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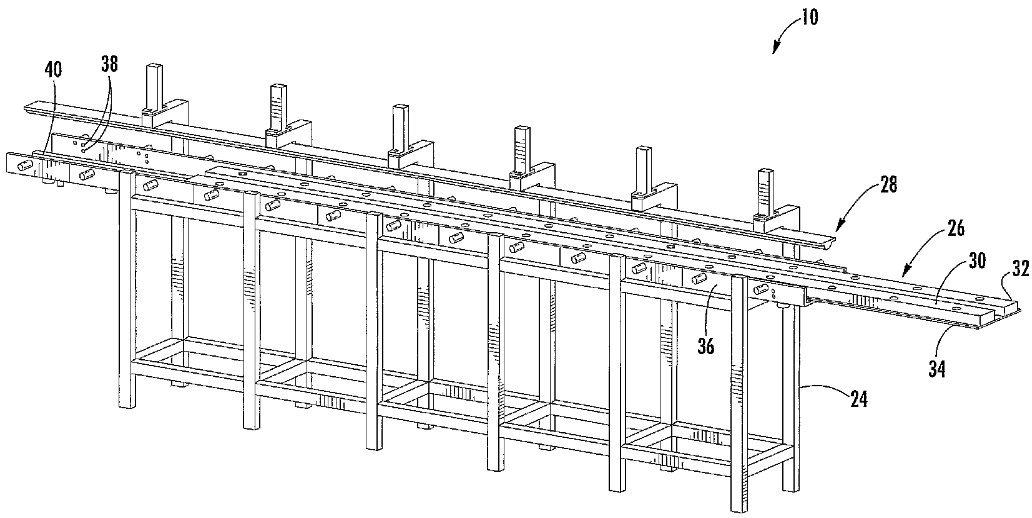
(54) **Title:** METHOD AND APPARATUS FOR FORMING STRUCTURAL MEMBERS



(57) **Abstract:** A method and associated apparatus for forming a composite structural member from a charge are provided. The charge can be disposed on a first die of the apparatus and formed to a desired configuration defined by a recess of the die by inserting a second die or a tool into the recess. In some cases, the first die can include two portions that are adjustable in a transverse direction so that the recess can be opened by the insertion of the second die or tool. The second die or tool can be a substantially rigid member or an inflatable bladder. In either case, the charge can be disposed on the first die, formed, and then further processed on the first die, thereby facilitating indexing of the charge for each operation.

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METHOD AND APPARATUS FOR FORMING STRUCTURAL MEMBERS

BACKGROUND OF THE INVENTION

Field of the invention

[0001] The present invention relates to the manufacture of structural members and, more particularly, relates to an apparatus and method for forming a contoured structural member.

Description of Related Art

[0002] Composite members are commonly used in applications, such as aircraft and other vehicles, where light weight and high strength are desired or required. Often the composite members must be formed in a contoured configuration according to the particular application for the member. Complex contoured composite members are typically configured in a desired configuration while the composite material is in a "green" or uncured condition and then cured while supported in the desired configuration. One conventional method for forming such contoured composite members is by manually laying the composite materials onto a mandrel or other tool defining a male pattern corresponding to the desired configuration. For example, the composite material can be disposed as pre-impregnated composite fiber plies ("prepregs") such as epoxy impregnated carbon fiber laminates. The plies are laid by hand onto the mandrel, and cured on the mandrel to form the member, typically using heat and/or pressure. Alternatively, the composite material can be disposed as dry fabric plies ("dry fabric"), and a bonding material can be added separately. In either case, the resulting structural member can be formed in a variety of desired shapes. However, such a manual layup process is time-consuming. Further, a separate mandrel must typically be provided for forming each particular configuration of composite member.

[0003] According to another conventional method for manufacturing composite members, known as drape forming, a flat sheet-like laminate charge or blank of composite material is formed against a mandrel. In particular, the charge is heated and forced around the male mandrel using a vacuum bag. Drape forming has been used successfully to form composite parts where the parts being formed have only a few prepreg plies. However, for thick laminates and complex shapes such as composite members defining C-, I-, or L-shaped beams, long flange lengths, contours along their length, variable thicknesses, joggles (or changes in direction), or offsets, vacuum bag drape forming can result in wrinkling of the plies.

[0004] U.S. Patent Application Publication No. 2004/0043196, titled “Forming Method for Composites,” published March 4, 2004, which is assigned to the assignee of the present application, describes a system and method for forming composite materials and reducing buckling of the fibers of the composite material. In particular, a composite charge can be formed over a mandrel using bladders and heater plates. U.S. Patent Application Publication No. 2004/0041304, titled “Composite Spar Drape Forming Machine,” published March 4, 2004, which is also assigned to the assignee of the present application, also describes a machine and method for forming composite materials about a mandrel. Both of U.S. Patent Application Publication Nos. 2004/0043196 and 2004/0041304 are incorporated by reference in their entirety.

[0005] While the foregoing devices and methods are useful for forming composite members, there exists a continued need for an improved apparatus and method for forming composite members. The method should be capable of producing composite members that define various contours, including contours including variations in thickness, curves, angles, flanges, and the like.

SUMMARY OF THE INVENTION

[0006] The present invention provides an apparatus and associated method for forming a structural member from a charge or blank. The charge can be disposed on a first die of the apparatus and formed to a desired configuration defined by a recess or cavity of the die by inserting a second die or a tool into the recess.

[0007] According to one embodiment of the present invention, the apparatus includes a first die supported by a frame. The first die has first and second longitudinal incompressible portions that are transversely adjustable between first and second positions to adjust a recess between the portions. A second die, which is also supported by the frame, defines an outer surface that corresponds to the recess of the first die. At least one of the dies is adjustable relative to the frame in a direction toward the opposite die so that the second die can be inserted into the recess of the first die, thereby adjusting the portions of the first die transversely outward and forming the charge between the first and second dies to the configuration of the structural member. At least one motion control device is configured to control the transverse adjustment of the portions of the first die. The first die can also be adapted to restrain transverse motion of the charge so that the opposite surfaces of the charge are stressed in tension during forming. The first die can be readily removable from the support frame with the formed charge supported by the die in the configuration of the structural member, e.g., without reconfiguration of the support frame and the second die so that the die can support the formed charge during a subsequent processing operation. In some cases, one of both of the dies can be flexible, and lock devices can be provided for retaining a position of each of the portions of the first die. Both of the dies can include a plurality of segments that are connected longitudinally.

[0008] According to another aspect, the present invention provides an apparatus including a support tray and first and second portions of a die that are supported by the tray. Each portion extends in a longitudinal direction and is transversely adjustable to define a recess between the portions for at least partially receiving the charge during forming. The position of each portion can be retained by one or more locks.

[0009] In addition, the present invention provides an apparatus including a die defining an aperture corresponding to a predetermined configuration of the structural member and a tool configured to be inserted into the aperture. A positioning device is configured to insert the tool at least partially into the aperture and thereby form the charge to a configuration defined between the tool and the die. In addition, a forming device is configured to adjust a portion of the charge outside the aperture of the die and thereby wrap the charge at least partially around the tool. The forming device and/or the positioning device are configured to compact the charge against the tool and thereby form the structural member to the predetermined configuration of the structural member. The tool can be a rigid member or an inflatable bladder, and the positioning device can be configured to selectively engage and disengage the tool so that the tool is configured to be wrapped with the charge. The positioning device can also be configured to urge the tool into the aperture in a first direction, and the forming device can be configured to extend in a second transverse direction to bend one or more of the edges of the charge about the tool.

[0010] According to method of the present invention, first and second dies are provided for forming the charge. The first die includes first and second portions that are adjustable in transverse directions between first and second positions and structured in the second position to cooperatively define a recess to at least partially receive the second die. A charge is disposed between the dies, and the second die is inserted at least partially into the recess so that the portions of the first die are adjusted transversely outward and the charge is formed between the dies to the configuration of the structural member. Each portion of the first die can be biased transversely inward to control the transverse motion of the portions.

[0011] The charge can be constrained to the first die so that the opposite surfaces of the charge are stressed in tension during forming, such as by evacuating gas through a plurality of apertures defined by the portions of the first die. In some cases, the first die is flexed during forming, and the position of the portions of the first die can be locked after the charge is formed. Thus, the charge can be supported by the first die during forming and also during a subsequent processing operation performed after the die is removed from the apparatus. In addition, the charge can be layed-up on the first die as a plurality of composite plies.

[0012] According to another method of the present invention, a charge is disposed on a die having first and second longitudinal portions, e.g., as a plurality of plies of a composite material. The portions are adjusted transversely so that the portions cooperatively define a recess. The charge is formed against the portions. Thereafter, while supported on the die, the charge is trimmed to a predetermined configuration of the structural member. The charge can be constrained to the die during forming so that both opposite surfaces of the charge are stressed in tension. Each portion can also be biased transversely inward during forming to control the adjustment of the portions. In addition, the portions of the die can be locked in position after forming to prevent transverse adjustment of the portions during trimming.

[0013] According to another embodiment of the present invention, the charge is disposed on a die that defines an aperture, and a tool is inserted at least partially into the aperture to thereby form the charge to a configuration defined between the tool and the die. For example, the tool can be selectively engaged with and disengaged from a positioning device so that the tool can be configured to be wrapped with the charge. A forming device is adjusted outside the aperture of the die to wrap the charge at least partially around the tool. Thereafter, the charge is compacted against the tool to form the structural member in a predetermined configuration such as a tubular configuration. For example, the tool can be inflated, or the positioning device or forming device can be urged toward the tool to compact the charge.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The accompanying drawings illustrate preferred and exemplary embodiments and are not necessarily drawn to scale.

[0015] Figure 1 is a perspective view illustrating an apparatus for forming a structural member according to one embodiment of the present invention.

[0016] Figure 2 is a perspective view illustrating the support frame of the apparatus of Figure 1.

[0017] Figure 3 is a partial perspective view illustrating a portion of the apparatus of Figure 1.

[0018] Figure 4 is a partial perspective view illustrating a portion of the apparatus of Figure 1.

[0019] Figure 5 is an elevation view illustrating the apparatus of Figure 1.

[0020] Figure 6-8 are elevation views illustrating the apparatus of Figure 1, shown with the second die in successively extended positions.

[0021] Figure 9 is a perspective view illustrating the support tray and first die of the apparatus of Figure 1.

[0022] Figure 9A is a section view illustrating a portion of the first die along line 9A-9A of Figure 9.

[0023] Figure 10 is a partial perspective view illustrating the support tray and first die of the apparatus of Figure 1.

[0024] Figure 10A is a section view illustrating a portion of the first die as seen in a direction parallel to the longitudinal direction of the first die.

[0025] Figure 11 is a perspective view illustrating the structural member during a trimming operation.

[0026] Figure 12 is a perspective view illustrating a structural member formed by the apparatus of Figure 1.

[0027] Figure 13 is an elevation view illustrating an apparatus for forming a structural member according to another embodiment of the present invention.

[0028] Figure 13A is an elevation view illustrating an apparatus for forming a structural member according to another embodiment of the present invention, shown with the charge unformed.

[0029] Figure 13B is an elevation view illustrating the apparatus of Figure 13A, shown with the charge partially formed.

[0030] Figure 13C is an elevation view illustrating the apparatus of Figure 13A, shown with the charge fully formed.

[0031] Figure 13D is a perspective view illustrating an apparatus according to an embodiment of the present invention including pogos for supporting the dies.

[0032] Figure 13E is a partial perspective view illustrating a portion of Figure 13D.

[0033] Figure 14 is a perspective view illustrating an apparatus for forming a structural member according to yet another embodiment of the present invention.

[0034] Figures 15-25 are perspective views illustrating the apparatus of Figure 14 shown during various stages during a forming operation according to one embodiment of the present invention.

[0035] Figure 26 is a perspective view illustrating a hat section stiffened composite formed by the apparatus of Figure 15.

DETAILED DESCRIPTION OF THE INVENTION

[0036] The present invention now will be described more fully with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. This invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth. Like numbers refer to like elements throughout.

[0037] Referring now to the drawings, and in particular to Figures 1, 5, and 12, the apparatus **10** for forming structural members **12** according to one embodiment of the present invention can be used for forming structural members **12** of various sizes and configurations. The configuration shown in Figure 12 and described throughout this description is a hat stringer for making a hat section stiffened composite. While shown as generally straight, the stringer may be curved or have complex curvature, as appropriate for the intended application. The structural members **12** are typically manufactured from a blank or charge **14**. In particular, the charge **14** can be a laminar member formed of a composite material, i.e., a fibrous reinforcement material disposed in a matrix material. Exemplary composite materials include reinforcement members such as individual fibers, strands, braids, woven or nonwoven mats, and the like that are formed of materials such as fiberglass, metal, minerals, graphite or carbon, nylon, aramids such as Kevlar®, a registered trademark of E. I. du Pont de Nemours and Company, and the like. The matrix material can be thermoplastic or thermoset polymeric resins. Exemplary thermosetting resins include allyls, alkyd polyesters, bismaleimides (BMI), epoxies, phenolic resins, polyesters, polyurethanes (PUR), polyurea-formaldehyde, cyanate ester, and vinyl ester resin. Exemplary thermoplastic resins include liquid-crystal polymers (LCP); fluoroplastics, including polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), perfluoroalkoxy resin (PFA), polychlorotrifluoroethylene (PCTFE), and polytetrafluoroethylene-perfluoromethylvinylether (MFA); ketone-based resins, including polyetheretherketone (PEEK™, a trademark of Victrex PLC Corporation, Thorntons Cleveleys Lancashire, UK); polyamides such as nylon-6/6, 30% glass fiber; polyethersulfones (PES); polyamideimides (PAIS), polyethylenes (PE); polyester thermoplastics, including polybutylene terephthalate

(PBT), polyethylene terephthalate (PET), and poly(phenylene terephthalates); polysulfones (PSU); or poly(phenylene sulfides) (PPS). Alternatively, the charge can be formed of other materials, including non-composite or non-reinforced materials including, but not limited to metals, polymers such as thermoplastics and thermosets, and the like, some of which may require heat during forming.

[0038] In some cases, the charge **14** is formed of a material with a low level of tackiness. That is, while conventional composite laminate materials typically have a tackiness sufficient for holding the layers of the laminate together during a manual layup operation and subsequent consolidation and forming, the tack level of the materials used in the present invention can be substantially less tacky, and the apparatus **10** can provide sufficient support to the charge **14** throughout the various operations of manufacture so that the layers are not separated from one another despite the low level of tack. For example, the material of the charge **14** can have a tack level that is between about 0.1 lbs/in and 1 lb/in, as measured by the force required to pull the material (at standard atmospheric conditions) from an AccuTack™ tack tester available from Thwing-Albert Instrument Company of Philadelphia, PA. One such low-tack material can be formed of Toray® 3900 series resin from Toray Industries Inc. of Tokyo, Japan, which can be used in combination with a reinforcement material such as carbon or glass fiber. In addition, the apparatus **10** can improve the levels of tackiness between plies as the material is formed. This improved tackiness is sufficient to hold the layers together and maintain the formed shape.

[0039] The charge **14** is typically a substantially flat member that is uncured. Thus, the charge **14** can be formed to the desired shape of the structural member **12** by pressure, with or without heating the charge **14**. The structural member **12** according to the present invention can define various contours and configurations including curves, angles, flanges, complex contours, and the like. In particular, the structural members **12** can define stringers or other long members having a cross-sectional profile that is uniform or nonuniform along the length of the member. According to one embodiment of the present invention, shown in Figure 12, the structural member **12** is a hat-shaped member, i.e., a member that includes a curved or angled portion **16** defining a slot or channel **18** along a longitudinal direction, and transverse flanges **20**, tabs **22**, or other features extending transversely outward from the curved or angled portion **16**. The structural members **12** can be used in a variety of industries and applications including, but not limited, in connection with the manufacture of aircraft and other aerospace structures and vehicles. Further, the structural members **12** can be used individually or in combination with other structures and devices. In particular, after the structural member **12** has been formed, the member **12** can be used in a fuselage section of an airplane structure. For example, before or after each structural member **12** is cured, one or more of the members **12** can be loaded onto a mandrel of a machine for making a fuselage section. Fiber-reinforced resin can be disposed over the member(s) **12**, and the fiber-reinforced resin can then be cured (or co-cured with the structural members **12**) to produce a finished assembly for an airplane fuselage.

[0040] Referring again to the embodiment of Figure 1, the illustrated forming apparatus **10** includes a frame **24** for supporting first and second dies **26**, **28** for forming the charge **14**. The first die **26** includes first and second portions **30**, **32** that are supported by a tray **34**. The second die **28** is configured to be adjusted toward the first die **26** for forming the charge **14** to the desired shape.

[0041] The tray **34** and the first die **26** can be inserted into and removed from the frame **24** of the apparatus **10**. In particular, as shown in Figures 2-3, the frame **24** can include a channel **36** for receiving the tray **34**. The channel **36** can include a plurality of rollers **38** extending inward from the walls of the channel **36** for supporting the tray **34**. That is, the rollers **38** can be arranged in pairs so that the tray **34** can be inserted between each pair of rollers **38** to thereby restrict the movement of the tray **34** through the frame **24** to the longitudinal direction. The channel **36** can also include guides **40** for contacting the bottom of the tray **34** to maintain the tray **34**, and hence the first die **26**, in the desired configuration. The tray **34** can be inserted into the channel **36** and, after the charge **14** on the first die **26** has been formed, the tray **34** can be removed with the first die **26** and the formed charge **14** disposed on the tray **34**. For example, the tray **34** can be inserted into the channel **36** in a first direction parallel to the longitudinal direction of the tray **34** and subsequently removed from the channel **36** in the same direction or an opposite direction. Alternatively, in other embodiments of the present invention, the tray **34** can be inserted and/or removed in other directions, such as directions transverse to the longitudinal direction of the tray **34** and dies **26**, **28**.

[0042] With the tray **34** positioned in the channel **36**, the first die **26** can be supported by the frame **24**, and the charge **14** can be positioned between the first and second dies **26**, **28**. In this regard, the charge **14** can be disposed on the first die **26** before or after insertion of the die into the frame **24** of the apparatus **10**. According to one embodiment of the present invention, the charge **14** can be formed on the first die **26**, e.g., by separately disposing a plurality of layers or plies of the composite material to lay-up the charge **14** directly on the first die **26**. In this way, the plies or other members of the charge **14** can be positioned relative to the first die **26** so that the charge **14** is indexed relative to the first die **26**. For example, if some of the plies of the charge **14** are to extend only partially along the charge **14**, the ends of the plies, or "ply drops," can be positioned accurately relative to the first die **26**. Further, if the charge **14** is to define features that are formed or disposed prior to forming, those features can be indexed relative to the first die **26**. For example, edges, apertures, thickened or thinned portions, embedded fasteners, supports, or other features of the charge **14** can be positioned accurately relative to the first die **26**. The first die **26** can then be indexed during forming and/or other processing. In this way, the charge **14** can be indexed once to the die **26**, and the die **26** can then be indexed relative to other devices for processing so that the charge **14** is accurately positioned without having to index the charge **14** directly for each process.

[0043] As shown in Figures 4 and 5, the first and second longitudinal portions **30**, **32** of the first die **26** are configured in a substantially parallel configuration to define a slot or recess **42** between the portions **30**, **32**. Each of the portions **30**, **32** of the first die **26** is adjustable in a transverse direction so that the recess **42** can be opened or closed by moving the portions **30**, **32** outward or inward, respectively. With the portions **30**, **32** of the first die **26** adjusted outward to a first or open position, the recess **42** can be large enough to at least partially receive the second die **28**. With the portions **30**, **32** of the first die **26** adjusted inward to a second or closed position, the recess **42** can be smaller than the second die **28**. In some cases, the portions **30**, **32** of the first die **26** can contact each other in the closed position.

[0044] The second die **28** is configured to be urged toward the first die **26** so that the charge **14** can be formed between the dies **26**, **28**. For example, as shown in Figure 6, the second die **28** can be connected to shafts **44** that are extended or retracted by a plurality of actuator devices **46**, such as hydraulic, pneumatic, or electric actuators. The second die **28** typically defines a contour that corresponds at least partially to the contour of the first die **26**. For example, the second die **28** can define a tapered or wedge-like portion **48** that corresponds to tapered or angled surfaces **50** defined by each of the portions **30**, **32** of the first die **26**. Further, the second die **28** can define flanges or stops **52** that extend outward on either side of the tapered portion **48**.

[0045] In some cases, the second die **28** can define a contour such as a ridge or slot **29** (Figures 13A-13C) that imparts a contour in the charge **14** during forming. For example, the slot **29** can extend longitudinally along the length of the second die **28**, and the charge **14** can be formed to define a contour that includes a channel- or slot-shaped feature that corresponds to the slot **29** in the second die **28**. For example, the pinch actuators **96** can be used to bias the material of the charge **14** into the slot **29**. In this way, various contours or features can be formed in the charge **14**. In some cases, the contours or features can remain in the structural member **12** that is formed from the charge **14**. Alternatively, however, such contours or features that are imparted into the charge **14** can be removed before the structural member **12** is fully formed, e.g., during curing of the charge **14**. In this regard, the temporary formation of such contours or features in the charge **14** can reduce stress in the charge **14** during forming and improve the dimensional accuracy of the finished structural member **12**, e.g., by providing additional material throughout the charge **14** as may be required if the materials of the charge **14** "debulk" or otherwise contract during curing, such as typically occurs when carbon fiber composite material is cured from a green condition. In any case, the second die **28** can be readily replaceable, e.g., by removing a pin **45a** that connects a t-nut or bobbin **45b** of the die **28** to the shaft **44**, so that dies of various configurations can be used with the apparatus **10**.

[0046] The apparatus **10** can also include motion control devices **54** along the length of the apparatus **10** that are configured to control the transverse position of each portion **30, 32** of the first die **26**. As shown in Figure 6, each of the motion control devices **54** can be extended to the first die **26** so that the opening of the first die **26** is controlled by the devices **54**. Thus, the devices **54** can oppose the outward motion of the first die **26** and, hence, the extension of the second die **28** into the recess **42** between the portions **30, 32** of the first die **26**. In other words, as shown in Figure 7, the extension of the second die **28** into the recess **42** tends to adjust the portions **30, 32** of the first die **26** outward; however, the outward motion can be controlled by the control devices **54**, thereby increasing the pressure exerted on the charge **14** between the two dies **26, 28**, the speed of the forming process, the extent of motion of the dies **26, 28**, and/or other aspects of the forming operation. Each control device **54** can be any of various types of actuator or other motion controller. For example, each control device **54** can be an active device such as a solenoid, stepper motor, other electric actuator, a hydraulically or pneumatically controlled cylinder, or the like. Alternatively, each control device **54** can be a generally passive device such as a mechanical spring, a passive hydraulic or pneumatic cylinder, or the like. In any case, the control devices **54** can slow or stop the motion of the portions **30, 32** of the first die **26**, e.g., to maintain a minimum predetermined pressure between the dies **26, 28** during forming. In some cases, the force exerted on the charge **14** between the dies **26, 28** can be monitored by a monitoring device, such as a load cell **33** (illustrated in Figures 13A-13C), which is typically an electronic transducer that provide an electronic signal indicative of the forming force.

[0047] Further, each of the control devices **54** can be independently adjusted so that the position of the portions **30, 32** of the first die **26** is selectively determined independently along the length of the apparatus **10**. In this regard, one or both of the dies **26**, **28** can be formed of materials that are generally incompressible and rigid but allow some flexibility. For example, each of the dies **26**, **28** can be formed of a polymer such as high density polyethylene (HDPE) or the like. By virtue of this flexibility, the dies **26**, **28** can be urged to a slightly nonlinear configuration to conform to nonuniformities along the length of the charge **14**. For example, if the charge **14** defines variations in thickness along its length, the portions **30**, **32** of the first die **26** may be pushed outward to a greater extent where the charge **14** is thickest, while the portions **30**, **32** are pushed outward to a lesser extent where the charge **14** is thinner. The portions **30**, **32** of the first die **26** may also be adjusted by nonuniform amounts to accommodate other features, such as nonuniformities or nonlinearity of the second die **28**, and the like.

[0048] The second die **28** is extended by the plurality of actuators **46** toward the first die **26** until the charge **14** is formed to a predetermined configuration, thereby urging the portions **30**, **32** of the first die **26** outward. As shown in Figure 8, the tapered portion **48** of the second die **28** can be completely inserted into the recess **42** between the portions **30**, **32** of the first die **26**, and the flanges **52** defined by the second die **28** can be urged toward the first die **26** to prevent further insertion of the second die **28** into the recess **42** and prevent further urging of the first die **26** outward by the second die **28**. That is, the flanges **52** of the second die **28** can act as a stop to prevent further forming of the charge **14**. In some cases, the second die **28** can be formed of a material that is at least slightly flexible, and the actuators can extend to slightly different positions so that the second die **28** is disposed against the charge **14** in a nonlinear configuration relative to the initial configuration of the second die **28**. Thus, the second die **28** can be flexed to conform to variations in the charge **14**, the first die **26**, or otherwise.

[0049] According to one embodiment of the present invention, the separation of the portions **30**, **32** of the first die **26** during forming puts the charge **14** in tension. More particularly, both a first surface **60** directed toward the first die **26** and a second surface **62** directed toward the second die **28** can be subjected to tension during the forming operation, instead of compressive stress that might otherwise occur at the first surface **60** of the charge **14** if the portions **30**, **32** of the first die **26** remained stationary in the open configuration throughout the entire forming operation. Although the present invention is not meant to be limited to any particular theory of operation, it is believed that maintaining the charge **14** in tension during the forming operation can reduce or eliminate the occurrence of wrinkling in the charge **14**.

[0050] In some cases, the charge **14** can be retained by and/or against the first die **26** during forming. For example, Figure 9 illustrates the tray **34** and the portions **30**, **32** of the first die **26** according to one embodiment of the present invention. The first portion **30** of the first die **26** is shown in its assembled configuration with a perforated cover sheet **64**, and the second portion **32** of the first die **26** is shown without the perforated cover sheet **64** only for purposes of illustrative clarity. Each portion **30, 32** defines a plurality of apertures **66** for evacuating gas from the surface of the respective portion **30, 32** upon which the charge **14** is disposed during forming. Thus, the charge **14** can be restrained by a partial vacuum formed between the charge **14** and each portion **30, 32**. The apertures **66** can connect to one or more internal chambers **68** (Figure 9A) extending longitudinally along each portion **30, 32**, each chamber **68** being maintained at a low pressure by a gas evacuation device **70** configured to evacuate gas from the chambers **68**. Each perforated cover sheet **64** can define a plurality of relatively small apertures **72** such that ambient air is drawn in through the entire cover sheet **64**, thereby restraining the charge **14** to the cover sheets **64** and, hence, the portions **30, 32** of the first die **26**. For example, the cover sheets **64** can be formed of a porous Vyon® sheet, registered trademark of Porvair of Norfolk, England.

[0051] The apparatus **10** can also be configured to secure the portions **30, 32** of the first die **26** in a particular position. For example, if the portions **30, 32** are urged outward by nonuniform distances at different points along the apparatus **10**, e.g., to define a nonlinear configuration of the portions **30, 32**, the portions **30, 32** can be locked in that position. With the first die **26** locked in the desired configuration of the charge **14**, the first die **26** can be removed from the frame **24** so that the first die **26** supports the charge **14** in the desired configuration during subsequent processing. For example, as illustrated in Figures 8 and 10, each portion **30, 32** of the first die **26** can be connected to the tray **34** by a plurality of locking devices **74**. In the illustrated embodiment, each locking device **74** includes a bolt **76** that extends through the tray **34**. Each bolt **76** extends through a slot **78** (Figure 10A) in the portion **30, 32** such that the portions **30, 32** are secured to the tray **34** by a head **80** of each bolt **76** disposed opposite the slot **78** from the tray **34** and each portion **30, 32** is slidably adjustable relative to the bolts **76**. That is, with the bolts **76** remaining stationary in holes defined through the tray **34**, each portion **30, 32** can be adjusted inward and outward to close or open the recess **42** between the portions **30, 32**. A spring **82** is provided on each bolt **76** between the tray **34** and a nut **84** on the bolt **76**. The spring **82**, which can be, e.g., a disc or Belleville spring, biases the nut **84** away from the tray **34**, such that the head **80** of the bolt **76** biases the respective portion **30, 32** against the tray **34**, thereby frictionally locking the portion **30, 32** to the tray **34**. The locking devices **74** can be located at a plurality of locations along the length of each portion **30, 32** so that each portion **30,**

32 can be independently secured in the desired configuration, which can include configurations in which each portion 30, 32 is flexed and/or nonlinear along its length. In operation, each locking devices 74 can be released by urging the nut 84 toward the tray 34 to overcome the spring force and release the frictional force between the respective portion 30, 32 and the tray 34. In fact, as shown in Figure 8, the apparatus 10 can include actuators 88 configured to extend and push against the locking devices 74 to unlock each device 74 during forming. The actuators 88 can retract and release the locking devices 74 once the charge 14 is formed to the desired configuration so that the portions 30, 32 of the first die 26 are then locked in place, even if the tray 34 is removed from the frame 24.

[0052] Thus, the structural member 12 can be removed from the apparatus 10 with the tray 34 and the first die 26 after forming. The tray 34 can then be delivered to a subsequent processing station for further processing of the structural member 12. Further, since the structural member 12 is indexed to the tray 34 and the first die 26, the tray 34 or first die 26 can be used for indexing the structural member 12 for subsequent operations. For example, the charge 14 can be further compressed and/or cured in the desired configuration while supported by the first die 26. In addition, as shown in Figure 11, the structural member 12 can be trimmed, such as with an ultrasonically reciprocating knife blade 90 that is controlled by a multi-axis adjustable automated trimming head 92. The tray 34 can be indexed to a worktable 94 or other structure associated with the trimming head 92 so that the trimming head 92 can accurately trim the structural member 12 to a desired configuration without requiring that the structural member 12 be directly indexed again.

[0053] As also illustrated in Figure 8, the apparatus 10 can include pinch actuators 96 that are configured to selectively extend or retract through holes 98 in the tray 34. In the extended position, each pinch actuator 96 can contact the charge 14, thereby biasing the charge 14 against the second die 28 and maintaining a position of the charge 14 relative to the second die 28 until the charge 14 is formed. An intermediary member, such as a longitudinal wedge, can be provided between the pinch actuators 96 and the charge 14 so that the charge 14 is held against the second die 28 along the entire length of the charge 14.

[0054] Figure 13 illustrates another embodiment of the present invention in which the apparatus 10 defines restraints 100 for restraining a motion of the charge 14 relative to each of the portions 30, 32 of the first die 26. The restraints 100 can be bracket-like members that extend along the length of the portions 30, 32 of the first die 26 and at least partially restrain transverse edges 102, 104 of the charge 14. For example, the restraints 100 can define slots 106 for receiving the transverse edges **102**, **104** of the charge **14** so that the edges **102**, **104** are held against the portions **30**, **32** of the die **26**. The restraints **100** can be fixed devices or can be adjustable, i.e., to urge the charge **14** against the portions **30**, **32** of the first die **26** and further constrain the charge **14**. The illustrated restraints **100**, or restraints of other configurations, can be used in combination with or instead of the evacuation device **70**.

[0055] The charge **14** can alternatively be secured or restrained during forming using a variety of other devices or methods. In some cases, restraining devices can be connected to the second die **28**. For example, Figures 13A-13C show another exemplary embodiment of the present invention in which the second die **28** of the apparatus **10** includes adjustable restraints **100a**. Each restraint **100a** includes a weight member **160** that is adjustably connected to one of the flanges **52** of the second die **28**. For example, the weight member **160** can define a slot **162** that receives a projection or pin **164** that extends from the respective flange **52**, so that the weight member **160** can be adjusted relative to the second die **28**, i.e., adjusted up and down relative to the flanges **52** as shown in Figures 13A-13C. Each weight member **160** can be biased toward the first die **26** as shown in Figure 13A by the weight of the member **160** and/or by a bias member such as a spring. Thus, as the second die **28** is adjusted toward the first die **26**, the weight members **160** can contact the charge **14** before the charge is significantly formed between the dies **26**, **28**. The weight members **160** can be sufficiently biased against the first die **26** so that the members **160** restrain the charge **14** during forming. In other embodiments of the present invention, the restraints **100a** can be actively adjusted. For example, a motor or other actuator can be provided for adjusting the position of the restraints **100a**. Further, the restraints can be formed of a flexible material such as rubber or polymer. In fact, in some cases, each restraint **100a** can include an inflatable bladder that can be filled with gas and thereby expanded toward the charge **14** on the first die **26** to hold the charge **14** in place during forming.

[0056] The first die **26** of the apparatuses **10** illustrated in Figures 1-13 can be used for forming as well as subsequent processing of the structural members **12**. Thus, the charge **14** can be disposed on the first die **26**, the charge **14** can be processed in the apparatus **10**, and the first die **26** can be removed from the apparatus **10** and further processed in another processing station or device. Thereafter, the structural member **12** can be removed from the first die **26**, and the first die **26** can be re-used for forming another structural member **12**. Of course, multiple first dies **26** can be utilized with the apparatus **10** so that the apparatus **10** can be operated even when one of the dies **26** is being used to support a charge **14** or structural member **12** outside the apparatus **10**. In some cases, the multiple dies **26** can define different lengths, cross-sections, and the like for forming structural members **12** of different configurations.

[0057] The first and/or second dies **26**, **28** can be adjustable to define non-linear configurations, e.g., for forming the charge **14** to a configuration that is curved about one or more axes. In this regard, Figures 13D-13E illustrate that the frame **24** of the apparatus **10** can include adjustable support devices such as pogos **25**, each of which typically includes an actuator **25a** that can selectively extend and retract an actuation rod **25b**. The actuation rods **25b** of the pogos **25** can also be rotatably adjustable by virtue of a rotatable connection **25c** so that the charge **14** can be supported in a curved, twisted, or otherwise three-dimensionally contoured configuration. Each rod **25b** can support the dies **26**, **28**, e.g., via channel sections **36a** that include rollers **38** arranged in pairs to define nips for receiving the tray **34** as similarly described above in connection with Figures 2 and 3. Thus, the pogos **25** can be adjusted to support the tray **34** and the first die **26** in a desired configuration, such that the charge **14** can be formed, cured, or otherwise processed in the desired configuration. The pogos **25** can form the frame **24** of the apparatus **10** that is used to support the tray **34** and the first die **26** while the charge **14** is formed using the second die **28**. Alternatively, the pogos **25** can be used to support the tray **34**, the first die **26**, the charge **14**, and the second die **28** during a separate forming operation that is performed before or after the forming of the charge **14** with the second die **28**. Thus, the charge **14** can be formed to a generally nonlinear configuration defined by the configuration of the pogos **25**, separately or in conjunction with the forming of the charge **14** between the first and second dies **26**, **28**.

[0058] Further, as shown, e.g., in Figure 11, each portion **30**, **32** of the first die **26** can include multiple segments **30a**, **32a** arranged longitudinally. Each segment **30a**, **32a** can be a modular device with connection features for connecting to the other segments **30a**, **32a** of the respective portion **30**, **32**. Thus, the first die **26** can be constructed using any number of the modular segments so that the first die **26** has a length corresponding to the length of the structural member **12** to be formed. The length of the die **26** can be adjusted so that the same modular segments **30a**, **32a** can be used for forming members **12** of different lengths. In particular, each modular segment **30a**, **32a** can define alignment rods **112** that extend from the segment for engaging corresponding alignment apertures **114** defined by an adjacent segment **30a**, **32a**. Further, if the first die **26** is configured to provide evacuation through a surface for constraining the charge **14**, the internal chamber **68** of each modular segment **30a**, **32a** can be connected to the adjacent segments **30a**, **32a** via corresponding vacuum connections **116** at each end of the segment **30a**, **32a**. The vacuum connections **116** at the exposed ends of the modular segments **30a**, **32a** positioned at the ends of the assembled die **26** can be sealed with a cap or plate, or those vacuum connections **116** can be used for connecting to the evacuation device **70**. Although not illustrated in Figure 11, the evacuation device **70** can continue to operate to provide a vacuum in the chamber **68** of each portion **30**, **32** of the first die **26** during operations subsequent to forming in the apparatus **10**, such as during trimming by the trimming head **92**.

[0059] While the structural member **12** formed according to the foregoing discussion defines a slot or channel **18** along its length, the apparatus **10** of the present invention can also be used to form partially or fully closed structural members **12a** (Figure 26). For example, Figures 14 and 15 illustrate another embodiment of the apparatus **10**, which can be used to wrap a composite material around an internal tool **120** to form the tube-like structural member **12a**. The apparatus **10** includes a frame **24** for supporting a die **122**, which defines a channel, slot, cavity, or other recess **124** for receiving the charge **14**. As illustrated, the die **122** defines a fixed configuration, but in other embodiments the die **122** can include multiple portions that can be adjusted to change the size and/or configuration of the recess **124**, e.g., as described in connection with portions **30**, **32**. In either case, the die **122** can be supported by the frame **24** in a predetermined configuration. Thus, as shown in Figure 16, the charge **14** can be provided on the die **122** and thereby indexed to a predetermined configuration relative to the apparatus **10**.

[0060] The second die or tool of the apparatus **10** is the internal tool **120**. The apparatus **10** can automatically position the internal tool **120** for forming and, in some cases, the internal tool **120** can be disconnected from the rest of the apparatus **10**. For example, the apparatus **10** can include a positioning device **126** for moving the internal tool **120** during forming. The positioning device **126** can selectively engage the internal tool **120**, e.g., using a vacuum rail **128** that evacuates air from a plurality of vacuum attachment devices **130** positioned along the length of the rail **128**. Thus, the positioning device **126** can engage the internal tool **120** and position the tool **120**, then disengage or release the internal tool **120** so that the charge **14** can be wrapped around the tool **120** without interference by the positioning device **126**. For example, as shown in Figure 16, the internal tool **120** can be positioned remotely from the recess **124** so that the charge **14** can be disposed over the recess **124**. Thereafter, a first set of actuators **132** of the positioning device **126** be used to extend the vacuum rail **128** to the internal tool **120** so that the vacuum attachment devices **130** can engage the internal tool **120**. The positioning device **126** can then urge the internal tool **120** into the recess **124** to at least partially form the charge **14**. For example, the actuators **132** of the positioning device **126** can lift the internal tool **120** (Figure

18), a second set of actuators **134** of the positioning device **126** can adjust the internal tool **120** to a position in alignment with the recess **124** (Figure 19), and the first set of actuators **132** can extend the internal tool **120** against the charge **14** and into the recess **124** so that the charge **14** is formed into the recess **124** between the die **122** and the internal tool **120** (Figure 20). The positioning device **126** can then release the internal tool **120** in the recess **124** and retract at least partially from the internal tool **120** to facilitate the wrapping of the composite charge **14** around the internal tool **120** (Figure 21).

[0061] In particular, a first forming bar **136** can slide inward on the die **122** to a position in which the internal tool **120** is disposed between the die **122** and the forming bar **136**. In this way, the forming bar **136** can bend one of the transverse edges **102, 104** of the charge **14** against the internal tool **120** (Figure 22). The first forming bar **136** can be retracted, and a second forming bar **138** can then extend to bend the other transverse edge **102, 104** of the charge **14** against the internal tool **120** (Figure 23). Each forming bar **136, 138** can be extended and retracted by one or more actuators **140, 142**, such as electric, pneumatic, or hydraulic actuation devices. The apparatus **10** can also include a heater **144** for heating the charge **14** to facilitate the forming of the charge **14**. For example, one or both of the forming bars **136, 138** can include a heater **144**, such as an internal electric resistive heating device that heats the charge **14** to a desired temperature and thereby softens the charge **14**. The internal tool **120** can also be heated by the heater **144**, for example, by resting the tool **120** on the forming bar **136** as shown in Figures 15 and 16. Other types of heaters can also be used to heat the charge **14** during forming, such as conduction or convection heaters, a resistive heater disposed in or on the second die **28**, or a heated blanket or other material that is placed in contact with the charge **14** or the apparatus **10** to thereby conductively heat the charge **14** or apparatus **10**.

[0062] The charge **14** can then be compacted in the desired configuration. For example, with the edges **102, 104** of the charge **14** folded against the internal tool **120** and the second forming bar **138** disposed opposite the edges **102, 104** from the internal member **120**, the positioning device **126** is again extended and exerts a force against the second forming bar **138**, thereby compressing the edges **102, 104** of the charge **14** between the internal tool **120** and the second forming bar **138**. In some cases, the internal tool **120** can be a rigid member, such that the edges **102, 104** of the charge **14** are compressed between the second forming bar **138** and the internal tool **120**. In addition, such a rigid internal tool can include apertures on its surface through which ambient air can be evacuated, e.g., by an evacuation device fluidly connected to an internal chamber of the tool. Thus, the evacuation device can draw the charge **14** against the outer surface of the tool. Alternatively, as shown in Figure 24, the internal tool **120** can be an inflatable bladder that is configured to receive a fluid from a pressurized fluid source **150** and thereby expand against the die **122** and the forming bar **138**. In this regard, the bladder can be expanded while positioned in the recess **124** to thereby provide sufficient rigidity to oppose the compressive force for compacting the charge **14**. After forming and compacting the charge **14** to the desired configuration of the structural member **12**, the positioning device **126** and the forming bar **138** are retracted so that the structural member **12** is again exposed, and the pressurized fluid provided in the internal tool (if applicable) is released. Thus, the structural member **12** can be removed from the die **122** and the internal tool **120** can be removed from the structural member **12**. In some cases, the structural member **12** can be further processed while supported by the die **122**, e.g., to trim the structural member **12** to a desired configuration, otherwise provide features in the structural member **12**, further cure the structural member **12**, or the like. In this regard, the die **122** can be readily removable from the support frame **24** so that the structural member **12** can be transported on the die **122** to other stations or equipment for processing the structural member **12**. That is, the die **122** can be adapted to be removed without significant reconfiguration of the support frame **24** or the die **22**, e.g., without cutting, bending, unscrewing, unbolting, or otherwise disconnecting the die **122** from the support frame **24** other than releasing readily removable connections such as the locking devices **74**.

[0063] In each of the examples, the apparatus **10** of the present invention is described as including a movable male forming member **28, 120** that is adjusted into a recess **42, 124** defined by a female forming member **26, 122**. However, in some cases, the male forming member can be a stationary device, and the female forming member is adjusted toward the male member. In either case, the charge **14** can be formed to the desired shape of the structural member **12**. Further, the structural member **12** can be removed from both of the forming members, or the structural member **12** can be supported by one or both of the forming members during a subsequent processing operation.

[0064] Many modifications and other embodiments of the invention will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, the invention is not to be limited to the specific embodiments disclosed and modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation.

WHAT IS CLAIMED IS:

1. A method for forming a fiber-reinforced resin composite structural member from a charge, the method comprising:

providing first and second incompressible dies extending in a longitudinal direction, the first die having first and second portions, the portions being adjustable in transverse directions between first and second positions and being structured in the second position to cooperatively define a recess between the portions configured to at least partially receive the second die;

disposing a charge between the first and second dies; and

inserting the second die at least partially into the recess defined by the first die such that the portions of the first die are adjusted transversely outward and the charge is formed between the first and second dies to the configuration of the structural member.

2. A method according to Claim 1, further comprising locking a position of each of the portions of the first die after the inserting step to prevent transverse adjustment of the portions.

3. A method according to Claim 1, further comprising at least partially constraining the charge to the first die such that opposite surfaces of the charge are stressed in tension during the inserting step.

4. A method according to Claim 3 wherein the constraining step comprises evacuating gas through a plurality of apertures defined by the portions of the first die such that the charge is constrained to the portions of the die.

5. A method according to Claim 1, further comprising:

supporting each of the first and second dies with a support frame during the inserting step;

removing the first die with the structural member from the support frame after the inserting step; and

processing the structural member supported by the first and second dies.

6. A method according to Claim 1, further comprising flexing the portions of the first die such that the charge is formed to a curved configuration.

7. A method according to Claim 1, further comprising biasing each of the portions of the first die transversely inward during the inserting step and thereby controlling the transverse motion of the portions.

8. A method according to Claim 1, wherein providing the first and second dies comprises providing at least one of the dies which defines a plurality of segments connected longitudinally.

9. A method according to Claim 1, further comprising providing the charge of composite material having a fibrous reinforcement material disposed in a matrix material.

10. A method according to Claim 1, further comprising providing the charge of a composite material having a tack level of between about 0.1 lb/in and 1 lb/in.

11. An apparatus for forming a structural member from a charge, the apparatus comprising:

a support frame;

a first die supported by the frame, the first die having first and second longitudinal portions, the portions being transversely adjustable between first and second positions and structured in the second position to cooperatively define a recess;

a second die supported by the frame, the second die extending longitudinally and defining an outer surface corresponding to the recess defined by the first die; and

at least one motion control device configured to control a transverse adjustment of the portions of the first die,

wherein at least one of the dies is adjustable relative to the frame in a direction toward the other die to at least partially insert the second die into the recess defined by the first die and thereby adjust the portions of the first die transversely outward and form the charge between the first and second dies to the configuration of the structural member.

12. An apparatus according to Claim 11, further comprising at least one lock device for retaining each of the portions of the first die in a respective position.

13. An apparatus according to Claim 11 wherein the first die is adapted to restrain a transverse motion of the charge such that opposite surfaces of the charge are stressed in tension during forming.

14. An apparatus according to Claim 11 wherein at least one of the dies is flexible.

15. An apparatus according to Claim 11 wherein at least one of the first and second dies defines a plurality of segments connected longitudinally.

16. An apparatus according to Claim 11, further comprising:

a support tray configured to support the first and second portions of the first die; and

at least one lock device for retaining each of the portions of the first die in a respective position relative to the support tray.

17. An apparatus according to Claim 11 wherein each of the portions of the first die defines a surface outside the recess for supporting the charge, each surface defining apertures configured to evacuate gas and thereby constrain the charge to the surface.

18. An apparatus for forming a structural member from a charge, the apparatus comprising:

a die defining an aperture corresponding to a predetermined configuration of the structural member;

a tool configured to be inserted into the aperture;

a positioning device configured to insert the tool at least partially into the aperture and thereby form the charge to a configuration defined between the tool and the die;

at least one forming device configured to adjust a portion of the charge outside the aperture of the die and thereby wrap the charge at least partially around the tool,

wherein at least one of the forming device and the positioning device is configured to compact the charge against the tool and thereby form the structural member in the predetermined configuration of the structural member.

19. An apparatus according to Claim 18 wherein the tool comprises an inflatable bladder.

20. An apparatus according to Claim 18 wherein the positioning device is configured to selectively engage and disengage the tool such that the tool is configured to be wrapped with the charge.

21. An apparatus according to Claim 18 wherein the positioning device is configured to urge the tool into the aperture in a first direction and the forming device is configured to extend in a second direction generally transverse to the first direction such that the forming device bends at least one edge of the charge about the tool.

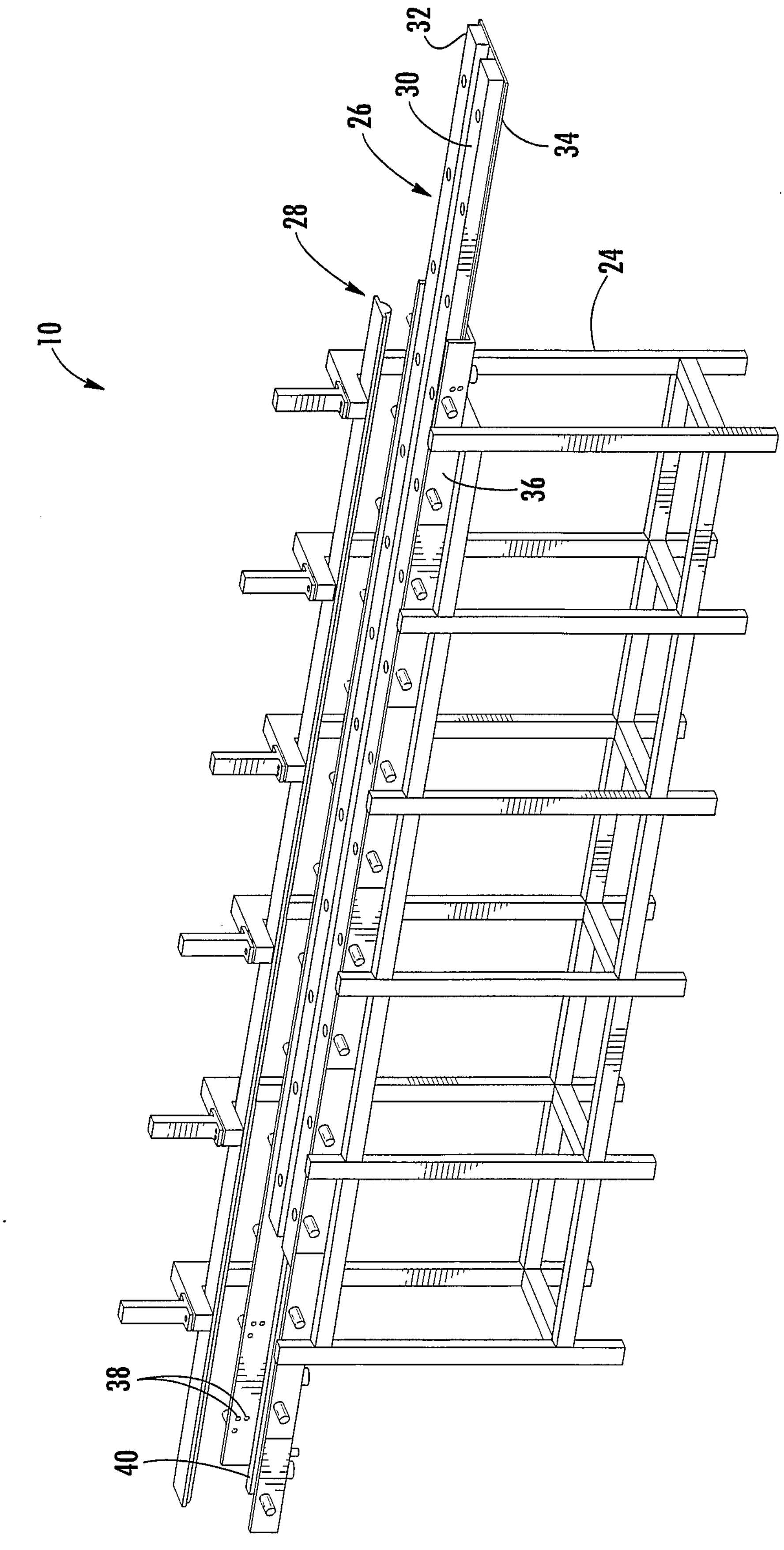

FIG. 1

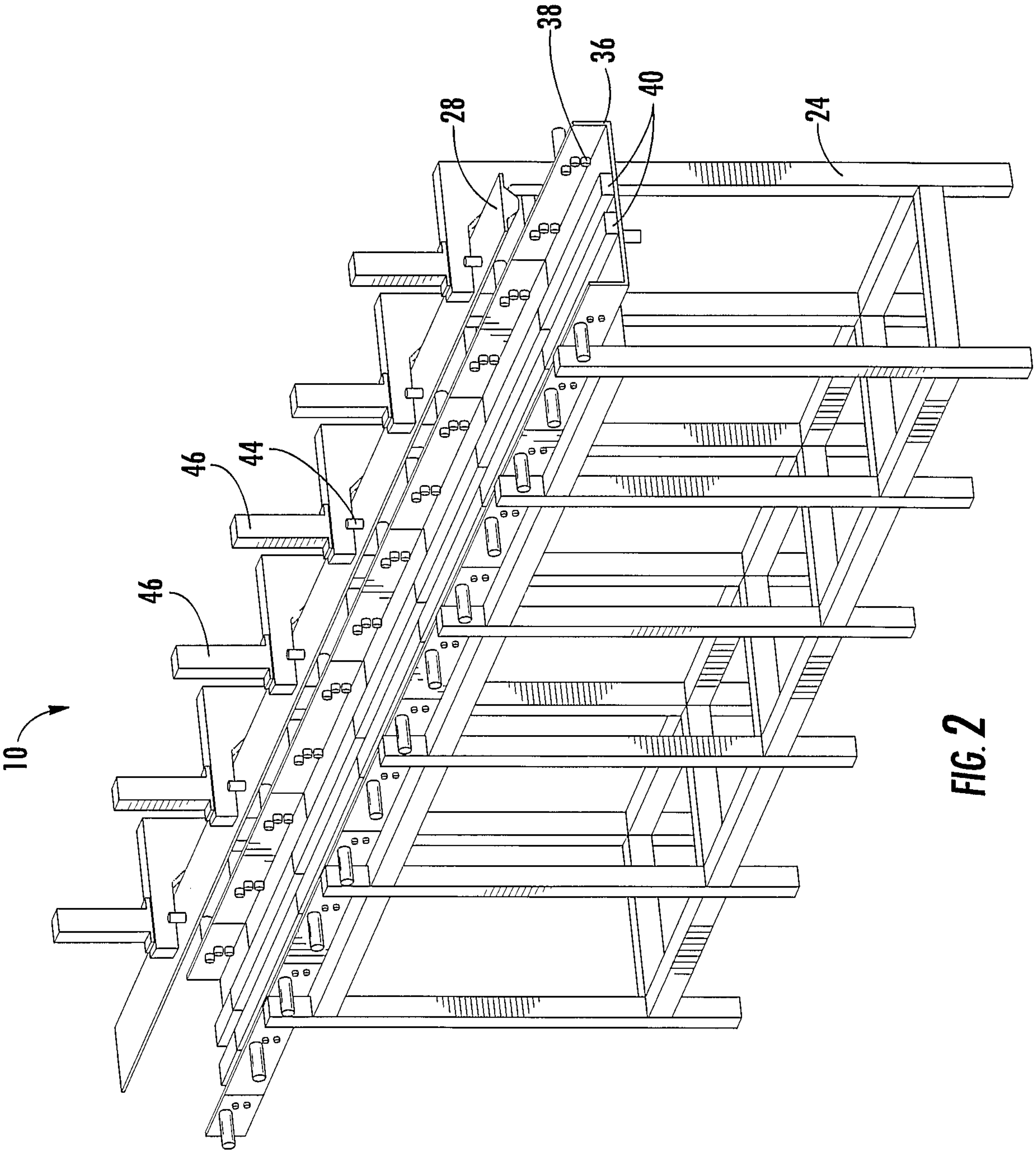

FIG. 2

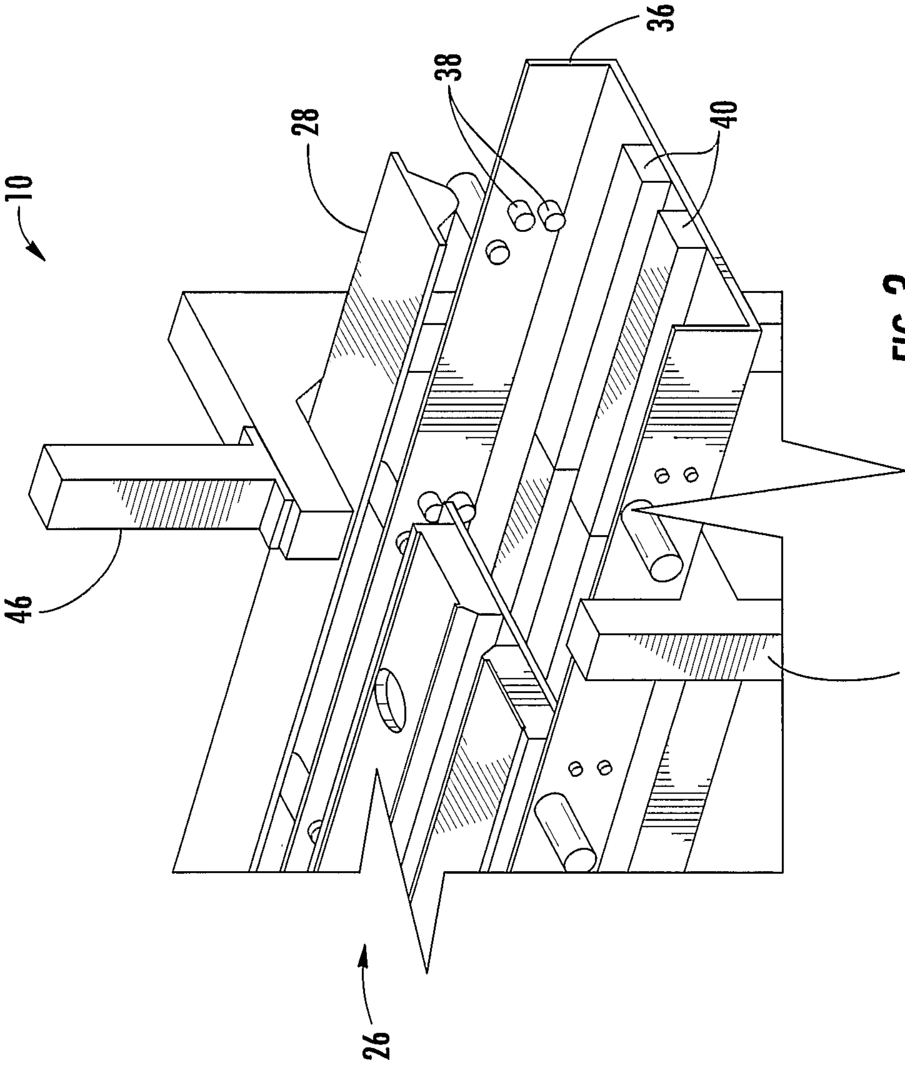

FIG. 3

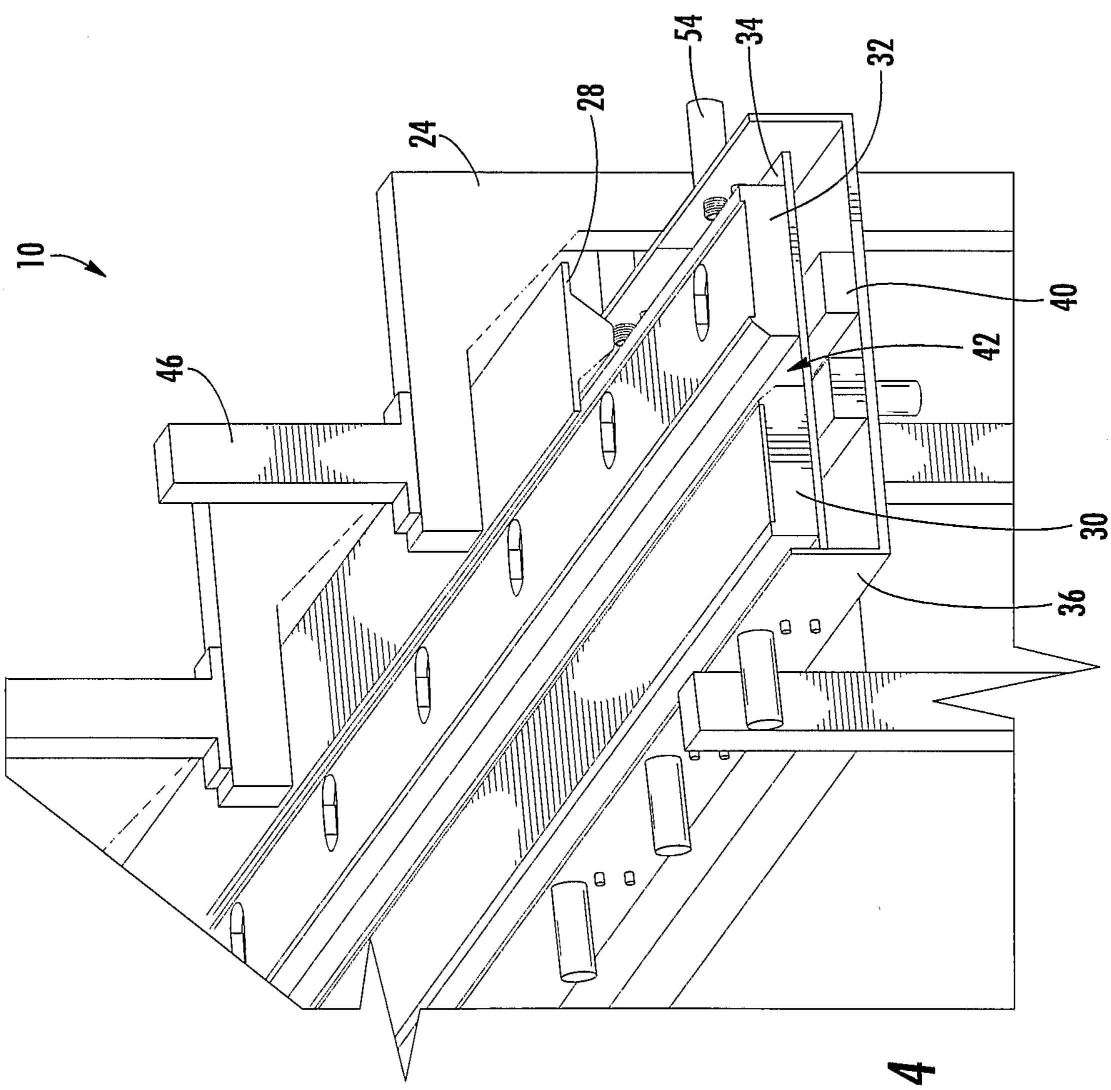

FIG. 4

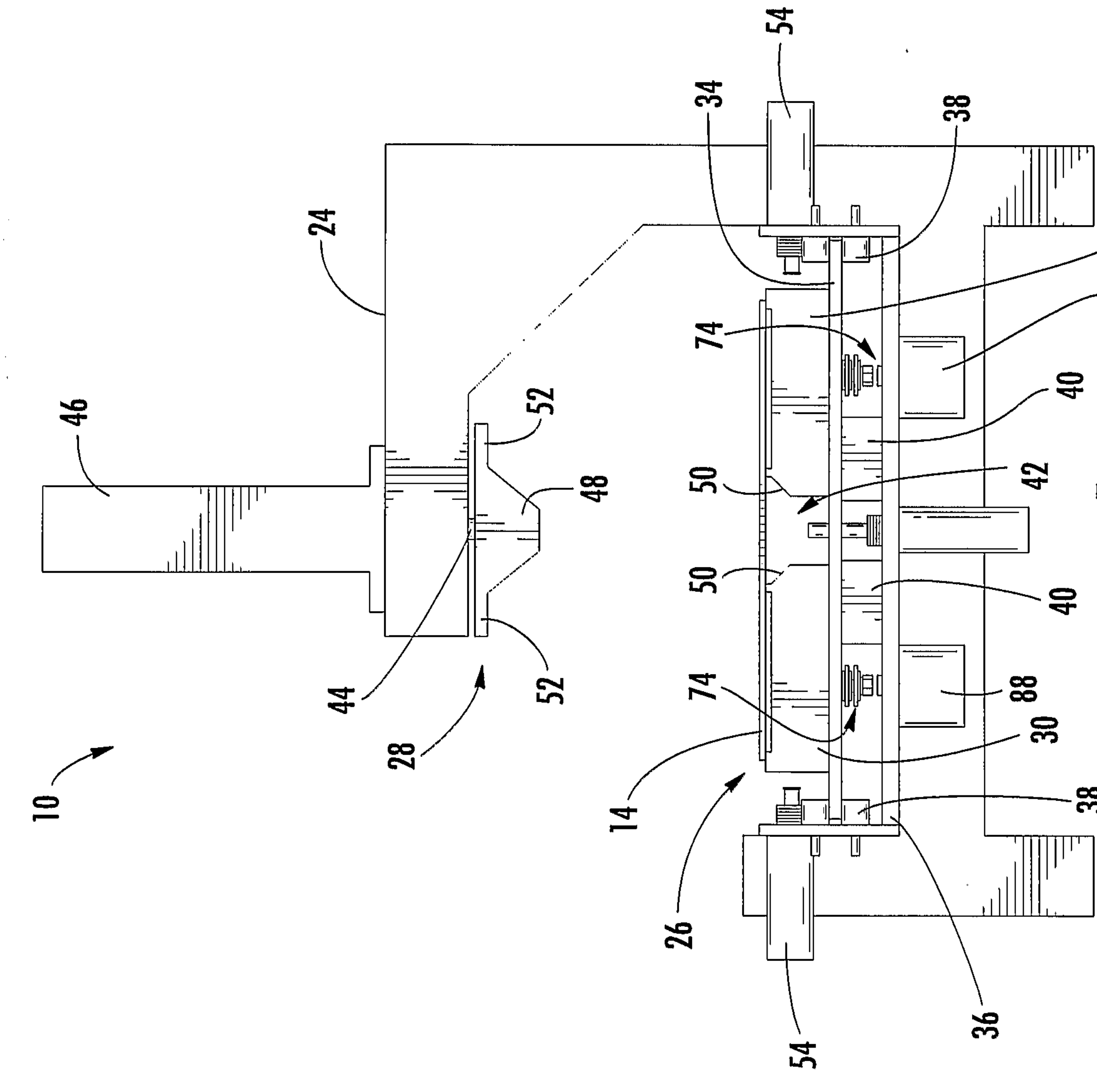
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FIG. 5

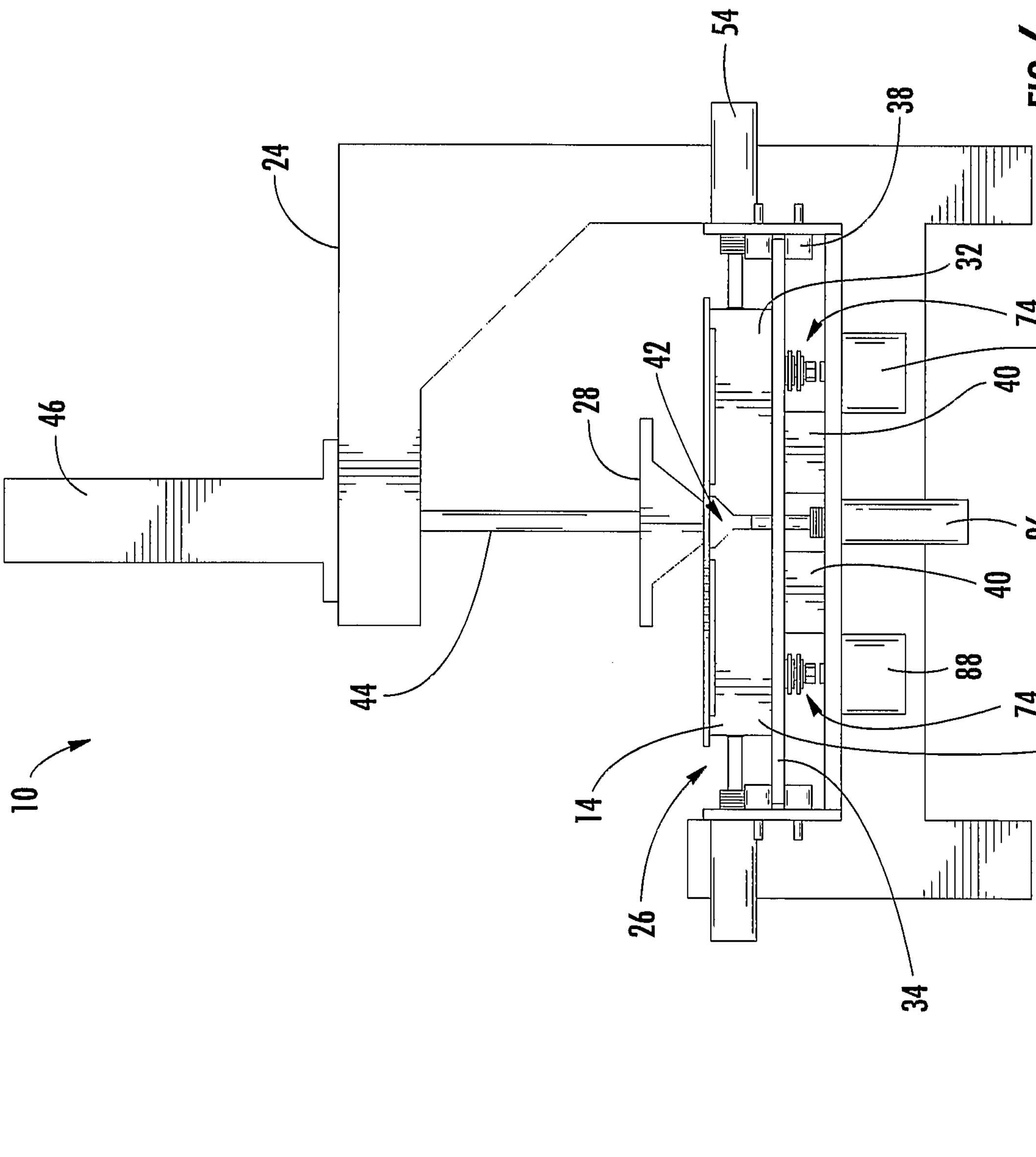

FIG. 6

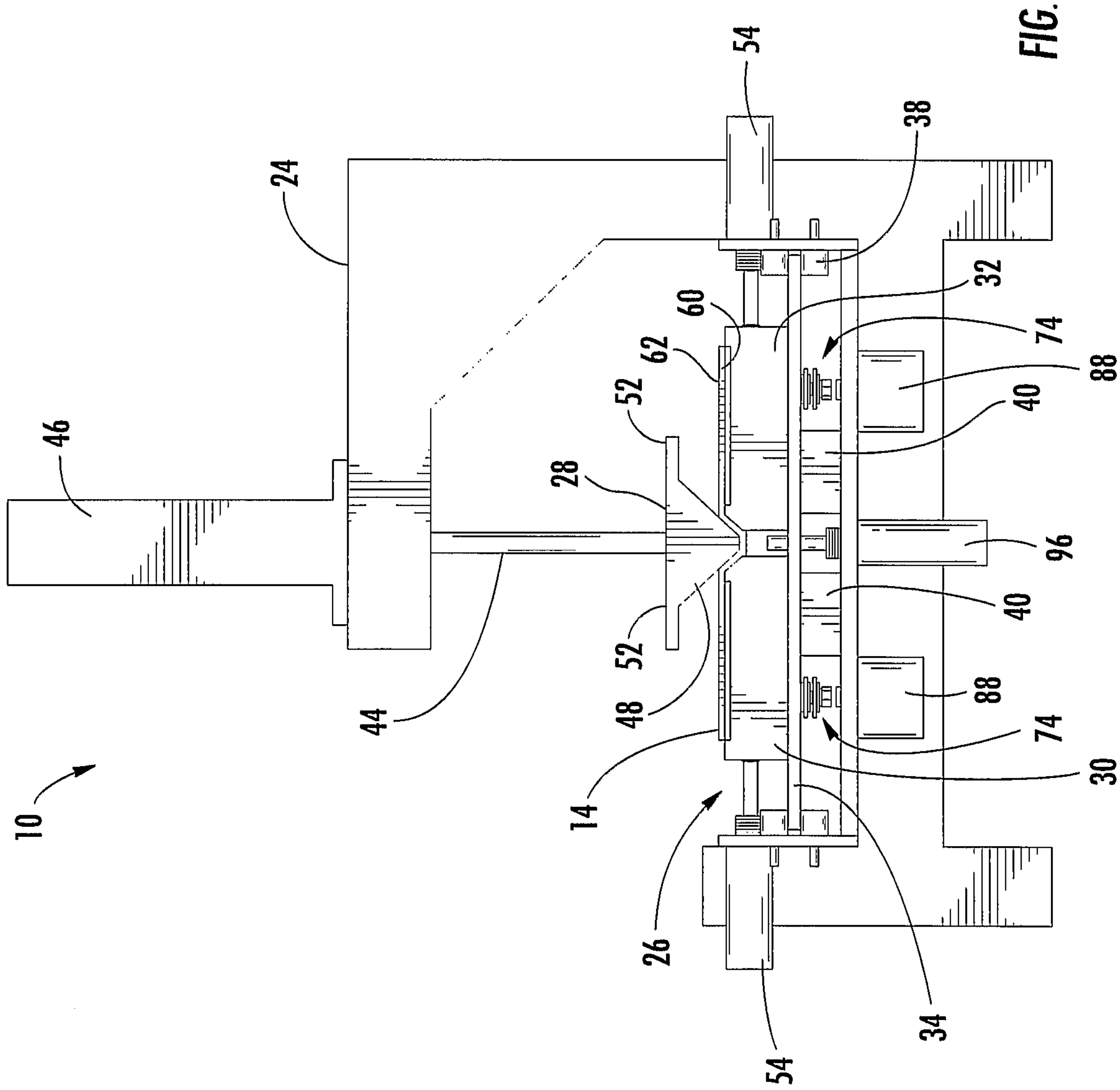
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FIG. 7

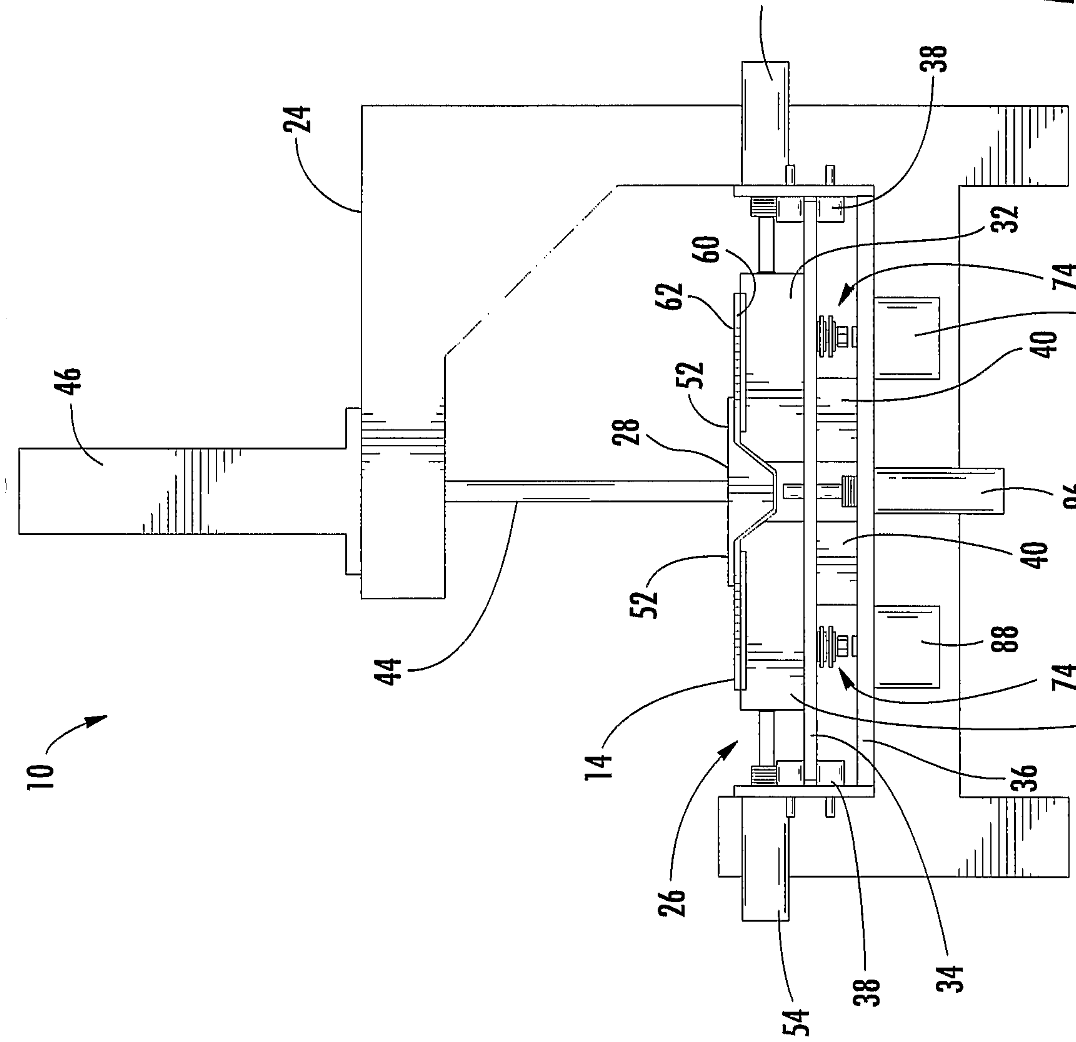
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FIG. 8

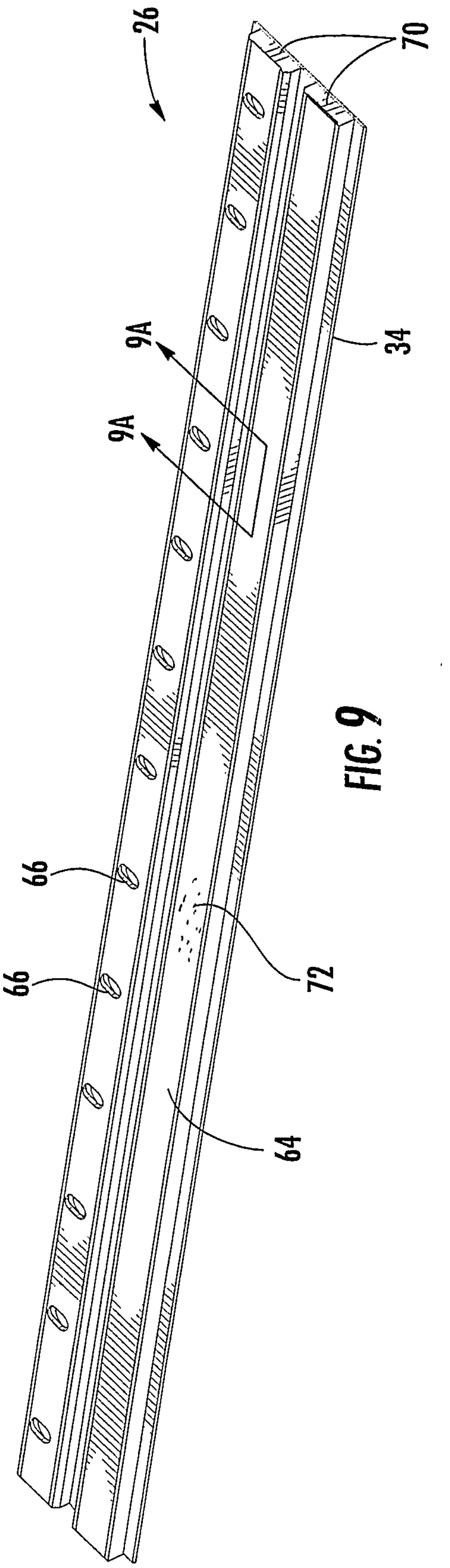


FIG. 9

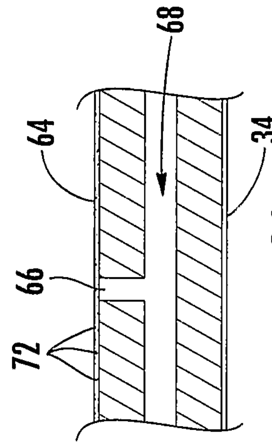


FIG. 9A

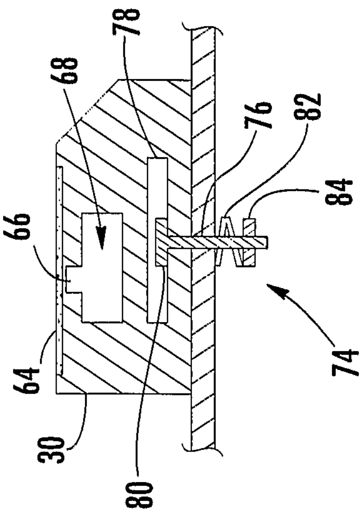


FIG. 10A

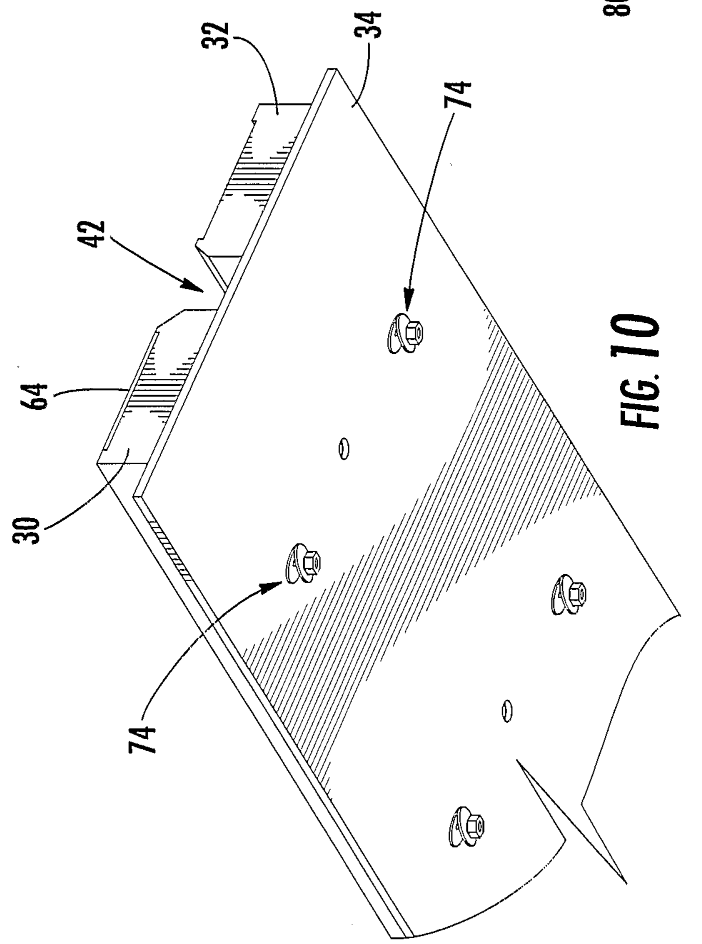
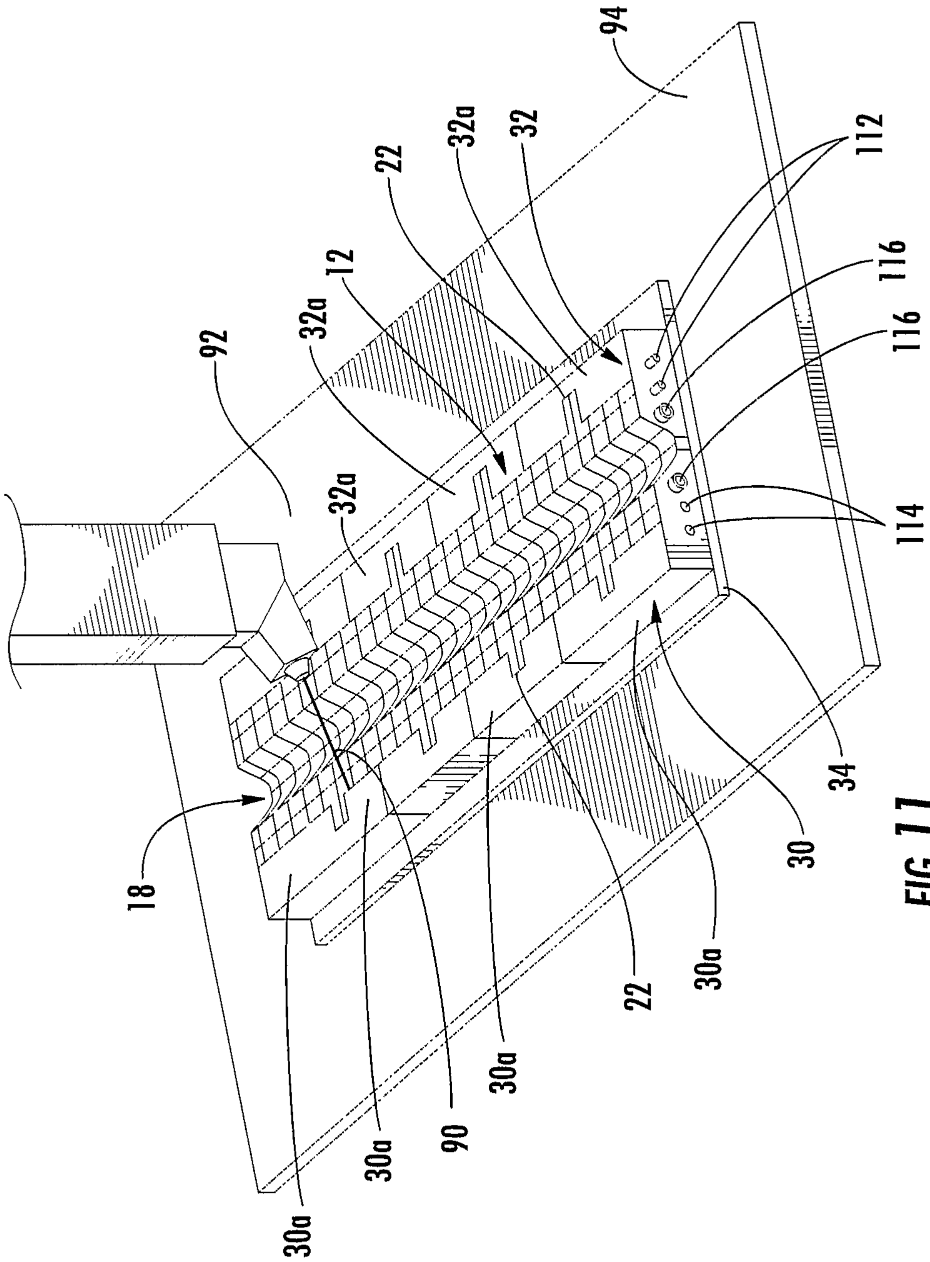


FIG. 10


94
92
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32a
32a
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116
116
114
18
90
30a
30a
30a
30a
30a
22
30
34

FIG. 11

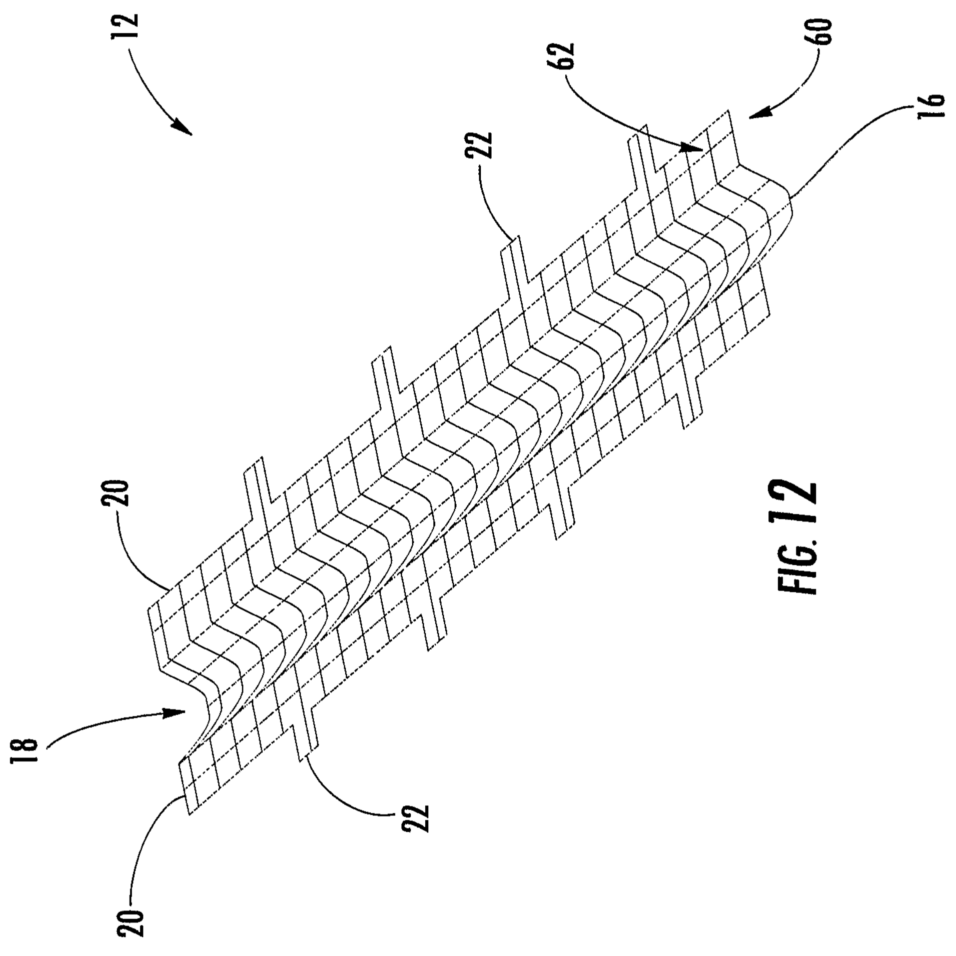


FIG. 12

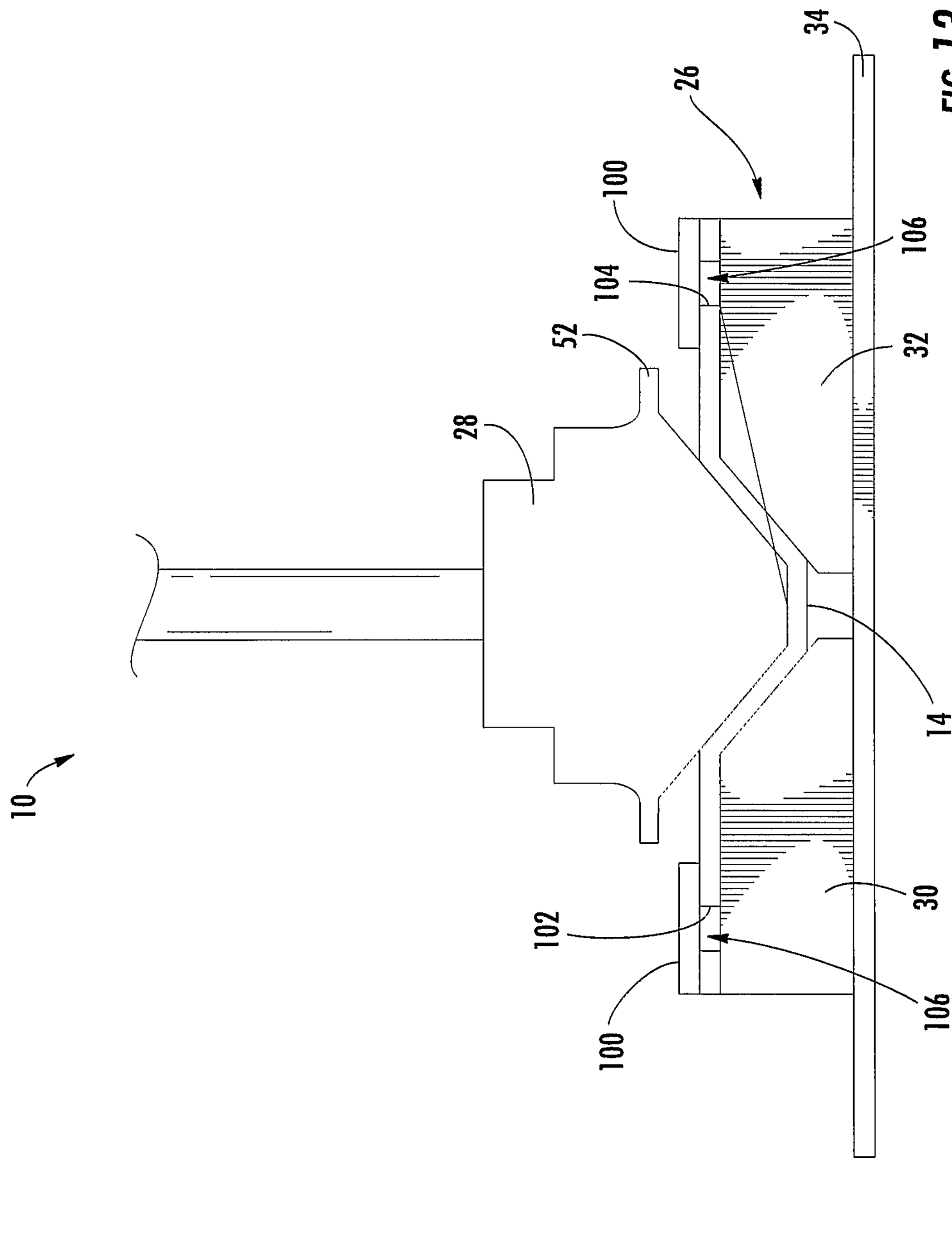
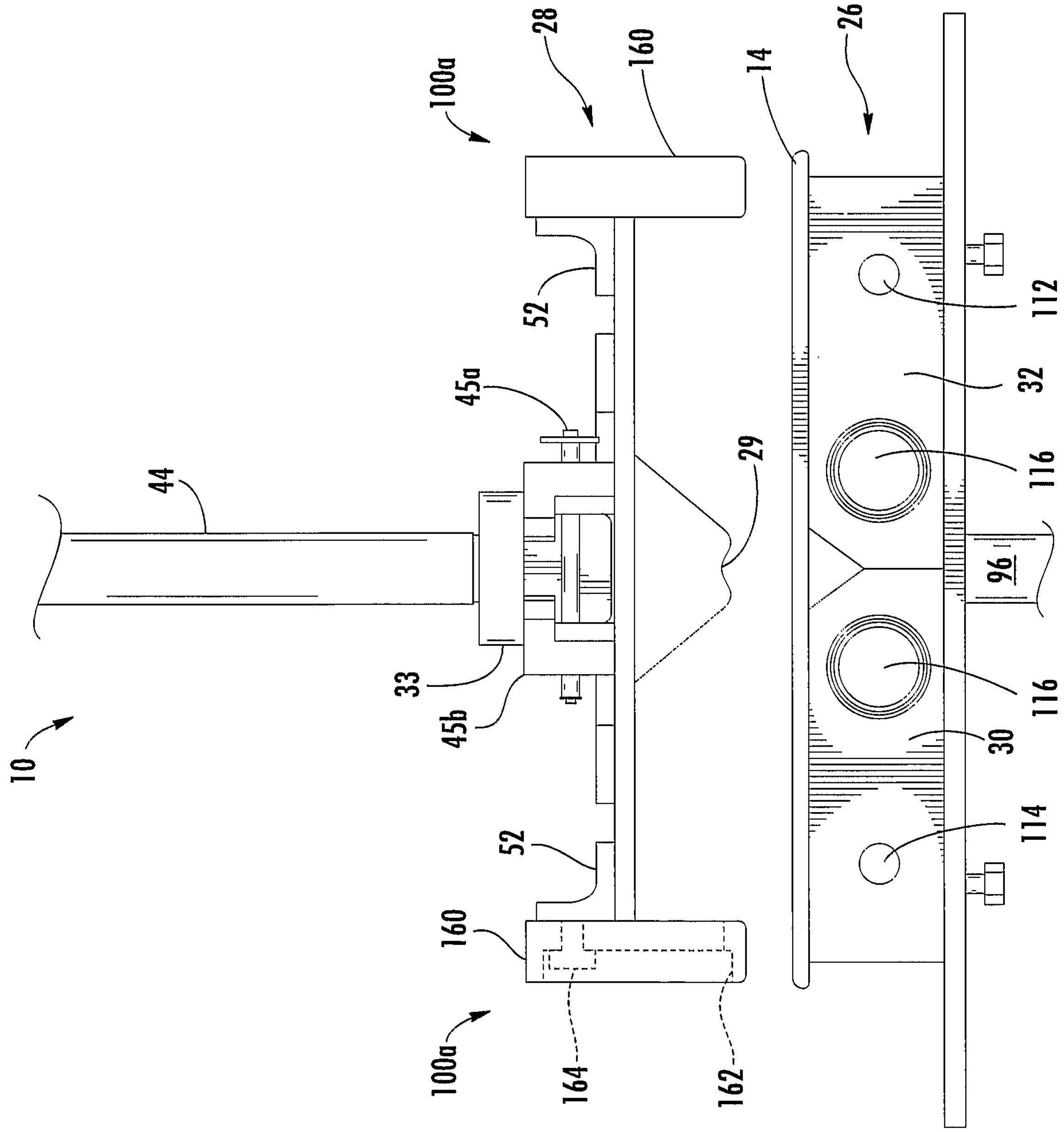


FIG. 13

FIG. 13A


10
44
33
45b
45a
29
52
52
160
160
28
100a
100a
164
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26
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116
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114

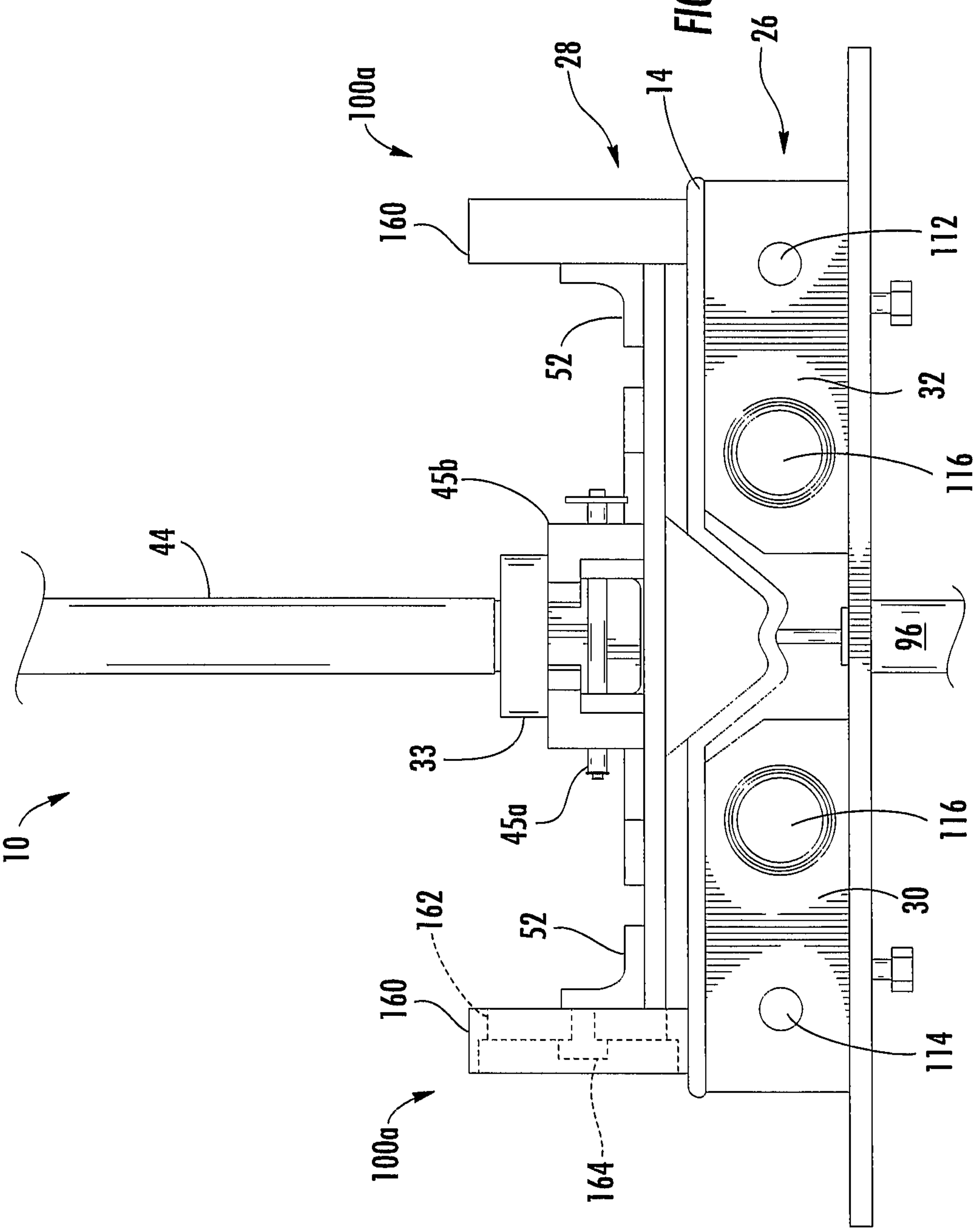
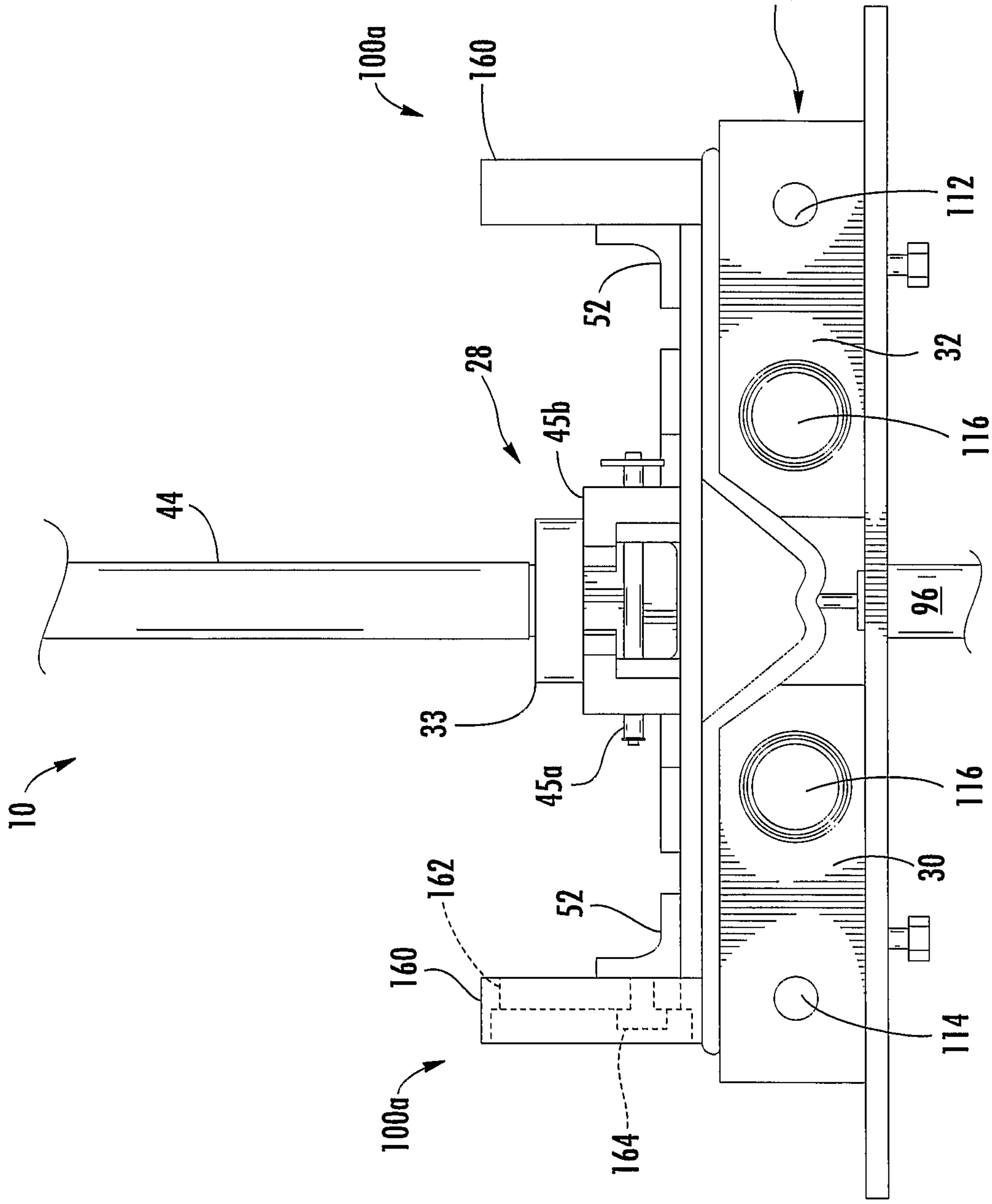


FIG. 13B


100a
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26
112
52
32
28
45b
116
44
96
33
45a
116
10
30
162
52
160
114
100a
164

FIG. 13C

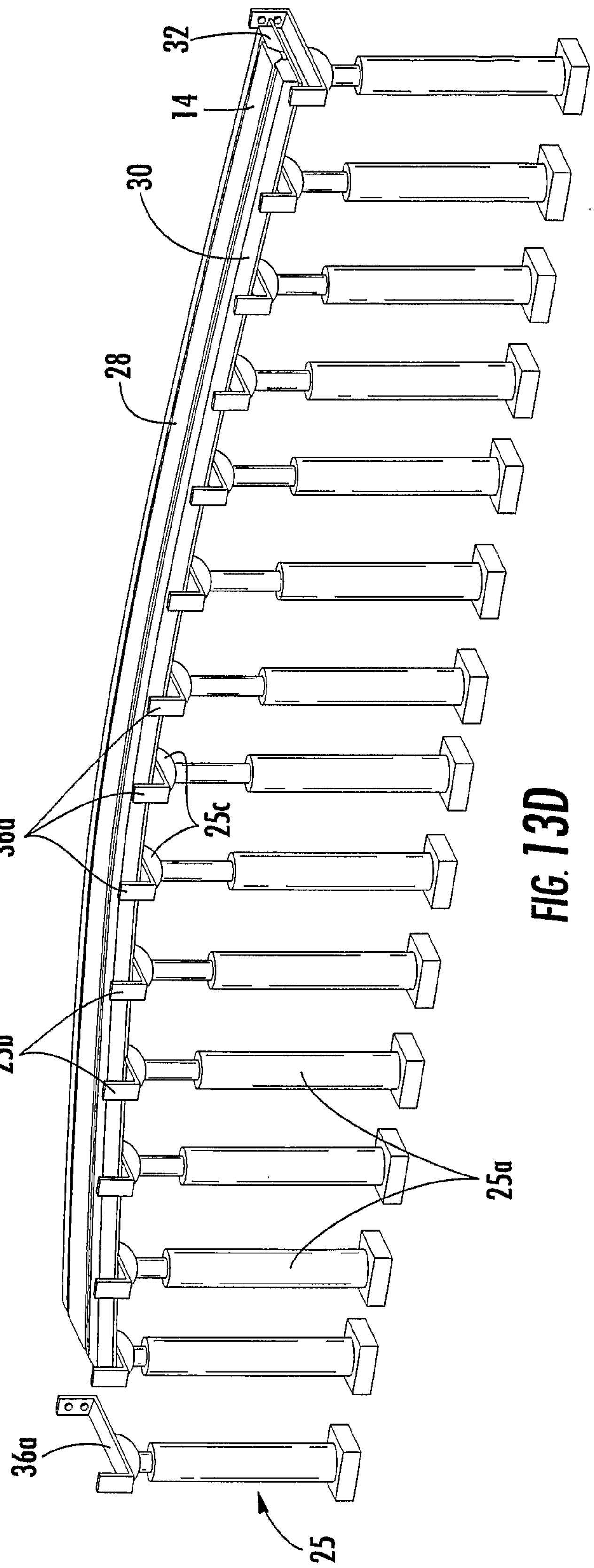


FIG. 13D

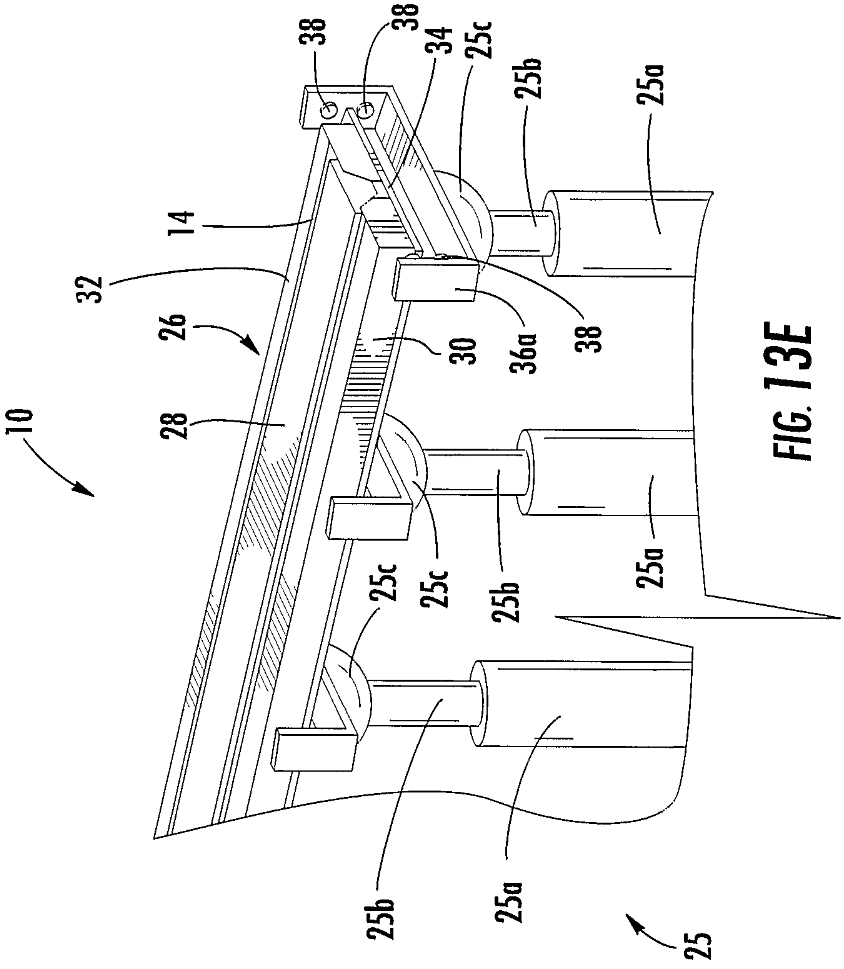
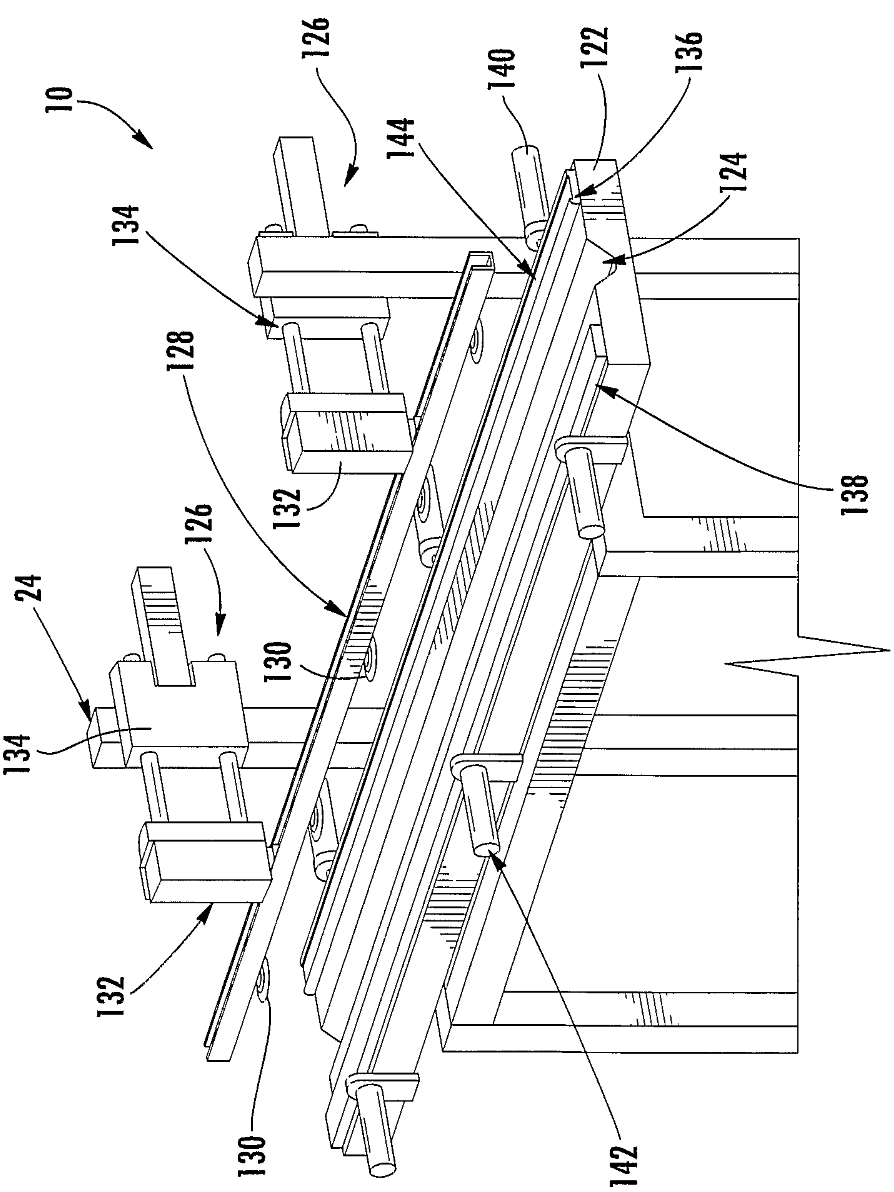

10
38
38
34
25c
25b
25a
14
32
26
28
30
36a
38
25c
25c
25b
25a
25b
25a
25

FIG. 13E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126
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122
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124
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138
132
126
24
130
134
132
130
142

FIG. 14

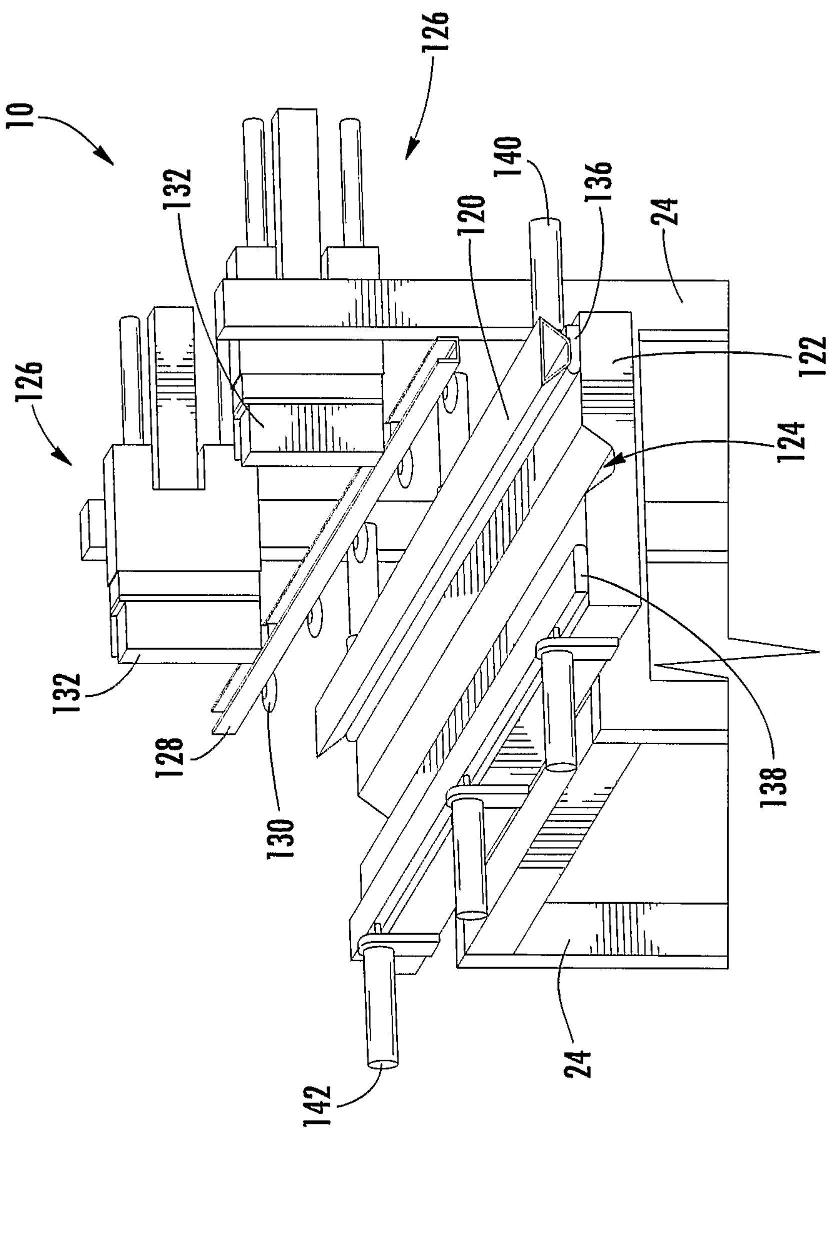


FIG. 15

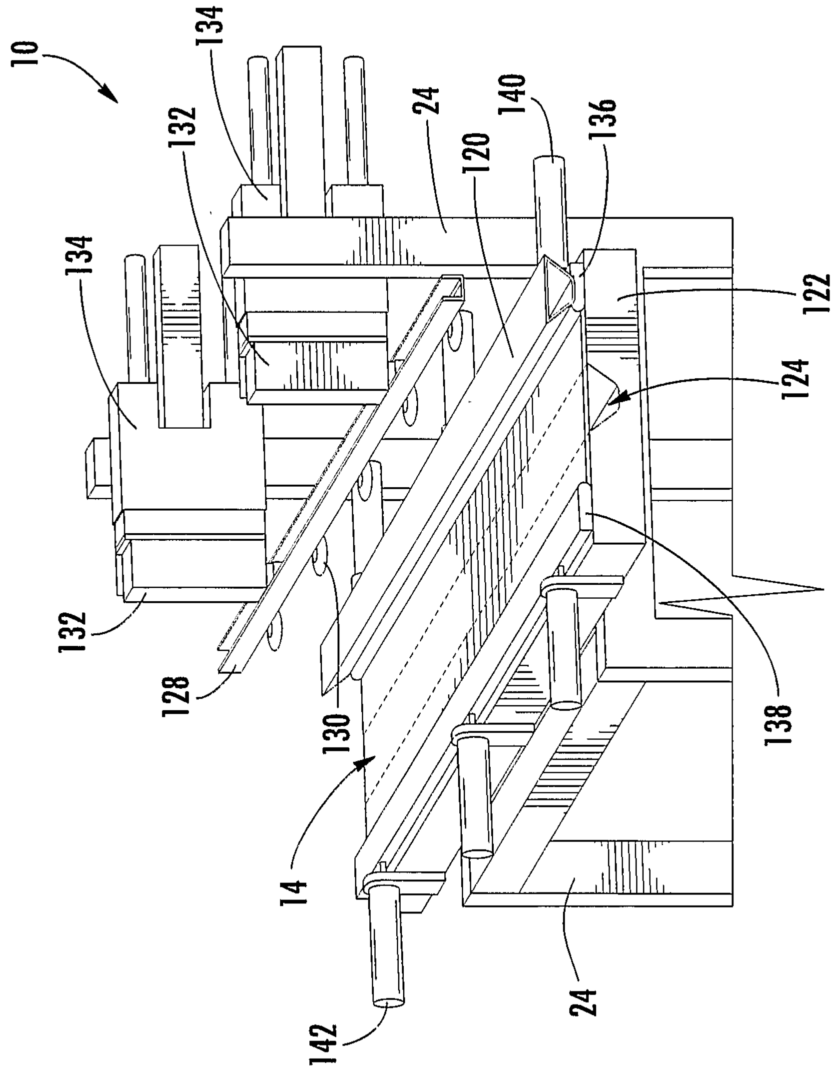


FIG. 16

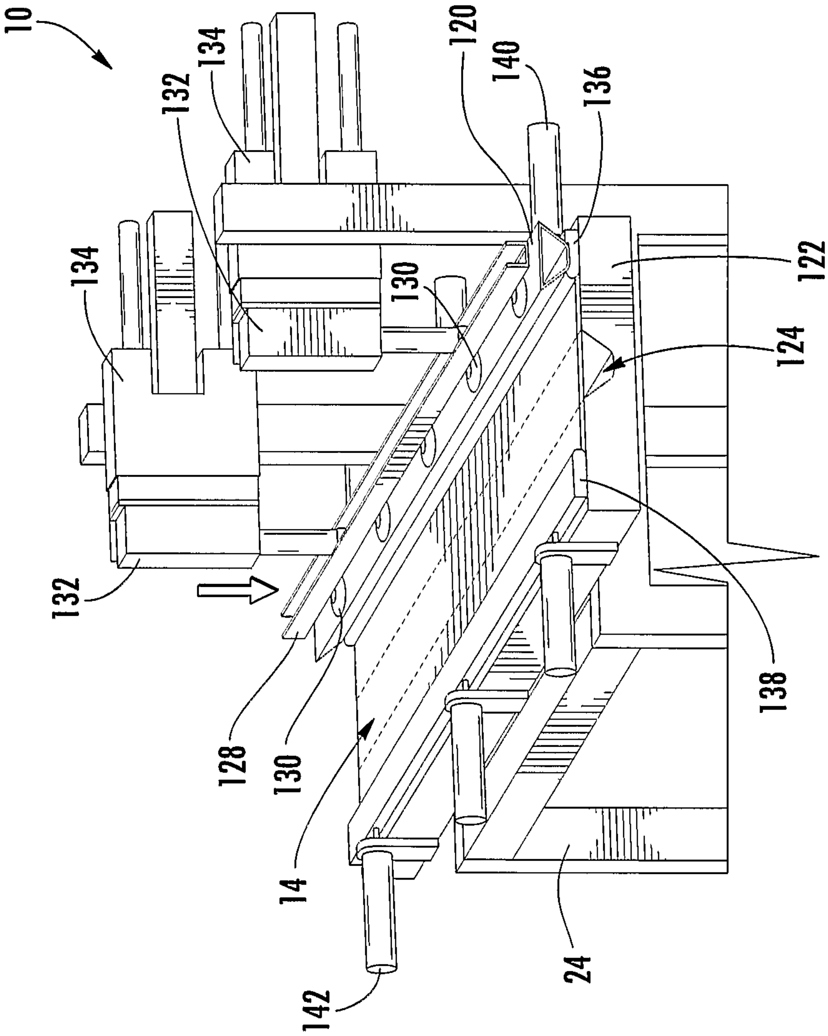


FIG. 17

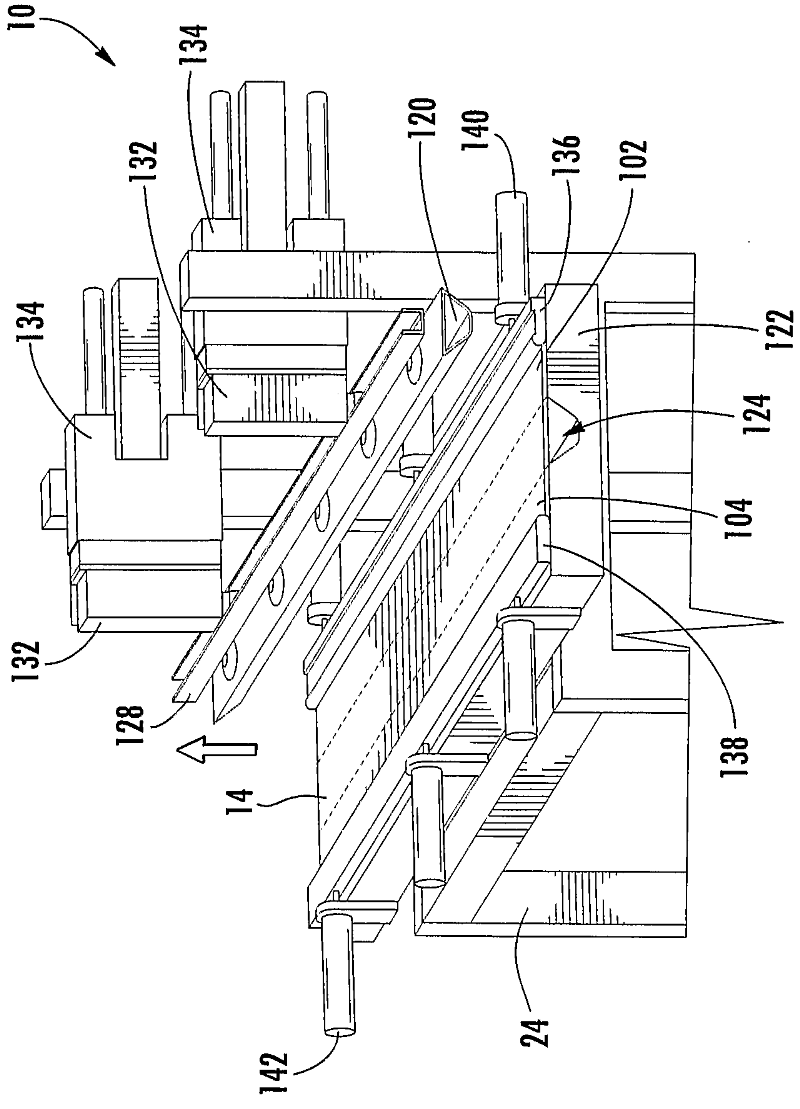


FIG. 18

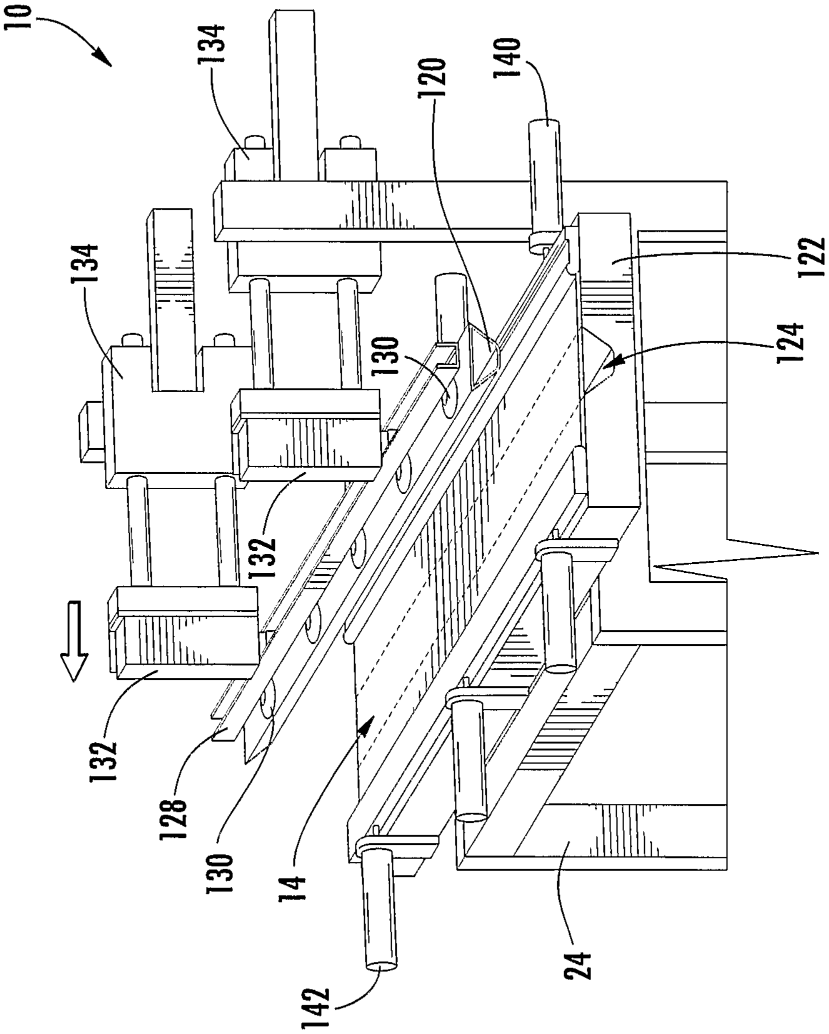


FIG. 19

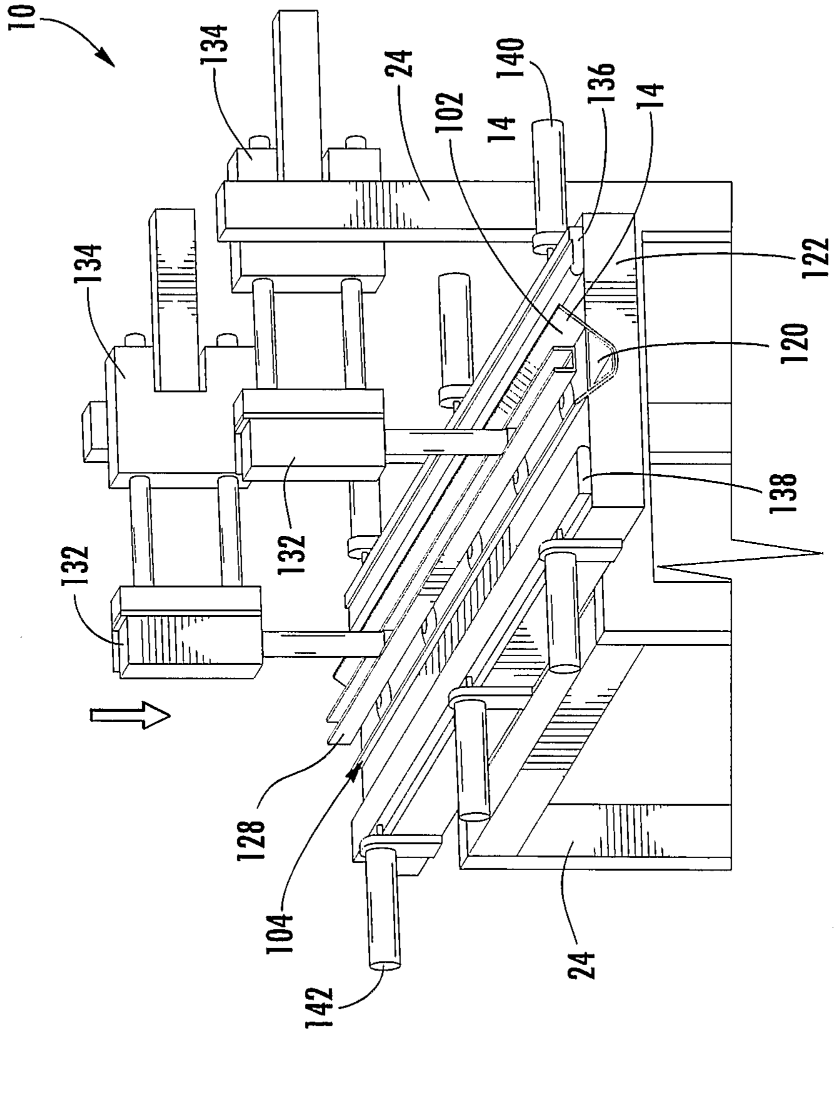
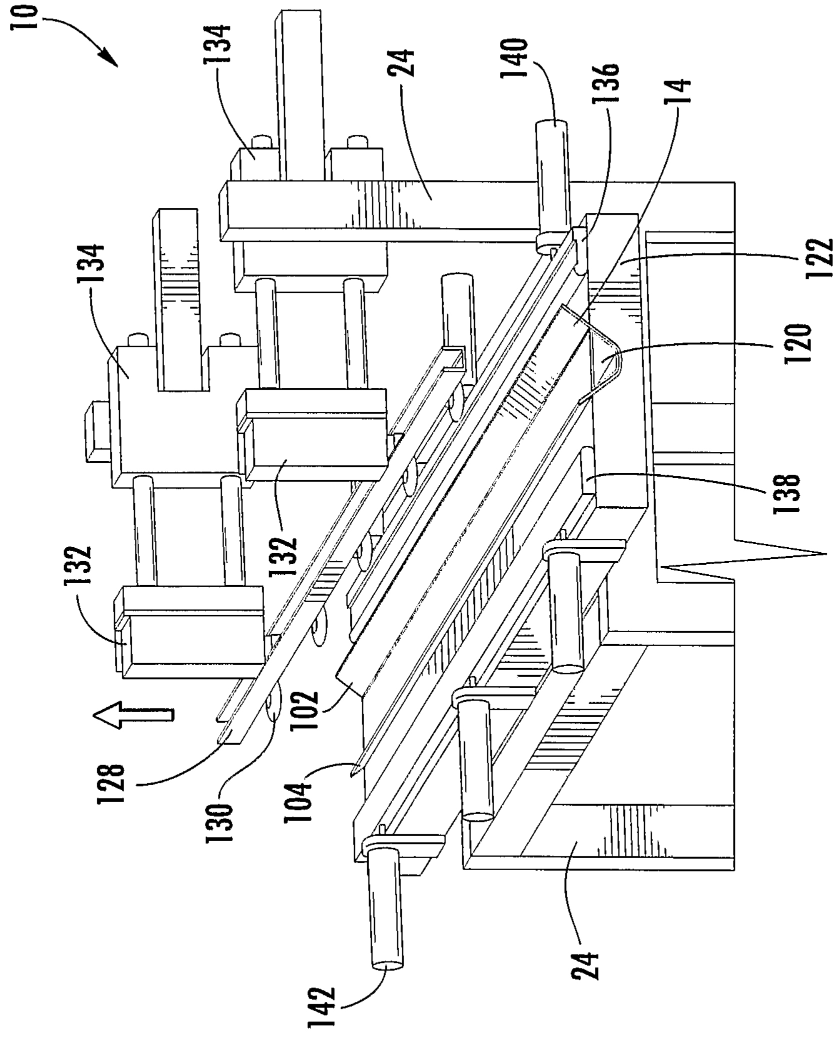


FIG. 20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102
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142

FIG. 21

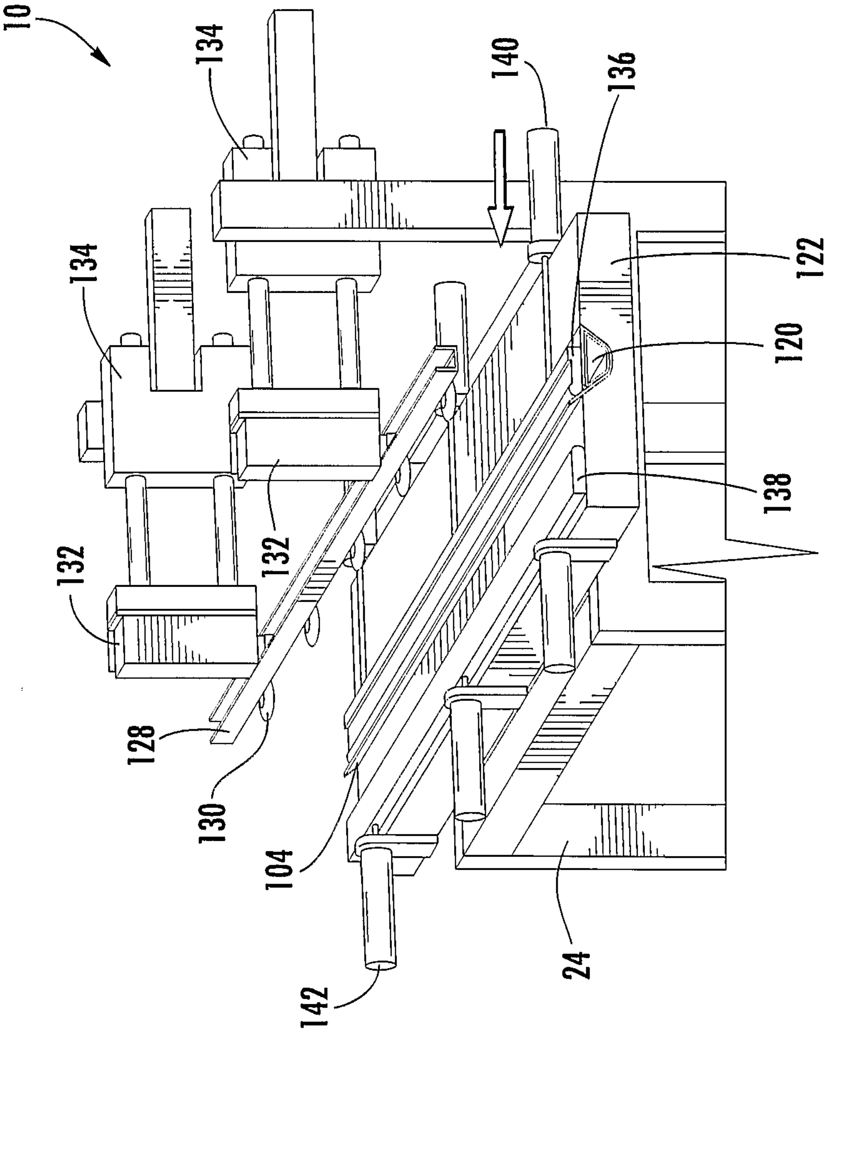

FIG. 22

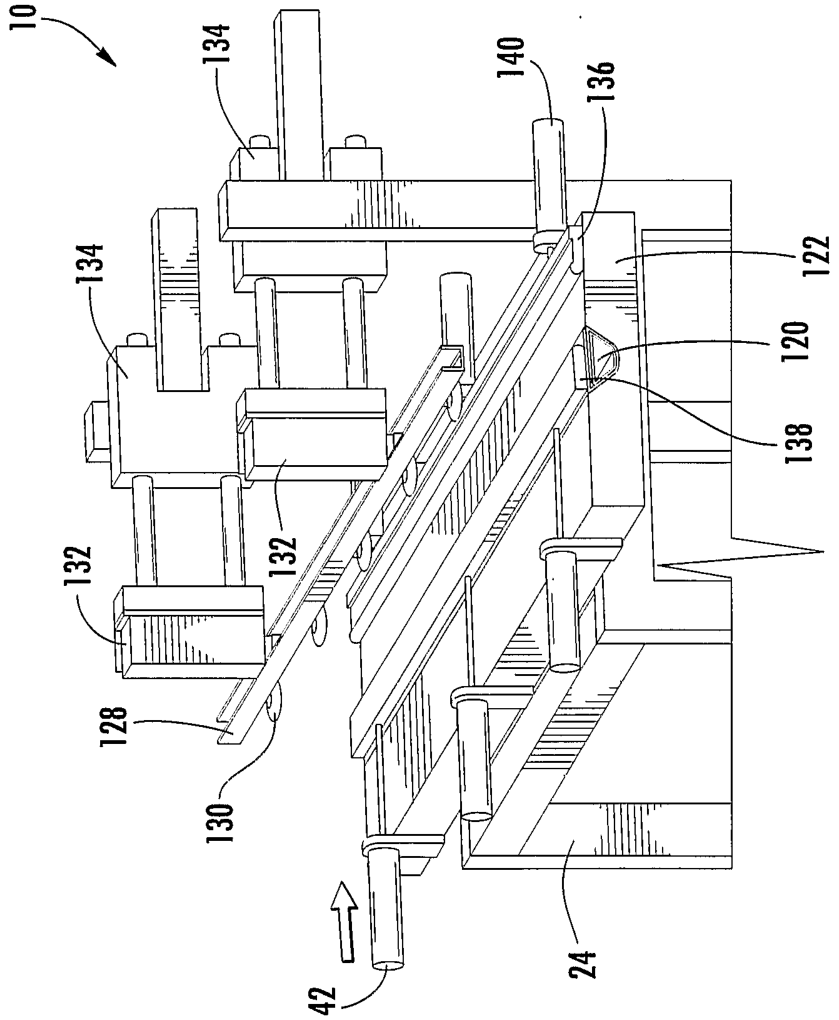

FIG. 23

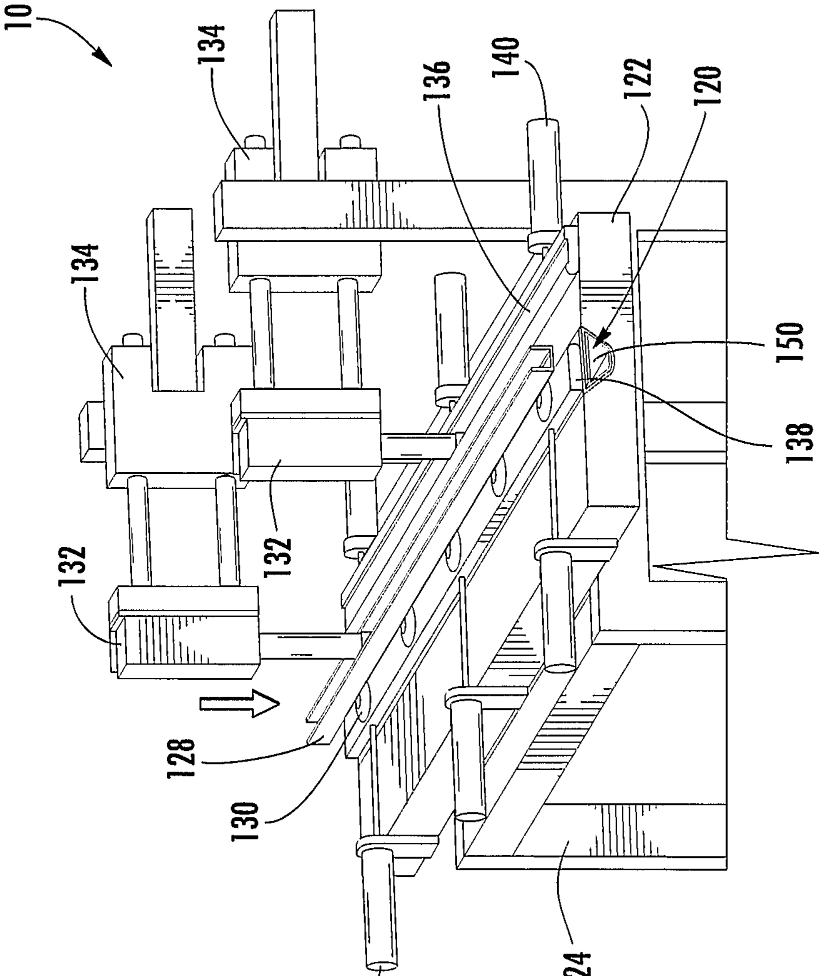

FIG. 24

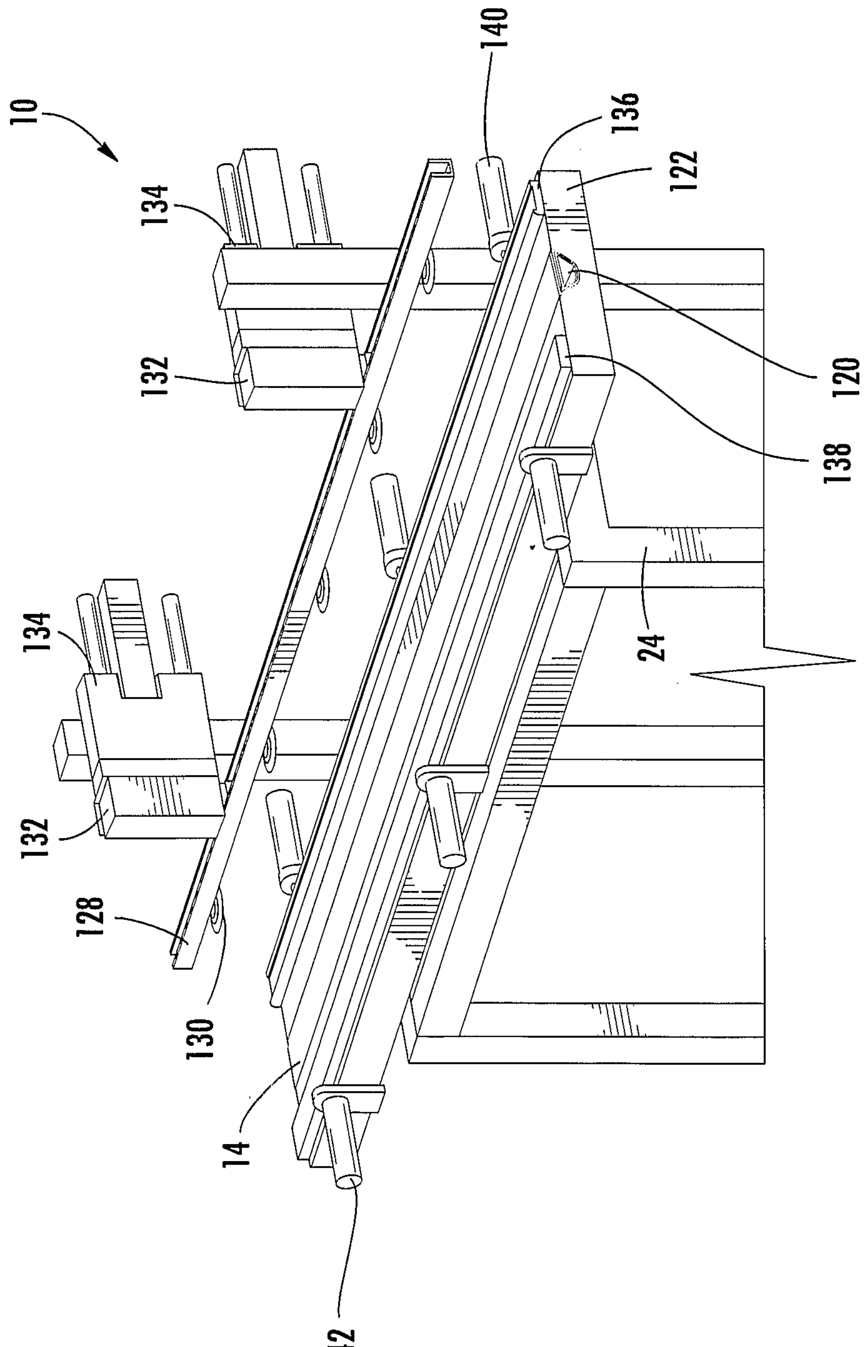

FIG. 25

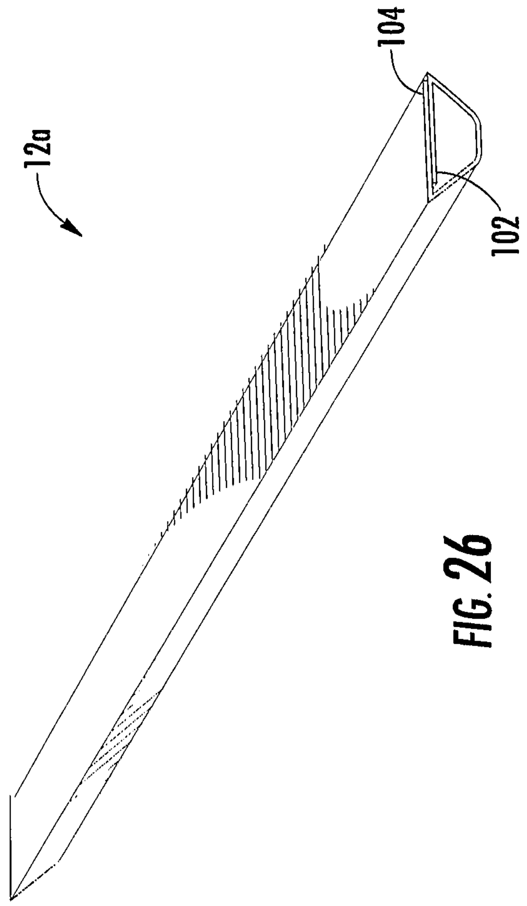

FIG. 26