of multiple layers forming the desired article.

A rapid prototyping system involves the molding of three-dimensional objects based upon design data which is provided from a computer aided design (CAD) system. Examples of apparatus and methods for rapid prototyping of three-dimensional objects by depositing layers of solidifying material are described in Crump U.S. Pat. No. 5,121,329, Batchelder et al. U.S. Pat. No. 5,303,141, Crump U.S. Pat. No. 5,340,433, Batchelder U.S. Pat. No. 5,402,351, Batchelder U.S. Pat. No. 5,426,722, Crump et al. U.S. Pat. No. 5,503,785, and Abrams et al. U.S. Pat. No. 5,587,913, all of which are assigned to Stratasys, Inc. The rapid prototyping systems disclosed in the '329, '433 and '785 patents ("Crump patents") describe an extrusion head which receives a solid state material used to form three-dimensional articles, heats the material to just above its solidification temperature, and dispenses the material as a fluid onto a base.

Various embodiments of the extrusion head are shown in the Crump '433 patent. Each embodiment includes a liquifier which consists of three zones: an entrance zone or cap, a heating zone or body and a nozzle. A first embodiment is shown in FIG. 3 of the '433 patent. FIG. 3 shows a liquifier within an extrusion head having a seal ring (i.e., a cap), a heating head (i.e., heating zone) and a nozzle. The seal ring receives a supply rod of solid material. An electric heater within the heating head heats the supply rod to a temperature exceeding its solidification temperature, reducing it to a liquid state. The liquid material then flows into the nozzle through a nozzle flow passage, and is dispensed through a nozzle dispensing outlet.

A second embodiment of the extrusion head is shown in FIG. 5 of the Crump '433 patent. In this embodiment, the supply material is in the form of a flexible strand in solid form. The flexible strand of material shown in FIG. 5 is fed through a guide sleeve to an extrusion head. The extrusion head contains a supply chamber in a top portion and a liquifier in a bottom portion. Drive rollers within the supply chamber introduce the flexible strand into the liquifier. The liquifier within the extrusion head includes a seal ring (i.e., a cap), a material supply and flow passage (i.e., heating zone) and a dispensing outlet orifice (i.e., a nozzle). The flexible strand is advanced into the liquifier through the seal ring, which provides a hydraulic seal around the internal surface of the flow passage. A heater in the form of a sleeve containing a heating coil is positioned around the flow passage and the orifice to heat the strand to a fluid state in the passage. The material is dispensed in a fluid state through the orifice.

A third embodiment of the extrusion head is shown in FIG. 13 of the Crump '433 patent. As with the embodiment shown in FIG. 5, the material is supplied in the form of a flexible strand in solid form. The strand is advanced into an extrusion head through a guide sleeve. A strand advance mechanism comprising a pair of motor-driven feed rollers or pulleys and advances the strand into the liquifier. The liqui-

fier of FIG. 13 is comprised of a tubular guide member, a seal ring, a liquifier nozzle and a removable tip. The tubular guide member and seal ring together form the cap zone. The tubular guide member is made of highly conductive metal, such as aluminum or silver. It dissipates heat rapidly to maintain the flexible strand at a suitable temperature during its movement from the strand advance mechanism into the heating zone. To further dissipate heat from the guide member, a blower may be used to circulate air into the extrusion head, around the guide member. A cooling fin extending from the guide member in an "L"-shape is additionally utilized to enhance the heat dissipation from the guide member. At its lower end, the guide member is supported on the seal ring. The seal ring is made out of heat-insulating plastic to serve as a thermal seal. The liquifier nozzle surrounded by a heating coil and an outer insulation sleeve provides a heating zone in which the strand material is melted. The liquifier nozzle (i.e., heating tube) is made of heat-conducting material such as silver or preferably aluminum. The removable tip is attached to the bottom end of the liquifier nozzle by a threaded connection.

A fourth embodiment of the extrusion head is shown in FIG. 6 of the Crump '433 patent. In this embodiment, multiple materials are dispensed through separate passages into a single discharge outlet. The embodiment of FIG. 6 allows utilization of different materials to form different layers of the same article.

The Crump '785 patent discloses an extrusion head carrying two liquifiers, each having its own nozzle. The liquifiers of the '785 patent each have a cap at a receiving end, secured by a mounting ring to a tubular dispenser (i.e., heating tube). A heating coil is wrapped around each tubular dispenser to heat and melt a filament of material. In each liquifier, the material is provided in a fluid state to a dispensing nozzle and discharged through a nozzle tip. Filament is conveyed to each liquifier from a supply spool by a pair of pinch rollers driven by stepper motors.

In the aforementioned liquifiers, the cap region serves as the transition zone for the modeling material where at the entrance to the cap the temperature is below the softening point of the material and the outlet of the cap is above the temperature required to pump the material in a semi-liquid state. This requires a change in temperature of up to 250° Celsius over the length of the cap. Ideal properties for the cap are a high thermal resistivity in the axial direction and low thermal resistivity in the radial direction. The previous designs, such as those described in the Crump patents, used high temperature thermoplastics or thermoset plastics such as Dupont "Vespel" SP-1, for the cap to accomplish these goals. These caps are expensive, have temperature limitations, and require a sealing mechanism between the cap and the heating body, which is typically formed of aluminum. The caps and seal are prone to leakage.

It would be desirable to form the cap zone of the liquifier out of the same medium used to form the liquifier body. A medium that is inexpensive, that allows bends in the liquifier path to be easily made, and that can further be used to form the nozzle zone would also be desirable.

SUMMARY OF THE INVENTION

The present invention is an improved liquifier for use in the extrusion head of a rapid prototyping system of the type generally shown in the Crump patents. The present invention provides a thin-wall tube liquifier formed of a single piece of thin-wall tubing encased in a heating block. The tube acts as both the heating zone and the cap zone of the liquifier. In

the preferable embodiment, the tube is made of metal. The nozzle zone can be formed by swaging the metal tube to a nozzle geometry, or, it may be brazed or welded to the bottom of the tube. The heating block is made of heat conductive material, such as aluminum or beryllium copper (BeCu).

The thin-wall tube has a inlet end for receiving a filament of molding material and an outlet end for delivering the material in liquid form. A first section of the tube adjacent the inlet end functions as the entrance or cap zone. This first section of the tube is exterior to the heating block. The tube has a second section which passes through the heating block forming a heating zone. The nozzle connects to the outlet end of the tube. The heating block preferably contains a heating element in heat exchange relation to the second section of the tube to heat the filament to a temperature just above its solidification temperature.

The filament is preferably of a very small diameter, on the order of $\frac{1}{16}$ th inch. The cap zone of the tube must dissipate heat rapidly to maintain the flexible strand at a suitable temperature during its movement into the heating zone, so that the strand will not become limp and buckle. A stainless steel tube having a wall thickness in the range of 0.008–0.015 inches is suitable and inexpensive for this purpose. The interior diameter of the tube is preferably on the order of 0.07 inches.

The filament may be fed or advanced in various ways to the liquifier. A pair of power-driven pinch rollers is a preferred advance mechanism for gripping and advancing the filament.

The heating block is preferably comprised of a first and a second section, which are mechanically detachable to allow access to and removal of the tube. This heating block design facilitates maintenance and replacement of the tube.

An alternative embodiment of the present invention provides two liquifiers that share a common nozzle for receiving two filaments of diverse materials and delivering each in liquid form. In this embodiment, two thin-wall tubes of the type described with reference to the first embodiment are braised or welded to a common nozzle. The heating block preferably has three mechanically detectable vertical sections, two outer sections and one interior section which positions the tubes and nozzle. One of the outer sections preferably contains a heating element in heat exchange relation to the second section of each tube.

The foregoing invention provides several advantages over the previous liquifier designs. It eliminates the need for a seal between the liquifier body and cap zones, and is simpler and less expensive to manufacture. The liquifier of the present invention further allows for simple or complex bends in the liquifier path to be easily made. Further, the nozzle zone of the liquifier can be formed out of the tube as well, by swaging the tube to the nozzle geometry. The tube is easily accessible by mechanically detaching the first and second sections of the heating block. The liquifier of the present invention can additionally be modified to dispense two materials through a common nozzle. This provides a system that is lighter, cheaper to manufacture, and easier to control than systems with two separate liquifiers.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an exterior front elevation view of the preferred embodiment of the invention, showing the system in a build state.

FIG. 2 is an exterior elevation view of the right side of the preferred embodiment of the invention.

FIG. 3 is an exterior elevation view of the left side of the preferred embodiment of the invention.

FIG. 4 is a front elevation view of the prototyping envelope, showing the system in a build state.

FIG. 5 is an electrical block diagram of the control system of the preferred embodiment of the invention.

FIG. 6 is a partially exploded perspective view of the prototyping envelope showing the modeling extrusion head in a build position.

FIG. 6A is a detailed view of a portion of FIG. 5 illustrating the vacuum platen grooves.

FIG. 6B is a detailed view of a portion of FIG. 5 illustrating the air bearing of the linear motor.

FIG. 7 is an exploded view of the filament spindle and filament spool shown in FIGS. 2 and 3.

FIG. 7A is a perspective view of the outward face of the EEPROM board.

FIG. 8 is a front elevation of the modeling extrusion head, with portions shown in sectional.

FIG. 9 is an exploded view of the liquifier.

FIGS. 10A and 10B show an alternative embodiment of the liquifier.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the preferred embodiment, the rapid prototyping system 10 is contained within a cabinet 12, as shown in FIG. 1. The cabinet 12 has doors and covers located on a front, left and right sides thereof. On the front of cabinet 12, there is an envelope door 14, a modeling waste tray door 16 to the right of envelope door 14, a touch screen display panel 21 to the right of modeling waste tray door 16, a support waste tray door 18 to the left of envelope door 14, and platform cover 20 below envelope door 14. A modeling drybox door 22 and an electronics bay cover 24 are located on the right hand side of cabinet 12. A support drybox door 26 is located above a compressor bay cover 28 on the left hand side of cabinet 12.

The upper right hand side of cabinet 12 houses a modeling extrusion apparatus 30, which comprises a modeling extrusion head 32 attached below a modeling x-y forcer 33 and connected to the end of a modeling arm 34 which rotates about a modeling pivot joint 36. Modeling extrusion apparatus 30 receives a filament of modeling material 40 from a modeling filament spool 42 located in a modeling drybox 45 (FIG. 2) below pivot joint 36 and accessible through modeling drybox door 22. Drybox 45 maintains low humidity conditions to optimize the condition of filament 40. Modeling extrusion apparatus 30 is used to dispense modeling material in layers onto a substrate 60. Modeling filament spool 42 mounted on a modeling spindle 43 in drybox 45 is more clearly shown in FIG. 2.

The left-hand side of cabinet 12 houses a support extrusion apparatus 44, which is comprised of a support extrusion head 46 attached below a support x-y forcer 52 and connected to the end of a support arm 48 which rotates about a support pivot joint 50. Support extrusion apparatus 44 receives a filament of support material 54 from a support filament spool 56 located in a support filament drybox 57 (FIG. 3) beneath support pivot joint 50 and accessible through support drybox door 26. Drybox 57 maintains low humidity conditions to optimize the condition of filament 54. Support extrusion apparatus 44 is used to dispense support material in layers. Support filament spool 56 mounted on a support spindle 58 in drybox 57 is more clearly shown in FIG. 3.

Modeling material extruded in layers by modeling extrusion apparatus **30** forms object **64**. The support material is used to support any over-hanging portions as the object is being built up. In building an object, over-hanging segments or portions which are not directly supported in the final geometry by the modeling material require a support structure. Support filament **54** is supplied to support extrusion head **46** which deposits material to provide the required support. The support material, like the modeling material, is deposited in multiple layers.

In building an object, only one extrusion apparatus at a time is in an active, extruding state. In FIG. 1, the system **10** is shown building a three-dimensional object **64**, with modeling extrusion apparatus **30** in an active build state, and support extrusion apparatus **44** in a home rest position. When modeling extrusion apparatus **30** is in an active state, modeling filament **40** travels through arm **34** to extrusion head **32**, where it is heated to a liquid state. Layers of modeling material in a molten state are deposited by head **32** through a liquifier **59** protruding through a bottom surface of head **32**, onto substrate **60**. Substrate **60** is supported upon a vacuum platen **62** and held in place by vacuum forces. When support extrusion apparatus **44** is in an active build state, support head **46** similarly receives support filament **54** via arm **48**, and heats it to a liquid state. Layers of support material in a molten state are deposited by head **46** through a liquifier **59** protruding through a bottom surface of head **32**, onto substrate **60**.

The filaments of modeling and support materials are each a solid material which can be heated relatively rapidly above its solidification temperature, and which will very quickly solidify upon a small drop in temperature after being dispensed from the extrusion head. A composition having a relatively high adhesion to itself upon which it is deposited when hot is selected for the modeling material. A composition having a relatively low adhesion to the model material upon which it is deposited is selected for the support material, so that the support material forms a weak, breakable bond with the modeling material and to itself. When the object is complete, the support material is broken away by the operator, leaving the object formed of modeling material intact.

The modeling material is preferably a thermoplastic material. Other materials that may be used for the modeling material filament include bees wax, casting wax, machinable and industrial waxes, paraffin, a variety of thermoplastic resins, metals and metal alloys. Suitable metals include silver, gold, platinum, nickel, alloys of those metals, aluminum, copper, gold, lead, magnesium, steel, titanium, pewter, manganese and bronze. Glass, and particularly Corning glass would also be satisfactory. Chemical setting materials, including two-part epoxies would also be suitable. A modeling material found to be particularly suitable is an acrylonitrile-butadiene-styrene (ABS) composition. A material found to be particularly suitable for the support material is an acrylonitrile-butadiene-styrene (ABS) composition with a polystyrene copolymer added as a filler (up to about 80%) to create a lower surface energy of the ABS composition, and to provide a lower cohesion and adhesion of the material. Both filaments of material are preferably of a very small diameter, on the order of 0.070 inch. The filament may, however, be as small as 0.001 inch in diameter.

FIG. 4 shows a build envelope **70** which is the central interior region of the system **10**, accessible through envelope door **14**. In FIG. 4, door **14**, platform cover **20**, and the adjoining face plates of cabinet **12** are removed. The enve-

lope **70** is where a three-dimensional object is built. Envelope **70** contains a build platform **74** which comprises vacuum platen **62** supported by a set of legs **76**, which ride on a platform drawer **78**. Build platform **74** moves vertically in a z-direction within envelope **70**. Movement of build platform **74** is controlled by a z-drive chain **80**, driven by a z-motor **114** (shown schematically in FIG. 5). Build platform **74** remains stationary during formation of a single layer. As each additional layer is deposited on substrate **60**, build platform **74** is lowered slightly so as to allow a space for forming the subsequent layer. Platform drawer **78** pulls forward to allow the operator ready access to vacuum platen **62**.

An electrical system **90**, shown schematically in FIG. 5, controls the system **10**. A CPU **92**, together with first input/output (IO) card **94** and second input/output (IO) card **96**, control the overall operation of the electrical system **90**. CPU **92** receives instructions from the operator through communication from touch screen display **21**. Similarly, CPU **92** communicates with touch screen display **21** to display messages for the operator and to request input from the operator. CPU **92** in turn communicates with IO cards **94** and **96**. A power supply **98** supplies power to electrical system **90**.

Envelope heaters **100** and envelope blower **102** establish and maintain a temperature in the envelope **70** of approximately 80° C. An envelope thermal cutout (THCO) switch **108** carries current through the machine's main contractor actuation coil. If the temperature reaches approximately 120° C. the THCO switch opens and current through the main contractor to the system is interrupted. The head blowers **104** and **106** supply air at ambient temperature to cool the pathway of filaments **40** and **54** as they travel into modeling extrusion head **32** and support extrusion head **46**, respectively.

CPU **92** also controls a compressor **110**. Compressor **110** supplies compressed air alternately to x-y forcers **33** and **52** provides a vacuum to platen **62**. CPU **92** provides layering drive signals to selectively actuate the z-motor **114**, which drives platform **74** along the z-axis.

IO Card **94**, under the control of CPU **92**, sends and receives signals associated with modeling extrusion head **32** and the filament supply thereto. IO card **94** sends drive signals that control the movement and position of x-y forcer **33**. IO card **94** further sends and receives signals to and from modeling extrusion head **32**, which includes a thermocouple **222** (TC), a heater **220** (HTR), a motor **246** (MM) and a safety switch **210** (SS) (shown in FIGS. 8-10). Safety switch **210** shuts down the system if the temperature in the modeling extrusion head **32** gets too high.

IO card **94** monitors data concerning modeling material filament spool **42** through communications with a modeling drybox processor board **116**. Modeling drybox processor board **116** is mounted inside of modeling filament drybox **45**. It receives data concerning the modeling filament from a modeling filament sensor **118** (located at the inlet to filament guide **236**, shown in FIG. 8) and a modeling EEPROM board **120**, which is a circuit board carrying an electronically readable and writeable device (EEPROM **188**, shown in FIG. 7), attached to modeling material filament spool **42**. EEPROM board **120** acts as an electronic tag with a variety of functions. It informs the control system **90** of the type of filament that is on the spool and of the lineal feet of filament on the spool. As filament **40** is wound off of the spool **42**, the CPU keeps track of how much material was commanded to be extruded, subtracts this amount from the

total on the EEPROM **188** and writes the new value to the EEPROM **188**. Preferably, the data on EEPROM board **120** is encrypted so that it can be updated the CPU **92**. Filament sensor **118** senses and indicates the presence or absence of filament at the entrance to the filament feed tube. With filament remaining on the spool the operator can then grab a hold of the filament and extract it from the extrusion head **32**. Unloading of the used filament and spool and reloading of a new spool is thereby made easier.

CPU **92** receives the modeling filament data from IO card **94**. At the outset of a job, the CPU **92** will calculate whether a spool **42** or **56** contains enough filament to complete the job. Operator notification is then provided via touch screen display **21**, stating either that the filament is adequate to complete the job, or that the filament spool will need replacement and reloading during the process. Also at the outset of a job, the CPU verifies that the modeling filament material on the spool is the same material specified in object data. If these materials are not the same, an operator notification is provided via touch screen display **21**, providing the operator an opportunity to switch spools.

IO card **94** additionally monitors the temperature in the envelope **70** via signals received from envelope thermocouple **122**, and it sends signals to and from a modeling head proximity sensor **124**, a high-z proximity sensor **126**, a low-z proximity sensor **128** and an xyz noncontact tip position sensor **130**, all of which are described below.

IO card **96** serves similar functions as IO card **94**, for the support extrusion head **52** and the filament supply thereto. IO card **96** sends drive signals that control the movement and position of x-y forcer **52**. IO card **96** further sends and receives signals to and from support extrusion head **46**, which includes a thermocouple (TC), a heater (ETR), a motor (MTR) and a safety switch (SS). The safety switch SS shuts down the system if the temperature in the modeling extrusion head **46** gets too high.

IO card **96** monitors data concerning support material filament spool **56** through communications with a support drybox processor board **132**. It receives data concerning the support filament from a support filament sensor **134** and a support EEPROM board **136**, attached to support material filament spool **56**. EEPROM board **136** acts as an electronic tag, in the same manner as EEPROM board **120**. CPU **92** receives the support filament data from support processor board **132**, and uses it to provide operator information in the same manner as described above with respect to the modeling filament.

IO card **96** further controls a first pressure valve **138** and a second pressure valve **140**, which alternately open and shut to direct the flow of air from compressor **110**. When valve **138** is closed and valve **140** is open, air from compressor **110** is directed to modeling head x-y forcer **33**. When valve **138** is open and valve **140** is closed, air from compressor **110** is directed to support head x-y forcer **52**. IO card **96** in addition communicates with support head proximity sensor **142**, which is described below.

To create an object using rapid prototyping system **10**, an operator must first power up the system by pressing a power on switch (not shown), located on touch screen display **21**. The system **10** then enters a maintenance mode, in which the system executes a routine to calibrate the locations of modeling extrusion head **32**, support extrusion head **46**, and build platform **74**. The calibration is done in two phases. In the first phase, the system initializes movement boundaries for the extrusion heads and the platform. Modeling head proximity sensor **124** initializes boundaries of the modeling

head **32**, and support head proximity sensor **142** initializes boundaries of the support head **44**. High-z proximity sensor **126** and low-z proximity sensor **128** together initialize the boundaries of platform **74**. In the second stage, the xyz noncontact tip position sensor **130** initializes the position of the tips of liquifiers **59** and **65**. The xyz noncontact tip position sensor **130** is a magnetic sensor imbedded in platform **74** which detects position of the liquifier tips with three displacement degrees of freedom. Tip position sensor **130** is of the type described in co-pending application Ser. No. 08/556,583, which is incorporated by reference.

After calibration is complete, the system exits the maintenance mode and enters a standby state. In the standby state, the design of a three-dimensional object **64** is input to CPU **92** via a LAN network connection (shown schematically in FIG. **5**) utilizing CAD software such as QUICKSLICE® from Stratasys, Inc., which sections the object design into multiple layers to provide multiple-layer data corresponding to the particular shape of each separate layer. After the layering data is received, the system **10** enters a warmup phase, during which the envelope **70** is heated. Upon reaching a temperature of 80° C., the system enters a build state during which it creates the three-dimensional object.

The modeling extrusion apparatus **30** is shown more particularly in FIG. **6**. Modeling extrusion apparatus **30** is movable in a horizontal plane in x and y directions. Modeling x-y forcer **33** is positioned beneath and parallel to a planer stator **150**, which contains a grid of stator elements (not shown). Together x-y forcer **33** and planer stator **150** form an electromagnetic linear stepper motor **152**. Commercially available linear stepper motors from Northern Magnetics, Inc. of Santa Clarita, Calif. are suitable. The x-y forcer **33** consists of two sets of single-axis forcers mounted at 90° to each other and permanent magnets which hold forcer **33** against the stator (not shown). A compressed air supply **154**, supplied by compressor **110**, is provided to x-y forcer **33** when modeling apparatus **30** is active. The compressed air supply **154** flows upward through x-y forcer **33** and exits through a top surface thereof, as is illustrated in FIG. **6B**. The exiting air forms an air bearing **156** between x-y forcer **33** and planer stator **150**, which allows nearly frictionless motion of the forcer in a horizontal plane below planer stator **150**. Drive signals to x-y forcer **33** are received through an electrical supply **158** which powers a stepper motor driver located within x-y forcer **33** (not shown) to achieve motion. Ordinarily, linear stepper motors of this type exhibit abrupt jarring motions which create mechanical resonance. This resonance typically precludes use of such motors in high-precision systems such as rapid prototyping systems. As described below, an umbilical to the head creates the surprising result of providing a damping effect sufficient to allow high-precision deposition at speeds far exceeding those possible in prior art rapid prototyping systems.

Modeling extrusion arm **34** is a flexible chain carrier that is flexible in a horizontal plane and substantially rigid in other directions. Arm **34** carries within it air supply **154** and forcer electrical supply **158**. Arm **34** also carries within it a modeling extrusion head electrical supply **160** and a flexible air tube **162** which contains an ambient air supply and modeling filament **40**, as depicted in FIG. **8**. Arm **34** together with air supply **154**, forcer electrical supply **158**, extrusion head electrical supply **160** and air tube **162** containing filament **40** form an umbilical **163** to extrusion head **32**. The umbilical **163** creates the surprising result of damping the mechanical resonance of extrusion head **32** with respect to stator **30**, which is produce by acceleration and deceleration

of the head **32** by forcer **33**. In the preferred embodiment, the combined weight of head **32** and x-y forcer **33** is less than or equal to approximately 8 lbs.

The resonant frequency is about 55 Hz for small oscillations and about 45 Hz for large oscillations, and the damping time to achieve 98% of the final value (which is equal to approximately 4 times the damping time constant) in this embodiment is less than or equal to about 150 ms. Oscillation and damping of mechanical resonance may be expressed as: $A=A_0 \sin(\omega t + \phi)e^{-t/\tau}$, where A =amplitude, A_0 =initial undamped amplitude, $\omega=2\pi f$, f =resonant frequency of the system, ϕ =a phase constant, t =time, and τ =damping time constant. Critical damping occurs when $\tau=1/\omega$. In the preferred embodiment described, the system is approximately a factor often from being critically damped. Further damping can, therefore, be added if desired. The damping time constant is affected by the combined weight of extrusion head **32** and x-y forcer **33**. The lighter the weight, the shorter the damping time constant.

Damping of mechanical resonance is achieved primarily by frictional forces produced during movement of umbilical **163**. Alternatively, other forms of damping means can be used, such as an oscillation dissipater (or shock-absorber) carried in extrusion head **32**. Also, further damping can be produced by decreasing the resistivity of the bucking of starter **150** (such as by using copper rather than steel) to increase eddy current losses within stator **150**.

While FIG. **5** has been described as depicting modeling apparatus **30**, it should be understood that support head apparatus **44** has a similar structure and has an umbilical of the same type described with reference to modeling apparatus **30**. Specifically, support x-y forcer **52** shares the planer stator **150** such that x-y forcer **52** and stator **150** form a second linear motor. Support apparatus **44** starts from the opposite side of cabinet **12** from modeling apparatus **30**. For ease of reference, only one head is shown in detail.

Vacuum platen **62** and substrate **60** are shown in an exploded fashion in FIG. **6**. Vacuum platen **62** has a top surface **167** comprised of a grid of grooves **164**, shown in detail in FIG. **6A**. In the preferred embodiment, grooves **164** are 0.06 inches deep, 0.06 inches wide, and are 1 inch on center apart. An orifice **166** extends through the center of vacuum platen **62**. Orifice **166** receives a vacuum hose **168** which connects to vacuum pump **112**. When the system **10** is powered up, a vacuum is applied to vacuum platen **62** by vacuum hose **168** and vacuum pump **112**. The vacuum provided to platen **62** pulls air through grooves **164** to distribute the vacuum along the platen. This vacuum holds the substrate **60** against the top surface **167** of platen **62**. In the preferred embodiment, substrate **60** is a flexible sheet. A polymeric material forms a suitable flexible sheet substrate. An acrylic sheet with a thickness of about 0.06 inches has been successfully used as a substrate. When a desired object is formed, the operator can remove substrate **60** from the platen **62** by lifting one corner of the sheet and breaking the seal of the applied vacuum.

Flexible substrate **60** can be flexed away from the object to peel the substrate from the object, if there is a weak breakable bond between substrate **60** and the object. This weak, breakable bond may be formed by depositing a first layer (or layers) of modeling material followed by a second layer (or layers) of support material on the substrate **60**. The modeling material and substrate are selected so that the modeling material is fully adhesive to the substrate. In forming an object, the modeling material is deposited in one or more layers on the substrate **60**. The support material is

then deposited in one or more layers over the modeling material. The object is then built up on the support material, using a plurality of layers of modeling and/or support material. When the object is complete, vacuum is broken by lifting a corner of the substrate **60**, and the substrate **60** is removed from the platen **62** by the operator. By flexing the substrate **60**, the operator then peels the substrate **60** from the object. The first layer(s) of modeling material will remain adhered to the substrate, but the weak bond between the first layer(s) of modeling material and the second layer (s) of support material is a readily separable joint which breaks to allow removal of the substrate **60** without damage to the object.

Other flexible sheet materials may be used as substrate **60**. For example, plain or coated paper, metal foil and other polymeric materials are suitable. For high temperature support and modeling materials, a polymeric material (e.g., Kapton) or metal foil is particularly desirable.

Although a vacuum is a preferred way to achieve a releasable hold down force to hold substrate **60** against platen **62**, other means for providing a releasable hold down force can also be used. For example, substrate **60** can be held against platen **62** by an electrostatic chuck or by a weakly adhering adhesive applied to the bottom surface of the substrate **60** or the top surface of the platen **62** (or both).

FIG. **7** shows a detailed exploded view of the filament spool and spindle shown in FIGS. **2** and **3**. The mechanical configuration of the filament spool and spindle is identical for both the modeling filament and the support filament. For convenience of reference, FIG. **7** is directed specifically to modeling filament spool **42** and modeling spindle **43**. Spindle **43** extends horizontally from drybox **45** and has a semi-circular shape. A semi-circular connector **174** having a set of six depressible connector pins **176** is mounted on top of spindle **43** adjoining drybox **45**. A spring-loaded latch **178** is embedded in the top of spindle **43** at an outer edge **179**.

Filament spool **42** is comprised of a center barrel **180** on which filament may be wound, a pair of spool flanges **181** extending from either end of barrel **180**, a sleeve **182** that fits within barrel **180** for receiving spindle **43**, and modeling EEPROM board **120** mounted inside sleeve **182** and perpendicular to barrel **180**. Barrel **180** rotates about sleeve **182** so that filament **40** may be unwound from spool **42**. Sleeve **182** has a flange **184** at one end, a flange **186** at the opposite end, and an interior semi-circular cavity for receiving spindle **43**. In the preferred embodiment, flange **184** is removable and flange **186** is fixed. Removal of flange **184** allows withdrawal of sleeve **182** from barrel **180**. As mentioned above, EEPROM board **120** carries EEPROM **188**. In a preferred embodiment, EEPROM board **120** is mounted adjacent fixed flange **186** by a pair of screws **190**, so that EEPROM **188** faces inward towards sleeve **182** for protection. EEPROM board **120** on its outward facing side carries a set of six round electrical contacts **192**, as shown in FIG. **7A**. Connectors **192** are configured so as to provide a receiving surface for connector pins **176** when spool **42** is mounted on spindle **43**.

Latch **178** must be manually depressed to allow insertion or removal of spindle **43** from sleeve **182**. When sleeve **182** is mounted on spindle **43**, latch **179** rests in an upward position so as to lock spool **42** into place such that contacts **192** fully depress connector pins **176**. When filament spool **42** is manually inserted onto spool holder **43**, electrical contact between EEPROM board **120** and drybox processor board **116** is made through the connector **190**.

Detail of the extrusion apparatus is shown in FIG. **8**. While FIG. **8** shows modeling extrusion apparatus **30**, it

should be understood that support extrusion apparatus 44 contains the same parts and operates in the same manner as modeling extrusion apparatus 30, at a 180° rotation. Extrusion head 32 is mounted below x-y forcer 38 by a pair of mounting plates 200. Two pairs of bolts 202 attach head 32 to plates 200. Two bolts 204 connect plates 200 to x-y forcer 38 to hold head 32.

Extrusion head 32 is formed of an enclosure 206 which holds liquifier 59, a filament drive 208 and safety switch 210. Liquifier 59 comprises a thermal conducting thin-wall tube 212, a heating block 214, an extrusion tip 216, a tip retainer 218, heater 220 and thermocouple 222. FIG. 9 shows liquifier 59 in an exploded view. As shown in FIG. 9, thin-wall tube 212 has an inlet end 224, an outlet end 226, and is bent at a 90° angle. In the preferred embodiment, tip 216 is soldered into the outlet end of tube 212. Alternatively, tip 216 may be brazed or welded to tube 212. Using a 0.070 inch filament, tube 212 preferably has an inner diameter of about 0.074 inches. The wall thickness of tube 212 is preferably between 0.005–0.015 inches. It is desirable to keep tube 212 as thin as possible to achieve maximum heat transfer across tube 212 to filament 40. In the preferred embodiment, tube 212 is made of stainless steel. Other metals may also be used, such as brass, copper, tungsten, titanium, molybdenum, beryllium copper or other steels. Other thermal conducting materials such as polyimide (Kapton), a plastic with a high melting temperature, may also be used to form the thin-wall tube.

Tube 212 fits into a channel 229 of heating block 214, between a front section 228 and a rear section 230 of the heating block. Heating block 214 is made of a heat conductive material such as aluminum or beryllium copper. A set of four bolts 232 extend through outer section 228 and rear section 230 of heating block 214 to hold tube 212. When mounted in heating block 214, a first section of tube 212 adjacent the inlet end 224 is exterior to heating block 214, and a second mid-section of tube 212 is clamped within heating block 214, and a third section of tube 212 including tip 216 extends through the bottom of block 214. The first section of tube 212 forms a cap zone for the liquifier 59, the second section of tube 212 forms a heating zone, and the third section forms a nozzle zone. The nozzle zone is contained within and silver soldered to extrusion tip 216, which is supported against heating block 214 by tip retainer 218, a square plate having a center orifice. Tip retainer 218 is press fit around the extrusion tip 216, and mounted beneath heating block 214 by a pair of screws 234.

The length of the cap zone of tube 212 is in the range of 0.15 inches and 2 inches. The cap zone must undergo a temperature gradient from about 70 degrees C. envelope temperature to about 280 degrees C. liquifier temperature. A shorter cap zone allows for greater control by the system over the rate that molten filament is extruded (i.e., flow rate), but makes it more difficult to maintain a cool temperature for the filament through the cap zone. The length of the heating zone is anywhere from 0.04 inches to 7 inches. The longer the heating zone, the higher the maximum extruded flow rate, but the slower that the flow rate can be accelerated and decelerated. A liquifier having a cap zone of between 0.02–0.04 inches long and a heating zone of about 2.5 inches long has been successfully used in a preferred embodiment of the system.

Cylindrical heater 220 and thermocouple 222 extend horizontally into rear section 230 of heating block 214. Heater 220 is positioned in heat exchange relation to the heating zone of tube 212, to heat the tube to a temperature just above the melting temperature of the filament. Using an

ABS composition for the filament 40, the tube is heated to about 270 degrees C. Thermocouple 222 is positioned adjacent tube 212 to monitor the temperature in the tube. Safety switch 210 will cause the system 10 to shut down if temperature exceeds a predetermined level.

A guide tube 236 guides filament 40 from pivot 36 to extrusion head 32, made of a suitable low friction material such as Teflon for support in motion. As described above, filament 40 within guide tube 36 are located within flexible tube 60 contained inside of arm 34. Filament 40 enters extrusion head 32 through an inlet aperture 238. Inside of extrusion head 32, filament 40 is fed through a tapered guide 240 having a restricted guide passage 242. Filament drive 208, comprised of a stepper motor 246, a pulley 248 and a pair of feed rollers 250 and 252. Roller 250 has a drive shaft 254 which is driven by stepper motor 246. Roller 252 is a rubber-coated idler. Filament 40 is fed from the guide passage 242 of tapered guide 240 into a nip between rollers 250 and 252. The rotation of roller 250 advances filament 40 towards liquifier 59. The inlet end 224 of thin-wall tube 212 is positioned to receive filament 40 as it passes through rollers 250 and 252. The flow rate of the molten filament out of liquifier 59 is controlled by the speed at which filament drive 208 advances the filament 40 into liquifier 59.

A blower 256 blows air at ambient temperature into flexible tube 60 to cool guide tube 236 and filament 40. Cooling of strand 40 is important so as to maintain the filament at a sufficiently low temperature that it does not become limp and buckled within the passages leading into the liquifier 59. Air from blower 256 travels through tube 60 and enters extrusion head 32 via an air conduit 258. Air conduit 258 provides a path for the air which is in a forward and parallel position from filament 40 within extrusion head 32.

FIGS. 10A and 10B show an alternative embodiment of the liquifier. FIG. 10A shows liquifier 259 in an assembled view, while 10B shows liquifier 259 in an exploded view. In this embodiment, two thin-wall tubes 260A and 260B of the type described above flow into one, nozzle 262. A liquifier of this type can be substituted into the dispensing head shown in FIG. 8 to provide one extrusion head that dispenses, at alternate times, two different deposition materials. The two deposition materials may be a modeling and a supply material, or they may be modeling materials of two different colors or having other diverse properties. Nozzle 262 is brazed or welded to the outlet ends 264 of tubes 260A and 260B. Nozzle 262 is positioned in a vertical orientation, while tubes 260A and 260B may be angled towards the horizontal. Separate feed mechanisms (not shown) are provided for tubes 260A and 260B so that filament material is fed into only one of the tubes at any given time.

Thin-wall tubes 260A and 260B are held into position by a heating block 266. Heating block 266 is comprised of an outer plate 268, an interior plate 270 and a rear plate 272. Rear plate 272 is mounted within the extrusion head, and holds a heater 274 which extends between tubes 260. Two channels 276 which hold tubes 260A and 260B are routed through interior block 270. A set of five bolts (not shown) extend through outer plate 268, interior plate 270 and rear plate 272 to detachably hold together liquifier 259. It is an advantageous that the liquifier be removable from the heating block, for replacement and cleaning.

Although the present invention has been described with reference to preferred 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.

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We claim:

1. An extrusion head for depositing layers of solidifying material in a desired pattern to form three-dimensional physical objects, the extrusion head comprising:
 - a heating block made of heat conductive material;
 - a heating element to heat the heating block;
 - a first thin-wall tube having an inlet end for receiving a filament of a first material, an outlet end for delivering the first material in a molten state, and having a first section adjacent the inlet end and exterior to the heating block and a second section which passes through the heating block;
 - a material advance mechanism positioned to advance the filament of first material into the inlet end of the first thin-wall tube; and
 - a nozzle at the outlet end of the first thin-wall tube for dispensing the first material in a molten state.
2. The extrusion head of claim 1 wherein:
 - the heating element is within the heating block and is in heat exchange relation to the second section of the first thin-wall tube.
3. The extrusion head of claim 2 wherein:
 - the heating block is comprised of a first and a second section, which are mechanically detachable to allow removal of the first thin-wall tube.
4. The extrusion head of claims 1, 2 or 3 wherein:
 - the first thin-wall tube is made of metal.
5. The extrusion head of claim 4 wherein:
 - the nozzle is swaged into the outlet of the first thin-wall tube.
6. The extrusion head of claim 4 wherein:
 - the first thin-wall tube is made of stainless steel.
7. The extrusion head of claim 6 wherein:
 - the filament of first material has a diameter of about $\frac{1}{16}$ th inches; and
 - the first thin-wall tube has a wall thickness in the range of 0.008–0.015 inches, and an interior diameter of about 0.07 inches.
8. The extrusion head of claim 7 wherein:
 - the nozzle is swaged into the outlet end of the first thin-wall tube.
9. The extrusion head of claim 7 wherein:
 - the first section of the first tube is in the range of 0.02–0.04 inches long, and the second section of the first tube is about 2.5 inches long.
10. The extrusion head of claim 1 and further comprising:
 - a second thin-wall tube having an inlet end for receiving a filament of a second material, an outlet end for delivering the second material in a molten state, and having a first section adjacent the inlet end and exterior to the heating block and a second section which passes through the heating block;
 - a second material advance mechanism positioned to advance the filament of second material into the inlet end of the second tube; and
 wherein the nozzle has a first entrance for receiving the first material, a second entrance for receiving the second material from the outlet end of the second tube, and angle exit for dispensing the first and second materials, at separate times, in molten states.
11. The extrusion head of claim 10 wherein:
 - the heating element is within the heating block and is in heat exchange relation to the second sections of the first and second metal tubes.

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12. The extrusion head of claim 11 wherein:
 - the heating block is comprised of a first, second and third sections, which are mechanically detectable to allow removal of the first and second thin-wall tubes.
13. The extrusion head of claim 10 or 11 or 12 wherein:
 - the first and second thin-wall tubes are made of metal.
14. The extrusion head of claims 13 wherein:
 - the first and second metal tubes are made of stainless steel.
15. The extrusion head of claim 14 wherein:
 - the filaments of first and second materials each have a diameter of about $\frac{1}{16}$ th inches; and
 - the first and second metal tubes each have a wall thickness in the range of 0.008–0.015 inches, and an interior diameter of about 0.07 inches.
16. The extrusion head of claim 15 wherein:
 - the first section of the first and second thin-wall tubes are each in the range of 0.02–0.04 inches long, and the second section of the first and second thin-wall tubes are about 2.5 inches long.
17. A liquifier for receiving a filament of material and liquefying the material for deposition in a molten state, comprising:
 - a heating block made of heat conductive material;
 - a first thin-wall tube having an inlet end for receiving a filament of a first material, an outlet end for delivering the first material in a molten state, and having a first section adjacent the inlet end and exterior to the heating block and a second section which passes through the heating block; and
 - a nozzle at the outlet end of the first thin-wall tube for dispensing the first material in a molten state.
18. The liquifier of claim 17 and further comprising:
 - a heating element within the heating block and in heat exchange relation to the second section of the first thin-wall tube.
19. The liquifier of claim 18 wherein:
 - the block heating is comprised of a first and a second section which are mechanically detachable to allow removal of the first thin-wall tube.
20. The liquifier of claims 17, 18 or 19 wherein:
 - the first thin-wall tube is made of metal.
21. The liquifier of claim 20 wherein:
 - the nozzle is swaged into the outlet of the first thin-wall tube.
22. The liquifier of claim 20 wherein:
 - the first thin-wall tube is made of stainless steel.
23. The liquifier of claim 22 wherein:
 - the filament of first material has a diameter of about $\frac{1}{16}$ th inches; and
 - the first thin-wall metal tube has a wall thickness in the range of 0.008–0.015 inches, and an interior diameter of about 0.07 inches.
24. The liquifier of claim 23 wherein:
 - the nozzle is swaged into the outlet end of the first metal tube.
25. The liquifier of claim 23 wherein:
 - the first section of the first metal tube is in the range of 0.02–0.04 inches long, and the second section of the first metal tube is about 2.5 inches long.

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26. The liquifier of claim 17 and further comprising:
a second thin-wall tube having an inlet end for receiving
a filament of a second material, an outlet end for
delivering the second material in a molten state, and
having a first section adjacent the inlet end and exterior
to the heating block and a second section which passes
through the heating block; and
wherein the nozzle has a first entrance for receiving the
first material, a second entrance for receiving the sec-
ond material from the outlet end of the second tube, and
a single exit for dispensing the first and second
materials, at separate times, in molten states.
27. The liquifier of claim 26 and further comprising:
a heating element within the heating block and in heat
exchange relation to the second sections of the first and
second thin-wall tubes.
28. The liquifier head of claim 27 wherein:
the heating block is comprised of a first, second and third
sections, which are mechanically detachable to allow
removal of the first and second thin-wall tubes.

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29. The liquifier of claim 26 or 27 or 28 wherein:
the first and second thin-wall tubes are made of metal.
30. The liquifier of claims 29 wherein:
the first and second metal tubes are made of stainless
steel.
31. The liquifier of claim 30 wherein:
the filaments of first and second materials each have a
diameter of about 1/16th inches; and
the first and second metal tubes each have a wall thickness
in the range of 0.008–0.015 inches, and an interior
diameter of about 0.07 inches.
32. The liquifier of claim 31 wherein: the first section of
the first and second metal tubes are each in the range of
0.02–0.04 inches long, and the second section of the first and
second metal tubes are each about 2.5 inches long.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 6,004,124

DATED : DECEMBER 21, 1999

INVENTOR(S) : WILLIAM J. SWANSON ET AL.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Col. 5, line 20, delete "suface", insert --surface--

Col. 7, line 33, delete "ETR", insert --HTR--

Col. 8, line 22, after "C", delete ---

Col. 9, line 15, delete "often", insert --of ten--

Col. 11, line 50, after "C", delete ---

Col. 13, line 8, delete "flament", insert --filament--

Col. 13, line 59, delete "angle", insert --single--

Col. 14, line 42, delete "block heating", insert --heating block--

Signed and Sealed this

Twenty-eighth Day of November, 2000

Attest:



Q. TODD DICKINSON

Attesting Officer

Director of Patents and Trademarks